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**PROCEEDINGS: THE 1992 GREENHOUSE GAS EMISSIONS AND  
MITIGATION RESEARCH SYMPOSIUM**

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#### NOTICE

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## ABSTRACT

The 1992 Greenhouse Gas Emissions and Mitigation Research Symposium, sponsored by the U.S. Environmental Protection Agency's Air and Energy Engineering Research Laboratory (EPA-AEERL), was held in Washington, D.C. on August 18-20, 1992. The purpose of this symposium was to provide a forum of exchange of technical information on global change emissions and potential mitigation technologies. The primary objectives of the meeting were dissemination of technical information and education in recent research. Oral papers along with an international panel discussion, overheads, slides, and a GloED demonstration provided for lively exchanges in the following areas: activities in EPA, DOE, and EPRI on greenhouse gas emissions and mitigation research, and AEERL's global emissions and technology databases; international activities of selected industrialized and developing countries; carbon dioxide (CO<sub>2</sub>) emissions and their control, disposal, and reduction through conservation and energy efficiency, and carbon sequestration including utilization of waste CO<sub>2</sub>; methane (CH<sub>4</sub>) emissions and mitigation technologies including such topics as coal mines, the natural gas industry, key agricultural sources, landfills and other waste management sites, and energy recovery by fuel cells; biomass emission sources and sinks, including cookstove emissions and control approaches; and energy sources, solar and renewable including renewable energy options, alternative biomass fuels, advanced energy systems, solar energy developments, and woodstove emissions and mitigation. The Symposium Proceedings contain 34 submitted papers.

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Frank T. Princiotta, Chairperson

**GREENHOUSE WARMING: THE MITIGATION CHALLENGE**  
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**AIR AND ENERGY ENGINEERING RESEARCH LABORATORY**  
**U. S. ENVIRONMENTAL PROTECTION AGENCY**

Human activity has led to an increased atmospheric concentration of certain gases, such as carbon dioxide, methane, and chlorofluorocarbons, which resist the outward flow of infrared radiation more effectively than they impede incoming solar radiation. This imbalance yields the potential for global warming as the atmospheric concentrations of these gases increase. For example, before the industrial revolution, the concentration of carbon dioxide in the atmosphere was about 280 ppm and it is now about 355 ppm. Similarly, methane atmospheric concentrations have increased substantially and they are now more than twice what they were before the industrial revolution, or about 1.72 ppm. The impact of man's activities is more dramatic with regard to chlorofluorocarbons. These compounds do not occur naturally; they were not found in the atmosphere until their initial discernible production several decades ago.

**FACTORS INFLUENCING GREENHOUSE GAS EMISSIONS**

The emissions responsible for increasing concentrations of greenhouse gases are associated with many human activities, especially the extraction and utilization of fuels, the large-scale deforestation in many developing countries, and other industrial and agricultural practices. Our goal at this conference is to discuss the state-of-the-art and the research opportunities associated with understanding the sources and mitigating releases of these greenhouse gases. I submit that to understand the mitigation opportunities we need to understand the fundamental driving forces for releases of these gases.

Let us concentrate for the moment on carbon dioxide, the most important of the greenhouse gases. The following expression relates the major factors influencing the growth of carbon dioxide emissions over time for a given country:

$$(CO_2)_t = (CO_2)_p \times (1 + P + I_p + E_i + C_e)^y$$

where:

$$(CO_2)_t = \text{projected } CO_2 \text{ emissions}$$

$$(CO_2)_p = \text{present } CO_2 \text{ emissions}$$

$$P = \text{annual population growth rate}$$

$$I_p = \left\{ \begin{array}{l} \text{annual growth rate: industrial production} \\ - \text{annual growth rate: population} \end{array} \right\} \approx \left\{ \begin{array}{l} \text{annual growth rate:} \\ \text{industrial production} \\ \text{per capita} \end{array} \right\}$$

$$E_i = \left\{ \begin{array}{l} \text{annual growth rate: energy use} \\ - \text{annual growth rate, industrial} \\ \text{production} \end{array} \right\} \approx \left\{ \begin{array}{l} \text{annual growth rate:} \\ \text{energy use per unit} \\ \text{unit of industrial} \\ \text{production} \end{array} \right\}$$

$$C_y = \left\{ \begin{array}{l} \text{annual growth rate: carbon emissions} \\ - \text{annual growth rate: energy use} \end{array} \right\} \approx \left\{ \begin{array}{l} \text{annual growth rate:} \\ \text{carbon per unit of} \\ \text{energy used} \end{array} \right\}$$

$y = \text{years into the future}$

The two major factors yielding emission growth are (1) population growth, and (2) industrialization. These factors can be compensated for by two factors which can mitigate growth of greenhouse emissions; these are (1) enhanced energy efficiency (i.e., reduced energy usage per unit of industrial production) and (2) the reduction in the carbon emitted per energy unit utilized.

It is interesting to note the relative magnitude of these factors expected to influence emissions of carbon dioxide over the period 1990 to 2025. The Intergovernmental Panel on Climate Change (IPCC-1992) in their most recent report included a base case of projected emissions for the greenhouse gases all the way to the year 2100. Table 1 illustrates my massaging of these data to extract the factors that are important for developed countries (Organization for Economic Cooperation and Development/OECD countries) versus developing, or poorer, countries (e.g., Asian countries). The table indicates that, for the developed countries, the drivers are projected to be primarily economic growth, whereas population growth is expected to be fairly modest over this time period. The mitigating factors although significant are projected to be insufficient to counteract population and economic growth, yielding an estimated 0.7% annual net growth of carbon dioxide emissions from the developed countries. The situation for the developing countries is even more troublesome. Since their level of economic activity is currently quite modest, it is projected that they will undergo rapid industrialization, at the same time that population is growing at a relatively fast pace. Mitigating factors, namely more efficient use of energy and less carbon intensive energy use, are projected to be modest over this time period. This yields an expected very large growth of 3.9% annual increase in carbon dioxide emissions over this period.

Figure 1 illustrates the expected growth in population by area (IPCC, 1992). As you can see, the developed countries are anticipating relatively low growth rates, whereas the developing countries, especially Asia, Africa, the Middle East, and (to a lesser extent) Latin America, are projected to have very large growth rates over the period 1990 to 2100. As stated earlier, population growth plus rapid industrial growth can yield large increases in carbon dioxide and other greenhouse gas emissions.

Figure 2 illustrates, based on the expected population and industrial growth, projected carbon dioxide emissions over the 1990-2100 time frame. The upper graphic in this figure is the base case for the IPCC 1992 report. It projects growth in emissions from about 7.3 to about 20 gigatons\* of carbon over this period, with Asia, Africa, and the Middle East providing much of the projected growth. The lower graphic is a case I developed to illustrate how important it is for developing countries to move in a more energy efficient, less carbon intensive path than have the developed countries during this century. This case was developed by assuming that by the year 2100 all the developing countries would have a carbon dioxide per capita emission rate

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(\*) 1 gigaton =  $10^9$  metric tons

TABLE 1.  
 ASSUMED ANNUAL GROWTH FACTORS INFLUENCING CO<sub>2</sub>  
 EMISSIONS (1990 - 2025)  
 (Derived from IPCC, 1992)

FACTOR	OECD	Asia
Growth of Economy Per Capita	2.2%	3.5%
Population Growth Rate	0.3%	1.5%
Growth Rate: Energy Use Per Economic Output	-1.1%	-0.8%
Growth Rate: Carbon Emissions Per Energy Use Unit	-0.7%	-0.3%
Annual CO <sub>2</sub> Growth Rate (Sum of above factors)	+0.7%	+3.9%

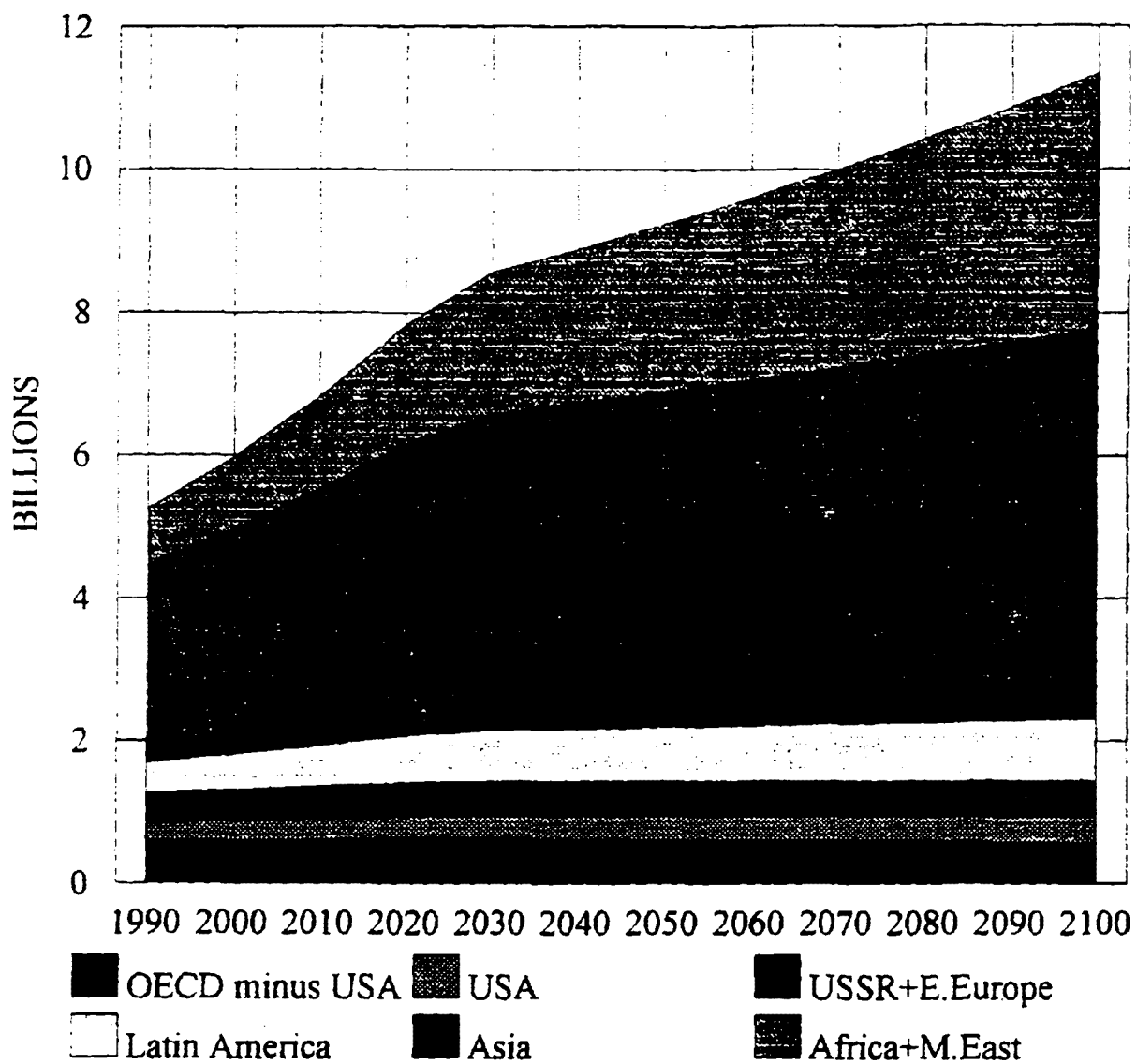
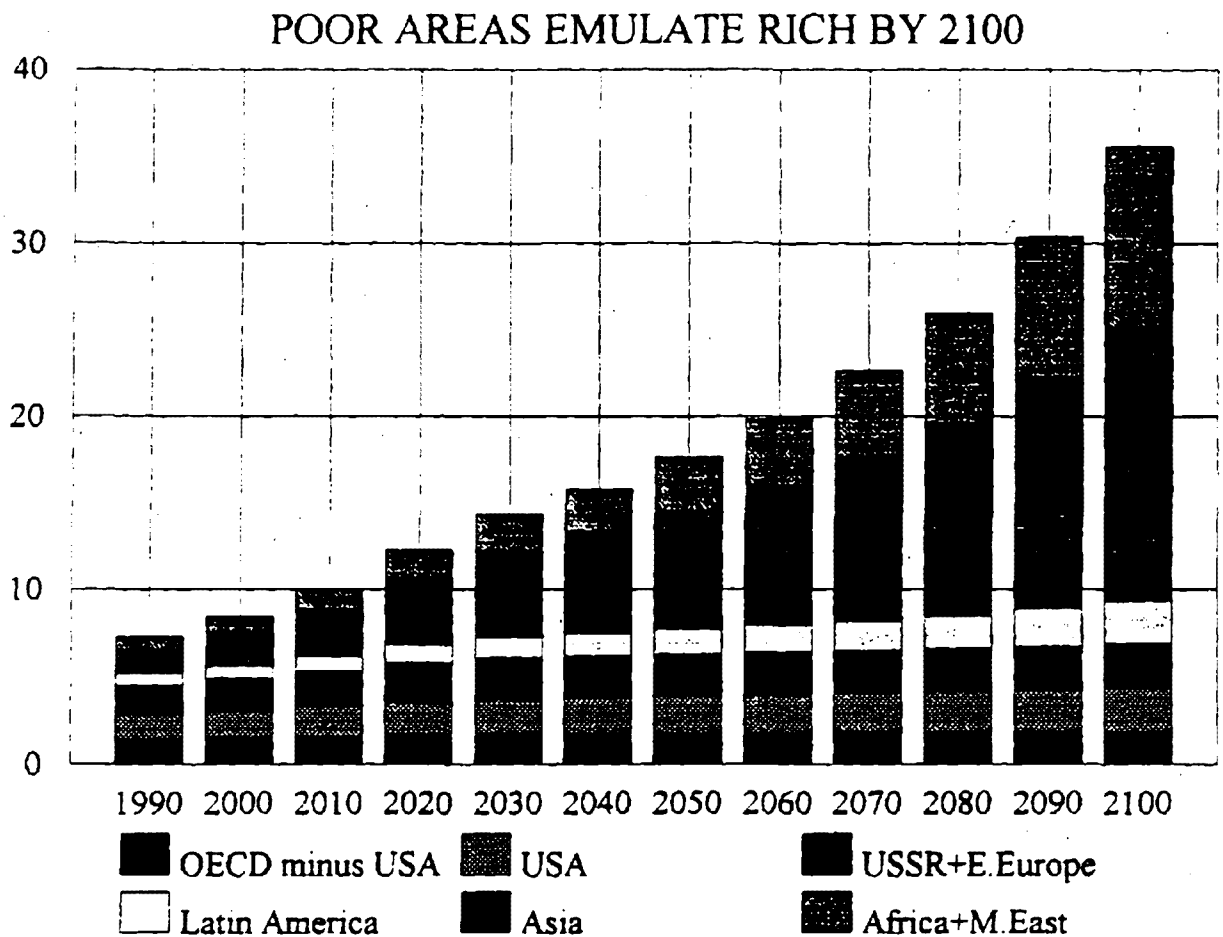
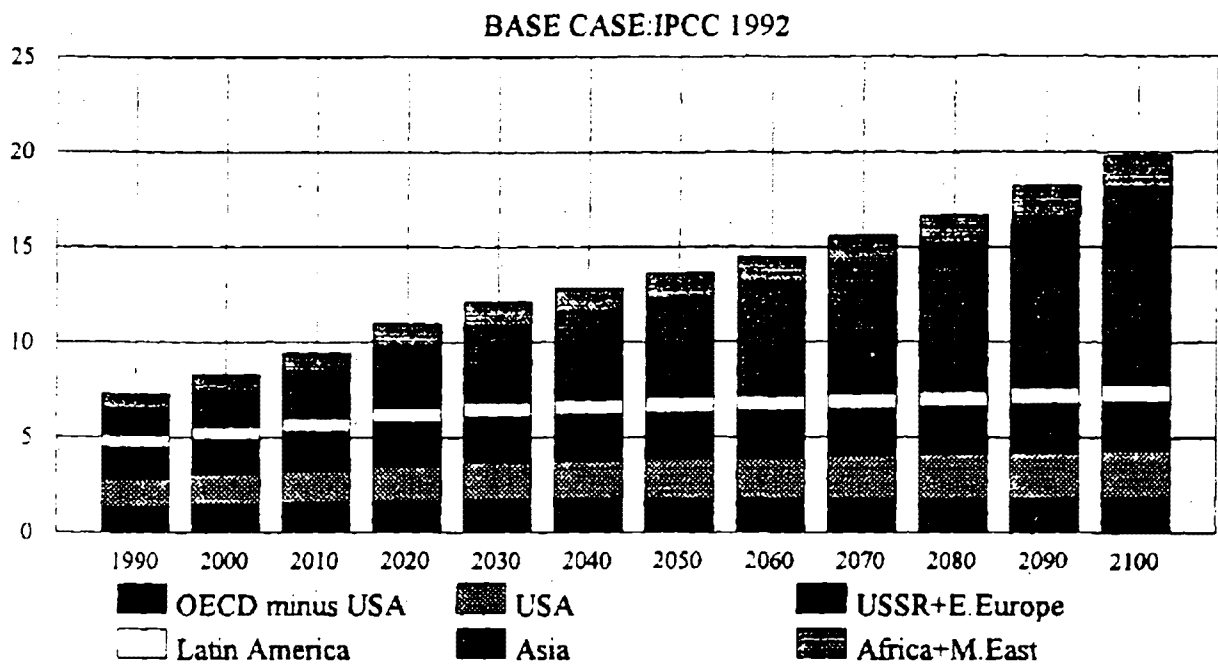


Figure 1. Projected population by area (Source: IPCC, 1992).



By 2100 developing countries have  
 $\text{CO}_2$  per capita =  $\frac{1}{2}$  current U.S. value = 2.9

Figure 2.  $\text{CO}_2$  Emissions: gigatons C for two uncontrolled cases.

one-half of the current U.S. value, or about 2.9 tons of carbon per capita. Stated another way, this case assumes that over the next 110 years all developing countries will have a standard of living and economic structure with an energy use pattern similar to contemporary Europe. In my view, this is not a wild assumption. Assuming this, emissions are almost twice that projected by the IPCC. Perhaps this case represents an upper limit of what could happen in the absence of serious changes in global energy use patterns.

### **PROJECTED GREENHOUSE WARMING**

It is instructive to relate these projected emissions to anticipated global warming. I have utilized a model I developed which relates emissions of individual greenhouse gases to equilibrium temperature increases using lifetimes, and radiative forcing functions contained in IPCC, 1990. Realized (or actual) temperature is estimated using realized projection calculations in IPCC, 1992, which have been correlated with the model's equilibrium calculations.

Figure 3 relates various emission grown scenarios to projected temperature rise. Note that this is referred to as realized (or transient) temperature rise, which attempts to take into account the thermal inertia associated with the Earth's features, especially oceans. (Equilibrium temperatures, on the other hand, are sometimes reported which ignore the thermal inertia factor. Typically, these temperatures are 1.5 to 2 times higher than the corresponding realized temperature increases.) Also note that there are large uncertainties in these numbers, probably by at least a factor of 2 on both the high and low ends. An atmospheric sensitivity to doubling carbon dioxide concentrations of  $2.5^{\circ}\text{C}$  was assumed in these calculations. The two uncontrolled emission projection cases we previously discussed were analyzed: the IPCC base case and what I call the fast growth case which assumes that the developing countries will approach the current industrialized world in terms of carbon dioxide emitted per capita. In the IPCC base case, warming is estimated at about  $3^{\circ}\text{C}$  by the end of the next century (consistent with IPCC, 1992). If we were to cap emissions of all greenhouse gases during the year 2000, it is expected that this warming can be reduced about 30% to a little over  $2^{\circ}\text{C}$ . If the international community would mitigate further and actually reduce emissions 1% a year starting in the year 2000, we can limit the rise to about  $1.5^{\circ}\text{C}$ .

This model calculates that it would require a 2%/yr emission reduction program to stabilize warming to about  $1^{\circ}\text{C}$  over 1980 levels. I believe that these numbers suggest the major challenge which faces humankind, if we decide to seriously limit the projected greenhouse warming.

### **A LOOK AT THE IMPORTANT GREENHOUSE GASES**

Let us now take a look at the important greenhouse gases and their relative contributions. Figure 4 shows the projected contributions by the major greenhouse gases assuming the IPCC (1992) base case over the period 1980 - 2100. As you can see carbon dioxide is the most important gas with methane and chlorofluorocarbons and their substitutes also important. Note that the analysis assumed that all countries would reasonably implement international agreements to phase out chlorofluorocarbons. The model, however, assumes that some of the substitutes, like HFC-134a, which are substantial greenhouse gases in their own right, will be produced and



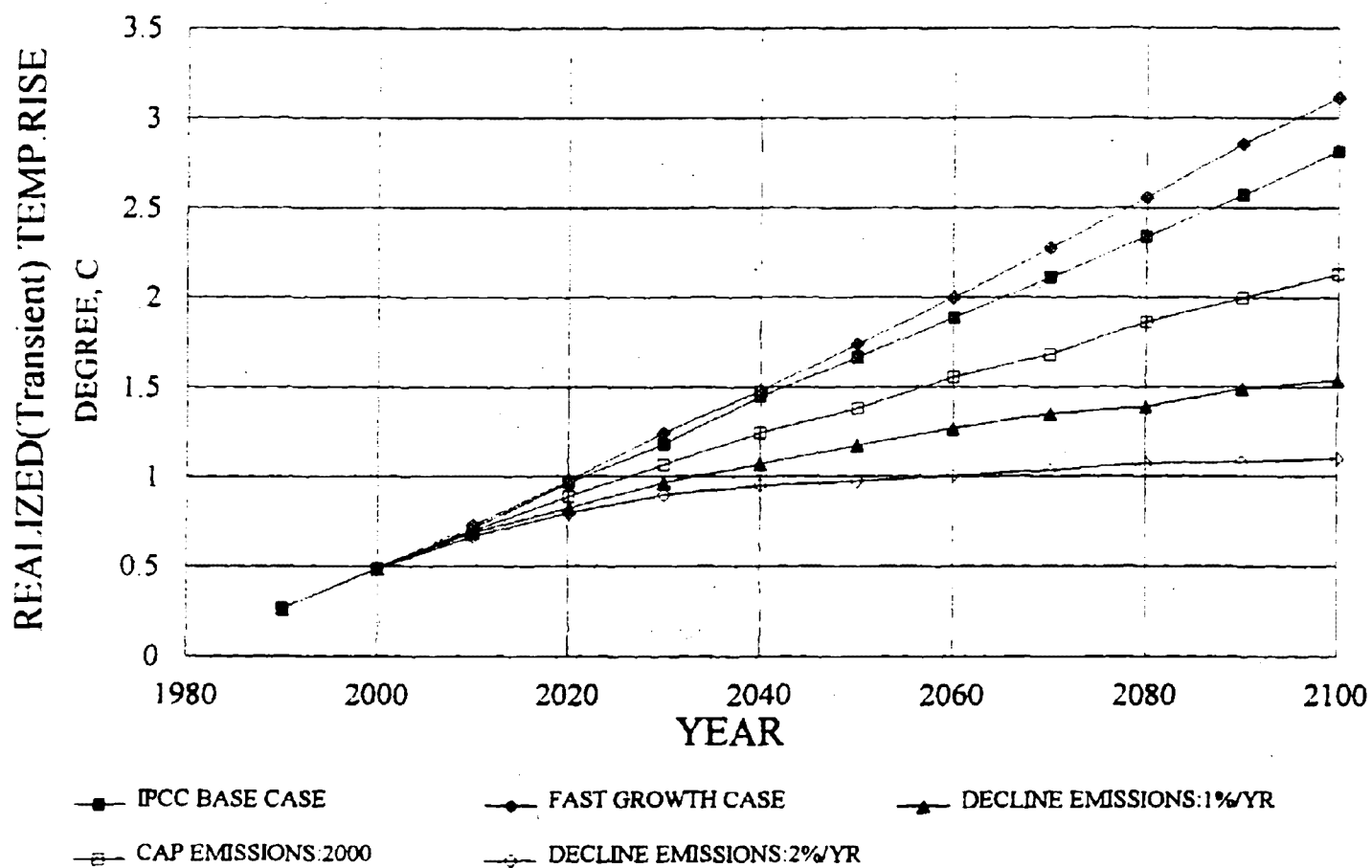


Figure 3. Global warming -- four cases (control starts: 2000).

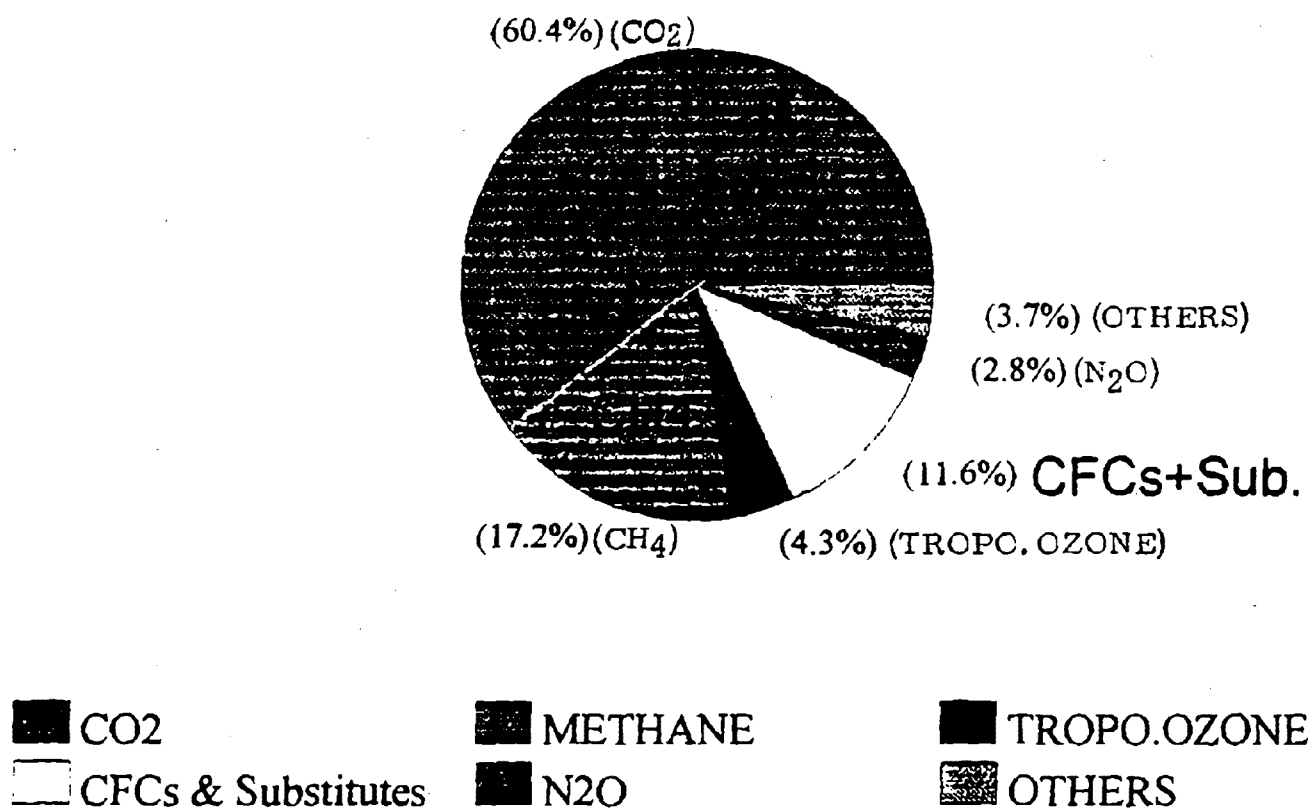


Figure 4. Equilibrium global warming by gas (1st year: 1980; end year: 2100).

emitted in large quantities.

Note that the contribution of carbon dioxide is probably the best documented of the gases. The methane calculations, for example, assume indirect effects of methane. Methane decomposes to other greenhouse gases in the atmosphere: ozone, carbon monoxide, carbon dioxide, and water. Note that there is a large degree of uncertainty over the magnitude, albeit not the direction, of these indirect effects of methane. Nevertheless, I included them here since I believe they ultimately will be important. Also note that other precursors of tropospheric ozone have many uncertainties as well. There is the need for considerable atmospheric modeling and measurements to relate emissions of volatile organic compounds, nitrogen oxides, and carbon monoxide to high-level tropospheric ozone to better understand the significance of this gas as a greenhouse warming contributor in the upper troposphere.

Figure 5 illustrates the relevant importance of gases over the 100-year time period of the analysis, again using the IPCC 1992 base case. (Note that the potential cooling effect of atmospheric aerosols has not been factored into the model calculations.) As you can note, the short-lived gases, such as methane and ozone, are more important contributors early in this time frame, with carbon dioxide becoming more dominant later in the time frame. This is associated with the decay rates of the gases involved. Figure 6 illustrates an important mitigative advantage in dealing with short-lived gases, such as methane, in that an aggressive control program can stabilize atmospheric concentrations and mitigate warming relatively quickly. This figure shows that, if all gases were controlled at 1% a year from the period 1980 to 2100, essentially all the methane projected warming could be mitigated whereas only about 60% of the carbon dioxide warming could be mitigated since the half-life in the atmosphere of carbon dioxide is so long that emission reductions don't lead to reduction in atmospheric concentrations until many decades later. Figure 7 illustrates this phenomenon by plotting concentration ratios relative to 1980 for two long-lived gases (carbon dioxide and nitrous oxide) and the short-lived methane, all of which had their emissions reduced by 1% a year starting in the year 2000. As you can see, because of methane's shorter half life, it responds more quickly to mitigation, yielding lower driving forces for greenhouse warming. Table 2 summarizes what we've discussed relative to the important greenhouse gases. Note that this table also briefly summarizes major uncertainties regarding each gas' warming potential, and identifies major human sources.

It is also instructive to estimate the impact of chlorofluorocarbons (and related compounds). Although these compounds are potent greenhouse gases based on their radiative properties, recent data suggest that they have been responsible for ozone depletion in the lower as well as the upper stratosphere. Since ozone in this lower region is a potent greenhouse gas, there is a net cooling associated with this ozone depletion which opposes the radiative warming impact. It appears that chlorofluorocarbons have not been the significant greenhouse warming contributors previously believed. Figure 8 shows the results of model calculations which do not take into account the cooling effect. What is most interesting is that it is possible that the net effect of replacing chlorofluorocarbons with compounds such as HFC-134a, which is a potent greenhouse gas in its own right, could be warming! This could occur since such replacements which are chlorine free (and therefore non-ozone depleting) will contribute to warming without the opposing cooling associated with ozone depletion.

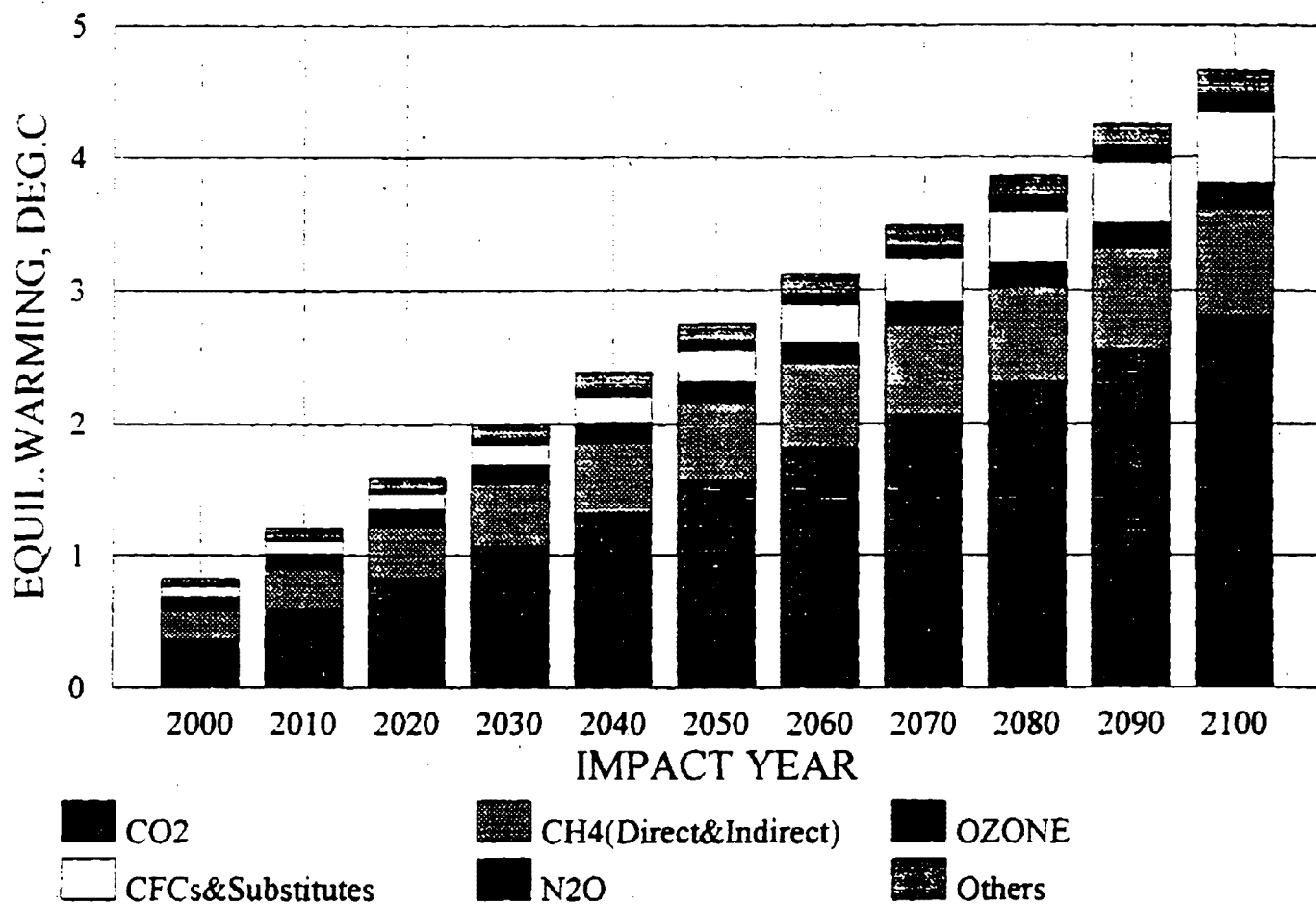


Figure 5. Equilibrium warming , °C, by gas (IPCC, 1992, base case).

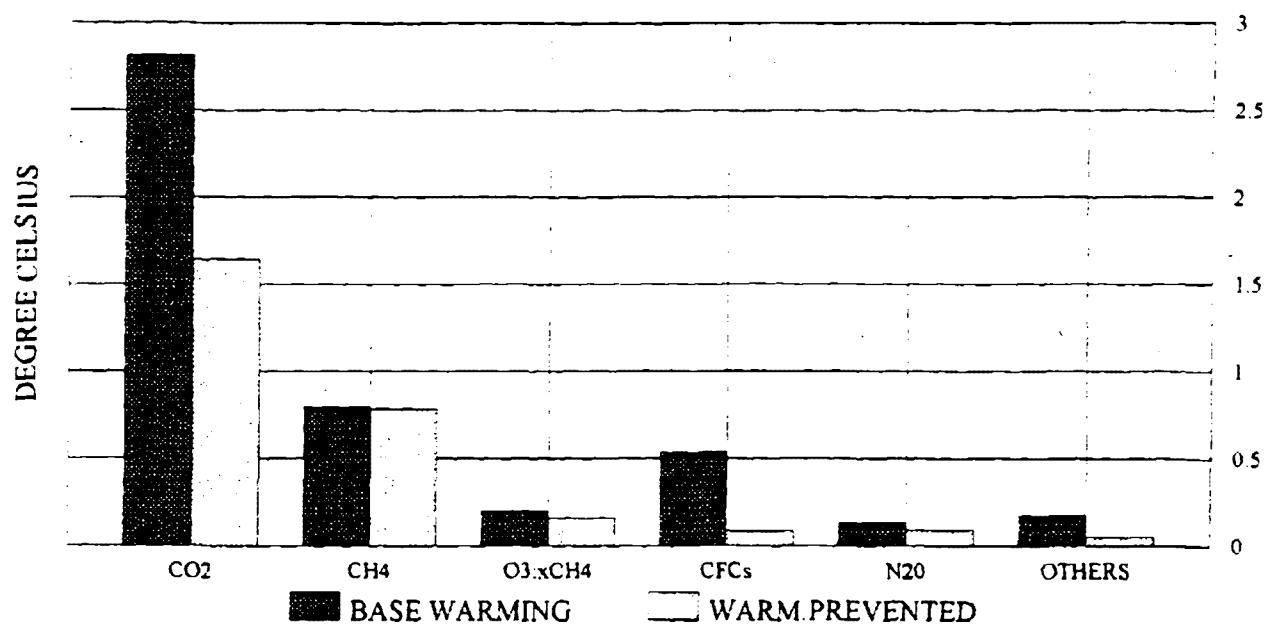


Figure 6. Warming prevented by 2000 emission control (period: 1980-2100; annual emission control: 1%/yr).

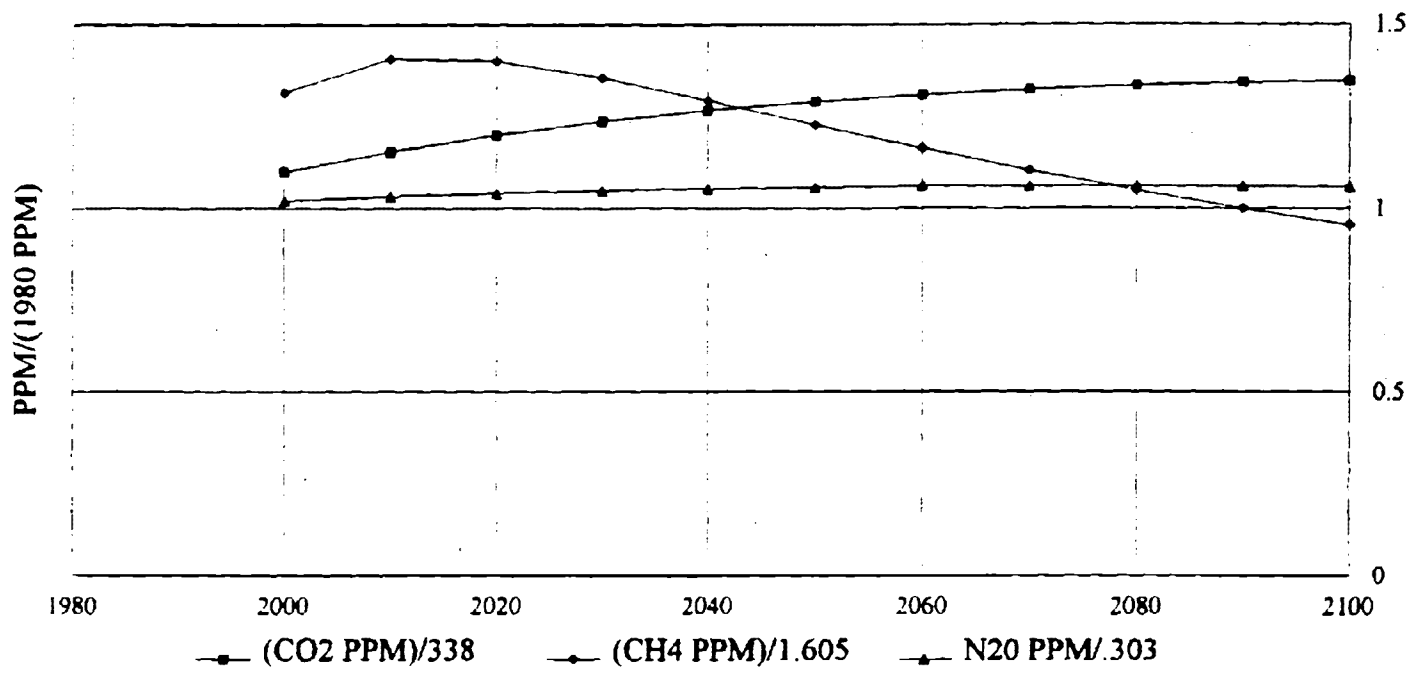


Figure 7. Concentration ratio for three gases (relative to 1980).

TABLE 2. GREENHOUSE GASES -- WHAT IS KNOWN AND WHAT ISN'T

GREENHOUSE GASES - WHAT IS KNOWN AND WHAT ISN'T						
Characteristic	Carbon Dioxide	Methane	CFC-11/CFC-12	HFC-134a	Tropo. Ozone	N <sub>2</sub> O
1. Atmospheric Lifetime (Yrs)	50-100	10-12.5	65/130	16	<<1	150
2. Current Concentration/ Pre-Industrial Concentration	1.26	2.15	Infinite (No Natural Sources)	New CFC Substitute	>1, But Poor Data	1.08
3. Projected Warming By Gas At the Year 2050	58%	22% (Incl. Indirect Effects)	0.2% (FOR CFC-11 + CFC-12) (Assumes Phaseout)	5%	6% (Excludes CH <sub>4</sub> source)	3.6%
4. Impact of 1%/yr Mitigation: Control Starts 2000, the Impact at 2050: Calculated as % of total mitigation:	47%	34%			8%	2%
5. Confidence in Warming Calculations for Items 3. and 4. Above	Good	Fair	Poor	Fair/Good	Poor	Fair
6. Major Uncertainties	Quantification of Terrestrial sinks	1. Quantific. of Natural, & Human Sources & Sinks 2. Explanation needed for decelerating growth in Atm. Concentrations	Recent data suggest strato. ozone depletion may counteract tropo. warming impacts	Since no Cl, Warming Impacts not Counteracted by Strato. Ozone Depletion	1. Atmospheric chemistry models insufficient 2. Data on Tropo. Ozone Trends Poor 3. Emission data for NO <sub>x</sub> , Hydrocarbons & CO Precursors poor	Atmospheric Concentration Rising Faster than known sources/sinks predict
7. Major Human Sources	Fuel Combustion - Electric Power - Mobile Sources - Industrial Deforestation	Coal Mining Natural gas & oil production and transportation Landfills Rice Paddies Ruminants Biomass burning	Refrigeration Cycles Plastic Foams Solvent Use	Refrigeration Cycles	Mobile Sources: VOCs, NO <sub>x</sub> and CO Stationary Combustion: NO <sub>x</sub> , CO Biomass Burning: CO, VOCs	Biomass Burning Adipic & 1,4-NO <sub>3</sub> production Mobile Sources Farming Stationary source Combustion

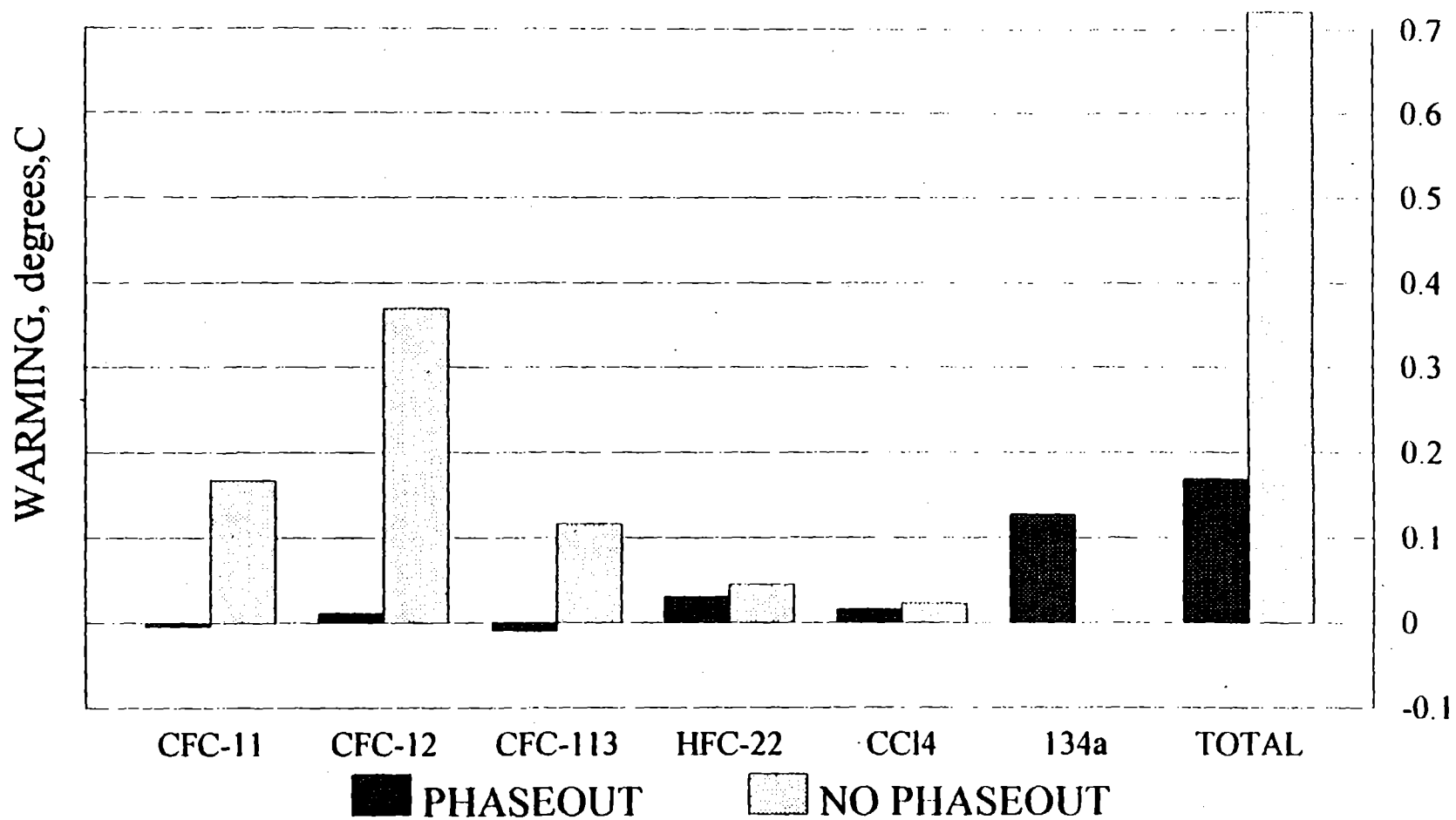


Figure 8. CFC Equilibrium Warming, °C (1st year; 1980; impact year: 2050; base: IPCC, 1992).



## WHAT PENALTIES ARE ASSOCIATED WITH DELAYING MITIGATION?

One important question relative to mitigation is: what penalties are associated with delaying implementation of a mitigation program? Or stated differently, how much mitigation opportunity would be lost if a mitigation program were started later rather than sooner? Figure 9 attempts to answer this question by plotting realized (transient) projected warming at 2100 for three cases as a function of the year the control of all greenhouse gases would be initiated. Included is a business-as-usual case per the IPCC 1992 emission scenario. Three control cases are included, two where emissions are reduced by 1% and 2% a year, respectively; and the third where emissions are capped at the year control is initiated at that emission level for all greenhouse gases. Looking at the two decline cases, you can see that a 10-year delay in initiation of a mitigation program yields a significant diminishment in the ability to mitigate projected global warming. The graphic suggests that a 20-year delay in a 1%/yr mitigation program would require a 2%/yr program to achieve the same degree of warming mitigation that would have been achieved by the more modest program 20 years earlier.

## MITIGATION CHALLENGES FOR THE U.S.

In order to understand the factors influencing greenhouse gas emissions in the U.S., I have utilized another projection model. This model calculates emissions of carbon dioxide, methane, and chlorofluorocarbons as a function of input factors such as population growth, industrial growth, fuel use patterns, energy utilization efficiency, introduction of renewable energy technology, and mobile source miles per gallon. This model incorporates the electric utility module described in an earlier paper (Princiotta, 1990).

Figure 10 shows projected equivalent emissions for the 1980-2020 time period for a business-as-usual case (DOE, 1987). Figure 11 shows the expected increase of carbon dioxide emissions over the same time period for the major energy/use sectors. This projection suggests that significant emission increases will result primarily from both increased use of coal to generate electricity, and growth in the mobile source sector due to a larger auto, truck, and aircraft fleet. Figure 12 shows that growth in electricity use is a critical parameter in determining carbon dioxide emissions from the important electric utility sector. Although introduction of renewable technologies, such as those based on solar or biomass energy sources, would help mitigate emissions later in this time frame (Princiotta, 1990), the use of so-called clean coal technologies such as integrated gasification combined cycle (IGCC) will have little impact. Figure 13 shows that, even with a major introduction of IGCC technology (up to 300,000 MW), only a modest amount of carbon dioxide is mitigated. These results assumed efficiency for IGCC is 41% vs 37% for conventional coal-fired units; yielding only an 11% savings in coal use.

Figure 14 illustrates current and projected emissions from the major U.S. sources of methane. Note the importance of landfills, emissions from cows and sheep, and coal mine and natural gas pipeline leakage.

Last year the Administration (DOE, 1991) proposed an energy strategy that would have a significant impact on greenhouse gas emissions. This strategy promoted a major research,

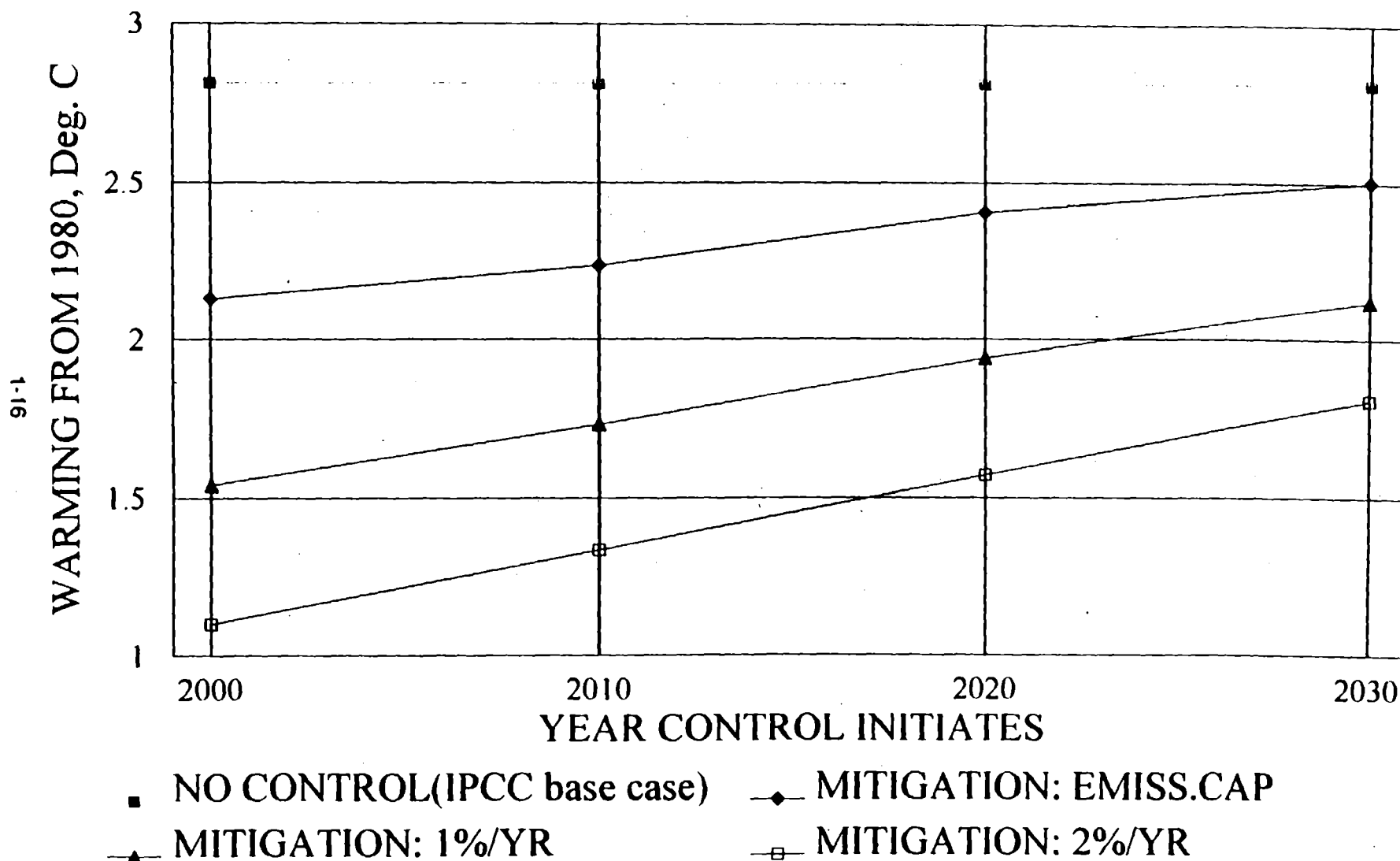


Figure 9. Warming vs. year control starts, impact year 2100.

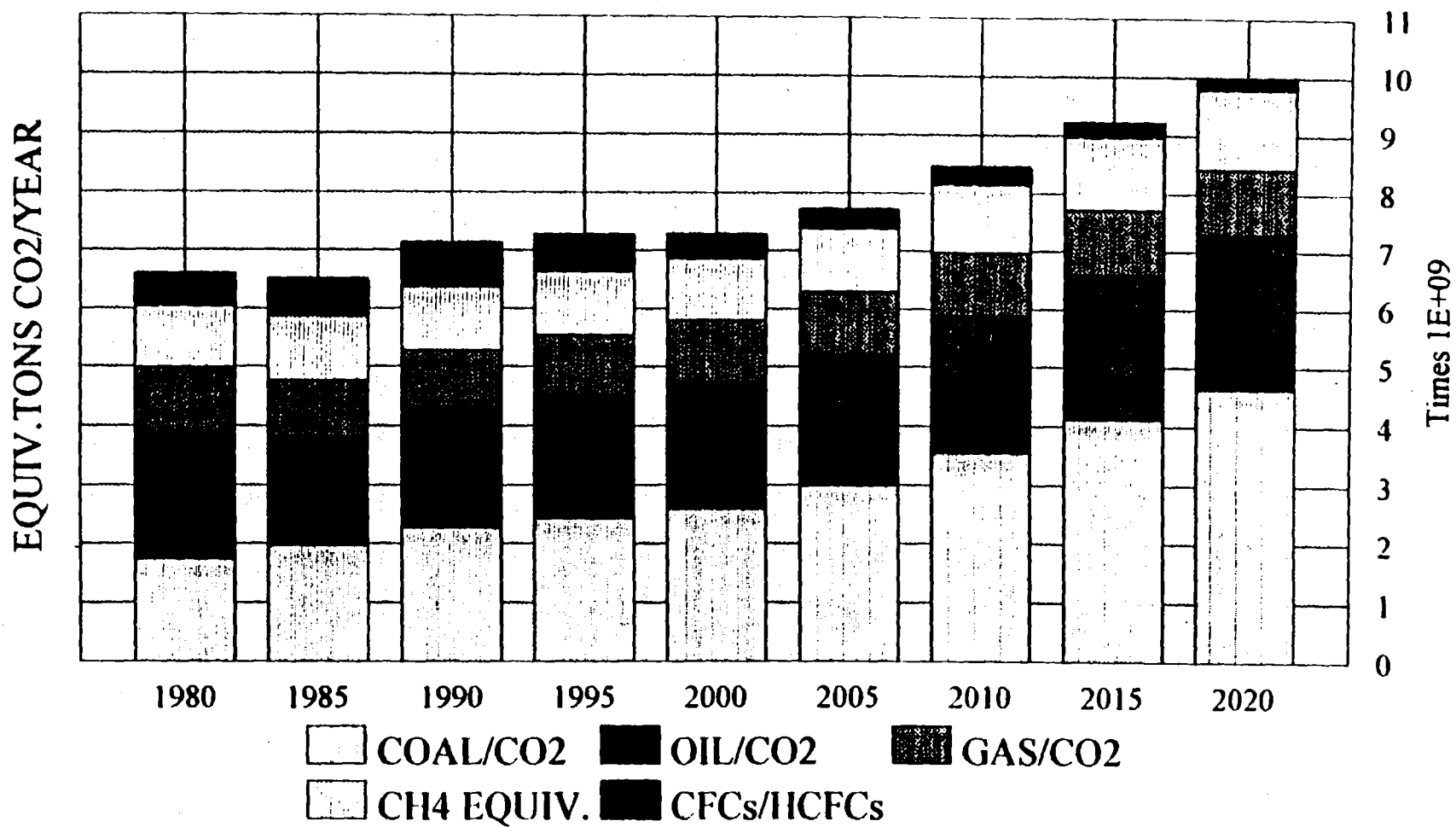


Figure 10. U.S. Equivalent CO<sub>2</sub> emissions [including methane (30 x equivalent), chlorofluorocarbons, and hydrochlorofluorocarbons].

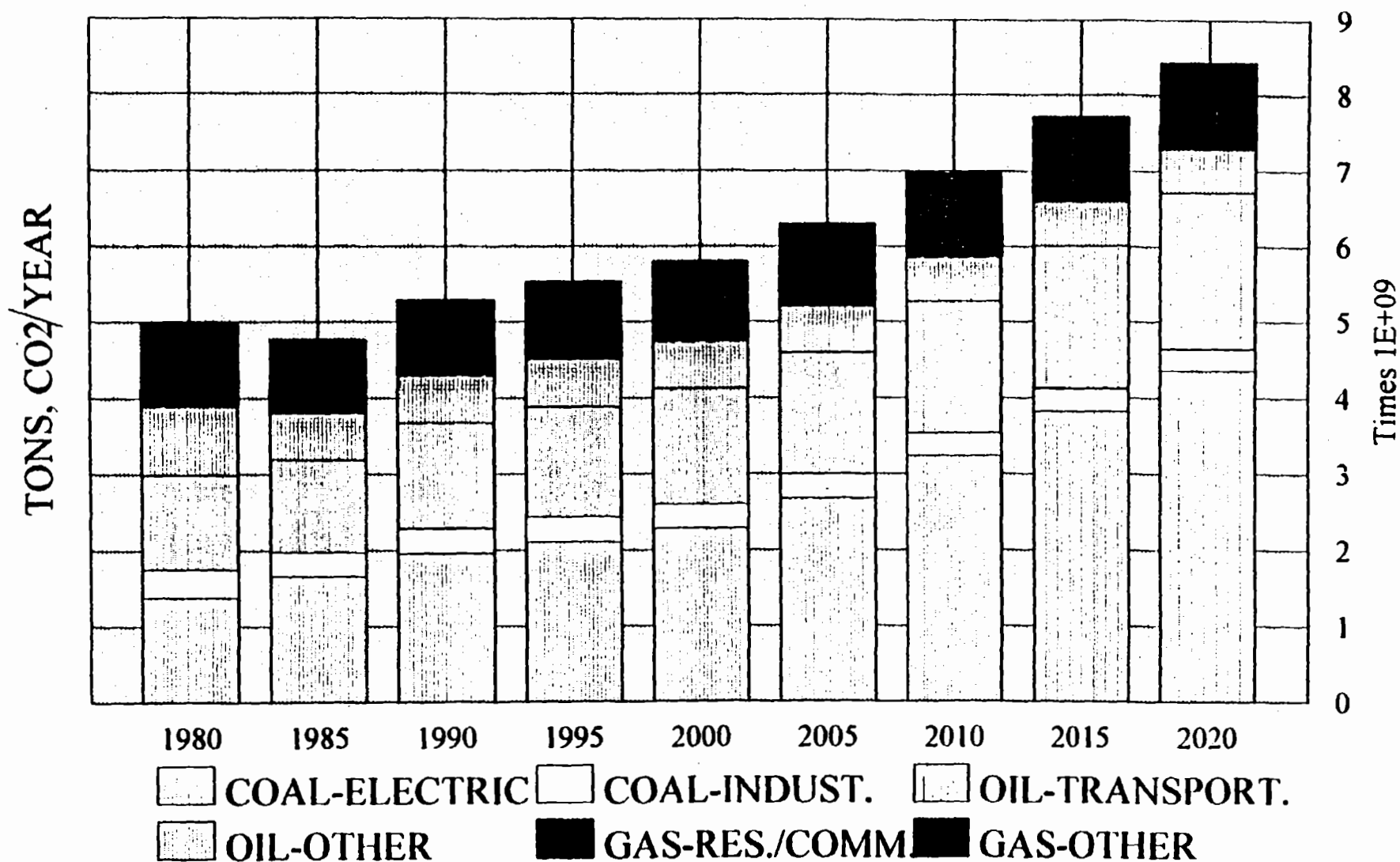


Figure 11. U.S. CO<sub>2</sub> Emissions by fuel/sector.

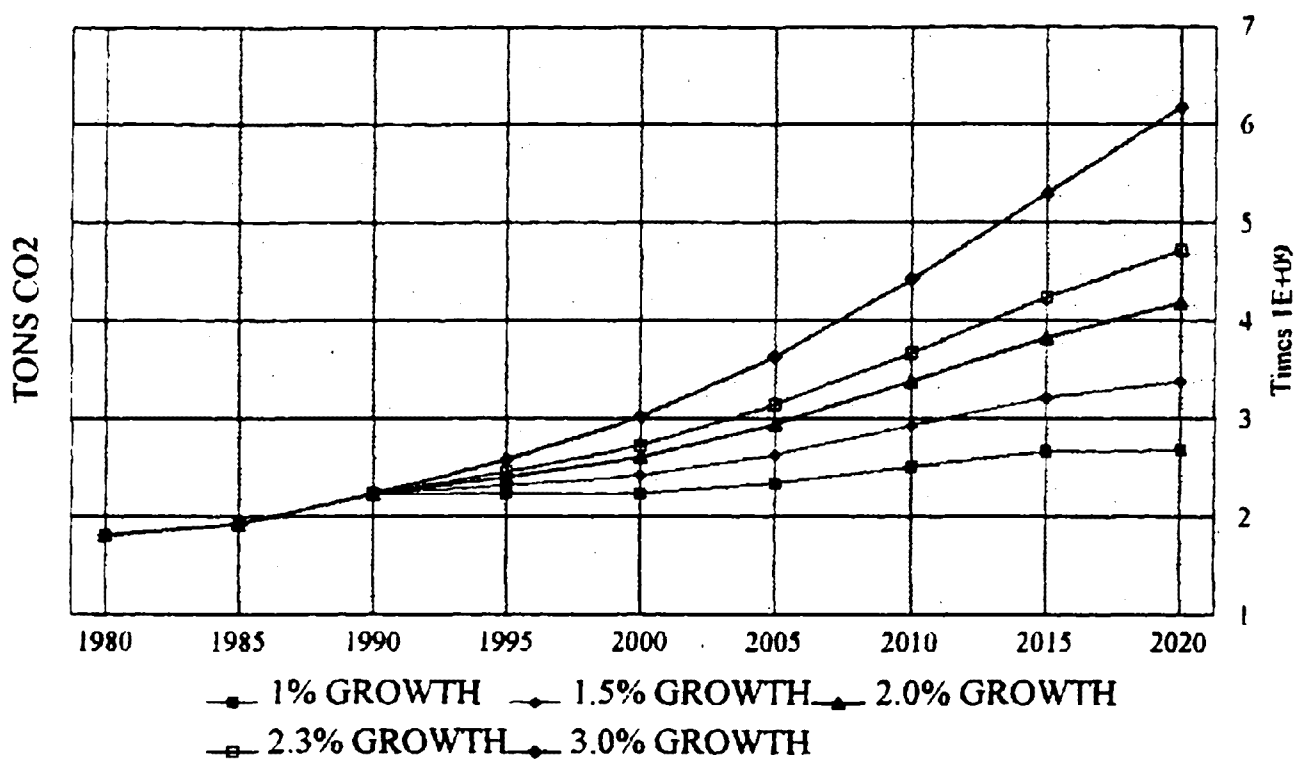


Figure 12. CO<sub>2</sub> Emissions from electricity production (vs. electricity annual demand growth).

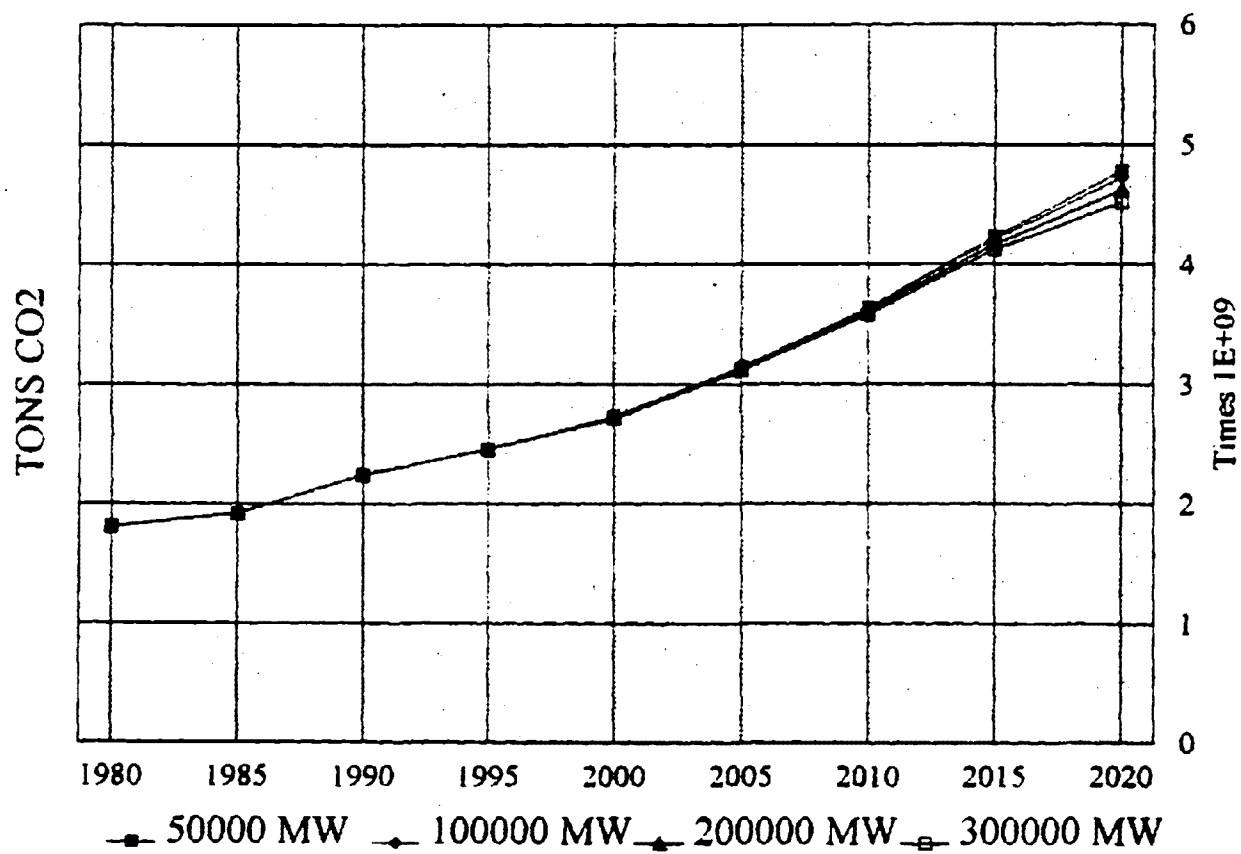


Figure 13. CO<sub>2</sub> Emissions from electric power (assuming various clean coal scenarios).

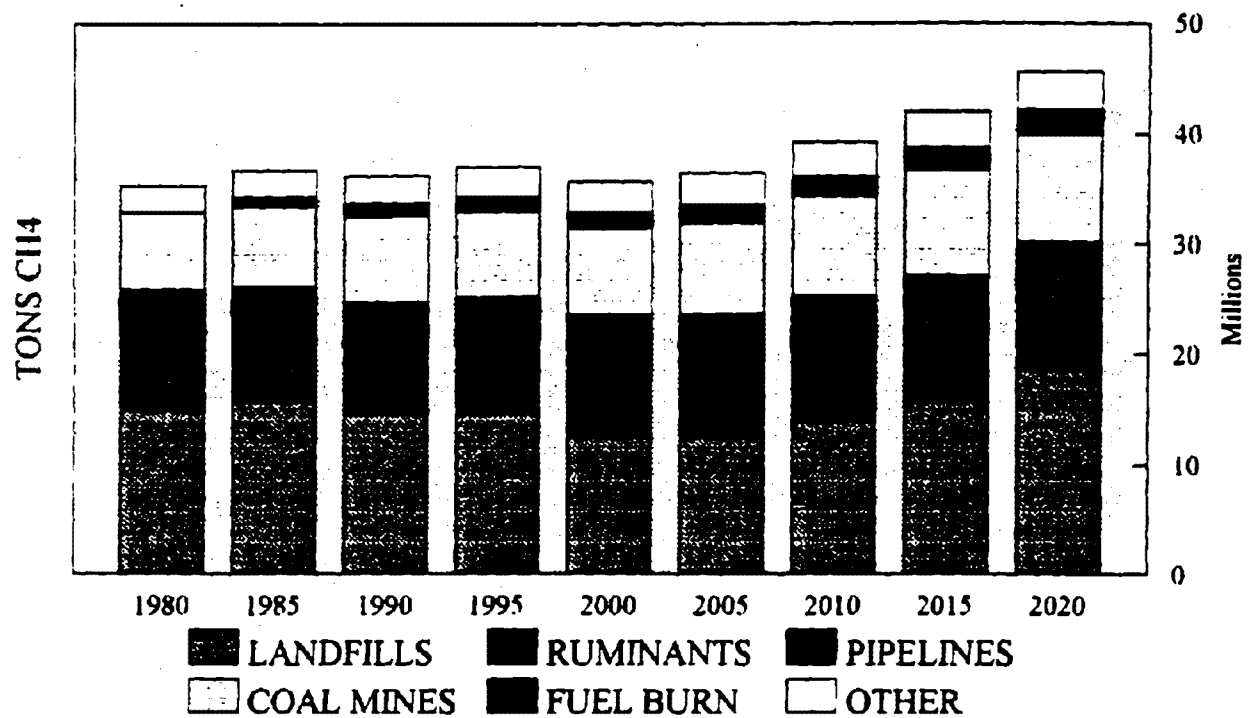


Figure 14. U.S. Methane emissions (for major sources).

development, and demonstration program to develop new fuel production and utilization technologies, with emphasis on renewable and nuclear systems. It also promoted the enhanced use of natural gas and nuclear power, and the use of renewables as electric utility and transportation fuels. More efficient utilization of energy, especially electricity, was also promoted.

The net effect of these policies, if successfully implemented, is shown in Figure 15. The bottom graphic compares carbon dioxide emissions for the U.S. strategy case with the previously discussed business-as-usual scenario (upper graphic). Such a policy can approach emissions stabilized at least over this time interval. As can be seen, the major reduction has been achieved in the coal-electric sector. This results from a lower growth in electricity demand due to enhanced end use efficiency, and due to increased use of gas, nuclear, and renewable power generation displacing carbon-intensive coal-fired power plants.

## CONCLUSIONS

Let me summarize what I believe all these graphics and analyses seem to tell those of us who are interested in greenhouse gas mitigation technology:

- (1) Agricultural, medical, and industrial technologies have allowed for unprecedented population and economic growth; development and application of low-emitting technology could deal with the potential of unacceptable greenhouse warming.
- (2) Technologies and practices could be developed that provide cost effective mitigation, not just for the developed countries that are generating the bulk of the emissions in the short term, but also for the developing countries that will likely be the dominant emitters in the longer term.
- (3) Research could help reduce the uncertainties associated with several key gases:
  - For methane, emission and activity factors need improvement, and the indirect effects of methane decomposition in the atmosphere needs clarification. Also the apparent deceleration in the growth of methane atmospheric concentrations cannot be easily explained by current source/sink information.
  - For tropospheric ozone, the mechanisms for formation in the upper troposphere from the important precursor gases are not fully understood.
  - For chlorofluorocarbons, the balance between radiative heating and stratospheric cooling needs to be better understood. Also, results of an evaluation of likely substitutes for global warming impact would be of interest.
- (4) Carbon dioxide is the key greenhouse gas which is directly linked to fossil fuel



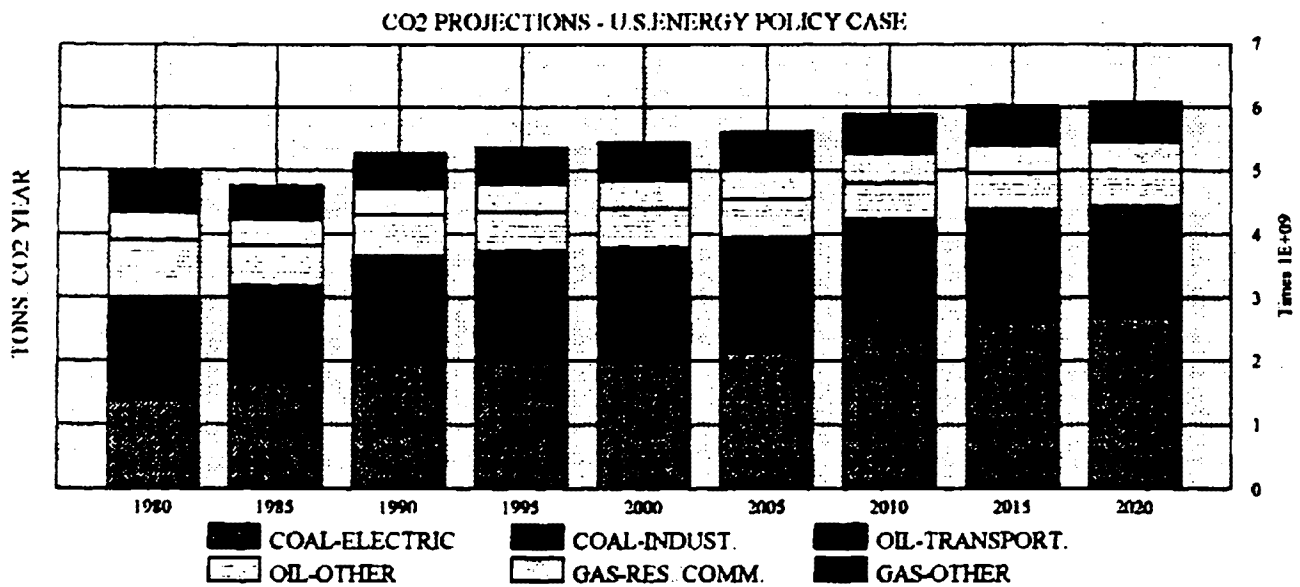
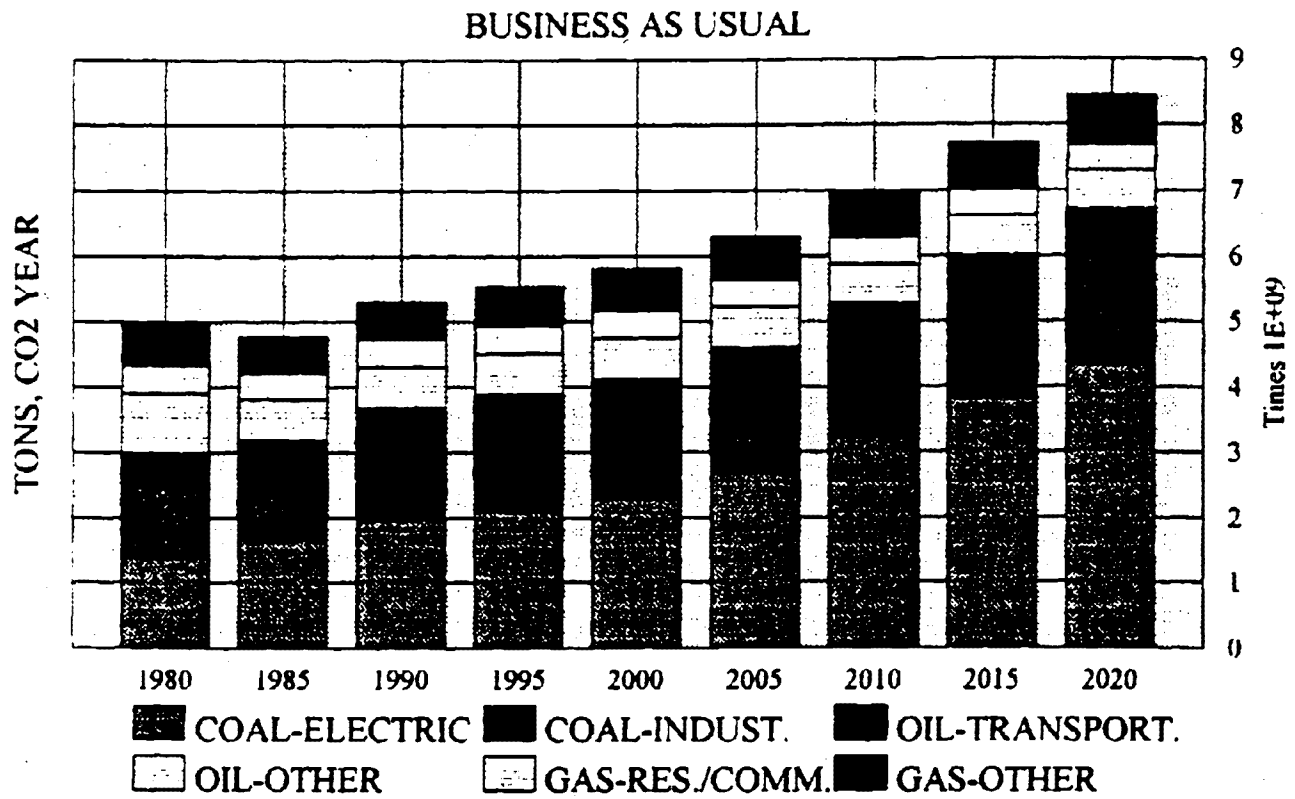


Figure 15. U.S. CO<sub>2</sub> Emissions by fuel/sector.

combustion, especially coal combustion. Major efforts could provide an alternative energy path emphasizing renewable technologies such as solar, and biomass with a focus on electric power production.

- (5) Methane provides a ripe opportunity for mitigation research. By controlling the major human sources, such as coal mines, landfills, and natural gas pipelines, methane atmospheric levels could be stabilized within a relatively short period, with substantial near-term mitigation impacts.

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**METHANE REDUCTIONS ARE A COST-EFFECTIVE APPROACH  
FOR REDUCING EMISSIONS OF GREENHOUSE GASES**

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Methane reductions can play a large role in providing low cost, if not profitable, opportunities for reducing greenhouse gas emissions, in addition to other benefits for the atmosphere. This paper reports on opportunities for reducing emissions of methane which have been examined through a number of EPA efforts and activities developed by the Intergovernmental Panel on Climate Change.

#### BACKGROUND: METHANE IS AN IMPORTANT GREENHOUSE GAS

Methane concentrations are currently rising in the earth's atmosphere and continuing increases have been projected for the future [1,2,3]. These increases are largely correlated with increasing populations, and currently about 60 percent of global methane emissions are associated with human activities (Fig. 1).

The benefits of reducing methane emissions from these anthropogenic sources will be substantial for several reasons. First, methane is a potent greenhouse gas and reductions in methane emissions would be 20 to 60 times more effective in reducing the potential warming of the earth's atmosphere over the next century than reductions in CO<sub>2</sub> emissions [2]. Second, methane released from human activities is a wasted resource, and these activities can likely be redesigned to profitably benefit from the efforts taken to reduce the methane emissions. Third, reductions in methane emissions will provide benefits of reducing the risks of increasing tropospheric ozone and reducing the earth's oxidizing potential [3,4,5,6,7]. Stabilizing CH<sub>4</sub> concentrations may reduce expected global tropospheric O<sub>3</sub> increases, and while more uncertain, may allow OH to return to about current levels by 2100 after a significant suppression [8].

Importantly, relatively small reductions in methane emissions of 40 to 60 Tg/yr, or about 10 percent of annual emissions, can halt the annual rise in methane concentrations. This assumes that the rate of CH<sub>4</sub> destruction (by OH) remains the same [2,3,8].

Due to the potency of methane in the atmosphere and its relatively short lifetime, stabilizing methane concentrations may act to substantially reduce potential warming. The results of holding methane emissions at about constant levels (i.e., 500 Tg) throughout the next century are shown in Fig. 2 (examined using the IPCC scenarios for future emissions of the greenhouse gases and the Atmospheric Stabilization Framework (ASF), a model used

in support of the IPCC [3]). The expected warming over the next century is reduced by about 1°C or 25 percent of the expected warming post 1990. This reduced warming is similar to the reduced warming which would result from stabilizing CO<sub>2</sub> emissions at 1990 levels (while concentrations continue to rise to over 500 ppm), and the reductions in warming from stabilizing CH<sub>4</sub> concentrations or CO<sub>2</sub> emissions are virtually identical through the year 2050 [9].

#### OPTIONS FOR REDUCING METHANE

Opportunities for reducing methane emissions from its major anthropogenic sources have been identified and reviewed through EPA efforts and expert meetings held under the IPCC [4,10,11]. In total, it currently appears to be technically feasible to reduce methane emissions on the order of 120 Tg/yr (75 to 170 Tg/yr). Over the next 10 years about one-third to one-half of these reductions would be needed in order achieve the necessary 40 to 60 Tg reduction to stabilize atmospheric methane concentrations.

The options for reducing methane emissions include:

- Ruminants: Ruminants world-wide are likely the second largest anthropogenic methane source, emitting 65 to 100 Tg [12]. Methane emitted from ruminants is a lost opportunity to transform more carbon into useful product such as meat or milk during the natural fermentation of feed. In developed countries, specific feeds have been identified which may reduce methane emissions while enhancing the productivity of the cattle. Additionally, in the United States, administration of bovine somatotropin (bST), provided it receives regulatory approval, could increase milk production while reducing methane emissions on the order of 10 percent [personal communication]. In other regions of the world, programs to increase animal productivity through strategic supplementation (i.e., the use of supplements such as molasses urea blocks to address livestock nutrient deficiencies) have been initiated. These programs have cost-effectively increased milk production and reproduction efficiency while reducing methane emissions by perhaps as much as 60 percent per gallon of milk [13].
- Animal wastes and wastewater treatment: Animal wastes may contribute about 20 to 30 Tg [14] of methane and wastewater treatment an additional 25 Tg [8]. Methane recovery systems can profitably capture 50 to 80 percent of the methane emitted by anaerobic waste management lagoons, as demonstrated by systems around the world. Such lagoons are used primarily at dairy and swine operations and account for over one-third of total emissions from animal wastes.

Recovered methane may be used directly or used to generate electricity [15]. Opportunities to employ methane recovery systems exist in the United States and many other countries.

- Rice cultivation: Rice cultivation may be the largest anthropogenic methane source. Over the long term, methane emissions can likely be reduced by 10 to 30 percent by an integrated management approach to irrigation, fertilizer application, and cultivar selection. Additional research is necessary to develop management practices for rice growing that will maintain rice productivity and reduce methane emissions [16].
- Biomass burning: Methane emissions resulting from biomass burning to clear new lands and after cropping and for energy purposes are estimated to range from 20 to 80 Tg. These emissions can be reduced through fire management programs, encouraging the use of alternative agricultural practices, and the use of more efficient cookstoves [12,17,18].
- Landfills: Landfills currently account for about 20 to 70 Tg of methane from the anaerobic decay of wastes [12], primarily from developed countries. Recovery systems can reduce emissions by 50 to 90 percent in existing landfills by collecting the medium BTU gas. The recovered gas may be burned directly in nearby industrial boilers or used to generate electricity, or at a minimum flared. The first two options could serve to displace CO<sub>2</sub> emissions from fossil-based fuels. Commercial operations in the United States, Western Europe, and other regions show that these systems are operated profitably. Furthermore, the United States is proposing rules to reduce emissions of air contaminants (primarily nonmethane organic compounds and air toxics) from landfills. As a side benefit methane emissions from U.S. landfills will be reduced by about 40 to 80 percent depending upon the stringency of the final rule [19].
- Coal mining: Coal mining accounts for 30 to 50 Tg of methane with most of the methane emitted from a small number of highly gassy mines [20]. Degasification using vertical wells in advance of and during the mining operation can reduce emissions of methane trapped in gassy underground mines by more than 50 percent while reducing the costs of necessary mine ventilation [8,11]. A portion of the recovered gas can be high BTU gas and fed directly into a pipeline or used to generate electricity. Gas of medium BTU quality recovered from gob wells over the mining operation (in the gob area) may be used to generate electricity. Many opportunities exist to cost-effectively expand methane recovery and use at coal mines in the United States, Poland, Czechoslovakia, the former Soviet Union, and the People's Republic of China, as well as elsewhere [21,22,23]. In the

future, emissions may be reduced further by using mine ventilation air that contains less than one percent methane as combustion air in gas fired turbines as is currently being done in Germany and being considered in Nova Scotia.

- Oil and natural gas systems: Oil and natural gas systems account for about 30 to 70 Tg of methane [12]. Most of the emissions are likely outside of the developed countries, with significant contributions from countries with economies in transition such as Eastern Europe and Russia. Improved handling of casing gas during oil production will reduce venting and flaring of natural gas during oil production. Improved technologies such as low bleed pneumatic instruments, high integrity piping, and new pipeline restoration techniques can also cost-effectively reduce methane emissions [8]. In addition, emissions from gas transmission and distribution in the USSR (where leakage has been estimated on the order of 5 percent of throughput) and Eastern Europe could be reduced substantially by improving these facilities [personal communication].

#### **EFFORTS REQUIRED TO ACHIEVE THESE REDUCTIONS**

These options for reducing methane emissions offer substantial reduction potential, but have not been implemented on a wide scale to date. A number of barriers currently limit the implementation of these options around the world. This includes financial, informational, political, and in some cases technical, barriers.

Future efforts should focus on removing these barriers. For example, in the United States, it can be profitable to recover and utilize methane that would have been emitted from coal mines due to the value of the methane and reduced ventilation costs, but institutional questions of methane ownership and constraints on receiving fair prices for gas or electricity may block implementation. These legal and pricing issues need to be resolved. Similarly, strategic supplementation of livestock can substantially increase livestock productivity and create a local market for supplementation crops, but lack of capital and infrastructure may block implementation in many countries.

In many cases, technology demonstrations will be crucial to removing existing barriers. Upon the clear demonstration that certain technologies have substantial pay backs and large environmental benefits, much more energy will be placed toward removing other barriers.

## SUMMARY AND CONCLUSION

Controlling methane emissions appears to be technically feasible and cost-effective with current technology. These reductions in CH<sub>4</sub> emissions appear to be very effective in mitigating radiative forcing in the atmosphere and eventual global warming. Reduction in CH<sub>4</sub> emissions will also likely moderate large-scale increases in tropospheric O<sub>3</sub> and to counter the suppression of OH.

Efforts to encourage methane reductions will require identification and removal of a number of barriers which hinder the implementation of available technologies. These efforts will need to include well-planned demonstration projects, in many cases.

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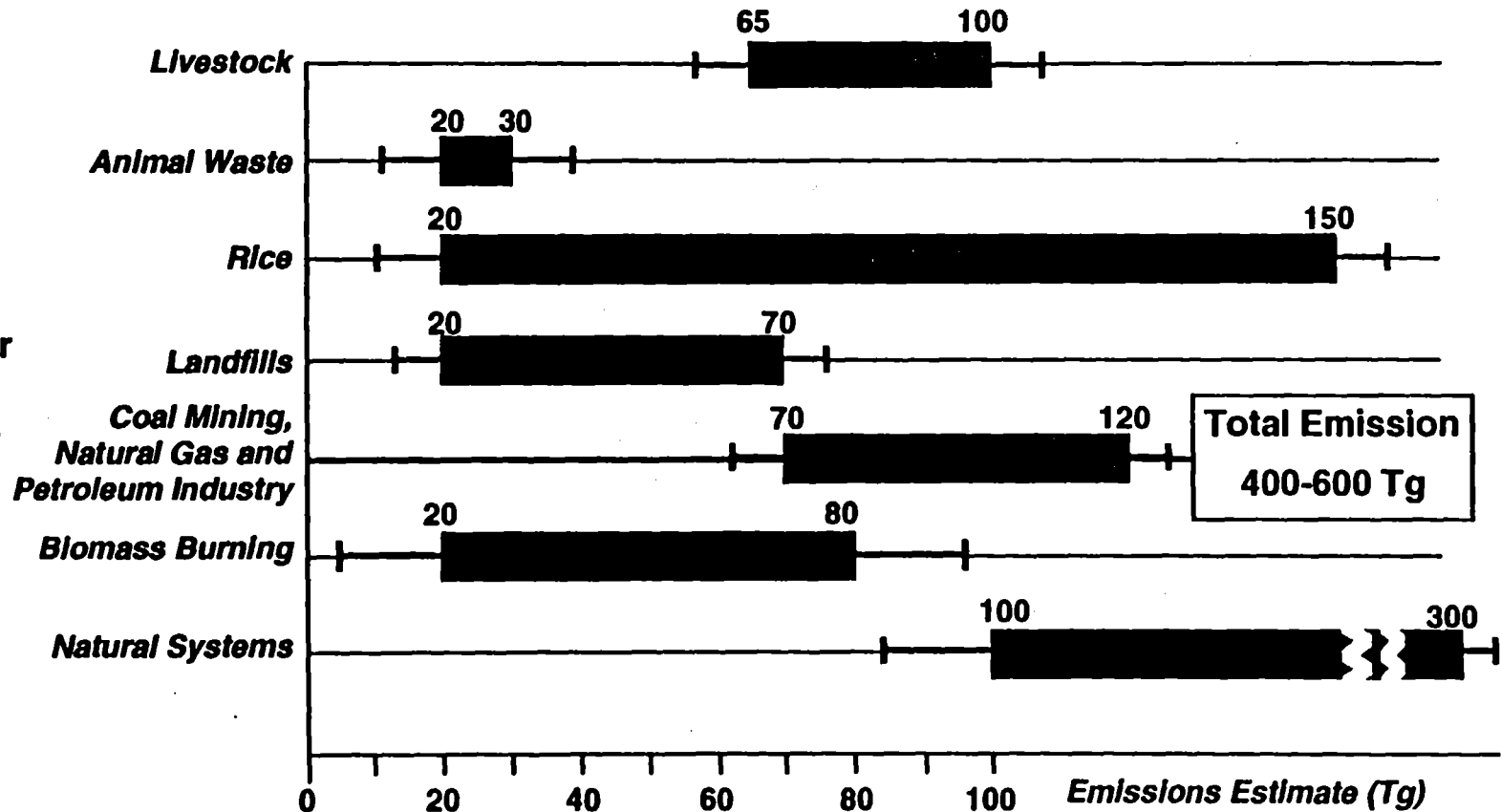
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# Methane Emissions Sources

1-33

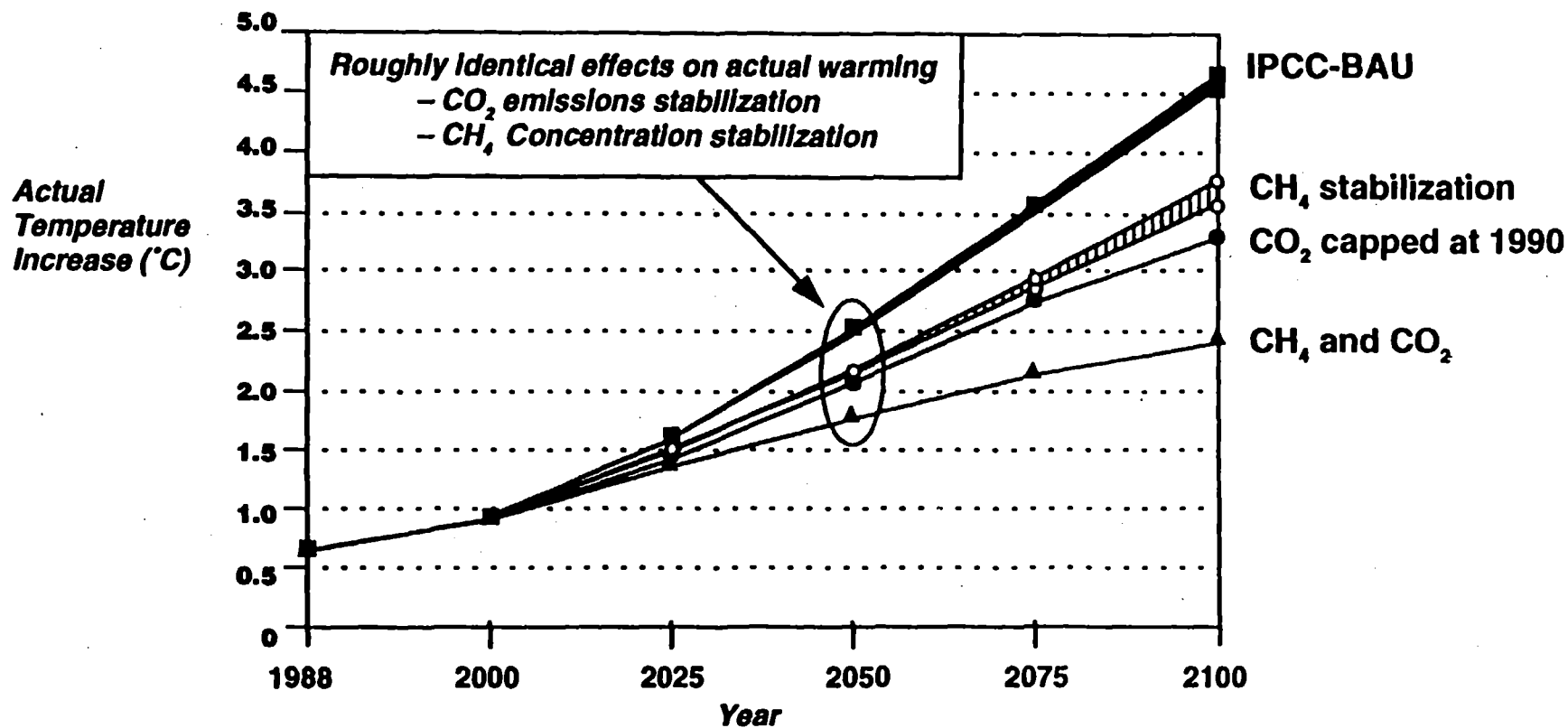
Human Activities Account for ~60% of Emissions



Since IPCC (based on NOAA work)

range of estimates

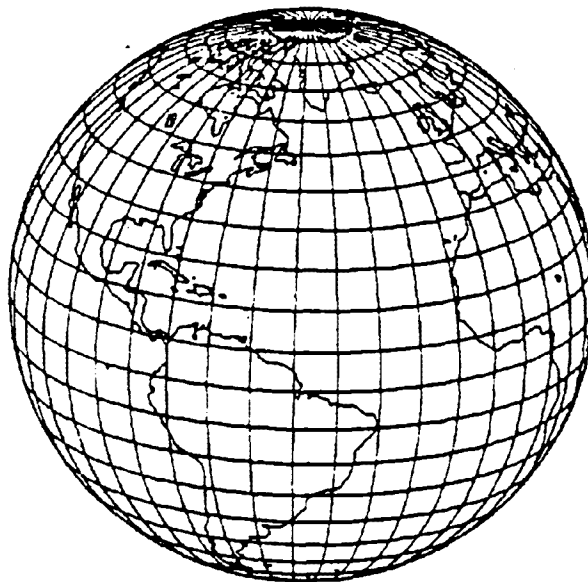
additional uncertainty



**Figure 2. Benefits of methane stabilization where methane emissions are capped at 540 Tg/yr as compared to capping CO<sub>2</sub> emissions at 1990 levels (and concentrations grow to over 500 ppm by 2100)**

# **Climate Change and Related Activities**

Kenneth Freidman  
Department of Energy  
Washington, D.C.



**U.S. Department of Energy**

Among all the challenges in our tenancy of this planet, climate change is, of course, foremost in our minds. We're leading the search for response strategies and working through the uncertainty of both the science and the economics of climate change. But there is one area where we will allow for no uncertainty—and this is our commitment to action—to sound analysis and sound policies.

*President Bush, White House Conference  
on Science and Economics Research  
Related to Global Change*

## Foreword

The production and consumption of energy contributes to the concentration of greenhouse gases in the atmosphere and is the focus of other environmental concerns as well. Yet the use of energy contributes to worldwide economic growth and development. If we are to achieve environmentally sound economic growth, we must develop and deploy energy technologies that contribute to global stewardship.

The Department carries out an aggressive scientific research program to address some of the key uncertainties associated with the climate change issue. Of course, research simply to study the science of global climate change is not enough. At the heart of any regime of cost-effective actions to address the possibility of global climate change will be a panoply of new technologies—technologies both to provide the services we demand and to use energy more efficiently than in the past. These, too, are important areas of responsibility for the Department.

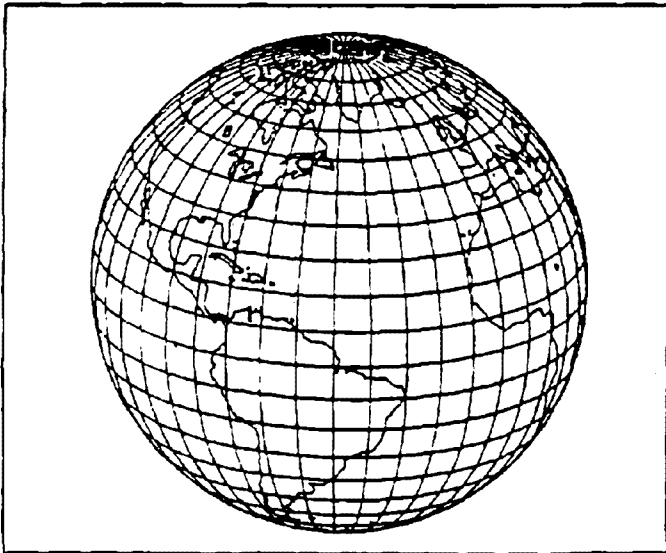
This report is a brief description of the Department's activities in scientific research, technology development, policy studies, and international cooperation that are directly related to or have some bearing on the issue of global climate change.

*James D. Watkins, Secretary of Energy*

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## Introduction

### The Earth's Climate

The Earth's atmosphere contains gases that absorb, and then radiate back to Earth, some of the Earth's thermal energy that would otherwise be radiated to outer space. These gases result from both natural and manmade processes and include carbon dioxide, nitrogen oxides, methane, chlorofluorocarbons, halogenated compounds, water vapor, and others. They are referred to as "greenhouse" gases because their action is somewhat like the process that makes it possible for a greenhouse to capture the heat of the Sun and maintain warmer temperatures during winter weather.

This "greenhouse" process regulates the Earth's climate at a level to sustain life, making our planet unique. The term "climate" refers not only to temperature, but also to the entire system of precipitation, cloudiness, and winds, as well as to the distribution of these features in space and time.

Human activities, in addition to natural processes, affect concentrations of greenhouse gases. These activities include energy production and use, agriculture, industry, and deforestation. It is the effect of these increasing manmade emissions that is the topic of current research and debate. Simply put, the research hypothesis is that manmade greenhouse gases in the atmosphere could cause changes in the Earth's climate. Figure 1 shows the contribution of different gases to the potential for warming (called radiative forcing).

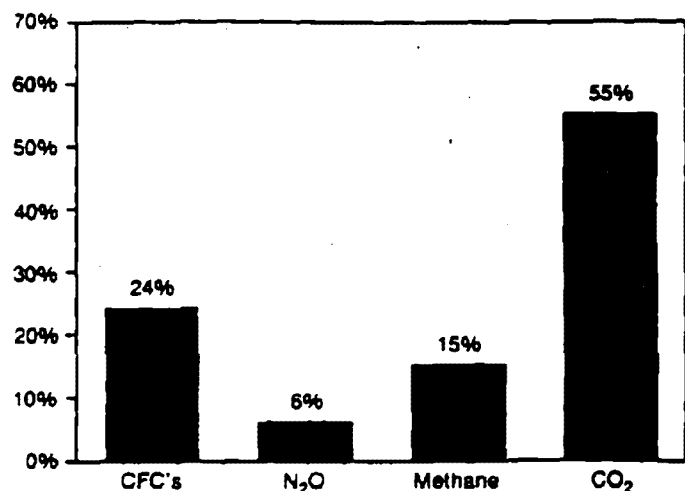
The scientific community is unsure about how the Earth responds to increases in manmade greenhouse gases. Does the ocean have processes that can absorb these extra greenhouse gases? Do clouds act as a natural buffer to regulate temperature changes? What kind of climate changes could occur, where, and when? These are the questions that scientists around the world are attempting to answer.

### DOE's Role: Historical Background and Issues

Global climate change is a significant issue for the U.S. Department of Energy (DOE) because greenhouse gases are emitted from the production and use of fossil fuels. Energy use and production now contribute more than half of the total manmade emissions on a global basis. Figure 2 shows an estimate of the relative contributions of various sources to total manmade emissions of greenhouse gases.

Our choice of energy sources can affect the emissions of greenhouse gases because some energy sources emit more greenhouse gases than others. Conversely, changes in climate could affect energy systems and energy demand. DOE is pursuing a wide range of new technologies that can help reduce future greenhouse gas emissions. These efforts include higher efficiency, cleaner electricity production, and a variety of

**Figure 1. Greenhouse Gas Contributions to Radiative Forcing**



Source: IPCC Scientific Assessment

Note: The contribution from tropospheric ozone may also be significant, but cannot be quantified at present.

renewable energy options. In addition, the Department is developing technologies for energy efficiency in buildings, industry, and transportation.

In 1977, the National Academy of Sciences challenged the scientific community on the subject of energy and climate by stating: "To reduce uncertainties and to assess the seriousness of the matter, a well-coordinated program of research that is profoundly interdisciplinary in character, and strongly international in scope, will be required."

Responding to this challenge and the growing concern about the long-range consequences of carbon dioxide emissions resulting from ever increasing fossil fuel combustion prompted the Department of Energy to undertake a thorough examination of the effects of carbon dioxide (CO<sub>2</sub>) emissions. The first step was to convene a Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels (1977, Miami Beach, FL). Some 75 scientists discussed the state of knowledge of the CO<sub>2</sub> cycle and the consequences of increases in atmospheric CO<sub>2</sub>. The workshop identified significant gaps in understanding and recommended actions to fill these gaps. This led to the development of the Carbon Dioxide Research Program at the Department of Energy in 1978.

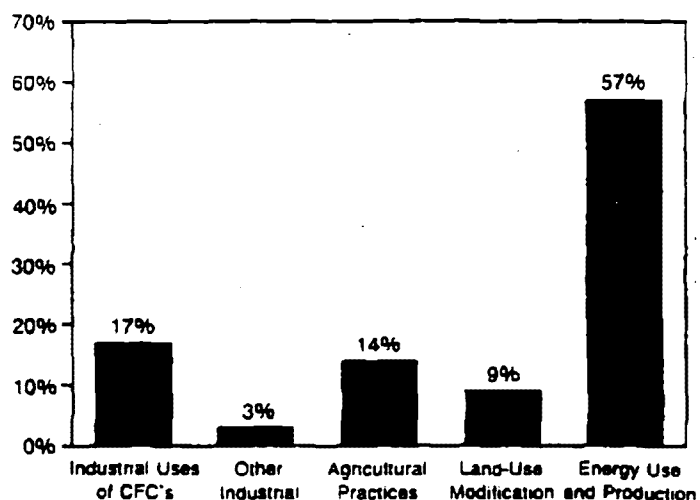
The 14 years of research since then by the Carbon Dioxide Research Program has laid the basis for the recent science assessment by the Intergovernmental Panel on Climate Change. Accomplishments along the way have included the global CO<sub>2</sub> emissions inventory, the global temperature data base used to assess climate change over the last 130 years, leading the diagnosis and improvement of climate models, establishing the CO<sub>2</sub> vegetative fertilization effect as a major beneficial impact, leading the development of a ground-based, remote sensing network to determine the role of clouds in climate change, and initiating the research to incorporate emerging supercomputer hardware and software into climate model development. The Program continues to provide scientific leadership on climate modeling, atmospheric, terrestrial, and oceanic data collection, measurement, and analysis.

The Department also established a Global Climate Change Executive Committee, jointly chaired by the Deputy Under Secretary for Policy, Planning and Analysis (PE) and the Assistant Secretary for International Affairs and Energy Emergencies (IE). The Committee includes Assistant Secretaries from tech-

nology development programs and provides a coordinated forum to guide DOE policy on global climate change.

This report is divided in two parts: (1) "focused activities" are those that are dedicated specifically to the issue of global climate change, and (2) "related activities" are those that are carried out for economic, energy development, and environmental reasons, yet nonetheless have some bearing on the topic of climate change.

**Figure 2. Relative Contributions of Economic Sectors to Radiative Forcing in 1980's**



Source: U.S. Environmental Protection Agency, *Policy Options for Stabilizing Global Climate*, draft report to Congress, 1989.

# Part I: Focused Activities

## Scientific Research

The Carbon Dioxide Research Program conducts the Department's focused scientific research on climate change. The goals of the program are to estimate the future levels and rate-of-increase in atmospheric carbon dioxide ( $\text{CO}_2$ ) and other energy-related emissions and to understand and predict potential effects of emissions on climate and biota. This information is required to scientifically underpin energy policy options aimed at preventing, mitigating, or adapting to increasing greenhouse gas concentrations and global environmental change. Major activities include (1) developing computer models to predict rate and magnitude of global and regional climate change; (2) understanding the systems that control the current and past climates of the Earth; and (3) exchanging and communicating data and modeling results with other climate researchers around the world.

## Computer Modeling

Complex computers are used as tools to predict future climate trends. The Department has extensive climate modeling capabilities using advanced supercomputers. However, additional computer power and an advanced climate model (ACM) will be needed to further improve climate modeling and prediction efforts.

The Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP) research program is a 1991 initiative of the Department of Energy's climate modeling program. The objective of the program is to accelerate and improve the global and regional predictive capability of climate models. This requires an ACM capable of more detailed simulations over longer time intervals and incorporates significant improvements in the representation of the physics and chemistry of the climate system.

CHAMMP addresses these challenges in a phased approach over ten years. In the near term (2 to 3 years), its goals are to improve performance of existing climate system models by taking advantage of emerging parallel computers. In the intermediate term (3 to 6 years), the CHAMMP program aims to develop initial versions of ACM systems that are capable of better than 100 gigaflop (billion floating point operations per second) performance. In the long term (6 to 10 years),

CHAMMP will improve the initial versions of the ACM components, assemble an optimized ACM, and begin detailed research calculations on the faster supercomputers.

## Earth Systems Research

### Carbon Cycle Research

Carbon cycle studies seek to better understand the different sources and sinks of carbon. A "source" emits carbon (in the form of  $\text{CO}_2$ ) into the atmosphere; a "sink" absorbs and stores carbon. For instance, trees are primarily made up of carbon absorbed from the atmosphere. Therefore, forests are considered sinks of carbon during their prospective lifetimes. As they decay or are burned, carbon is released back into the atmosphere in the form of  $\text{CO}_2$  and the tree becomes a source.

There are other sinks of carbon, including surface soils and the surface of the ocean, about which little is known. The Department conducts and supports carbon cycle research because a better understanding of natural sinks and sources of carbon will help to determine the extent of increased atmospheric concentrations of manmade greenhouse gases. Carbon cycle research is a common thread in the fabric of DOE's atmospheric, oceanic, and terrestrial research.

### Atmospheric Research: Atmospheric Radiation Measurement

The Atmospheric Radiation Measurement (ARM) program has three main goals. The first is to measure and describe the radiation balance (natural greenhouse effect) from the Earth's surface to the very "top" of the atmosphere. The second is to understand the role clouds play in this process, so that climate models can be improved. The third is to assist in verifying satellite measurements with ground-based data.

The program will accomplish these goals by establishing five observing stations around the world. These sites will be selected to provide a worldwide view of differing cloud and atmospheric conditions. The sites will employ specialized ground-based remote sensing instrumentation, specialized aircraft, and balloon platforms to collect and analyze data. The first ARM site will be established in 1992.

## Oceanic Research

The ocean research objectives are to produce a global survey of carbon dioxide in the ocean, to better understand the ocean's role as a source and sink of carbon dioxide, and to improve ocean circulation models for climate research. To meet these objectives, DOE supports laboratory, observational, and modeling studies to understand the mixing, transport processes, and carbon cycling in the ocean, and the exchange of heat and carbon between the ocean and the atmosphere. A better understanding of these issues is necessary to estimate the ocean's uptake of carbon dioxide produced by fossil fuels.

### ***At-Sea Data Collection and Analysis***

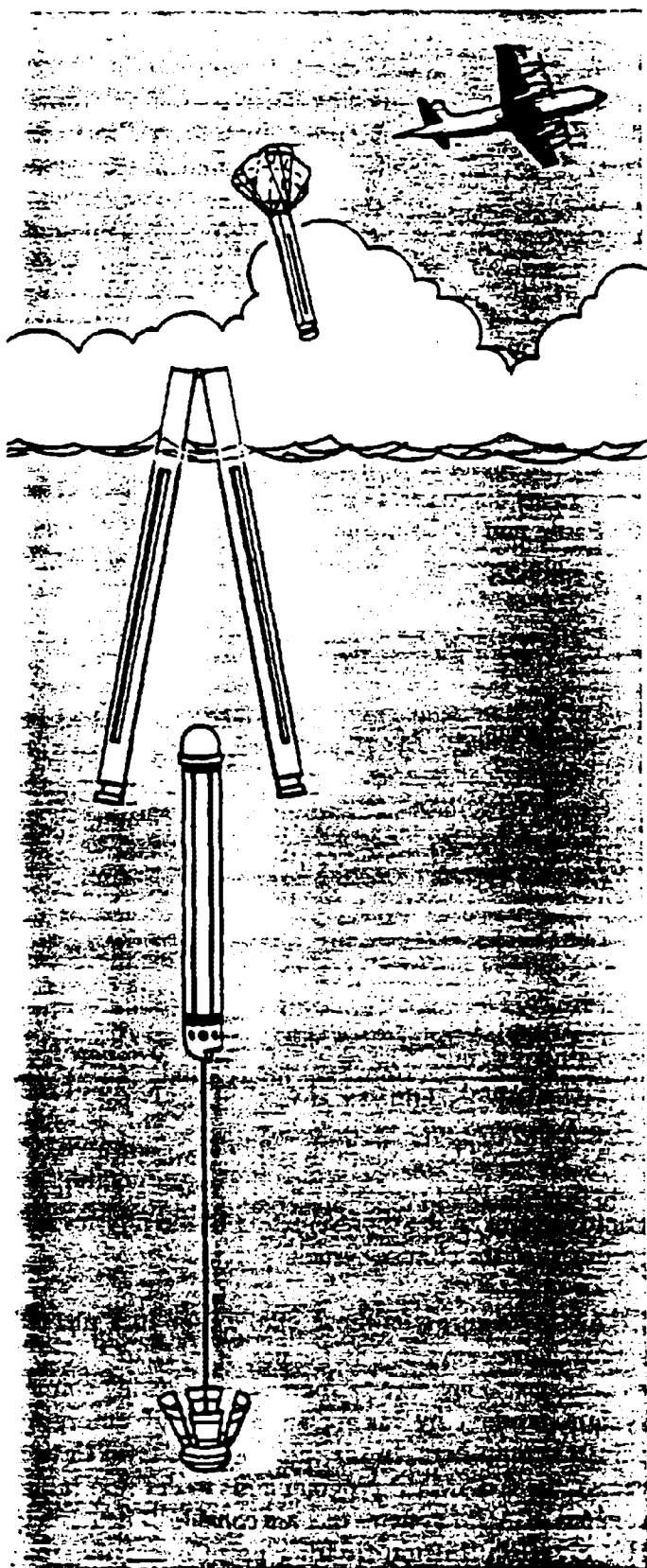
The Department cooperates with other Federal and international agencies in collecting ocean data. The World Ocean Circulation Experiment is coordinating a global survey of oceanic carbon dioxide. Specialized research ships collect data from both the Atlantic and Pacific Oceans. DOE continues to develop the instrumentation needed to collect and analyze oceanic carbon dioxide data.

### ***Remote Sensing: "Smart Buoys" and the Heard Island Experiment***

At-sea data collection could be complemented by a device now under development by the Department. Expendable Ocean Sensors or "smart buoys" are remote sensing devices that can submerge to the ocean floor to collect ocean temperature, salinity, and density data on their descent. At a programmed time interval, the buoys ascend to the ocean's surface, collecting the same data during ascent. Once at the surface, the buoys transmit the data to a satellite. These devices could verify satellite observations and provide new data for the next generation of ocean models. Figure 3 shows a diagram of such a buoy.

The objective of the Heard Island Experiment is to assess the feasibility of using sound as an ocean thermometer. The speed of sound in seawater is determined by water temperature. The travel time for a sound signal to cross the ocean is therefore proportional to the average temperature of the ocean along the sound path. The Department's Environmental Sciences Division, in cooperation with the Office of Naval Research, the National Science Foundation, the National Oceanic and Atmospheric Administration, and 10 foreign countries have supported the Scripps Institute of Oceanography in executing the Heard Island

**Figure 3. Diagram of a "Smart Buoy" Remote Sensing Device**



**Experiment.** The experiment transmitted a low frequency sound from a ship near Heard Island in the south Indian Ocean. Sensors around the world were used to detect the signal. An assessment of the experimental data is expected in late 1992.

### **Terrestrial Research: Vegetation**

The Department's unique research on plant response to variable CO<sub>2</sub> concentrations will focus on plant carbon metabolism in response to higher concentrations of CO<sub>2</sub>. Field experiments have shown dramatic biological responses to elevated levels of carbon dioxide. The Free Air CO<sub>2</sub> Enrichment (FACE) experiment is an open-air control system in which plants are exposed to high concentrations of CO<sub>2</sub>. Cotton was first used to test the FACE system, and the experimental results were striking. Plants grown at elevated CO<sub>2</sub> produced a marketable cotton yield 5 weeks earlier than usual, and with 50 percent more biomass.

These results have profound implications for the capacity of vegetation to fix and sequester atmospheric CO<sub>2</sub>, and thus possibly slow the rate of atmospheric CO<sub>2</sub> increase and its possible effect on global climate.

### **Outreach, Communication, and Exchange of Data**

#### **Carbon Dioxide Information Analysis Center**

The Department provides climate data and information services to the domestic and the international scientific communities. The Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory is a public repository of greenhouse gas data and information. CDIAC maintains format and quality control standards and catalogs diverse data sets to provide a uniform data library and easy conversion to modeling systems so that researchers can easily access and characterize the data.

For more information please contact:

Oak Ridge National Laboratory  
Carbon Dioxide Information Analysis Center  
Building 1000  
Box 2008, MS-6335  
Oak Ridge, TN 37381-9984

### **Climate Model Diagnosis and Comparison**

The Program for Climate Model Diagnosis and Intercomparison (PCMDI) assists scientists in determining the reasons for variation in climate modeling results. The program compares different modeling systems by examining the data sets and parameters used to obtain the results. This service helps scientists improve or modify their models. PCMDI is expanding to lend support to the international efforts being coordinated by the World Climate Research Program.

### **Climate Scholarships**

An educational initiative of the Global Change Program is to award competitive fellowships and scholarships at the postdoctorate, graduate, and undergraduate level. Special emphasis will be given to involving students in ongoing research at the National Laboratories to achieve practical experience in the multidisciplinary sciences of global change.

For more information please contact:

Oak Ridge Associated Universities  
Science / Engineering Education Division  
P.O. Box 117  
Oak Ridge, TN 37831-0117.

### **Policy Analysis**

The Department conducts analytical studies to examine current and future emissions of greenhouse gases, policies for influencing those emissions, impacts from potential climate change, and policies to adapt to climate change. In addition to studies, the program also includes the development of computer models to estimate greenhouse gas emissions, analysis of the potential of certain policies to reduce emissions, and the development of policy-oriented models for estimating atmospheric effects such as the radiative forcing of different greenhouse gases.

In early 1989, four congressionally mandated studies were initiated. These studies are now complete:

- *A Compendium of Options for Government Policy to Encourage Private Sector Responses to Potential Climate Changes*—a study of how private interests can be encouraged to participate in emissions reductions.

- *Global Climate Trends and Greenhouse Gas Data: Federal Activities in Data Collection, Archiving, and Dissemination*—an analysis of government data bases, including access and availability to interested parties.
- *Confronting Climate Change: Strategies for Energy Research and Development*—a study by the National Academy of Sciences and the National Academy of Engineering to evaluate the potential of Alternative Energy Systems to affect greenhouse gas emissions.
- *Limiting Greenhouse Gas Emissions in the United States*—an analysis of policy options to achieve specified levels of emissions reductions in the United States over the next 10 to 20 years.

Copies of the listed or additional studies can be obtained by contacting:

U.S. Department of Energy  
Office of Environmental Analysis, PE-63  
1000 Independence Avenue, SW.  
Washington, D.C. 20585.

## International Activities

The Department of Energy participates in a number of international activities in the area of global climate change:

- The United Nations (U.N.) *Intergovernmental Negotiating Committee (INC)* was established in December 1990 to negotiate an international framework convention on climate change to be ready for signature at the U.N. Conference on Environment and Development to be held in Brazil in June 1992.
- The *Intergovernmental Panel on Climate Change (IPCC)* was established in November 1988 under the joint auspices of the World Meteorological Organization and the U.N. Environment Program to assess the science, impacts, and possible responses to global climate change.
- The *Preparatory Committee Meetings for the 1992 U.N. Conference on Environment and Development*

(*UNCED*). The 1992 UNCED is a major environmental activity that is a follow-on conference to the 1972 Stockholm Conference on the Environment. It will examine strategies on the environment and development in an attempt to reach specific agreements and commitments by governments and international organizations. Virtually all environmental concerns will be addressed, including biodiversity, transboundary air pollution, water quality, and financial and technology transfer issues.

DOE officials represent the Department on U.S. delegations to these bodies and DOE experts participate in the preparation of technical assessments. The IPCC completed its *First Assessment Report* in August 1990, which was adopted at Ministerial level at the Second World Climate Conference in November of that year. The report is a comprehensive assessment of the state of knowledge of climate change and a roadmap to the areas where major uncertainties remain and continuing research is required. More than 30 DOE scientists participated in the scientific portion of the report; DOE experts also contributed heavily to the assessment and overview of response strategies where the energy sector was a major area of focus.

The IPCC is undertaking new scientific, technological, and economic studies in support of the INC negotiations, and DOE will be a key contributor to these studies.

The INC has held three negotiating sessions in February, June, and September 1991, and two additional sessions are scheduled for December 1991 and February 1992. Working groups on Commitments and on Mechanisms have been formed.

These working groups have begun to address the major issues to be negotiated, including commitments related to net greenhouse gas emissions; financial and technological assistance to developing countries; research needs, monitoring, assessment, and information exchange; legal and institutional mechanisms; financial resources; and technological cooperation. Energy considerations are integral to all facets of this process.

## Part II: Related Activities

Related activities are those that are carried out by DOE for economic, energy development, and environmental reasons, yet nonetheless have some bearing on the matter of climate change.

### Scientific Research

DOE conducts fundamental research in physics, chemistry, biology, medicine, environmental sciences, ecology, geology, engineering, and mathematics. A portion of this long-term effort will contribute to our understanding of the causes and effects of possible climate change. Atmospheric chemistry, solid earth studies, and solar radiation physics contribute important information to support Earth Systems Research.

Ecosystems research also supports Earth Systems Research efforts. Baseline data have been obtained at seven DOE national Environmental Research Parks, DOE arctic sites, and the National Science Foundation's Long-Term Ecological Research sites. The objective is to strengthen the basis for a theoretical understanding of complex global environmental systems.

### Transportation

The U.S. transportation sector accounts for about 27 percent of national energy use. This sector of the economy is unique in its near total dependence on petroleum. Research and development (R&D) activities in DOE's Transportation Program are designed to improve the efficiency of oil use in the transportation sector and to increase the availability and use of alternative fuels. Program efforts center on developing advanced, high-efficiency alternatives to the internal combustion engine, evaluating the combustion and emissions characteristics of alternative fuels, demonstrating alternative-fuel vehicles in realistic settings, and developing biofuels from renewable resources. These activities can reduce the threat of climate change by developing alternative fuels that emit less greenhouse gas and by increasing transportation efficiency to use less fuel for comparable performance.

### Alternative Fuels Development

#### Natural Gas

The United States retains large supplies of natural gas, some of which are difficult to extract. The Department's Unconventional Gas Recovery Program seeks to develop geological data and advanced technologies for extracting gas from very large but currently uneconomical gas resources. Estimates of resources and methods to evaluate potential recovery from deposits have been improved. Compared to gasoline, natural gas as a transportation fuel can reduce nitrogen oxide ( $\text{NO}_x$ ) and  $\text{CO}_2$  emissions, as well as other pollutants.

#### Biofuels

Biofuels (ethanol and methanol) from biomass (trees, grasses, waste paper, and so forth) could create a "closed"  $\text{CO}_2$  system in addition to reducing other pollutants associated with gasoline. During combustion, biomass-derived fuels emit  $\text{CO}_2$ . However, the trees or grasses that are harvested to produce the fuel must be replanted for the next "fuel harvest." During the plants' growth cycle, the  $\text{CO}_2$  emitted into the atmosphere during combustion is reabsorbed by the plants. This creates a rotating fuel cycle in which there is little or no net increase in  $\text{CO}_2$  emissions.

DOE carries out research to develop processes that make the mass production of biofuels economically feasible, as well as works closely with the Department of Agriculture to develop fast-growing and productive plants for fuel use (Figure 4).

#### Vehicle Development

In addition to engine technology development to utilize alternative fuels, electric battery development is another component of the Department's vehicle development program. Electric vehicles could play a key role in helping to reduce urban air pollution. These vehicles could also reduce  $\text{NO}_x$ , an important greenhouse gas, and  $\text{CO}_2$  emissions, depending on the generation method used to produce the electricity to charge the battery (Figure 5).

**Figure 4. Sweet Sorghum, Used in the Production of Ethanol**



An electric battery consortium has been formed bringing together the three major U.S. automakers with battery developers and electric utilities to cost-share with DOE a multiyear research program. In addition, research is being conducted on fuel cells and alternative hybrid propulsion systems. Fuel cells, which use a chemical process to extract energy from hydrogen, offer the long-term prospect of efficiency that is twice that of internal combustion engines, with little or no emissions. The gas turbine and low-heat rejection diesel are also being researched for their fuel efficiency and alternative fuel use potential.

## **Residential, Commercial, and Industrial Efficiency**

### **Building, Appliance, and Equipment Efficiency**

Residential and commercial buildings account for 36 percent of the Nation's energy use. Improvement in the energy efficiency and substitution of renewable resources to replace carbon-based fuels in this sector can reduce greenhouse gas emissions. Because of the size and diversity of the building sector, this task involves a cooperative effort among government agencies, industries, manufacturers, professional and trade associations, and environmental and citizen groups.

In addition to maximizing the efficiency of energy consumed and the proportion of renewable resources

for the building sector, recently the Department has focused on finding substitutes to replace building and appliance materials that contain ozone-depleting chlorofluorocarbons (CFC's), which are also potent greenhouse gases. These CFC materials have been used in foam insulation and refrigerants.

The main elements of a building that affect energy use are divided into two parts: (1) the envelope, which includes walls, roof, foundation, doors, and windows; and (2) building equipment and appliances.

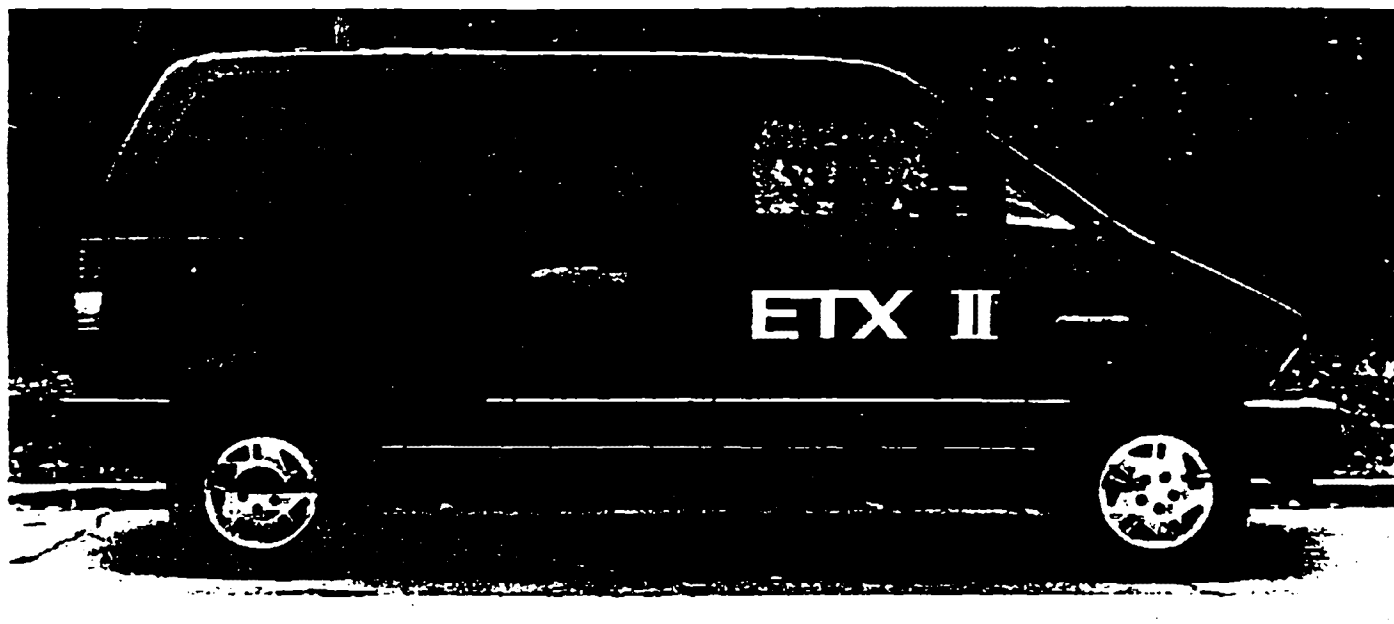
### ***The Envelope***

**Analysis Tools.** The Department supports the development of computer software to assist builders and architects in evaluating the efficiency of different building designs. DOE-2 is a public domain computer program used for energy analysis of residential and commercial buildings. It is used to design energy-efficient new buildings, analyze efficiency improving modifications for existing buildings, calculate energy design budgets, and perform cost-benefit analyses of new technologies (Figure 6).

**Window Technology Development.** Windows, which are responsible for one-fourth of the energy required to heat and cool buildings, offer a large opportunity to save energy. Improving window quality through the use of treated glass and airtight window framing are key



Figure 5. Electric Vehicle



factors in the research cosponsored by the Department and the window industry.

The National Fenestration Rating Council (NFRC), an organization composed of representatives of the fenestration industry, building industry, Federal, State and local governments, utilities, and public interest groups, has been working to develop a standardized rating system to provide a measure of the energy performance of windows, doors, and skylights to be used for a voluntary rating system.

**Passive Solar Design and Construction.** Proper orientation, adding thermal mass, and controlling and distributing heat allow a building to take advantage of passive solar energy and reduce the need for energy expended for heating, cooling, and lighting purposes. In addition, the use of trees to shade buildings can reduce energy consumption for cooling.

#### ***Appliance and Equipment Efficiency***

The Department of Energy will continue its efforts to improve the energy efficiency of appliances and equipment. The Department has established standard test procedures, which are used by manufacturers for energy-intensive residential appliances (such as refrigerators, air conditioners, stoves, and furnaces).

**HVAC (Heating, Ventilation, and Air Conditioning) Equipment.** Space heating and cooling equipment uses about half of all primary energy consumed in residential and commercial buildings. Research cosponsored by the Department and the manufacturing community concentrates on non-CFC refrigerants, thermally activated heat pumps, advanced materials and subsystem components for active solar systems, and desiccant materials for cooling and dehumidification. Research for furnaces and boilers focuses on oil-fired equipment, including controls, fuel atomization, emissions, venting, and efficiency degradation in relation to fuel quality.

**Lighting.** The Department's lighting research efforts have concentrated on efficiency and the effectiveness of electric lamps and fixtures. Research has resulted in the improvement of fluorescent lamps and the development of electronic ballasts. The Department supported research that has demonstrated fixture concepts that enhance efficiency by 15 to 20 percent. A series of these prototype fixtures is being transferred to industry for commercialization (Figure 7).

#### **Industrial Process Technologies**

Significant cost-effective improvements in industrial energy efficiency are possible. The Department's

**Figure 6. Energy-Efficient House**



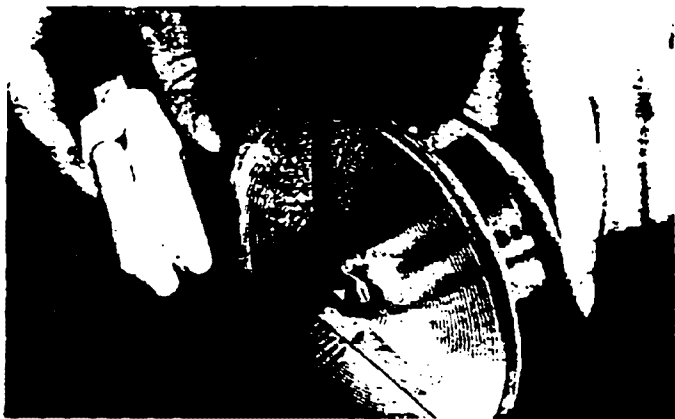
industrial efficiency programs concentrate on seven major areas, common to many industrial operations: materials processing, electric motor drive, separation technology, sensors and controls, bioprocessing, advanced materials, and process heating and cooling. These programs are expected to yield advanced drying systems for paper production, improved control systems for temperature and moisture control, high temperature heat pumps, improved membrane separation equipment, new steelmaking processes, and advanced sensors for critical online process measurements. For the longer term, DOE is working with industrial partners to

develop corrosion-resistant, ultra-high-temperature materials, low energy sulfur-free pulping processes, near-net shape casting, and continuous fiber ceramic composites.

### **Industrial Waste Minimization**

The Department conducts research to improve industrial energy efficiency. A major emphasis of the program addresses the fact that a great deal of energy is wasted each year in the form of embodied energy, of unused or poorly used raw materials, in the energy content of industrial waste streams, and in the energy used to clean up and dispose of wastes. DOE has recently begun a research program, cost-shared with industry, to develop technologies to reduce wastes at the outset rather than cleaning them up after they have been generated. In addition to reducing waste, this approach saves money and thus improves the productivity and competitiveness of U.S. industry.

**Figure 7. Fluorescent Lamp and Heat Sink**



### **Electricity Generation and Use**

#### **Integrated Resource Planning**

Integrated Resource Planning (IRP) is a process by which utilities decide how to best provide energy-related services at the least cost to consumers. In the

past, utilities have built new power generating plants to meet additional demands for energy. A different approach is to allow utilities the regulatory flexibility, and financial return needed, to meet customer demand through efficiency improvement, load management, and other measures in addition to traditional supply options. This "stretches" the ability of the same amount of generated power to meet additional needs, eliminating the necessity to build additional power plants. Successful IRP programs can limit future additional emissions of greenhouse gases by reducing the need for new fossil fuel powerplants.

The Department provides an information clearinghouse and technical assistance to States and utilities who are trying to start or improve their Integrated Resource Planning efforts. States can share information on and learn from others how to improve their planning efforts, as well as keep abreast of regulatory or legislative changes.

## Electricity Generation

### Renewables

A number of renewable energy technologies can contribute to electricity generation in the future while helping to reduce greenhouse gas emissions. Implementation of the National Energy Strategy actions is projected to increase the amount of electricity produced from renewable energy by an estimated 16 percent in the year 2010.

**Wind Energy.** The goal of the Department's wind research is to improve the efficiency and cost-competitiveness of wind energy systems to make them commercially competitive in many areas of the world (Figure 8). Research activities are focused on solving the structural fatigue problems of rotors and blades, and improving manufacturability and reliability. In cooperation with utilities and system manufacturers, the program plans to develop a cost-shared advanced wind turbine development program.

**Photovoltaics.** The Department's research and development efforts to convert sunlight directly into electricity (photovoltaics) have assisted in making this technology economically feasible in remote sites where other power sources would not be cost-effective. The program continues to pursue its goal of developing photovoltaics as an economical bulk power option for the United States. Utility-sized photovoltaic systems for

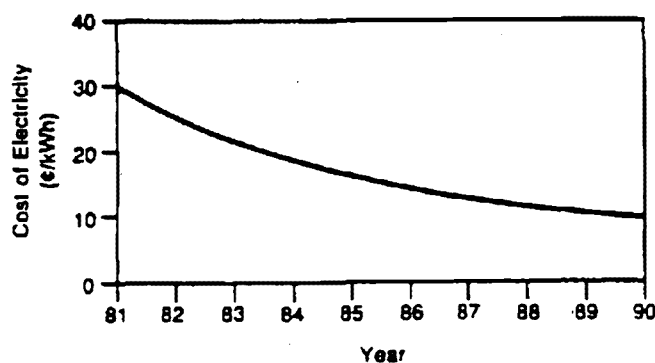
sites with high sunlight intensity are expected within the next few years. DOE-sponsored research is directed towards increasing conversion efficiencies and reducing manufacturing costs. DOE will continue to assist the industry to maintain and extend its world leadership role in the manufacture and commercial development of solar equipment, components, and systems.

**Solar Thermal.** Solar thermal systems use large fields of mirrors to concentrate the Sun's heat in a working fluid that is then used to generate electricity. Since 1984, over 355 Megawatts (MW) of solar thermal electric capacity has been installed in the United States. DOE-sponsored research is directed towards reducing costs of large utility systems and producing small cost-effective nonutility systems.

**Geothermal.** Geothermal systems generate electricity using heat from the Earth. Currently, electric generating capacity using geothermal energy is about 2,800 MW. Development has been limited to locations where there is a concentrated heat source. DOE-sponsored research is directed toward obtaining a better understanding of geothermal reservoirs and reducing the costs of exploration.

**Hydropower.** Hydropower provides over 9 percent of the Nation's electricity supply with a generating capacity of over 70,000 MW by harnessing the energy produced by falling water. DOE efforts are directed toward identifying improved methods of addressing environmental concerns and removing unnecessary regulatory barriers to development, especially at existing dams.

**Figure 8. Levelized Cost of Energy From Wind Turbines**



**Nuclear.** Nuclear power, which produces no greenhouse gases, accounts for about 20 percent of the Nation's electricity supply. The goal of the nuclear energy program is to remove undue regulatory and institutional barriers to the use of safe, economical nuclear power. New nuclear reactor designs incorporate evolutionary improvements to current designs. These designs are simpler, standardized, safer and more economic to build and operate. DOE will continue to work closely with industry, utilities, and independent research organizations to make progress in the development of nuclear power generating technologies.

**Fusion.** At sufficiently high pressures and temperatures, the nuclei of light atoms are forced together, causing the nuclei to fuse and, in the process, to release energy. Fusion is a long-term energy option that could become a principal energy source in the next century. It can use an inexpensive, vast, and secure fuel resource while offering attractive environmental and safety aspects. Fusion development also drives technology advances in fields as diverse as plasma physics, superconducting magnets, high-power accelerators and radiofrequency systems, advanced materials development, and computer science, to name just a few.

The fusion programs of the world currently have vigorous international cooperation and collaboration that include scientific and technological exchanges, joint experiments, and joint planning activities. The U.S. program contributes and is a leader in these activities by emphasizing early international involvement in planning for major new activities and facilities.

### Fossil

Worldwide burning of fossil fuels is a major source of greenhouse gas emissions. However, the worldwide fossil energy resource base is large, and economic development policies indicate continued reliance on these fuels.

One option that would reduce the amount of CO<sub>2</sub> emitted from fossil fuel combustion involves the utilization of advanced fossil fuel technologies, such as the clean coal technologies being developed by DOE.

**Clean Coal Technologies.** In cooperation with industry, DOE is demonstrating 35 different clean coal technology (CCT) options. Activities now in progress range from fact-finding to plant construction and

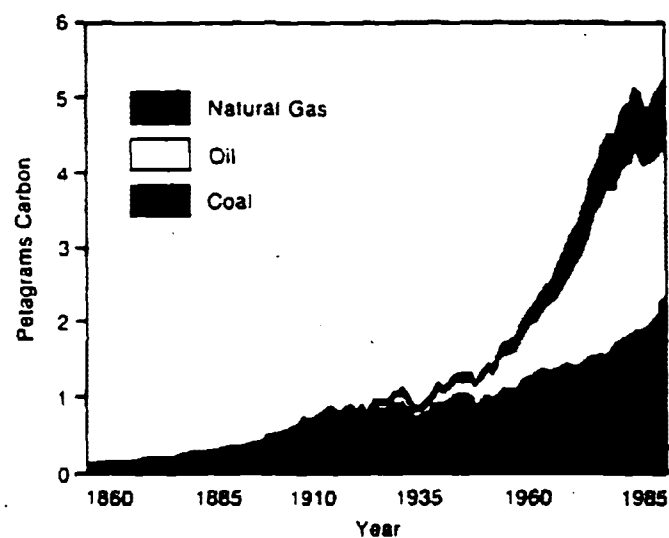
operation. The objective of this program is to achieve commercial availability of these technologies beginning in the mid 1990's. Industry cost sharing accounts for about two-thirds of the total program cost.

CCTs have lower CO<sub>2</sub> emission rates because of their higher conversion efficiencies: 40 to 50 percent for CCTs versus 30 to 35 percent for conventional technologies with SO<sub>2</sub> controls. Table 1 compares CO<sub>2</sub> emissions from several coal-fired technologies.

Combustion efficiency improvements in countries currently using fossil energy technologies, together with increased reliance on clean coal technologies in developing countries that are projected to have rapidly increasing emissions of greenhouse gases, could achieve reductions in these emissions.

Since so much coal is used worldwide, efficiency improvements can have a large effect upon reducing CO<sub>2</sub> emissions. Figure 9 shows historical global consumption of coal and other fossil fuels.

**Figure 9. CO<sub>2</sub> Emissions Due to Fossil Fuel Consumption (1980–1985)**  
(petagrams carbon)



**Table 1. Carbon Dioxide Emissions from Coal-Fired Technologies**

Technology	Efficiency (percent)	CO <sub>2</sub> /year (million tons)	% Change from conventional technology
Conventional plant with scrubber	33	3.1	0
Atmospheric fluidized bed combustion	36	2.8	-10
Pressurized fluidized bed combustion	40	2.5	-19
Gasification combined cycle (with fuel cell)	42	2.4	-23
	50	2.0	-35
MHD	55	1.8	-42

## Policy Analysis

### National Energy Strategy

The National Energy Strategy (NES) lays the foundation for a more efficient, secure, and environmentally sustainable energy future. One chapter of the NES is devoted to global environmental issues, primarily global climate change. Consideration of climate change and other environmental issues is woven throughout the NES and its action recommendations. Under current policy scenarios, the global warming potential of U.S. greenhouse gas emissions in 2030 is projected to increase by more than 40 percent over 1990 levels. In contrast, the NES measures, taken together, are estimated to keep U.S. greenhouse gas emissions, as measured by global warming potential, at or below present levels through 2030.

All energy programs described in this inventory were analyzed by the NES for the effect on greenhouse gas emissions. Figure 10 shows the NES analysis of the timeline during which specific energy technologies, now undergoing R&D, are expected to come into more widespread use.

### Alternative Fuels

To address both energy security and environmental issues associated with oil use in transportation, a

multiyear study of alternative fuels is being conducted. Methanol, ethanol, compressed natural gas, liquefied petroleum gases, and electricity are being examined for the time period 1995–2010.

This study characterizes the emissions of alternative fuels, relative to gasoline and diesel fuel, for both light and heavy duty vehicles. Pollutants being examined include hydrocarbons, nitrogen oxides, carbon monoxide, carbon dioxide, particulates, and aldehydes. This analysis will be used by the Interagency Commission on Alternative Motor Fuels to make recommendations for future development of alternative fuels for transportation.

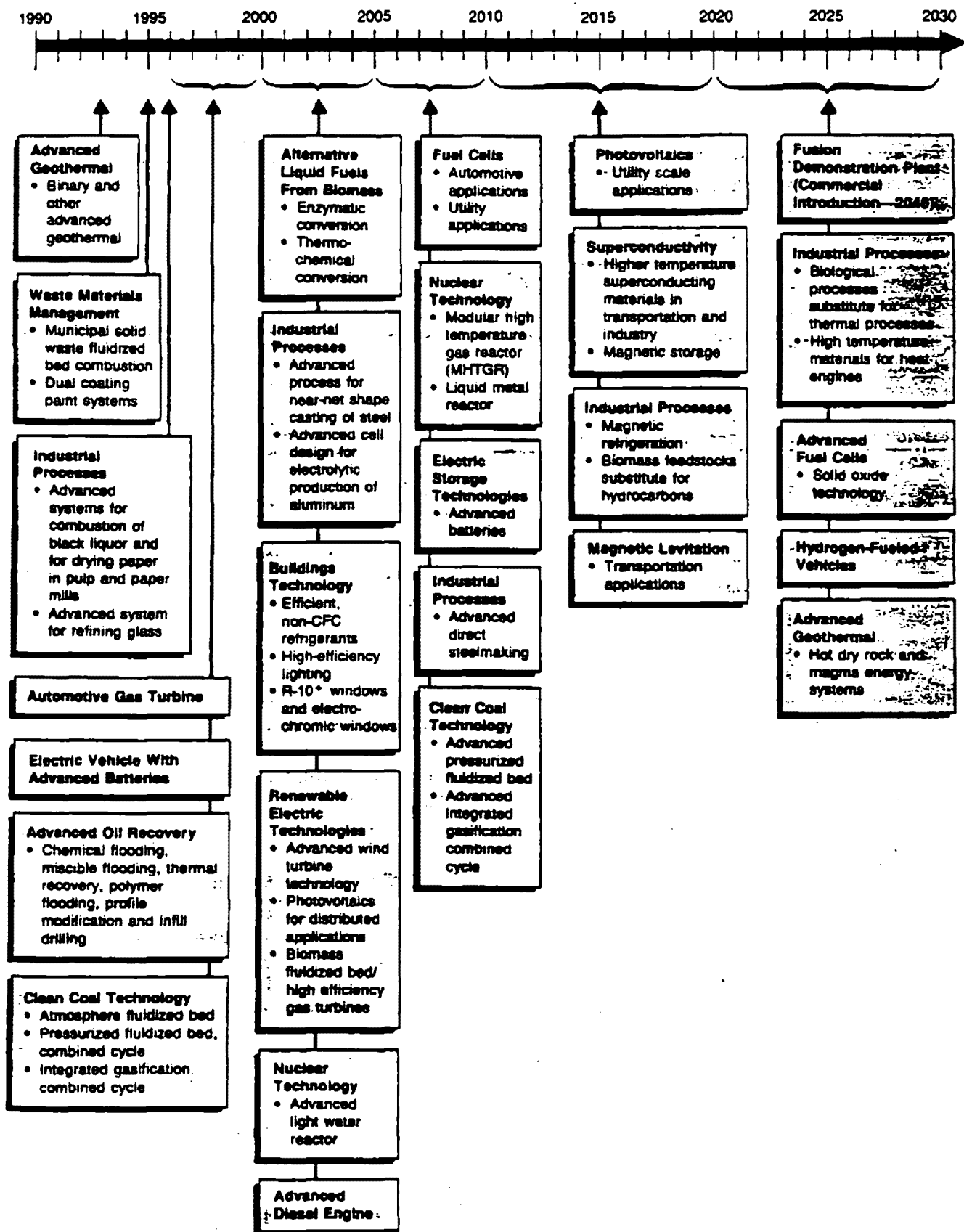
### Conservation and Efficiency Studies

Currently, five ongoing analyses of conservation and efficiency are underway to examine the structural, behavioral, technical, and economic factors that explain trends in energy efficiency and provide estimates of future potential. The areas being examined are oil conservation potential, electricity conservation, transportation fuel efficiency, energy in trade competitiveness, and energy efficiency and the environment.

### Additional Studies

The Department also supports policy analysis of pollutants from energy-related activities, including the

Figure 10. Timeline for Commercial Introduction of Selected Energy Technologies



development of analytical tools and assessments of energy technologies. Pollutants of local interest may interact to influence greenhouse gases or may relate to climate change in other ways. Policies to control greenhouse gases may be antagonistic to or synergistic with control of environmental pollutants.

### **Related International Activities**

The Department of Energy participates in a number of international activities related to global climate change. These include bilateral and multilateral discussions on climate change and energy policy; international R&D cooperation in science and technology to mitigate greenhouse gas emissions; and promoting the export of U.S. technologies and services.

### **International Agreements**

The Department administers approximately 160 international agreements between the Department and over two dozen countries in Europe, the Americas, Asia, and Australia. These agreements facilitate information exchange on pollution control, clean coal technology, renewable energy, energy efficiency, and nuclear energy.

Enhanced international collaboration in energy research and technology development to address environmental issues such as climate change is an increasingly important aspect of the Department's international activities.

For instance, new activities have been launched: a collaborative \$10 million clean coal technology program with Poland for the retrofit of an existing coal plant; a joint project with Mexico to help monitor air quality in Mexico City and identify mitigating measures; and a joint study with the European Community to study the full fuel cycle costs of various energy systems.

### **Bilateral and Multilateral Cooperation**

DOE conducts bilateral consultations on energy issues to provide an opportunity for international energy information exchange and for promotion of U.S. views on energy-related environmental concerns. Bilateral consultations are held on a periodic basis with Canada, Indonesia, Japan, Norway, Mexico, the Republic of Korea, Venezuela, and several oil-producing countries in the Middle East. DOE is also represented in

multilateral programs dealing with energy and environmental issues. These include the International Energy Agency (IEA), the International Atomic Energy Agency, the United Nations Economic Commission for Europe, and the Minerals and Energy Forum of the Pacific Economic Cooperation Conference.

Environmental issues such as climate change are now a major feature of the agendas and discussions of these organizations. For instance, the IEA has completed a number of major studies on the environment, has surveyed and compiled an inventory of the climate policies of its member nations, and is undertaking new studies on the technological potential, costs, and energy market impacts of responses to climate change. Through its participation in the various IEA Standing Groups, in the IEA Governing Board, and at Ministerial meetings of the IEA, the Department has been instrumental in shaping this agenda.

### **Promoting U.S. Exports**

The Department participates in interagency efforts to promote the export of U.S. energy-related technology and services. DOE is currently implementing a major new initiative to identify and promote the export of U.S. oil and gas technology and services, conservation and renewable technologies, clean coal technology, and nuclear energy technology. These technologies can promote environmental quality by replacing outmoded or less efficient technologies, encouraging enhanced energy efficiency, and promoting cleaner use of fossil fuels and safer use of nuclear energy.

## Working Group of the DOE Climate Change Executive Committee

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	Ted Williams, PE-63	202-586-2061
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	Mike Delello, S-1	202-586-0509
General Counsel	Rebecca Thomson, GC-15	202-586-0393
Public Affairs	Phil Keif, PA-3	202-586-5806
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	William Brennan, CP-33	202-586-4827

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## **EPRI'S GREENHOUSE GAS EMISSIONS ASSESSMENT AND MANAGEMENT RESEARCH PROGRAM**

**D. F. Spencer, G. M. Hidy  
Electric Power Research Institute  
Palo Alto, CA 94304**

### **ABSTRACT**

This paper will briefly review the rationale and need for an electric utility Greenhouse Gas (GHG) emissions assessment and management research program, as well as potential cost implications to society of short-term control requirements. The balance of the paper will focus on EPRI's directly-related R&D program and its key elements, namely a) model development and model evaluation activities, b) ecological effects, c) management/mitigation research, and d) the development of an integrated assessment framework. EPRI's directly-related GHG research program, including cofunding, is expected to expend approximately \$60.0 million over the next four years to address key aspects of this significant environmental issue.

### **BACKGROUND AND INTRODUCTION**

Over the last 100 years, the dramatic enhancement of national economies and individual well-being, particularly in industrialized nations, has resulted in large increases in the use of energy and, particularly, fossil fuels. Simultaneously, large land areas in both developed and developing countries have been converted from forests and grasslands to agricultural lands, with concomitant impact on the global carbon balance. Finally, the world population explosion, as well as lengthening life spans, have propelled the world to levels of activity which are challenging the environment locally, regionally, and globally.

These activities are producing a wide variety of gases, which when released to the atmosphere, produce a significant biogeochemical perturbation of the natural environmental system. The gases include carbon dioxide, sulphur oxides, nitrous oxides, chlorofluorocarbons, methane, volatile organic compounds, etc. In addition, the transitioning of forested lands to agricultural uses alters a) the biofixation potential of specific regions, b) soil nutrient and moisture contents, c) surface albedo, d) ecological habitats, etc. These perturbations of the earth's atmospheric composition and land use, in turn, result in modified physical, chemical and biological properties of the atmosphere, land, and ocean systems.

Two of these modified properties have been the focus for many studies of the impacts of so-called "greenhouse gases," namely the projected mean temperature increase of the earth's atmosphere and sea-level rise. Obviously, many other properties will also be modulated

simultaneously including those arising as a result of induced changes resulting from temperature change, etc. Our present ability to assess most first and second order effects and system feedback, and to properly consider all system responses is greatly limited.

Examples of limitations include our present inability to a) adequately account for changes in solar radiation fluxes, b) properly evaluate the role of cloud feedback on climate, c) properly consider aerosol cooling, from natural and anthropogenic sources, d) include biofeedback, both terrestrial and oceanic, etc. Each of these processes plays an important role in maintaining either our earth's radiative or chemical balance. It is incumbent upon us to develop a more thorough understanding of these processes, and associated effects, in order to develop meaningful policy and technological responses.

It is the purpose of EPRI's Greenhouse Gas (GHG) Emissions research and development (R&D) program to a) assess the overall scientific level of understanding of these limitations and identify research opportunities, b) assess the impact of the U.S. electric utility industry on GHG emissions and the effects of climate change on the industry, c) estimate expected effects of increasing concentrations of GHG and economic consequences, domestically and internationally, and d) develop management and mitigation options to minimize deleterious effects on the climate, ecological and human systems.

### **PERSPECTIVE ON U.S. ELECTRIC UTILITY GREENHOUSE GAS EMISSIONS**

At present, the U.S. electric power industry generates approximately 33% of the carbon dioxide produced in the U.S.(1) This is equivalent to 7% of the total anthropogenic CO<sub>2</sub> generated annually on a global basis and accounts for less than 4% of the global warming potential (GWP). The GWP provides a means for a simple comparison of the radiative forcing of various greenhouse gases. It is, by definition, "the time integrated commitment to climate forcing from the instantaneous release of 1 kgm of trace gas expressed relative to 1 kgm of carbon dioxide."

The U.S. power industry has traditionally depended on coal as its preferred fuel. In 1991, the U.S. power industry consumed more than 800 million tons of coal to generate more than half of the electricity produced in the U.S. Present coal-fired plants have the reputation of being "dirty" and environmentally acceptable, only with retrofit emission control technology.. Trends in new coal-fired generation, spurred by the Clean Air Act and its amendments, are leading to a whole new breed of higher efficiency, environmentally benign systems.(2)

Although short-term generation additions in the U.S. are projected to primarily rely on natural gas, it is expected that coal will play an important and perhaps increasing role in future U.S. electricity generation well into the mid 21st century. As a result, it is expected that overall emissions of carbon dioxide from powerplants will rise with increased demand for electricity over the next 15 to 20 years.

On the other hand, projected increases in electricity end use efficiency and substitution of electricity for other end use fuels; e.g., natural gas, can lead to substantial overall reductions in CO<sub>2</sub> emissions. These so-called "wiser and wider" uses of electricity are forecast to have the potential to reduce U.S. CO<sub>2</sub> emissions by nearly 700 million tons by 2010, or approximately 13% of our nation's present CO<sub>2</sub> emissions.(3) Therefore, it is imperative that we evaluate the benefits of electric power from the generating plant through the final end use to properly assess the contribution to GHG emission reductions.

## OPTIONS FOR GREENHOUSE GAS EMISSIONS MANAGEMENT

Over the short-term (the next five to ten years), the options available to the electric power industry for reducing GHG emissions are limited. Any such controls, at the powerplant site, would have to be made on the existing 494,000 Mwe of fossil generating capacity to significantly reduce emissions. Most of these units do not have space for so-called CO<sub>2</sub> scrubbers, and cost and efficiency losses from such systems would make them totally uneconomical.(4)

The only real short-term options are a) improving end-use efficiency, b) improving the efficiency of existing fossil generating units, c) carbon dioxide systems dispatch, and d) natural gas substitution. Each of these options is discussed in reference 1, with the following estimated reduction potentials over the next ten years:

- It is estimated that between 3% and 8% of the unconstrained CO<sub>2</sub> powerplant emissions in 2000 could be eliminated by actively promoting end-use efficiency improvements.
- Although heat rate efficiency gains of 1% to 5% are possible with existing fossil units, new Clean Air Act amendments are likely to result in a net decrease in the efficiency of coal-fired units.
- If gas/oil-fired units were dispatched in place of coal, utilities might further reduce CO<sub>2</sub> emissions by 3% to 5%; however, this would obviously produce higher cost power.
- The greatest CO<sub>2</sub> emission reduction potential would result from mass substitution of natural gas for coal. If CO<sub>2</sub> emission levels were to be held to today's levels, nine to ten trillion cubic feet of new natural gas annually would be used by the power industry. This is extremely unlikely and extremely costly. Cost estimates, taken from reference 1, indicate that maintaining constant CO<sub>2</sub> emissions over the next decade would require annual expenditures of \$17 to \$42 billion (\$1990) in 2000. In addition, substantial new gas pipeline capacity would be required and it is likely that the additional demand for natural gas would result in even higher gas prices; i.e., greater annual costs than the estimated \$17 to \$42 billion.

In the longer term (beyond 2000), many new options will become available to the electric power industry and its customers to effect significant reductions in GHG emissions. These options (5) include further improvements in end-use efficiency, powerplant generation efficiency improvement, substitution of nuclear and renewable powerplants for fossil power, carbon dioxide scrubbing and sequestration, and terrestrial and, perhaps, oceanic phytomass production and storage or substitution for fossil fuels. Further, there are opportunities for selective natural gas substitution or co-firing, for development of integrated energy facilities, and the transfer of energy-efficient electric technologies from developed countries to developing countries.

Of course, all of these control strategies come at some price, and costs of carbon emissions reduction programs range from net benefits of end-use efficiency gains to costs of \$350 to \$700 per ton of CO<sub>2</sub> sequestered or averted.(5) A long-term management, mitigation strategy, based on minimizing the costs to society, is a major objective of EPRI's assessment and GHG emissions reduction research program.

## EPRI'S GREENHOUSE GAS RESEARCH PROGRAM

EPRI has been supporting greenhouse gas research for over a decade. Early sponsored research focused on carbon cycle modeling, the role of the ocean in CO<sub>2</sub> uptake, and two international symposia on "Carbon Dioxide Transfer in the Atmosphere-Ocean-Terrestrial System." This early work included support for Dr. Charles Keeling's key geophysical monograph series published in 1989.(6) This work included:

- Three-dimensional modeling of atmospheric CO<sub>2</sub> transport, including the influence of El Nino events on biospheric and oceanic CO<sub>2</sub> exchange and identification of the biosphere becoming a key CO<sub>2</sub> source term in the mid-1970s time frame.
- Modeling of CO<sub>2</sub> sources and sinks including fossil fuel CO<sub>2</sub>, exchange between the terrestrial biosphere and atmosphere, and air-sea exchange, driven by prescribed temporal and spatial variations of CO<sub>2</sub> in surface waters.
- Modeling of the mean annual cycle and interannual variations in atmospheric CO<sub>2</sub>, as well as comparison with measurements over a 25-year period from pole to pole over the Pacific Ocean.

Other research included development of an 11 compartment (box) model of the ocean-atmosphere system which predicted large increases in Antarctic surface water biological production during the last ice age. This may have resulted in a net organic flux into the oceans, lowering the atmospheric CO<sub>2</sub> concentration by 90 to 110 ppm.(7) The workshops held in 1985 and 1988, brought together international experts in the global carbon cycle to discuss the state of carbon cycle modeling, ice core and tree ring data, ocean circulation, terrestrial biospheric changes, etc. These workshops played a key role in facilitating information exchange among experts on various elements of the carbon cycle.

In the last few years, EPRI's directly-related GHG research and development program has greatly expanded to include a) the reliability and completeness of climate prediction studies, b) assessment of effects on human and natural systems, c) GHG management/mitigation options, and d) a focus on the development of an integrated assessment framework. These activities are in addition to a broad range of indirect efforts which would support electric utility CO<sub>2</sub> emission reductions including a) increased emphasis on end-use efficiency improvements, b) advanced, higher efficiency, fossil power cycles, c) renewables and biomass technologies, and d) advanced nuclear powerplants.

EPRI's research priorities have been established to

- Assess uncertainties associated with General Circulation Model process and data limitations,
- Provide bounding analyses of physical, ecological, and economic impacts resulting from global climate change,
- Identify and develop "least cost" management options for the power industry, including adaptation and mitigation.

## ASSESSMENT OF CLIMATE MODELS

In 1991, EPRI, in conjunction with the National Science Foundation, and a group of international organizations, initiated a program to assess the accuracy and uncertainties associated with climate models. This program is known as the Model Evaluation Consortium for Climate Assessment (MECCA). The objectives of the MECCA program are to: a) quantify the probably range of future climate change, b) provide policy-makers with information that could be used to coordinate decisions with scientific developments, and c) identify key topics needing research to improve climate forecasts.

MECCA's research plan (8) includes two key elements, a set of carefully selected model experiments, designed to supplement ongoing work by other modeling groups and an analysis strategy that focuses on the impact-oriented needs of policy-makers and the private sector. The primary elements of the modeling strategy include:

- Large-scale climate changes including global temperature, precipitation, and pressure patterns,
- Regional climate simulation, at subcontinental grid scales to aid an understanding of local impacts on agriculture, commercial, and industrial activities;
- Extremum events that might be associated with climate change such as droughts, floods, storms, prevailing lows, etc., and
- Model evaluation experiments which simulate today's climate in order to identify any potential systematic modeling errors and needs for model improvement.

Current MECCA experiments include evaluations of the sensitivity of climate model outputs to a) CO<sub>2</sub> concentration, b) model grid size, c) atmosphere-ocean coupling, d) land surface interactions; e.g., tropical deforestation, e) ice dynamics, and f) cloud parameterization. In addition, regional climate studies and general circulation model prediction variability in century-long simulations are being studied.

An example of the evaluations underway is an estimate of the global mean equilibrium atmospheric temperature as a function of ambient CO<sub>2</sub> concentration. These studies have shown that the mean global atmospheric temperature rises very non-linearly with CO<sub>2</sub> concentration. Maximum equilibrium temperatures of slightly less than 300°K are predicted for CO<sub>2</sub> partial pressures of 1000 ppm. The estimated temperature rise for a doubling of CO<sub>2</sub> from 280 ppm to 560 ppm is approximately 5°K, consistent with other model projections.

Another of the studies underway is evaluating the relative influence of the sensitivity of surface temperature to shortwave (solar constant) changes as compared with longwave (CO<sub>2</sub>) changes. Preliminary results indicate a nearly linear response of temperature to variations of the solar constant of + 5%, as compared with the logarithmic response noted above for changes in CO<sub>2</sub> concentration. Temperature sensitivity about the present value of the solar constant is approximately 1°K per 1% change in the solar constant.

A third analysis is focusing on the use of different surface hydrology models in General Circulation Models (GCMs). The models compare results from so-called "bucket" models with more accurate variable infiltration capacity (VIC) models. Results show that evaporation rates in the two models are very similar over a GCM grid cell; however, the bucket model predicts much

higher near-surface soil moisture contents. These are obviously very important in estimating biological growth rates and carbon fixation potentials.

A fourth study is evaluating the role of cirrus cloud albedo on global temperature. The suggestion is that penetrative convection under the condition of warm ocean temperatures is strong enough to drive large amounts of moisture into the troposphere and to generate dense cirrus clouds capable of substantially increasing the earth's albedo. Preliminary results indicate that when the ocean surface temperature exceeds 303°K, the middle and high altitude cloud albedo rises rapidly to levels comparable to low-level clouds (~0.6). This increase in cirrus cloud albedo keeps the tropical temperature of the simple mixed layer ocean near 303°K and cools the entire planet. Thus, the overall increase in planetary albedo is creating a negative feedback which limits surface air temperature increases.

Another key element of EPRI's GHG modeling efforts has been the development of the personal computer based global carbon cycle model, GLOCO.(9) The GLOCO model integrates a set of mechanistic modules of the atmosphere, oceans, and terrestrial ecosystems into a single global carbon cycle model. In addition to representing the basic reactions of the global carbon cycle, the model includes the cycling of nutrients that limit the growth of marine and terrestrial biota.

The terrestrial ecosystems are represented by six biomes - tropical, temperate, and boreal forests, grassland, tundra, and desert. Carbon in each biome in the model occurs as plant and soil matter. The primary process driving the terrestrial carbon cycle is the fixation of atmospheric carbon dioxide as organic carbon via photosynthesis. The earth's atmosphere is represented as a single box in the model, with two atmospheric carbon compounds, namely CO<sub>2</sub> and CH<sub>4</sub>. The concentrations of each are calculated from the balance of inputs to the atmosphere, uptake by the oceans and terrestrial ecosystems, and atmospheric reactions.

The oceans model includes the biogeochemical cycling of five chemical components, namely total inorganic carbon, dissolved organic carbon, particulate organic carbon, alkalinity, and phosphate. Both physical and biological carbon exchange between the atmosphere and ocean are included in the model.

GLOCO was calibrated by assuming that only fossil fuel carbon and land-use changes altered the atmospheric CO<sub>2</sub> concentration from 1700 to present. The calculated CO<sub>2</sub> concentrations are within 5 ppm of ice-core inferred values for the period 1700-1950 and within 2 ppm of the Mauna Loa measured values (1958-1990).

GLOCO projects future atmospheric carbon dioxide concentrations to the year 2100 utilizing IPCC fossil fuel emission scenarios and projected land-use conversions. The model is particularly capable of permitting a number of sensitivity tests to examine the implications of uncertainties in key parameters or permitting "worst" case analyses to be performed. Examples of variations in input parameters which have been assessed are:

- Simultaneous carbon and nitrogen fertilization effects on forest ecosystems,
- Evaluation of the effect of different CO<sub>2</sub> gas exchange fluxes (atmosphere/ocean) on the oceanic uptake of CO<sub>2</sub>,
- Impacts of increased oceanic upwelling velocity on CO<sub>2</sub> uptake,
- Assessments of the sensitivity of atmospheric carbon dioxide to oceanic productivity.

In general, GLOCO offers a means to assess in a globally aggregated way, the relative importance of a variety of physical and biological processes on future concentrations of atmospheric carbon dioxide.

## ECOLOGICAL EFFECTS AND CO<sub>2</sub> MANAGEMENT

EPRI's GHG ecological effects program focuses on development of tools for conducting assessments and experimental programs to evaluate forest response to CO<sub>2</sub>. The potential for ecological effects is one of the primary concerns expressed by environmentalists. Preliminary analyses suggest that unmanaged ecosystems may be the most sensitive of the potential impact areas, and the levels of atmospheric carbon dioxide and rate of change of mean atmospheric temperature are extremely important parameters. Of course, it is very important to know whether the severity of effects accelerates rapidly with a 2°C or 4°C temperature increase, or at a rate of change of temperature of 0.1°C per decade or 0.2°C per decade. Another important element may be whether these increases reflect average maximum daylight temperatures or average minimum nighttime temperatures, as is indicated by some models.

EPRI research is exploring the range of possible effects of climate change, develop models and data for assessing climate change effects and quantifying uncertainties, and develop methods for utilities to use in evaluating and managing power system related water resources susceptible to climate induced changes.

Two of our present GHG ecological effects studies focus on biomass production in loblolly pines at elevated CO<sub>2</sub> partial pressures and the effects of elevated CO<sub>2</sub> on grasslands. Results of initial growth studies of loblolly pine indicate that elevated CO<sub>2</sub> alone will have little influence on biomass growth; however, addition of other nutrients, specifically nitrogen and phosphorus, can increase biomass yields up to 25% over yields with today's atmospheric CO<sub>2</sub> concentrations.

Another study being performed for EPRI by the Nature Conservancy is evaluating the effects of climate change on plant diversity in North America. The impacts of climate change on 14,000 plant species is being assessed, including stand geographical migration patterns and species losses.

EPRI is also assessing a variety of indirect and direct management mitigation options to limit ecological or other damage. There presently is little agreement about which potential impacts are of greatest significance or concern; and generally accepted methods for cost/benefit analyses for slowing climate alteration do not exist. Further, benefits may accrue to certain world regions while costs may be borne by another region.

EPRI's primary research emphasis will be to develop "least cost" systems to ameliorate GHG emissions to acceptable levels. Of course, the degree to which each component of such a strategy can be utilized to mitigate the problem is dependent, not only on the total control level to be achieved, but also the degree to which each alternative actually penetrates the market as a function of time.

Reference 5 reviews the variety of options available to reduce CO<sub>2</sub> emissions and prioritizes them on the basis of cost per ton of C averted or sequestered. It is clear that energy efficiency improvements, both at the end-use and at the power production level, should be emphasized in addressing the GHG control issue from an electric utility viewpoint. Beyond these efficiency measures, there are a range of options for limiting CO<sub>2</sub> emissions; e.g., nuclear and renewables that are more attractive than the "CO<sub>2</sub> scrubbing and sequestration" approach.

EPRI is sponsoring research relating to range of biospheric options for mitigating atmospheric carbon dioxide levels.(10) Terrestrial approaches include halophyte production in semi-arid regions and short-rotation woody crop production and utilization. Ocean marine systems research includes a) evaluating the CO<sub>2</sub> sequestration capability of the oceans and sediments, b) ocean circulation studies, c) sequestering carbon dioxide in the form of clathrates in the deep ocean, d) development of free-floating or structured macroalgal species/systems to biologically fix CO<sub>2</sub>, and e) optimal conversion/sequestration strategies.

All of these efforts focus on increasing yields per unit area of biomass, assessing long-term storage potential, and estimating sequestered (or averted) carbon costs per ton. A combination of these processes could reduce atmospheric loading by 2.0 to 10.0 gigatons per year at costs of \$100 to \$300 per ton of carbon. Although none of the biological approaches offers a clear cost advantage over CO<sub>2</sub> scrubbing, they may offer a preferred solution since infrastructure, transport, etc., requirements may be less cumbersome. In addition, there may be additional advantages associated with energy or food byproducts which could alter the relative benefit of biospheric systems.

In addition to our CO<sub>2</sub> mitigation program, EPRI is aggressively contributing to the development of non-ozone depleting; i.e., non-halogenated hydrocarbon refrigerants, which will also have a minimum impact on the global radiative balance. A major program has just been initiated to develop new working fluids for unitary heat pumps, air conditioners, and electric chillers which use neither chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). HCFC and CFC based vapor compression systems account for 23% of utility loads and revenues; thus developing substitute working fluids is a high priority. The two parallel projects are aimed at replacing HCFC 22 in heat pump and small building cooling applications and HCFC 123 for large system cooling. The challenge will be to develop substitute working fluids with no decrease in the cycle efficiency. Pure fluids, azeotropic and non-azeotropic mixtures will be characterized and evaluated.

## INTEGRATED ASSESSMENT FRAMEWORK

The final major component of EPRI's Greenhouse Gas Emissions Assessment and Management Research Program is the development of an integrated assessment framework. The purpose of this research program is to provide a consistent and comprehensive approach for evaluation of GHG management proposals and associated R&D strategies. The strategy is being designed to provide an evaluation framework for measuring the impact of GHG control strategies on the overall domestic, as well as international, economies, major industries, and the public.

In concert with the National Science Foundation and the Department of Energy, EPRI is supporting the construction of a group of models which will synthesize information on the relationship between human activities and GHG emissions, the effect of GHG emissions on climate, and the impact of climate changes on human and natural systems. By linking this information together in a cohesive way, analysts will then be able to evaluate the costs and benefits of policy proposals in a consistent manner, as well as evaluate the potential value of alternative R&D strategies. The results from a first analysis using the framework should be available by 1994 and periodic refinements will be made throughout the decade as new knowledge and methods evolve.

The framework will consist of a series of linked modules representing the major processes, including a) the emissions of radiatively important gases, b) natural system disposition and



reactions to the emissions of these gases, and c) the reaction of human and natural systems to changes in the atmosphere-climate system. As we all know, the development of such an assessment framework, with its scope and complexity, is a formidable task. Initially, three contractors will be developing alternative approaches. This collection of models will include estimates of "damage functions" to develop a specific quantitative impact and risk assessment basis, both temporally and regionally.

Our approach to the development of an integrated assessment framework must be iterative. At the present time, our understanding of each of the relevant processes and how they interact is incomplete. However, enough is known to permit initial development of the entire system. At that point, the framework can be used to identify those elements of the climate problem that contribute the largest uncertainties to our ability to provide knowledge or predict outcomes of importance to policy-makers. For example, we will be able to explore the sensitivity of policy proposals to different assumptions about natural system processes. In this way, we can identify critical uncertainties and identify where additional research is most needed. The framework can thus be used to help guide its own future development.

Another important component of EPRI's risk assessment activities includes evaluations of the impact of climate changes on utility systems and their operations, specifically, the implications of potential global, or regional warming on air-conditioning loads, cooling water availability, and potential implications to hydroelectric generating capacity. To date, our assessments indicate that expected impacts on utility systems operations are minimal; however, as we develop better estimates of potential regional climatic changes, there may be regions wherein these impacts are important.

## **EPRI'S GHG R&D RESEARCH STRATEGY AND PROGRAM EMPHASIS**

As indicated above, a focal point of EPRI's research on climate change is the development of an integrated assessment framework that will be used to compare the costs and benefits of alternative climate change management proposals. An important feature of the integrated assessment framework is the ability to treat uncertainty probabilistically rather than generating single point estimates of expected outcomes for given scenarios.

Given the vast number of scientific, political, economic, and technological uncertainties associated with global climate change concerns, the possibilities for designing a research program are myriad. In recognition of these factors, as well as our awareness that the U.S. federal government will be spending approximately \$1.0 billion annually, the remainder of the EPRI program has been designed based on meeting one or more of the following criteria:

- The research should provide input to integrated assessments in the form of models and estimates of key parameters and their associated uncertainty.
- The research should address key electric utility issues.
- The research should help identify and fill critical gaps in the research being done by the federal government and other organizations through the world.
- The research should help influence key elements of the national program; thus achieving a significant leveraging of EPRI's funds.

Through a carefully designed program, carved out in a timely manner, EPRI research can help decision-makers in the electric utility industry and elsewhere understand the implications of proposals for addressing the issue of climate change.

As was stated previously, EPRI recently has significantly expanded its GHG R&D program. The Institute is planning to expend approximately \$40 million on direct global change research over the next four years, with annual funding by 1995 of \$12 to \$15 million. In addition, a number of programs are being cofunded, with estimated cofunding of \$20-\$25 million over the period 1992-1995. The allocation of these R&D funds over the next four years are expected to be:

• Integrated Assessment Framework	\$ 4.4
• Global Carbon Cycle	3.2
• Climate Change Prediction	23.4
• Effects	9.7
• Valuation of Effects	4.5
• Costs	13.4
• Mitigation and Adaptation	<u>1.4</u>

Total (92-95) \$60.0

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## GLOBAL EMISSIONS DATABASE (GloED) SOFTWARE

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### ABSTRACT

The EPA Office of Research and Development has developed a powerful software package called the Global Emissions Database (GloED). GloED is a user-friendly, menu-driven tool for storage and retrieval of emissions factors and activity data on a country-specific basis. Data can be selected from databases resident within GloED and/or imputed by the user. The data are used to construct emissions scenarios for the countries and sources selected. References are linked to the data to ensure clear data pedigree. The scenario outputs can be displayed on thematic global maps or other graphic outputs such as bar or pie charts. In addition, data files can be exported as Lotus 1-2-3, dBase, or ASCII files, and graphics can be saved as a .PCX file or exported to a printer. This paper describes GloED and how it works. It also presents future plans for software enhancements and populating the databases.

## **BACKGROUND AND INTRODUCTION**

The Global Emissions Database (GloED) was designed initially as an internal data management tool to handle the large number of greenhouse gas data generated as the result of international greenhouse gas research activity. Not only was there a large amount of data but the databases were rapidly changing based on continuing studies and new information. Initial attempts at handling the data electronically involved using commercial software such as Lotus 1-2-3 and dBase. These initial efforts were frustrating partially because of the limitations of the software and partially because of the limitations of user expertise. Initial limitations included keeping track of which data sets were used in constructing emissions inventories and identifying the quality of the data in each data set. It soon became apparent that a better system needed to be developed by professionals in software development.

The GloED software subsequently developed is personal computer (PC)-based and very user-friendly with little or no computer expertise needed. Using GloED, the storage and retrieval of data is quick and easy. This is important so that updates can be stored as better data become available. Consequently, current best estimates are always available. Another advantage of GloED is that units specified by the user are automatically generated by GloED. If the user calls for units that are not recognized by GloED, then GloED allows for the input of an algorithm that will define the new unit.

Another important attribute of GloED is that references are linked to the data. Consequently, there is the ability of the user to establish the origin of every individual piece of data in the scenario constructed. An additional advantage of GloED is its ability to interface with other software packages such as Lotus 1-2-3 and dBase for those scientists and engineers familiar with these commercial software packages.

After establishing the utility of GloED as an internal data handling tool, it was presented to an emissions workshop sponsored by the Intergovernmental Panel for Climate Change (IPCC) in December 1991. As a result of this exposure to the IPCC and the Organisation for Economic Co-operation and Development (OECD), interest grew in GloED as a standardized tool which could be used by all researchers to develop quality assured, country-specific, emissions inventories. The United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro just 2 months ago underscored the need for a system to establish baseline emissions and to track emissions reduction progress by country. GloED has the potential for providing this system for implementing of the goals proposed at this historic Earth Summit meeting.

## **GLOED DESCRIPTION**

GloED is a software system designed as a tool for generating estimates of global emissions. GloED generates emission inventories by combining information about activities with pollutant-specific emission factors for those activities. Activities

are defined in terms of processes that occur in a specific pollutant source category in a specific country or at a specific latitude and longitude. Activities are grouped into discrete data sets within the GloED system. The user selects one or more data sets and then has the option of narrowing the scope of the inventory by selecting a limited number of countries, source categories, and pollutants. The final set of data selected is called a *scenario*. GloED also can accept data provided by user-input. Consequently, the emissions inventories can be updated as new data become available to the user. GloED calculates an emissions inventory based on the scenario generated by the user and can present summaries of the inventory graphically and in textual form.

The contents of the emissions inventories can be reported in a variety of ways. A text summary of the emissions inventory will print a tabular breakdown of the results by country, source category, and/or pollutant. GloED can develop a pie chart or bar chart showing the top pollutants or countries or source categories in a form that allows easy comparison among them. Finally, GloED can project the results of an emissions inventory onto a global map, using different colors to designate the type and distribution of pollutants in the selected scenario. All of these output formats can be viewed on the screen, saved to a file, or printed as a hard copy. The data can also be exported to Lotus, dBase, or ASCII.

## USING GLOED

Each level of the program has a menu that allows the user to select the operations that the program should perform at that level. The user can select the actions in the menu either by clicking a mouse on the desired menu selection or by typing the first letter of that selection. The GloED main menu always appears along the top of the screen and is a set of pull-down menus, which means that the user can "pull down" further options by selecting a menu item. When the user selects a menu option--either with a mouse or with the cursor keys--GloED will lead the user to the screens that apply to that menu option.

Most of the menu items selected will call up a screen of "scroll boxes" that allow the user to define more specifically the way in which the selected menu function is performed. To move among the different scroll boxes, the mouse is used to click in the desired box, or the user can press the [TAB] key to move clockwise--or [SHIFT] and [TAB] to move counterclockwise--through the scroll boxes and buttons on the screen. The user can move *within* the scroll boxes either by using the cursor (or arrow) keys on the keyboard or by clicking with the mouse on the "scroll bar" (the vertical shaded strip with arrows at top and bottom) on the right-hand side of each scroll box. The user can jump quickly to the very first entry in the scroll box by pressing the [HOME] key on the keyboard and can jump to the last entry in the scroll box by pressing the [END] key on the keyboard. The user can view the next or previous boxful of information in the scroll box by pressing [PAGE UP] or [PAGE

DOWN], respectively. When the item to be selected is highlighted, the user can select it by pressing [ENTER] or by clicking on it with the mouse.

Any of three methods can be used to exit one of the screens in GloED at any time:

- (1) Pressing the "escape" [ESC] key;
- (2) Moving the mouse to the on-screen [CANCEL] button, and then "clicking" the button on the mouse to select cancel; or
- (3) Using the [TAB] key to tab clockwise (or [SHIFT] and [TAB] for counterclockwise) through the on-screen scroll boxes and buttons in sequence until the [CANCEL] button is selected, and then pressing the [ENTER] key.

Any of these operations will take the user out of the screen in which the user is working and return to the last active screen before arriving at this screen.

#### The GloED Main Menu

<b>Scenario Database Calculate Map Reports Help Quit</b>
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Figure 1. The GloED Main Menu

The GloED main menu is shown in Figure 1. It is represented by a bar that will remain at the top of the screen as long as GloED is running, and offers choices of the type of function the user would like GloED to perform. The user can move between menu options with the mouse or with the arrow keys. The user selects an item by clicking on it or by typing the first letter of its name. The menu options and their general functions are:

- **Scenario**--This menu allows the user to load a previously created scenario, generate a new scenario, combine elements of two or more scenarios, or delete a previously created scenario.
- **Database**--This menu allows the user to edit data entered by the user or to import data sets to be combined with the system database files.
- **Calculate**--Commands the software to create an emissions inventory based on the currently defined scenario.

- **Map**--Allows the user to display the emissions inventory in the form of a gridded or thematic map. (Only thematic maps are currently available.)
- **Reports**--Allows the user to review the emissions inventory in a point-by-point fashion and to search for a specific data point in the inventory. It reports the results of the inventory calculation in text form (as tables) or as graphics (bar charts or pie charts).
- **Help**--Allows the user to receive on-screen assistance while operating the software.
- **Quit**--Allows the user to leave the program.

### The Scenario Menu Option

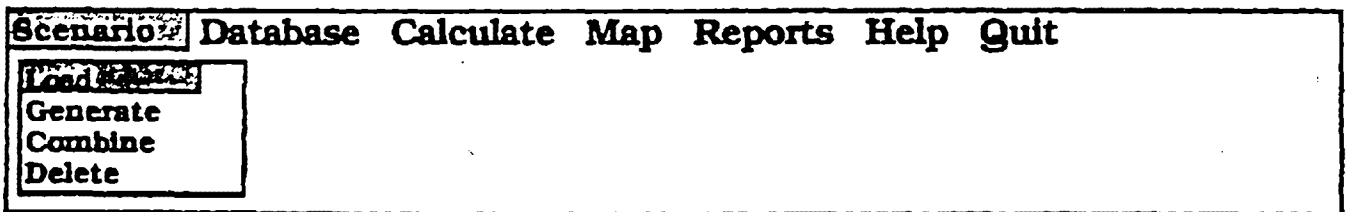


Figure 2. Pull-Down Menu for Scenario Options

The user arrives at the step described in this section by choosing the **scenario** option on the GloED main menu. The menu that will pull down when the user selects the scenario option is shown in Figure 2. It offers the option to load a scenario from the user's disk, generate a new scenario, combine two or more existing scenarios, or delete a scenario from a disk. By pressing [ESC], or the left-arrow key, the user closes this pull-down menu and returns to the main menu.

### **The Scenario Load Screen**

After selecting scenario in the main menu, the user can choose the load option, which will cause a scroll box to come up on the screen. The scroll box will list all of the scenarios that have been generated in previous sessions. To create a different report from a previously generated scenario, the user can mouse-click on the name of that scenario, or use the cursor keys to select the scenario and then press the [ENTER] key. Now the user can click on the [OK] button and GloED will load the selected scenario. It is important to remember that the user must now select the calculate option on the main menu bar before using GloED to generate reports of this scenario.

The scenario load screen is shown in Figure 3.



**Select an Existing Scenario**

---

**Scenario:** NEWONE.SCN

**Scenarios:**

NEWONE.SCN

OK

Cancel

Figure 3. The Scenario Load Screen

### The Scenario Generate Screens

If the user selects the **generate** option in the Scenario menu, GloED will guide through a series of screens in which the user names, describes, and defines the parameters of the scenario to be generated. When this option in the scenario menu is selected, a dialogue box entitled "Create a New Scenario" will appear. In this dialogue box, the user enters the name of the scenario to be created. The user should enter a valid DOS file name that is sufficiently descriptive to be remembered if it is to be used again later. Then [TAB] to or mouse-select on the [OK] button and the Scenario Description screen will come up to allow entering a description of the scenario to be generated.

To *replace* an existing scenario with the one the user plans to generate, press the [TAB] key or use the mouse to enter the scroll box that appears at the bottom of the dialogue box. Then use the mouse or cursor keys to select the scenario to be replaced. When the appropriate scenario is highlighted, press the [ENTER] key and its name will appear on the scenario name line at the top of the box. Then mouse-click on the [OK] button or [TAB] to the [OK] button and press the [ENTER] key. Since this scenario exists, a warning box will appear on the screen that says **"This Scenario exists! Rebuild?"** and gives on-screen buttons that say [OK], which replaces the existing scenario with your new one, or [CANCEL], which cancels the scenario generate routine. Select [OK] and the Scenario Description screen (Figure 4) will come up to allow entering a description of the new scenario to be developed.

### The Scenario Description Screen

This screen will first ask the user to enter a long description of the scenario to be generated.

<b>Scenario Description</b>	
<b>Description:</b>	<div style="border: 1px solid black; padding: 5px; min-height: 40px;"> <b>This scenario generates an inventory of global NO<sub>x</sub> emissions resulting from fossil-fuel production.</b> </div>
<b>Brief Description:</b>	<div style="border: 1px solid black; padding: 2px;"> <b>Global NO<sub>x</sub> from fossil fuels,</b> </div>
<b>Units:</b>	<div style="border: 1px solid black; padding: 2px;"> <b>MT</b> </div>
<div style="display: inline-block; border: 1px solid black; padding: 5px 15px; margin-right: 10px;">OK</div> <div style="border: 1px solid black; padding: 5px 15px;">Cancel</div>	

Figure 4. The Scenario Description Screen

**The Unit Conversion Utility**--After entering the long and short descriptions of the scenario, hit the [TAB] key again. The user will now be in the "Units" field of the scenario description screen. In this field, enter the *target* units in which the inventory is to be reported. The user does not need to know the units used by the individual data sets because GloED contains a unit conversion utility that will automatically convert the results of the scenario to the units defined as targets. This utility will be especially useful in comparing the results of a series of scenarios. If entering the same units for all of the scenarios, no conversion will be required to make a comparison.

### **The Scenario Generate Screen**

Once the new scenario is described to the user's satisfaction, select [OK] and GloED will lead to the Scenario Generate screen (Figure 5). This screen has four scroll boxes, one each for data sets, countries, source categories, and pollutants. Move among the scroll boxes and buttons on this screen, using the mouse to select a scroll box item or pressing the [TAB] key to move clockwise, or [SHIFT] and [TAB] to move counterclockwise. The other scroll boxes will show the source categories, countries, and pollutants that are defined in the selected data set. When the screen first comes up, nothing will be selected. After the user has selected the data set(s) to use, the other boxes will fill with the countries, source categories, and pollutants in that data set.

<b>Scenario Generate</b>			
<b>Data Sets:</b>	<b>Source Categories:</b>	<div style="display: inline-block; width: 45%; border: 1px solid black; padding: 5px;"> ALL CLEAR GLOBAL VOC INVENTORY BIOGENIC SOURCES </div> <div style="display: inline-block; width: 45%; border: 1px solid black; padding: 5px;"> ALL CLEAR AGRICULTURE (coal) AGRICULTURE (gas) </div> <div style="display: inline-block; width: 45%; border: 1px solid black; padding: 5px; margin-top: 10px;"> OK </div>	
<b>Countries:</b>	<b>Pollutants:</b>		
ALL CLEAR ALBANIA ALGERIA	ALL CLEAR NO <sub>x</sub> CO <sub>2</sub>	<div style="display: inline-block; width: 45%; border: 1px solid black; padding: 5px;"> Cancel </div>	

Figure 5. The Scenario Generate Screen

When defining a new scenario, it is important to be aware of the order in which the items are added to the scroll boxes. When a data set is selected, the other three scroll boxes will automatically list all of the countries, source categories, and pollutants included in that data set. GloED defines the items in the other scroll boxes on the basis of a hierarchy. The countries listed depend upon the data set(s) chosen. The source categories listed depend upon the data set(s) chosen and the countries that have been selected within those data sets. The pollutants listed depend upon the data set(s), countries, and source categories chosen. Thus, every time the selection of elements in a scroll box is changed, the contents of the other boxes will change according to this hierarchy.

The user can select a different data set or add data sets to the scenario. Data sets can be selected or deselected by clicking them with the mouse or by using the cursor buttons to highlight the desired data set and then pressing the [ENTER] key. Once the data set(s) are selected, the user can [TAB] or move the mouse through the next boxes and select the specific source categories, countries, and pollutants to be reflected in the emissions inventory. ALL automatically selects all of the items in each list. To select a large number of items, select ALL and then deselect the few items not wanted in the scenario. CLEAR automatically deselects everything in the list, and can be used to clear all selections if an error has been made or to select a few elements in a scroll box. At least one item in each scroll box must be selected for a scenario to be generated. If the user has selected a combination of data sets, countries, source categories, and pollutants that does not reflect an actual combination in the system databases, an error message will request fewer restrictions on the scenario. When all of the specific items for the desired scenario have been defined, tab to the [OK] button on the screen, or click on it with the mouse. GloED is now prepared to calculate the emissions inventory.

### The Calculate Menu Option

When the calculate option is selected in the GloED main menu, the system will generate an emissions inventory based on the current scenario. This is the inventory that will be used in all of the following mapping and reporting menu options. Only one emissions inventory will be generated for each scenario.

### The Map Menu Option

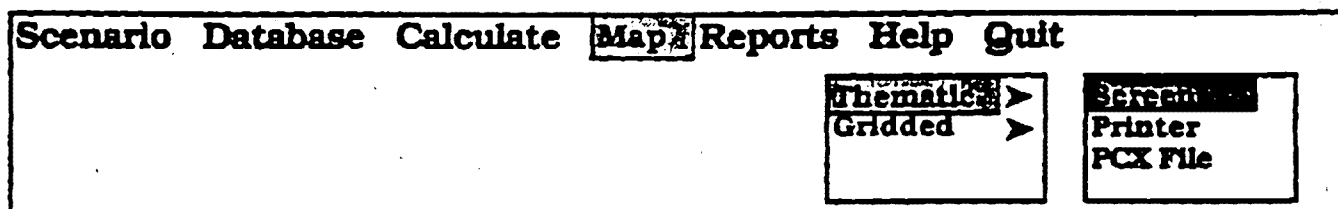


Figure 6. Options in the Map Menu

Once a scenario is defined and an emissions inventory is calculated for it, the user is ready to create a map that reflects the results of the inventory. When the user selects the map option in the main menu, the user will be given the option to tell GloED to display the results either on a gridded map or on a thematic map (see Figure 6). Gridded maps display the distribution of emissions in the form of ranges on a latitude/longitude grid. (Gridded maps are not yet available.) Thematic maps display ranges of emissions on a country basis. Figure 7 is an example of a thematic map.

When the type of map to be created is selected, another menu will pull down and request definitions of the output location for the map. If the user selects Screen, the map will appear on the computer's video monitor. To send the map to the printer, a dialogue box will appear on the screen and ask for selection of the available printer output port to which the file is to be sent and for definition of the type of the user's printer (either by selecting the name with the mouse or by pressing [ENTER] on the appropriate output port and printer name). Finally, to save the map as a graphic .PCX file, a dialogue box appears and requests entry of a valid DOS file name (ending with .PCX) for the map file. At the end of each of these processes, select [OK] and the Text Report Priorities screen will appear.

When the user has the inventory appropriately constructed and has selected the map type, GloED will prepare the map and then give the option of displaying the map on the screen, sending it to the printer/plotter, or saving it on a disk.

# Methane Emissions From Rice Cultivation kg/year

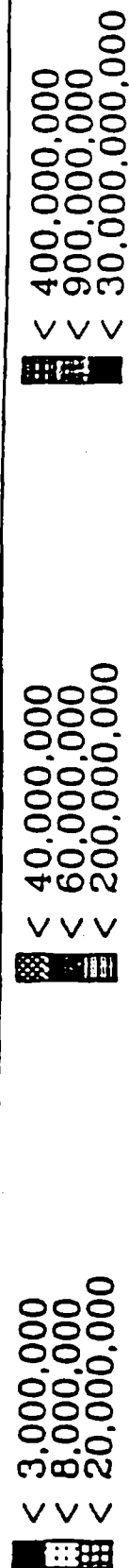
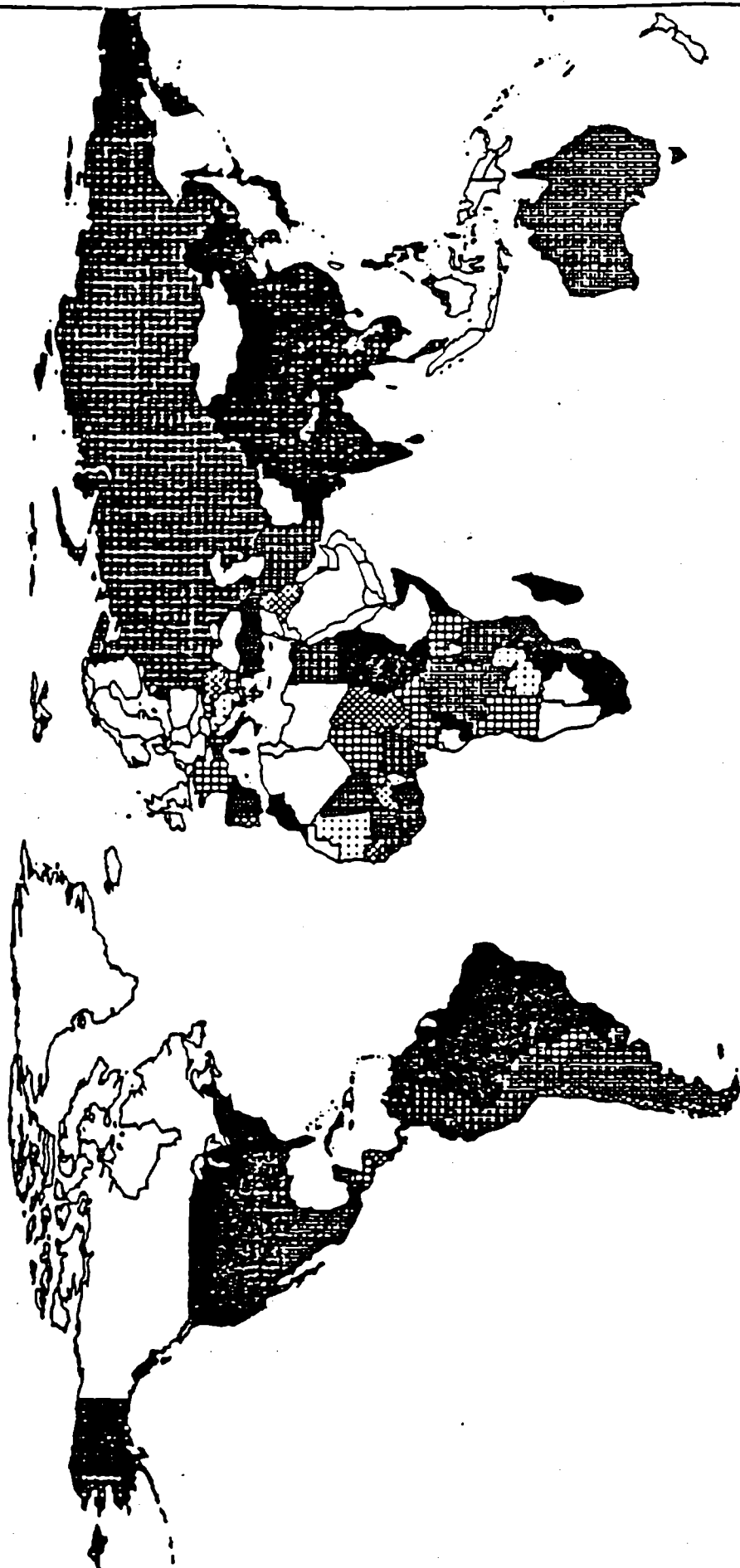


Figure 7. Thematic Map

## The Reports Menu Option

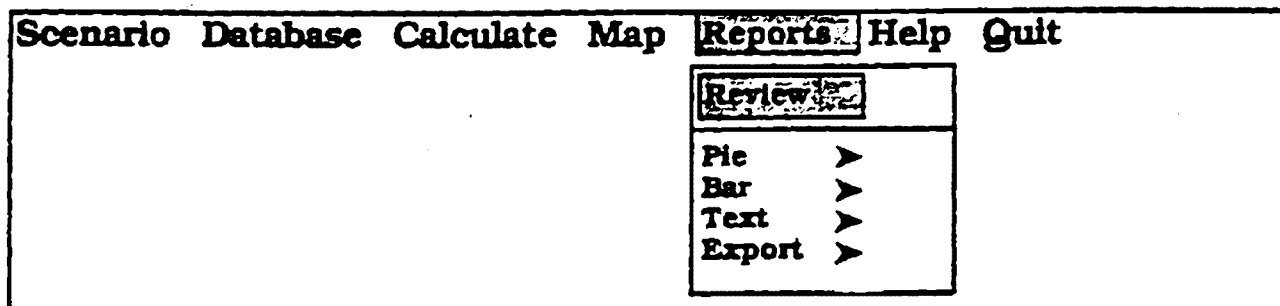


Figure 8. The Reports Menu Option

When the reports option in the main menu is chosen, the menu that pulls down (see Figure 8) gives the following options: Review, Pie, Bar, Text, and Export. The Pie and Bar functions create graphical reports of the emissions inventory. The Text function prepares a complete, tabular report of the emissions inventory, and the Review option allows viewing complete information on individual data points in the emissions inventory.

The Export menu option is used to save the tabular results of the emissions inventory. When the user selects this option in the Reports pull-down menu, another menu pulls down and gives the option of saving the report in Lotus 1-2-3 format, ASCII format, or dBase III format. Figure 9 is a Reports Export screen for exporting a GloED data file to dBase.

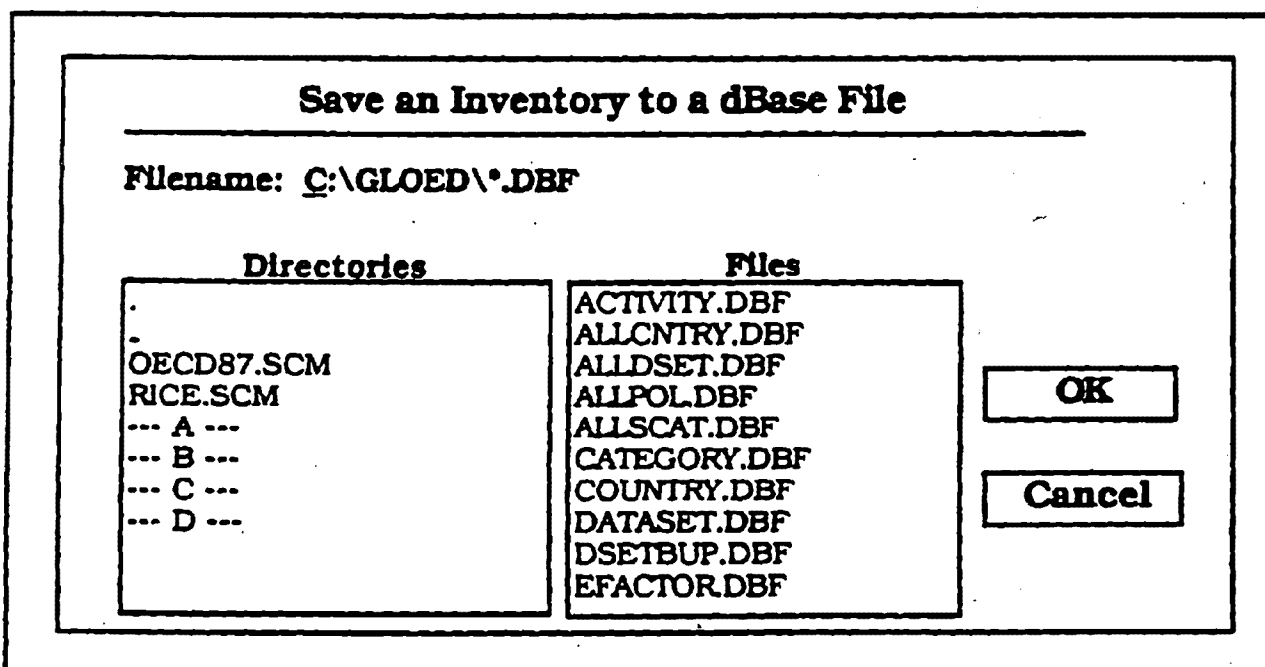


Figure 9. The Reports Export Screen

## Graphical Reports

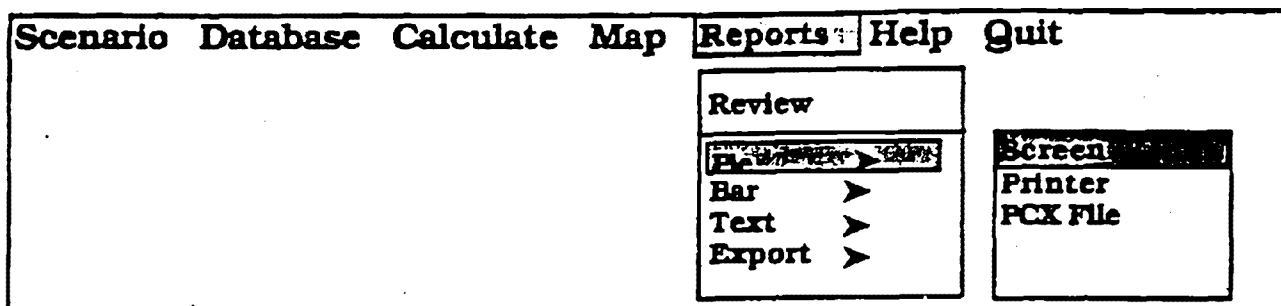


Figure 10. The Graphical Reports Option

In choosing to report the results of the scenario graphically, the user has the option of presenting them in bar chart or pie chart format. Select **Bar** or **Pie** in the Reports menu and then choose to have the graphical report appear on screen, be sent to a printer, or saved on disk as a .PCX file. In selecting the printer option, a new screen appears (Figure 11), asking for the printer type and output port for the file. When the print location is designated, select [OK] and the title screen will appear. In this screen, type the primary title for the graphical report, press [TAB] or mouse-click on the second title field, and enter the secondary title (usually a reference for the data, the units for the graph, or some sort of explanatory note) for the graph. Now, select [OK] and GloED will send the report to the printer. Figures 12 and 13 are examples of a bar and a pie chart, respectively.

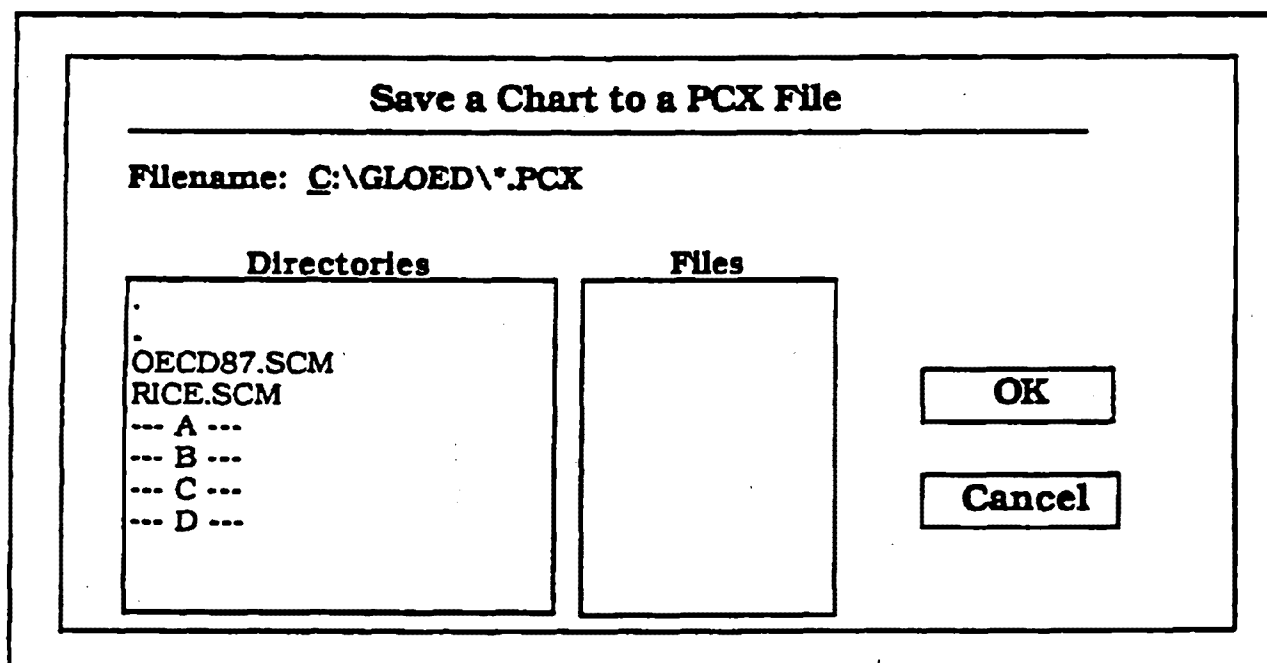


Figure 11. The Reports Menu for Saving a Pie Graph to a .PCX File

# Methane Emissions From Rice Cultivation

## Percent Emissions

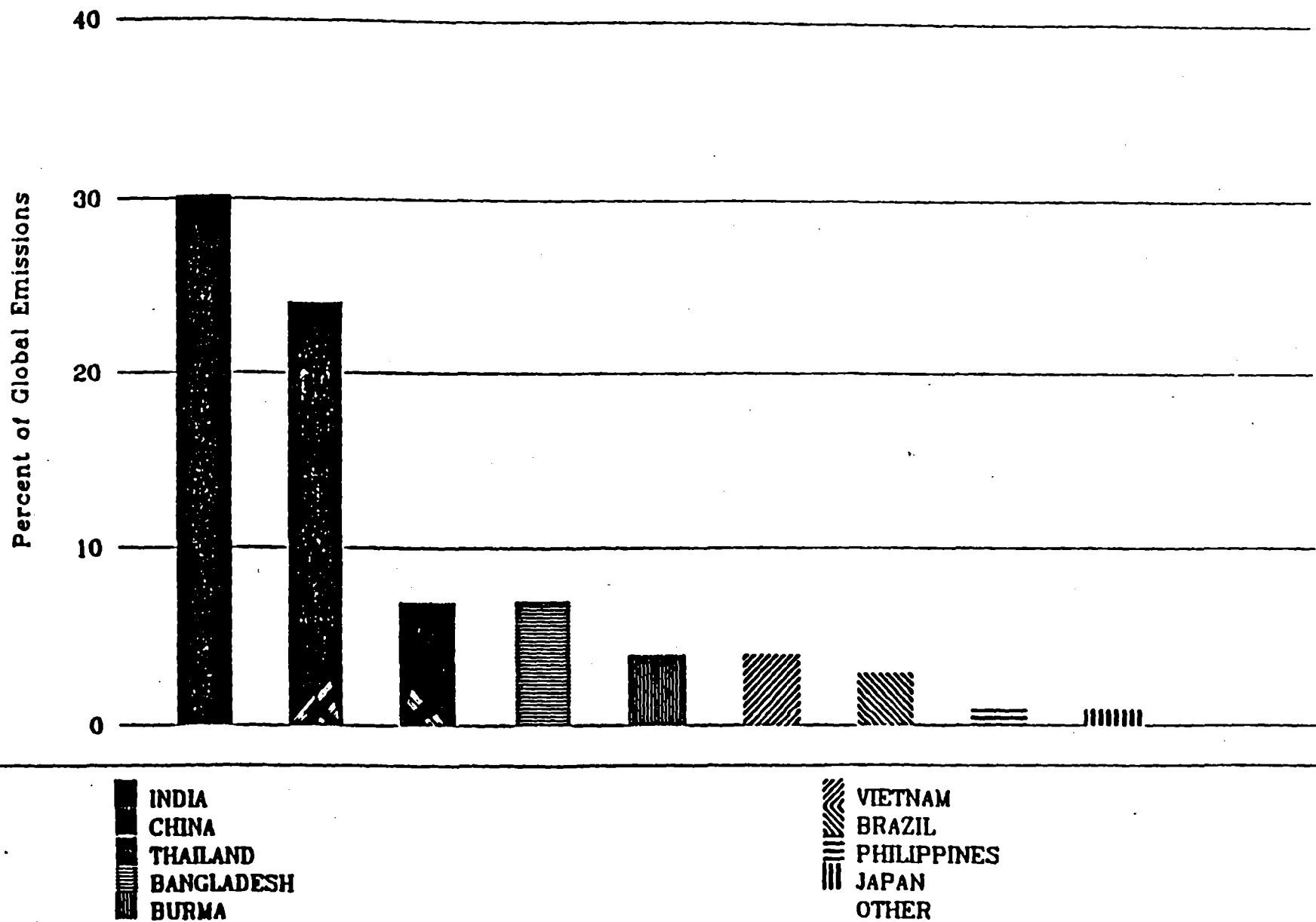
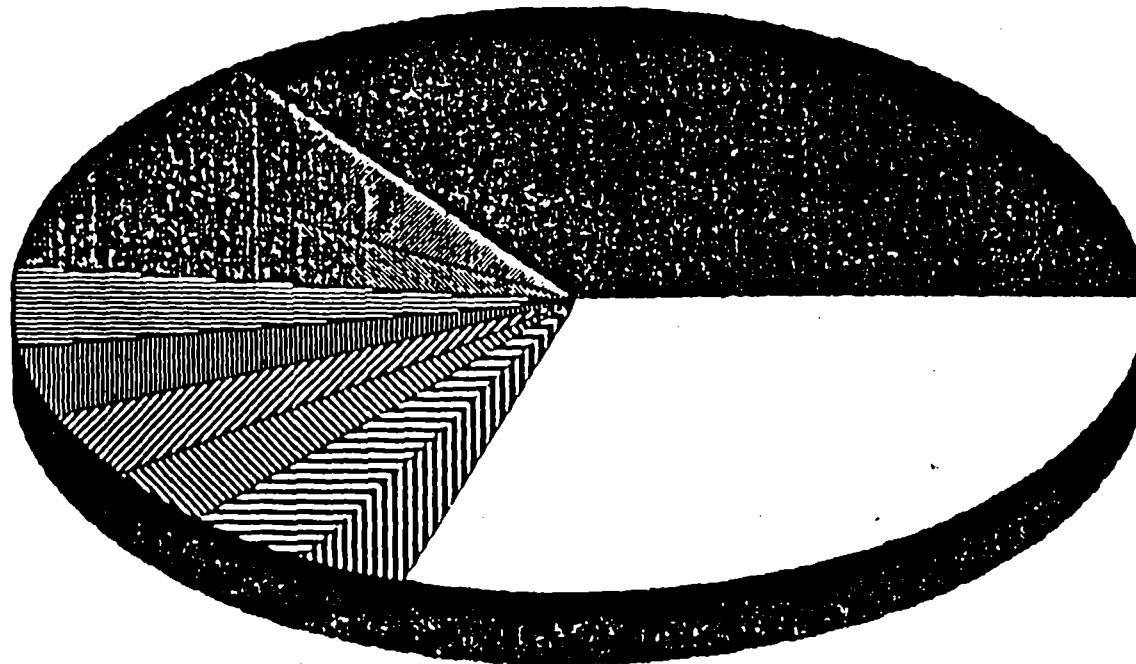


Figure 12. Bar Chart



## Methane Emissions From Landfills



USA  
USSR  
CHINA  
INDIA  
CANADA

UNITED KINGDOM  
GERMANY  
ITALY  
JAPAN  
OTHER

Figur 3. Pie Chart

## Text Reports

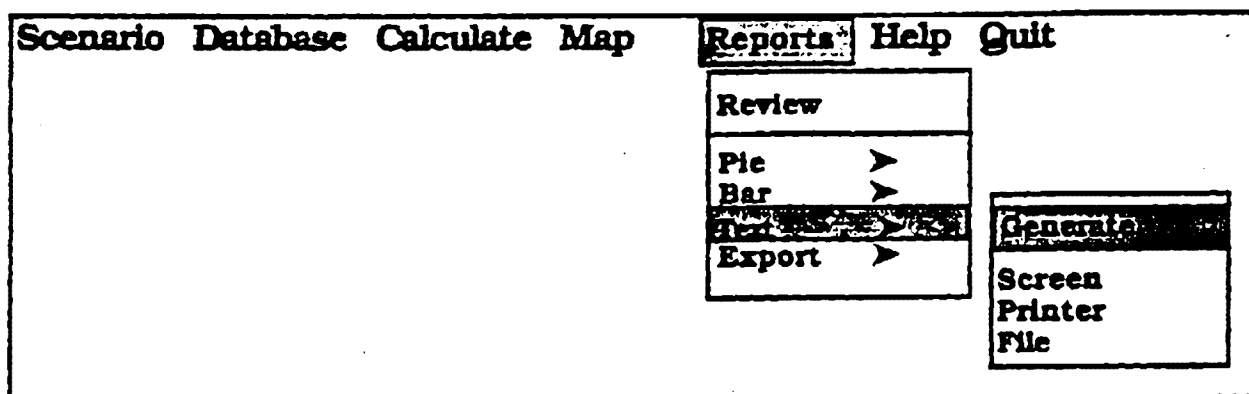


Figure 14. Options in the Reports Menu

To present the results in the form of a table, referred to here as a text report, mouse-click on the **Reports** option in the GloED main menu, or type an *R* to open the menu. Then select the **Generate** option in the menu shown in Figure 14 that appears at the right of the pull-down menu. A dialogue box, called the **Text Report Priorities Screen**, will appear. It will allow assignment of totalling priorities to the pollutants, source categories, and countries that will appear in the tabular report.

When the report has been prepared, use the GloED main menu bar to display the report on the screen, to send it to the printer, or to save it on a disk. To see the report without printing it, sending it to the screen allows using the GloED **Browser Screen** to scan the report, using it like hard copy. The browser screen, showing a section of a report, is shown in Figure 15. This screen functions very much like the smaller scroll boxes in GloED except that it has both horizontal and vertical scroll bars. Mouse-clicking on the arrows at the ends of the bars moves one line per click in the direction indicated by the arrow. For larger jumps in the report, slide the narrow bars in the middle of the scroll bars in the desired direction.

# **NOx -- France, Canada, U.S. -- Fossil Fuels**

COUNTRY	SOURCE CATEGORY	EMISSIONS
CANADA	AIR (oil)	5.406285E+04
CANADA	AUTO OF ELEC (gas)	1.747200E+01
CANADA	AUTO OF ELEC (oil)	8.216900E+02
CANADA	PUB SERV ELEC (coal)	5.616418E+05
CANADA	PUB SERV ELEC (gas)	5.457480E+03
CANADA	PUB SERV ELEC (oil)	1.867441E+07
CANADA	RESIDENTIAL (gas)	1.860558E+04
CANADA	RESIDENTIAL (oil)	1.165500E+04
CANADA	ROAD (oil)	5.729220E+05
CANADA	TOTAL INDUSTRY (gas)	4.867460E+05
CANADA	TOTAL INDUSTRY (oil)	8.117909E+04
FRANCE	AIR (oil)	4.206498E+04
FRANCE	AUTO OF ELEC (gas)	7.956000E+03
FRANCE	AUTO OF ELEC (oil)	3.985520E+03
FRANCE	PUB SERV ELEC (coal)	7.106130E+04
FRANCE	PUB SERV ELEC (gas)	2.044000E+01
FRANCE	PUB SERV ELEC (oil)	8.545440E+06
FRANCE	RESIDENTIAL (gas)	1.324134E+04
FRANCE	RESIDENTIAL (oil)	4.969440E+03
FRANCE	ROAD (oil)	5.848920E+05
FRANCE	TOTAL INDUSTRY (gas)	2.864420E+05
FRANCE	TOTAL INDUSTRY (oil)	1.024266E+05
UNITED STATES OF AMERICA	AIR (oil)	9.154994E+05
UNITED STATES OF AMERICA	PUB SERV ELEC (coal)	1.050033E+07
UNITED STATES OF AMERICA	PUB SERV ELEC (gas)	6.912297E+05
UNITED STATES OF AMERICA	PUB SERV ELEC (oil)	2.716832E+08
UNITED STATES OF AMERICA	RESIDENTIAL (gas)	1.908788E+05
UNITED STATES OF AMERICA	RESIDENTIAL (oil)	8.908956E+04
UNITED STATES OF AMERICA	ROAD (oil)	6.855030E+06
UNITED STATES OF AMERICA	TOTAL INDUSTRY (gas)	3.270462E+06
UNITED STATES OF AMERICA	TOTAL INDUSTRY (oil)	6.462365E+05
		3.249974E+08
		3.249974E+08

Figure 15. The Text Report Browser Screen

To see a specific data point in the scenario, or to review the set of elements chosen for the loaded scenario, use the Review option in the Reports menu. When Review is selected in the Reports pull-down menu, the Review Emissions Inventory screen (Figure 16) appears on the screen. When it first comes up, the screen shows the emissions of the first pollutant chosen for the first country and source category in the first database used in the currently loaded scenario.

<b>Review Emissions Inventory</b>	
Dataset:	OECD-1987
Country:	CANADA
Source Category:	TOTAL INDUSTRY (gas)
Pollutant:	NOx
Emissions:	486746.0000000
Units:	kg/y
<b>Up</b>	<b>Down</b>
<b>Filter</b>	<b>Review</b>
<b>OK</b>	

Figure 16. The Inventory Reports Review Screen

From this point, the on-screen [UP] and [DOWN] buttons allow movement through the scenario, one point at a time, in the indicated direction.

The [REVIEW] button opens a second window, in which appears the database from which the data have come, the reference for the data, and the emission and activity factors from which the emission estimate has been calculated.

If the user already knows the data point sought, or to narrow the search, select the [FILTER] button, which activates the Search Inventory screen. The Search Inventory Screen looks and works exactly like the Scenario Generate Screen, but the scroll boxes on this screen contain only the database(s), countries, source categories, and pollutants chosen for the currently loaded scenario. As a result, this screen serves as a reminder of the complete contents of the loaded scenario and as a tool for performing a very specific search of the emission inventory. To search for an item in the loaded scenario, use the [TAB] key or the mouse to move through the scroll boxes on the screen and select, with the [ENTER] key or the mouse, the parameters of the data point. When the user selects the [OK] button, GloED returns to the Review Emissions Inventory Screen, now containing the information about the data point of interest.

## RELATED ACTIVITIES AND FUTURE PLANS

So far, EPA efforts have been directed toward development of the GloED software and development of emission factors and activity data for anthropogenic sources of methane and nitrous oxide. With the completion of GloED software, population of the software will begin with available information on greenhouse gas emissions data on a country and source specific basis. This data development

activity can be thought of as filling a 3-D matrix. This 3-D matrix can be envisioned as a matrix cube with countries along the vertical axis, greenhouse gases along the horizontal axis, and sources or sectors filling the third dimension. EPA will begin loading the software with information on methane emissions and will complete the inventory data entry with available information from other sources. After published data are loaded and quality checked, additional data estimates will enable a global inventory of all greenhouse gases. It is recognized that some of the estimates will be based on very weak information. However, data quality will be identified throughout the matrix. This will be a beginning point for identifying where data quality needs to be fortified.

Though the GloED emissions database will continue to be the primary emphasis of database software development throughout 1993, we hope to begin development of a companion database that will contain information on greenhouse gas mitigation technologies. This database will be called GloTech. It will be an electronic file cabinet that will house greenhouse gas mitigation technology and report parameters such as emissions reduction capability, cost, and date of availability of the technology. When populated with data, GloTech will allow scenario development and file interaction similar to GloED. This will enable the user to perform cost effectiveness calculations for an array of technologies that will be constructed in a scenario. Once the scenario is constructed the user could then determine total cost, total emissions reduction performance, and other parameters such as secondary impacts (water, solid waste, etc.), estimated dates of availability of the technology, and limits to market penetration. Like GloED, GloTech will allow construction of the scenarios based on information resident within the software. It will also allow the user to input new data or to modify data within the databases. GloTech will also have each piece of information linked to its reference to ensure a clear data pedigree.

After GloED and GloTech are operational and fully tested, they could be linked so that the user can perform "what if" scenarios. These scenarios would provide estimates of the effect of implementation of certain technologies on country specific emissions, and what the cost of those technologies would be.

## **SUMMARY**

GloED is a powerful emissions database handling software package that is nearing completion. It has been presented to OECD for consideration as a standard tool for global greenhouse gas emission databases. The GloED software will continue to be refined and updated, and enhancements are planned to enable GloED to accept gridded information and to interface with geographical information systems. Parallel to the development of the software, data population activities will produce a global emissions database which may help to establish baseline emissions for an international greenhouse gas emissions treaty such as was proposed at the U.N. Earth Summit in Rio de Janeiro last June. GloED could also be the mechanism to track progress under such a treaty by allowing annual updates of emissions information on a country and sector specific basis.

The development of GloTech will allow estimation of the costs associated with greenhouse gas emissions reduction. Finally, the GloED and GloTech software working in concert will allow the user to construct reduction scenarios, estimate impacts, and view the results of the implemented technologies.

#### Reference

1. Intergovernmental Panel on Climate Change. "Workshop on National Inventories of Greenhouse Gas Emissions and Sinks. 5-6 December, 1991. Geneva, Switzerland. Proceedings." World Meteorological Organization/United Nations Environment Programme. Edited by P. Schwengels.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

## SESSION II: INTERNATIONAL ACTIVITIES

Jane Leggett, Chairperson

Beyond Rio,  
a Dutch perspective on the future of research and policies on climate change

by Hans van Zijst, LL.M.  
Counselor for Health and Environment at the Royal Netherlands Embassy in Washington

Mr. Chairman, ladies and gentlemen,

I am honoured to have the opportunity today to give you the Dutch perspective on the future of research and policies on climate change. A future that started with the worldcommunity signing the Convention on Global Climate Change in Rio this summer.

The Netherlands has been widely recognized as being proactive in the field of the greenhouse gas effect. But -quite frankly- we believe that we have no choice. We are the only industrialized country in the world that lies for more than 50% below sealevel. We are therefor vulnerable to climatological changes, specifically a rise of the sealevel. In the National Environmental Policy Plan of 1989 the Dutch government laid out its plans for the future with a long-term approach to combat pollution and to implement the Brundtland-concept of sustainable development.

The Plan introduces the five-scale model to classify the size of environmental problems and to indicate the geographical size of the solutions. If a problem is global, like for instance the climate change issue, the solution is global and the level of negotiations and implementation is global.

Therefor the Dutch decisionmakers in the field of global climate change became diplomats.

And they will probably stay that way for the coming years, because having a convention (how hard the battle to achieve it may have been) is just the beginning of a long process of national planning, monitoring, research, cost/benefit analyses and maybe renegotiations. It is therefor that I welcome the opportunity to share our thoughts on the future with you today, i.e. to give prompt start to the necessary implementation of the Rio result.

Current Dutch policy goals (table 1)

The Dutch government has taken measures to reach a stabilization of CO<sub>2</sub>-emissions in 1994/1995 at the level of 1989/1990 (i.e. 182 million tonnes per year). It is intended to achieve an absolute reduction of between 3 and 5% (i.e. to a level of 173-177 million tonnes) by the year 2000. The long-term goal is reaching the sustainable level according to today's scientific know-

how in the year 2010 and that means an absolute 20-30% reduction of CO<sub>2</sub>-emissions by the year 2010 as compared to 1989/1990. For this long-term goal no policies have been implemented yet. I will focus on the measures we are taking for the short-term goal of stabilizing the CO<sub>2</sub> emissions in 1995.

We have been focusing heavily on CO<sub>2</sub> because this greenhouse gas accounts for half the problem and is relatively well-known in its sources and effects. Additional policy goals for other greenhouse gases have been developed too. For methane (accounting for approximately 20% of the greenhouse gas emissions) the policy goal is a 10% reduction in 2000 as compared to the 1990 level. For Nitrous oxide (N<sub>2</sub>O) the goal is stabilization of the 1990 level in 2000. For ozone-triggers like reactive odd-nitrogen and volatile organic gases the goals are considerably higher, ranging between 50 and 60% reduction in 2000 as compared with the 1988 level. The policy goal for CFC's is total banning of all production by the year 1993 and the rapid phasing out of all use as soon as possible.

#### Current Dutch policy measures

The current Dutch policy measures are laid down in the Memorandum on Climate Change, which is generally accepted as the National Plan under the Convention on Climate Change. Additional measures are taken on basis of the Memorandum on Energy Conservation and the Structurescheme for Traffic and Transport. In choosing from a wide set of opportunities the Dutch government favors measures that are more cost-effective and those that will have positive side-effects in other fields. For instance, measures aimed at energy saving, more efficient use of energy resources, waste prevention, the reduction of growth in mobility and afforestation will help to combat acidification and the smog problem as well as promote the better management of resources and enhance sustainable development.

Before I show you the measures we are taking, please take a look at table 2 on sources of CO<sub>2</sub> emissions in the Netherlands. As you can see Industry and Power plants take care of almost half of the emissions. Another interesting feature is that only households have succeeded in reducing their emissions between 1985 and 1988. The fastest grower is waste incineration. Although only accounting for 1% of the emission, it increased with almost 25% over the three year timeframe.



The measures we are currently taking are shown in table 3. The measures are divided in four categories:

- \* Energy saving
- \* Fuel consumption
- \* Traffic and transport
- \* Waste sector.

In the energyfield we must achieve an average improvement of 2% energy efficiency per year over the last decade of the 20th century. It can be achieved by insulation of existing buildings and houses as well as sharper energy standards for new buildings and by increasing the energy-efficiency of Dutch industry. Instruments are among others subsidies on investment in new technology and on high-efficiency central heatingsystems, information transfer and consumer awareness building.

In the fuel consumption field the decreased use of coal for electric utilities and industries are heavily advocated. In part coal can be replaced by natural gas, but also solar and wind energy have a high feasibility for a considerable group of industry. Investment subsidies and demonstrationprojects are the most important instruments.

In traffic and transport the biggest help comes from the almost gridlocked situation on the Dutch highway system during rush hours. By improving public transport (which compared to the US is already superb) and enforcing growth limitation to car traffic the goals for traffic and transport could be achieved. In addition transportmanagement by companies and the improvement of driving behaviour (speed as well as car maintenance) can contribute to achieving the goals. Part of the solution must come from European legislation on fuel efficiency standards for cars. Fiscal measures to favor smaller and cleaner cars are considered.

In the waste sector policies are put in place to considerably lower the amount of waste that has to be incinerated. Especially compost forming and anaerobic fermentation make that possible.

Furthermore we are thinking about commercially extracting methane gas from waste dumps.

Not on this table but also an integral part of the Dutch approach is afforestation. In accordance with the outcome of the 1989 Ministerial conference in Noordwijk, The Netherlands has pledged to plant about 3500 hectares per year. In addition to that the Dutch Association of Electricity Utilities has taken the initiative to reforest in Eastern Europe and in tropical areas (which is more cost-effective than taking domestic measures).

## **CO2 and/or energytax**

On top of these measures the Dutch government is a strong advocate of the OECD-wide introduction of an energytax on fossil fuels. The Dutch proposals and the report of the Dutch Wolfson Commission have been negotiated dramatically inside the Netherlands. The economic effects of unilaterally introducing such a fiscal measure can be strong, even if macro-economic calculations show that recycling the assets in the economy for environmental and energy-efficient purposes can have a positive effect on the Gross National Product. On a micro-economic level distortions can take place, if the tax is equally applied to all industries and utilities. For the time being we wait for the negotiations in the coming months of the proposal of the European Commission.

## **Is it enough?**

Although the Dutch approach is in our own eyes rather comprehensive and for the short term hopefully will show to be sufficient, it will not be enough. Greenhouse gas emissions are a long way from the sustainable level. According to the first evaluation of the Netherlands Environmental Policy Plan, called 'National Outlook 2, 1990-2010' the Dutch Research Institute for Public Health and the Environment concludes that further dramatic reductions will be necessary in the first decade of the next century. The forecast shows a setback in our current expectations for 2010. To justify stronger measures science will have to move on in clarifying the process of global warming, indicating the sources, the interaction of human and natural sources, explaining the role of sinks like trees and oceans, explaining the role of clouds and other climatological phenomena. And politicians will be asked to decide on basis of the outcome of that research, even if the answer is that science doesn't know yet.

Therefor we strongly support the continuation of the IPCC work, the International Geosphere Biosphere Programme, and similar international efforts as well as we continue and fortify our national research program on climate change. Our national efforts shall shift its focus to the development of policy modelling, long-term qualitystandards and scenario's for sustainable

solutions (with technical, economical, socio-psychological, administrative and regulatory options). We will also support developments in the field of monitoring, like the remote sensing program of the European Space Agency.

#### International cooperation

Apart from the evident need to share international knowledge of science there is the need of international cooperation in implementing the Convention on Climate Change. As I said earlier Rio is only the beginning and we must push for a prompt start to keep the momentum going or create new momentums in the near future, otherwise the chemistry of the UNCED-summit will be gone. The call for national plans must be transformed in the drafting of these plans. The Dutch government will strongly support the call for speedy ratification and implementation of the convention in domestic policies, in the developing as well as in the OECD-countries. We will support the reconvening of the INC-meetings for further clarifying of some open points in the convention and to speed up the implementation process. The work of the IPCC must be continued and among other things could be focused on the development of internationally agreed methodologies and reporting formats for emission inventories. In that framework I am happy to say that the Dutch Research Institute for Public Health and the Environment will host an IPCC-workshop in early February next year in Amersfoort, The Netherlands. The workshop is about Methane and nitrous oxide and will focus on methods in national inventories and options for control. Those of you who want to have a copy of the first announcement can give me your business card and I will make sure that you get a copy.

Table 1

**Policygoals for GHG's**

**CO2**

Baselevel	1989/1990	182 MT/Yr
Stabilization	1994/1995	182 MT/Yr
Reduction 3-5%	2000	173-177 MT/Yr
Sustainable level	2010	127-145 MT/Yr

**CH4**

Baselevel	1990	960 KT/Yr
Stabilization	1995	940 KT/Yr
Reduction 10%	2000	840 KT/Yr

**N2O**

Baselevel	1990	40 KT/Yr
Stabilization	2000	40 KT/Yr

**Ozone-related gases (CO, NOx, VOG)**

Baselevel CO	1990	1100 KT/Yr
Reduction	2000	540 KT/Yr
Baselevel NOx	1988	560 KT/Yr
Reduction	2000	240 KT/Yr
Baselevel VOG	1988	490 KT/Yr
Reduction	2000	205 KT/Yr

Table 2

**Sources of CO<sub>2</sub> emissions in the Netherlands  
(1988 figures)**

<u>Source</u>	<u>Share of total</u>	<u>Trend 1985-1988</u>
Industry	24%	+ 0.7% annual
Power plants	22%	+ 4.5% annual
Traffic	16%	+ 2.5% annual
Private homes	14%	- 1.5% annual
Refineries	8%	+ 10.4% annual
Warehouses	5%	+ 13.4% annual
Waste incineration	1%	+ 23.3% annual
Other sources	10%	+ 0.7% annual
<b>Total</b>	<b>100%</b>	<b>+ 3.3% annual</b>

Table 3

**Concrete measures in implementation to decrease level of CO2 emissions**

Energy saving	* Improved insulation of existing homes and other buildings
	* Increasing the energy efficiency of machines
	* Investment in energy saving
	* Construction of homes and other buildings with low energy consumption
Fuel consumption	* Decreased coal use in power plant sector
	* Disincentives to coal use in industry
Traffic and transport	* Improvements in public transport
	* Car traffic growth limitation
	* Transport management in companies
	* Improvements in driving behaviour
Waste sector	* Compost forming
	* Anaerobic fermentation
	* Recycling of energy-intensive products
	* Methane gas extraction from waste dumps
	* Gasification of synthetic materials

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# Carbon Dioxide Sequestration

by

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## ABSTRACT

Mitigation of global climate change will require the stabilization of atmospheric concentration of greenhouse gases, especially carbon dioxide (CO<sub>2</sub>). CO<sub>2</sub> can be sequestered by flue-gas and fuel CO<sub>2</sub> sequestration or by atmospheric CO<sub>2</sub> fixation/utilization. Flue-gas sequestration involves separation/concentration, transport, and either disposal or use. Disposal options are either land or ocean based. Utilization is by either chemical or biological utilization (recycling). Flue-gas-oriented techniques in general have high economic and energy costs, but a few areas show potential and warrant research and development (R&D) attention, especially those holding promise of combined CO<sub>2</sub>/sulfur dioxide (SO<sub>2</sub>)/nitrogen oxides (NO<sub>x</sub>) control and the integrated gasification combined cycle approaches. CO<sub>2</sub> disposal is neither a "sure thing" nor a permanent solution, with options needing further environmental assessment. Near term, some CO<sub>2</sub> recycling is possible, and R&D to examine longer-term prospects seems warranted. Atmospheric CO<sub>2</sub> fixation/utilization involves either enhanced terrestrial or marine fixation with utilization of the biomass in some cases. Atmospheric fixation approaches which seem most attractive are those involving enhanced biomass CO<sub>2</sub> sequestration combined with utilization of the biomass for energy to displace fossil fuel. Of these the most attractive for R&D appear to be advanced direct combustion using biomass and use of biomass as a source of hydrogen to leverage fossil fuel use for methanol production (Hydrocarb process).

## Introduction

International scientists working on the problem of global climate have concluded that increasing concen-

trations of greenhouse gases, especially CO<sub>2</sub> (Figure 1), are leading to global warming (Figure 2). The predicted extent of such warming is the subject of substantial research with model-dependent estimates having considerable uncertainty. The Intergovernmental Panel on Climate Change (IPCC) 1990 estimate was 0.3 °C/decade with a range of 0.2 to 0.5 °C/decade. The 1992 IPCC Supplement implies a warming rate at the lower end of this range. Warming has also been studied

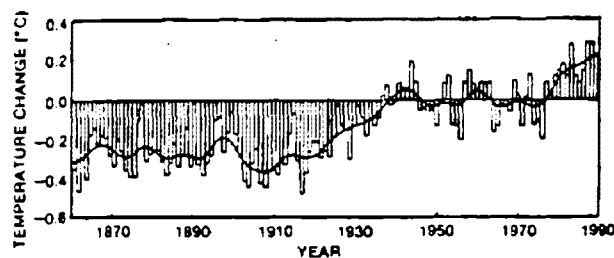


Figure 2. Global-mean combined land-air and sea-surface temperatures, 1861-1989, relative to the average for 1951-80 (IPCC, 1990). (Reproduced with permission.)

based on past temperature records, and has been determined to be on the order of 0.3 to 0.6 °C/decade since the turn of the century. This trend is illustrated in Figure 2. The abundance of fossil fuels and their relatively low cost will probably ensure their use as a principal energy source for the foreseeable future. Once decisions are put in place to utilize fossil fuels in the energy infrastructure, long-term commitments will have been made to release CO<sub>2</sub> emissions to the atmosphere. In the absence of constraints, the CO<sub>2</sub> emission rate can be expected to continue the rapid growth indicated in Figure 3. This suggests the need for

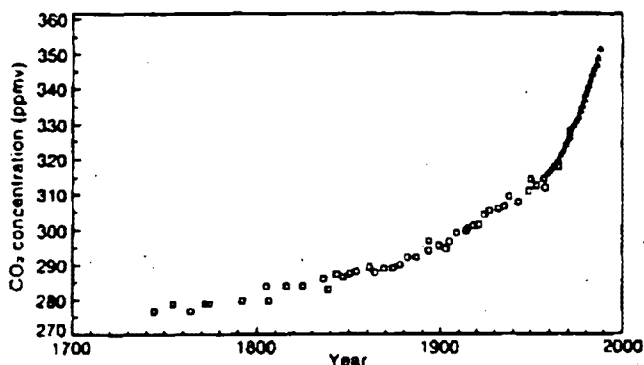


Figure 1. Atmospheric CO<sub>2</sub> increase in the past 250 years (IPCC, 1990). (Reproduced with permission.)

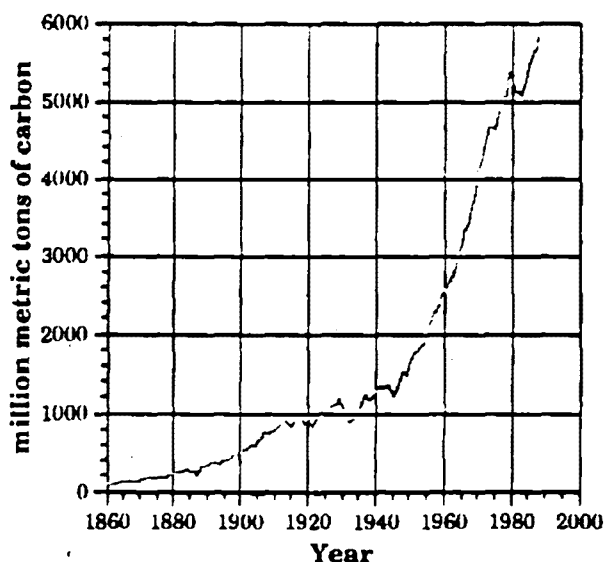


Figure 3. Annual global CO<sub>2</sub> emissions for fossil fuel combustion, cement production, and gas flaring, 1860 to 1988 (ORNL, 1990).

prudent and timely R&D to provide a technological base for preventing the increasing global emissions consistent with economic growth.

### Evaluating Potential and R&D Needs of Sequestration Options

The general options for CO<sub>2</sub> sequestration, summarized in Table 1, include both flue-gas CO<sub>2</sub> sequestration and atmospheric CO<sub>2</sub> fixation in the biosphere. Flue-gas CO<sub>2</sub> sequestration seeks to remove and dispose of carbon as a part of fossil fuel use and requires several steps to be undertaken: CO<sub>2</sub> must first be separated and/or concentrated to obtain an economically handleable volume, which is then transported, either to a point of disposal or to a point of utilization. Disposal may be on the land or in the ocean. Utilization can involve direct use of CO<sub>2</sub> as a product (e.g., enhanced oil recovery) or it can be reacted to a product such as a hydrocarbon or alcohol. Atmospheric CO<sub>2</sub> fixation/utilization on the other hand is aimed at enhancing or accelerating natural CO<sub>2</sub> fixation processes via either terrestrial or marine routes. These include forest management and ocean fertilization, followed by utilization for energy or other products.

Table 1. General options for carbon dioxide sequestration.

- Flue-gas & fuel CO<sub>2</sub> sequestration
  - Separation/concentration
  - Transport
  - Disposal
    - Land or sea
  - Chemical/biological utilization (recycling)
- Atmospheric CO<sub>2</sub> fixation/utilization
  - Terrestrial
  - Marine

A variety of technology assessment factors are significant for evaluation of the options for CO<sub>2</sub> sequestration (Table 2). The status of a technology can be measured by its level of development relative to commercial application. Mitigation potential (possible carbon sequestration) for a particular technology can be characterized in part by measures such as breadth of applicability and applicability to developing countries. Applicability to developing countries is an estimate of the potential for use where energy infrastructures are

evolving and economic and other factors differ substantially from those of the industrialized world. The cost-effectiveness assessment factor can be measured by an engineering estimate of the cost per metric ton of CO<sub>2</sub> emissions prevented.

Table 2. Technology assessment factors for CO<sub>2</sub> sequestration options.

- Status of the technology
  - Level of development
- Mitigation potential
  - Breadth of applicability
  - Applicability to developing countries
- Cost-effectiveness
  - \$/metric ton of CO<sub>2</sub> emissions prevented
- Environmental and energy considerations
  - Potential for adverse effects
  - Product versus disposal
  - Natural resource use
  - Earth surface area required (land use)
  - Additional fossil energy required
- Probability of success and R&D requirements

Environmental and energy considerations can be gauged by the potential for adverse environmental effects, whether or not an approach results in a useful product or waste requiring disposal, natural resource use, and land use. Approaches requiring large surface areas of the Earth for implementation need examination for social and ecological impact. The additional fossil energy requirement for implementation needs to be examined as a rough measure of overall life cycle efficiency. Finally, the probability of success and R&D requirements need to be assessed.

### Flue-Gas and Fuel CO<sub>2</sub> Sequestration

A number of approaches are possible for separation/concentration of CO<sub>2</sub> from fossil-fuel combustion sources. Figure 4 illustrates some of the possibilities including various flue-gas scrubbing approaches, oxygen (O<sub>2</sub>)/CO<sub>2</sub> combustion with CO<sub>2</sub> recycle, and coal gasification combined cycles with carbon monoxide (CO) shifted to hydrogen (H<sub>2</sub>) and CO<sub>2</sub>.

The categories of flue gas scrubbing (CO<sub>2</sub> separation/recovery) include absorption processes, adsorption processes, cryogenic separation, and membrane separation. Of the flue-gas scrubbing approaches, amine scrubbing is already in commercial use on a relatively small scale, but has been demonstrated on coal-fired power plants as large as 800 metric tons per day (TPD) (Barchas, 1992). Current application is for enhanced oil recovery (EOR) and production of soda ash, urea,



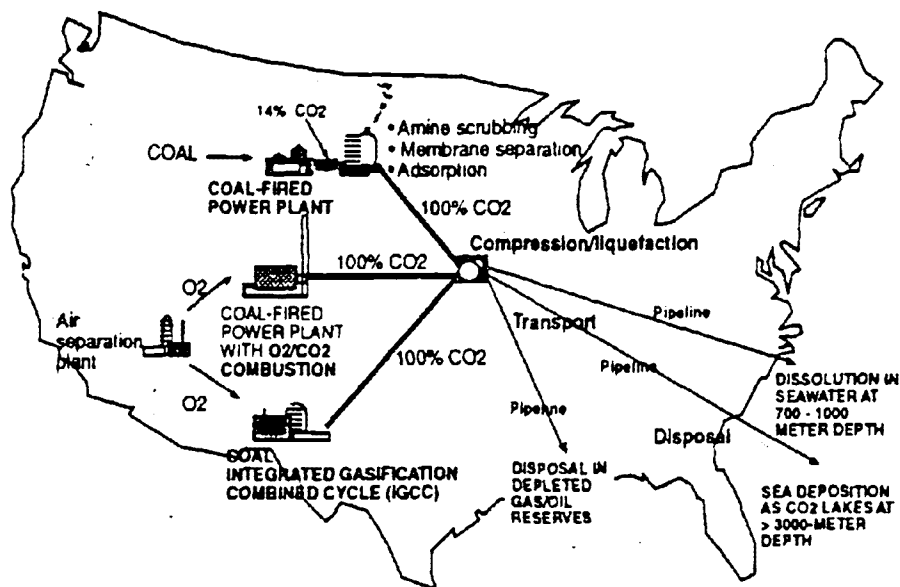


Figure 4. Flue-gas CO<sub>2</sub> sequestration options with CO<sub>2</sub> disposal in the ocean or depleted gas/oil reserves

and methanol with Kerr McGee and Fluor Daniel as major suppliers of the technology at a cost of \$40/ton of CO<sub>2</sub> recovered (not including transport, disposal, or power replacement). Japanese research (Kansai Electric Power) is focused on this approach which they think can operate with only 10.8% of boiler energy output for CO<sub>2</sub> recovery and liquefaction (Suda, 1992). Potential exists for overcoming some of the efficiency losses through heat recovery (Steinberg, 1991), but in general, investigators report discouraging cost and energy prospects. Smelser (1991) estimates that a grass-roots pulverized coal plant with 90% CO<sub>2</sub> removal can do much better than a retrofit; however, the heat rates are 12.7 versus 15.7 MJ/kWh (12000 versus 14900 Btu/kWh). The flue-gas scrubbing approaches, of all categories, such as sorption, cryogenic separation, and membrane separation, seem to share the potential problems of high cost and substantial decreases in power plant operating efficiency, but opportunities seem to exist for research in such areas as cryogenics and membranes (Smith, 1991). For example, cryogenics might offer the potential for combined SO<sub>2</sub>, NO<sub>x</sub>, and CO<sub>2</sub> control. Accepting lower CO<sub>2</sub> removal efficiencies may also reduce cost.

CO<sub>2</sub>/O<sub>2</sub> combustion with CO<sub>2</sub> disposal is a medium-term option and appears to need engineering evaluation along with substantial pilot-scale development work (Wolsky, 1991). Moritsuka (1991) concludes that such systems will be more cost-effective than flue-gas scrubbing approaches. Herzog (1991) concluded that CO<sub>2</sub>/O<sub>2</sub> combustion would require the least incremental energy. This approach requires CO<sub>2</sub> utilization via EOR, or disposal via depleted petroleum formations or

ocean injection. It has potential for NO<sub>x</sub> and SO<sub>2</sub> removal. Re-release of CO<sub>2</sub> and other environmental problems associated with utilization/disposal are not quantified. Mitigation potential includes the utility sector (new and retrofit). Small-scale pilot and demonstration work is underway with Japan planning a demonstration. In Canada Saskatchewan Power is planning a 150 to 350 MW demonstration. Canada is also researching land disposal of CO<sub>2</sub>: 1) in depleted hydrocarbon reservoirs starting at 50,000 metric TPD, and 2) EOR utilization at 6000 to 8000 metric TPD (Sypher: Mueller International, 1991). Canadian EOR CO<sub>2</sub> use will be expanded substantially in 1992. The likelihood of success is

high, but applicability depends on the ability to minimize air in-leakage and environmental acceptability of CO<sub>2</sub> disposal. An engineering analysis of a 500-MW power plant was discussed by British Coal at the recent First International Conference on Carbon Dioxide Removal in Amsterdam (Cross, 1992). Another analysis was presented by Air Products (UK) (Allam, 1992). These studies indicate that O<sub>2</sub>-combustion/CO<sub>2</sub> recycle will be 20% cheaper than amine (MEA) systems, can be retrofitted to existing power plants, and would result in lower power efficiency loss (8.6%). Capital cost for a new plant would also be lower than for a conventional PC plant. Cost was estimated at \$49 per metric ton of CO<sub>2</sub> removed. Distillation of liquefied CO<sub>2</sub> to recover SO<sub>2</sub> could produce credits that would reduce cost to \$16/metric ton.

Considering that this process or flue-gas scrubbing processes may have the potential for inherent SO<sub>2</sub> and NO<sub>x</sub> control, it is of interest to compare the costs of CO<sub>2</sub> control with that for SO<sub>2</sub> plus NO<sub>x</sub> control on a cost per metric ton of carbon basis. This is done in Figure 5 for low and high ranges of cost per ton of SO<sub>2</sub>, NO<sub>x</sub>, and CO<sub>2</sub> removed. Costs for combined flue gas desulfurization (FGD) and flue gas treatment (FGT) are put on a per metric ton of carbon basis and compared with the cost of CO<sub>2</sub> control on a per ton of carbon basis. High- and low-range costs are assumed for FGD, FGT, and CO<sub>2</sub> control. However, if SO<sub>2</sub> and NO<sub>x</sub> control were not required or already in place, then this comparison would have little meaning. Even with the offsets in cost for possible inherent SO<sub>2</sub> plus NO<sub>x</sub> control, a substantial cost increase for CO<sub>2</sub> control can be seen. Overall plant energy efficiency is reduced for the flue gas

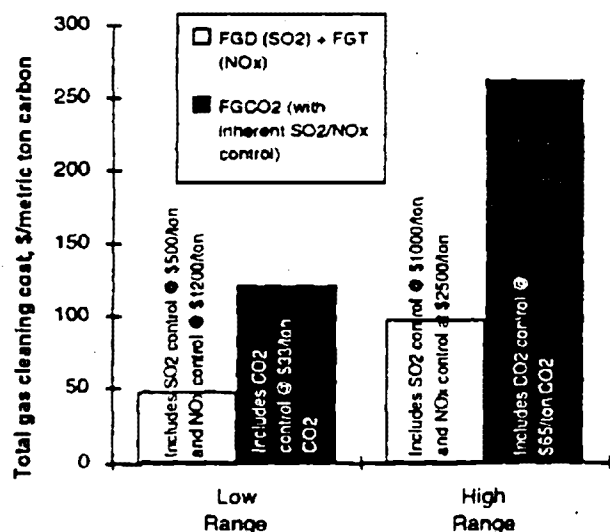


Figure 5. Comparison of costs for SO<sub>2</sub> and NO<sub>x</sub> with the costs of CO<sub>2</sub> control on a per metric ton of carbon basis. (FGD and FGD cost ranges are derived from Emmel, 1990).

sequestration options compared to conventional boiler without CO<sub>2</sub> control. A similar analysis for energy use offsets could be done by comparison to plants using SO<sub>2</sub> plus NO<sub>x</sub> control, but is not done in this paper.

Integrated gasification combined cycle (IGCC) with CO<sub>2</sub> disposal is another option shown in Figure 4. One conceptual design is based on modification of conventional gasification combined cycle plants with added steps to shift all CO to CO<sub>2</sub> for separation. The resulting hydrogen-rich fuel when burned in a turbine suffers efficiency loss. An alternative design would increase efficiency by applying CO<sub>2</sub>/O<sub>2</sub> combustion to the turbine combustor. No design studies are available to determine the potential of the latter approach. Mitigation potential would include new utility applications only. Canada is planning to investigate the approach at pilot scale in conjunction with the design of a planned 250 MW IGCC plant (Sypher/Mueller International, 1991). The feasibility study was completed in 1991, and the plant was scheduled to be in operation by 1996. The likelihood of success seems to be reasonable, but the process needs pilot and demonstration work.

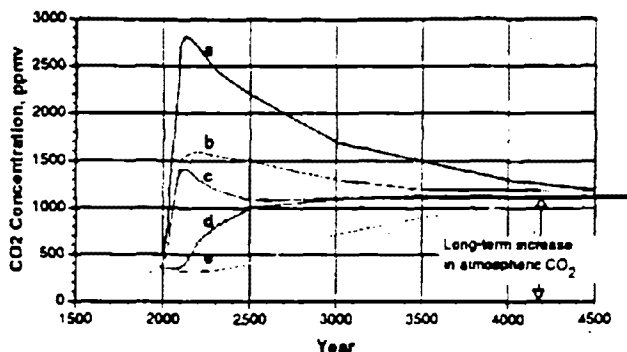
Several innovations of the IGCC concept were reported at a recent Amsterdam Conference on CO<sub>2</sub> removal. They were mainly centered on the development of a high temperature membrane for separation of CO and H<sub>2</sub> from the gasifier. The separated gas streams are fed to different turbines, one of which is fed with pure O<sub>2</sub> and recycled CO<sub>2</sub>. The combustion gases are then fed to boilers and steam turbines. The exhaust from the CO<sub>2</sub> turbine is collected (less recycle) for disposal. This

unit is expected to operate at 35% efficiency and 88% CO<sub>2</sub> reduction with the cost of electricity increased by 30%. Capital cost is \$1100/kW; CO<sub>2</sub> recovery cost is \$16/metric ton (Hendricks, 1992). Replacement of the turbine of an IGCC plant with a molten carbonate fuel cell can increase the generating efficiency to nearly 48% while removing 90% of the CO<sub>2</sub>. The fuel cell is able to convert CO to CO<sub>2</sub> using air without mixing N<sub>2</sub> with the oxidation products. Consequently, no air separation plant is needed. A demonstration IGCC plant is under construction in Germany (RWE Energie) and will start operation in 1995 using brown coal. Efficiency is expected to be 45% without CO<sub>2</sub> recovery and 38.6% with recovery of 86% of CO<sub>2</sub> emissions. Investment cost without CO<sub>2</sub> recovery would be 10% less than for a conventional plant; with recovery, it is 30% more. A systems study by British Coal concluded that the IGCC system is the best choice for the UK, especially if operated under pressure so that the CO<sub>2</sub> can be absorbed in seawater for disposal without liquefaction. Cost of pipelines for liquid CO<sub>2</sub> disposal in deep oceans was judged to be prohibitive. A thermodynamic analysis of the IGCC system indicates that MEA scrubbing after combustion is preferable to air separation prior to combustion. Steam for CO<sub>2</sub> stripping can be extracted from the turbine. They conclude that the system is technically and economically feasible at an increased power cost of \$0.015-0.02 per kWhr.

Fuel CO<sub>2</sub> (carbon) sequestration has been evaluated extensively by Steinberg (1991). These are methods that basically remove carbon from a fuel like coal resulting in a hydrogen-enriched fuel. The removed carbon is then sent to storage/disposal. The problems with carbon disposal can be minimized by using a variation of this approach, called the Hydrocarb process, where biomass is used as a source of H<sub>2</sub>. This is discussed later with the atmospheric fixation approaches.

## CO<sub>2</sub> Disposal

**Ocean disposal.** Any of the flue-gas CO<sub>2</sub> sequestration approaches discussed above, implemented on a massive scale, require consideration of disposal of CO<sub>2</sub> in the ocean as well as on land. Although ocean disposal has been and is being studied (Hoffert, 1979; Herzog, 1991; Wilson, 1992), it may only be semi-permanent storage and has enough environmental issues to make the option longer term. The ocean options considered include disposal as liquid, solid, and gaseous CO<sub>2</sub>. Key practical considerations are economic means for getting massive amounts of CO<sub>2</sub> down to depths where it will stay or sink. Solid CO<sub>2</sub> or CO<sub>2</sub> hydrates (clathrates) will sink on their own. Smith (1991) suggests that the



- a 100% into the atmosphere
- b 50% at 1500 m depth into the ocean
- c 50% at 4000 m depth into the ocean
- d 100% at 1500 m depth into the ocean
- e 100% at 4000 m depth into the ocean

Figure 6. Modeled atmospheric  $\text{CO}_2$  resulting from use of all fossil fuel over time with  $\text{CO}_2$  disposed of at various depths.

costs for the solids disposal approach make it a less likely option. Liquid  $\text{CO}_2$  needs to be injected below 1000 m and -- to reduce re-release -- 3000 to 4000 m is seen to be safer. Scrubbing of stack gas with sea water and reinjection in the ocean below 1000 m might be adequate. However, none of these options may really be permanent. As shown in Figure 6, some part of the  $\text{CO}_2$  will return to the atmosphere as a function of disposal depth and time (Hoffert, 1979). However, reaction of  $\text{CO}_2$  with calcium carbonate in the ocean bottom sediments could fix some of this  $\text{CO}_2$  as the bicarbonate and thus reduce the potential for return to the atmosphere (Wilson, 1992). Another estimate for the residence time of  $\text{CO}_2$  deposited at a 1000 m depth is 200-300 years (Liro, 1992). Modeling of projected, long-term atmospheric  $\text{CO}_2$  concentrations appears to be a major research need.

Formation and stability of  $\text{CO}_2$  clathrates are currently the subject of additional research. Clathrates can form at various depths depending on temperature. In arctic regions they can form at depths as shallow as 70 m. Relatively little fundamental data are available. Its density is somewhat uncertain but appears to be 1.02 to 1.12 times that for sea water; therefore, it sinks. Large amounts of  $\text{CO}_2$  can be tied up per unit volume of clathrate. Figure 7 shows the structure of  $\text{CO}_2$  clathrate. About 6 molecules of  $\text{CO}_2$  are combined with about 44 of  $\text{H}_2\text{O}$  in the clathrate crystal lattice. It has appearance of wet snow. Nishikawa (1992) has determined some additional phase equilibrium data and pH data for sea water, but finds that long-term testing will be needed to obtain dissolution information.

Ocean  $\text{CO}_2$  disposal environmental issues which

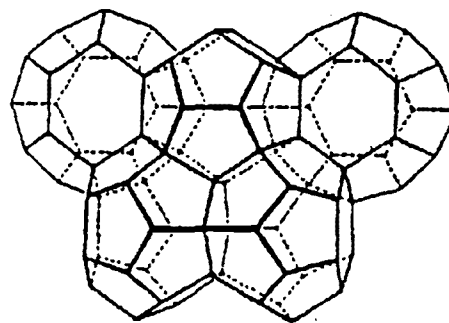


Figure 7.  $\text{CO}_2$  Clathrate lattice has approximately 6 molecules of  $\text{CO}_2$  to 44 of  $\text{H}_2\text{O}$  (Miller, 1974). (Reproduced with permission.)

need to be resolved include:

- Potential for re-release of  $\text{CO}_2$  via up-welling of  $\text{CO}_2$
- Conversion of high density hydrates to low density
- Catastrophic releases in transport or storage.
- Potential that long-term circulation could return  $\text{CO}_2$  to atmosphere.
- Potential for local/regional acidification of ocean with biological impacts
- Chances for reduction of biological diversity in the column and ocean floor.
- Potential for accumulation of clathrates on sea-floor would impair normal biological processes in and on the sediment and cause disturbance of bottom sediment
- Potential for local extinction of animals beneath the deposited material

A report by Golomb (1989) includes a discussion by Woods Hole researchers of some potential biological impacts.

The cost of a pipeline for deep ocean disposal appears to be a major obstacle to this option. A preliminary cost estimate by British Coal for a 250 km pipeline for a 500 MW power plant is about \$270 million dollars or 30% of the capital cost of the power plant. British Coal favors the depleted oil and gas field option although it will also require pipelines (presumably shorter).

On-land disposal. Options include disposal in depleted oil/gas formations, salt domes, aquifers, and other geological voids. Smith (1991) estimates a  $\text{CO}_2$  capacity for depleted gas fields worldwide at 1.3 GtC with new capacity becoming available at 0.7 GtC/year. On-land disposal is less costly than ocean disposal, especially inland. We do not know for sure if it is more secure than ocean disposal and the extent of re-release. The potential exists for use in EOR, but economic

feasibility in terms of credits for  $\text{CO}_2$  may be limited under conditions of low oil prices. Also the capacity seems limited, probably amounting to only a small fraction of a GtC/yr. After a few years of injection,  $\text{CO}_2$  is likely to show up at the well head. We do not know the extent of re-release of  $\text{CO}_2$  used for EOR or the potential for prevention of re-release, but it is conceivable that measures could be taken to prevent leaks and recycle the  $\text{CO}_2$ . Other issues arise where  $\text{CO}_2/\text{SO}_2/\text{NO}_x$  mixtures would be injected. These include the transport of the  $\text{CO}_2/\text{SO}_2/\text{NO}_x$  mixture over long distances, the disposition of the  $\text{SO}_2/\text{NO}_x$  contaminants injected in oil reservoirs, and the potential for pluggage of the reservoir (Sparrow, 1988). We do not know the potential for catastrophic release. Disposal in aquifers is another option currently being discussed, but questions on the resulting underground chemistry and fate remain to be resolved.

### $\text{CO}_2$ Utilization

In the near term,  $\text{CO}_2$  utilization is the most available and environmentally unquestioned option. A good example is the emerging practice in the chemical industry of co-siting  $\text{CO}_2$ -using processes with  $\text{CO}_2$ -producers -- specifically, integration of methanol production (a  $\text{CO}_2$ -using process) with ammonia production (a concentrated  $\text{CO}_2$ -production process). What is the longer-range importance of carbon recycling? Carbon is a key transport agent for  $\text{H}_2$ ; e.g., methane ( $\text{CH}_4$ ) and other hydrocarbons provide a "natural," convenient, and practical means for  $\text{H}_2$  energy transport and use. On the other hand,  $\text{H}_2$  is difficult to store, transport, and use directly. The world's fossil fuel reserves are the most economically available, concentrated source of carbon, but are rapidly being consumed. Carbon resources can be preserved as an energy transport medium for future generations by recycling existing concentrated sources of  $\text{CO}_2$ . At the same time,  $\text{CO}_2$  emissions to the atmosphere can be reduced along with the attendant global warming. What are some of the currently wasted  $\text{CO}_2$  resources which could be managed for synthesis of future hydrocarbons? They include: 1) fossil fuel combustion (e.g., coal-fired power plants), 2) calcination of limestone, 3) oxygen-blown blast furnace gas, 4) natural gas acid gas stripping, and 5) ammonia production to name a few. Carbon (as  $\text{CO}_2$ ) can also be recycled from carbonate rock or from the atmosphere to produce synthetic fuel but at much greater cost (Steinberg, 1977).

Figure 8 illustrates some longer-term integrated sys-

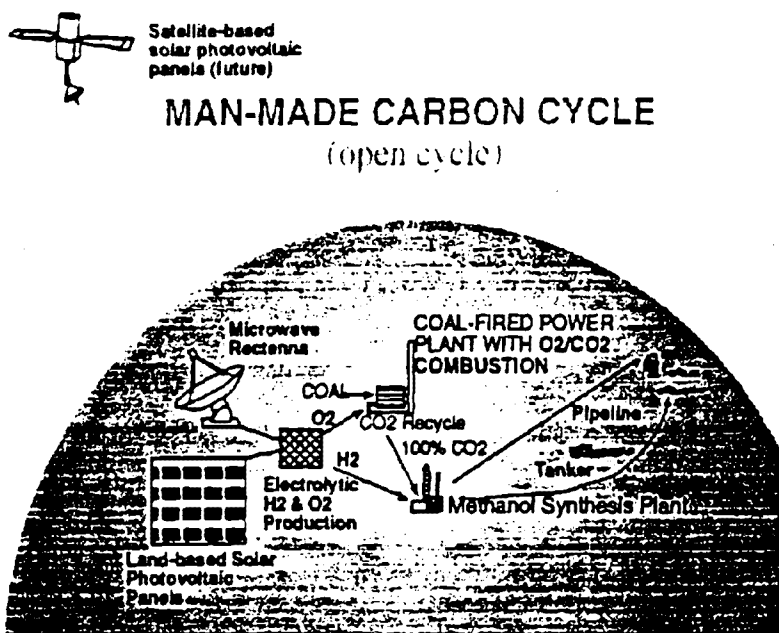
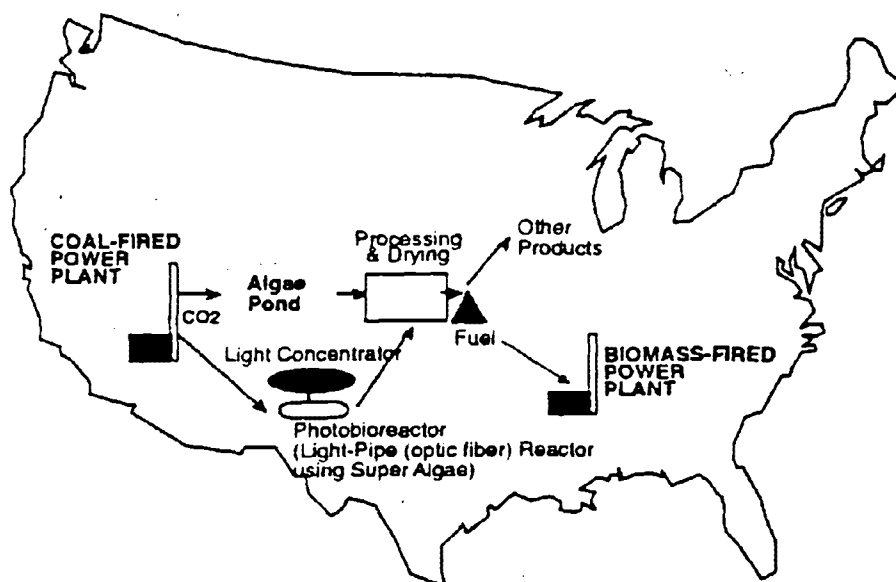


Figure 8. Long-term integrated systems for carbon recycle.

tems for carbon recycling. Utilizing  $\text{CO}_2$  via a "man-made" carbon cycle needs overall assessment and cost feasibility studies. It is a chemical-based recycling approach with no  $\text{CO}_2$  disposal required. This makes it environmentally attractive.  $\text{H}_2$  (with  $\text{O}_2$  as a by-product) can be produced by using land-based solar-photovoltaic produced electricity to electrolyze water. For projected huge energy demands by the year 2100, satellite- or lunar- based photovoltaic generation may be required (Hoffert, 1991).  $\text{CO}_2$  is reacted with  $\text{H}_2$  to form methanol. Methanol can be further reacted via dehydration to produce gasoline if desired. Steinberg (1977) investigated a similar concept using nuclear power as the energy source. The system eliminates need for an air separator and  $\text{CO}_2$  disposal. Mitigation potential includes the utility, industrial, and transportation sectors (new and retrofit). If shown to be feasible, the high mitigation potential and elimination of the  $\text{CO}_2$  disposal problem argue for R&D to reduce  $\text{H}_2$  production cost. Recent breakthroughs in production of solar photovoltaic cells should help this somewhat, but innovative means for producing  $\text{H}_2$  is a fertile research area. Credits for  $\text{SO}_2/\text{NO}_x$  control could help to reduce costs. Feasibility as a system needs to be determined. The Japanese are pursuing R&D on system components (Arakawa, 1992a&b).  $\text{CO}_2/\text{O}_2$  combustion is in the early stages of development (small-scale pilot, small demonstration) as discussed previously. The likelihood of success depends on key components, including low-cost photovoltaic electricity generation,  $\text{H}_2$  production, and  $\text{CO}_2/\text{O}_2$  combustion. If this long-range concept proves to be feasible it could have several advantages: 1) fossil fuel can continue to be

used, 2) transportation and gas turbine fuels are made available, 3) fossil carbon reserves are extended for future use, 4) the energy storage problem and global transportability problem associated with solar energy are solved, 5) the approach appears highly applicable to developing countries, 6) solves the problem of difficult storage, transport, and use of  $H_2$ , and 7) provides a transition to a direct-use  $H_2$  economy by building up the necessary  $H_2$  production infrastructure. Ultimately, the " $CO_2$ -synfuel" being produced can be recycled itself, thus achieving a closed cycle.



Flue-Gas Sequestration (Biological Processes)

Figure 9. Biologically based flue-gas  $CO_2$  sequestration processes (with microalgae flue-gas  $CO_2$  removal).

Flue-gas sequestration via microalgae flue-gas  $CO_2$  capture is illustrated in Figure 9. The concept is attractive, but difficult to implement because of the large surface area required for exposing microalgae to  $CO_2$  in the flue gas. A 100-MW power plant would require an algae farm surrounding the plant out to a distance of 4.3 km (Brown, 1990). Direct use of the biomass generated appears to be difficult, but it can be processed for lipids or to other hydrocarbon fuels such as methane. Mitigation potential exists for new and retrofit utility applications but is probably limited to only certain areas with enough land, proper terrain, nutrient capital, and adequate water and evaporation rates. No reliable estimates of costs are available. SERI is doing bench scale research and the Japanese are looking at photobioreactor concepts which would allow more efficient and concentrated biological growth.

options in perspective, however, consider, that if the entire U.S. current annual wood production (net growth of 493 million dry metric tons/year) were diverted to wood energy, it optimistically could provide only  $7 \times 10^{18}$  J (7 quads). Figure 11 is based on wood production on U.S. timberlands as projected by Sampson (1991). It is likely that only a fraction of these amounts would be used for energy. Approximately  $1.5 \times 10^{18}$  J (1.4 quads) is used for energy currently (High, 1990). Only a fraction of the land area of a country is suitable, by climate or terrain, for energy plantations. Within that fraction, only an area within a reasonable distance of an energy plant can be considered useful because of the high transportation costs of biomass (one trainload of coal is equivalent to the energy content of eight trainloads of biomass). In any event it appears that the most

## Atmospheric $CO_2$ Fixation

### Enhancing Terrestrial Fixation

Figure 10 illustrates some of the options for enhancing terrestrial fixation. Options include reforestation and forest management (0.1 - 1 Gt/yr), reducing deforestation (1 Gt/yr), and enhanced soil C sequestration (0.1 - 0.5 Gt/yr). While there do not appear to be any "silver bullets" in the options available, it makes sense to continue efforts underway to maximize potential benefits. To put these

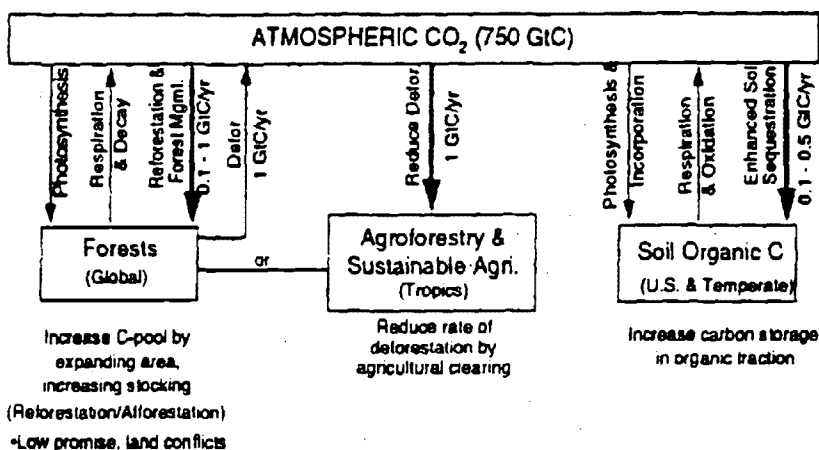


Figure 10. Means for increasing atmospheric  $CO_2$  fixation via enhancement of terrestrial system uptake. Units are metric gigatons of carbon (GtC).

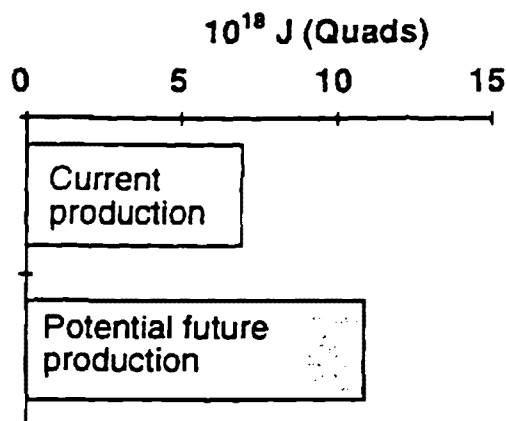


Figure 11. Energy from biomass if total wood production were diverted to energy: 1) all current U.S. wood production and 2) all potential future U.S. production (not including dedicated energy plantations).

effective approach for taking advantage of terrestrial fixation is to use the biomass resources produced to produce energy to displace fossil energy (Hall, 1992). Lee (1991) estimates that short rotation energy crops could provide an additional 6 to 13 x 10<sup>18</sup> J (6 to 12 quads). Vitousek (1991) finds that new tree plantations without energy use can at best cause a brief delay in CO<sub>2</sub> accumulation. He also points out the concerns that 1) the biomass truly replaces fossil fuel and not just simply increases energy available to energy deficient people, and 2) energy plantations be developed on land that is not now forest covered because of a substantial net loss of carbon during the transition. Better yet, approaches like the Hydrocarb process, if successful, may leverage available biomass by using fossil fuels as feedstocks.

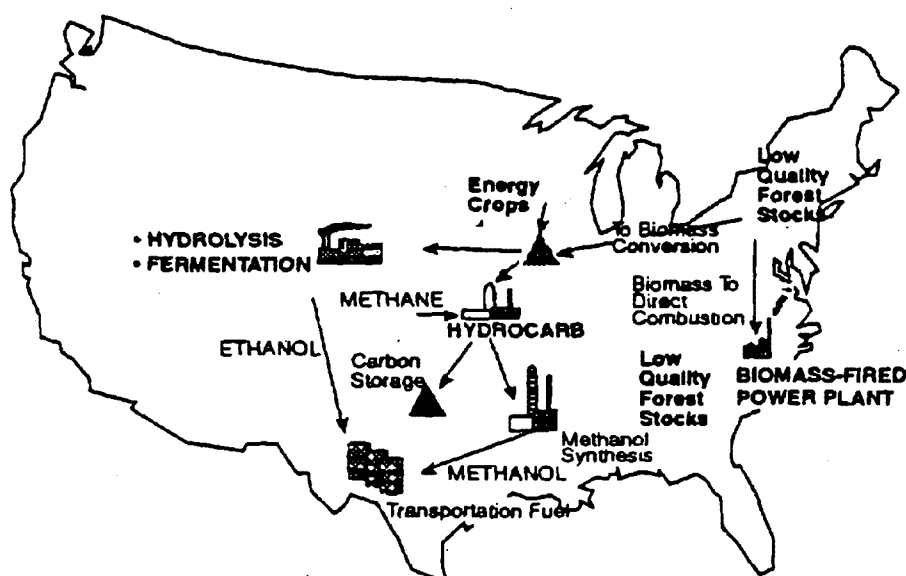


Figure 12. Atmospheric sequestration options involving direct-combustion or conversion utilization of biomass.

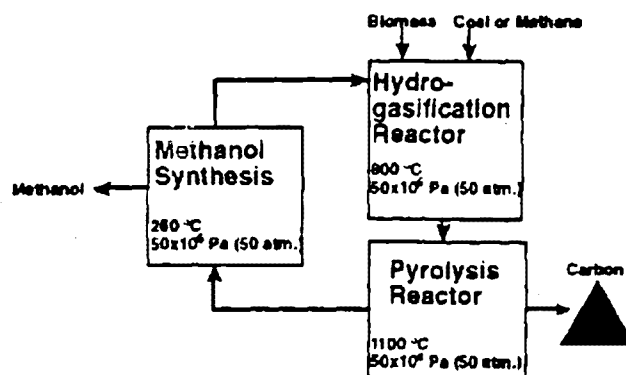


Figure 13. The basic Hydrocarb process involves three basic process steps which allow conversion of biomass with fossil fuel to methanol and carbon.

### Direct Combustion or Conversion Utilization

Figure 12 illustrates some of the options for atmospheric CO<sub>2</sub> fixation via direct combustion or conversion. These options include utilization of atmospheric carbon fixed as biomass via either direct combustion or conversion to another fuel form before combustion. Harvesting new biomass and using it for energy production maximizes the benefit from biomass carbon sequestration since the energy generated can displace that from fossil sources. Of the various options covered in Figure 12, direct combustion and the Hydrocarb process both seem to have special advantages. EPA is currently pursuing a joint program with the State of Vermont and Brazil to explore the potential for an advanced biomass utilization approach involving gasification with turbine combustion/generation. A basic

Hydrocarb process configuration is shown in Figure 13. It appears to be a cost-effective option at this early point in development with the potential for leveraging biomass supply with fossil fuel. Because of substantial substitution of H<sub>2</sub> from biomass, some of the sulfur and ash free carbon can be used for a power plant fuel without losing the carbon sequestration advantage.

### Enhancing Uptake by Aquatic Systems

Figure 14 illustrates some of the proposed options for enhancing aquatic fixation, including iron (Fe) fertilization of microalgae and enhanced macroalgae production.

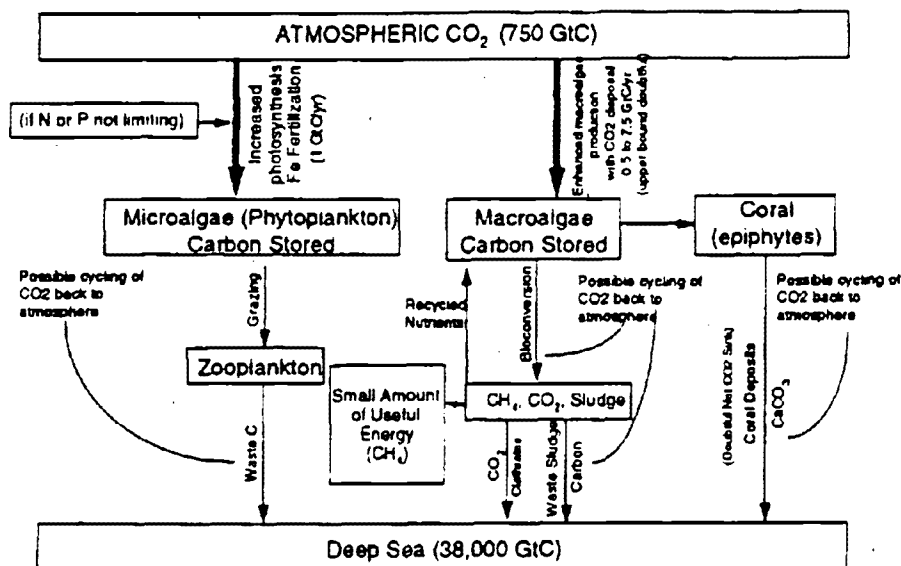


Figure 14. Illustration of means for increasing atmospheric CO<sub>2</sub> fixation via enhancement of aquatic system uptake. Units are metric gigatons of carbon (GtC).

**Macroalgae farming.** Atmospheric CO<sub>2</sub> sequestration via macroalgae farming is illustrated in Figure 15. These ideas are difficult to evaluate at this point, but, Lee (1991) estimated that to generate  $1 \times 10^{16}$  J (1 quad) of natural gas would require 1000 kelp farms, each 34 km long and 0.5 km wide. Capital costs would be over \$75 billion. Spencer (1991) has also estimated mitigation potential and cost. The following environmental issues must be considered:

- Little is known about environmental effects
- Ocean warming feedbacks
- May require ocean dumping of processed sludges

**Ocean fertilization.** Microalgae fertilization has been proposed as a means for enhancing carbon uptake. The theory behind Fe, manganese, and phosphorus limitations is not well understood or accepted universally. However, considerable scientific interest in testing the Fe limitation hypothesis exists, and it will likely be pursued. Sarmiento (1991) and Joos (1991) have done 3-D modeling simulations of the impact of Fe fertilization in the oceans of the Southern Hemisphere. Little is known about potentially large, adverse effects and therefore environmental considerations will top the list of research priorities. Research is likely to focus on ocean environments where key micronutrients are thought to be limiting to productivity. This approach to CO<sub>2</sub> sequestration requires consideration of the following environmental concerns:

- Fertilization of large areas of the Southern Atlantic and Southern Pacific Oceans
- The potential for deep ocean anoxia and feedback of CH<sub>4</sub> and nitrous oxide (N<sub>2</sub>O)
- Potential for increased release of CO<sub>2</sub> from ocean if fertilization stopped
- Potential for dramatic changes in species composition
- May favor phytoplankton species more susceptible to ultraviolet (UV)-B radiation
- Potential for altered fertility in other ocean regions

- Potential for increased CH<sub>4</sub> formation, especially for sinking options
- Effective use will require CO<sub>2</sub> disposal which has several environmental consequences
- Difficulty in supplying and recycling needed nutrients
- Potential for storm disturbance and loss
- Potential increase in haloform production (methyl bromide) and increased ozone depletion
- Respiration by organisms forming coral may release CO<sub>2</sub> to the atmosphere

## Observations and Conclusions

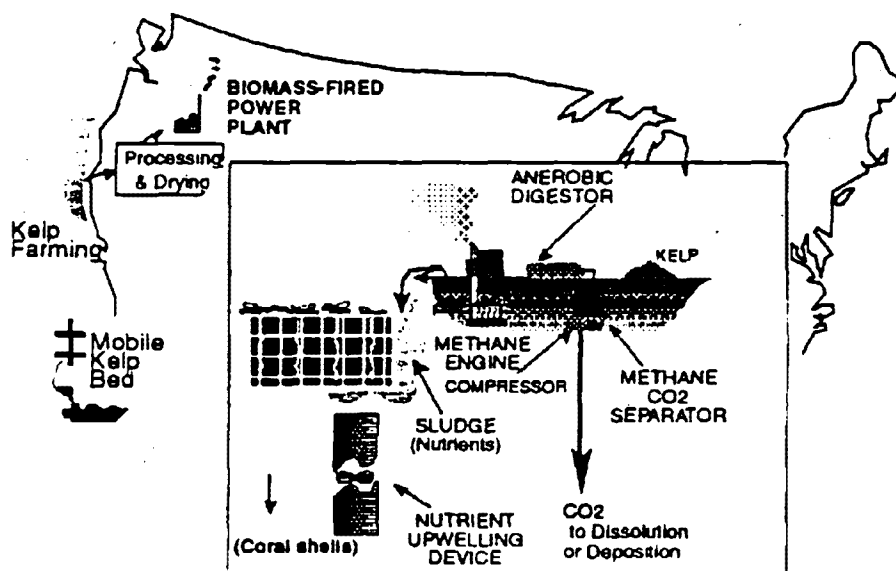


Figure 15. A proposed macroalgae ocean atmospheric CO<sub>2</sub> fixation approach.

Many cost-effective approaches will be needed to deal with increasing greenhouse gas emissions. Those that are likely to be implemented before CO<sub>2</sub> sequestration are chlorofluorocarbon/halon prevention, prevention and control of CH<sub>4</sub> and other tropospheric ozone precursors, accelerated conservation, and accelerated development/use of renewables. Available data on many CO<sub>2</sub> sequestration/fixation technology options are weak, but globally, R&D is increasing in these areas. Table 3 summarizes the current picture of the CO<sub>2</sub> sequestration/fixation systems discussed in this paper. Tables 4 and 5 summarize the overall systems possibilities on a time frame basis. The underlying construct for these tables was borrowed from the Greenhouse Gas R&D Programme (IEA, 1992) but has been modified and expanded to cover additional technologies and atmospheric fixation options.

### Flue Gas Sequestration

Currently, there is no EPA activity underway on flue-gas CO<sub>2</sub> sequestration, and there is very little U.S. R&D in this area in general. Globally, a considerable amount of R&D work is being initiated: The Japanese are especially active with joint government/industry projects, and other work is underway in Europe. The major limitations now are high cost and increased energy usage. Perhaps some increase in cost-effectiveness can be achieved from the simultaneous removal of SO<sub>2</sub>, NO<sub>x</sub>, and particulates along with the CO<sub>2</sub>. CO<sub>2</sub>/O<sub>2</sub> combustion appears to have research merit as a technology for concentrating CO<sub>2</sub>, but much development lies ahead. IGCC options look especially attractive, but apply primarily to new power plant capacity. Flue-gas CO<sub>2</sub> sequestration requires utilization or disposal of the CO<sub>2</sub> in conjunction with any of the above technologies.

The option which offers near-term market solutions for utilization/dis-

posal (for limited quantities) is for product use, including chemical feedstocks and enhanced oil recovery. Many options for co-siting chemical facilities exist where CO<sub>2</sub> can be effectively used. While this will not solve the CO<sub>2</sub> problem by itself, worthwhile contributions to reduce CO<sub>2</sub> can be made. One example that is already being used is co-siting of ammonia and methanol production facilities. Methanol production operations can use the extra CO<sub>2</sub> from the ammonia plant, and the whole facility can be optimized for energy use.

Table 3. Flue-gas CO<sub>2</sub> sequestration and atmospheric CO<sub>2</sub> fixation systems.

TECHNOLOGY	STATUS OF TECHNOLOGY	CARBON MITIGATION POTENTIAL	COST-EFFECTIVENESS	ENVIRONMENTAL CONSIDERATIONS	R&D OPPORTUNITIES
<b>FLUE-GAS CO<sub>2</sub> SEQUESTRATION</b>					
Co-siting of industrial CO <sub>2</sub> producers with CO <sub>2</sub> scale smaller than power plants	NEAR TERM Commercialized as a scale smaller than power plant applications.	LOW	HIGH	Attractive: prevention and recycling. No CO <sub>2</sub> disposal.	Systematic engineering screening and evaluation across industry
Conventional combustion with flue-gas scrubbing	NEAR TERM Commercialized as a scale smaller than power plant applications.	HIGH	MEDIUM TO LOW with no credit for NO <sub>x</sub> and SO <sub>2</sub> control.	CO <sub>2</sub> disposal is a key concern. Simultaneous NO <sub>x</sub> /SO <sub>2</sub> removal.	Engineering eval./cost study along with pilot-scale dev. work. Evaluate options for reducing efficiency loss via heat recovery?
CO <sub>2</sub> /O <sub>2</sub> combustion with CO <sub>2</sub> disposal	MEDIUM TERM Small scale pilot & demo. work - Japan, Canada	HIGH	MEDIUM with no credit for NO <sub>x</sub> and SO <sub>2</sub> control.	CO <sub>2</sub> disposal is a key concern. Simultaneous NO <sub>x</sub> /SO <sub>2</sub> removal.	Engineering eval./cost study along with pilot-scale dev. work. Possible demos.
Man-made carbon cycle	LONG TERM Conceptual enrg. cost/feasib. study - Japan	HIGH	No cost estimate available.	Inv. attractive. No CO <sub>2</sub> disposal required.	Feasibility studies. Research to reduce solar hydrogen cost.
Integrated gasification combined cycle (IGCC)/shifted CO with CO <sub>2</sub> disposal	MEDIUM TERM Conceptual design based on mod. of IGCC designs.	HIGH	MEDIUM	Key areas of concern are CO <sub>2</sub> disposal options.	Research on separation. CO <sub>2</sub> subseal dev. Pilot and demonstration projects.
Microalgae flue-gas capture	LONG TERM Attractive but difficult to implement - SERI & Japanese small-scale research	LOW	LOW	Large-scale ponds and related evap. & escape.	Feasibility studies and evaluation of innovative concepts of small scale
<b>ATMOSPHERIC CO<sub>2</sub> FIXATION</b>					
Increased terrestrial biomass - direct combustion	NEAR TERM Tech. currently eval. and adv. tech. (whole-tree & gas turbine) in the pilot/demo (U.S.)	LOW	HIGH	No key concerns except high intensity biomass farming.	Engineering design and cost studies. Pilot and demo tests of combined cycles and whole-tree burning.
Increased terrestrial biomass - Hydrocult	MEDIUM TERM Enrg. anal., exp. work, & cost studies. Coal options require C storage (U.S.)	MEDIUM	MEDIUM	Short-rotation, high-intensity farming, C storage/disposal, and/or CO <sub>2</sub> disposal.	Increased biomass yields. Bench- and pilot-scale research to establish design specifications.
Increased terrestrial biomass - ethanol via hydrolysis	NEAR TO MED. TERM Tech. is commercial but adv. res. on coenergy eff. (SERI)	LOW	LOW	Short-rotation, high-intensity biomass farming.	Enzyme and other research to improve yields from conventional biomass.
Agroforestry	NEAR TERM Agroforestry tech. implemented. R&D on h-yield sustain. crop cult. & soil mgmt.	LOW	HIGH	Lead to forest fuel based, mechanized agriculture?	Research on soil fertility, fertilizer mgmt, hydrological systems, tolerance to soil acidity, etc.
Microalgae ocean fertilization	LONG TERM Paper & modeling studies. Limited field evaluation	LOW	HIGH	Many significant concerns.	Environmental assessment including ecological effects research.
Macroalgae farming with anaerobic digestion and ocean disposal	LONG TERM Early concept. EPRINQAA have done paper studies	MEDIUM	MEDIUM TO LOW	Large number of potential problems.	Environmental assessment including ecological effects research.
Increased marine biomass (coastal kelp) with direct combustion	LONG TERM Early conceptualization	LOW	LOW	Disruption of coastal environmental systems	Environmental assessment including ecological effects research.



Table 4. Overall summary flue-gas sequestration systems.

Time Frame	Technology	CO <sub>2</sub> Removal	CO <sub>2</sub> Disposition
Current	Industrial processes (e.g., ammonia & methanol facilities)	Co-siting for CO <sub>2</sub> use	Chemical feedstock
Near-term	Conventional fossil-fueled utility boilers	Amine & other flue-gas removal tech.	Enhanced oil recovery use & disposal in depleted oil & gas formations
Medium-term	Integrated gasification combined cycle  CO <sub>2</sub> /O <sub>2</sub> combustion (new & retrofit) with O <sub>2</sub> from air separation	Absorption, cryogenics, & membranes  Not required	New chemical products and disposal in salt domes/aquifers
Long-term	CO <sub>2</sub> /O <sub>2</sub> fossil fuel combustion with O <sub>2</sub> from solar photovoltaic electrolysis of water  CO <sub>2</sub> /O <sub>2</sub> "synthetic methanol"-fueled advanced comb. cycles (closed carbon cycle)  Other: - Other adv. cycles - Fuel cells	Not required  Not required	Methanol transportation and peaking fuel from CO <sub>2</sub> & H <sub>2</sub> from solar photovoltaic electrolysis of water - also provides O <sub>2</sub> for combustion  Ocean disposal
Long-term	Conventional utility fossil-fuel combustion & microalgae fuel	Microalgae flue-gas sequestration	Recycled as fuel or used for other products

Table 5. Overall summary of atmospheric fixation systems.

Time Frame	Technology	CO <sub>2</sub> Capture	CO <sub>2</sub> Disposition
Near-term	Increased terrestrial biomass (via forest mgmt., forestation, agroforestry) -- Direct combustion -- Ethanol conv. hydrolysis	Atm. fixation	None
Medium-term	Increased terrestrial biomass (short-rotation intensive culture) - Advanced cycles - Hydrocarb - Ethanol adv. hydrolysis	Atm. fixation	None
Long-term	Microalgae fertilization (ocean)  Macroalgae farming with anaerobic digestion (ocean)	Atm. fixation	None  Ocean disposal

Disposal of CO<sub>2</sub> in depleted oil and gas reserves is the nearest-term straight disposal approach. Ocean CO<sub>2</sub> disposal approaches appear to be rather costly and have a major research need on modeling to determine the new, longer-term atmospheric concentration levels resulting from disposal. All of the disposal options are longer-term options because of the environmental assessment required before implementation. The man-made carbon cycle has the potential for high mitigation

without the problems of CO<sub>2</sub> disposal; research needs to be done to establish feasibility and reduce potential costs, especially for the solar hydrogen production required.

### Atmospheric Fixation

EPA and others are actively working on forestation, agroforestry, soil sequestration, direct combustion/utilization, and the Hydrocarb process development. Sequestration via microalgae and macroalgae are long term possibilities requiring years to decades of ecological effects research. There is no scientific consensus on the duration of sequestration or the effectiveness of biological mechanisms in carbon fixation over long terms. As we learn more, more potential problems seem to arise. R&D on direct utilization of biomass offers near term benefits. Direct biomass utilization is currently utilized in the energy sector and is projected to be more efficient in the future. Competition for biomass feedstocks is a serious limitation. For instance the wood products industry demands increasing amounts of fiber and can pay more for the resource than the energy sector can afford due to the higher value of final products. EPA is currently examining the potential for advanced cycles using biomass. Development of cost-effective technologies provides incentives to grow increasing amounts of biomass. The Hydrocarb process is a medium-term technology and appears to provide means of mitigation of CO<sub>2</sub> and other emissions from transportation sources. Current research options for the terrestrial biosphere research appear justified; near-term benefits and costs appear to be reasonable, although the sequestration potential is limited. The serious environmental concerns associated with ocean microalgae fertilization and macroalgae farming make them longer-term options requiring intensive environmental assessment.

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This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

PAPER 3-C

THE NOAA CARBON SEQUESTRATION PROGRAM

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Increasing attention is being given to oceanic techniques for sequestering carbon in various molecular forms as part of an overall global-change strategy. EPRI, through a Caltech contract, is looking at the formation and semi-permanent retention of CO<sub>2</sub> hydrates at ocean depths of 1,000 meters or so. Similar investigations are being actively pursued by the Japanese. And EPRI and NOAA, assisted by Caltech and George Washington University, are re-examining the feasibility of large-scale farming of microalgae as a way of collecting CO<sub>2</sub> from the atmosphere and upper ocean layers, sequestering it in liquid or hydrate form in the deep ocean and/or locking up the carbon in the farm structure, and using the farm-produced methane and perhaps methanol as a CO<sub>2</sub>-neutral fossil fuel substitute.

INTRODUCTION

Detailed papers and reports in preparation by EPRI will describe the CO<sub>2</sub> hydrate research being conducted at Caltech.\* This work suggests the likely feasibility of large-scale hydrate deposition, but the possible long-term effects on ocean ecology must be examined in detail before any sound decision on a major program can be made.

Whether or not this technique is determined to be economically and ecologically acceptable, however, the concept of large-scale ocean farming as a strategy for significant global-change mitigation should be carefully investigated. The growing of biomass constitutes a natural and logical technique for fixing atmospheric carbon in the form of plant hydrocarbons. To the extent that world-wide fuels are derived from biomass fuels, the build-up of atmospheric CO<sub>2</sub> will be slowed by recycling. And the oceans, constituting over 70% of the world's surface, may well offer the greatest opportunity in such a strategy.

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\* See in particular:

"Climate Alteration - A Global Issue for the Electric Power Industry  
in the Twenty-First Century" --

a paper being submitted for publication in the Annual Reviews of  
Energy and the Environment;

"Investigations of CO<sub>2</sub> Hydrate Formation and Dissolution" --

a progress report by the California Institute of Technology.

## 1. BACKGROUND

Starting in the late 1960s, the Naval Undersea Center at San Diego (now the Naval Ocean Sciences Center) initiated some preliminary research and testing of possible techniques for open-ocean farming of macroalgae -- with the seaweed product put through anaerobic digestion to produce methane. The inquiry at that time was driven mainly by a concern about the exhaustion of natural gas reserves. It was recognized, however, that the plant pressings and digester residues would also provide important pharmaceuticals and chemicals (including natural fertilizer and fodder) and that the farms, as natural biomes, would attract large harvestable fish populations. A small moored grid (Fig. 1) was installed off the north end of San Clemente Island and tested briefly with Macrocystis plants tied to the grid lines. And a test-module design was prepared for an offshore buoy with radial arms and circumferential lines (the plant substrate) -- with a pump and tailpipe to bring up lower-layer water for plant nutrition (Fig. 2).

With the support of the American Gas Association's Gas Research Institute, and with modest participation by DOE's Solar Energy Research Institute (now the National Renewable Energy Laboratory), the research and testing program was taken over by the General Electric Company in the mid 1970s. A buoy module was constructed and moored in 1500 feet of water some eight miles off Laguna Beach, again with Macrocystis plants tied to the lines. Serious problems with plant damage were experienced because of

divergences between storm-wave frequencies and the buoy-and-mooring response harmonics, and the strong current at that location reduced the residence time and thus nutrient effect of the upwelled water. In spite of these problems, however, the test demonstrated that Macrocystis plants could be grown in that setting -- and regenerate themselves after suffering storm damage.

A comprehensive summary of this experience is available in Seaweed Cultivation for Renewable Resources -- a compilation of detailed papers prepared by the principal program participants, edited by Kimon Bird and Peter Benson and published by Elsevier in 1987(1).

The world-wide drop in oil and natural gas prices in the early 1980s caused this test program to be abandoned. But low-keyed plant research continued through the decade at Caltech and UCal (Santa Barbara) for Macrocystis and at Woods Hole for Sargassum and Gracilaria; and the anaerobic digestion techniques were pursued at the University of Florida.

Interest in the ocean-farming potentials was rekindled, however, by "The Hot Summer of 1988." With growing agreement among climatologists on the link between CO<sub>2</sub> emissions and global warming, "the greenhouse effect" started to receive serious public attention. It became clear that all serious possibilities for long-term control of atmospheric CO<sub>2</sub> should be examined. CO<sub>2</sub> is released, of course, in the combustion of all carbon-based fuels. In contrast with fossil fuels, however, the CO<sub>2</sub> from the burning of biomass fuels is all recovered when the replacement crops are grown.

Because the oceans cover 70% of the world's surface, they offer the greatest potential in this respect -- if substantial production rates can be achieved. Added to the current natural absorption in the earth and oceans, this technique might thus permit an actual reduction in the future atmospheric CO<sub>2</sub> concentration.

In recognition of these potentials, and with support from the Electric Power Research Institute (EPRI), the Board on Biology at the National Academy of Sciences assembled the principal participants in the 1970s tests for a workshop in late 1989 to consider whether a new ocean-farming R&D initiative was justified. The clear conclusion was affirmative.

This conclusion was reviewed and confirmed in a detailed workshop conducted by Caltech (again with EPRI support) in mid-1990. The implications were further examined in a NOAA-sponsored seminar and detailed workshop in 1991; the potentials for specific farm concepts (see below) were considered in an intensive conference in late 1992 (again with EPRI support); and the possible arrangements for computer analysis and model design and testing of these concepts were discussed in a January 1993 workshop at the David Taylor Model Basin.

## 2. CURRENT PRODUCTIVITY AND COSTS

As indicated above, the key to a successful ocean-farming program will be the productivity achievable with open-ocean farms. This productivity will determine the cost of the farm-based fuels and co-products.

The baseline for examining this question is the typical productivity calculated from past and current growth tests in natural kelp beds here and abroad.

Benson (2) summarizes two recent-year specific tests as follows:

<u>Researchers</u>	<u>Plant</u>	<u>Year</u>	<u>Location</u>	<u>Productivity</u> (DAFMT/A/Y)
Tseng	Laminaria	1987	Yellow Sea	3.8
Neushul & Harger	Macrocystis	1990	Ellwood (CA)	6.0

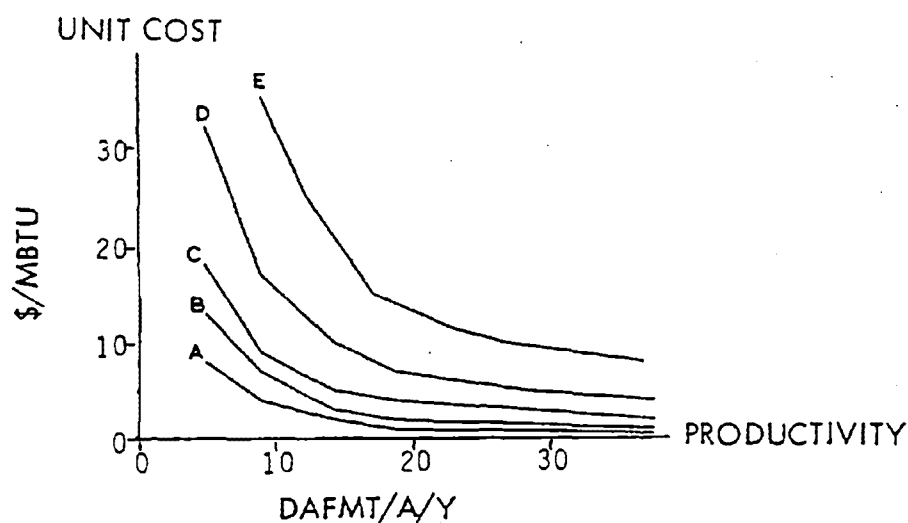
In a paper currently being reviewed for publication, North (3) shows a range of typical *Macrocystis* productivities running from about 3.5 to 12.7 DAFMT/A/Y.

Bird (1), using the *Macrocystis* growth-rate estimates from the 1970s GE tests, shows a "baseline" productivity of 13.8 DAFMT/A/Y.

The costs per unit of energy produced from the macroalgal feedstock will vary greatly depending not only on the seaweed and farm type, funding/management arrangements and local environment but also on the conversion process efficiency and the credits obtainable from the marketing of byproducts and from the avoidance of carbon-emission taxes.



Using the 1970s GE data, Bird depicted the general relationship of methane cost to seaweed productivity in a set of curves based on this first set of factors (that is, without regard to byproduct or tax credits) and depending on the farm life and maintenance/capital-cost ratio (running from 20 years and 0% [A] to 5 years and 20% [E]) as follows:



Source: (1)p.337

These figures were calculated with *Macrocystis* in Southern California coastal waters, using the conversion efficiencies achieved in the mid-70s tests. They could change significantly with a different seaweed, farm concept and setting, a refined conversion process, and a sophisticated byproduct strategy.

### 3. PROJECTED PRODUCTIVITY AND COSTS

The future prospects for increased plant productivity and thus reduced product cost will depend on a complex interaction of several factors -- including ocean settings, farm geometry, nutrient regimes, species selection, and

possible genetic engineering. Table 1 lists the principal candidate species and selection criteria.

These potentials are illustrated by a recent coastal test conducted by LaPointe and Ryther in the Florida Keys and cited by Ryther (4). In contrast with the typical figures shown above for *Macrocystis* and *Laminaria*, this *Gracilaria* test (with favorable current and nutrient conditions) showed a productivity of 41.2 DAFMT/A/Y. And LaPointe (4) states that productivity rates approaching these values might also be obtained with some strains of *Sargassum*.

Whether productivity approaching these high rates can be achieved in continuous open-ocean operations will only be determined by further tests. As one example, such tests might be pointed toward farms consisting of large grids which would migrate east and west in the Pacific Equatorial Currents and Countercurrent as shown conceptually in Fig. 3.

The optimum farm configuration and size for such an operation can only be decided after intensive model testing. One possibility, illustrated in Fig. 4, would include a servicing vessel to provide low-speed towing for position-keeping and plant nutrition--with additional nutrients provided by artificial upwelling and recirculation of the digester liquors through leaker hoses along the edges of the farm modules. And as suggested in Fig. 5, such farms might be provided with a submersion capability to improve night-time nutrition and minimize storm damage to the plants and structure.

The servicing vessel could have the versatility to vary the product mix according to world market conditions. The conversion operations involved here could include fish harvesting and processing in various forms, pharmaceutical and chemical production, and (depending on the emissions-tax situation) carbon sequestration in a CO<sub>2</sub> liquid or hydrate form.

To illustrate a further synergy in such an integrated farming operation, the servicing vessel could include equipment for converting the digester-produced methane into methanol for delivery to shoreside energy users and plastics plants, with the tanker backhaul consisting of polyester pellets which could be shaped aboard ship into the elements (lines, nets, hoses and trusses) needed for farm expansion and replacement.

The potential impact of byproduct sales on energy costs can be critical. Wilcox (5) estimated in 1976, for instance, that giving full credit for byproduct (and particularly fish) sales would reduce the methane cost to something like \$4/MBTU. And the recent increases in plant productivity cited above would further improve this prospect. Based on the relative prices of methane and fish products in the mid-70s, Wilcox estimated that devoting 1% of the seaweed crop to fish production would cover 50% of the farm costs.

#### 4. ISSUES AND RESEARCH NEEDS

The most basic lesson from the 1970s tests -- as emphasized by North in the first of the 1980s reappraisal workshops (6) -- is that success in large-scale ocean farming will depend on a good marriage of the biological and engineering

elements. (The biology in the 1970s program was well-conceived, but the engineering was not.)

The issues relating to this marriage can be arranged on a scale starting with mainly biological objectives and extending through combined questions to mainly engineering objectives. This array is shown in Table 2, and the research needs can be discussed for each numbered issue.

- (1) The opportunities for improving productivity have been discussed above. Since the fuel-product volume will be proportional to the plant carbon content, a major objective in species selection and stock refinement (and genetic engineering) will be to maximize the plant C/N ratio.
- (2) The problem of macroalgal releases of methyl halides needs careful attention as a potential threat to stratospheric ozone. A joint Caltech/UCal-Irvine research project funded by DOE is studying the methyl halide releases of natural kelp beds. This work should be extended to cover other major plant species and to include possible releases in the plant harvesting and processing stages.
- (3) The required nursery techniques will depend on the overall farm concept and can best be studied as part of an integrated system analysis.
- (4) One example of a favorable ocean-current setting is depicted in Fig. 3. Detailed analyses should be made of other good possibilities

around the world -- considering the current characteristics in terms of the plant and engineering requirements and the resulting costs and projected multi-product revenues.

- (5) Effective nutrient management (a key factor in issue (1) above) will require careful cost-and-benefit research to determine the best nutrient-regime combination for each plant and setting.
- (6) Marine-fouling control can be critical in the operation of structured farms. R&D already performed or in process for naval and commercial vessels and ocean rigs can suggest the various chemical and mechanical control possibilities and performance prospects (including toxicity problems), and these will be major factors in the selection of farm designs. Illustrating the combined biological and engineering challenge in this program, a biological-control strategy similar to the shoreside integrated-pest-management technique may turn out to be part of the marine-fouling solution in large-scale ocean farming.
- (7) Further increases in conversion-process efficiency are achievable -- again through a combination of engineering (reactor design and operating conditions) and biology (selection and possible genetic improvement of the methanogens).
- (8) In the design of structured farms, the drag characteristics of the plants and the farm structure itself will be critical in determining the overall costs and thus the program feasibility. Computer analysis

followed by design and testing of scaled-up models can provide early indications of this feasibility at modest cost -- and this research must have a high immediate priority.

- (9) In the investigation of warm-ocean farming possibilities such as the Pacific Equatorial Belt depicted in Fig. 3, as indicated above, the continuous survivability of fragile plants can be critical. Rather than accepting substantial plant and farm damage during storm periods, it may be feasible to incorporate in the farm design a capability to submerge to a plant depth of 50 to 100 feet (below the zone of intense wave action) and return to the sunlit surface when the storm has passed. One possible submersion scheme is shown in Fig. 5, and there may well be others that offer greater economy and dependability.

Here again, some initial model testing and then a trade-off analysis will be required. And the potential benefits in this analysis may include the ability to improve plant nutrition with routine night-time submergence.

- (10) The selection of materials for the farm elements is principally a challenge in plastics chemistry and engineering. The possibility of a farm that could largely "grow itself" has been described above. And major opportunities exist here for plastics recycling -- not only of the farm elements themselves but of shoreside plastic wastes

carried as backhaul (say polyester pellets) in the methanol tankers and shaped into farm expansion or replacement elements aboard the servicing vessel. As  $C_1$  chemistry is refined in future decades, furthermore, the potentials for direct shipboard production of plastics suitable for farm elements may well increase.

This issue again underscores the need to treat the farm program as an integrated-system challenge -- continuously optimizing the system as a whole for any momentary combination of product markets.

In summary, the overall biological and mechanical farm efficiency and versatility will be the basic determinant of the farm-based energy costs.

## 5. POTENTIAL MARKETS

The overall picture of potential ocean-farm products is shown in Fig. 6. Included in the page-heading list but not shown in the diagram is the potential for major cultivation, harvesting, processing and marketing of fish.

To minimize transportation costs and maximize the market-targeting flexibility, and to justify a major hull for purposes of all-weather survival, most of the seaweed-to-product conversion processes shown here (plus the fish operation) should be performed on the servicing vessel.

The existence of major methane pipeline networks in industrial countries will justify a substantial world-wide delivery of the shipboard digester gas product in this form by LNG tanker. But because it can be readily produced from the digester gas aboard the servicing vessel and easily transported by

conventional bulk carrier to a large future global market, methanol will probably be the main farm product. And these same carriers can transport ashore the food, pharmaceutical and chemical products shown in Fig. 6. As indicated above, the product emphasis at any given time can be tailored to the prevailing mix of price levels in the major world markets.

Because a major ocean-farming program would take several decades to implement, and because world-wide population growth, lifestyle changes and environmental constraints over this period cannot be accurately predicted, it is impossible to project at this time the size of the market for these various products. It seems clear, however, that the most important markets will be in food and energy.

The market for ocean-farm food products (frozen and canned fish, fish meal, fodder-nourished meats, and carageenan as a meat supplement) will depend not only on global birth rates and consumption habits but also on chronic drought and flooding problems (which may be global-warming related), long-term land use pressures, and a possible decline in agricultural productivity.

The market for ocean-farm energy products will depend on global climate reactions to the continued build-up of atmospheric CO<sub>2</sub> from fossil fuel emissions. Again depending on population growth and lifestyle changes, the rate of CO<sub>2</sub> discharge from the burning of these carbon-based fuels -- including the weight of the oxygen as an integral part of this "greenhouse" gas molecule -- will probably continue to rise above the current level of 22 GTY or 44,000



tons/minute. And at some point, this huge human intervention in the regime of the biosphere may possibly trigger one or more of the positive feedbacks outlined in Table 3 -- setting in motion a massive upward spiral.

At that point -- unless large-volume fusion power has proven to be safe and economical -- there will be a strong surge of interest in ocean farming as a protection against runaway global warming. And the corollary world-wide demand for farm-derived fuels will constitute a massive market.

The basic questions will then be:

- (1) Which of the ocean-farm techniques have the greatest "greenhouse" control potential? and
- (2) How rapidly can they be scaled up?

The answers will depend on the farm characteristics and on the scale of the crisis. In theory, however, such a program could eventually satisfy the world's full energy requirements while stabilizing the atmospheric CO<sub>2</sub> level. If world energy consumption were to continue at today's level, for instance, and if the plant productivity demonstrated in the recent Caribbean coastal tests can be achieved in open-ocean farms, the total world fuel demand could be met by the farming of about 5% of the Pacific Equatorial Belt shown in Fig. 3. This would seem to leave substantial room for the growth of farm-supplied energy use in subsequent decades.

One question that comes up in any such theoretical projection is what would be done about aviation fuel. The world-wide consumption in aircraft, primarily as kerosene, is only about 5% of the global liquid-fuel consumption -- but as shown in Fig. 7, a British researcher has recently asserted that the  $\text{NO}_x$  emitted by aircraft turbines at typical cruising altitudes has about thirty times the infrared-absorption potency as this same gas at sea level. The "greenhouse" impact of aircraft-fuel emissions may thus be a substantial portion of the total fossil-fuel impact from all sources.

The significance for ocean farming can be seen in two curves (Fig. 8) resulting from a decompression-chamber test conducted by GE with an aircraft-turbine combustor in the mid-1980s, using methanol compared with aviation kerosene (Jet A). For the same power, the combustor radiant heat flux was much lower with the methanol fuel -- resulting in greatly reduced  $\text{NO}_x$  emissions.

What this suggests is that methanol may well be a desirable aviation fuel in a future "greenhouse-sensitive" world -- at least for short- and medium-haul flights where the two-to-one weight penalty (due to methanol's lower energy density compared to kerosene) can be tolerated. And for the long-haul flights, the fuel of choice in this situation could be cryogenic methane from oceans farms. The extra-potency  $\text{NO}_x$  would still be a problem, but the  $\text{CO}_2$  released by these engines would eventually be completely recovered in the growing of seaweeds for the replacement fuel.

## 6. CONCLUSION

This review suggests that the ocean-farming techniques may have a very large potential for production of future fuels and complementary products -- and for stabilizing the global atmosphere in the process. (Coastal versions of these techniques may well have great utility in absorbing waste nutrients and recycling heavy metals and other problem-discharge components.)

There are major questions, however, about the economic and engineering feasibility of these techniques and about the possible environmental effects.

World-wide concerns about the global-warming impacts of fossil fuels and about the future adequacy of land-based food production argue for an intensive R&D program that can answer these questions in the latter half of this decade.

Only in this way can timely and credible decisions be made about the proper role of ocean farming in a global strategy for energy and food production and environmental protection.

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- 4) Ocean-Farm Candidate Concept Papers  
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George Washington University, IUDR - November 16-17, 1992, and  
statement by Brian LaPointe in post-conference discussion
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March 10-11, 1976 Proceedings, p. 271,  
published by the Bio-Energy Council.
- 6) statement by Wheeler North in a workshop on ocean farming,  
National Research Council Board on Biology  
December 7, 1989, unpublished minutes

Fig. 1 Coastal Grid Farm

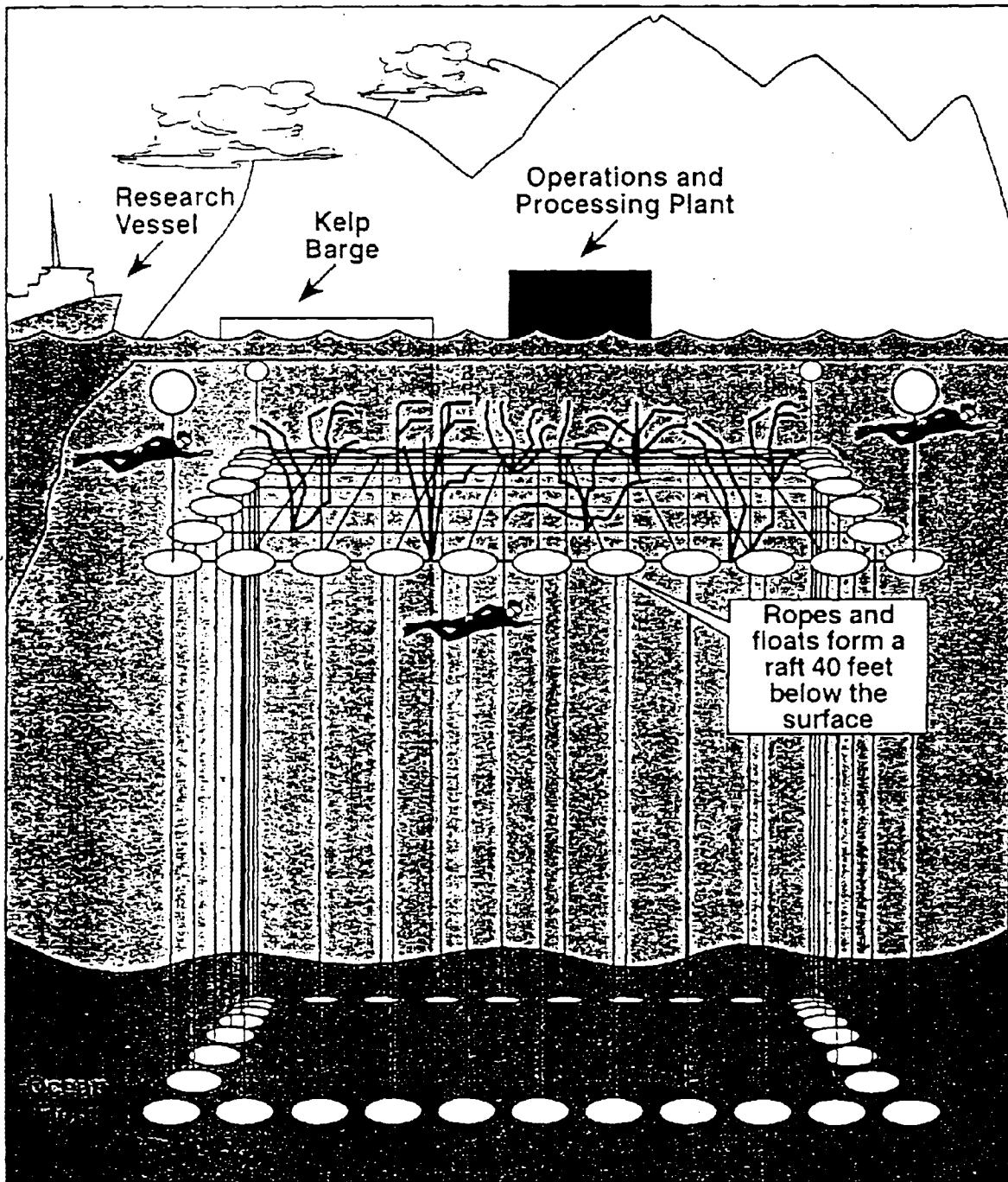


Fig. 2. OFFSHORE MODULE CONCEPT

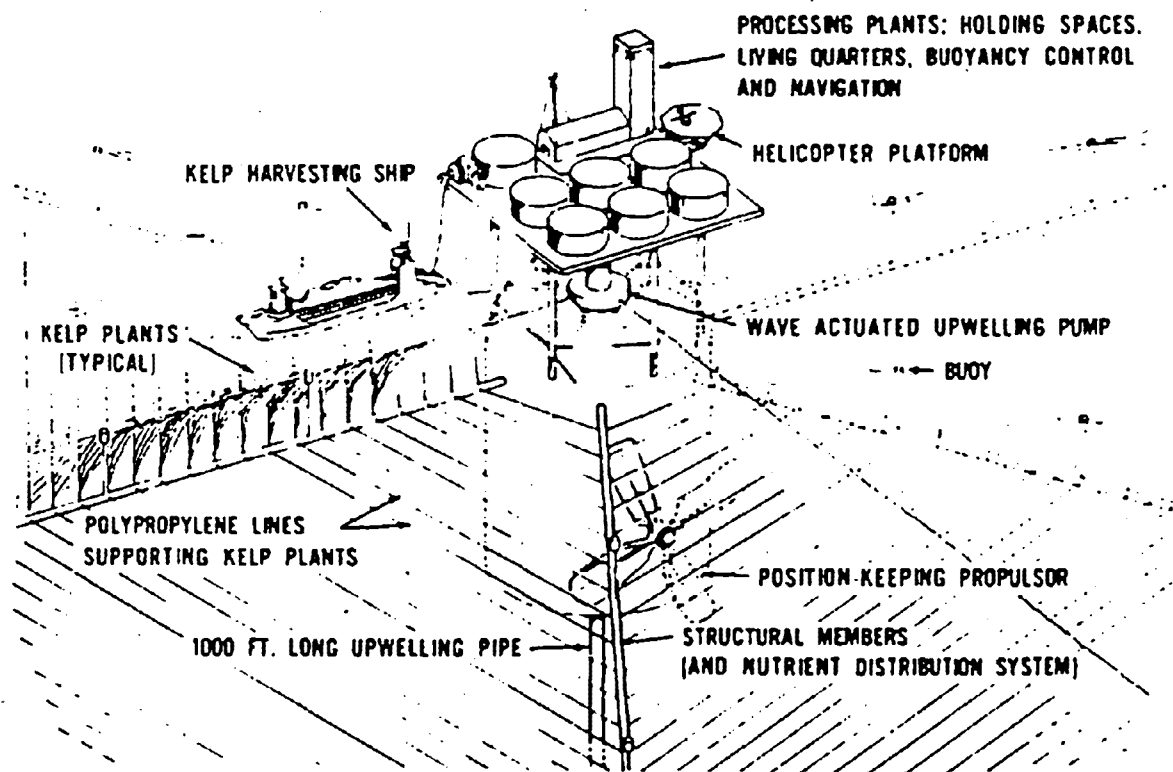
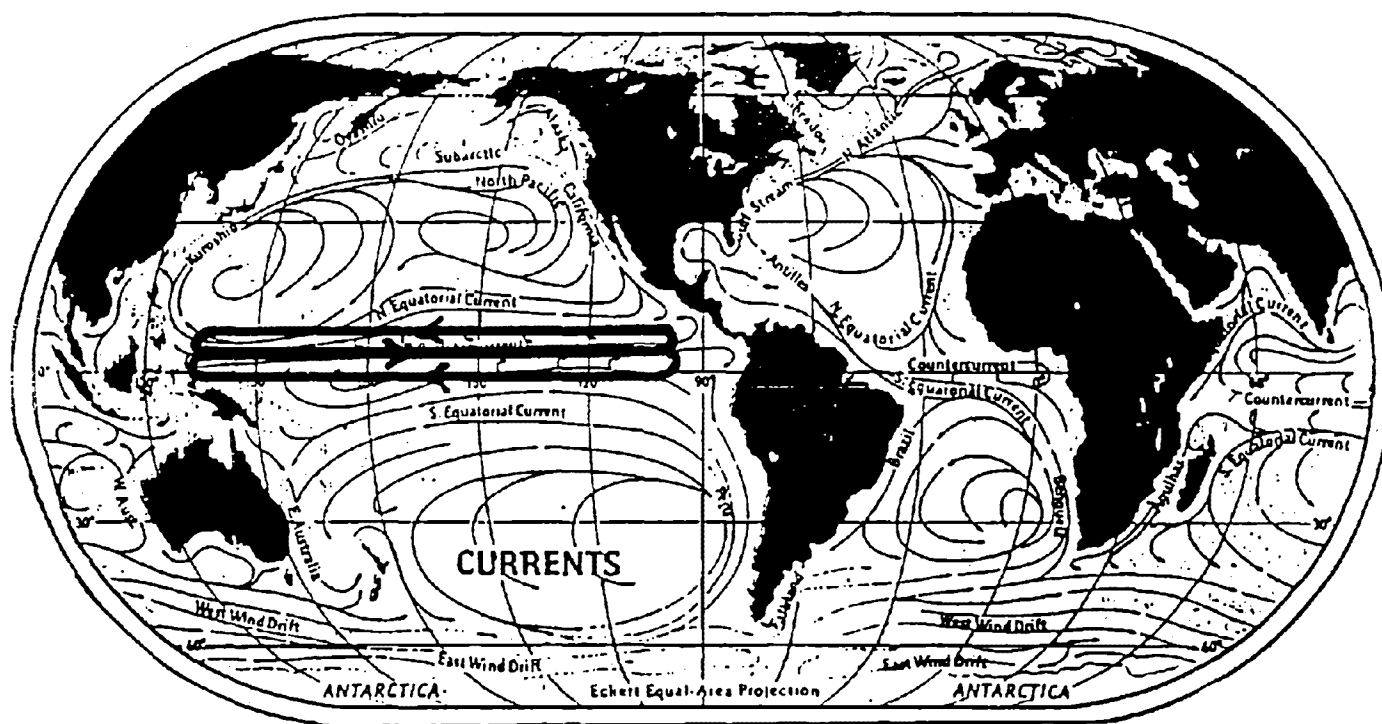


Fig. 3 PACIFIC EQUATORIAL CURRENT PATTERN



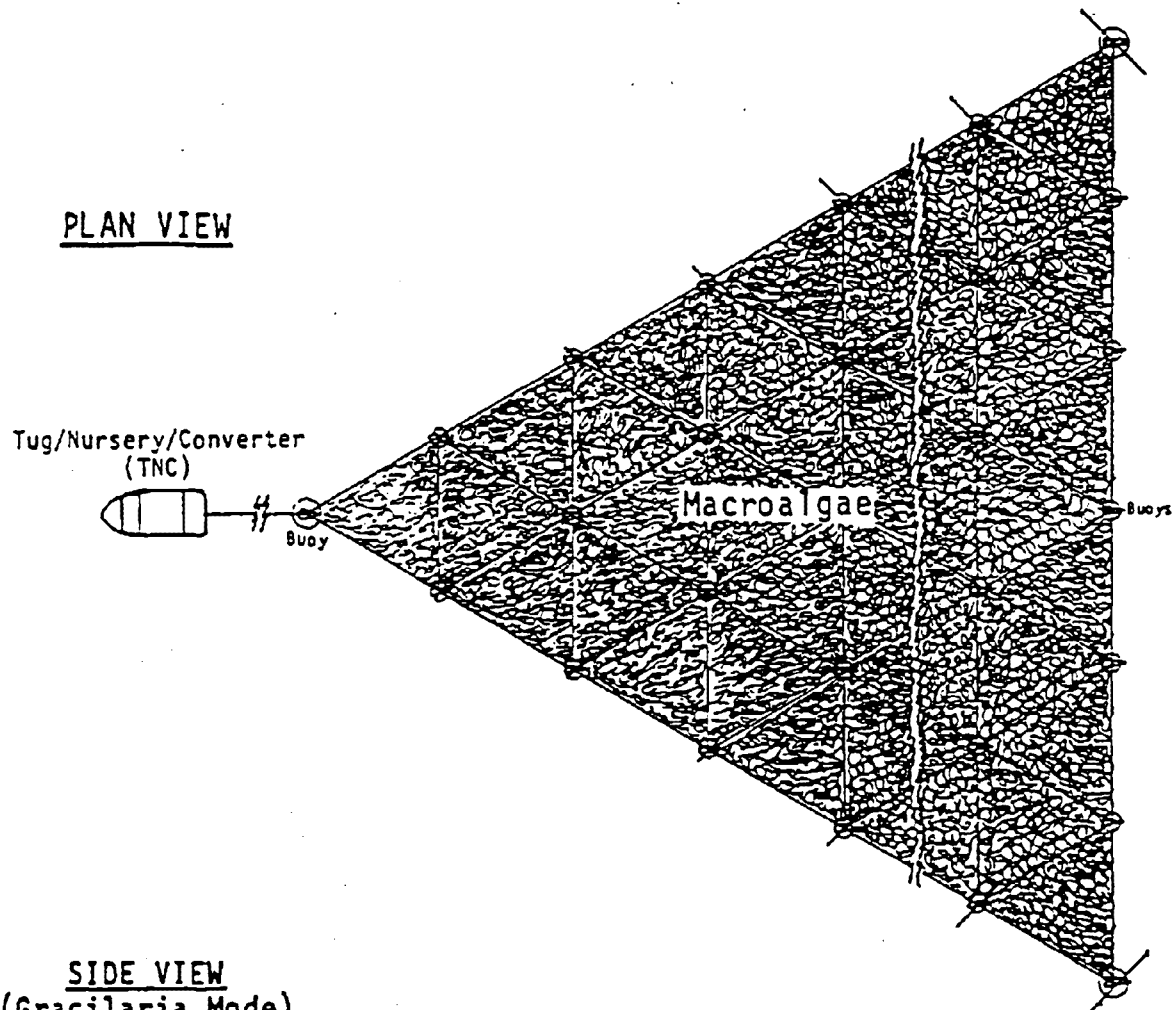
Ocean Areas (Square Miles)

Pacific	-	64,186,300
Atlantic	-	33,420,000
Indian	-	28,350,500
Arctic	-	5,905,700

Total: 131,862,500

Fig. 4 OCEAN GRID CONCEPT

PLAN VIEW



SIDE VIEW  
(Gracilaria Mode)

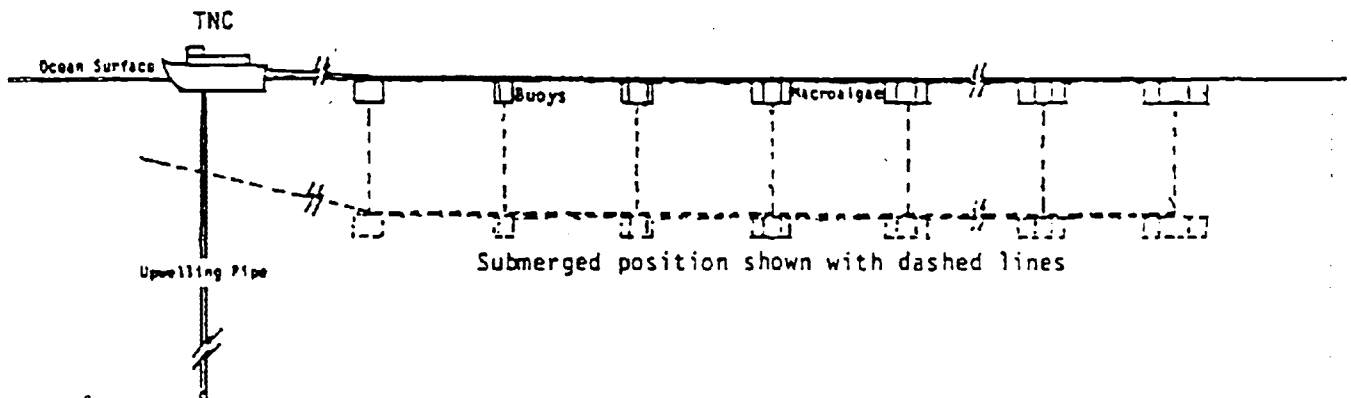




Fig. 5 CONCEPTUAL OCEAN-GRID SUBMERSION SYSTEM

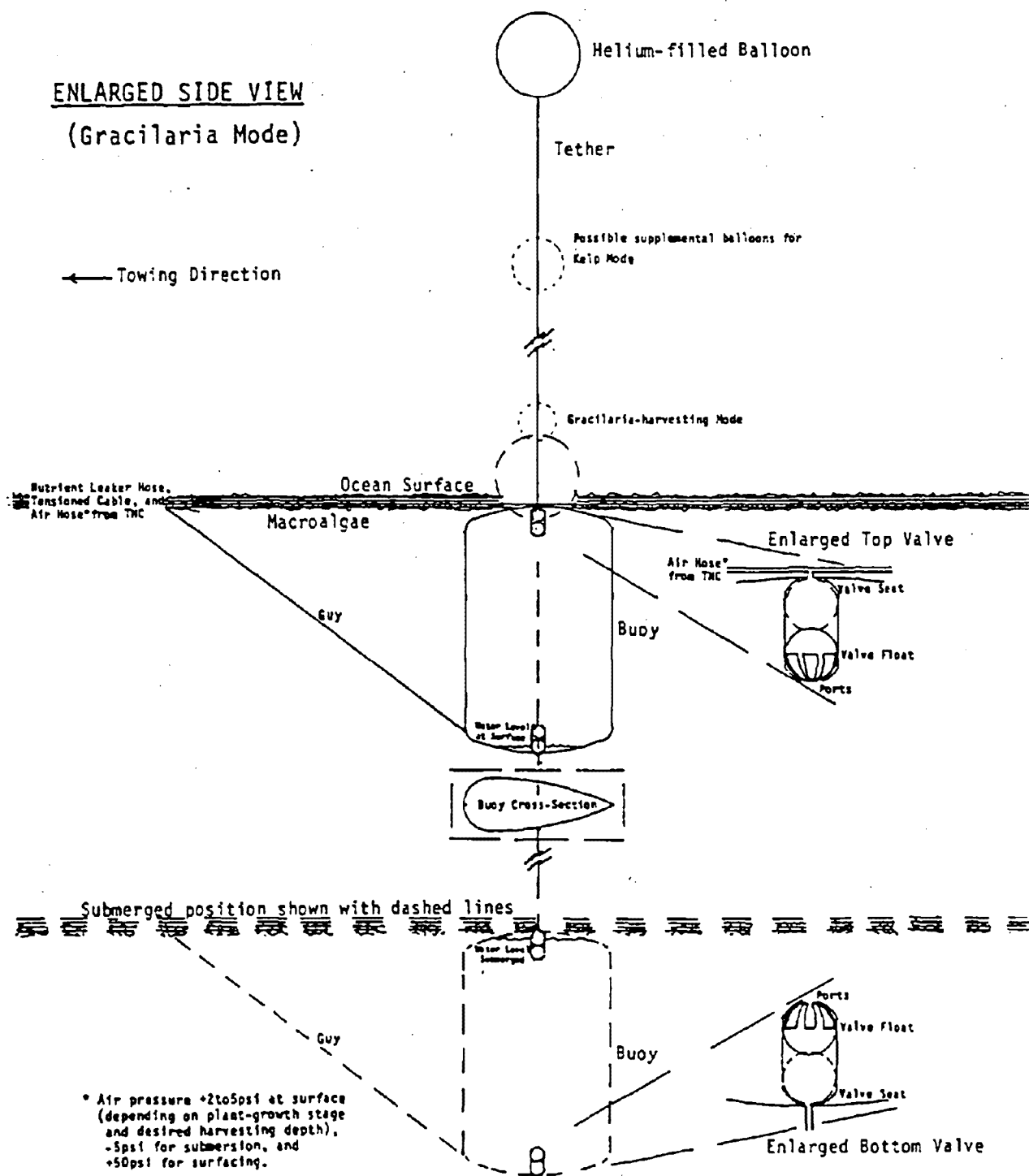
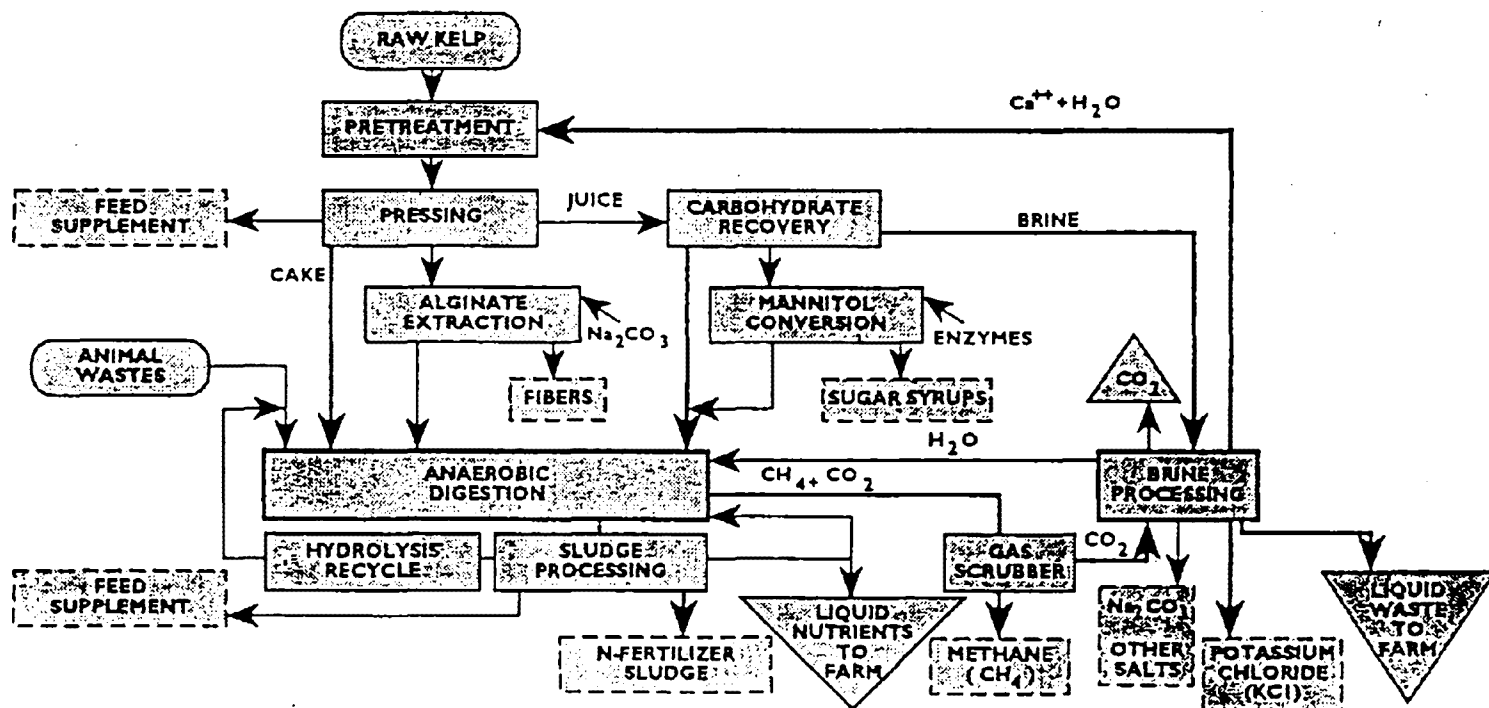


Fig. 6

## POTENTIAL OCEAN-FARM PRODUCTS

<b>Fuel Production</b> (e.g. methane, alcohols, oils)	<b>Protein</b> (e.g. invertebrate and fish cultivation)	<b>Metallic chemicals</b>
<b>Organics production</b> (e.g. acetone, organic acids)	<b>Pharmaceuticals</b>	<b>Cloud nucleation</b>
<b>Biopolymers</b> (e.g. agar, algin, carrageenan)	<b>Fertilizers and soil conditioners</b>	



## SCIENCE WATCH

# Global Warming Threat Found in Aircraft Fumes

**N**ITROGEN oxide fumes emitted by aircraft exert 30 times as great an effect on climate as the same fumes emitted at ground level by industrial processes and the burning of fossil fuels like coal and oil, British scientists have calculated.

The nitrogen oxides react with other chemicals in the air to create ozone in the troposphere, or lower atmosphere. At higher altitudes, in the stratosphere, ozone blocks ultraviolet rays from the sun that can cause cancer in humans. In the troposphere, ozone is toxic to plants and animals, and it is one of a number of tropospheric gases — carbon dioxide is the chief one — that trap heat. Many scientists believe that increases in the gases as a result of human activity will cause the earth's climate to warm substantially in coming decades.

If the growth in aircraft traffic in the 1990's continues at current rates, nitrogen oxides would result in the trapping of enough solar energy to raise the earth's temperature by about two-hundredths of a degree Fahrenheit, according to calculations by Dr. Colin Johnson of the United Kingdom Atomic Energy Authority's Harwell Laboratory and colleagues. By way of comparison, they calculated, this is about one-seventh the heating effect exerted by increased carbon dioxide emissions from 1970 to 1980.

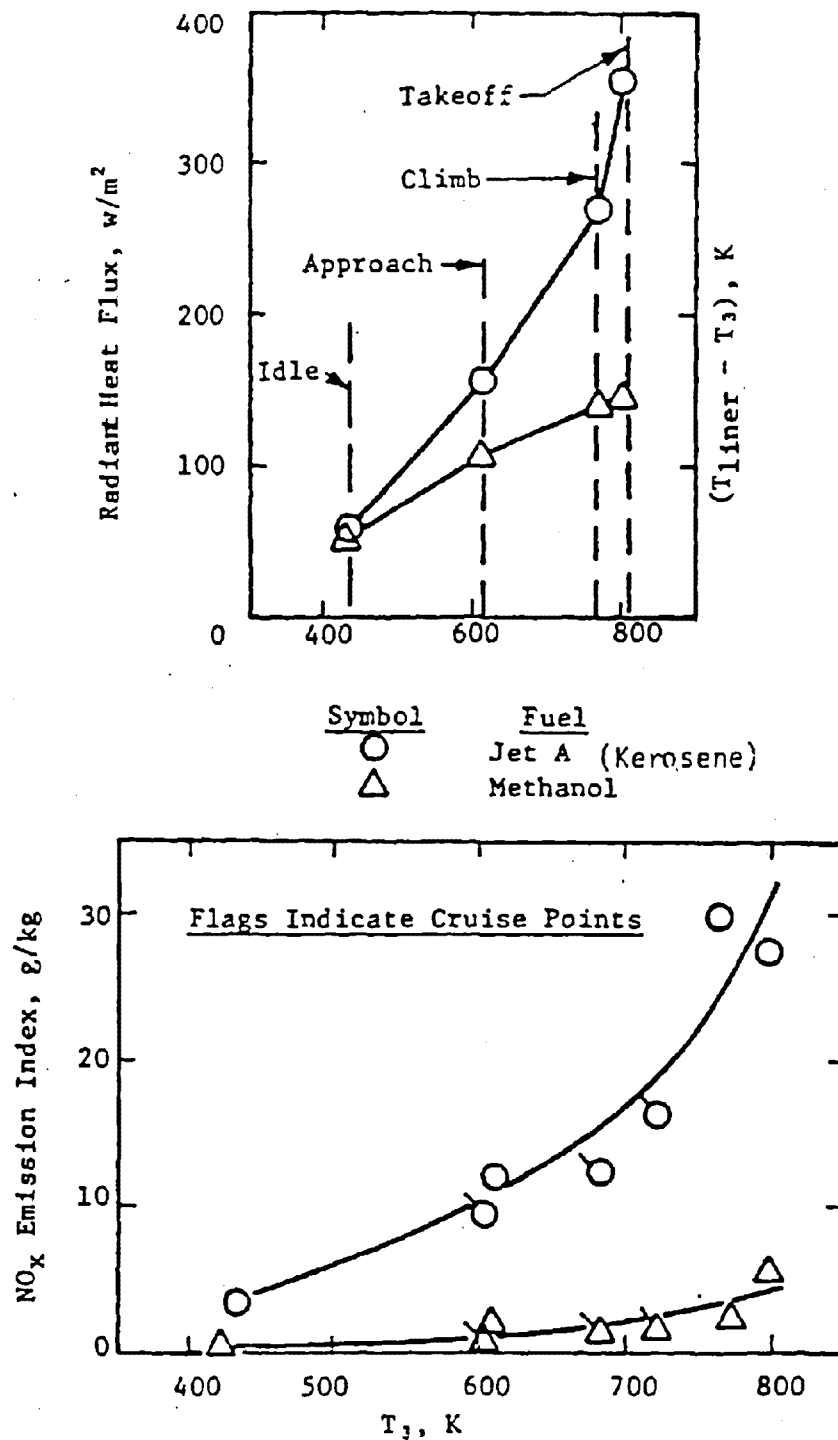
Working with a computerized model of the atmosphere, they found that nitrogen oxide emissions from aircraft contributed about as much to global warming as emissions from ground-based sources like automobiles, even though aircraft account for only 3 percent of all nitrogen oxides produced by human activity. One reason, they said in a paper in the current issue of the journal *Nature*, is that nitrogen oxides last longer when they are higher in the atmosphere.

The heating effect of ozone, carbon dioxide and all the other heat-trapping gases may be diminished or en-

hanced by a number of competing factors, scientists say. Similarly, Dr. Johnson said, the effect of nitrogen oxides is only one of a number of factors that must be considered in coming to a total understanding of the climatic effects of ozone. He pointed out, for example, that chlorofluorocarbons, industrial chemicals that also trap heat, destroy ozone, canceling out part of the total effect from all sources. Still, Dr. Johnson said, it is necessary to understand the effect of nitrogen oxide emissions aloft, since aircraft traffic is increasing.

WILLIAM K. STEVENS

Fig. 8 AIRCRAFT TURBINE HEAT AND NO<sub>x</sub> EMISSIONS



(Courtesy General Electric Company)

Table 1 MACROALGAE TYPES AND PROPERTIES

<u>Alaria</u>	<u>A. fistulosa</u> is float-bearing, arctic
<u>Corallina</u>	calcareous, widely distributed, small, might be cultured with other large species
<u>Cystoseira</u>	temperate, has float-bearing repro. struct.
<u>Ecklonia</u>	subtropic & temperate, one float-bearing sp.
<u>Egregia</u>	temperate, float-bearing, very durable
<u>Eucheuma</u>	tropic, cultivated, mod. size
<u>Gracilaria</u>	widely distrib., cultivated, high product.
<u>Laminaria</u>	intensely cultivated, temperate
<u>Macrocystis</u>	semi-cultivated, harvested, temperate
<u>Pterygophora</u>	temperate, very durable
<u>Sargassum</u>	widely distrib. incl. Sargasso Sea, many spp, float-bearing, temperate & tropic


SELECTION  
CRITERIA:

HIGH PRODUCTIVITY  
 TOLERATES FULL SUNLIGHT  
 COPPICEABLE  
 EASILY HARVESTED MECHANICALLY  
 CONDUCTIVE TO CULTURING AND TRANSPLANTING  
 REPRODUCTION PROLIFIC  
 REASONABLY TOUGH  
 GOOD POTENTIAL FOR BYPRODUCTS  
 TRANSLOCATES  
 TOLERATES WIDE ENVIRONMENTAL FLUCTUATIONS  
 GOOD YIELDS FROM FUEL CONVERSION PROCESS  
 DISEASE RESISTANT  
 SUPPORTS AN ASSOCIATED COMMUNITY OF USEFUL ORGANISMS  
 PERENNIAL AND LONG-LIVED  
 HIGH SURFACE/VOLUME RATIO  
  
 GROWS WELL AT LOW N-CONTENT  
  
 SIMPLE NUTRIENT REQUIREMENTS  
  
 HIGH UPTAKE RATES  
  
 SURVIVES IN HIGH-ENERGY ENVIRONMENTS  
  
 EASILY MOORED OR RESTRAINED

Table 2

TECHNICAL ISSUES

Biology

- 
- 1) Raising the plant productivity (and maximizing the carbon/nitrogen ratio) through nutrition management, species selection, stock refinement and genetic engineering.
  - 2) Investigating the extent of methyl halide releases during the candidate-plant growth and decay phases.
  - 3) Developing economical and dependable shipboard nursery techniques.
  - 4) Selecting the optimum ocean current settings for farm nutrition, storm minimization, traffic avoidance and market access (see Fig. 3).
  - 5) Achieving an economical and environmentally-acceptable combination of nutrient recycling, low-speed towing, artificial upwelling and possible submersion for plant nutrition.
  - 6) Reducing the incidence of marine fouling of the farm structures and servicing vessels.
  - 7) Increasing the efficiency (cu.ft.methane/kg.solids) of shipboard anaerobic digestion.
  - 8) Reducing the plant and farm-structure drag to minimize the towing power requirements.
  - 9) Determining the engineering and economic feasibility of farm submergence to reduce storm damage and increase nighttime nutrition.
  - 10) Selecting or developing the optimum farm-element plastics -- including the use of recycled plastics and the shipboard shaping of farm expansion or replacement elements.

Engineering

Table 3

Possible Positive Feedbacks from Global Warming

A. General

1. Increased evaporation persisting as water vapor or low-reflection clouds
2. Increased release of CO<sub>2</sub> and possibly CH<sub>4</sub> from accelerated aerobic and anaerobic digestion of dead organisms
3. Possible release of CO<sub>2</sub> and CH<sub>4</sub> from hydrate deposits
4. Reduced absorption of anthropogenic CO<sub>2</sub> due to general heat-induced reduction of plant growth
5. Reduced snow cover and reflectivity

B. Additional Ocean-Related Possibilities

1. Direct release of dissolved CO<sub>2</sub> through increased ocean temperatures
2. Indirect release of dissolved CO<sub>2</sub> through violent wave action in intensified storms

# The Role of DOE Energy Efficiency and Renewable Energy Programs in Reducing Greenhouse Gas Emissions

Eric Petersen, Director  
Division of Applied Analysis  
Office of Conservation and Renewable Energy  
U.S. Department of Energy



# **U.S. Commitment to Global Climate Change Mitigation**

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- U.S. committed to aggressive, but economically sound, programs to reduce GHG emissions
- Commitment articulated in *U.S. Views on Climate Change*
- Major focus of the U.S. approach is energy:
  - improving the efficiency of energy conversion and consumption
  - switching away from relatively carbon-intensive fuels
  - eliminating CFCs in energy-using equipment

## **Federal Mechanisms to Achieve Energy GHG Reductions**

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- Administration comprehensive National Energy Strategy
- EPA voluntary conservation programs
- DOE programs in energy conservation and energy efficiency, renewable, nuclear and fossil energy technology R&D

# What is CE?

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The mission of the Office of  
Conservation and Renewable Energy

*Develop and promote the adoption of cost-effective renewable energy and energy efficiency technologies and practices, in conjunction with the states and with partners in the buildings, industrial, transportation, and utility sectors, for the benefit of the economic competitiveness, energy security, and environmental quality of the Nation.*

# CONSERVATION AND RENEWABLE ENERGY

## Yesterday and Today

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### Yesterday:

- CE research and development focused on long-term, high risk activities.
- Office structure not effectively responsive to needs of the changing market sectors.

### Today:

- CE program offices reorganized to better interact with and respond to the four market end use sectors: **Utilities, Buildings, Industry, and Transportation.**
- The Office of Technical and Financial Assistance created to promote CE technologies and work with the States.
- Strong emphasis is placed on *increasing productivity and enhancing competitiveness.*
- Development of *public/private partnerships* is a *top priority.*

# Options in the Building Sector

## SUPPLY

### Primary Fuels

Renewables

Oil, Gas  
Coal  
Nuclear

Natural  
Gas

Petroleum

### End-Use Fuels

Steam &  
Waste Heat

Electricity

Propane

Fuel Oil

## DEMAND REDUCTION

Efficient Lighting & Appliances  
Advanced Windows & Glazings  
Improved Heating/Cooling Equipment  
Building Standards/FEMP

Heating  
Cooling  
Lighting

# Quality, Affordable Housing

## Current Situation

### Energy

Average home uses >100 MMBtu/Yr  
(> 15 quads total)  
60% heating and cooling  
23% lighting and appliances

### Environment

60 pounds of SO<sub>2</sub>/year/house  
3400 pounds of CO<sub>2</sub>/year/house

New homes and appliances  
use 100 million lbs CFCs/Yr.

Construction wastes  
(2.5 tons/house)

### Technology

On-site, "Stick" built with  
limited quality and high waste  
Non-integrated, non-optimized  
HVAC, appliances, and controls

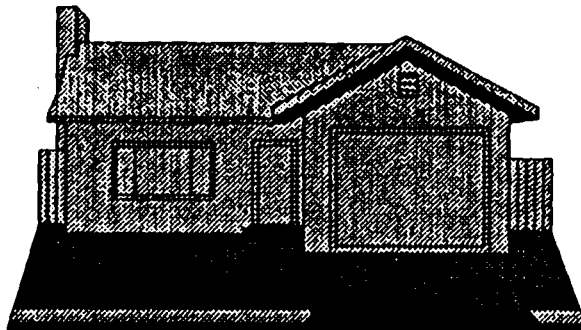
### Productivity

Construction output/hour  
down 1.7%/yr, while manufac.  
output up 2.7%/yr

\$8 billion/year trade deficit  
in building components

Energy costs per house:  
\$1200/Year

Median new home price rising  
50% faster than earnings/worker



## Objectives

### Energy

Over 50% reduction in  
energy requirements:  
Reduction in new home heating  
and cooling energy by 2/3  
100% efficiency improvement  
lighting and appliances

### Environment

Carbon emissions from home  
energy use down over 50%  
Elimination of CFC/HCFCs in  
new homes and appliances

### Technology

Integrated, optimized  
buildings designed and built  
in an industrialized system  
HVAC load reduced 50%  
with advanced windows,  
insulation, and design

### Productivity

Housing industry  
productivity gains  
comparable to manufacturing

Reverse trade deficit:  
High-value building products  
for export

Household energy costs cut  
by 50% in new homes

## Initiatives

Century 21 Design,  
Manufacturing and Delivery

Improve Shell Technologies

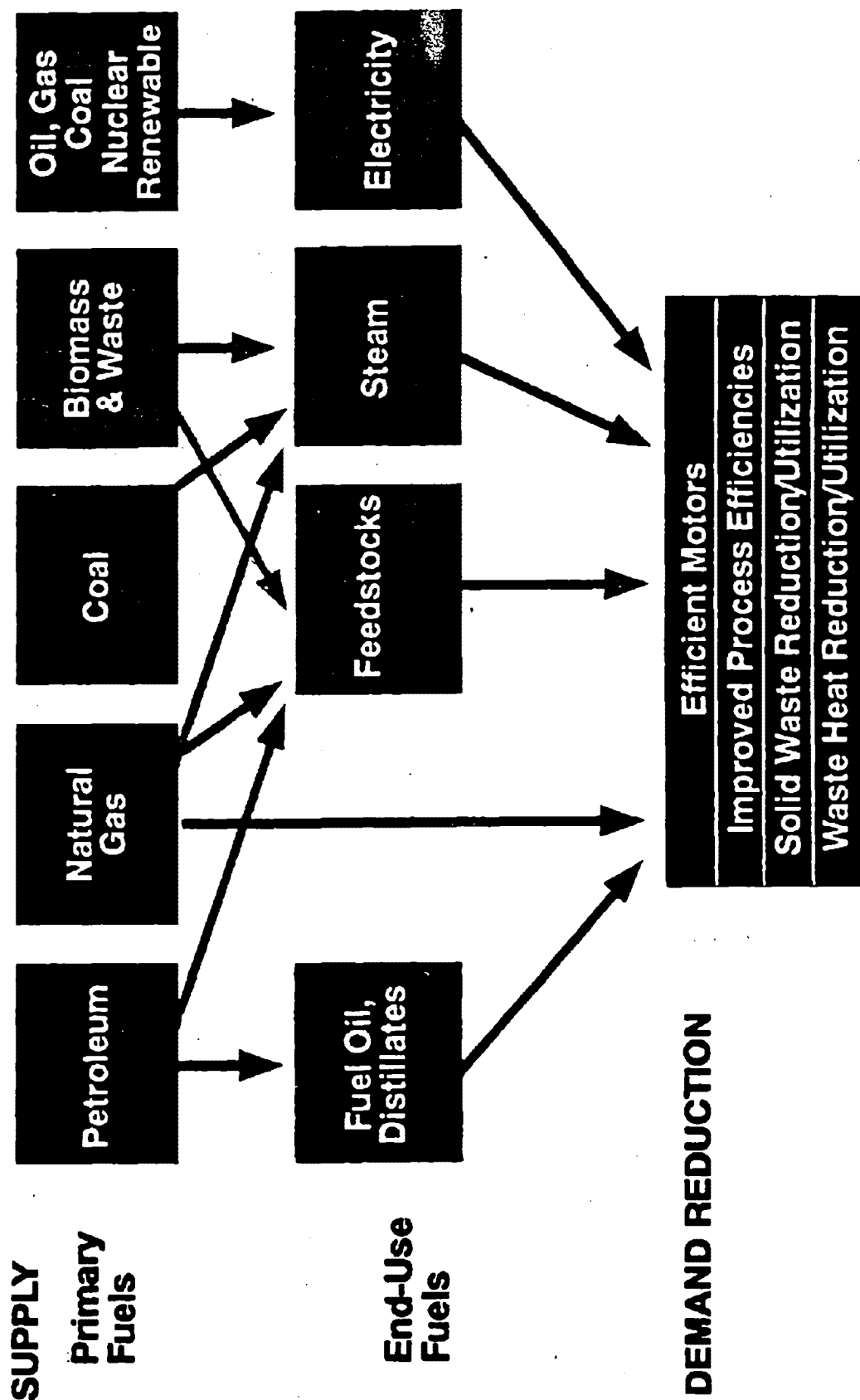
Advanced HVAC/Appliances

Advanced Lighting Technologies

On-Site Power from Fuel  
Cells and PV

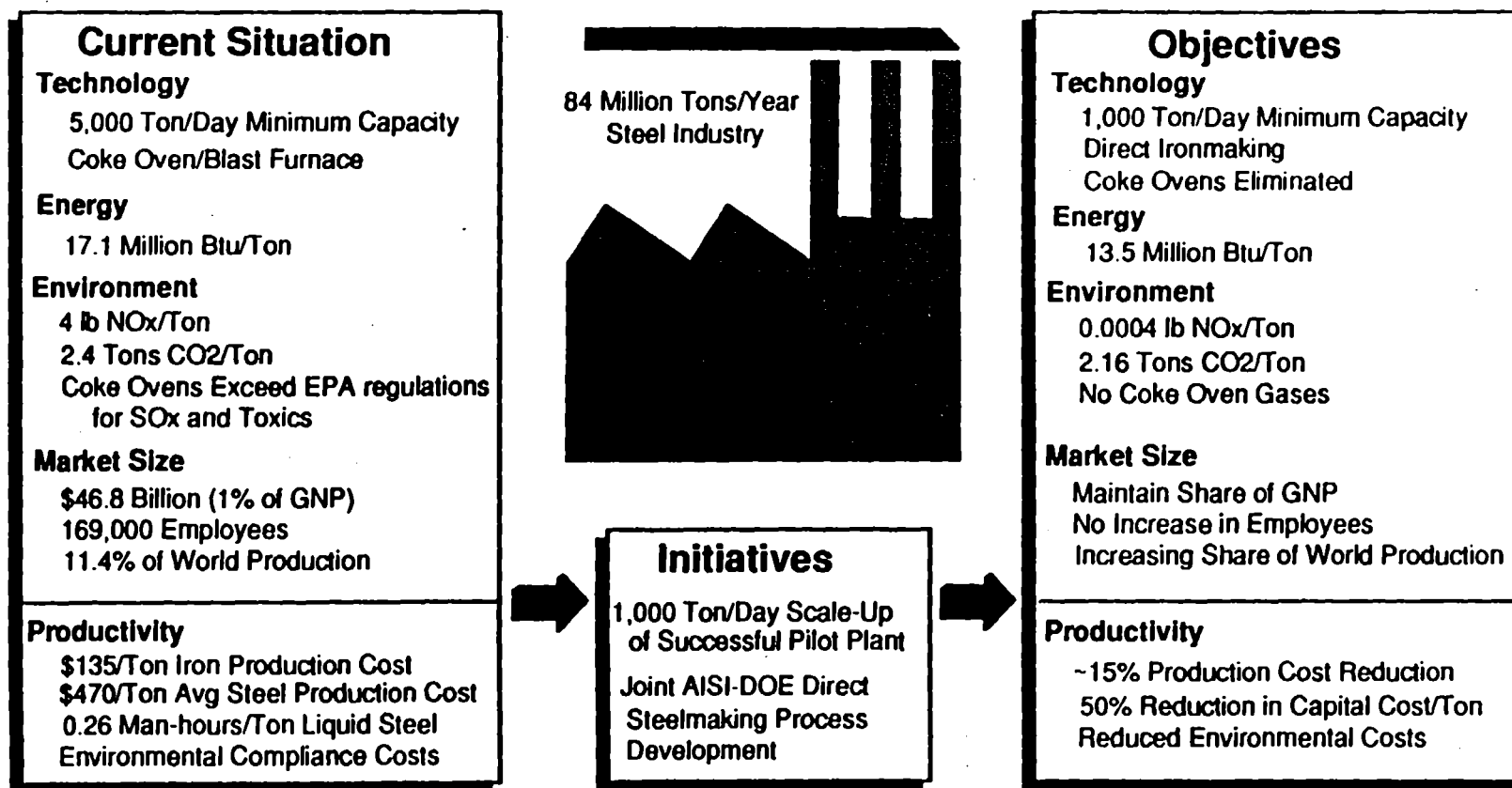
Energy-Efficient Mortgages/  
Home Energy Rating Systems

# Options in the Industrial Sector



# Direct Steelmaking

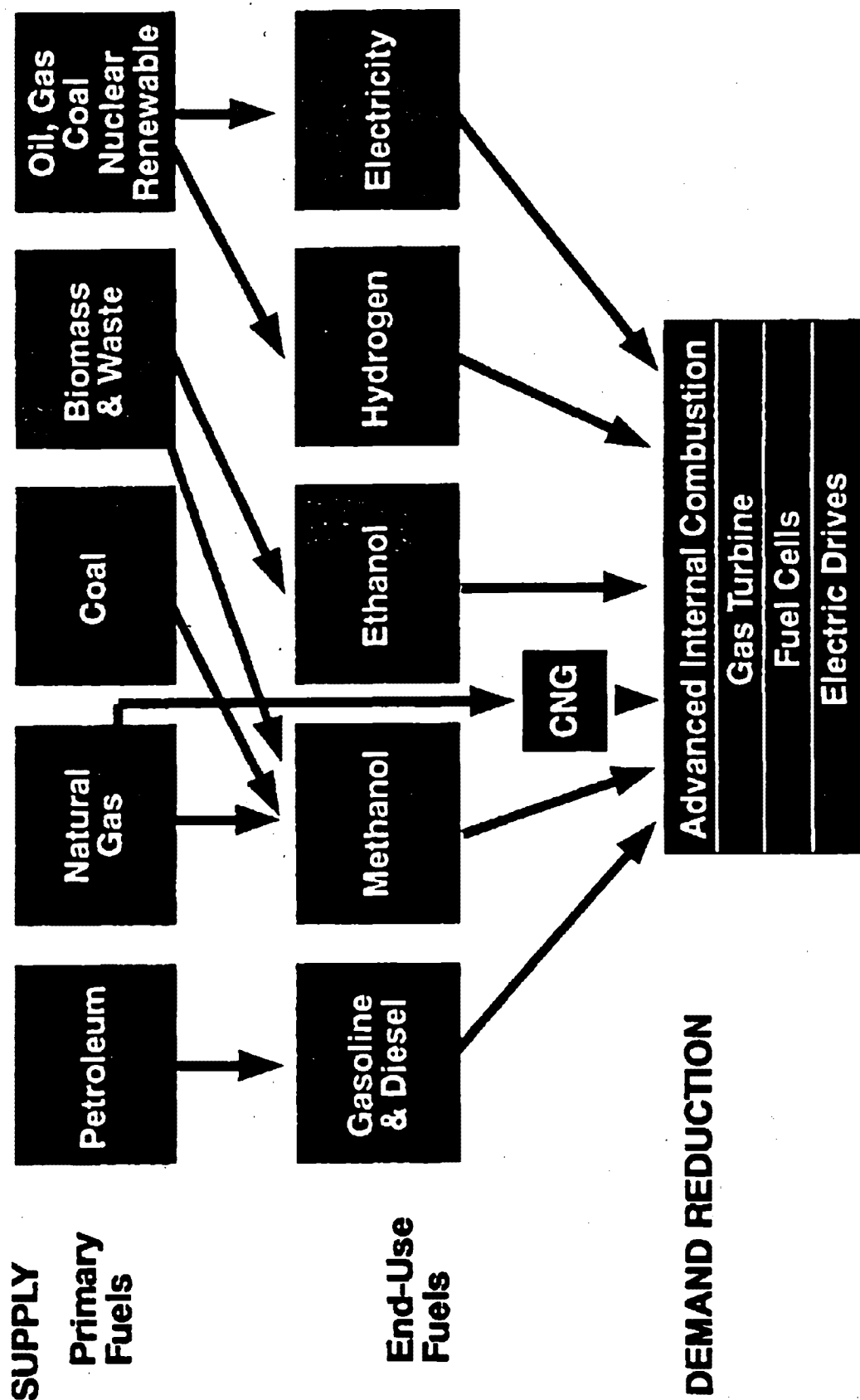
3-50



Sources: Energetics, Inc., "Energy Profiles for US Industry: Iron and Steel Industry Profile," December 1990; US Department of Commerce, Statistical Abstract of the United States 1991; 1989 AISI Statistical Abstract; Paine Webber, World Steel Dynamics service; and Office of Industrial Technologies estimates.



# Options in the Transportation Sector



# Advanced Light Duty Vehicles

## Current Situation

### Energy

- 8,095 Btu/Vehicle Mile
- 100% Petroleum

### Environment

- 0.54 Grams/Mile VOC
- 0.8 Grams/Mile NOx
- .35 lb/mile carbon

### Vehicle Characteristics

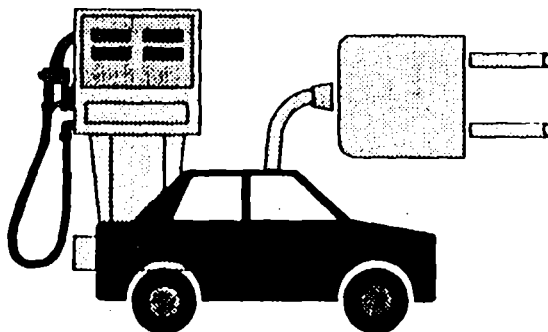
- Typical 3,500 pound, 5-passenger, Mid-Sized

### Market Size

- 71% of US Auto Market Made in U.S.
- 24% of World Auto Market Made in U.S.
- \$344 Billion (8% of GNP)
- 4,108,000 Jobs

### Productivity

- 41 ¢/mile Operating Cost
- 5.1 Million Barrels/Day from Imported Petroleum



## Initiatives

- Battery Research
- Fuel Cell Technologies
- Hybrid Propulsion Systems R&D
- Ceramics in Engines
- Gas Turbine Technology
- Engine Optimization
- Lightweight Materials
- Bioethanol Production Research
- AMFA
- Alternative Fuels Data Center

## Objectives

### Energy

- 2,090 Btu/Vehicle Mile
- 100% Alternate Fuels, Ethanol, Methanol, Natural Gas, Hydrogen

### Environment

- Zero Emissions First 60 Miles
- Remainder of Range: 0.04 Grams/Mile VOC, 0.2 Grams/Mile NOx, Reduction of carbon emissions 80-100%

### Vehicle Characteristics

- 2,500 Pound Vehicle Avg.
- Comparable Performance

### Market Size

- 90+% of U.S. Auto Market Made in U.S.
- 30+% of World Auto Market Made in U.S.

### Productivity

- Comparable Cost
- ~100% LDV Fuel from Domestic Sources

# Options in the Utility Sector

## SUPPLY

### Primary Fuels

Natural  
Gas

Petroleum

Coal

Nuclear

Renewables  
Wind  
Solar Thermal  
Geothermal  
Photovoltaics  
Biomass/MSW  
Hydropower

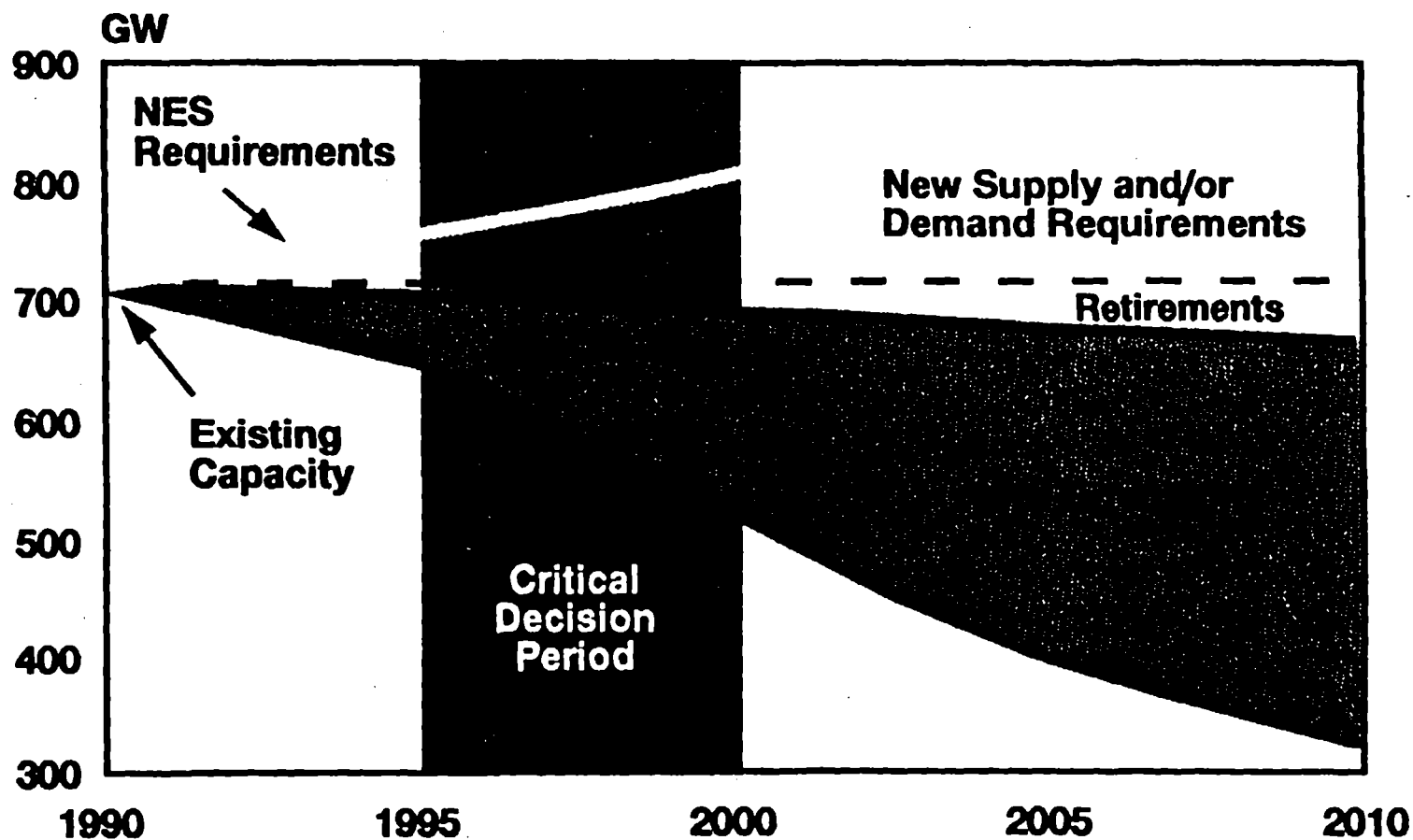
### End-Use Fuels

Electricity

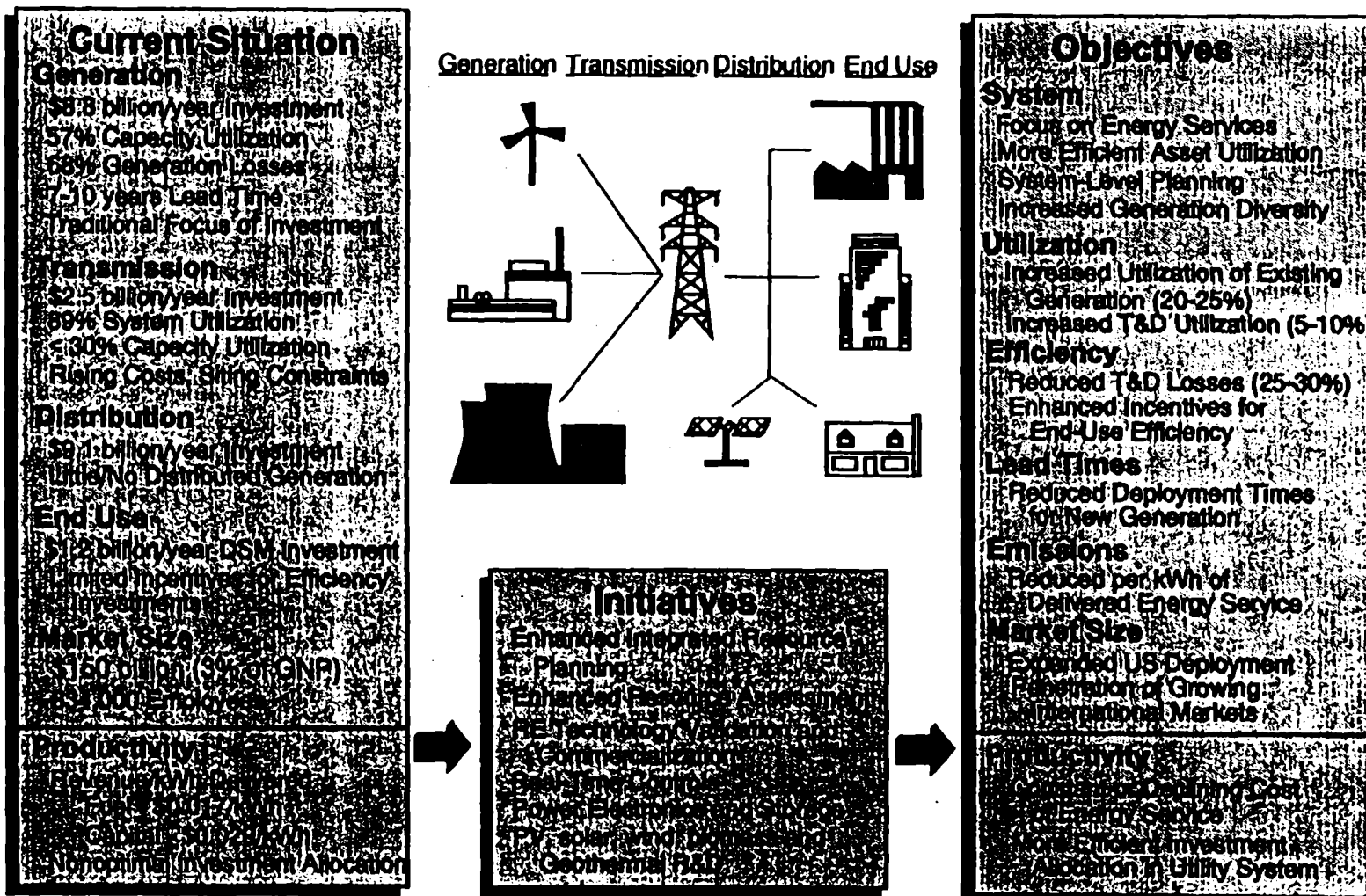
## DEMAND REDUCTION

DSM/IRP Strategies
Advanced Battery/Thermal Storage
Improved T&D Systems
High Temperature Superconductivity

# U.S. Electric Generating Capacity Trends (National Energy Strategy)



# Electric Utility System



Sources: EEI Electric Utility Statistics (1991), NERC 1990 Reliability Assessment (1990), Electric Sales and Revenue 1990 (1992), EIA Annual Electric Outlook (1991), Electric Light and Power (Apr. 1, 1991), Annual Energy Review 1990 (1991), EIA Electric Power Monthly (April 1992)

# Wind Energy Program

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- **Market Status**
  - 1500 MW of capacity, 2.5 billion kWh
  - understanding of wind forces and resources
  - rotor durability issues
- **On verge of a major market breakthrough**
  - costs down by two thirds in the last decade to \$0.08 per kWh
  - modular units allow incremental additions with short lead times
  - zero emissions
  - renewable energy production credit in H.R.776
- **DOE wind energy program major thrusts**
  - development of wind systems with lower costs and greater reliability with industry collaboration
  - assisting utilities in evaluation of wind power potential
- **Market Potential**
  - 1.0 to 2.3 quads in 2010; 2.9 to 10.7 quads in 2030 (SERI 1990)
  - estimated low-end carbon savings 16 MMT in 2010, 48 MMT in 2030

# **Transferring CE Technology to the Marketplace**

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CE energy efficiency and renewable energy programs incorporate means to effectively transfer technologies to the marketplace.

Wide variety of mechanisms used:

- financial partnerships with private industry in technology R&D
- CRADAs between DOE laboratories and private industry
- user facilities for private industry testing of new technologies
- demonstration of new technologies in federal facilities
- interaction with trade and professional associations
- establishment of industry advisory groups
- publications
- education programs

Some mechanisms (CRADAs) used across all programs, others are applied as appropriate

# **BUILDING PUBLIC/PRIVATE PARTNERSHIPS**

## **A New Era In Cooperative Leadership**

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### **National Technology Initiative**

In the fall of 1991, President Bush launched a new Administration-wide initiative to promote U.S. industry's use of technology to strengthen the domestic economy and enhance competitiveness in global markets -- the National Technology Initiative (NTI).

As President Bush said, there are

"...steps we can take right now to guarantee progress and prosperity into the next American Century. We get there by investing in the technologies of tomorrow, with Federal support of R&D at record levels. We need to share the results, get the great ideas generated by public funds out into the private sector, off the drawing board and onto store shelves. Our National Technology Initiative will do just that...."



## **Building Public/Private Partnerships A New Era in Cooperative Leadership (continued)**

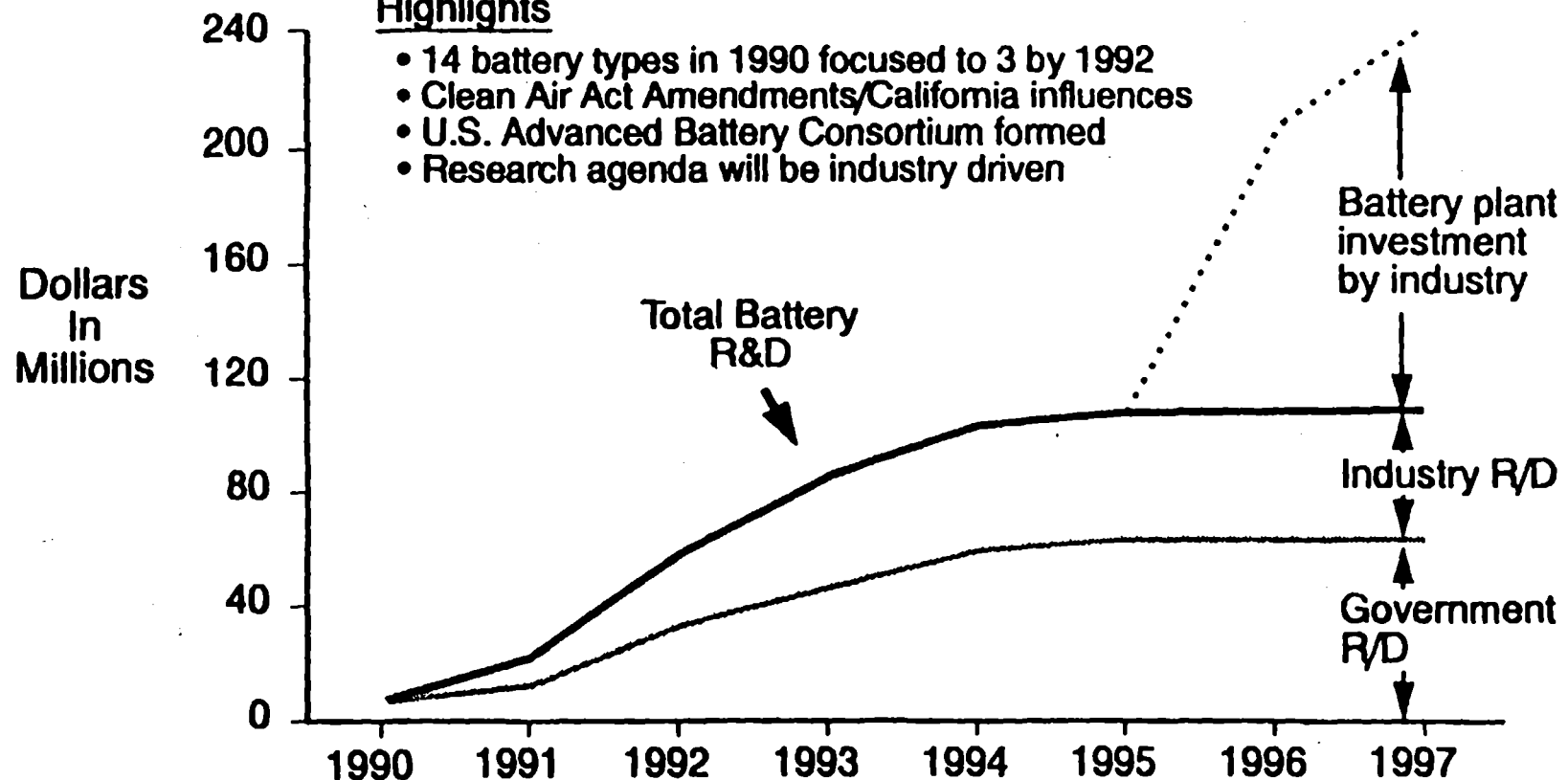
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- Since the launching of NTI in late 1991, CE has entered into about 50 CRADAs, that could lead to the commercialization of energy efficiency and renewable energy technologies
- Examples CRADAs with significant GHG emissions reduction potential:
  - waste minimization technology to reduce the use of CFC-based solvents (Motorola)
  - waste paper to methanol conversion process (AMOCO)
  - battery development under the U.S. Advanced Battery Consortium (Auto industry)

# Government Industry Battery Cost Sharing R&D

## Highlights

- 14 battery types in 1990 focused to 3 by 1992
- Clean Air Act Amendments/California influences
- U.S. Advanced Battery Consortium formed
- Research agenda will be industry driven



# LOOKING FORWARD

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## **Strong support for Energy Efficiency and Renewable Energy:**

- The FY 1993 funding request of \$330 million for energy efficiency R&D is double the funding for FY 1989 when the Bush Administration took office.
- The FY 1993 funding request of \$250 million for Renewable Energy R&D is more than 65% higher than the FY 1989 funding.
- President Bush established the National Renewable Energy Laboratory in September 1991. Construction of a \$20 million, state-of-the art Solar Energy Research Facility began in June 1992.

## **The National Energy Strategy: A Continuing Process**

- The NES will continually evolve and be refined as new opportunities and technological advances emerge.
- Development of NES II is underway.

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

**FUZZY LOGIC CONTROL OF AC INDUCTION MOTORS  
TO REDUCE ENERGY CONSUMPTION**

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**ABSTRACT**

Fuzzy logic control of electric motors is being investigated under sponsorship of the U.S. Environmental Protection Agency (EPA) to reduce energy consumption when motors are operated at less than rated speeds and loads. Electric motors use 60% of the electrical energy generated in the U.S. An improvement of 1% in operating efficiency of all electric motors could result in savings of  $17 \times 10^9$  kWh/yr in the U.S. New techniques are required to extract maximum performance from modern motors. This paper describes EPA's research program, as well as early stages of work, to implement fuzzy logic to optimize the efficiency of alternating current (AC) induction motors.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

## INTRODUCTION

Electric motors use over 60% of the electrical power generated in the U.S. [1]. There is a population of approximately 1 billion motors in the country, using over 1700 billion kWh per year. Over 140 million new motors are sold each year. A review of the U.S. motor population reveals:

- 90% of the motors are less than 1 hp\* (fractional motors) in size, but use only 10% of the electricity consumed by motors;
- 95% of the electricity used by motors is consumed by approximately 2% of the motor population (motors greater than 5 hp); and
- 85% of the electricity used by motors is consumed by less than 1% of the motor population (motors greater than 20 hp).

Based on these facts, it is clear that large energy savings from improvement in motor efficiency could be achieved with a relatively small motor population. Each 1% improvement in motor efficiency could result in:

- 17 billion kWh per year of electrical energy saved;
- over \$1 billion in energy costs saved per year;
- an equivalent of 6 -10 million tons\*\* per year of uncombusted coal; and
- approximately 15 to 20 million tons less carbon dioxide released into the atmosphere.

AC induction motors have high reliability and low cost and therefore perform over 80% of the motor tasks in the U.S. Their speed of operation is determined by the frequency of the input power, and their efficiency is low when operating at part load. To control the speed of an AC induction motor and thereby match motor speed to load requirements requires the use of a device called an adjustable-speed drive (ASD). Significant energy efficiency gains are achieved when induction motors are controlled by ASDs [2]. ASDs use semiconductors and switching circuits to vary the voltage or current and frequency of a motor's power supply thereby controlling the applied torque and speed to satisfy the process or load requirements [2]. ASDs are

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\*1 hp = 746 W<sub>e</sub>

\*\*1 ton = 907 kg

basically power electronic devices consisting of a rectifier and a computer-controlled inverter. The rectifier converts the standard 60 Hz AC to direct current (DC). The inverter then converts the DC output of the rectifier to a variable-frequency, variable-voltage/current AC.

While ASDs can minimize power losses, they do not optimize operations for maximum efficiency. The goal of this program is to utilize the inherent capabilities of fuzzy logic set theory in an integrated intelligent energy optimizer in conjunction with an ASD to improve the energy or power efficiency of electric motors, primarily AC induction motors, while at the same time meeting the demands of the process equipment and load operations which are driven by the motors. Fuzzy logic has the proven ability to represent complex, ill-defined systems that are difficult or impractical to model and control by conventional methods [3]. In addition, fuzzy logic is a form of artificial intelligence that can be implemented in an integrated electronic circuit device or microchip. This ability is especially important in the case of the modification, or retrofitting, of existing electric motors, since microchips can be readily added through an add-on circuit board to existing ASD drives and require little additional electric power for their operation.

#### FUZZY LOGIC ENERGY OPTIMIZER

Figure 1 is a block diagram of the overall control approach. A fuzzy logic energy optimizer is used to control the ASD which in turn controls the motor. A feedback signal, usually motor speed, from the motor is shown by the dashed line in the figure to indicate that the control scheme may be open-loop (no feedback) or closed-loop (feedback).

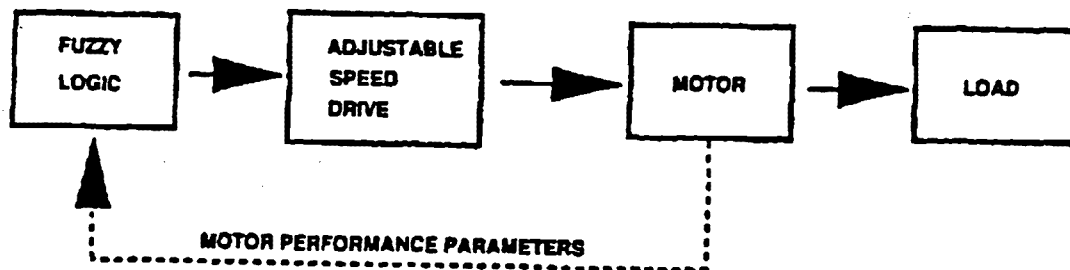


Figure 1. Fuzzy Logic Energy Optimizer for Improved Energy Efficiency

A motor drive (ASD) may be controlled according to a number of performance functions, such as input power, speed, torque, airgap flux, stator current, power factor, and overall calculated motor efficiency. Normally in a drive system, the

machine is operated with the flux maintained at the rated value, or with the voltage to frequency ratio (V/Hz) held essentially constant in relation to the value at rated conditions. This allows speed control with the best transient response. The constant V/Hz approach is used wherever actual shaft speed is not measured; i.e., in open-loop speed control. The open-loop control approach is most effective when applied to industry applications that do not require tight or accurate process control such as pumps or blowers. The computer simulated results presented in this paper are based on the open-loop control approach.

A fuzzy logic energy optimizer is also being developed for the closed-loop situation which permits precision speed control. Additionally, work is proceeding on the development of a fuzzy logic energy optimizer for the most advanced control scheme known as closed-loop speed control with indirect vector control. This scheme performs efficiency optimization control without sacrificing transient response. This is very important for high performance applications such as electric vehicles.

For all the control methods the optimization approach proceeds as follows. The input power is measured and then the control variables (input voltage, input current, or input frequency) are varied from the initial setting. The input power is measured again and compared with the previous value. Based on the sign and magnitude of the input power signal, as well as the value of the last change in the control variable, a new value for the control variable is computed using the fuzzy logic energy optimizer. Sequential decrementation/incrementation is continued until the minimal input power level is reached. This is the operating point for best efficiency for the particular load torque and speed condition. If a speed increase is demanded or the load torque increases, the flux can be established to full value to get the best transient response. When the new steady-state condition is attained, the fuzzy logic efficiency optimization search begins again to obtain the most energy efficient operating point.

Figure 2 is a conceptual flow diagram illustrating details of the fuzzy logic energy optimizer which is contained within the dotted lines. Detailed explanation for each block of the fuzzy logic energy optimizer is beyond the scope of this paper. It suffices to say that the basic underlying principle of operation relies on the fuzzy rule base consisting of several linguistic IF-THEN rules. A suitable rule base for the open-loop situation is illustrated below. Additional information on the fuzzy logic concepts contained in Figure 2 can be found elsewhere [3]. The database includes the necessary information regarding the motor parameters or other pertinent data. The "fuzzification" stage is where the process measurements are usually represented as fuzzy singletons, such as big, medium, and small. The "defuzzification" stage is where fuzzy outputs are typically converted to real numbers. The most common procedure for this conversion is the center-of-area method, much like that used for calculating

centroids of various combined areas. The computation unit represents microprocessor functions for interfacing and recalculation.

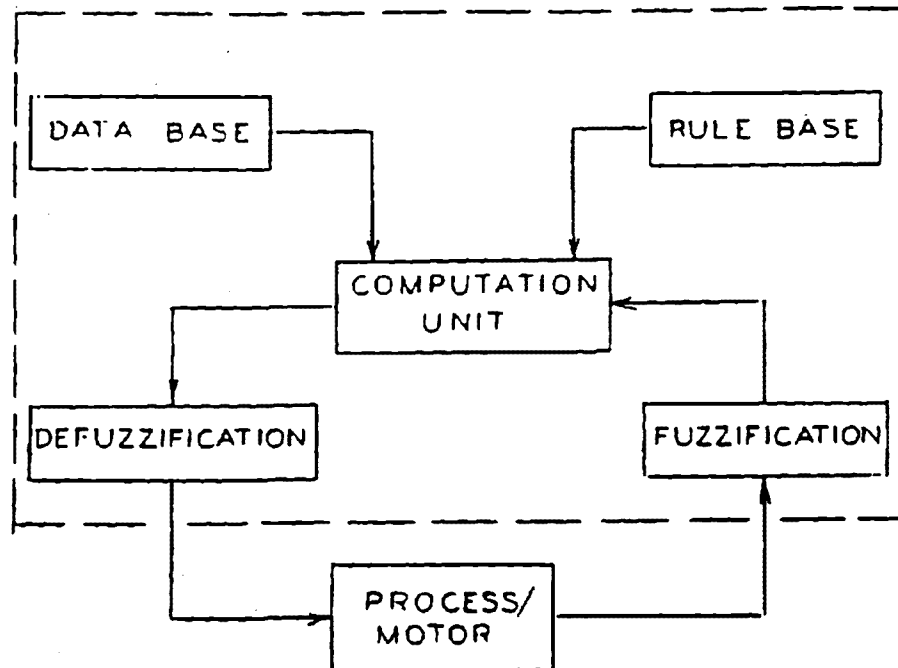


Figure 2. Block Diagram of the Fuzzy Logic Energy Optimizer

### SIMULATED PERFORMANCE

The preliminary open-loop fuzzy logic controller [4] was demonstrated by computer simulation. The control variable was the input voltage. Results show improvement in motor efficiency using fuzzy logic control while maintaining good performance in other areas; e.g., maintaining desired torque and speed at steady levels. For example, Figure 3 compares the efficiency of a motor over a broad range of loads and operating under both conventional constant V/Hz control and fuzzy logic control. The load torque relation to rotor speed simulates the behavior of pump or fan loads, where load torque is proportional to the square of the rotor speed. Efficiency improvement by the fuzzy logic energy optimizer was achieved for all speed/torque combinations.



The following rule base was used for the calculation. Three fuzzy sets (N standing for negative, P for positive, and Z for zero) were chosen to relate the fuzzy variables, along with the simple set of rules:

1. IF  $\Delta P_{in}$  IS N AND  $\Delta V_{old}$  IS N, THEN  $\Delta V_{new} = N$ .
2. IF  $\Delta P_{in}$  IS N AND  $\Delta V_{old}$  IS P, THEN  $\Delta V_{new} = P$ .
3. IF  $\Delta P_{in}$  IS P AND  $\Delta V_{old}$  IS N, THEN  $\Delta V_{new} = P$ .
4. IF  $\Delta P_{in}$  IS P AND  $\Delta V_{old}$  IS P, THEN  $\Delta V_{new} = N$ .
5. IF  $\Delta P_{in}$  IS Z AND  $\Delta V_{old}$  IS ANY, THEN  $\Delta V_{new} = Z$ .

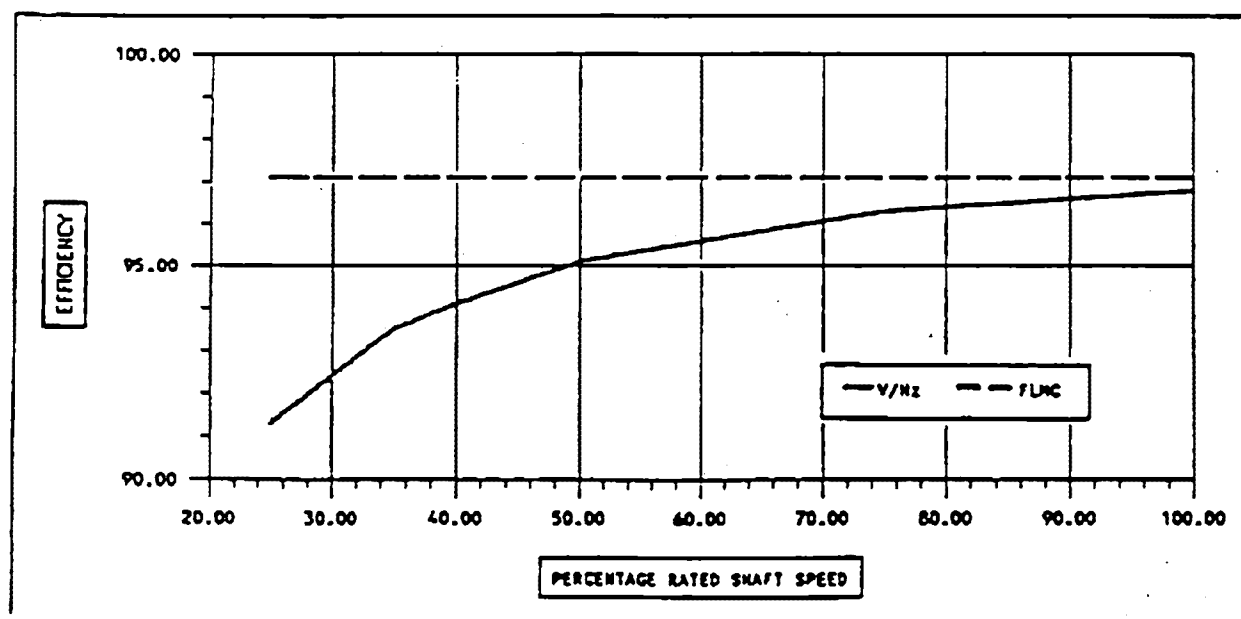


Figure 3. Fuzzy Logic Control Compared with V/Hz Control for a 100 HP Motor with Torque Proportional to Speed Squared

Rule 5 is needed for convergence on an optimum input power; i.e., the point where any small change in voltage results in negligible change in input power. The quantities  $V_{old}$  and  $V_{new}$  represent old and new values, respectively, for the control variable (input voltage) as the optimization approach proceeds to minimize the input power. The change in input power level is designated by  $\Delta P_{in}$ . To allow adjustment of step size (for faster convergence with no overshoot), additional linguistic variables (e.g.,

positive medium, PM, and negative medium, NM) were added. A set of 13 rules was found to be adequate to relate the variables for the simple control problem.

## CONCLUSION

Computer simulated results for the open-loop controller show that the fuzzy logic energy optimizer can significantly enhance the operational efficiency of AC motors. Future computer simulation developments will include a closed-loop controller with a dual-variable (voltage and frequency) fuzzy logic energy optimizer. Additional effort is taking place to provide fuzzy logic efficiency optimization for induction motors which use indirect vector control.

Initial results further indicate that fuzzy logic energy optimizers can, in a collective sense, consistently improve motor operational efficiency over conventional speed control techniques (ASDs) by increments of 1 to 4%. This is highly significant in terms of potential U.S. energy savings and pollution abatement possibilities. Figure 4 illustrates potential improvements based on conservative estimates of overage energy savings for the motor classes indicated on the figure and typical coal-fired power plant heat rates and emissions. The addition of a fuzzy logic energy optimizer microchip to a 100 hp motor and ASD should result in energy savings amounting to a cost payback within 3 to 5 months.

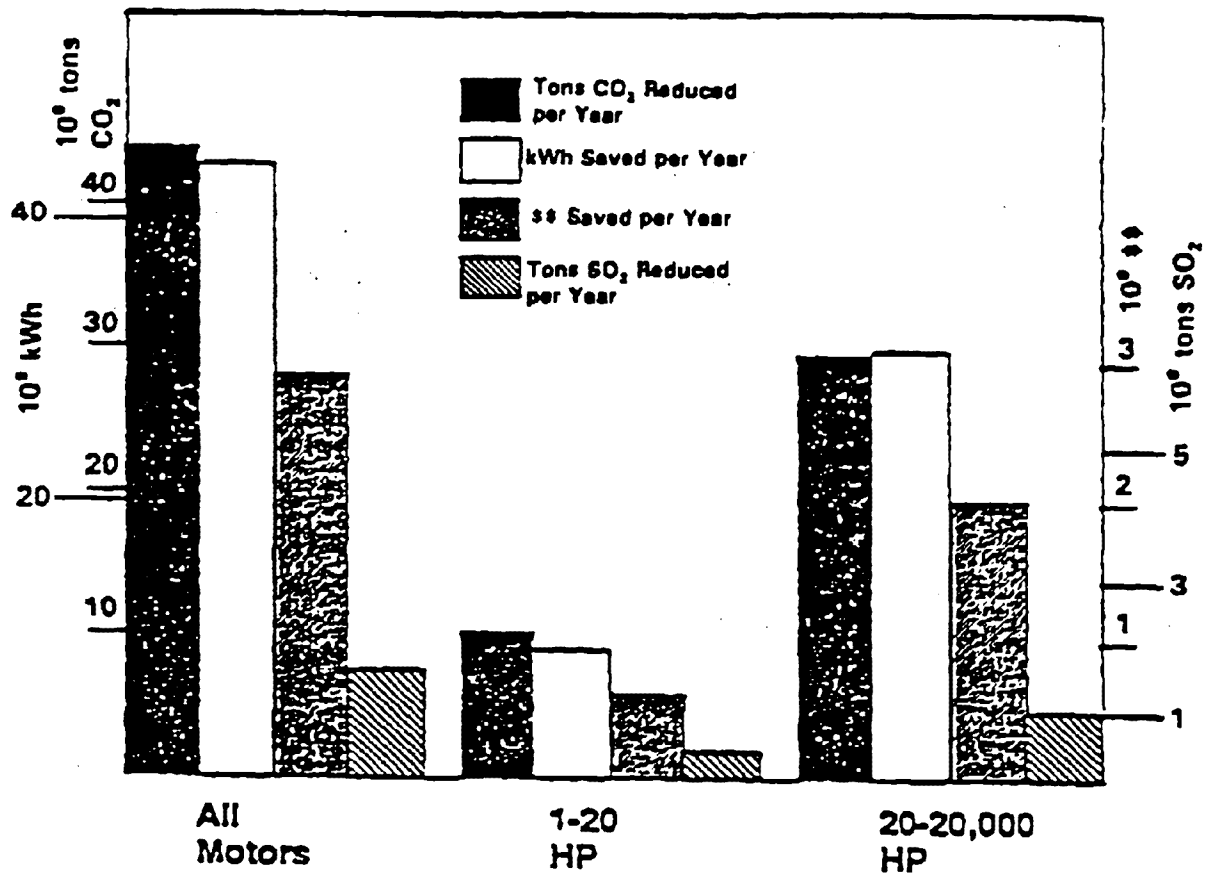


Figure 4. Projected Collective Savings from Fuzzy Logic Motor Control for Improved Efficiency

Once these optimizers have been thoroughly developed using computer simulation models, prototype hardware devices will be tested in the laboratory. A block diagram of the motor testing facility is shown in Figure 5. The motor output power is measured using the dynamometer, and the 3-phase input power is measured with high precision wattmeters. This configuration allows the motor/drive efficiency to be determined. A personal computer (PC) microprocessor will monitor the data acquisition systems and communicate with the ASD to alter the ASD voltage and frequency output. Various degrees of load on the motor are achieved by varying the strength of the field in the DC brake via the dynamometer.

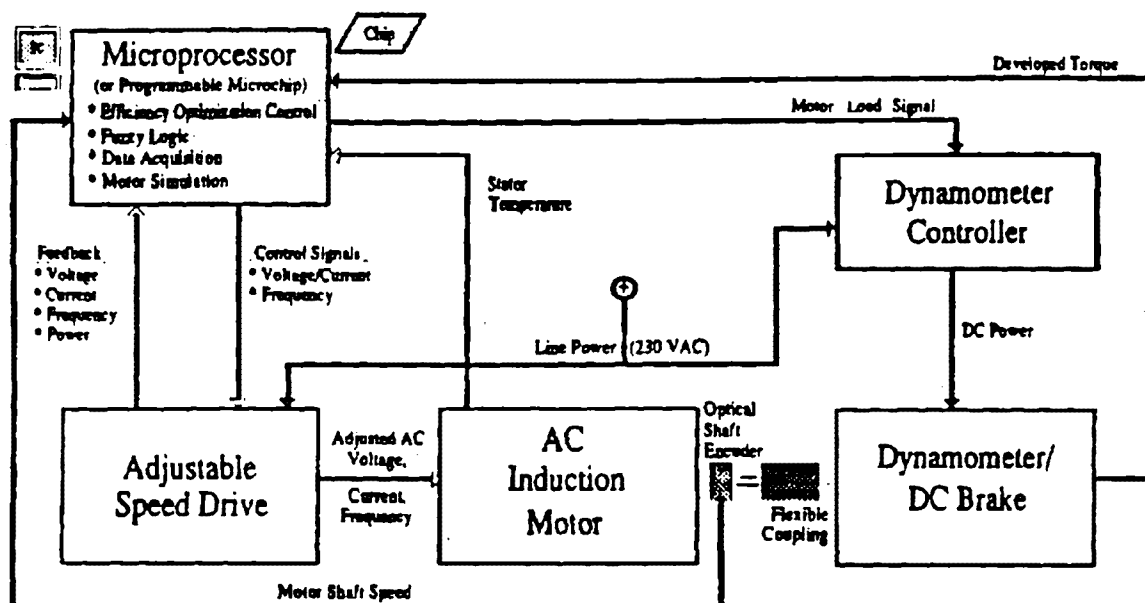


Figure 5. Block Diagram of the Motor Testing Facility

After laboratory testing has been completed, extensive field testing will be undertaken in an industrial setting.

#### REFERENCES

1. Baldwin, S.F., Energy Efficient Electric Motor-Drive Systems. From Electricity. Johansson, T.B., Bolund, B., and R.H. Williams, eds. Lund University Press. 1987.
2. Bose, B.K., Adjustable Speed AC Drives - A Technology Status Review. Proc. IEEE, Vol. 70, No. 2, pp. 116-135. Feb. 1982.
3. Kevin, S., Designing with Fuzzy Logic, IEEE Spectrum, pp. 42-44, Nov. 1990.
4. Cleland, J., Turner, W., Wang, P., Espy, T., Chappell, J., Spiegel, R., and Bose, B., Fuzzy Logic Control of AC Induction Motors, IEEE International Conf. on Fuzzy Systems, San Diego, CA, Mar. 1992.

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

# **METHANOL PRODUCTION FROM WASTE CARBON DIOXIDE**

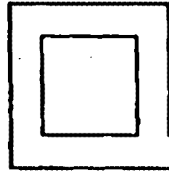
**Presented to  
Symposium on  
Greenhouse Gas Emissions  
Mitigation Research**

**August 1992**

**By Stefan Unnasch  
Acurex Environmental**

0830-70101M-1

**Acurex  
Environmental**  
CORPORATION

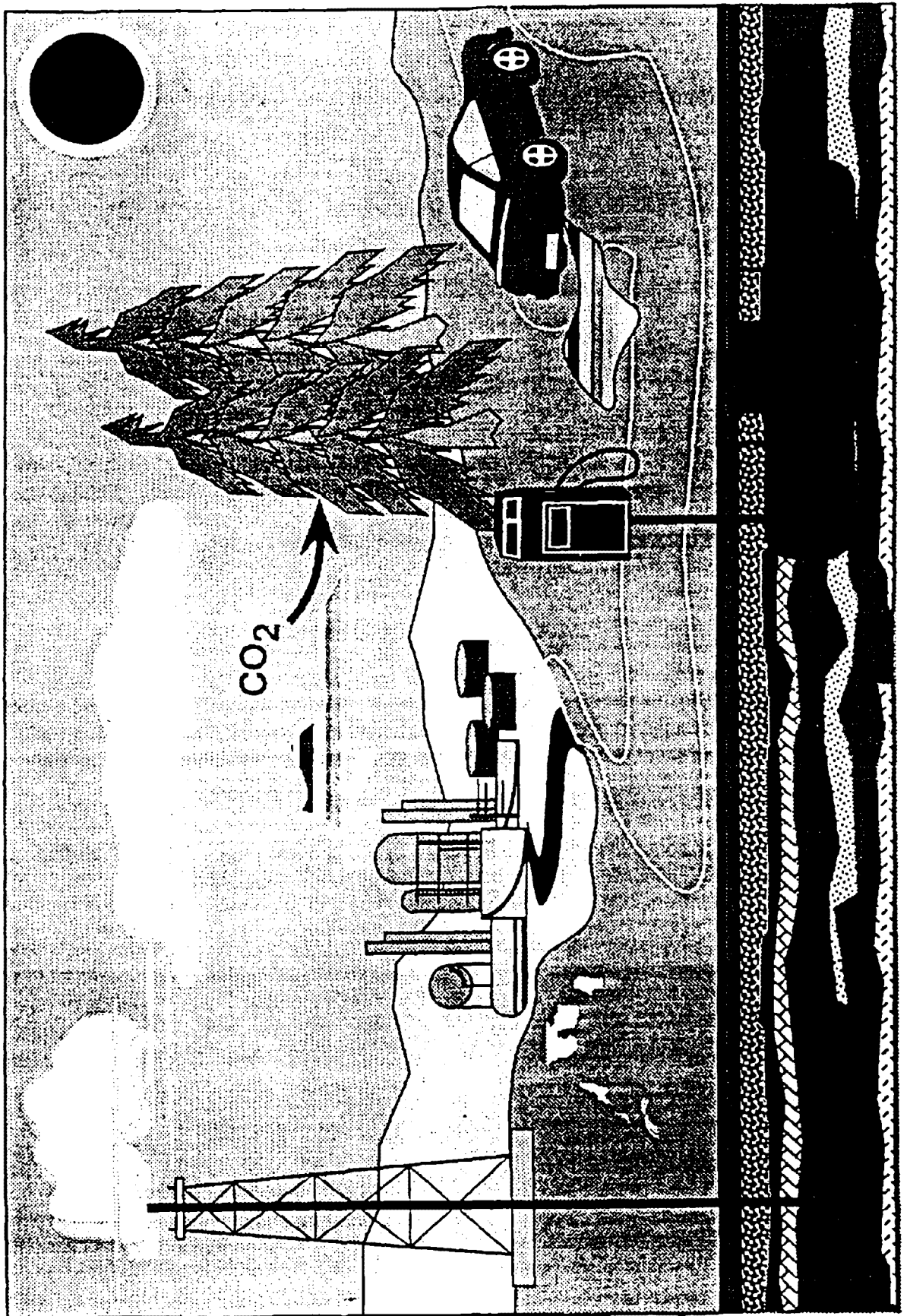


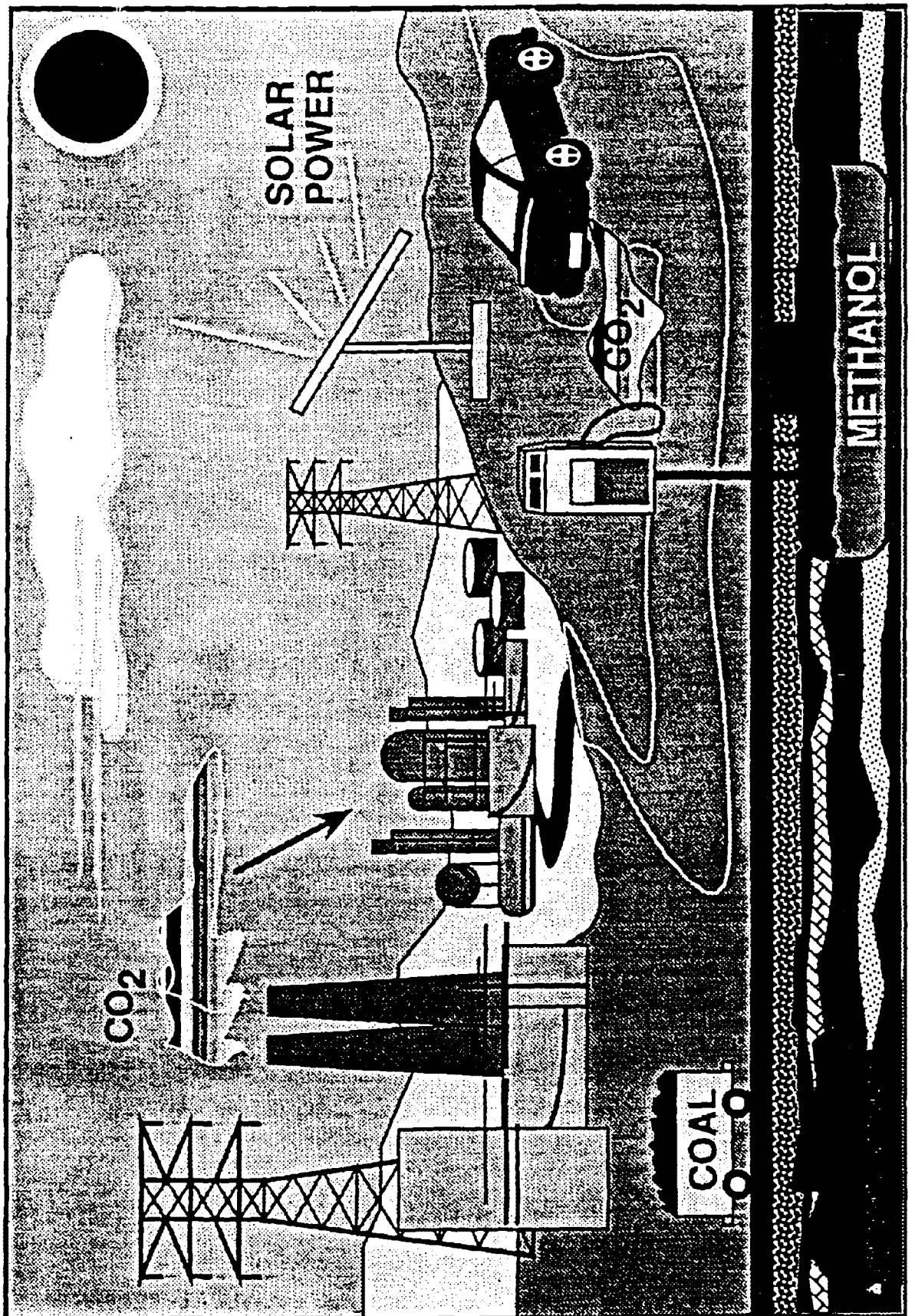
# Outline

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0830-7077M- 2

- Motivation
- H<sub>2</sub> production
- CO<sub>2</sub> production
- Methanol production









# HYDROGEN PRODUCTION TECHNOLOGIES

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0830-7077M- 3

## Technology

## Energy Input

**Methane reforming**

**Natural gas**

**Partial oxidation**

**Natural gas**

**Coal gasification**

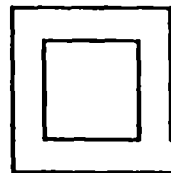
**Coal**

**Electrolysis**

**Electricity**

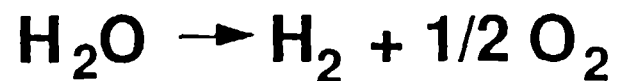
**Thermal dissociation**

**Heat**

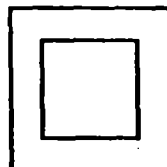


# HYDROGEN PRODUCTION COSTS

0830-7077M- 4



<u>Energy Source</u>	<u>Electricity (\$/kWh)</u>	<u>Hydrogen (\$/lb)</u>
1990 photovoltaic	0.101	2.4
2000 photovoltaic	0.027 to 0.05	0.6 to 0.9
Nuclear	0.067	1.6



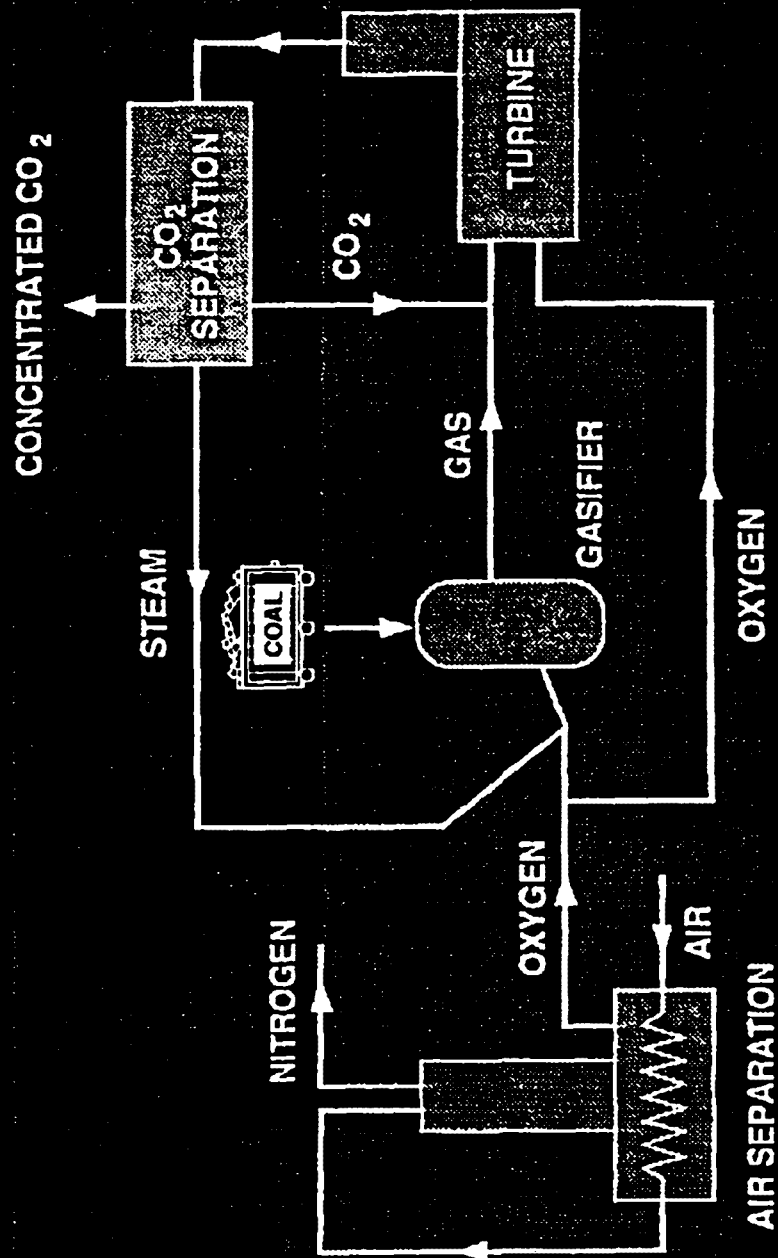
# CO<sub>2</sub> RECOVERY ENERGY REQUIREMENTS

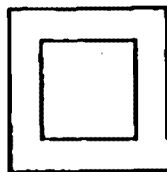
0830-7077M-5

CO <sub>2</sub> Source	Technology	Energy Requirement (kWh <sub>e</sub> /lb CO <sub>2</sub> )
Concentrated sources	Ready for use	None
Flue gas	Absorption stripping monoethanolamine (MEA)	0.27
Flue gas	Solid adsorbents	0.4
Flue gas	O <sub>2</sub> combustion/ CO <sub>2</sub> recycle	0 to 0.12
Atmosphere	Various	6 to 10

# CO<sub>2</sub> CONCENTRATION WITH OXYGEN COMBUSTION

ESD434-90

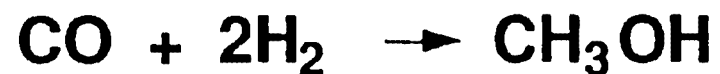




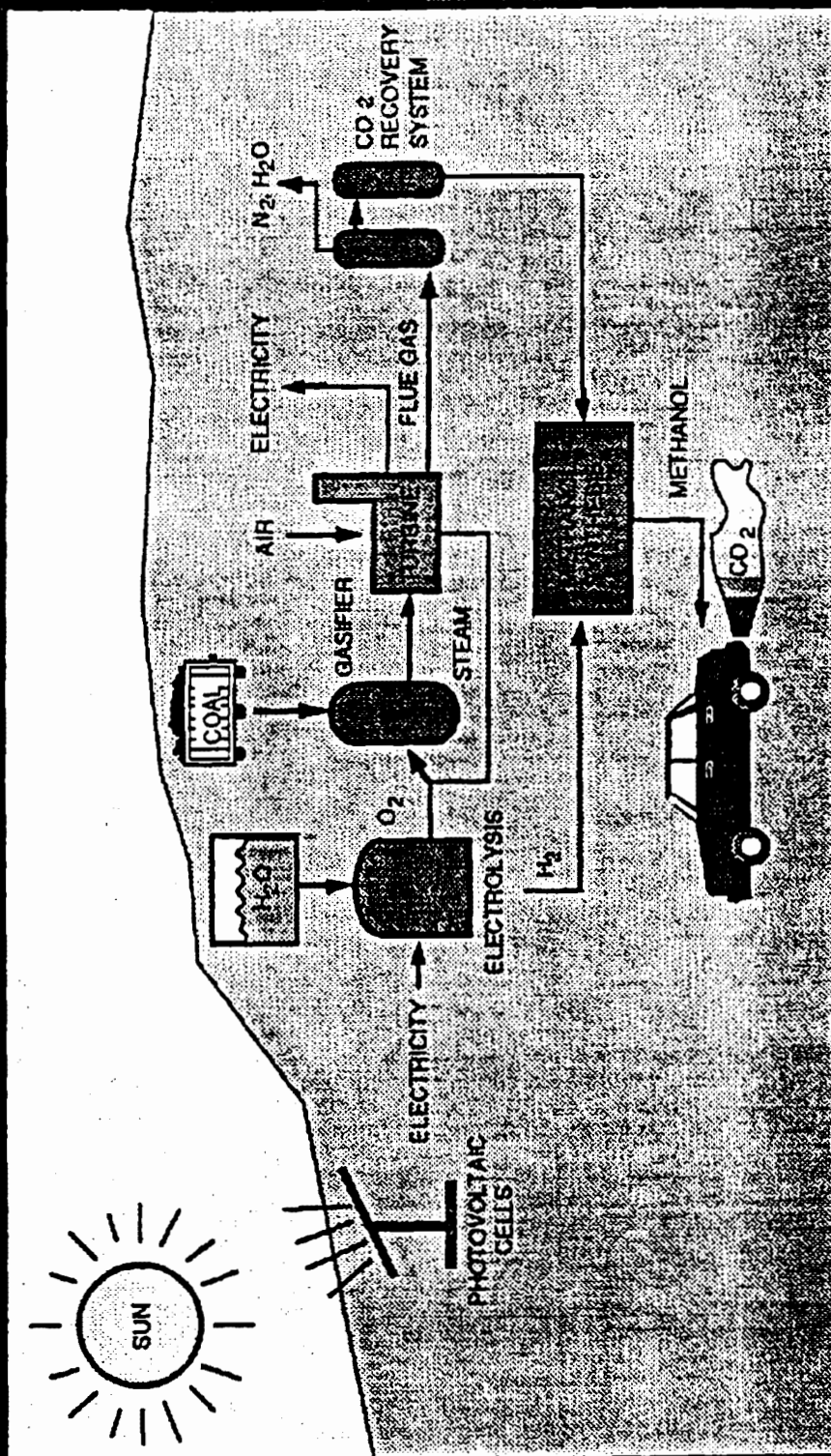
# METHANOL PRODUCTION

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0830-7077M-6



# METHANOL PRODUCTION FROM HYDROGEN AND CO<sub>2</sub>



# METHANOL PRODUCTION FROM HYDROGEN AND CO<sub>2</sub>

N<sub>2</sub>, H<sub>2</sub>O  
CO<sub>2</sub> RECOVERY  
0.37 kWh<sub>th</sub>

1,375 lb CO<sub>2</sub> RECYCLE

FLUE  
GAS

DIESEL

COAL  
0.484 lb MAF  
6,765 Btu

ELECTRICITY

0.73 kWh<sub>th</sub>

HYDROGEN  
0.188 lb

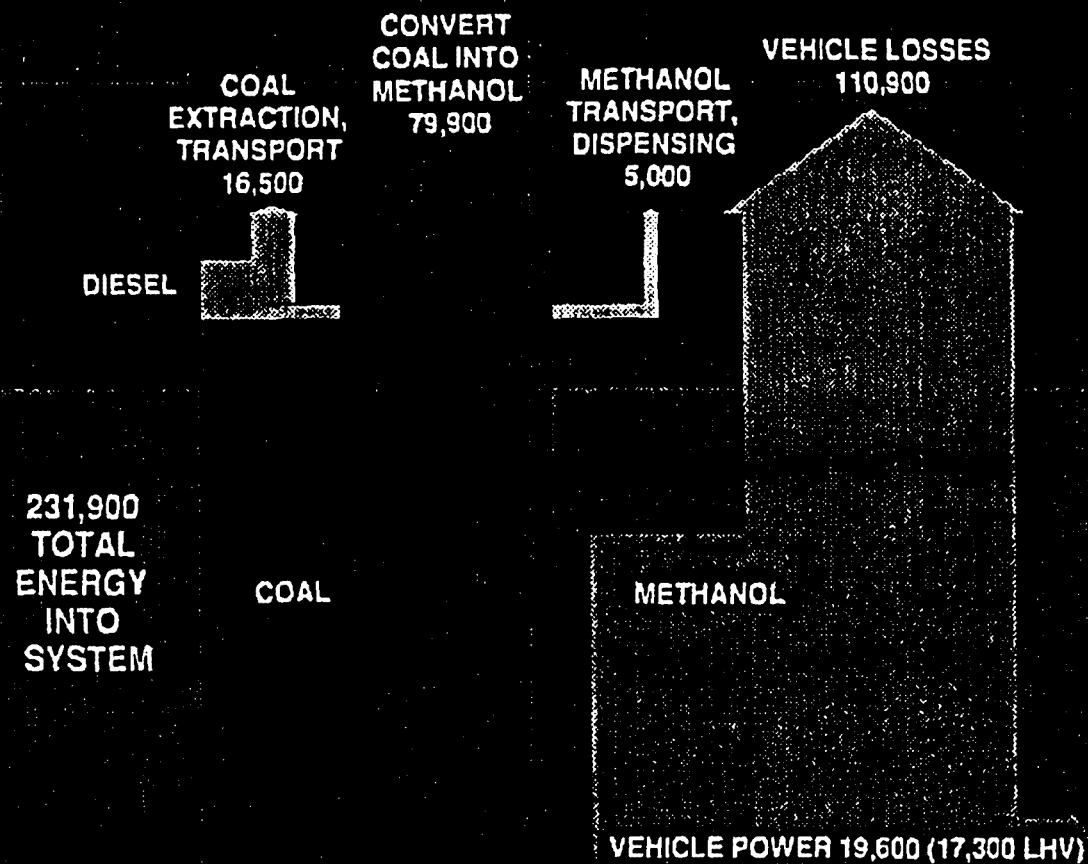
ELECTRICITY

SOLAR ENERGY

METHANOL

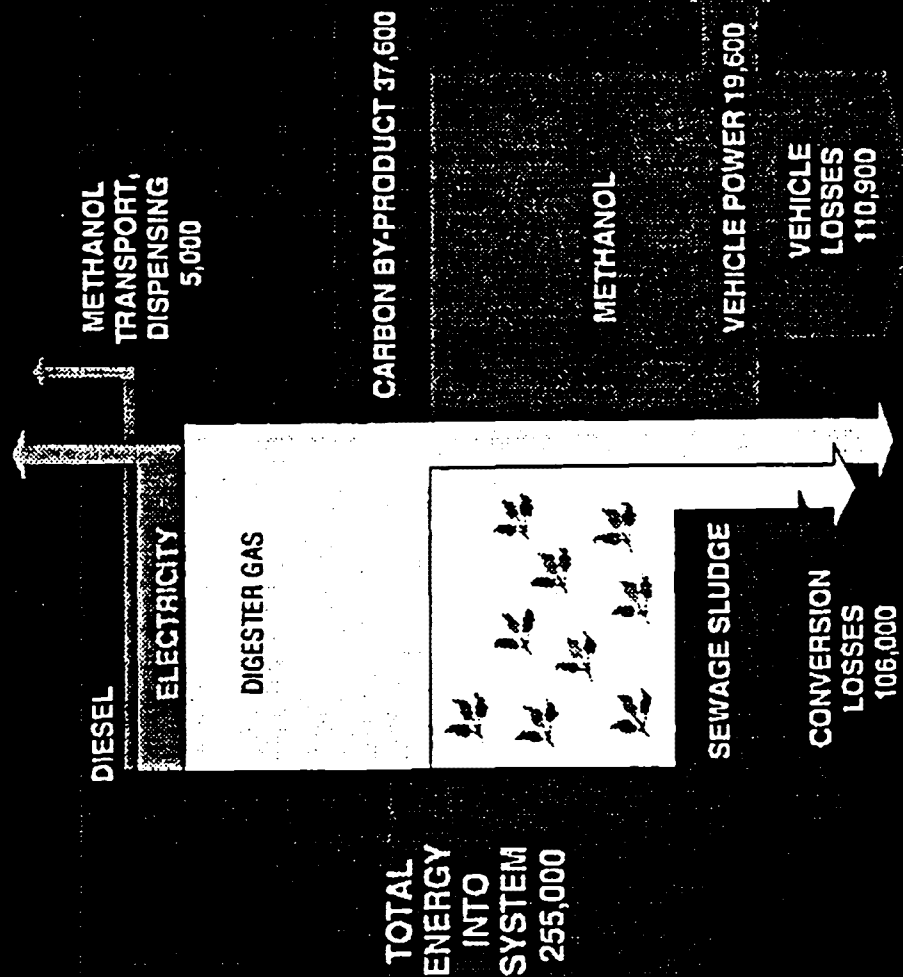
CONVERSION LOSSES

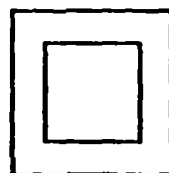
# METHANOL FROM COAL FUEL-CYCLE





# METHANOL FROM BIOMASS AND DIGESTER GAS FUEL-CYCLE



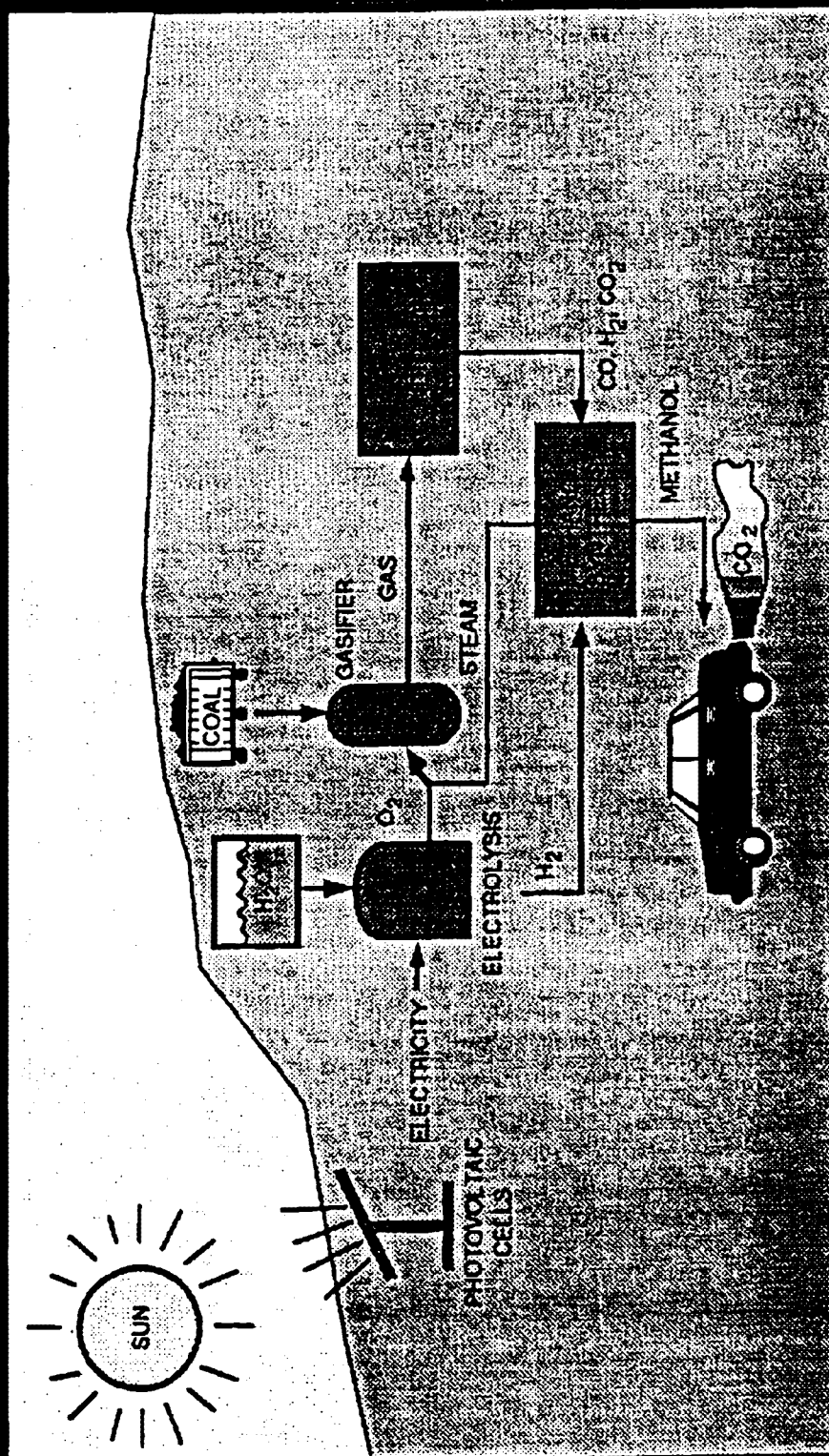


# ENERGY REQUIREMENTS FOR METHANOL PRODUCTION

0830-3077M-10

Component	CO <sub>2</sub> Recovery From Coal Plant	H <sub>2</sub> + Coal-based Methanol	H <sub>2</sub> + Conc ated
Coal (Btu)	6875	6875	---
Power output (kWh)	0.733	0	—
PV equivalent (kWh)	—	0.733	—
CO <sub>2</sub> recovered (lb)	1.375	0	1.375
PV input (kWh)	0.37	0	0
H <sub>2</sub> electrolysis (lb)	0.188	0.088	0.188
PV input (kWh)	4.0	1.89	3.76
Total PV (kWh)	4.37	2.62	3.76
Methanol (lb)	1.0	1.0	1.0

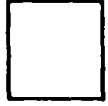
# METHANOL PRODUCTION FROM HYDROGEN AND COAL



# COST OF METHANOL PRODUCTION (1990 \$)

0830-7077M-11

Component	CO <sub>2</sub> Recovery From Coal Plant	H <sub>2</sub> + Coal-based Methanol	H <sub>2</sub> + Concentrated CO <sub>2</sub>
<b><u>Hydrogen</u></b>			
Mass (lb)	1.24	0.58	1.24
Cost (\$/lb)	0.60 to 2.50	0.60 to 2.50	0.60 to 2.33
Cost (\$)	0.74 to 3.10	0.35 to 1.45	0.74 to 2.89
<b><u>CO<sub>2</sub></u></b>			
Mass (lb)	9.08	Obtained from coal	9.08
Cost (\$/lb)	0.02	0.00	0.00
Cost (\$)	0.19	0.00	0.00
<b><u>Methanol Production</u></b>			
Capital (\$/gal)	0.64	2.34	0.64
15% recovery	0.10	0.35	0.10
Operating (\$/gal)	0.05	0.14	0.05
Total Cost (\$)	1.08 to 3.44	0.84 to 1.94	0.89 to 3.04



## **SURELY YOU'RE JOKING**

0830-7077M- 14

- **Why generate power from coal if PV is available?**
- **What are the environmental benefits of recycling CO<sub>2</sub>?**
- **What are the technical benefits?**
- **Are there cheaper alternatives?**



## SESSION IV: EMISSIONS AND MITIGATION OF METHANE AND OZONE PRECURSORS

M.J. Shearer, Chairperson

### GLOBAL ATMOSPHERIC METHANE: Trends of Sources, Sinks and Concentrations

by

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#### Abstract

The global cycle of methane is driven by emissions around 550 Tg/yr from both natural and sources related to anthropogenic activities, particularly the production of food and energy. Major sources are rice agriculture, domestic ruminants, and wetlands. Methane is removed from the atmosphere mostly by reacting with OH radicals. Some methane is removed by the soils. Over the past decade methane concentrations have been increasing at about 1%/yr or 16 ppbv/yr. A record of atmospheric methane extending back 150,000 years has been constructed from the analysis of polar ice cores. It shows that, during this time, methane concentrations have never been more than half of present levels. The recent increase of methane was probably caused by increasing emissions. Recent changes in the trend of methane may also be attributed to changing levels of OH. This paper deals with the changes in global methane concentrations in the past, the causes of increased levels at present and the future of atmospheric methane. The present understanding of the global methane budget provides critical facts for policies related to controlling man-made sources.

## 1. INTRODUCTION

It has been nearly 10 years since it was conclusively established that methane concentrations are increasing in the earth's atmosphere (Rasmussen and Khalil, 1981a, 1981b). Since then, considerable progress has been made towards an understanding of the global methane cycle and the causes of the increasing trends. This paper is a review of the current understanding. We examine first the recent global budgets and then the recent and long-term trends of atmospheric methane. Next we will review the trends of emissions and the role of human activities. Finally we will relate the trends of emissions and atmospheric concentrations to establish a coherent view of the global cycle of methane and discuss the implications for the future of methane.

## 2. GLOBAL BUDGETS

### 2.1 SOURCES AND SINKS

About a dozen complete budgets of methane have been proposed in recent years, most of them over the last 10 years (Ehhalt, 1974; Ehhalt and Schmidt, 1978; Donahue, 1979; Sheppard et al., 1982; Khalil and Rasmussen, 1983; Blake, 1984; Bolle et al., 1986; Bingemer and Crutzen, 1987; Cicerone et al., 1988; see also Warneck, 1988). A number of other studies have concentrated on specific sources and their global distributions. The published budgets are listed in Table 1 from Khalil and Rasmussen (1990a). The main sources affected by human activities are rice fields and ruminants, mostly cattle. Other anthropogenic sources also include biomass burning, coal mining, oil and gas use, landfills, automobiles, and a variety of other even smaller sources. The main natural emissions are from the wetlands, with smaller contributions from a number of other sources, such as the tundra, lakes, rivers, oceans, and termites.

The total emissions are about 550 tg/yr ( $1 \text{ tg} = 10^{12} \text{ gm}$ ), of which some 60% of the emissions are from anthropogenic sources. Once methane gets into the atmosphere it has a lifetime of 8-10 years. It is removed primarily by reacting with OH radicals ( $\sim 490 \text{ tg/yr}$ ), but smaller amounts ( $\sim 20 \text{ tg/yr}$ ) are also removed by the soils, and even smaller amounts are removed by other chemical processes in the troposphere and stratosphere. The present imbalance between sources and sinks is about 40 tg/yr, which is observed as an increasing atmospheric trend of about 1% per year.

### 2.2 PRESENT GLOBAL DISTRIBUTION

The present global distribution is shown in Figure 1. Because most of the sources are land-based and many are related to human activities, concentrations of methane are higher over continents and over the northern hemisphere in general. The present global average concentration is about 1680 ppbv.



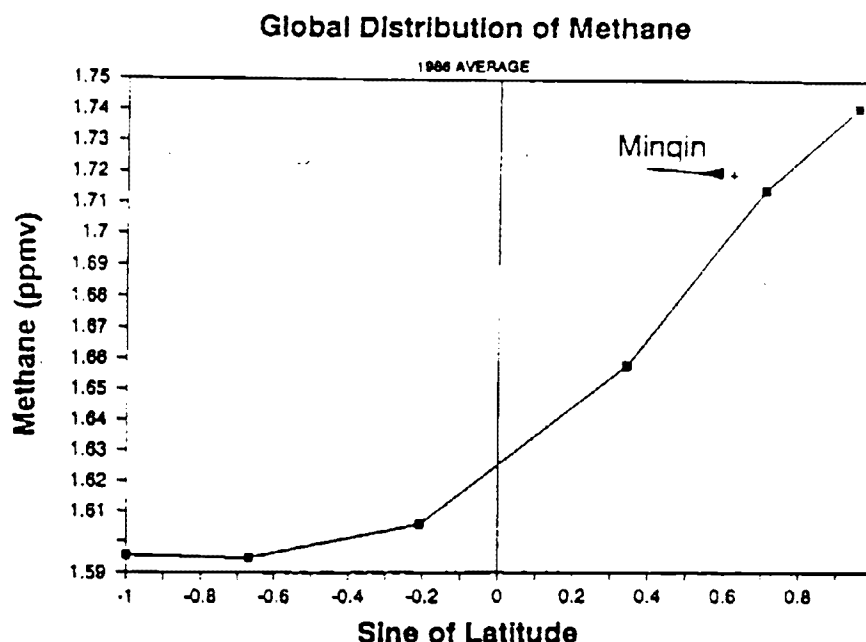


Figure 1. The latitudinal distribution of methane. Data are average values for 1986 at six long-term flask sampling stations from the arctic circle to the south pole. The annual average concentrations at Minqin, Gansu, China are shown for comparison.

### 3. GLOBAL TRENDS

#### 3.1 TRENDS OF CONCENTRATIONS

The global atmospheric trends are summarized in Figure 2 from Khalil and Rasmussen (1990b). It shows the results of three systematic global studies spanning the decade between 1978 and 1988 (Steele et al., 1987; Blake and Rowland, 1988; Khalil and Rasmussen, 1990b). There is remarkably good agreement among the studies even though the methods and strategies were quite different.

From the systematic studies, it is apparent that the trends have not been constant even over the past decade. The early parts of the record in the late 1970s shows a faster rate of increase than the more recent measurements in the later part of the 1980s. This variation of the rate of increase has led to some confusion as to how fast methane is really increasing. Our early work showed rates of increase of somewhat less than 2%/yr; our later work showed increasing rates of 1.4%/yr; Blake and Rowland (1988) found rates of increase of 1%/yr and Steele et al. (1987) reported rates of increase of somewhat less than 0.8%/yr. All these findings are consistent when the variability in the rate of increase is taken into account. This is shown more clearly in Figure 3 from Khalil and Rasmussen (1990b). Over the decade the average rate of increase is 1%/yr, although within this decade there were 2-year periods when the rate of increase was as low as 0.7%/yr or as high as 2%/yr (in the earlier years).

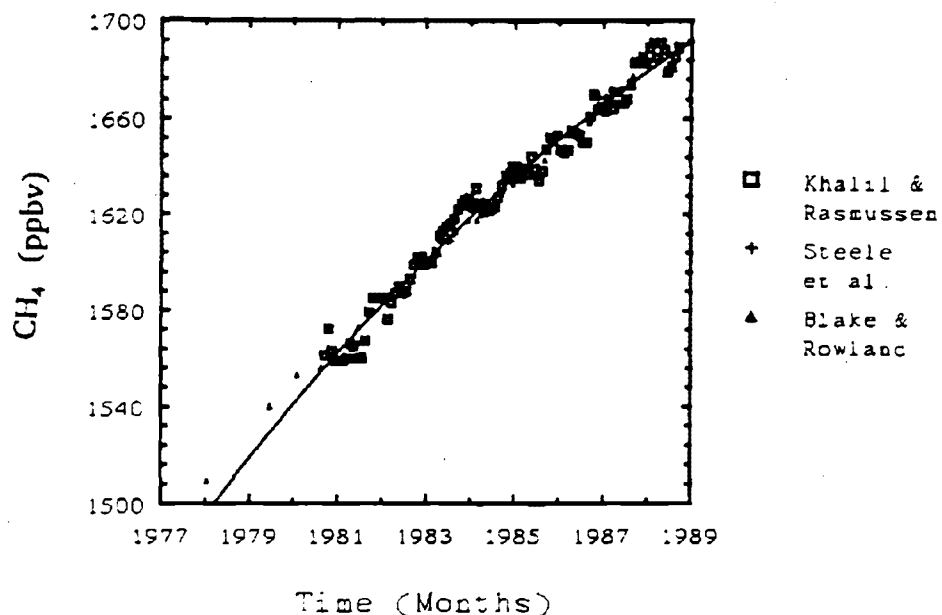


Figure 2. Comparison of methane trends from three systematic global long-term studies (Steele et al., 1987; Blake and Rowland, 1988; Khalil and Rasmussen, 1990a).

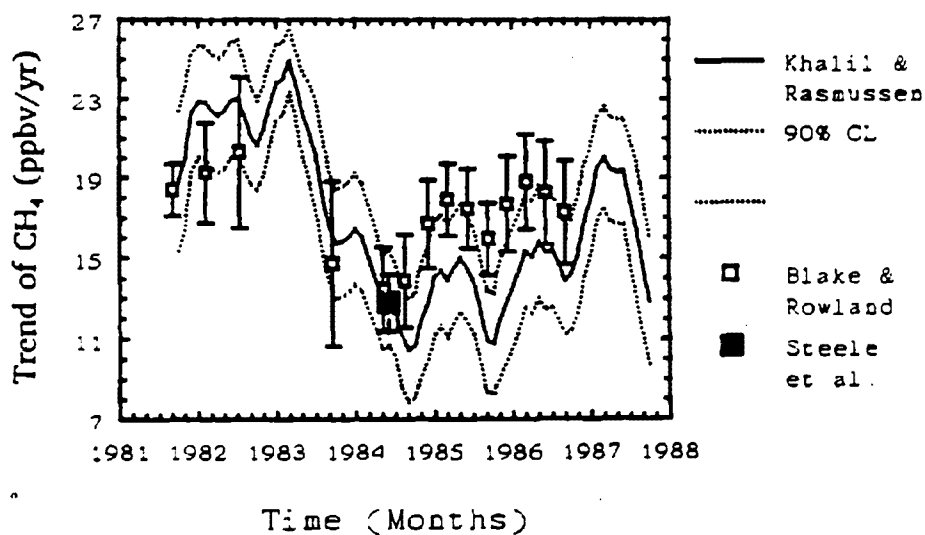


Figure 3. Trends over successive two-year periods and 90% confidence limits in the middle of the time period of calculation. The rate of increase is not constant, and trends over short times may not reflect long-term tendencies.

Systematic measurements were not taken before this period; however, there are published data taken during the 1960s and 1970s. An analysis of these data shows trends of similar magnitude during the 2 decades as shown in Figure 4 (Khalil et al., 1989a).

Over still longer periods spanning the last 150,000 years, there is a remarkable record of atmospheric methane from the analysis of polar ice cores (Khalil and Rasmussen, 1989b; Stauffer et al., 1985; Raynaud et al., 1988). This record shows that methane concentrations have varied naturally because of changing climatic conditions from ice ages to inter-glacial periods. The record also shows that the present (Figure 5) increase started about only a hundred years ago with small trends going as far back as two hundred years. The pattern of the past rapid increase was therefore likely to be caused by human activities linked to the rapidly rising population. During the 150,000-year record concentrations have never been more than half of present levels.

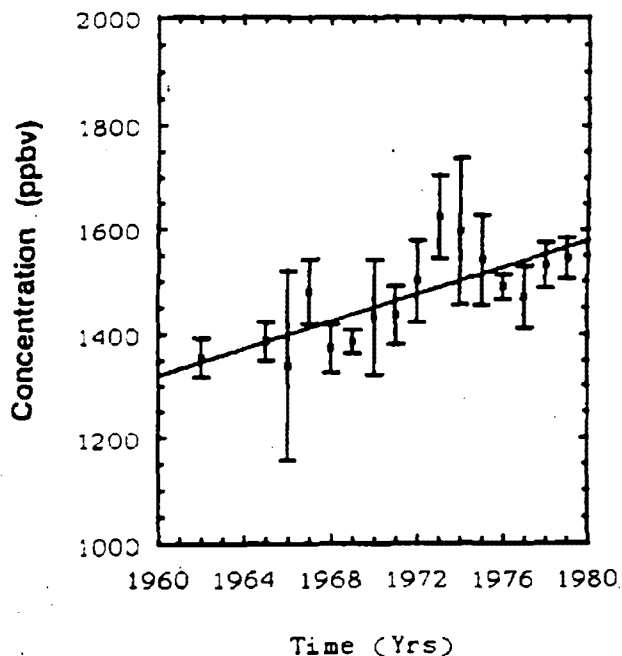


Figure 4. Annual average concentrations during the 1960s and 1970s (Khalil et al., 1989) (Reproduced with permission.)

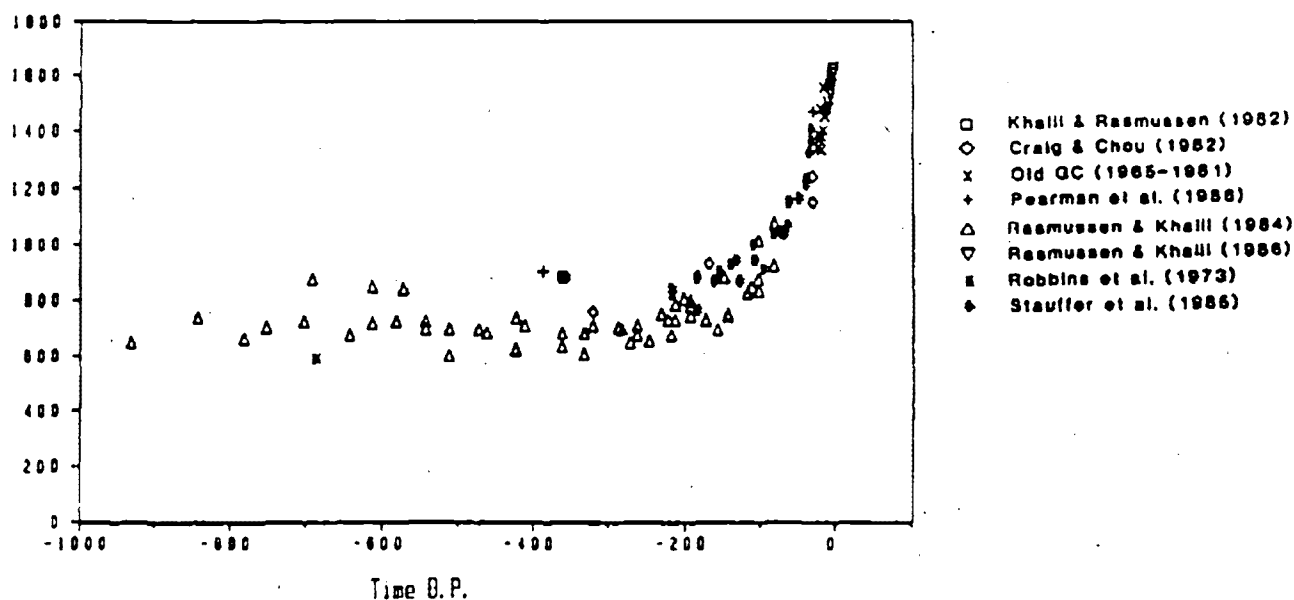


Figure 5. The atmospheric concentrations of  $\text{CH}_4$  over the last 1000 years (in ppbv). (From Khalil and Rasmussen, 1987).

### 3.2 TRENDS OF SOURCES

The emissions of methane from domestic ruminants and rice fields have increased steadily over the past 100 years. More recently, emissions from other human activities such as oil, gas and coal production, landfills, and other waste processing have also been increasing. We have compiled data from a number of sources to estimate the increase of emissions from anthropogenic activities. The results are summarized in Figure 6.

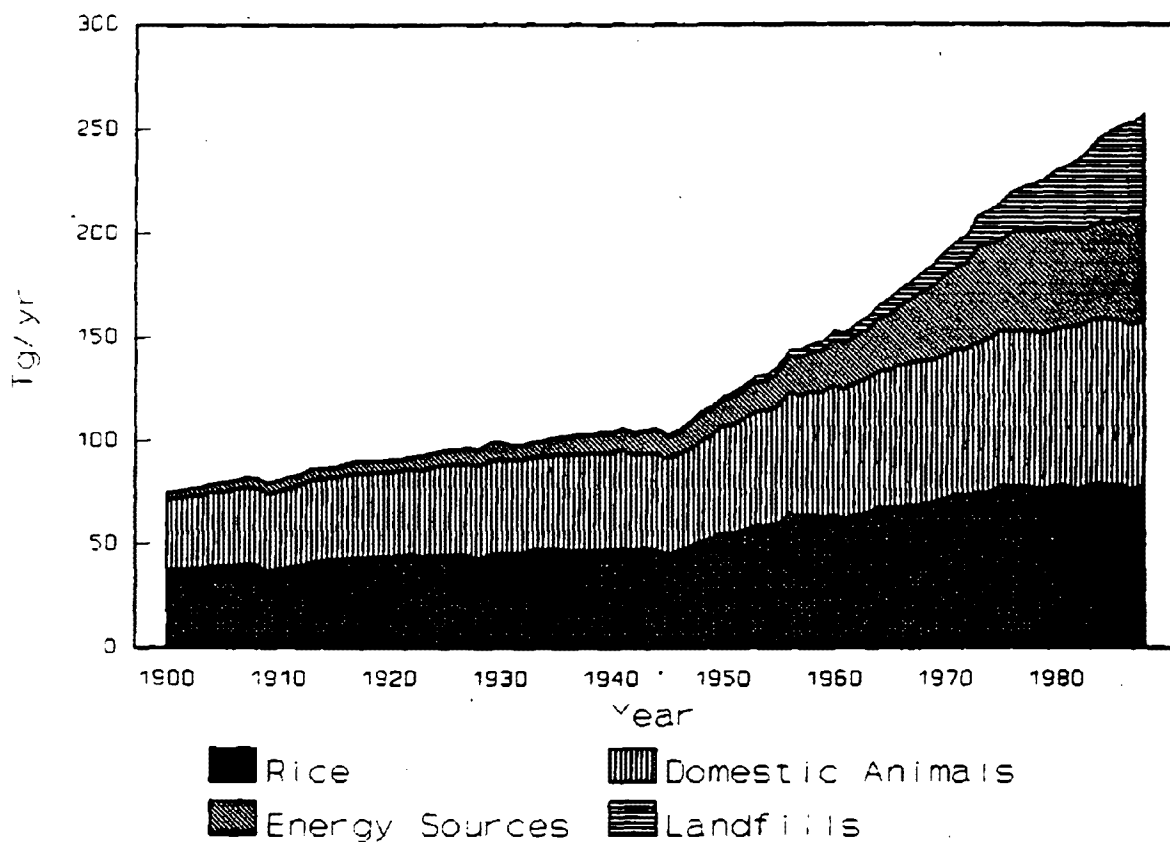


Figure 6. Estimated annual emissions of methane from human-influenced sources.

### 4. CAUSES OF INCREASING METHANE

The mass balance of methane in the atmosphere can be written as:

$$\frac{dC(t)}{dt} = S(t) - \frac{C(t)}{\tau(t)} \quad (1)$$

where  $C$  is the concentration,  $S$  the emission rate, and  $\tau$  is the atmospheric lifetime. The concentration can increase only if the sources increase or the sinks decrease. For methane, both possibilities are plausible. Since methane is removed

mostly by reacting with OH, a reduction in OH could lead to an increase of methane. The decrease of OH was expected because CO and CH<sub>4</sub> were both increasing and these gases are the major sinks of OH. Now it appears that these factors may be compensated by enhanced production of OH, particularly because of increasing tropospheric ozone and also because of other considerations. It also appears the OH concentrations are stabilized against changes (see Pinto & Khalil, 1991; Lu and Khalil, 1991). On the other hand, there is very good evidence that the sources have increased, although uncertainties and issues still remain. A good case can be made that most of the increase of methane has occurred because of increasing emissions. This still leaves a margin for the contribution of declining OH (Khalil & Rasmussen, 1985, 1987).

## 5. THE FUTURE

We have shown a coherent picture of the global methane cycle in which the trends from different experiments agree and the increase both at present and over the past 100 years is dominated by increasing emissions from human activities.

In spite of our present knowledge of the methane budget, there are still too many unknowns that make it impossible to predict future levels with any degree of confidence.

If an increase of OH is not the main cause for the slowdown in the methane concentration then it must be explained by the changes of sources. Increases of methane over the last century appear to be affected significantly by increasing cattle populations and acreage under rice agriculture. It is now evident that the area of rice agriculture is no longer expanding. Higher yields are being achieved by use of hybrid species and artificial fertilizers neither is likely to increase methane emissions. Thus the lack of increase in the area of rice planted may lead to a lack of increase of methane emissions from this source. Similarly, the world cattle populations are no longer increasing because of various reasons including lack of suitable range lands. It seems therefore that the two major sources affected by human activities, rice agriculture and domestic cattle (and perhaps also other animals), are no longer increasing because of natural limitations on these activities. There are a number of more recent sources of methane, mostly related to energy production and waste disposal such as in landfills, that are probably still increasing.

In addition to the complications already mentioned, there are two other processes that may significantly affect future levels of methane. First the draining wetlands over the past century and the continuing loss of wetlands at present is not fully understood but may lead to a reduction in natural emissions. And second, there is the possibility that the warming of the world (caused by increasing CO<sub>2</sub> and trace gases) will lead to an increase of methane emissions from natural sources or even destabilize large reservoirs of methane such as the permafrost, thus overcoming the diminishing role of the sources we know today. These matters greatly complicate predicting future methane levels or the benefits of controlling the well known major sources.

If these ideas are correct two important conclusions emerge:

- 1). If the sources that contributed to past increases of methane are not increasing

any more, then the past record of methane is becoming uncoupled from the future. Future increases of methane will be caused by newer sources that were not important in the past thus the past does not serve as an indicator of the future. Population change for instance is no longer an indicator of future methane emissions. Thus reliable projections of methane concentrations into the future are virtually impossible at present. It is even possible that changes in OH, most likely declining concentrations, will contribute more and more to the future trends of methane.

2). The second conclusion is that the global methane trends are slowing down without any legislative intervention, most likely from natural limits to growth of the major anthropogenic sources. This aspect is particularly interesting since most control strategies cannot guarantee the reduction of the growth rate by a factor of two within a decade as has already occurred. The notion that any trend or an atmospheric trace gas can continue for decades or centuries has no philosophical or scientific basis, but is commonly assumed in many assessments of the future levels of man-made trace gases including methane.

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#### ACKNOWLEDGEMENTS

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COAL MINE METHANE EMISSIONS AND MITIGATION

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ABSTRACT

Estimates of methane ( $\text{CH}_4$ ) emissions from coal mines range from 25 to 45 Tg/yr with a recent estimate as high as 65 Tg/yr. At 46 Tg/yr, the estimate produced by this project, coal mines contribute about 10% of anthropogenic  $\text{CH}_4$  emissions and may contribute significantly to the global change phenomenon. While emissions from underground mines are now believed to be adequately characterized, virtually no data are available on emissions from surface mines, and data are totally lacking on emissions from abandoned/inactive mines and coal handling operations. The methodology developed to calculate emissions from underground mines is briefly described, as is the Fourier transform infrared spectroscopy technique being employed for measuring emissions from surface mines. A nitrogen-flooding technique for enhancing the recovery of  $\text{CH}_4$  from coalbeds in advance of mining is described as a possible measure for mitigating  $\text{CH}_4$  emissions from underground mines.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

## INTRODUCTION

Methane ( $\text{CH}_4$ ) is a radiatively important trace gas which accounts for about 18 percent of anthropogenic greenhouse warming. Atmospheric concentrations of  $\text{CH}_4$  are now increasing at the rate of 1 percent per year [1]. Although the global  $\text{CH}_4$  cycle is not fully understood, significant sources of emissions include wetlands, ruminants, rice paddies, biomass burning, coal mines, natural gas transmission facilities, landfills, termites, and tundra [2]. Improved emissions estimates for these sources will allow their relative contributions to the global  $\text{CH}_4$  cycle to be better understood, and will provide a means for focusing future emissions mitigation research.

Attempts made to estimate global emissions from coal mining operations have generally relied solely on global coal production data and emission factors derived from  $\text{CH}_4$  contents of coalbeds [3,4,5]. These estimates are based on the assumption that emissions are equal to the amount of  $\text{CH}_4$  trapped in the coal removed from the mine. Although this trapped  $\text{CH}_4$  is liberated when coal is fractured and removed from the mine, there are other  $\text{CH}_4$  release mechanisms in the mining process which this assumption fails to take into account. For example,  $\text{CH}_4$  may be released from: (1) exposed coal surfaces throughout the mine workings (e.g., the roofs, floors, and walls); (2) gas which is trapped in the strata adjacent to the mined seams; and (3) underlying seams close to the seam being mined. Commonly cited global mine emissions estimates range from 25 to 45 teragrams (Tg) of  $\text{CH}_4$ /year, which corresponds to roughly 10 percent of the total annual  $\text{CH}_4$  emissions from anthropogenic sources [5]. A recent report contains emissions estimates as high as 33 to 64 Tg  $\text{CH}_4$ /year [6].

Underground, surface, and abandoned or inactive mines comprise the three general sources of mine related  $\text{CH}_4$  emissions. Emissions from underground mines can be liberated from three sources: (1) ventilation shafts; (2) gob wells; and (3) crushing operations. Ventilation air, although generally containing 1 percent or less  $\text{CH}_4$ , contributes the majority of mine emissions because of the enormous volume of air used to ventilate mines. Gob wells are drilled into the area immediately above the seam being mined. They provide conduits for venting  $\text{CH}_4$  which accumulates in the rubble-filled areas formed when the mine roof subsides following longwall mining. Their purpose is to remove  $\text{CH}_4$  which would otherwise have to be removed by larger and more costly shaft ventilation systems. Currently, no published data for the release of  $\text{CH}_4$  from gob wells exist. However, preliminary data obtained from the coal mining industry indicate that gob well  $\text{CH}_4$  emissions could account for a significant fraction of the total emissions associated with some longwall mines [7]. Emissions data for crushing operations are also extremely limited.

In surface mines, the exposed coal face and surface, and in particular areas of coal rubble created by the blasting operation, are expected to provide the major sources of  $\text{CH}_4$ . As in underground mines, however, emissions may also be contributed by the overburden and by underlying strata. Emissions from abandoned mines may come from unsealed shafts and from vents installed to prevent the buildup of  $\text{CH}_4$  in the mines.

The main purpose of this research has been to develop an improved methodology for estimating global  $\text{CH}_4$  emissions from underground coal mining operations and to produce a global emissions estimate using this methodology where country-specific estimates are not available. The underground mine methodology integrates data on coal production, coal properties, coalbed  $\text{CH}_4$  contents (i.e., the volume of  $\text{CH}_4$  per ton of coal), and coal mine ventilation air emissions from U.S. mines. The objective was to develop a procedure which can be used to estimate mine emissions from generally available coal analyses and production data where coalbed  $\text{CH}_4$  data or emission estimates are not available for a country. This procedure will be briefly described.

Since emissions data are presently not available for surface mines, the Air and Energy Engineering Research Laboratory (AEERL) of the U.S. Environmental Protection Agency (EPA) has embarked upon a measurements program to quantify  $\text{CH}_4$  emissions from selected surface mines in the United States for later inclusion in this work. The methodology employed will be discussed. Similarly, virtually no data exist on emissions from handling operations (i.e., crushing, grinding, transport, and storage) although their magnitude will certainly depend, to a large extent, on the desorption characteristics of individual coals. There are also no data available on abandoned inactive mines; therefore, AEERL is initiating assessments in both of these categories.

Since one purpose of producing these estimates of emissions is to identify appropriate targets for control within the coal industry, it is also necessary to evaluate means of mitigating the emissions. Currently the most logical target for mitigation is underground mines because they are the largest sources of emissions in the industry and they consist of one or more point sources. The largest source of emissions from an underground mine is ventilation air but, because of the enormous volumes of air produced,  $\text{CH}_4$  concentrations in the air are typically less than 1 percent. No technologies are currently available to make economic use of such dilute streams. It is believed that the most effective means of addressing the problem is to degasify coal seams prior to mining. To make this process more economical the efficiency can be increased by enhancing the recovery of  $\text{CH}_4$  from coal. AEERL is studying a nitrogen-flooding technique developed by the Amoco Production Company for the coalbed  $\text{CH}_4$  industry to accomplish this purpose.

## EMISSIONS

Numerous studies have examined the physical relationships which control the production and release of  $\text{CH}_4$  by coal. These studies have been conducted either to evaluate the potential of coalbed  $\text{CH}_4$  resources or to enhance the safety of underground mines. Generally, the studies address one of two topics: (1) factors controlling coalbed  $\text{CH}_4$  content; or (2) factors controlling the concentration of  $\text{CH}_4$  in the mine atmosphere and mine ventilation air.

Studies in the first group have identified pressure, coal rank, and moisture content as important determinants of coalbed  $\text{CH}_4$  content. Kim related gas content to coal temperature and pressure, and in turn to coal depth [8]. After including coal analyses data to represent rank, Kim produced a diagram relating gas content to coal depth and rank. Although the validity of the rank relationship has been questioned, it generally appears to have been accepted by recent authors [9,10,11,12]. Independently of Kim's work, Basic and Vukic established the relationship of  $\text{CH}_4$  content with depth in brown coals and lignite [13].

Several studies have recognized the decrease in  $\text{CH}_4$  adsorption on coal as moisture content increases in the lowest moisture regimes [14,15,16]. Moisture content appears to reach a critical value above which further increases produce no significant change in  $\text{CH}_4$  content. Coals studied by Joubert et al. showed critical values in the range from 1 to 3 percent [16].

Investigations which attempt to identify correlates of  $\text{CH}_4$  content in coal mine ventilation air include those by Irani et al. [17] and by Kissel et al. [18]. Irani et al. developed a linear relationship between  $\text{CH}_4$  emissions and coal production depth for mines in five seams. Kissel et al. demonstrated a linear relationship between  $\text{CH}_4$  emissions and coalbed  $\text{CH}_4$  content for six mines. Although both studies suffer from a paucity of mines and/or seams in their analyses, Kissel et al. made the important observation that mine emissions greatly exceed the amount expected from an analysis of coalbed  $\text{CH}_4$  content alone. Emissions are produced not only by the mined coal, but also by the coal left behind and by surrounding strata. For the six mines studied, emissions per ton of coal mined exceeded coalbed  $\text{CH}_4$  per ton by factors of from six to nine.

## MINE EMISSIONS ESTIMATE

Historically coal mine  $\text{CH}_4$  emission estimates have relied on coal production and a value for coalbed  $\text{CH}_4$  content. The implicit assumption was that emissions were the same as the  $\text{CH}_4$  content of the coal removed from the mine. A recent estimate by

Boyer et al. [6] took into account the fact that emissions are six to nine times that expected based on coal CH<sub>4</sub> content alone. This estimate is considerably more defensible than earlier ones for this reason. Our study refined the estimation procedure even further by using a series of regression equations to predict coal mine CH<sub>4</sub> emissions from those coal characteristics known to be related to CH<sub>4</sub> content: depth, moisture content, and indicators of rank such as heating value and fuel ratio (fixed carbon/volatile matter). The first step in the process uses the above coal characteristics and one of two regression equations, depending upon heating value, to produce estimates of in-situ coalbed CH<sub>4</sub> content. The coalbed CH<sub>4</sub> values along with coal production statistics are then used in a second regression equation to predict CH<sub>4</sub> emissions. The equations have R<sup>2</sup> values from 0.56 to 0.71 suggesting that the independent variables used explain 56 to 71 percent of the variability in the estimated values. Although the equations were developed using U.S. coal data, they are believed to be universally applicable since they employ coal characteristics which are known to control coalbed CH<sub>4</sub> content. The calculations are generally performed at the basin level of disaggregation since this is the type of coal data usually available. A detailed description of the estimation methodology is reported by Kirchgessner et al. [19]. It produces a global estimate of CH<sub>4</sub> emissions from underground mines of 36.0 Tg/year. This estimate is believed to be of sufficient quality to obviate the need for further work on this category of mines.

Very little data exist on which to base estimates of emissions from surface mines. A single emission analysis has been conducted to date by the EPA at a large Powder River Basin surface mine in Wyoming [20]. Using open-path Fourier transform infrared (FTIR) spectroscopy, an emission rate of about 4,814 m<sup>3</sup>/day was determined. Using a single coalbed CH<sub>4</sub> content for the same county and coal seam, it was estimated that, at the mine's actual coal production rate of 11.8 million tonnes per year, potential emissions from the mined coal alone should be 1,008 m<sup>3</sup>/day. This would suggest, as noted by Kissell et al. [18] for underground mines, that actual mine emissions exceed, by a factor of about five in this case, the emissions which would be expected based on coal production and coalbed CH<sub>4</sub> content alone.

Rightmire et al. [21], in their study of coalbed CH<sub>4</sub> resources in the United States, report 38 analyses of shallow coals (104 m deep or less) with CH<sub>4</sub> contents ranging from 0.03 to 3.6 m<sup>3</sup>/tonne coal. One analysis of 9.6 m<sup>3</sup>/tonne for the Arkoma Basin was not included because it is known to be anomalously high for shallow coals. Coalbed CH<sub>4</sub> analyses for shallow coals from other countries are lacking, so this study is temporarily making the gross assumption that the range of 0.03 to 3.6 m<sup>3</sup>/tonne coal reflects the CH<sub>4</sub> content range for shallow coals worldwide. Multiplying the average value for this range (1 m<sup>3</sup>/tonne) by 1987 world surface coal production of about 1.8 x 10<sup>9</sup> tonnes/year [6], and expanding the results by a factor of five as discussed above, produces an estimate of about 6.3 Tg/year. Adjusting

this value upward by 10 percent to represent 1989 coal production yields an estimate of 6.9 Tg/year. As additional surface mine emissions are sampled under the EPA test program, the factor by which actual surface mine emissions exceed expected emissions may change, in which case this portion of the emissions estimate will require modification.

No data were found on CH<sub>4</sub> emissions from handling operations. Boyer et al. [6] estimate that 25 percent of the CH<sub>4</sub> contained in the mined coal is released during post-mining operations. There is no compelling reason not to follow this precedent for now; therefore, coal handling emissions were estimated by assuming that 25 percent of the in-situ CH<sub>4</sub> content for all coal produced is released in post-mining operations. If warranted after further EPA investigation, these assumptions will be adjusted. Country-specific results of underground mine estimates are shown in Table 1.

TABLE 1. SUMMARY OF ESTIMATED GLOBAL METHANE EMISSIONS FROM COAL MINES FOR 1989

Country	1989 Underground Mine Coal Production (10 <sup>6</sup> tonnes)	Disaggregation Level	Coalbed Methane Values 3 (m <sup>3</sup> tonne)			Emissions	
			Average	Maximum	Minimum	6 3 (10 <sup>6</sup> m <sup>3</sup> /yr)	(Tg/yr)
China	1,053	21 Provinces	4.0	13.9	2.7	12,942	9.3
Former Soviet Union	418	6 Basins	5.6	9.2	2.2	11,045	7.9
Poland	181	3 Basins	7.8	7.8	7.7	5,013	3.6
United States	356	19 Basins	3.9	11.4	0.2	4,871	3.5
United Kingdom	71	12 Basins	6.0	18.4	0.3	1,756	1.3
West Germany	73	4 Basins	-	-	-	1,529	1.1
Australia	59	3 Basins	4.6	7.1	2.1	1,529	1.1
India	95	8 States	2.0	4.7	0.3	935	0.7
South Africa	115	4 Basins	0.9	1.4	0.6	963	0.7
Country Total	2,421					40,583	29.2
Rest of World	567					9,487	6.8
Total (Underground)	2,988					50,070	36.0
Total (Surface)						9,629	6.9
Total (Handling)						3,770	2.7
Total						63,469	45.6

\*1990-1991 Production

## SURFACE MINE EMISSION MEASUREMENT

A fundamental goal of the sampling methodology is to obtain an emission rate for total CH<sub>4</sub> emissions from a surface mine. The heterogeneity and size of the source called for a creative measurement approach. Since smoke releases show that emissions from surface mines diffuse out of the pit in the direction of the prevailing winds, a near-ground-level concentration measurement downwind from the mine is used to estimate a total CH<sub>4</sub> emission rate for the mine. A CH<sub>4</sub> measurement of the cross-wind-integrated concentration of the plume at near-ground level is made using an open-path Fourier transform infrared (FTIR) sensor. Using this near-ground-level concentration measurement and a measured background or natural ambient CH<sub>4</sub> concentration, the total mine release is estimated using an appropriate plume dispersion model. If site-specific plume dispersion characteristics can be determined, they can be used in the model to more accurately represent the behavioral characteristics of the plume at a given site. Using a tracer gas, these site-specific plume characteristics can be estimated as described below.

A tracer gas release can be assumed to be a continuously emitting point source. Based on this assumption and on the results of the smoke release studies conducted at strip mines, standard Gaussian dispersion equations can be applied. When the standard Gaussian equation is integrated across the y direction (y is assumed to be in the direction normal to the wind direction) from  $-\infty$  to  $+\infty$ , the following relationship can be developed [22]:

$$C_{CWI} = \frac{2Q}{(2\pi)^{1/2} u \sigma_z} \exp [-1/2(H/\sigma_z)^2] \quad (1)$$

where,

- $C_{CWI}$  = ground-level cross-wind-integrated concentration (g/m<sup>2</sup>)
- $Q$  = emission rate (g/s)
- $u$  = average wind speed (m/s)
- $\sigma_z$  = vertical dispersion coefficient (m)
- $H$  = effective emission height of plume centerline above ground level (m)

For a ground-level source such as a tracer release at a surface coal mine,  $H$  is effectively equal to zero so the exponent of the expression is equal to 1. Thus, Equation (1) can be simplified to:

$$C_{CW1} = \frac{2Q}{(2\pi)^{1/2} u \sigma_z} \quad (2)$$

Equation (2) can be used to obtain site-specific  $\sigma_z$  values for a mine if the values of the remaining unknowns can be determined. Specifically,  $\sigma_z$  can be determined for the plume given: (1) a measured tracer gas concentration ( $C_{CW1}$ ) from an FTIR sensor; (2) a measured value of  $u$  from a meteorological station located near the FTIR path; and (3) a known release rate  $Q$  from a tracer gas source, such as a metered gas cylinder located at the mine. To use this technique to estimate total mine emissions, a number of  $\sigma_z$  values must be determined based on tracer gas releases conducted at several different distances upwind from the monitoring path. These resulting values are used to construct a relationship of  $\sigma_z$  versus distance from the path for the area source. All tracer gas releases used to determine this  $\sigma_z$  relationship should be conducted as close in time as possible because atmospheric stability may change, thus changing the  $\sigma_z$  relationship.

A similar and somewhat simpler technique can also be used to assess plume dispersion characteristics using fewer tracer gas measurements. Given measured values for the tracer gas release rate  $Q$ , tracer release location, wind speed  $u$ , and wind direction, an appropriate area source plume dispersion model can be used to predict  $C_{CW1}$  for the tracer gas plume. The model is run to predict concentrations of the tracer gas at various points along the FTIR monitoring path. These predicted concentrations are integrated using the trapezoidal rule to calculate a path-integrated concentration or  $C_{CW1}$  for the FTIR monitoring path. The model is run seven times, once for each of the seven Pasquill-Gifford (P-G) atmospheric stability classes [22]. These varying P-G assumptions, which incorporate the influence of  $\sigma_z$ , simulate increasing atmospheric stability and its effect on the dispersion of the tracer gas plume. Since several model results are produced, a range of  $C_{CW1}$  values are predicted under varying degrees of atmospheric stability. The predicted  $C_{CW1}$  value which most closely matches the  $C_{CW1}$  measured by the FTIR is used to define the P-G atmospheric stability class which occurred during the tracer gas monitoring event. If simultaneous  $CH_4$  measurements are also collected during this monitoring event, this stability assumption is applied to the  $CH_4$  plume. The model is then run assuming a unity emission rate for  $CH_4$  (i.e., a homogeneous release rate of 1 g/m<sup>2</sup>-sec) and the P-G stability determined as described above. The model is run to predict concentrations of  $CH_4$  at various points along the FTIR monitoring path. By again applying the trapezoidal rule to these predicted point concentrations, a path-integrated concentration or  $C_{CW1}$  for the assumed homogeneous release is predicted along the FTIR monitoring path. Of course the FTIR is actually measuring a path-integrated concentration due to a heterogeneous emission release pattern from the coal seam. However, this measured value is comparable to the concentration determined from



the model for an assumed homogeneous release because the FTIR measurements integrated or 'averaged out' the variable concentrations which exist in the plume from the mine.

The actual CH<sub>4</sub> release rate for the mine is then calculated using the simple relationship shown below where Q<sub>(predicted)</sub> is the unity emission rate for CH<sub>4</sub>.

$$\frac{Q_{(\text{actual})}}{Q_{(\text{predicted})}} = \frac{\text{Concentration}_{(\text{measured})}}{\text{Concentration}_{(\text{predicted})}} \quad (3)$$

This technique is used to estimate CH<sub>4</sub> release rates in this study. The Point Area and Line (PAL) source model is used to predict point concentrations along the measurements path as described above [23]. A non-reactive gas, sulfur hexafluoride (SF<sub>6</sub>), is the tracer gas used. Use of a synthetic trace gas such as SF<sub>6</sub> is important to the determination of plume dispersion characteristics because it is non-reactive, does not naturally occur, and there is no background concentration to cause potential interferences.

Applying this methodology at a large, strip mine in the Powder River Basin of Wyoming produced a CH<sub>4</sub> emission rate of 4,814 m<sup>3</sup>/day. An important observation was, as in underground mines, that actual emissions exceed expected emissions by a factor of about five in this instance. Details of the methodology have been discussed previously by Piccot et al. [ 24 ] and Kirchgessner et al. [20]. A validation study of the methodology designed to answer questions raised during the first sampling trip has recently been completed and the data are being analyzed.

## COAL MINE METHANE MITIGATION

AEERL is participating in a demonstration of the Amoco Production Company's nitrogen-flooding process to enhance the recovery of CH<sub>4</sub> from coal seams. Although Amoco's interest in developing the technology is focused on CH<sub>4</sub> as the saleable resource, the methods involved will translate fully from the coalbed CH<sub>4</sub> industry to the coal mining industry. The goal of the project is to demonstrate that the 50 percent average CH<sub>4</sub> recovery rate from coal seams using current practice can be increased to 80 percent or more using nitrogen flooding. The final objective of the Laboratory's involvement is to transfer the practice to the coal industry as needed. The enhanced recovery, if achieved in a premine degasification program, will allow a mine to reduce its costly ventilation air requirements, and to retrieve more CH<sub>4</sub> for utilization or sale for a given drilling cost. In this fashion a consistent program of premine degasification may become not only less costly, but an actual economic benefit.

In conventional reservoirs  $\text{CH}_4$  is contained as a free gas. In contrast,  $\text{CH}_4$  in coal seams is stored as a gas adsorbed on the internal micropores of the coal matrix. The conventional practice of recovering coalbed  $\text{CH}_4$  is to reduce total reservoir pressure by pumping water out of the coal. Some  $\text{CH}_4$  desorbs from the coal surface, migrates through the micropores to the cleat or fracture system, and then travels to the recovery well along with the water. Although the system is simple it is inefficient because at the lower economic limit of pumping, about 150 psi (1000kPa), as much as 50 percent or more of the original  $\text{CH}_4$  may remain in the coal. An additional drawback to reducing the total reservoir pressure is that the driving force for gas expulsion is lost.

An alternative to reducing the total reservoir pressure is to reduce the partial pressure of  $\text{CH}_4$  by introducing an inert, low-adsorbing gas at a constant pressure [25]. Partial pressure of a component is equal to the total system pressure multiplied by the component's mole concentration in the gas phase. Therefore the injection of nitrogen reduces the relative concentration of  $\text{CH}_4$  and hence its partial pressure while, in some cases, increasing total reservoir pressure. Laboratory studies have shown  $\text{CH}_4$  recoveries of over 80 percent as well as significantly enhanced rates of recovery. Modeling studies suggest that the cost of nitrogen is more than offset by the improvement in production.

The demonstration tract is located in the northern portion of the San Juan Basin, approximately 9 miles (14.5 km) southeast of Durango, Colorado. The source of the  $\text{CH}_4$  is in the coals of the Upper Cretaceous Fruitland formation at a depth of about 2800 feet (853.5 m). The tract is 80 acres (32.5 hectares) in size with four injection wells located at the four corners of the tract, and a recovery well located approximately in the center of the tract. The objective is to demonstrate an economic  $\text{CH}_4$  recovery rate of 80 percent or better using nitrogen flooding, with minimal or no effects on neighboring wells. The project began in the summer of 1992.

## SUMMARY

AEERL is actively involved in a program of estimating and measuring global  $\text{CH}_4$  emissions from coal mines, and of developing mitigation technology for underground mines should control of this source be deemed prudent. The estimation of emissions from underground mines is regarded as complete and has produced a value of 36.0 Tg/year. Emissions from surface mines were estimated to be 6.9 Tg/year using a single measured value. A sampling campaign at selected surface mines will be conducted using an open-path FTIR instrument and dispersion modeling. If necessary the estimate for surface mines will be adjusted using these data. Emissions from coal handling operations were estimated using a technique from the literature, but

emissions from abandoned/inactive mines have not been addressed. Programs are underway in both of these areas and the current global estimate of 45.6 Tg/year will be modified as appropriate when they are complete.

A technology for enhancing the recovery of CH<sub>4</sub> from coalbeds is being demonstrated. It is expected that the increased efficiency will improve the economics of premine degasification and provide a reasonable method of mitigating CH<sub>4</sub> from underground mines should control of these sources become advisable.

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Emissions and Mitigation  
of Methane  
from the Natural Gas Industry

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ABSTRACT

The Gas Research Institute and the U.S. Environmental Protection Agency are cofunding and comanaging a program to evaluate methane emissions from U.S. natural gas operations. The purpose of the program is to provide an emissions inventory accurate enough for global climate modeling and for addressing the policy question of "whether encouraging the increased use of natural gas is a viable strategy for reducing the U.S. contribution to global warming." The program is composed of three phases: Scoping, Methods Development, and Implementation.

The purpose of Phase I was to define the problem. Phase II of the program concentrated on developing techniques for measuring steady or fugitive emissions and for calculating the highly variable unsteady emissions from the variety of sources that comprise the gas industry. Because of the large number of sources within each source type, techniques were also developed for extrapolating emissions data to similar sources within the industry.

Phase III of the program was started in early 1992 and should be completed in early 1994. The purpose of the current phase of the program is to collect sufficient data to achieve the accuracy goal of determining emissions to within  $\pm 0.5$  percent of production.

Based on the limited amount of data collected to date, methane emissions from the U.S. gas industry appear to be in the range of 1 percent of production.

## SECTION 1.0

### INTRODUCTION

The combustion of natural gas produces less carbon dioxide per unit of energy generated than either oil or coal. For this reason, a number of organizations have suggested that global warming could be reduced by encouraging fuel switching. However, methane is a more potent greenhouse gas than carbon dioxide. Since natural gas is approximately 90 percent methane, leakage of natural gas could reduce or even eliminate the inherent advantage that natural gas has because of its lower carbon dioxide emissions.

In order to accurately evaluate the impact of various fuels, the emissions of all greenhouse gases must be considered as well as the end use efficiency. In such an analysis, two major issues have been identified: The magnitude of the methane emissions for each fuel (coal, gas, and oil), and the impact of methane relative to carbon dioxide; i.e., the global warming potential (GWP) of methane. The uncertainty surrounding these two issues overwhelms all other considerations. For this reason, the Gas Research Institute (GRI) and the U.S. Environmental Protection Agency (EPA) have developed a jointly funded and managed program to better define emissions from the U.S. gas industry. It is a comprehensive study to quantify methane emissions from the wellhead to and including the customer's meter.

The goal of the study is to determine emissions to within 0.5 percent of production or approximately 100 billion cubic feet (BCF)\* per year.

The purpose of this paper is to describe the GRI/EPA program, present interim results, describe future work, and discuss mitigation strategies. These four topics also comprise the four major subsections of the paper.

\* English units are used in this paper because it is the accepted practice in the U.S. gas industry. The table below can be used to convert from English to metric units.

Conversion Table

FROM	TO	MULTIPLY BY
ft	m	0.3048
ft <sup>3</sup>	m <sup>3</sup>	0.02832
lb	kg	0.4536
hp	watts	745.7
mile	km	1.610

## SECTION 2.0

### DISCUSSION

#### 2.1      GRI/EPA Program

The GRI/EPA program is divided into three phases:

Phase I	Scoping
Phase II	Methods Development
Phase III	Implementation

##### 2.1.1      Phase I

Scoping studies were conducted by GRI and EPA independently, before the formation of the joint program. It was clear from these scoping studies that three major problems needed to be solved in order to quantify methane emissions from the U.S. gas industry.

First it was recognized that all types of emissions could not be measured. Steady emissions -- which are defined as emissions that are nearly constant in time such that a measurement made over a relatively short period (1 hour) is representative of the annual average value -- can be evaluated by measurement. However, it would be impossible, certainly impractical, to try to measure unsteady emissions; i.e., those that are highly variable with time. Therefore, techniques needed to be developed to calculate the unsteady emissions from all the different source types.

The second problem was that proven techniques for measuring the steady emissions from the different source types were not available. New techniques needed to be developed and validated.

Lastly, it was clear that, even if methods for calculating the unsteady emissions and measuring the steady emissions were available the emissions from all sources could not be evaluated because the number of sources was overwhelming. For example, there are a quarter million gas wells, over a million miles of pipe, and hundreds of thousands of pressure regulators. Because emissions from all these sources could not be measured, scientifically defensible techniques needed to be developed that would allow data obtained for a set of sources to be extrapolated to similar sources throughout the industry.

In summary, the scoping studies established that three major tasks needed to be accomplished in Phase II or the Methods Development Phase of the program. These are to develop methods for:

- Measuring Steady Emissions
- Calculating Unsteady Emissions
- Extrapolating Emissions Data



### 2.1.2 Phase II

The block diagram in Figure 1 illustrates the approach taken in the program. The gas industry was disaggregated until techniques could be identified for evaluating emissions from the various types of sources. In some cases emissions from the basic components of the industry (e.g., pipes, valves, flanges) needed to be considered. It was necessary to develop techniques not only for measuring the steady emissions from these sources, but also for calculating the unsteady emissions. In addition, accuracy targets for the emissions data from each source had to be established.

Accuracy targets were established in such a way that, if the target is met for each source, the overall accuracy of the program ( $\pm 100$  BCF) would automatically be achieved. In addition, the accuracy target is established as a function of the size of the source. A higher degree of accuracy is required for the larger sources, and this approach provides an automatic mechanism for apportioning the needed resources to the most important sources.

The flow chart for Phase II is presented in Figure 2. The first step is to gather information on the gas industry in order to better define and understand the problem to be solved. Developing methods for measuring, calculating, and extrapolating emissions proceeded along parallel tracks. The last step of the process is to validate the methods developed. The experimental methods were validated by conducting a "proof of concept" test not only to demonstrate that the method worked under controlled conditions, but also to establish error bounds. The technique was then demonstrated in the field by measuring emissions from actual sources. The methods for calculating the unsteady emissions and for extrapolating the data were validated by documenting the methods and subjecting them to a critical review by experts.

#### Measurement Techniques

Developing techniques for measuring steady emissions from all the different types of sources has presented the most difficulty. Figure 3 lists the five techniques that have been developed for measuring emissions from the different segments and source types comprising the industry. The essence of each method is described below.

Emission Factor Approach This approach is used to determine emissions from different source types based on measurements of emissions from individual pipe fittings such as valves, flanges, seals, and threaded fittings. Emissions from a large number of fittings are measured and an emission factor (i.e., average emission rate per fitting) is determined for each fitting type. Emissions from a source are calculated by multiplying the number of fittings comprising the source by the appropriate emission factor. The emissions are measured using the bagging technique; i.e., enclosing the leak in a bag, blowing uncontaminated air through the bag at a constant rate, and measuring the concentration in the stream. The emission rate is the product of the flow rate and concentration.

Correlation Equation Technique Like the Emission Factor Approach, this technique is based on measuring emissions for individual pipe fittings. However, a screening value is also obtained. The screening value, which is the maximum concentration measured on the fitting at the point of the leak, is correlated with the emission measurement. To determine the emissions from a specific source, the concentration measured from every leaking fitting is used with the correlation equation to calculate the emission rate for each fitting. The emissions from all the fittings comprising the source are summed to obtain the total value.

Tracer Gas In this approach, a tracer gas is released at a known constant rate at the methane source, and the concentration of both the tracer gas and the methane is measured at a point downwind where these gases are uniformly mixed. The emission rate of the methane source ( $E_M$ ) is calculated from the expression  $E_M = (C_M/C_T)E_T$ , where  $C_M$  is the methane concentration corrected for background,  $C_T$  is the tracer gas concentration, and  $E_T$  is the emission rate of the tracer gas.

Leak Statistics Method This method is directed toward evaluating emissions from buried pipelines in distribution systems and gathering lines in production fields. Emission rates are measured for a large number of leaks in order to accurately determine the average emission rate per leak as a function of pipe material, age, pressure, and soil characteristics.

The leak data recorded by individual gas distribution companies are statistically analyzed to determine the actual number of leaks in the system. Total emissions from the underground pipe system are calculated by multiplying the appropriate average emission rate per leak by the number of leaks per mile and the number of miles of pipe in each category.

Mass Balance Approach This method uses the existing metering system to perform a mass balance. The difference between the amounts entering and leaving a system is equal to the amount leaked to the atmosphere plus an error term. The key to the technique is to minimize the error. This can be accomplished by carefully selecting the site and by calibrating and characterizing the meters in the system.

### Calculating Unsteady Emissions

Techniques for calculating the unsteady emissions are described in Reference 1.

Emissions from a given source can be caused by any of the following activities:

- Normal operations,
- Maintenance,
- Upsets,
- Mishaps,
- Leaks, and
- Combustion.

Because the technique for calculating the unsteady emissions is dependent on not only the type of source, but also the cause of the emissions, as many as six equations are needed to specify the unsteady emissions from a given source type.

Initial studies indicated that emissions from compressor exhaust and venting activities accounted for nearly 98 percent of the unsteady emissions. Therefore, Radian Corporation, the contractor for this portion of the work, focused their resources during Phase II on these two categories.

#### Extrapolation Technique

Emission and activity factors will be used to extrapolate the measured or calculated emissions data. These factors are defined in such a way that their product will be equal to the total emissions from a given source type or category.

In the simplest case, the emission factor would be defined as the average emission rate calculated from a large number of measurements of randomly selected sources of a given type. The activity factor would then be the number of sources within the U.S. For example, total U.S. emissions from pressure regulating and metering stations could be calculated by multiplying the emission factor, which would be the average emission rate (cubic feet/station-year), by the activity factor, which would be the total number of stations.

In applying the approach, two major problems can be encountered. The first is that the variability in the emissions data is very large which could mean a very large number of expensive tests would be required to achieve the desired accuracy target. This problem can often be alleviated by presenting the emission and activity factors as a function of other parameters that affect the emission rate.

The second problem is that the sources tested cannot be randomly selected for a number of practical reasons. This can induce bias in the results. The bias can often be found through an analysis of the data. For example, Table 1 presents the measured emission rate from 39 pressure regulating and metering stations along with the emission and activity factors and the extrapolated emissions for this source type. The extrapolated emissions for this source category are 140 BCF. However, if the data are subdivided into two categories (pressure regulating stations, and regulating and metering stations), the estimated emissions for this category decrease to 81 BCF. If these categories are then subdivided into discrete operating pressure ranges, the estimated emissions decrease to less than 27 BCF. The bias, which was caused by testing a disproportionate number of high pressure facilities, can be removed by refining the emission factor. As shown in Table 1, the extrapolated emissions decreased by over a factor 5 as a result of analyzing the data to refine the emission and activity factors.

## 2.2 Results

### 2.2.1 Measurement Techniques

As part of the process to develop and validate experimental techniques, tests were conducted to first prove the concept. These tests were then followed by a series of demonstration tests to verify that the technique could be used to measure emissions from specific types or groups of sources. The purpose of the Phase II effort was to develop and validate methods, not to collect data on a wholesale basis.

#### Proof of Concept Tests

Emissions Factor/Correlation Equation Method These methods are standard techniques approved by EPA (Reference 1) for measuring fugitive or steady emissions from oil, gas, and chemical production and processing facilities. The methods were originally developed based on data collected in the late 1970's. Because the validity of these data has been questioned, tests were conducted in the spring of 1990 at a gas/oil production site. Although the test program was limited, it was determined that the emission factor approach over estimated emissions by a factor of 5 to 20, that there was large uncertainty in the correlation equation approach, and that an extensive data collection effort was required to develop new emission factors and to select the proper correlation equation from the many found in the literature (Reference 2).

Tracer/Proof of Concept Test A proof of concept test was conducted by SRI International to demonstrate that a tracer gas could be used to measure emissions from a point source. In this test, methane, ethane, and a tracer gas were released at a constant rate from the same location. The release rate was carefully measured for all the gases. Air samples were collected at 15 minute intervals at three downwind distances and analyzed to determine the concentration of the gases. It was found that the release rate of methane and ethane could be calculated to within 10 percent of the true value (Reference 3) using the relationship that the ratio of emission rates ( $E_M/E_T$ ) is equal to the ratio of concentrations ( $C_M/C_T$ ).

A similar proof of concept test was conducted by Washington State University (WSU) teamed with Aerodyne Research Inc. (ARI). For this test a real-time instrument, developed by WSU for measuring the tracer gas, was mounted in a truck with a helium/neon laser, developed by ARI for measuring methane. The laser system is capable of measuring methane in real-time to within  $\pm 5$  ppb. These mobile instruments were then used to traverse the plume generated by releasing methane and the tracer gas at a known constant rate. Tests were conducted with the sources colocated and also separated by 100 feet. In both cases, the emission rate of the methane source was calculated to be within 10 percent of the true value (Reference 4).

Leak Statistics and Mass Balance These techniques have been used by the gas industry to account for the gas moving through the system (Reference 5). The difference between the metered volumes entering and leaving the system is equal to that used in the system plus a residual often called "unaccounted

for" (UAF) gas. UAF gas results from accounting errors, metering errors, theft, and leakage. To assess the leakage component, the industry has used the leak statistics method for a number of years; therefore, there was not a need to perform proof of concept tests for either of these methods.

### Demonstration and Other Test Results

#### Tracer Method

SRI APPROACH... SRI International conducted tracer tests at two gas/oil production facilities. The test results are documented in Reference 5. The purpose of these tests was to demonstrate that the tracer technique could be used to measure emissions from sources generally found at production/processing sites such as wells, separators, heaters, gas plants, and compressor stations. SRI used as many as 30 sequential samplers to collect air samples over eight 15 minute periods. The samples were later analyzed in a field laboratory using a gas chromatograph to measure the ratio of methane to tracer gas. Although the tests were successful, it was concluded that real-time instruments were needed if tracer tests were to be conducted routinely. Analysis of the large number of samples (20 to 30 samplers with 8 bags per sampler) was too expensive. Also, it was hard to detect interference from other sources, and the success or failure of the experiment could not be confirmed until all the air samples had been analyzed. It was also determined that the tracer technique could not be used effectively to measure the emission rate from wells because only 2 or 3 percent leak at a detectable rate and significant resources are needed merely to find the few leaking wells.

ARI/WSU APPROACH... A team consisting of ARI and WSU personnel demonstrated that the tracer or modified tracer technique could be used to measure emissions from production/processing facilities and from distribution systems. The team used a truck outfitted with instruments capable of measuring methane, SF<sub>6</sub> (tracer gas), and carbon dioxide nearly continuously in real time.

These tests (References 6 and 7) demonstrated that the tracer technique is well suited for measuring emissions from a point source or any group of spatially concentrated sources. These include metering/pressure regulating facilities, compressor stations, gas processing plants, separators, and metering facilities. The method is not well suited to measure emissions from wells and customer meters because of the large effort required to identify the few that leak. Tracer tests of 39 pressure regulating/metering stations are summarized in Table 1 and were discussed in Section 2.1.2.

Screening tests were also conducted by ARI/WSU to find a suitable site for demonstrating that the tracer technique could be used to determine the emissions from a complete distribution system. A requirement of the tracer method is that the tracer and methane plume are uniformly mixed. This means that the measurement must be made a sufficient distance downwind of the source to allow the plumes to mix properly. The screening tests showed that methane sources are so widely dispersed within a city that the methane plume is only a few hundred ppb above the background level at the edge of the city. The background concentration is typically 1850 ppb with a temporal

variability of  $\pm 100$  ppb. The plume from the city disperses rapidly and cannot be distinguished from background levels long before the tracer gas plume can be mixed with the methane plume from the city.

As described in References 8 and 9, a variety of modified tracer techniques were formulated and explored. The basis of these methods is that an equation can be derived from the Gaussian plume dispersion model which relaxes the requirement that the tracer and methane plumes be uniformly mixed. The relationship for any point, line, or uniform area source is that the ratio of emission rates ( $E_M/E_T$ ) is equal to the ratio of the cross wind integral of the concentration ( $IC_M/IC_T$ ) at any point downwind of the source.

A test was conducted in a city which appeared to be best suited for demonstrating the various modified tracer techniques based on screening tests conducted in 15 cities around the country. This test indicated that whole city methane emissions can be measured with roughly  $\pm 50$  percent accuracy. However, such measurements include all sources of methane, and it was concluded that emissions from the natural gas system could not be determined with sufficient accuracy for this program.

#### Emission Factor/Correlation Equations

A test program designed to develop new emission factors and a new correlation equation was funded by GRI and the American Petroleum Institute (API). Star Environmental is the contractor on the project.

Bagging and screening tests were conducted at 16 onshore sites in the four major gas/oil production regions in the continental U.S. The 16 sites were evenly divided among heavy and light oil, gas production, and gas processing. Nearly 175,000 components were screened, and the emission rates were measured for 750 randomly selected fittings using the bagging technique.

Bagging and screening tests were conducted on four offshore gas/oil production platforms in the Gulf of Mexico. This program was designed to complement the 1990 study sponsored by Mineral Management Services to collect data from gas/oil production platforms off the California coast (Reference 10).

Data on emissions and the percent of leaking components determined in this program are compared in Table 2 with similar data collected by Rockwell for API in the late 1970's. These data indicate that facilities are significantly tighter now. About one third as many components leak, and the emissions are a factor of 3 to 8 lower than the API/Rockwell data.

A plot of the correlation equations developed from the recent API/GRI data, the API/Rockwell data, and the curve recommended by EPA are compared in Figure 4. Because the correlation equation should be independent of the leakiness of a facility, the correlation equations would be expected to be the same. There is good agreement between the API/GRI and the older API/Rockwell curves. However, the EPA curve would overpredict emissions from the facilities tested by a factor of 3 to 10.

#### Mass Balance Approach

The emissions from a transmission system are being calculated by Southwest Research Inc. using the mass balance technique. The results from this method will be available in October 1992.

#### Leak Statistics Method

This technique is costly to apply on a national scale. Therefore, a cooperative study was formed with nine U.S., two Canadian, and two European distribution companies to measure leakage from distribution systems. This Leakage Measurement Program is intended to be a separate project designed to provide participating companies a leakage estimate of sufficient accuracy that operational issues can be addressed.

Data currently available are presented in Table 3 in aggregate and separately for mains and services. As more data become available, the data will be analyzed to determine the effect of age, material, pressure, size, and soil characteristics as well as the leak survey technique used by the participating companies.

#### Summary of Test Results

Tests conducted to determine the steady emissions for the various source categories are summarized in Table 4. The table presents the number of tests, the emission factor determined from the test data, the activity factor, and a current estimate of steady emissions from the gas industry. It is clear that much more data are required before a defensible estimate can be made of emissions from U.S. gas operations. For example, the emissions from only 13 meters in one distribution system have been measured out of an estimated 50 million customer meters. The uncertainty in the estimate cannot be evaluated. Although the random error in the emissions data is a straightforward calculation, the bias cannot be addressed until data are collected from other systems around the country.

#### 2.2.2 Unsteady Emissions

The latest calculations of the unsteady emissions are summarized in Table 5. As discussed previously, the unsteady emissions are a function of the cause of the emissions from each source. Although as many as six calculations would be required to account for all the unsteady emissions from each source, most are negligible. As shown in Table 5, 97 percent of all unsteady emissions are caused by normal operations, combustion, and maintenance operations. Nearly 80 percent result from three activities, pipe and facility blowdowns, compressor exhausts, and venting from pneumatic devices.

The calculated unsteady emission rates for a source are analogous to measurements of the steady emissions. For the most part, information needed to calculate unsteady emissions is obtained during site visits in which information is also collected to quantify the activity factor. The columns labeled "Number of Calculations" and "Number of Sites" in Table 5 indicate the number of sources for which the emission rate was calculated and the number of sites represented in the estimate.

In developing the Phase III implementation plan, the variability in the emissions is used to calculate the additional data needed to achieve the accuracy target for each source. An analysis of the emissions data is also used to assess bias and the need to collect data from a larger number of sites. The results of this analysis are summarized in Table 5 under the column, "Number Of Sites To Be Visited."

#### 2.2.3 Total Emission Estimate

The unsteady emissions are estimated to be 102 BCF, and the estimate for the steady emissions is 84 BCF. This gives a total of 186 BCF for the U.S. gas industry or approximately 1 percent of gas production.

The uncertainty, the target accuracy of each source, and the number of additional data points required to achieve the target accuracy are routinely calculated each time a new emissions estimate is made. The current uncertainty is around  $\pm 80$  percent. However, this calculated uncertainty includes only random error, not bias. The possibility of large bias errors exists in the current estimate because of the limited number of sites visited. For this reason, a defensible estimate of the uncertainty cannot be provided at this time.

### 2.3 Future Activities/Phase III

The purpose of Phase III is to collect sufficient emissions data to determine emissions for the U.S. gas industry within 0.5 percent of production. The flow chart for Phase III is presented in Figure 5.

The first task is to apportion available resources to focus on sources with the largest emissions and highest uncertainty in the emissions estimate. Each source is examined to determine if the accuracy target has been achieved. If not, the number of additional data points needed to achieve the accuracy target is calculated from the standard deviation for a 90 percent confidence level. If there is more than one method of obtaining emissions data, a cost optimization program is used to select the most cost effective approach.

The most cost effective approach typically depends on the accuracy of the method, the cost per data point, and the number of data points needed. Because the standard deviation of the emissions data will change as additional data are collected, optimizing the Phase III effort will be an iterative procedure.

The second task of Phase III is to develop an implementation plan. The Phase III implementation plan which defines the data needed and how, where, and when the data will be collected, has been completed and documented (Reference 11).

Testing started in the early summer of 1992 and will continue through the summer of 1993. Facilities around the country will be visited to collect the information needed to calculate the unsteady emissions and to quantify the



activity factors. The unsteady emissions will be calculated and the steady emissions will be measured at a sufficient number of sources to achieve the accuracy target.

The last step of Phase III is to extrapolate the emissions data using the emission and activity factors to obtain the national emissions estimate.

The current estimate of the additional measurements that are required to achieve the accuracy target for each source is presented in Table 6. The table also indicates which measurement techniques were determined to be the most cost effective. In some cases, however, data will be collected

using more than one method in order to address the question of bias or to improve the credibility of the data by demonstrating that different methods give the same results.

Table 7 is a summary of the number of site visits that will be made during Phase III and the information that will be collected to determine the activity factors and to calculate the emission factors for the unsteady emissions.

#### 2.4 Mitigation of Emissions

Emission estimates from the GRI/EPA program, although preliminary, were used as the basis for a study conducted by Radian to examine cost effective techniques for reducing emissions from the gas industry. This work was sponsored by EPA and was not part of the GRI/EPA emissions study. A cost/benefit analysis was conducted in which the "net present value" (NPV) was calculated for 22 mitigation techniques. The net value was calculated as the difference between the cost of implementing the control strategy and the value of the gas saved. By ignoring any environmental benefit, the analysis would indicate which control measures would make sense to implement, based on reducing operating cost independent of the environmental benefit.

The assumptions used in the NPV analysis are:

- The value of benefits is only the value of the gas saved.
- The average wage is \$25 per hour and increases by 2 percent per year in real terms (i.e., no inflation).
- The discount rate and opportunity cost of equity is 6 percent in real terms.
- The value of natural gas saved per 1000 cf is \$1.59 for production, \$2.01 for transmission, and \$2.91 for distributors. The value is assumed to increase 2 percent per year in real terms.

The results of the study are summarized in Table 8 for the 22 techniques evaluated.

The study indicates that improved inspection and maintenance programs,

installation of low-bleed pneumatic devices, recompression of gas during maintenance activities, pipe replacement, and use of glycol dehydrator exhaust as fuel could be cost effective in some circumstances.

The use of low-bleed control devices is found to be cost effective if installed as the high-bleed devices are retired after a full lifetime. There is only a small incremental capital and installation cost. The cost effectiveness of inspection and maintenance programs is very sensitive to labor cost and the amount of gas leaked. The use of glycol dehydrator exhaust as fuel is predicated on having accumulators installed to capture the hydrocarbons as part of a control program for toxic emissions that may be required by new regulations. Pipe replacement is cost effective only in areas with low installation cost (\$80/ft) and a high repair rate (25 leak repairs/mile). The reduction in gas lost had a negligible effect on the analysis of the pipe replacement strategy.

The cost effectiveness of recompression and reinjection of gas back into the pipeline during maintenance operations varies from case to case. It is generally sensitive to whether the compressor is rented or purchased and whether the study assumes that the strategy will be implemented all year or only when demand is low. Typically, a downtime of 4 days could be required to recompress the gas, while venting the gas could take only 4 hours. The difference in downtime during peak periods could be unacceptable.

Gasunie, a gas transmission company in The Netherlands, also conducted a study to determine if recompression of gas was a cost effective approach of reducing emissions (Reference 12). Because the compressor was rented, the cost effectiveness of recompression depends on the amount of gas in the line. In The Netherlands, recompression was found to be cost effective if more than 2.3 million cf of gas is recovered.

Since the benefit in the cost/benefit analysis is the value of the natural gas saved, the results are obviously highly dependent on the accuracy of the emissions data. This is a problem not only for the current study, but one that is likely to affect future studies unless it is specifically addressed. At this stage of the GRI/EPA emissions study, it is not possible to give a credible estimate of the uncertainty in the emissions data. This will be possible as the study progresses further into Phase III. However, this program was never designed to determine emissions from specific types of sources with a high degree of accuracy.

The goal of the program is to determine overall emissions to within 0.5 percent of production. This can be achieved even if the error bound on the emissions estimate for specific source categories is  $\pm$  a factor of 2. This is not sufficiently accurate for a cost/benefit analysis to decide which mitigation strategies are cost effective.

To provide sufficiently accurate data for these studies would be cost prohibitive. There seem to be two alternatives. The first is to improve the accuracy of the emissions estimate for a targeted set of sources that are candidates for mitigation measures. The second is to reverse the roles and use a cost/benefit analysis to determine the emissions that are required for

specific mitigation strategies to be cost effective. These results would provide valuable guidelines to the industry on ways of reducing operating cost. Emission rates vary substantially from site to site. Although a specific mitigation technique may not be cost effective for the average facility, many companies could find it very profitable to implement the technique because their emissions are much higher than the average value. As the industry implements these cost saving techniques, their feedback will provide the accurate, detailed information needed to refine the mitigation strategies.

## SECTION 3.0

### SUMMARY/CONCLUSIONS

The primary purpose of the study is to provide an emission inventory accurate enough for global climate modeling studies and for addressing the policy question of whether or not to encourage the increased use of natural gas in order to reduce global warming.

The GRI/EPA program is designed to determine methane emissions from the U.S. gas industry within  $\pm 0.5$  percent of gas production. The purpose of Phase I was to define the problem. Phase II was spent developing the tools needed to measure or calculate methane emissions from the various source types that comprise the industry. Also, because of the large number of sources within each source type, techniques were developed for extrapolating emissions data to similar sources within the industry. The purpose of Phase III is to collect sufficient data to achieve the accuracy goal of the study.

Emissions data are also needed for examining cost effective techniques for mitigating emissions from the gas industry. Unfortunately, it would be cost prohibitive to determine the emissions from all sources with the accuracy needed for cost/benefit studies. This problem can be alleviated by improving the emissions estimate for a targeted group of source types. However, another approach would be to reverse the roles, and use the cost/benefit analysis to determine the emissions that would be required for selected mitigation strategies to be cost effective.

Phases I and II have been completed. Phase III was started in early 1992, and the data collection effort will be completed in the summer of 1993. The entire study is expected to be completed by early 1994.

Based on the limited amount of data collected to date, methane emissions for the U.S. gas industry appear to be in the range of 1 percent of production. The estimate of the unsteady emissions is 102 BCF, and the steady emissions are estimated at 84 BCF per year.

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This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

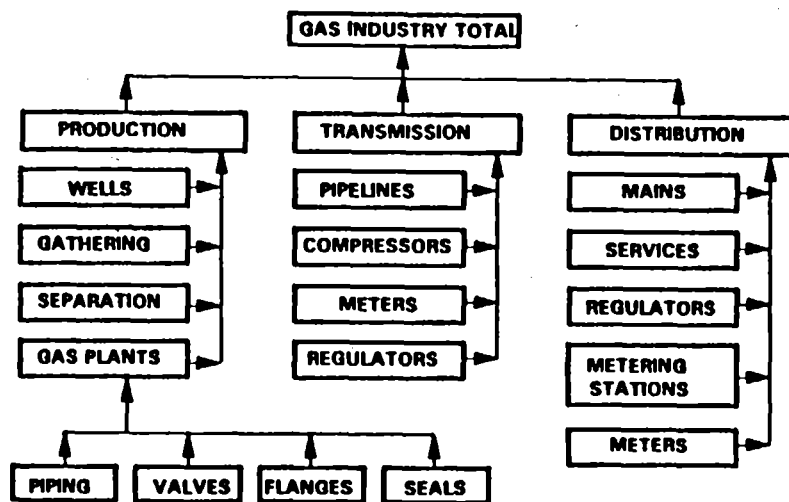


Figure 1 U.S. Gas Industry Disaggregated by Source

EPA/600/1-87/001

## PHASE II METHODS DEVELOPMENT

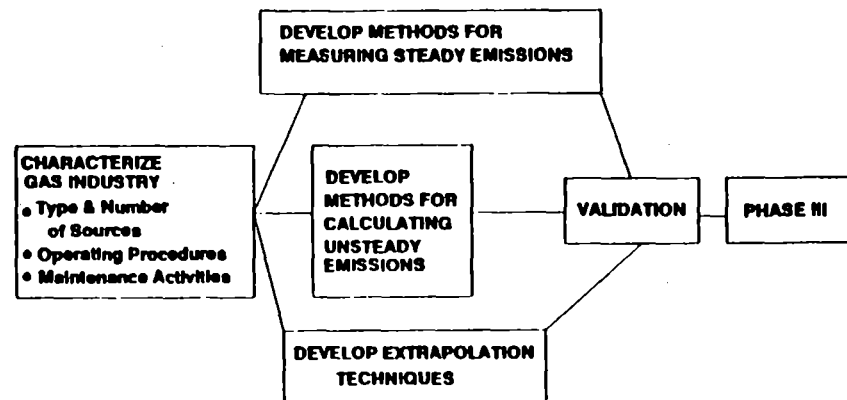


Figure 2 Flow Chart of Phase II

EPA/600/1-87/001

SEGMENTS/ SOURCE TYPES	TECHNIQUES				
	EMISSION FACTOR	CORRELATION EQUATION	TRACER GAS	LEAK STATISTICS	MASS BALANCE
PRODUCTION					
• WELLS	●	●			
• GATHERING				*	○
• SEPARATION	●	●	●		
• GAS PLANTS	●	●	●		
TRANSMISSION					○
• PIPE LINES				*	
• COMPRESSORS	●		●		
• METERS		●	●		
• REGULATORS		●	●		
DISTRIBUTION			●		
• MAINS				●	
• SERVICES				●	
• METERING STATIONS		●	●		
• REGULATOR STATIONS		●	●		
• METERS	●	●			

○ IN PROGRESS

● COMPLETED

\* BASED ON DATA FROM DISTRIBUTION SYSTEMS

Figure 3 Techniques Developed for Measuring Steady Emissions

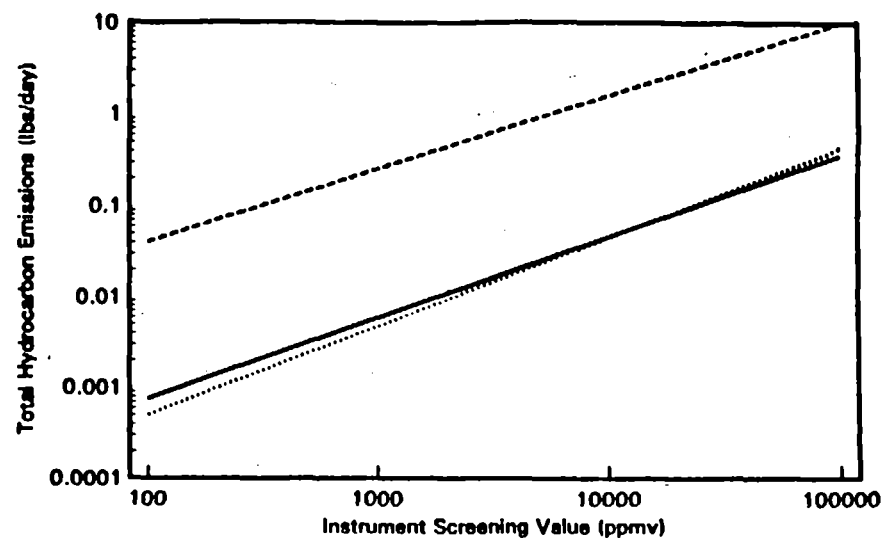
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TABLE 1: MEASURED METHANE EMISSIONS FROM METERING  
AND PRESSURE REGULATING STATIONS

CATEGORY	NUMBER OF TESTS	EMISSION FACTOR (CF/HR)	ACTIVITY FACTOR NO. OF FACILITIES	EMISSIONS (BCF)	TOTAL EMISSIONS (BCF)
All	39	120	135,000	140	140
Reg. Stations	27	63	132,000	75	
M & R Stations	12	260	2,600	6	81
Reg. Stations:					
> 300	12	87	3,700	2.8	
100 to 300	7	85	18,000	13.6	
40 to 100	4	0.80	90,000	0.6	
< 40	4	0.90	20,000	0.2	
M & R Stations:					
> 300	8	370	14,000	4.5	
100 to 300	1	590	1,000	5	
40 to 100	3	0.05	200	0.0	
< 40	0	0	0	0	26.4

TABLE 2: COMPARISON OF BAGGING AND SCREENING DATA

TYPE FACILITY	DATA SET	% COMP. LEAKING	EMISSIONS LBS/COMP.-DAY
Gas Plants	API/Rockwell	12.0	0.130
	API/GRI 1992	4.2	0.017
Gas Production	API/Rockwell	4.7	0.070
	API/GRI 1992	3.4	0.020
Off-Shore Platforms Gulf of Mexico	API/Rockwell	3.8	0.057
	API/GRI 1992	1.1	0.007



EPA Flanges API/Rockwell API/GRI  
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Figure 4 Correlation of Instrument Screening Values to Total Hydrocarbon Emissions

TABLE 4: SUMMARY OF STEADY EMISSIONS

CATEGORY	NUMBER OF TESTS	EMISSION FACTOR (CF/YR)	ACTIVITY FACTOR (%)	EMISSIONS (BCF)
Production/Processing:				
Wells	321	2,000	540,000	1.0
Gathering Lines	**	20,000	91,000	1.8
Separators	114	8,000	10,000	1.4
Heaters	84	9,000	54,000	0.5
Dehydrators	32	11,000	20,000	0.2
Meters	15	20,000	20,000	0.4
Gas Plants	42	1.0 X 10 <sup>6</sup>	742	0.7
Transmission:				
Compressor Stations	0	6.5 X 10 <sup>6</sup>	2,000	13.0
M&R Stations	8	3 X 10 <sup>6</sup>	5,000	16.0
Distribution:				
Mains	37	20,000	836,000	16.5
Services	30	65	45 X 10 <sup>6</sup>	3.0
Pressure Reg > 100	19	800,000	22,000	16.0
Pressure Reg < 100	8	8,000	110,000	0.8
M&R > 100	1	5 X 10 <sup>6</sup>	1,000	5.0
M&R < 100	3	500	200	0.0
Customer Meters	13	140	50 X 10 <sup>6</sup>	7.0
TOTAL:				83.3

\* Number of facilities or miles of pipe for mains and gathering lines

\*\* Based on data for mains

TABLE 3: LEAKAGE MEASUREMENTS OF BURIED PIPE IN DISTRIBUTION SYSTEMS

CATEGORY	NUMBER OF TESTS	AVERAGE (CF/HR)	COEFFICIENT OF VARIATION
ALL	62	2.3	3.4
MAINS	30	3.6	3.2
SERVICES	32	1.2	1.4

**TABLE 5: CALCULATED VALUES OF THE UNSTEADY  
EMISSIONS FROM U.S. GAS OPERATIONS**

CATEGORY	NUMBER OF CALCULATIONS	NUMBER OF SITES	NUMBER OF SITES TO BE VISITED	EMISSIONS (BCF)	% OF TOTAL EMISSIONS	% OF UNSTEADY EMISSIONS
Normal Operations:						
Pneumatics	26	26	31	37	19	36
Compressor Start/Stop	1	1	37	8	4	8
Dehydrator Vents	2	2	23	9	5	9
Combustion:						
Compressor Exhausts	861	112	37	22	12	22
Maintenance Operations:						
Well Workovers	2	2	23	2	1	2
Facility & Pipe Blowdowns	1	1	27	21	11	20
Mishaps:						
"Dig Ins"	1	1	27	3	1.5	3
Upsets	—	—	56	—	—	—
Leaks	—	—	9	—	—	—
<b>TOTAL:</b>			<b>56*</b>	<b>102</b>	<b>54</b>	<b>100</b>

\* The total consists of visits to 9 distribution systems, 18 transmission segments, 23 production fields, and 6 processing plants.

### PHASE III IMPLEMENTATION

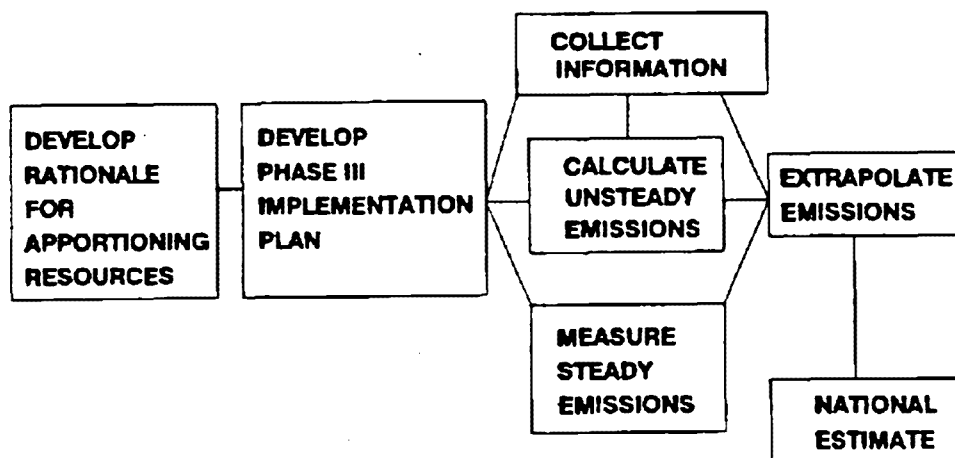


Figure 5 Flow Chart for Phase III



**TABLE 6: SUMMARY OF PHASE III TEST PLANS**

SEGMENTS/ SOURCE TYPES	BAGGING		EMISSION FACTOR		CORRELATION EQUATION		TRACER		LEAK STATISTICS	
Production										
- Wells	321 4	0 0	0 0	4600 23						
- Separators	114 4	0 0	0 0	920 23			0 0	18 6		
- Heaters	84 4	0 0	0 0	230 23			0 0	12 6		
- Dehydrators	32 4	0 0	0 0	184 23			0 0	6 6		
- Meters	15 2	0 0	0 0	1380 23			0 0	12 6		
- Gas Plants	4 4	0 0	0 0	6 6			1 1	3 3		
Transmission										
- Compressor Stations					0 0	20 6				
- M & R Stations							7 6	24 6		
Distribution										
- Mains									30 2	100 13
- Services									32 2	100 13
- Metering Stations							5 3	30 6		
- Regulator Stations							27 11	45 6		
- Meters	26 2	0 0			100 2	1000 5				

1	3
2	4

1 = No. of Tests  
 2 = No. of Sites  
 3 = No. To Be Tested  
 4 = No. of Sites

**TABLE 7: SUMMARY OF SITE VISITS AND INFORMATION TO BE GATHERED**

<b>SITB TYPE</b>	<b># OF SITES VISITED</b>	<b># OF SITES TO BE VISITED</b>	<b>ACTIVITY FACTOR DATA</b>	<b>EMISSION FACTOR DATA</b>
Gas/Oil Field	2	23	Separators per well Heaters per well Field throughput Dehydrators per well Vessel blowdown frequency Compressor start/stop frequency PRV* lift frequency Pneumatics per equipment type Number of compressors, type	Dehydrator conditions Vessel volumes Compressor volumes Field pressure Pneumatic device types Compressor exhaust, fuel use
Gathering Facilities	0	20	Station throughput & mileage Line blowdown frequency Compressor start/stop frequency Pneumatics per equipment type Number of compressors, type	Volume of lines Compressor volumes Blowdown volumes
Gas Plants	3	6	Maintenance frequency Compressor start/stop frequency Number of compressors, type Dehydrator count PRV lift frequency	Plant volumes & practices Compressor volumes Compressor exhaust, fuel use Dehydrator conditions
Transmission Facilities	1	18	Throughput and mileage Compressor start/stop frequency Number of compressors, type Pneumatics per equipment type PRV lift frequency Mishap frequency	Compressor volumes Compressor exhaust, fuel use Pneumatic device types Mishap volumes
Distribution Systems	2	9	Mileage main & services, type Number class I leaks PRV lift frequency Mishap frequency Pneumatics per equipment type	Blowdown volumes Pneumatic device types Mishap volumes

\*PRV = Pressure Relief Valve

TABLE 8

# SUMMARY COMPARISON OF ECONOMIC COSTS AND BENEFITS FOR METHANE EMISSION REDUCTION TECHNIQUES

Date Sheet No.	Technique	Net Present Value (Millions \$)	Incremental Cost per BCF Product (\$)	Cost per Activity Unit (\$)	Activity	Annual Methane Reduction (BCF/yr)
<b>PRODUCTION</b>						
1	Fugitives: directed inspection and maintenance of leaking components—gas well sites	-21,000	-97,400	-5,789	Well Site	8.320
2	Fugitives: directed inspection and maintenance of leaking components—gathering line compressor stations	+0.092	-0	+15 +0.007	Station Mile	3.744
3	Control of methane losses by substitution of low-blend pneumatic devices for existing devices—90% control efficiency, completed in seven years	+409	+5,660	+118	Device	17.420
4*	Flaring methane emissions from glycol dehydrators	-520	-1,760	-1,891	Dehydrator	6.084
5*	Using methane exhaust from glycol dehydrators as boiler fuel—accumulators in place	-17	-30	-61	Dehydrator	6.084
6*	Using methane from glycol dehydrators as boiler fuel—accumulators additional	-570	-1,900	-2,056	Dehydrator	6.084
7	Control of compressor exhaust through retrofit with catalytic converters	-180	-10,200	-9.87 -9,935	hp Compressor	1.144
<b>PROCESSING</b>						
8*	Flaring methane emissions from glycol dehydrators	-55	-270	-606	Dehydrator	1.872
9*	Using methane exhaust from glycol dehydrators as boiler fuel—accumulators in place	-5.5	-20	-61	Dehydrator	1.872
10*	Using methane exhaust from glycol dehydrators as boiler fuel—accumulators additional	-190	-920	-2,056	Dehydrator	1.872
11	Control of compressor exhaust through retrofit with catalytic converters	-220	-2,220	-9.87 -9,870	hp Compressor	1.508
<b>TRANSMISSION</b>						
12	Fugitives: directed inspection and maintenance of leaking components—compressor stations	+88	+360	+4,349 23	Station Mile	11.960
13	Control of methane losses by substitution of low-blend pneumatic devices for existing devices—90% control efficiency, completed in seven years	+275	+1,190	+149	Device	9.256
14*	Flaring methane emissions from glycol dehydrators	-160	-680	-1,891	Dehydrator	1.872
15*	Using methane exhaust from glycol dehydrators as boiler fuel—accumulators in place	+6.4	+27	+76	Dehydrator	1.872
16*	Use of methane exhaust from glycol dehydrators as boiler fuel—accumulators additional	-160	-690	-1,919	Dehydrator	1.872
17*	Use of portable compressors to capture vented gas during transmission line blowdowns	+0.743	+10	+72 +0.088	Blowdown Mile	9.360
18*	Control of methane losses during the blowdown of pipelines (i.e., for routine maintenance) through the use of mobile flares	-6.5	-30	-1,384 -7,118	Blowdown Flare Unit	11.440
19	Installing a gas turbine opposed to a reciprocating engine in a new compressor station — 5,000 hp compressor	+0.175	N/A	+82.52	hp-yr	0.090
20	Control of compressor exhaust through retrofit with catalytic converters	-650	-10,530	-9.87 14,905	hp Compressor	5.252
<b>DISTRIBUTION</b>						
21	Fugitives: directed inspection and maintenance of leaking components	+70	+320	+1,380	Station	4.212
22	Replacement/insertion of leaky pipe with plastic pipe (per mile basis) Low: High:	+\$ 1,400 -\$ 43,000	+168,000,000 -\$ 5,158,000,000	+\$ 1,400 -\$ 43,000	Mile Mile	8.32E-6

\*Glycol dehydrator options are mutually exclusive within each sector

\*Mobile flares and compressors may be used in tandem or separately, but total reductions will not be more than 11.44 BCF/yr.

**EMISSIONS AND MITIGATION AT LANDFILLS  
AND OTHER WASTE MANAGEMENT FACILITIES**

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## ABSTRACT

Landfills and other waste management sources of methane are amenable to cost-effective control. Consequently these sources have been given a high priority for clarification of their emission potential. The United States Environmental Protection Agency (U.S. EPA) is conducting research to determine the emission potential and mitigation opportunities for cost-effective control for the major sources of greenhouse gases. EPA's Air and Energy Engineering Research Laboratory (AEERL) is responsible for developing more reliable global and country-specific estimates for the major sources of greenhouse gases including waste management, coal mines, natural gas production/distribution, energy usage, cookstoves, and biomass combustion. AEERL has gathered data which have resulted in the development of more reliable estimates for landfills. Research has been initiated to characterize the methane potential of other waste management facilities including wastewater treatment lagoons, septic sewage systems, and livestock waste.

AEERL is also documenting the current state of technology for utilization projects. Currently there are 114 landfill gas to energy projects in the U.S. and about 200 worldwide. Technology transfer/technical assistance programs have been initiated to help encourage the utilization of waste methane and to help implement the upcoming Clean Air Act (CAA) regulations for municipal solid waste landfills. For example, AEERL is working with a consortium of local government representatives to explore the application of EPA research on methane/energy recovery from municipal solid waste landfills. AEERL also serves on the International Energy Agency Expert Working Group on Landfill Gas and the Steering Committee for the Solid Waste Association of North America. AEERL is also responsible for demonstrating innovative approaches to the control of waste methane such as the application of fuel cell technology to recover energy from landfill gas and digester gas.

This paper describes the emission potential for waste management sources and the mitigation opportunities. It also provides an overview of some of the barriers in the U.S. that affect methane utilization. This research is funded through EPA's Global Climate Change Research Program. This paper has been reviewed in accordance with EPA's peer and administrative review policies and approved for presentation and publication.

## INTRODUCTION

Waste disposal results in emissions of greenhouse gases including methane ( $\text{CH}_4$ ), carbon dioxide ( $\text{CO}_2$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), ozone precursors, and chlorofluorocarbons. The major sources of  $\text{CH}_4$  from waste management include landfills, wastewater treatment lagoons, and livestock waste. Current estimates suggest that this source accounts for up to 125 Tg/yr or ~40% of the estimated total global anthropogenic emissions of 300 Tg/yr (IPCC, 1992). Landfills have been estimated to contribute as much as 60 Tg/yr of  $\text{CH}_4$ . Policies are being considered to reduce greenhouse gas emissions to meet the goals of the United Nations Conference on Environment and Development held in Rio de Janeiro in June. Emissions sources that are amenable to control — such as landfills — have been given a high priority for clarification. (EPA, 1989)

“Waste”  $\text{CH}_4$  results from the anaerobic decomposition of biodegradable waste found in landfills, open dumps, waste piles, wastewater treatment lagoons, septic sewage systems, and livestock waste. This waste  $\text{CH}_4$  can be a source of pollution as well as a resource. There are 114 landfill gas (LFG)-to-energy projects in the U.S. (Thorneloe, 3/92) and 200 LFG-to-energy projects worldwide (Richards, 1989). Landfill gas is utilized (1) as medium-heating-value fuel, (2) to generate electricity using internal combustion engines, or gas and steam-fed turbines, and (3) as high-heating-value fuel in which case the gas is upgraded and fed into a nearby natural gas pipeline. U.S. landfills currently generate 344 MW of electricity (Thorneloe, 3/92). The gas that is formed from anaerobic decomposition is typically 50 to 55%  $\text{CH}_4$ , 45 to 50%  $\text{CO}_2$ , and <1% trace constituents.

The  $\text{CH}_4$  is a concern because of its global warming effects and explosive potential. Emissions of nonmethane organic compounds (NMOC) contribute to tropospheric ozone which aggravates urban smog and is a concern to human health and the environment. Other LFG constituents such as vinyl chloride, benzene, carbon tetrachloride, and methylene chloride are a concern for their cancerous and noncancerous effects. The Agency has proposed CAA regulations for emissions from municipal solid waste (MSW) landfills (FR, 1991) which will reduce five health and welfare effects: (1) explosion hazards, (2) global warming effects from  $\text{CH}_4$  emissions, (3) human health and vegetation effects caused by ozone formed from NMOCs, (4) carcinogenicity and other possible noncancerous health effects associated with specific landfill emissions constituents, and (5) odor nuisance (U.S.EPA, 3/91). Estimates from the proposed regulations indicate that 621 landfills of the 6,000 existing active landfills would be required to collect and control MSW landfill emissions (p. 24480, FR, 1991).

The proposed Clean Air Act regulations do not require utilization of the gas. Although increased  $\text{CO}_2$  emissions are being traded off for reduced  $\text{CH}_4$  emissions, there is a net benefit due to the difference in the radiative forcing capacity between  $\text{CO}_2$  and  $\text{CH}_4$ . The radiative forcing capacity of  $\text{CH}_4$  to  $\text{CO}_2$  on a molecular basis is 21 times that of  $\text{CO}_2$  (p. 53, IPCC, 1990). It is hoped that the sites affected by these regulations will consider LFG to energy as opposed to flaring the gas. The use of energy recovery for the control of MSW landfill air emissions will result in decreased emissions of  $\text{CH}_4$ , NMOCs, and toxics. Additional benefits include the conservation of global fossil fuel resources, reduction of emissions at coal-fired power plants, reduced dependency on imported oil, and cost savings to public entities that receive royalty payments (Thorneloe, 6/92). However, there are many barriers in the U.S. associated with the utilization of waste  $\text{CH}_4$ .

This paper provides data and information that characterize the  $\text{CH}_4$  potential of different waste management sources including landfills, wastewater treatment lagoons, septic sewage systems, and livestock waste. Mitigation opportunities are identified and the different options are described. Barriers that affect waste  $\text{CH}_4$  utilization are identified. This paper describes research that is being conducted through EPA's Office of Environmental Processes and Effects Research on

Global Climate Change. AEERL has responsibility for characterizing the emission potential and investigating mitigation opportunities for the major sources of greenhouse gas emissions (Thorneloe, 1991).

#### "Waste" CH<sub>4</sub> Potential from "Waste" Management Sources

The major sources of CH<sub>4</sub> from the anaerobic decomposition of waste include landfills, wastewater treatment lagoons, septic sewage systems, and livestock waste. Table 1 presents an estimate of the relative contributions of each of these sources for the U.S. and globally. These estimates suggest that these sources on average account for 80 Tg/yr or ~30% of the total global anthropogenic emissions of 300 Tg/yr (IPCC, 1992).

Table 1. U.S. and Global Estimates (Tg/yr) of "Waste" Methane Emissions

	U.S.		Reference	Global		Reference
	Avg.	Range		Avg.	Range	
Landfills	9	(6-13)*	U.S. EPA, 7/92	30	20-70	IPCC, 1992
Wastewater Treatment/ Sewage Treatment	?			25	?	IPCC, 1992
Livestock Waste	4		Safle, 1992	25	(20-30)	IPCC, 1992

\*Potential emissions, not corrected for the amount that is flared or utilized. Approximately 1.2 million tonnes of CH<sub>4</sub> is being recovered from U.S. landfills (Thorneloe, 3/92).

Estimates of global CH<sub>4</sub> emissions were summarized by the IPCC and suggest that landfills contribute ~30 Tg/yr with a range from 20 to 70 Tg/yr (p. 35, IPCC, 1992, Khalil and Rasmussen, 1990). Preliminary estimates generated using AEERL's empirical model indicate that potential landfill CH<sub>4</sub> emissions in the U.S. range from 6.3 to 13 Tg/yr, with an average of 10 Tg/yr. Global estimates suggest a range of 20 to 40 Tg/yr of CH<sub>4</sub> emissions with an average of 30 Tg/yr. Estimates generated using Bingemer and Crutzen's approach – which is currently proposed as the official IPCC methodology (OECD, 1991) – indicate that landfill CH<sub>4</sub> emissions contribute 60 Tg/yr globally and 23 Tg/yr in the U.S. (U.S. EPA, 7/92).

The estimates generated using the empirical model are thought to more accurately reflect the amount of CH<sub>4</sub> from landfills that is contributing to the global CH<sub>4</sub> flux (Campbell et al., 1991, Peer et al., 3/92, Peer et al., 1992). The estimate using the empirical model uses data from landfill gas recovery systems and accounts for CH<sub>4</sub> oxidation and gas recovery efficiency. The data that were used to develop the empirical model were collected from over 100 U.S. landfills. An EPA report is being published that documents the development of the model and the estimate of CH<sub>4</sub> emissions for U.S. landfills. Future refinements of this estimate will adjust for waste composition using data being developed on the gas potential of different biodegradable waste streams.

Estimates for wastewater treatment are less reliable primarily due to a lack of country-specific data needed to characterize the CH<sub>4</sub> potential of municipal and industrial wastewater treatment. There is also a lack of field data characterizing the CH<sub>4</sub> potential from lagoons (Thorneloe, 2/92). Lagoons (or surface impoundments) are usually earthen pits used to contain and process wastewater. AEERL is initiating a field test program in 1993 to collect lagoon characterization data such as the biological oxygen demand (BOD) loading, flow rates, and

retention time. These data will be used to develop a methodology for estimating greenhouse gas emissions from lagoons including CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>O, and NMOC emissions. Initial estimates for this source suggest that CH<sub>4</sub> emissions range from 10 to 40 Tg/yr (EPA, 7/92).

CH<sub>4</sub> emissions from wastewater treatment lagoons are not expected to be a major source in the U.S. since many digesters flare and sometimes utilize the gas to control hydrogen sulfide emissions. However, lagoons may be a more significant source in developing countries where lagoons are being more frequently used and the gas is not controlled. Agencies such as the World Bank (Bartone, 1990) recommend the use of lagoons for wastewater treatment for developing countries since land space is readily available, operation is relatively simple, cost is low, and energy requirements are minimal. This represents a potential opportunity to work with developing countries to demonstrate that the CH<sub>4</sub> can be utilized as an alternative energy source.

Individual onsite wastewater treatment systems, such as septic systems, are used throughout the world. In China, there are an estimated 10 million biogas pits, which are designed to produce biogas for household use. However, the majority of the world does not collect the gas from septic systems. A portion of this CH<sub>4</sub> will be oxidized and some will be emitted to the atmosphere. Field test work by EPA/AEERL is planned in FY94 to collect data that will result in more reliable estimates for this source and to determine if this source is amenable to cost-effective control.

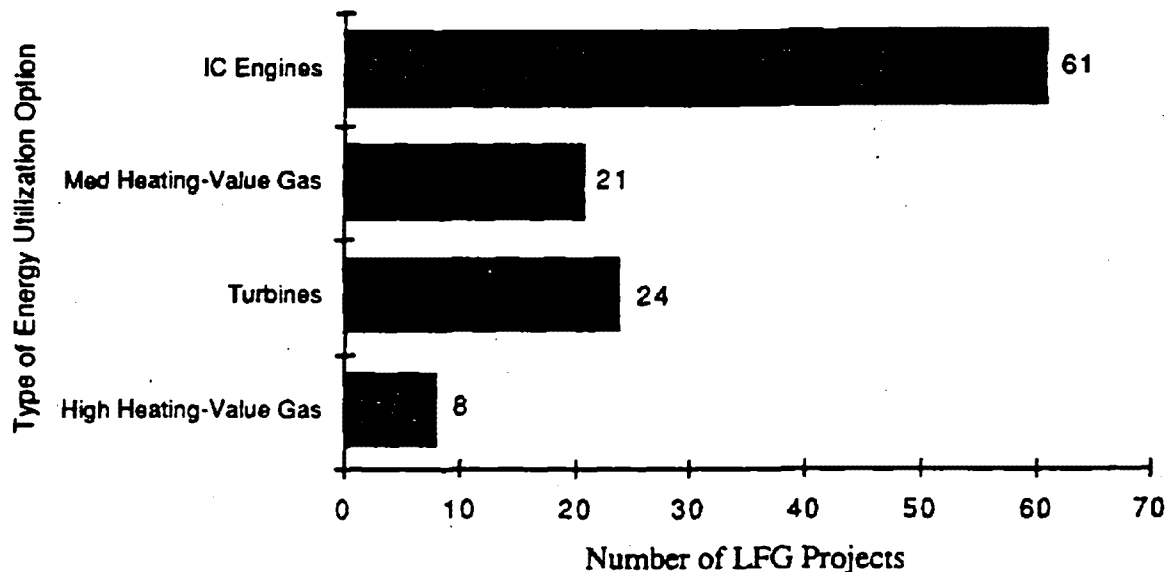
The only published global estimate for livestock waste suggests that CH<sub>4</sub> emissions from this source are about 28 Tg/yr with a range of about 20 to 35 Tg/yr (Safle et al., 1992). These estimates were made by collecting information from animal waste management systems and the quantity of animal waste managed by each system. Information was also collected from government statistics and literature reviews. The major uncertainty regarding these estimates is due to the assumptions and data characterizing the CH<sub>4</sub> potential from the waste of free-range animals. AEERL is planning to conduct laboratory and field studies in FY93 that will help reduce the current uncertainty with these estimates and will investigate opportunities for cost-effective control.

## MITIGATION OPPORTUNITIES FOR "WASTE" METHANE

The recently proposed regulations for MSW landfills will result in the reduction of 5 to 7 millions tonnes of CH<sub>4</sub>. Currently U.S. landfills are recovering 1.2 million tonnes of CH<sub>4</sub> and producing 344 MW<sub>e</sub> of power. In the U.S., there are 114 LFG-to-energy projects (Thorneloe, 3/92). The breakdown of these projects by energy utilization option is presented in Figure 1. The majority of these projects (i.e., 75%) generate electricity which is either used onsite or sold to a local utility. These projects are located across the U.S. in 28 states, with 38 LFG-to-energy projects in California and 14 in New York. Of the 24 projects using turbines, 21 projects are gas-fed and 3 projects are steam-fed. The largest project in the world is the Puente Hills Landfill in Whittier, California. It is operated by the Los Angeles County Sanitation Districts and generates 50 MW<sub>e</sub> (Valenti, 1992). The majority of projects that produce electricity (i.e., ~80% or 66 out of 85) produce 1 to 5 MW<sub>e</sub> (Thorneloe, 6/92). Typically there are three to five engines or one to two turbines per project.



Figure 1. Number of U.S. Landfill Gas Projects by Energy Utilization Option  
(Source: Thomeloe, 3/92)



Globally there are about 200 LFG-to-energy projects (Richards, 1989). There are also digesters in use for livestock waste and wastewater treatment sludge that utilize the waste  $\text{CH}_4$  for producing steam or electricity. Data are not presently available to calculate the extent of digester gas utilization. The Expert Working Group on Landfill Gas of the International Energy Agency is compiling data on waste  $\text{CH}_4$  projects (Lawson, 1992). These data will be available in the future to adjust current estimates of "waste"  $\text{CH}_4$  for the amount that is controlled. In the U.S. 1.2 millions tonnes of waste  $\text{CH}_4$  is being utilized by LFG-to-energy projects (Thomeloe, 3/92).

The utilization of waste  $\text{CH}_4$  can also result in a substantial cost savings to public entities that own landfills and receive royalty payments. For example, Pacific Energy -- who has developed 25 LFG-to-energy projects -- has paid out \$13 million in royalties, mostly to public entities. On average, Pacific Energy's projects are in the sixth year of operation under anticipated 20-year project lives (Wong, 1992). Other economic benefits include the purchase of goods and services. In 1991, Pacific Energy purchased over \$4 million in outside goods and services to support its LFG projects plus a payroll of >\$3 million. LFG to energy projects tend to be capital intensive and are typically built on what is considered undevelopable acreage. Pacific Energy's eight LFG-to-energy projects in California pay >\$350,000 per year in property taxes in California and require few public services (Wong, 1992).

There are emerging technologies for waste  $\text{CH}_4$  utilization. For example, AEERL initiated a project in 1991 to demonstrate the use of fuel cells to recover energy from landfill gas. There are a number of advantages with the use of fuel cells including higher energy efficiency, availability to smaller as well as larger landfills, minimal byproduct emissions, minimal labor and maintenance, and minimal noise impact (i.e., because there are no moving parts). The type of fuel cell being demonstrated for LFG application is the commercially available 200  $\text{kW}_e$  phosphoric acid fuel cell (PAFC) power plant. The 1-year full-scale demonstration is scheduled for 1993 (Sandelli, 1992).

The major technical issue associated with the application of fuel cell to LFG is finding a gas cleanup system that effectively and economically cleans the gas to the fuel cell's stringent requirements. LFG composition can be quite variable as to the type of constituents and concentration. Chloride and sulfur compounds are quite common. "Slugs" of condensate have also been known to cause havoc at gas turbine and internal combustion engine projects (Augenstein and Pacey, 1992). If this project is successful, it will provide a more environmentally attractive option for waste CH<sub>4</sub> utilization that is also more energy efficient.

A second project has been initiated by AEERL to demonstrate the use of fuel cells to recover energy from digester gas. Digesters are frequently used at wastewater treatment (WWT) facilities to process sludge. The digesters can utilize the waste heat from the fuel cells which would result in an energy efficiency approaching 80%. The same type of commercially available fuel cell will be used. The three issues to be addressed in this project are (1) feasibility of integrating the PAFC power plant operation with the WWT plant, (2) anaerobic digester gas/waste CH<sub>4</sub> cleanup and processing requirements for fuel cell operation, and (3) improved fuel cell performance on reduced heating value fuel (i.e., waste CH<sub>4</sub> versus natural gas). This project is to begin this fall and a 1-year demonstration is planned for FY94. It is expected that the LFG cleanup process can also be used for digester gas. Generally digester gas trace constituents are less variable than LFG although concentrations of sulfur compounds tend to be greater. The first phase of the project will evaluate the requirements for the digester gas cleanup process and the application of fuel cells to recover energy from a sludge digester at a WWT plant. The design specifications for the digester gas/fuel cell system will be provided in the Phase 1 Report.

Other emerging technologies for landfill gas include the production of liquid diesel fuel such as the process in Pueblo, Colorado, that began operation last year. A second site in the U.S. has been proposed to produce vehicular fuel from landfill gas. The South Coast Air Quality Management District has awarded a contract to demonstrate a process for producing methanol from landfill gas. The site selected for this demonstration is the BKK landfill, where there was co-disposal of hazardous and municipal waste. TeraMeth Industries is responsible for the demonstration which is scheduled to begin in 1993.

To help promote and encourage landfill gas utilization, case studies of six sites were conducted in FY91/92. The final report (Augenstein and Pacey, 1992) contains detailed information on the six LFG-to-energy projects. In addition, the report provides information on a project recently developed by Michigan Cogeneration Systems (Appendix N), 25 Waste Management LFG-to-energy projects (Appendix M), 11 Laidlaw LFG-to-energy projects (Appendix L), and 4 case studies of United Kingdom LFG-to-energy projects (Appendix K). This report is being referenced in the upcoming CAA regulations for U.S. MSW landfills as an "enabling" tool that provides up-to-date information on LFG utilization for landfill owners and operators. The report has generated a great deal of interest both in the U.S. and internationally through the International Energy Agency, The International Solid Waste Association, and the Solid Waste Association of North America.

A follow-up technology transfer project is focusing on the technical issues associated with LFG cleanup and energy equipment modifications (i.e., application to LFG versus natural gas). There are different philosophies associated with "waste" CH<sub>4</sub> utilization. Information provided by industry experts in the U.S. and Europe is being collected. These projects have been in existence since the early 1980s and much has been learned as to what constitutes a "successful" project. The EPA report that is scheduled to be published in the Fall of 1993 will review the current state of knowledge for successful waste CH<sub>4</sub> utilization projects. This technology-transfer project is intended to help ensure that future utilization projects are designed and operated using the most up-to-date knowledge and information on gas cleanup and energy equipment modifications.

## BARRIERS TO "WASTE" CH<sub>4</sub> UTILIZATION IN THE U.S.

A major factor in helping to encourage LFG-to-energy projects is the Public Utility Regulatory Policy Act (PURPA). It guarantees that utilities will purchase power that was generated from landfills at a price related to the costs that utilities would experience to produce the same amount of power. Although this guarantees a purchaser for the power, the power sale revenues may be low if the utilities' own generating costs are low. This is the case in parts of the U.S. where electricity is generated using water power (i.e., hydroelectric). However, with current low energy prices, most regions of the U.S. also have unattractive "buy-back rates" for the electricity that is generated using waste CH<sub>4</sub>. In addition, incentives such as federal tax credits that have helped to encourage these projects appear to be losing favor. Industry experts think that many of the marginal projects cannot continue without these tax credits. Current trends are toward lower energy prices, reduced tax incentives, and increasing environmental liability.

Although there are more than 6000 landfills in the U.S., there are less than 120 LFG-to-energy projects. During the oil crisis in the 1970s/1980s, when the price of oil increased from \$6-8 per barrel to \$35 per barrel, there was much more interest in developing alternative sources of energy such as LFG-to-energy projects. With the current prices of energy, it is much more difficult to find projects that are economical. Most U.S. projects that have had to cease operation did so primarily due to economics. Projects that are upgrading the gas to pipeline quality have been especially hard hit due to high operating costs and low revenue. Projects of that type are not being planned in the U.S. However, sites in the Netherlands are finding more favorable economics (Scheepers, 1991).

Laidlaw Technology Inc. suggests that "successful" LFG projects need to be over 1 MW<sub>e</sub> and have an electrical price of at least \$0.06-0.07/kWh including any capacity payments. Royalties should not exceed 12.5% at this energy pricing (Jansen, 1992). Laidlaw also suggests that, if higher royalties are offered, the percentage should be a function of energy pricing over and above the base energy rate as inflation occurs. The early LFG projects were based on an established firm price for net energy which provided a substantial degree of security to developers. Contracts for many LFG projects do not allow for fluctuations in energy rates and costs. Revenues for energy sales are usually based on prices of the "competition" of equivalent energy sources (e.g., petroleum products). Since the value of the energy base commodity can fluctuate, this can impact profit.

Administrative and development costs have increased as revenues have decreased. These costs include legal fees, permit applications, and contract negotiations for gas lease agreements and power purchase agreements. These costs may vary widely depending on the environmental issues, development considerations, and regulatory requirements. John Pacey of Emcon Associates has found that these costs can vary from \$30,000 to \$1,000,000 per kWh for a 1 MW<sub>e</sub> LFG-to-energy project (Augenstein and Pacey, 1992). The costs for a 1 MW<sub>e</sub> project are summarized in Table 2. The gas extraction/collection systems are less than 15% of the total cost of the project. The major cost component is the electricity generating equipment.

Tax credits are proportional to gas energy delivery as legislated by Congress (Section 29 of the IRS Code) in 1979 to encourage non-fossil fuel use. These credits are a direct offset to taxes and can be used only to offset a profit. The tax credits will extend to the year 2003 and are allowable for extraction systems installed prior to the end of the year 1992. Robert F. Hatch of Cambrian Energy Systems -- whose company has been involved in arranging financing for many U.S. LFG to energy projects -- thinks that many of the projects would not be in existence if the tax credits were not available. Since energy prices are relatively low, some projects today can be financed only because of the tax credits. The tax credits are intended to help promote the development of a domestic resource as opposed to using foreign oil (Hatch, 1991). These credits

have helped to encourage LFG-to-energy projects and also have helped municipalities defray the cost of environmental regulations.

Table 2. Estimate of Capital Costs for a 1 MW<sub>e</sub> Landfill Gas-to-Energy Utilization Project

Item	Cost <sup>a</sup> (\$10 <sup>3</sup> )	Percent <sup>a</sup>	Range of Value (\$10 <sup>3</sup> /kWh) <sup>b</sup>
Extraction/Collection System <sup>c</sup>	200	13	200-1000
Fees--Planning/Environment/Legal <sup>d</sup>	30	2	30-1000
Interconnect Cost	76	5	20-500
Generating Equipment	970	65	500-2000
Contingency	225	15	---
Total	1500	100	850-4500

<sup>a</sup>These costs were provided by Laidlaw Technologies, Inc. (Jansen, 1992)

<sup>b</sup>Augenstein and Pacey, 1992.

<sup>c</sup>The range in cost of gas cleanup systems is \$10,000-\$500,000/kWh)

<sup>d</sup>Legal fees are approximately 50% of the total (i.e., ~\$15,000-\$500,000/kWh)

Another barrier to LFG (or waste CH<sub>4</sub>) utilization can be environmental regulations. Typically the overall environmental benefit as well as the energy and economic benefits are not considered. Many LFG projects are operated such that New Source Review is avoided. This results in less CH<sub>4</sub> being utilized. For example, a project in Phoenix, Arizona, is producing 50% of the energy that is possible to avoid triggering New Source Review. The project was not allowed to take credit for the offset in emissions from a coal-fired power plant. The developer found out that the New Source Review process would take an extra 2 years to obtain a permit. Rather than delay receiving payback on the investment, the decision was made to operate the project at half of its potential.

Another dis-incentive is that some operators of LFG-to-energy projects are finding that the cost of condensate disposal is becoming a major expense. The condensate is formed when the gas is compressed. The LFG condensate -- which is being classified as a hazardous waste -- requires disposal at a Subtitle C facility. This cost [i.e., \$0.18/L (~\$0.70/gal)] can be significant for a site where lean-burn engines or turbines are used as compared to the use of flares -- where minimal condensate is collected [i.e., 3,800 L/day (1000 gpd) for lean-burn engines or turbines versus 760 L/day (200 gpd) for flares] (Jansen, 1992).

Industry experts are finding that air, water, and solid waste agencies have conflicting goals. LFG-to-energy projects have been forced to shut down due to concerns for by-product emissions of nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO). In California last year, 48 items of state legislation affecting solid waste were enacted (SWANA, 1992). Regulatory priorities often appear to conflict.

## CONCLUSIONS

Landfills and other waste management sources such as wastewater treatment lagoons, septic sewage systems, and livestock waste are amenable to cost-effective control and are relatively significant sources of CH<sub>4</sub>. The EPA's Global Climate Change Research Program is conducting research to (1) reduce the uncertainty in global emission estimates for those sources amenable to

control, (2) target control strategies that are cost-effective, and (3) provide data and information that will help support regulatory activities and IPCC activities.

Currently, U.S. LFG-to-energy projects recover ~1.2 million tonnes of CH<sub>4</sub> and produce 344 MW<sub>e</sub> of power. The proposed CAA regulations for MSW landfill air emissions are expected to result in additional reductions ranging from 5 to 7 million tonnes of CH<sub>4</sub>. Utilization of LFG for those sites affected by the proposed CAA regulations has the potential to result in increased benefits to the national economy and global environment. The utilization of alternative energy sources such as "waste" CH<sub>4</sub> extends our global fossil fuel resources. Not only are emissions directly reduced when waste CH<sub>4</sub> is recovered and utilized, but emissions are also indirectly reduced when secondary air emission impacts associated with fossil fuel use are considered.

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FUEL CELL POWER PLANT FUELED BY LANDFILL GAS

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**ABSTRACT**

International Fuel Cells Corporation (IFC), a subsidiary of United Technologies Corporation, is conducting a U.S. Environmental Protection Agency (U.S. EPA) sponsored program to demonstrate methane control from landfill gas using a commercial phosphoric acid fuel cell power plant. This is the world's first commercial-scale demonstration to control methane emissions from landfills using a fuel cell energy recovery system. The U.S. EPA is interested in fuel cells for this application because it is potentially the cleanest energy conversion technology available. This paper discusses the project in general and describes some results to date, with emphasis on the landfill gas pretreatment system.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.



## INTRODUCTION

The U.S. EPA has proposed standards and guidelines [1] for the control of air emissions from municipal solid waste (MSW) landfills. Although not directly controlled under the proposal, the collection and disposal of waste methane, a significant contributor to the greenhouse effect, would result from the emission regulations. This U.S. EPA action will provide an opportunity for methane control as well as for energy recovery from the waste methane that could further benefit the environment. Energy produced from landfill gas could offset the use of foreign oil, and air emissions affecting global warming, acid rain, and other health and environmental issues.

To demonstrate that methane control and subsequent energy recovery via fuel cells are technically, economically, and environmentally feasible, two key issues must be addressed: to define a gas pretreatment system to render the landfill gas suitable for fuel cell uses and to design the modifications necessary to ensure that rated power is achieved from the dilute methane fuel. Only relatively simple engineering modifications, albeit initially costly to implement, are required to ensure that rated power is achieved from the dilute landfill gas. The toughest and most critical problem is the gas cleanup system. Therefore, the R&D focus of this project is on the landfill gas contamination problem.

International Fuel Cells Corporation (IFC), a subsidiary of United Technologies Corporation, was awarded a contract by the U.S. EPA to demonstrate methane destruction and energy recovery from landfill gas using a commercial phosphoric acid fuel cell. IFC is conducting a three-phase program to show that fuel cell technology is economically and environmentally feasible in commercial operation. Work was initiated in January 1991. A U.S. EPA report [2] describes the results of Phase I, a conceptual design, cost, and evaluation study, which addresses the problems associated with landfill gas as the feedstock for fuel cell operation.

Phase II of the program includes the design, construction, and testing of the landfill gas pretreatment module to be used in the demonstration. Its objective will be to determine the effectiveness of the pretreatment system design to remove critical fuel cell catalyst poisons such as sulfur and halides. A challenge test is planned to show the feasibility of using the pretreatment process at any landfill in conjunction with the fuel cell energy recovery concept. The gas pretreater is described here.

Phase III of this program will be a demonstration of the fuel cell concept. The demonstrator will operate at Penrose Station, an existing landfill-gas-to-energy facility owned by Pacific Energy in Sun Valley, CA. Penrose Station is an 8.9 MW internal combustion engine facility supplied with landfill gas from four landfills. The electricity produced by the demonstration will be sold to the electric utility grid.

Phase II activities began in September 1991, and Phase III activities are scheduled to begin in June 1993.

## FUEL CELL CONCEPT

During Phase I, a commercial fuel cell methane destruction and energy recovery system concept was designed. The system, shown in Figure 1, is based on commercially available equipment adapted for operation on landfill gas. The system was sized to be broadly applicable to a large number of landfills.

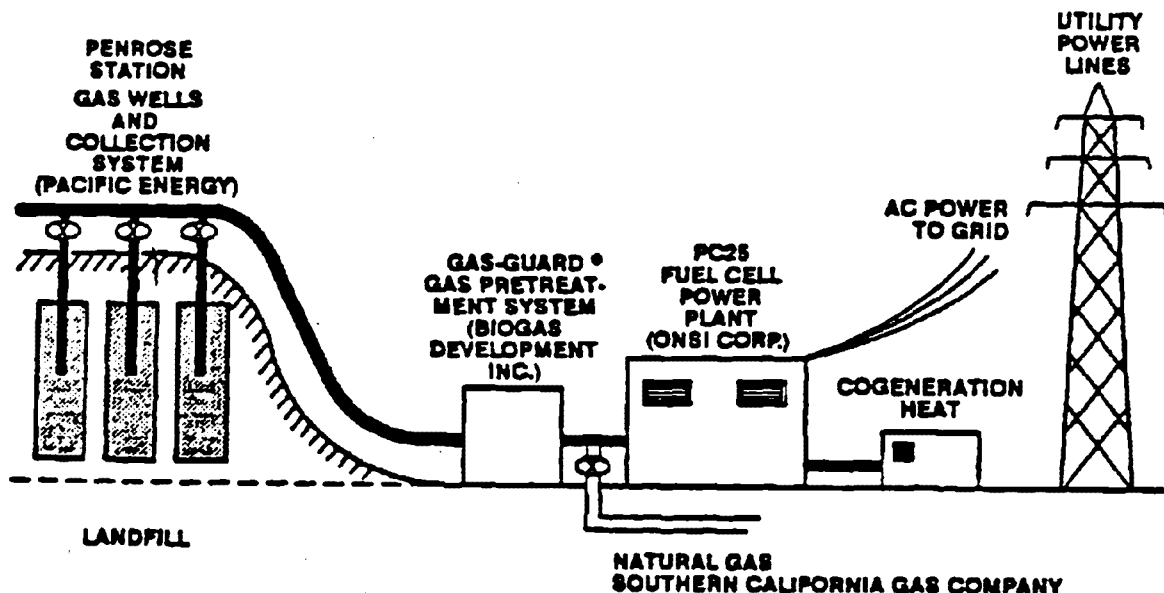


Figure 1. Project Conceptual Design

Landfill gas is collected by a series of wells in the MSW landfill and piped to a gas pretreatment module. The pretreatment module removes contaminants such as sulfur and halides which affect the operation of the fuel cells. The contaminants are concentrated on an absorption bed to a predetermined level. Then during a regeneration cycle they are stripped from the absorption media and destroyed by incineration. Hydrocarbon condensates which form in the pretreater are also incinerated. The resulting output is a medium heat value methane fuel suitable for use in the fuel cell.

The concept utilizes four modular 200-kW phosphoric acid fuel cells generating electricity to be sold to the electric utility grid. The fuel cell power plants are adaptations from the natural-gas-fueled PC25 fuel cell sold by ONSI Corporation, an IFC subsidiary. Only simple modifications are required to ensure that rated power is achieved from the dilute landfill gas.

The MSW landfills in the United States were evaluated to determine the potential commercial market which could be derived using a 200-kW fuel cell. Each fuel cell would consume 2832 scmd (100,000 scfd) of landfill gas to generate 200 kW, assuming a heating value of 19 MJ/dscm (500 Btu/dscf).

The potential commercial market available for fuel cell operation was evaluated using a U.S. EPA estimate of methane emissions in the year 1997 [3] and an estimate of landfill gas production rate of 0.0028 scm/yr per tonne (0.1 scf/yr per ton) of refuse in place [4]. An estimated 4370 MW of power could be generated from the 7480 existing and closed sites that were identified [2]. The largest number of potential sites greater than 200 kW occurs in the 400 to 1000 kW range. This segment represents a market of 1700 sites or 1010 MW. The assessment concluded that these sites are ideally suited to the fuel cell concept. The concept can provide a generating capacity tailored to the site because of the modular nature of the commercial fuel cell. Sites in this range are also less well served by competing options, especially Rankine and Brayton Cycles, which exhibit poorer emission characteristics at these power ratings.

## ENVIRONMENTAL ASSESSMENT OF THE FUEL CELL SYSTEM

The environmental impact from commercial application of the fuel cell concept to the market described previously can be assessed. For the purpose of the evaluation, a site capable of supporting four fuel cell power modules (800 kW total capacity) was selected. The site would produce approximately 11,328 scmd (400,000 scfd) of landfill gas per day. The gas contains approximately 50% methane with a heating value of 19 MJ/dscm (500 Btu/dscf).

The analysis of the environmental impact shows that the fuel cell can be designed to eliminate the methane and non-methane organic compounds (NMOCs) from landfill gas streams. With the fuel cell system, significant amounts of CO<sub>2</sub> and SO<sub>2</sub> will also be reduced due to the fuel cell energy generation. Using an 80% capacity factor for the fuel cell and offsetting emissions from electric utility power generation using a coal-fired plant meeting New Source Performance Standards, it can be shown that for the example site the fuel cell energy conversion system provides 5.6 million kWh of electricity per year and a reduction of emissions for CH<sub>4</sub>, NMOCs, CO<sub>2</sub>, SO<sub>2</sub>, and CO of 1200, 35, 4200, 36, and 0.6 Mg/yr, respectively. These reductions can be

used as environmental offsets, particularly in critical areas such as California or other locations with severe environmental restrictions.

The environmental impact of the fuel cell concept to the potential U.S. market can also be estimated. If the viable market is assumed to range in sites that have energy capacities from 200 kW up to 1 MW, then the fuel cell system can provide an approximate net reduction in emissions for CH<sub>4</sub>, NMOCs, CO<sub>2</sub>, SO<sub>2</sub>, and CO of 2x10<sup>6</sup>, 6x10<sup>4</sup>, 7x10<sup>6</sup>, 6x10<sup>4</sup>, and 1x10<sup>3</sup> Mg/yr, respectively.

## FUEL CELL POWER PLANT

A design of a fuel cell power plant was established to identify the design requirements which allow optimum operation on landfill gas. Three issues specific to landfill gas operation were identified which reflect a departure from a design optimized for operation on natural gas. A primary issue is to protect the fuel cell from sulfur and halide compounds not scrubbed from the gas in the fuel pretreatment system. An absorbent bed was incorporated into the fuel cell fuel preprocessor design which contains both sulfur and halide absorbent catalysts. A second issue is to provide mechanical components in the reactant gas supply systems to accommodate the larger flow rates that result from use of dilute methane fuel. The third issue is an increase in the heat rate of the power plant by approximately 10% above that anticipated from operation on natural gas. This is a result of the inefficiency of using the dilute methane fuel. The inefficiency results in an increase in heat recoverable from the power plant. Because the effective fuel cost is relatively low, this decrease in power plant efficiency will not have a significant impact on the overall power plant economics.

The landfill gas power plant design provides a packaged, truck transportable, self-contained fuel cell power plant with a continuous electrical rating of 200 kW. It is designed for automatic, unattended operation, and can be remotely monitored. It can power electrical loads either in parallel with or isolated from the utility grid.

In summary, a landfill-gas-fueled power plant can be designed to provide 200 kW of electric output without need for technology developments. The design would require selected components to increase reactant flow rates with a minimum pressure drop. To implement the design would require non-recurring expenses for system and component design, verification testing of the new components, and system testing to verify the power plant performance and overall system integration.

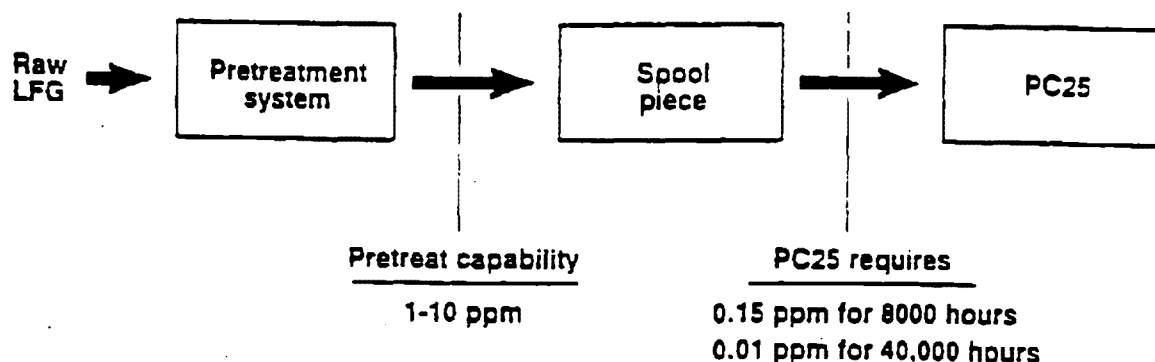
## LANDFILL GAS PRETREATMENT SYSTEM

The available information on landfill gas compositions was evaluated to determine the range of gas characteristics which a fuel cell landfill-gas-to-energy power plant will encounter. This information was used to set the requirements for the gas pretreatment and fuel cell power plant designs.

The major non-methane constituent of landfill gas is CO<sub>2</sub>. The CO<sub>2</sub> ranges from 40 to 55% by volume of the gas composition with a typical value of 50%. Other diluent gases include nitrogen and oxygen, which are indicative of air incursion into the well (most frequently in perimeter wells). Nitrogen concentrations can range as high as 15%, but typical values are 5% or less. Oxygen concentrations are monitored closely and held low for safety reasons.

Landfill gas constituent compounds reported by U.S. EPA [3] indicate a typical value for the total NMOCs of 2700 ppmv, ranging from 240 to 14,000 ppmv (expressed as hexane). The NMOC concentration in the landfill gas is an important measure of the total capacity required in the gas pretreatment system, while the specific individual analyses provide a basis for gas pretreatment subcomponent sizing. The specific contaminants in the landfill gas, of interest to the fuel cell, are sulfur and halides (chiefly chlorides and fluorides). The sulfur level ranges from 1 to 700 ppmv, with a typical value on the order of 21 ppmv. Sufficient data were not available to assess the range of the halides, but a typical value of 132 ppmv was calculated for this contaminant [3]. The range of contaminant values varies not only from site to site, but also at any given site with time due to seasonal weather or moisture content. These characteristics require the pretreatment system design to be capable of handling these gas quality variations to avoid expensive site specific engineering of the pretreatment design which would affect the marketability and economics of the concept.

Figure 2 illustrates the overall design strategy for the gas cleanup system. As shown, the raw landfill gas pretreatment system is designed to reduce the primary fuel cell contaminants (sulfur and halides) to levels between 1 and 10 ppm. A nominal value of around 3 ppm is the design goal. An additional spool piece is added to protect the fuel cell from sulfur and halide compounds not removed from the gas in the pretreatment system. This is an absorbent bed incorporated into the fuel cell preprocessor design which contains both sulfur and halide absorbent catalysts. Note that the capacity of this bed for contaminant removal is dictated by the number of hours the fuel cell can operate before these poisons contaminate the fuel cell, requiring refurbishing.



LFG = Landfill Gas

Figure 2. Block Diagram of Overall Landfill Gas Contaminant Removal Process

A block diagram of the landfill gas pretreatment system is shown in Figure 3. The landfill gas pretreatment system, designed by Bio-Gas Development, Inc., is optimized to handle a wide range of landfill gas contaminant levels and compositions. This was achieved by utilizing a staged contaminant removal approach which enhances the operation of each successive process step. This is accomplished by removal of contaminants which adversely affect downstream processes and controlling the temperature of each step to optimize its efficiency. Figure 3 summarizes the staged contaminant removal processes which produce clean landfill gas to meet the fuel cell specification.

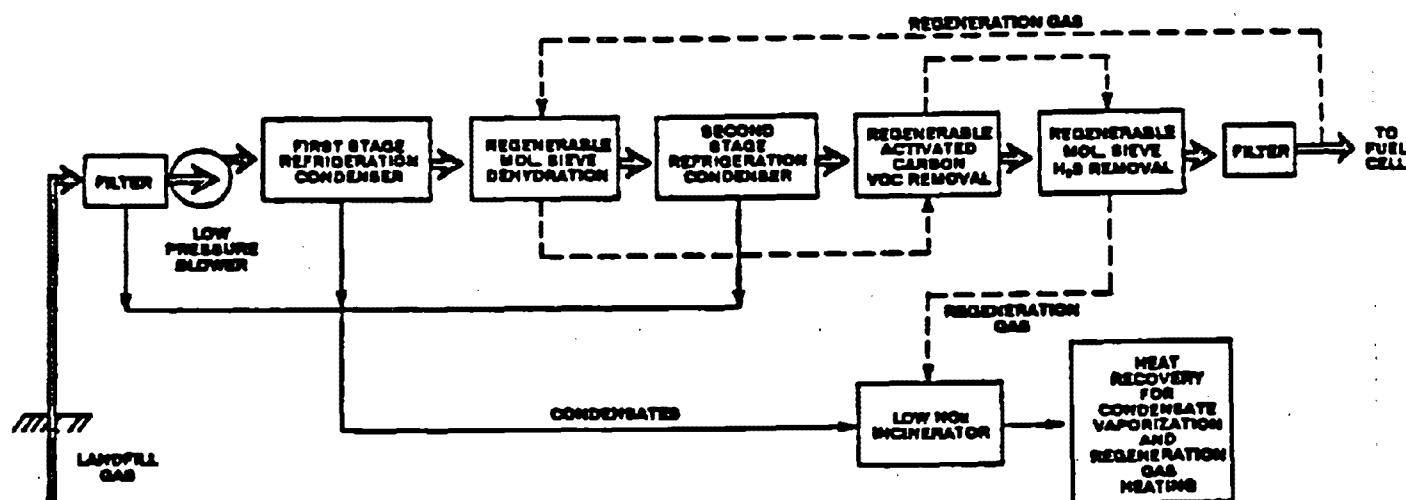


Figure 3. Block Diagram of the Landfill Gas Staged Contaminant Removal System

The landfill gas is first cooled to approximately 1°C to remove water and heavy hydrocarbon contaminants. Following further dehydration in absorption media, the landfill gas temperature is lowered to optimize the operating temperature of the downstream activated carbon/NMOC removal and molecular sieve/H<sub>2</sub>S removal steps. We anticipate that low molecular weight NMOCs will be removed in the second cooler by non-steady state adsorption in the liquid film on the heat exchanger tubes, a concept proprietary to Bio-Gas Development, Inc. The final stage of NMOC removal is by absorption in activated carbon bed media. Hydrogen sulfide is selectively absorbed on a molecular sieve media placed downstream of the activated carbon in the same vessel.

The presence of CO<sub>2</sub> in the gas produces competition for active adsorption sites in the H<sub>2</sub>S mole sieve and can potentially produce carbonyl sulfide (COS) by reaction with H<sub>2</sub>S. This competition is minimized by operating at low pressure which favors H<sub>2</sub>S adsorption over CO<sub>2</sub> adsorption. The production of COS is minimized by maintaining low bed temperatures to slow the kinetics for this reaction. The specific adsorption media was selected to maximize H<sub>2</sub>S removal.

Lastly a particulate filter will remove fines which may be produced from successive thermal regeneration cycling of the adsorption beds. The cleaned landfill gas is delivered to the fuel cell.

Approximately 15% of the cleaned gas is used to regenerate the absorption beds. This gas, containing a high concentration of desorbed contaminants, is flared to achieve 98% destruction of NMOCs.

## CONCLUSIONS

A demonstration project design was established which addresses the key technical issues facing commercial application of the fuel cell methane control and energy recovery concept to the market. A site was selected (Penrose Power Station) which represents the landfill gas market. A gas pretreatment system has been designed, and construction of the system is underway. No technical "show stoppers" are apparent, but the success of the project clearly will be determined by the effectiveness of the landfill gas pretreatment system to remove critical fuel cell catalyst poisons. These critical tests, which will commence soon, will ultimately decide the fate of fuel cell application on landfill gas.

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## METHANE EMISSIONS FROM RICE AGRICULTURE

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### ABSTRACT

Rice agriculture has long been recognized as a major source of methane ( $\text{CH}_4$ ). Global budgets of methane have generally included emissions of about 100 Tg/yr (Tg =  $10^{12}$  grams) from rice agriculture (range of 50-300 Tg/yr) and constituting about 20% of emissions from all sources (range 14%-40%).

During the last decade a number of systematic experiments have been reported on methane emissions from rice fields. Seasonal averages range from 0 to 40 mg/m<sup>2</sup>/hr. Factors affecting the flux of methane include irrigation regime, fertilizer, soil temperature, and soil type.

The most recent global estimates put the emissions from rice paddies at 50 to 100 Tg/yr. The major cause of increasing methane emissions from rice paddies over the past 50 years appears to be the tremendous increase in area planted to rice. Emissions appear to have stabilized over the past decade. Future increases in methane emissions from rice will probably depend on access to irrigation and the use of organic fertilizer.

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## 1. INTRODUCTION

Rice agriculture has long been recognized as a major source of methane ( $\text{CH}_4$ ). Global budgets of methane have generally included emissions of about 100 Tg/yr from rice agriculture (range of 50-300 Tg/yr) and constituting about 20% of emissions from all sources (range 14%-40%) (Ehhalt and Schmidt 1978; Donahue, 1979; Khalil & Rasmussen 1983; Blake 1984; Bolle et al. 1986; Bingemer and Crutzen 1987; Cicerone and Oremland 1988; Warneck 1988). The increase in rice agriculture was probably one of the main contributors to the increase of methane during the last century. It is estimated that rice agriculture contributes some 300 ppbv of methane to the present atmosphere and may be responsible for some 20% of the increase of methane during the last century (Khalil and Rasmussen, 1991).

Estimating the flux of methane from rice fields in various parts of the world requires knowledge of two factors: the emission rates and the regional or global extrapolant. The emission rate or flux depends on different internal and external variables. Internal variables include: soil characteristics; rice cultivar; and soil microbiology. External factors include: soil temperature (driven by solar radiation); meteorological conditions; water level, which is affected by rainfall and availability of irrigation; and treatments such as the type and amount of fertilizers. The extrapolant is the area with similar values of the different variables. The flux of  $\text{CH}_4$  from rice fields from any region is:

$$F = \sum_{j=1}^N \phi_{(x_j)} A_{j(x_j)} \quad (1)$$

where  $\phi$  is the flux and  $A_j$  are the areas within the region of interest that have similar values of the variable  $x_j$ .

At present most integrated regional and global emissions are calculated using a measured flux from a region and multiplying it by the area of that region in the hope that the local measurement represents an average emission rate for the whole area. In recent years some progress has been made in identifying the factors ( $x_j$ ) that can be used to obtain better regional flux estimates.

## 2. METHANE EMISSION RATES FROM RICE FIELDS

### 2.1 FLUX MEASUREMENTS

During the last decade a number of systematic experiments have been reported on methane emissions from rice fields. All are based on static chamber methods. While there are many variants, the method consists of enclosing a part of the rice fields within a chamber and taking periodic samples. The samples are analyzed for methane content usually by gas chromatography using flame ionization detectors (GC/FID). Methane emitted from the rice builds up in the chamber. The rate of accumulation is directly proportional to the flux or the rate of emission from the area covered by the chamber. The relationship is:

$$\text{Flux} = \frac{\rho M V}{N_0 A} \times 10^{-4} \frac{dC}{dt} \quad (2)$$

where  $\rho$  is the density of air (molecules/m<sup>3</sup>),  $C$  is the concentration of methane (ppbv) and  $dC/dt$  is in (ppbv/hr),  $A$  is the area covered (m<sup>2</sup>),  $V$  is the volume (m<sup>3</sup>),  $M$  is the molecular weight and  $N_0$  is Avogadro's number. The most common units for reporting fluxes are milligrams (mg)/m<sup>2</sup>/hr.

The advantages of this measurement method are that it is inexpensive, is easy to use in remote locations and is coupled to a highly sensitive and precise measurement method using GC/FID. Since the fluxes of methane are quite large, the plants need not be exposed to the unnatural conditions of the chamber environment for very long; often 10 minute exposures are sufficient. This fact also makes chamber methods suitable for methane measurements even though they may not be convenient for other gases.

The disadvantages are that placing the chamber can disturb the soil and release abnormal amounts of methane. Several methods have been devised to reduce, if not overcome this problem. In the studies of Khalil et al. (1991) a permanent aluminum base is installed in the soil at the time rice is planted and chambers fit into grooves in this base. In studies reported by Schütz et al. (1989, 1990) a large permanent chamber is used that has a lid that opens and closes, but the chamber itself is not removed until the rice is harvested. Both these methods create some feedbacks that may affect flux estimates. The chambers also affect the immediate environment of the rice plant by causing heating and a buildup of CO<sub>2</sub>, which may affect emissions of methane. Finally, since most chambers are small, the extrapolation of direct flux measurements to large regions is unreliable because of heterogeneities within fields, within local regions and within different parts of the same country.

Remote sensing methods would overcome the problems of using small plots and disturbing the soil or plant environments. However, the measurement accuracy of these methods is not as high as the GC/FID.

Modern measurements of methane from rice fields are based on the chamber methods described above. Most experiments have been carried out for an entire growing cycle from seedling to harvest. (See Table 2.1). The earliest experiments of this type made it clear that these are large systematic changes in methane emissions during the growing cycle. Changes of emission rates during the growing cycle are driven by several factors including the growth of root mass, availability of nutrients and fertilization, and the seasonal change of temperature.

## 2.2 FACTORS AFFECTING FLUX MEASUREMENTS

Methane is produced in paddy soils by anaerobic bacteria (methanogens), which use chemicals from the decay of organic matter as their food source and produce methane as a by-product. This process takes place only where oxygen is not available, as in the flooded soils of paddy fields and wetlands (Neue et al., 1990; Boone, in press; Neue and Roger, in press). Temperature, water regime, nutrient availability, and soil properties such as structure and pH affect the growth of the methanogen

Table 2.1: Methane Flux Measurements

Study	Location	Treatment	Rice Cultivar	Soil Type	Flux mg/m <sup>2</sup> /hr	Emission Season days
Cicerone et al., 1983	California, USA	Nitrogen fertilizer	M101	Vertisol, Capay clay	10.4	100
Seiler et al., 1984	Andalusia, Spain	Nitrogen fertilizer	Bahía	Not given	4.0	125
Schütz et al., 1989	Vercelli, Italy	Unfertilized	Roma	Sandy Loam	11.7	105 to 120
		Rice straw			17.6	
		Nitrogen			10.5	
		Straw + N			18.1	
Yagi and Minami, 1990	Ibaraki Prefecture, Japan	Mineral(avg)	Koshihikari	Gley soil	2.9	119
		Organic(avg)		"	6.7	115
		Rice straw		Peat soil	16.3	115
		Mineral(avg)		Andosol: humic	1.3	124
		Organic(avg)		"	3.1	129
		Mineral		Andosol: volcanic	0.2	125
		Rice straw		"	0.4	115
Sass et al., 1990, 1991a, and 1991b	Texas, USA	Nitrogen	Jasmine 85	Typic Pelludert	8.7	85
		Rice straw		"	15.2	86
		Nitrogen		Entic Pelludert	2.5	85
		Rice Straw		"	5.6	86
		Nitrogen		Vertic Ochraqualf	14.0	76 to 85
		Rice Straw		"	18.2	
Dai, 1988; and Schütz et al., 1990	Hangzhou, China	Late rice, average	Not given	Not given	26.4*	62
		Early rice, average			6.6*	70
Khalil et al., 1991	Sichuan, China	Organic	local and hybrid	"purple soil"	36.6	120
Chen et al., 1992	Beijing, China	N + Organic: F†	Huang jinguang	Sandy Loam	34.1	
		N + Organic: II			14.6	
		N + Organic: D			-0.0	
	Nanjing, China	Average, all	Shanyou 63	"yellow-brown earth"	8.8	

\* Values for Schütz et al. (1990) were digitized from the figures.

† F: flood irrigation; II: intermittent irrigation; D: dry culture.

populations and ultimately the methane flux from the paddy fields.

Properties which affect methane flux can be roughly divided into factors internal to the plant and planting site, and external factors such as the weather or man's actions. These can be re-organized for the purpose of modelling into categories of factors which change with time or space.

Table 2.2 Factors affecting methane fluxes from rice paddies.

Internal Factors	External Factors	Temporal Factors	Spatial Factors
Soil:	Weather:	Season	Type of
Texture	Temperature		Fertilizer
Mineralogy	Rainfall	Planting date	
Eh/pH buffer system			Irrigation projects
Microbiology	Agricultural Practices:		
	Irrigation		Soil Type
Rice Cultivar	Fertilization		

The internal factors of soil microbiology, soil properties, and different rice cultivars are at present the most difficult to incorporate into regional estimate of methane flux from rice paddies. The variation in the factors is very high and their effects can be difficult to measure in the field.

External factors are sometimes easier to measure, but the relationships vary from year to year and place to place. For example, Khalil et al. (1991) found a good correlation between soil temperature and methane flux, with a  $Q_{10}$  of -3 (see Figure 1). However, they found a slightly different relationship between 1988 and 1989; and Chen et al. (1992) found higher average fluxes in Beijing vs. Nanjing, China, with lower average temperatures.

Rice agriculture may be roughly divided into wetland and dryland (or upland) culture (Grist, 1986; Neue et al., 1990). In wetland culture, the soil is prepared (puddling) to reduce water loss, and dikes or levees are built to contain the water. Wetland culture may be separated into irrigated and rainfed rice. While rainfed rice is planted during the wet season, it is susceptible to drought, and if the soil dries, methane emissions stop. Dryland culture is a low-yield, subsistence agriculture, highly susceptible to drought. Dryland rice may not be a source of methane at all, as the soil is not saturated long enough for a methanogen population to build up. Most of the studies in Table 2.1 were carried out where flood irrigation was practiced. The exception, Chen et al. (1992), tested several irrigation regimes and found lower fluxes whenever the top of the soil was allowed to dry. Field measurement on wetlands and on tropical soils (Harris, 1982; Keller, 1986) found that methane flux stops and methane oxidation (conversion to  $CO_2$ ) begins once the soil dries out.

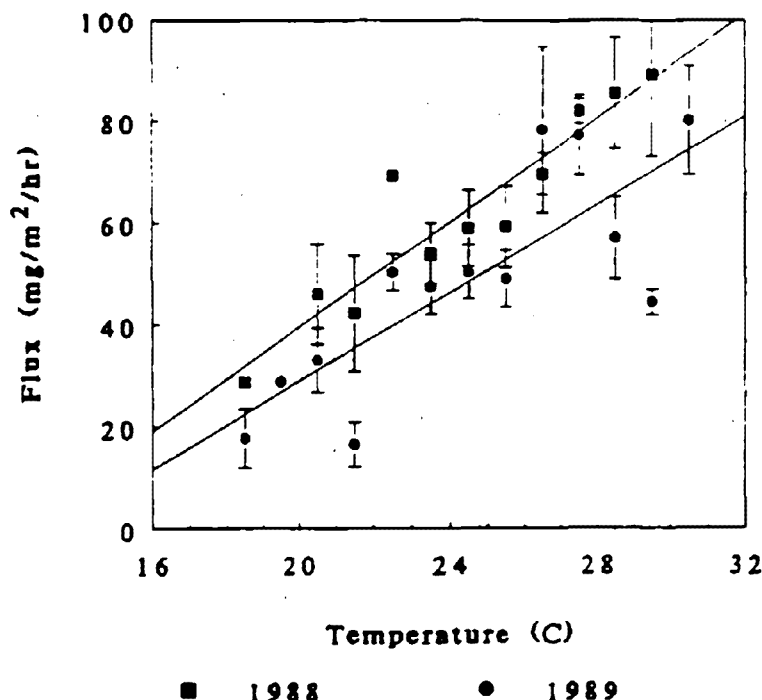


Figure 1. Relationship between flux and soil temperature. (From Khalil and Rasmussen, ES&T, 1991)

### 3. REGIONAL AND GLOBAL EXTRAPOLATIONS

Every methane budget includes an estimate of emissions from rice paddies; however, only two have been published that include details of regional emissions (Aselmann and Crutzen, 1989, hereafter Aselmann and Crutzen; Matthews et al., 1991, hereafter Matthews et al.). While both studies were done to provide data for global transport-chemistry models for methane, they concentrated on different variables, and the authors made different types of information available. An estimate of regional emissions by the Global Change Research Center (GCRC) at the Oregon Graduate Institute is compared to these two studies.

#### 3.1 RECENT STUDIES AND DATA BASES

Aselmann and Crutzen provided detailed tables of the percent of the area in 2.5° latitude by 5° longitude boxes. The percentages reflect the area in rainfed and irrigated rice only for Asia (no upland or dryland rice), but show total area for Africa, Central and South America. Fluxes were adjusted from the work of Holzapfel-Pschorn and Seiler (1986), taking a base rate of 300 mg/m²-day (12.5 mg/m²-hr) for average soil temperatures of 20°C and below, and assuming a linear relationship between flux and temperature up to 1000 mg/m²-day (42 mg/m²-hr) for soil temperatures of 30°C. The reader must construct the exact fluxes used, as well as the monthly

allocations of area under cultivation.

Matthews et al. published detailed rice crop calendars, indicating the months of possible cultivation of rice by country, each Indian state and each province of China. Area was allocated by 1° latitude by 1° longitude cells. Matthews et al. used a flux rate of 0.5 g/m<sup>2</sup>-day (21 mg/m<sup>2</sup>-hr) for all areas.

For our (GCRC) estimates we developed an inventory of direct flux measurements and modified the information from Matthews et al. regarding areas and growing seasons to estimate global annual emission rates. The flux from rice fields is calculated using Equation (1), where the  $x_i$  are the length of the season of methane emission, the area in rice (irrigated and rainfed), and the seasonal (or monthly) average flux of methane (mg/m<sup>2</sup>-hr). Each of these main variables is discussed separately.

### 3.2 SEASON LENGTH

The estimate of the season length from the literature may be confused by whether season refers to the season of methane emission; the cultivar growing season (or time from planting or transplanting to harvest); the total growing season (or frost free season); the total growing duration, which in the case of transplanted rice, includes the time in the seedling beds. For example, in the study of Sass et al. (1991a) the total growing season is about 245 days, the rice cultivar needs 140 days from planting to harvest, while methane was emitted 85 days (flood irrigated period).

Growing season was estimated from Matthews et al., Tables 1a-c. The growing season was defined to be the length of time from first seeding or transplanting until harvest. Table 3.1 compares the growing season and season of methane emission estimated from the literature (see Table 2.1) with the growing season estimated from Matthews et al. With the exception of Italy, the difference between the estimated growing season and season of methane emission is about 40 to 50 days.

Table 3.1: Seasonal Factors for Methane Emissions From Rice Fields

References	Planting Season days	CH <sub>4</sub> Season days	Growing Season days <sup>†</sup>
Cicerone et al. (1983): USA	145	100	152
Holzapfel-Pschorn and Seiler (1986): Italy	147	126	122
Yagi et al. (1990): Japan	140	115	152
Sass et al. (1991a): USA	140	85	152
Khalil et al. (1991): Sichuan	120	120	168
Chen et al. (1992): Beijing	100	87	137

<sup>†</sup> Estimated from Matthews et al. (1991). See text.

We assumed that using the growing season calculated from the crop calendar and average flux rates reported in the literature will probably lead to an overestimate of total emissions. Therefore, Matthews et al.'s growing seasons were modified as follows: growing seasons of 140 to 170 days were reduced by 30 days; growing seasons of 110 to 140 days were reduced by 20 days; and growing seasons of fewer than 110 days were reduced by 10 days. This adjustment is arbitrary, but better reflects results of the field measurements.

### 3.3 METHANE FLUX FACTORS

Fluxes from the studies listed in Table 2.1 were used for the major seasonal divisions of Chinese and Indian rice; the countries where samples were taken, and estimated for other rice growing countries.

### 3.4 AREA PLANTED TO RICE

Time series of harvested rice area were constructed for all rice growing countries. Historical statistics compiled by Mitchell (1980, 1982 and 1983), and more recent data available from the Food and Agriculture Organization of the United Nations (Yearbook, various years between 1956 and 1988) were the primary sources of information. For China, the areas used were reported by either the USDA (1984) or the 1985 China Agriculture Yearbook. From 1980 to 1990 the total areas are from the FAO Production Yearbooks or the China Agriculture Yearbooks, which are in good agreement for that period.

Total area was broken down further by province for China and by state for India. The fraction of the total areas in each Chinese province was calculated by taking the average of the areas reported in the China Agriculture Yearbooks (all years) and the values in Matthews et al., Table 1c. The fraction of the total area in each Indian state was calculated using the values given in Table 1b of Matthews et al. and Appendix 9 in Bansil (1984). These percentages represent only the 1980s; however, the areas which are the largest producers are probably the same.

The total areas were reduced by the percentage in dryland (upland) rice culture. Estimates of the percentages were taken from tables in Huke (1982), Grist (1986), Morris et al. (1984), and De Datta (1975). Where there was more than one estimate per country, an average was taken. If there was no estimate for a particular country, but there was reason to suppose a significant percentage of the rice area was in upland rice, e.g. countries in Africa or Central America, an average was taken of the published estimates for neighboring countries, or the average for the continent was used, usually for African nations.

## 4. REGIONAL AND GLOBAL EMISSIONS

Different estimates of global and regional emissions are compared in this section. Recent estimates of the global source range from 50 to 100 Tg ( $10^{12}$  grams) per year



(see Table 4.1). Source estimates by country vary greatly with the assumptions made on the importance of different factors affecting the methane flux, and the information on the factors presently available.

#### 4.1 GLOBAL EMISSIONS

Three recent estimates of the global rice source are shown in Table 4.1. (Matthews et al. (1991) assumed a global source of 100 Tg.)

	GCRC (1992)	Aselmann and Crutzen (1989)	IPCC (1992)
Tg/year	80	92 (53 <sup>†</sup> )	60
Year of Estimate	1990	1985	Not given
<sup>†</sup> Number in parenthesis assumes a constant flux of 13 mg/m <sup>2</sup> -hr			

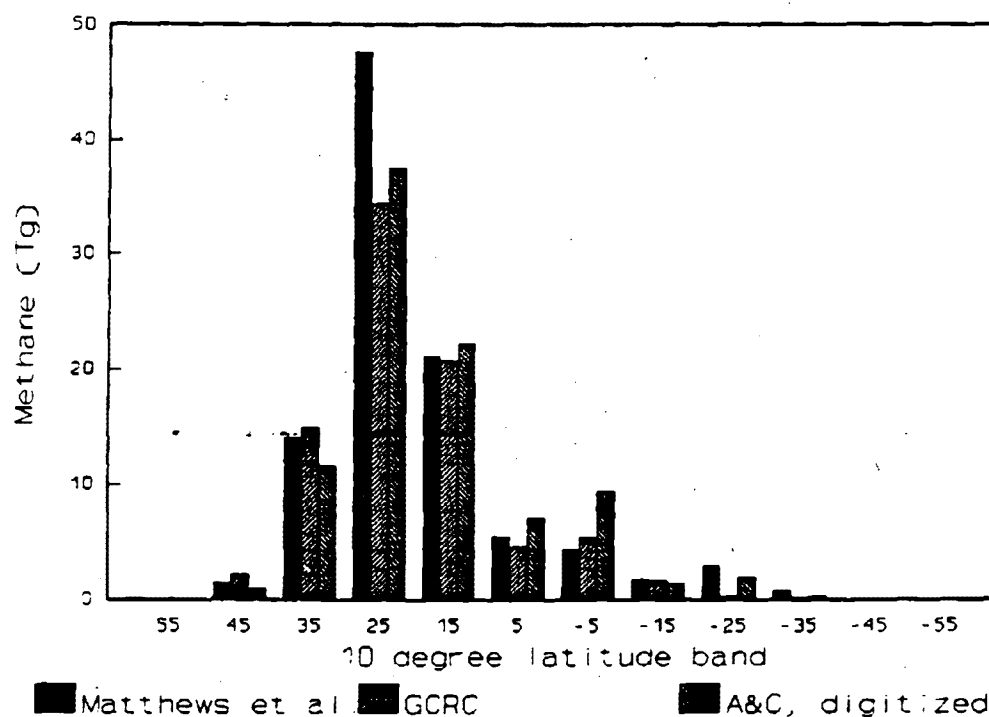


Figure 2. Methane from rice paddies apportioned to 10 degree latitude bands: a comparison of three studies.

The major difference between these estimates is probably in the way a weighted average flux rate is calculated. Bachelet and Neue (in press) calculated a range of 40 to 80 Tg/year in the rice source for Asia, making different assumptions about the effects of soil type, rice yield, temperature, and organic matter incorporated in the soil. The Global Change Research Center (GCRC) estimate takes a seasonally averaged flux, based on field studies, and applies it to the seasonal area in wetland rice culture.

#### 4.2 REGIONAL EMISSIONS

Regional emissions are compared by latitudinal bands, and by countries. The methane source, apportioned to 10 degree latitude bands, is shown in figure 2. The overall similarity between the estimates is the result of the allocation of rice area; all three studies use the FAO Agricultural Yearbook data. The GCRC estimate and Aselmann and Crutzen (1989) differ from Matthews et al. (1991) in the 20 to 30° N latitude band because the former studies reduce the total area by the estimated area in dryland cultivation. The GCRC estimate also reduces rice area in Africa and central and South America by the percent in dryland cultivation.

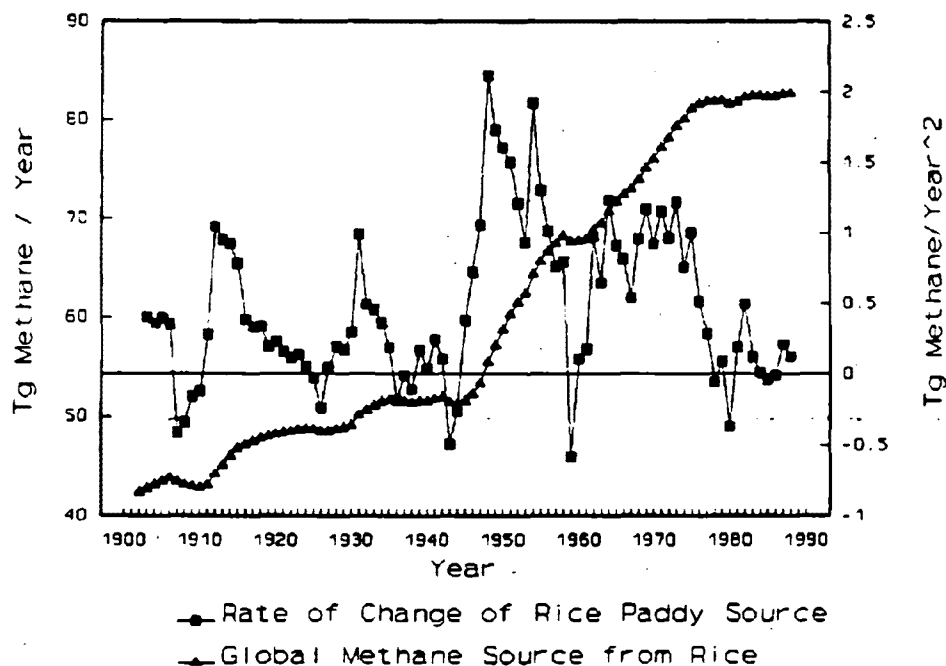


Figure 3. The GCRC time series of global CH<sub>4</sub> from rice and rate of change of global rice emissions

## 5. THE ROLE OF RICE AGRICULTURE IN THE BUDGET OF ATMOSPHERIC METHANE

The increase in rice agriculture was likely one of the main contributors to the increase of methane during the last century. It is estimated that rice agriculture contributes some 300 ppbv of methane to the present atmosphere and may be responsible for some 20% of the increase of methane during the last century (Khalil and Rasmussen, 1991). However, factors which were important causes of the increase in the past are changing, and probably will not be as important in the future (see figure 3). The GCRC time series of global methane emissions from rice is largely influenced by tremendous increase in area planted to rice in the last four decades. By the early 1980s this growth had slowed significantly. A linear projection of the increase of methane from rice made from the trend in the last decade would indicate an increase of only 0.2 Tg/year.

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## 6. ACKNOWLEDGEMENTS

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## LIVESTOCK METHANE: SOURCES AND MANAGEMENT IMPACTS

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### ABSTRACT

Herbivorous animals, particularly ruminants, have a digestive tract that facilitates extensive symbiotic microbial digestion of dietary structural plant carbohydrates. A byproduct of this symbiotic microbial process is an estimated 70 Tg of methane globally per year, primarily from cattle and buffalo. Cattle methane emissions equal  $6 \pm 0.5\%$  of their diet energy (2% by wt) for most global conditions studied. Emissions by U.S. feedlot cattle are uniquely lower at about 3.5% of diet energy. A major lack of information on size, diet, class distribution and percentage loss from developing country livestock precludes accurate definition of this source, which is about 2/3 of global. Manure disposal from livestock may produce an additional 12 Tg globally, primarily through anaerobic lagoons. Possible ameliorative strategies include the decreased use of lagoon disposal or the capture of this methane. General efforts should concentrate on improving productivity of beef and dairy cattle production systems, which will secondarily reduce methane.

## METHANE EMISSIONS: A BYPRODUCT OF ANIMAL MICROBIAL SYMBIOSIS

Digestive secretions by the gastrointestinal tract of animals, per se, can digest no structural components of plants. They can only digest the soluble and/or starchy components. The only digestive enzymes that can unlock the cellulose base of the structural components of plants are those produced by microorganisms. Since about 75% of the photosynthetically fixed plant material is cellulosic or structural, it perhaps is not surprising that many herbivorous animals developed a symbiotic relationship with microorganisms in their gastrointestinal tract to assist in utilizing these materials. All animals have some microbial action in their gut, however, it is very extensive only in the herbivores, particularly the ruminant herbivore. This fortuitous symbiotic relationship between animal and microbe allows the utilization of vast tonnages of cellulosic materials, i.e., grass, which would otherwise be left to decompose on the earth's surface.

The microbes that function in the gastrointestinal tract, particularly the carbohydrate utilizing anaerobes, require a sink to dispose of excess hydrogen other than oxygen. Several species of the archebacteria fill this niche nicely. These methanogens reduce  $\text{CO}_2$  with the available hydrogen to produce methane. In doing so, they doubly enhance the symbiotic relationship. First, they facilitate the cellulolytic function of other bacteria and secondly, they increase the supply of amino acids and vitamins to the host animal.

In general, the more extensive the gut microbial digestion of an animal species, the higher the fraction of dietary loss as methane. Ruminant animals (i.e., cattle, sheep and goats) with their large foregut fermentation vat, the rumen, eructate or belch approximately 95% of the emissions from all animals. Cattle in particular, because of their large numbers (1.2 billion), their large size and appetites, coupled with this extensive symbiotic microbial fermentation in their gastrointestinal tract account for some 71% of the approximately 70 Tg of methane produced globally by animals each year. Another approximately 8% is contributed by buffalo, with sheep and goats producing approximately 12%.

We have compiled the available observations of methane production (i.e., Table 1, cattle data) from the literature into a ruminant methane data base. This data base includes 400 treatment mean observations of methane losses from cattle and sheep, and minor numbers of measurements from other species. Methane loss varied from 2.0 to 11.6% of dietary gross energy. Measurements included describe the many different weights and physiological states of the animals fed and diets ranging from all forage to all concentrate diets or mixtures thereof. An auxiliary spreadsheet lists approximately 1000 individual animal observations.

Many important concepts have emerged from our query and analysis of this data set. The majority of the world's cattle, sheep and goats under normal husbandry circumstances likely produce methane very close to 6% of their daily diets gross energy (2% of the diet by weight). Although individual animals or losses from specific dietary research circumstances can vary considerably, the average for the vast majority of groups of ruminant livestock are likely to fall between 5.5 to 6.5%. We must caution, however, that little experimental data is available for two-thirds of the world's ruminants in developing countries. Available evidence suggests similar percentage of emissions, but this supposition needs confirmation. More importantly, data is skimpy or unavailable to describe diet consumption, animal weight and class distribution.



TABLE 1. SUMMARIZED VARIABLES FOR BEEF CATTLE FROM RUMINANT METHANE DATABASE

Variable	Minimum	Maximum	Mean
Observed methane, % gross energy	2.6	11.5	6.8
Observed methane, % digestible energy	3.3	16.7	9.8
Animal weight, kg	217	627	402
Dry matter intake, kg/d	2.1	10.9	5.4
Digestible energy, %	50.4	87.8	70.6
Level of intake, multiple of maintenance	0.4	2.9	1.5

One exception to this 6% rule is where cattle or sheep are fed very high concentrate diets (> 80% grain and/or supplement). When fed these diets, likely methane emissions will be 3.5% of gross energy. Frequently, they fall as low as 2%. Such dietary circumstances occur almost exclusively in the U.S. feedlot operations. Globally it has little reducing effect on emissions, approximately 27 million head of cattle fed for 140 days per year, with current emissions of about .4 Tg/year.

Another important finding is the transitory effect of ionophores on reduction of methane emissions. Ionophores are a class of antibiotic feed additives which have been considered to suppress methane losses by 20-30%. This degree of suppression persists for some two weeks or less. Therefore, the methane reduction effect of ionophores is more modest and primarily results from a 6 to 7% reduced total feed requirements for production.

Another surprising finding was the uniqueness of one class of feedstuffs. Brewery and distillery byproduct feeds produce about half as much methane as other common feeds fed to ruminants (1). While of little impact globally because of the limited amounts of such feed supplies, it could provide a clue to control of methanogenesis.

An important principle influencing methane emissions from ruminant systems is the inverse relationship between rate of productivity and methane losses, especially when expressed per unit of animal product. Methane losses are closely related to the amount of feed resource used to produce an animal product. An increase in rate of production commonly decreases the feed/product by decreasing the maintenance feed subsidy. Placing a beef calf directly into the feedlot in the United States rather than the slower growth stocker phase preceding the feedlot is expected to reduce the methane per lifetime of a steer by some 34% while producing the same amount of product (2). Perhaps more dramatically, the supplementation of a moderate to low quality forage diet as might be employed in Australia or South America, could increase the daily average gain from .35 kg up to .7 kg. This increased rate of productivity would reduce the methane emissions per lifetime of the steer from 170 to 100 kg, again without changing product. Likewise, stimulating the rate of milk production by using bovine somatotropin in the dairy cattle industry in the United States is expected to reduce methane production by the industry some 9%, essentially producing the same amount of milk with less feed and less methane losses (3).

One important additional source of methane indirectly emanating from the livestock industry is that from manure disposal systems. The potential production is huge, considerably larger than that coming directly from livestock, however, measurements made in our laboratory (4) and in Australia (5) show a very small production rate from manure disposed under simulated or actual range or pasture situations. Thus, the major global disposition of manure on pasture likely produces little methane. The critical question then becomes what fraction of manure is disposed of by anaerobic lagoons a figure which is not known very accurately. Our present best estimate of global manure methane adjusts the disposal method data of Saffley et al. (6) to our estimates of range or pasture production. With these suppositions, the estimate of global methane entry from manure disposal approximates 12 Tg annually.

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# Ozone and Global Warming

by

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## ABSTRACT

Changes in several trace substances in the Earth's atmosphere are affecting global radiative forcing. Those substances which seem to be in the greatest state of change now and projected into the future are carbon dioxide, ozone (and its precursors and depleters), and aerosols. It is conceivable that countervailing changes in the radiative forcing effects of these substances, especially ozone and aerosols, may be temporarily hiding or at least changing the "greenhouse signal" — an unfortunate circumstance, particularly if the overall impacts that will eventually occur are unpredictable or difficult to reverse quickly. If in fact the greenhouse signal is partially being obscured at present, there is also potential for this effect becoming less significant in the decades ahead because of 1) a continuation of increases in greenhouse gas emissions, 2) saturation of the tropospheric aerosol effect plus controls on sulfur emissions, and 3) increasing tropospheric ozone. The substantial complexities in factors affecting ozone and aerosols are discussed with emphasis on ozone and its precursors, including methane, nonmethane hydrocarbons, carbon monoxide, and nitrogen oxides. Quantifying radiative forcing is of substantial importance. EPA is undertaking research to enhance the ability to estimate indirect factors contributing to forcing, including measures such as Global Warming Potentials. Many of the important but difficult factors to resolve are of the indirect type. A number of potential indirect forcing effects are identified along with an estimate of direction (sign).

## Introduction

Several trace substances affect global radiative forcing levels (changes in net downward flux of energy at the tropopause). Some of the major ones are water vapor, carbon dioxide ( $\text{CO}_2$ ), ozone ( $\text{O}_3$ ), methane ( $\text{CH}_4$ ), chlorofluorocarbons (CFCs), nitrous oxide ( $\text{N}_2\text{O}$ ), and aerosols. The continuing increase in the concentration of these constituents has created considerable concern among scientists regarding the potential for climate change. The observed increases are believed to have begun near the turn of the century with the continuing Industrial Revolution and rapidly increasing technology. This period is marked with the beginning of an increasing energy demand and conversion of forests to agricultural land to accommodate increasing world population. Radiative forcing for individual trace gases and aerosols varies greatly, and depends on their concentrations. On the other hand these constituents are controlled by various factors in addition to emissions, including mass transfer, chemical interactions, and atmospheric lifetime. Ozone is a major factor in global radiative forcing but is not well quantified because its high temporal and spatial variability make the quantification difficult. Ozone levels in the troposphere depend on both transport of ozone from the stratosphere and on local chemistry. Production of tropospheric ozone is dependent on concentrations of precursors (substances which produce ozone), including  $\text{CH}_4$ , carbon monoxide ( $\text{CO}$ ), nonmethane hydrocarbons (NMHCs), and nitrogen oxides ( $\text{NO}_x$ ). Ozone levels in the stratosphere now depend on concentrations of ozone-depleting substances, including CFCs, halons, other halogenated organics, and  $\text{N}_2\text{O}$ . Temperature, amount of sunlight, global transport, amount of aerosols present, and other factors are also of importance. On the other hand, methane and NMHCs inactivate  $\text{O}_3$ -depleting chlorine in the stratosphere. Radiative forcing for ozone is a strong function of altitude. Because of the importance of ozone and its precursors as radiative and photochemical trace gases, EPA has accelerated its research on global tropospheric ozone. EPA has had ongoing research on boundary-layer ozone for many years in support of the ambient air standards dealing with the adverse effects of ozone on human health. Ozone is also a toxicant to young trees and leafy crops (Reich, 1987; Heck, 1982).

Understanding of trace gas effects on global ozone and radiative forcing continues to emerge. For example, in the stratosphere newly discovered heterogeneous reactions have been found to promote the formation of the ozone hole in Antarctica and generally appear to promote the loss of ozone in the lower stratosphere. The loss of ozone in the lower stratosphere has had an important impact on radiative forcing (Ramaswamy, 1992). Similarly, initial attempts have been made recently to quantify the effects of tropospheric ozone on radiative forcing (IPCC, 1990). This paper describes how ozone fits into the global picture and covers some of EPA's related

research.

### Obscuration of the Greenhouse Effect?

Global surface temperatures have risen somewhere near 0.3 to 0.6 °C over the last century (IPCC, 1990). Figure 1 gives the global-mean combined land-air and sea-surface temperatures for the period 1861-1989 based on historical records and various adjustments (IPCC, 1990). In addition to these past records, model predictions of warming based on growth in greenhouse gas loadings in the atmosphere imply substantial future warming (IPCC, 1992). However, some -- e.g., Michaels (1991) -- have expressed skepticism about the "popular vision" of global warming.

Example concerns include 1) adequacy of correction for the urban heat island effect, 2) less than expected warming, relative to that predicted by modeling, and 3) the nature of how the warming has (or has not), taken place -- such as, little increase in extreme high temperatures in the northern latitudes. However, it is likely that, while the Earth has seen some global warming, some potential warming has been hidden by temporary offsetting effects of other anthropogenic global changes. Changing ozone and aerosol levels over the last several decades may have produced some net negative radiative forcing. This negative radiative forcing, along with a slight decrease in solar irradiance, may have partially hidden the greenhouse signal predicted by general circulation models (GCMs), especially in the Northern Hemisphere. Global changes other than warming may have resulted. The changes taking place are difficult to predict as are any future consequences.

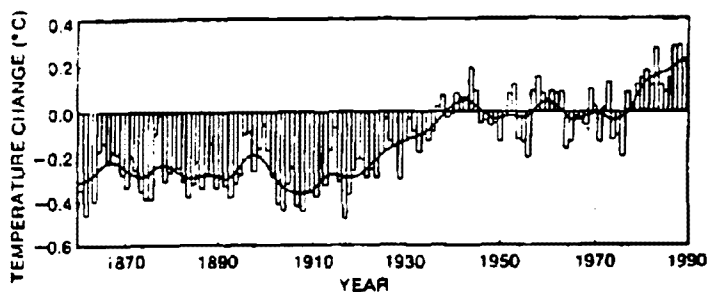


Figure 1. Global-mean combined land-air and sea-surface temperatures, 1861-1989, relative to the average for 1951-80. (IPCC, 1990; Reproduced with permission.)

The effects of observed trends in atmospheric ozone on climate, while difficult to quantify, have been established directionally (Lacis, 1990; Ramaswamy, 1992). Radiative forcing from loss of ozone in the lower stratosphere implies a cooling effect on the Earth's surface and in the stratosphere. Effects from an increase in tropospheric ozone implies higher temperatures at the Earth's surface and in the free troposphere. More indirectly, increased ozone in the atmospheric boundary layer reduces tree growth resulting in reduced carbon sequestration (Reich, 1987).

Estimates of the negative radiative forcing effects of aerosols range up to -2 watts(W)/m<sup>2</sup> for tropospheric sulfate (Charlson, 1992). Penner (1991b) estimates from modeling work that aerosols from biomass burning could contribute a radiative forcing mask of -1.8 W/m<sup>2</sup> with aerosols from fossil fuel contributing even a larger negative forcing. Kaufman (1991) concludes (with substantial uncertainties noted) that increased future sulfur dioxide (SO<sub>2</sub>) emissions from fossil fuel combustion will likely produce a cooling effect from increases in cloud condensation nuclei. On the other hand biomass burning is seen overall to have a net warming effect, because significant ozone precursors are injected into the atmosphere in addition to aerosols (Kaufman, 1991). Stratospheric aerosols from the eruption of Mt. Pinatubo in 1991 should produce a very significant negative forcing on the climate system (UNEP/WMO, 1991). Hansen (1992) estimates that the global mean climate forcing due to Pinatubo will peak at about 4 W/m<sup>2</sup> in early 1992, noting that this exceeds the accumulated forcing due to all anthropogenic greenhouse gases added to the atmosphere since the industrial revolution. Global climate changes that might be expected from increased tropospheric sulfate concentrations include the following (Michaels, 1991):

- Increased cloudiness
- Enhanced brightening of low-level clouds near sulfate source regions
- A counteraction of daytime warming by the greenhouse forcing because of an increase in clouds
- Night warming from an increase in both clouds (especially stratocumulus) and greenhouse forcing
- A decrease in daily temperature range
- Decrease in ultraviolet (UV)-B in affected areas
- Concentration of these effects in the industrial Northern Hemisphere

The connection between aerosols and all of the above effects is by no means proven. Other factors must be

involved in reducing the predicted increases in the daily maximum temperature in a large portion of the Northern Hemisphere (Karl, 1991). Some of these other factors could include changes in cloudiness and aerosol loadings, but could also just be natural fluctuations of the climate system. These investigators were examining the nature of and evidence for asymmetric diurnal temperature change in large areas of the Northern Hemisphere. These are areas where, over the last several decades, most of the warming can be attributed to an increase of mean minimum (mostly nighttime) temperatures with mean maximum (mostly daytime) temperatures displaying little or no warming. These are also areas where there has been increasing extreme minimum temperatures but little change in extreme maximum temperatures, leading to a decrease in the extreme temperature range.

### Reduced Obscuration of the Greenhouse Effect?

Why should all this cause concern? Many climate scientists think that serious greenhouse effects are possible, and that lack of a strong greenhouse signal may lead to inaction in dealing with emissions, particularly  $\text{CO}_2$ , because of its long atmospheric lifetime. Furthermore, significant atmosphere-related global change may have already taken place with unknown long-term consequences. In addition, if we are having substantial current obscuration of the greenhouse signal, this obscuration may become less significant in the decades ahead because of 1) a continuation of increases in greenhouse gas emissions, 2) saturation of the tropospheric aerosol effect, and 3) increasing tropospheric ozone.

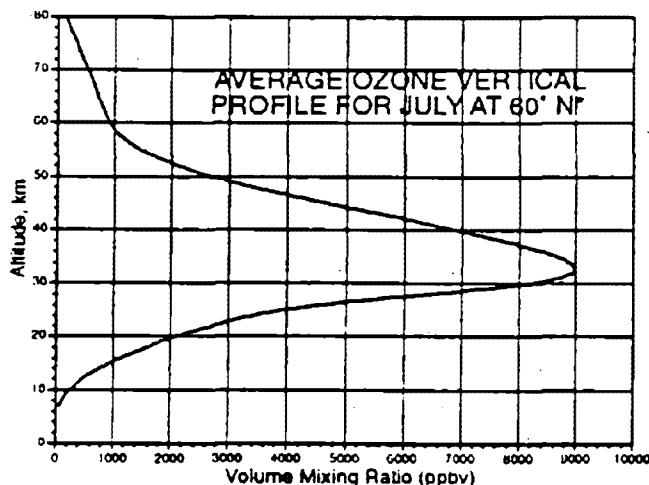


Figure 2. Ozone altitudinal profile (data derived from chart on p. 422 of Vol. II of Atmospheric Ozone 1985 (WMO, 1985).

atmosphere, the UV-C component is of sufficient energy to photodissociate oxygen ( $\text{O}_2$ ), resulting in the formation of ozone ( $\text{O}_3$ ) in the upper stratosphere and UV-C absorption. UV-B radiation, on the other hand, penetrates to lower altitudes and has enough energy to dissociate ozone (UV-B is absorbed in this process). Figure 2 illustrates a typical ozone concentration profile for July at 60° N. This particular profile was derived from data which did not include boundary layer measurements, and therefore does not show a typical increase near the Earth's surface. The profile reveals a maximum mixing ratio near 30 km for this latitude. The ozone essentially filters out most of the short wavelength ultraviolet radiation from the Sun. Figure 3 gives a simplified overall view of the formation/destruction of ozone in the atmosphere. The destruction of ozone proceeds until these halogen atoms are chemically bound in stable reservoir forms such as hydrochloric acid (HCl) and hydrobromic acid (HBr). In general, atmospheric models utilizing homogeneous gas-phase chemistry provided a reasonable scientific tool that explained the catalytic destruction of the ozone layer. With the formation of the ozone hole over the Antarctic, atmospheric scientists began to investigate heterogeneous chemical mechanisms to explain the rapid loss of ozone during the September-October time period in the Southern Hemisphere. The most critical aspect of the heterogeneous mechanism is the destruction of active chlorine sinks by reactivating HCl and chlorine nitrate ( $\text{ClONO}_2$ ) and at the same time removing  $\text{NO}_x$  from the stratosphere. Lower levels of  $\text{NO}_x$  limit the degree to which chlorine can be tied up as  $\text{ClONO}_2$ . The sulfuric acid aerosols in the low to middle latitudes of the lower

Regarding saturation of the aerosol effect Kaufman (1991) sees that, for a large increase in fossil fuel use, emissions of  $\text{SO}_2$  may saturate the cloud condensation nuclei effect. For a doubling of  $\text{CO}_2$ , the aerosol radiative forcing effect is estimated to be only 0.1 to 0.3 of that for  $\text{CO}_2$  compared to 0.4 to 8 times at current emission levels.

Relative to tropospheric ozone, ozone is increasing on a global basis with the rate of increase depending on location and altitude.  $\text{CH}_4$ , NMHCs, CO, and  $\text{NO}_x$  are all tropospheric ozone precursors, and their global emissions are all increasing. In addition to surface-based emission sources, emissions from aircraft at cruise altitude seem to affect the ozone profile and are similarly increasing (Wuebbles, 1990; Barrett, 1991).

### How is $\text{O}_3$ Formed and Destroyed?

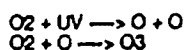
As the solar ultraviolet radiation enters the Earth's

stratosphere of the Northern and Southern Hemispheres play a role similar to that of the polar stratospheric ice crystals in contributing to ozone depletion in the polar areas, especially Antarctica.

In the boundary layer ozone is formed photochemically from other gases (precursors). Within urban-suburban areas, ozone formation is driven by the emissions of the precursors NMHCs and  $\text{NO}_x$ , in the presence of sunlight. The formation of ozone in remote areas of the boundary layer, in the free troposphere, and in the lower stratosphere involves the less reactive hydrocarbons such as methane. The production of ozone is known to be complex and is not linearly proportional to increases in precursor emissions. Atmospheric modeling as well as photochemical simulations indicate that the formation of ozone may indeed be  $\text{NO}_x$ -limited over certain portions of the globe. These studies indicated that concentrations of  $\text{NO}_x$  above a range of 10 to 25 pptv are required for ozone production, while lower concentrations

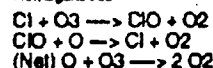
## How is O<sub>3</sub> formed and destroyed?

### Formation:

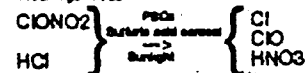


### Destruction:

#### Homogeneous



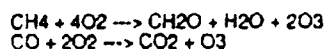
#### Heterogeneous



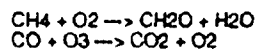
## Stratosphere

## Troposphere

### Formation (high $\text{NO}_x$ ): (Net reaction)



### Destruction ( $\text{NO}_x < 20$ pptv): (Net reaction)



### Boundary Layer

Figure 3. Overview of ozone formation/destruction in the atmosphere.

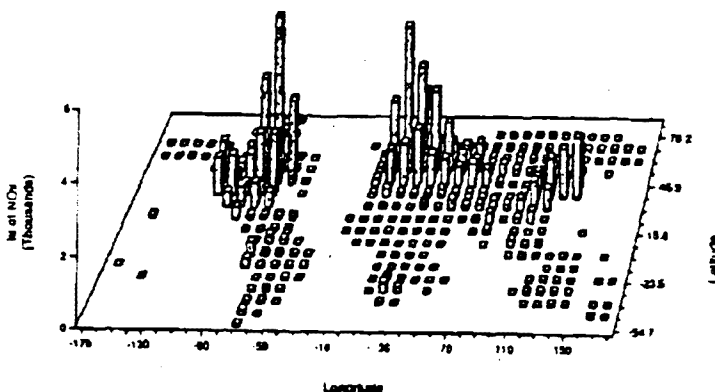


Figure 4. Spatially allocated global  $\text{NO}_x$  emissions from anthropogenic and natural sources in 1980.

sources is the first step in developing a 3-D Global Chemical Model for predicting atmospheric loadings of ozone and other greenhouse gases from emissions. Ozone is also destroyed by surfaces, by reactions with olefinic gases, and by photodissociation that leads to production of hydroxyl (OH) radicals. The oxidizing power of the Earth's atmosphere is controlled by the abundance of these radicals. It is estimated that OH radicals account for about 85% of the loss of methane (Cicerone, 1988). Some of the directional effects of precursor emissions on ozone-related atmospheric chemistry are indicated in Figure 5 as derived from UNEP/WMO (1991). For example, increasing the precursor  $\text{CH}_4$  will decrease OH, increase  $\text{O}_3$ , and increase the lifetime of various organics such as HCFCs.

## Trends in Ozone

Figure 6 illustrates the change in total column ozone in the period 1979 - 1991 from data reported by UNEP/

would lead to destruction (Hameed, 1979; Lin, 1988). This implies that there are areas within the boundary layer as well as free troposphere where the photochemistry is forming ozone and other areas where photochemistry is destroying ozone. Scientists at Lawrence Livermore National Laboratory (LLNL) are developing a 3-D chemistry model to predict global atmospheric loadings and distributions of  $\text{NO}_x$  including nitric acid from anthropogenic and biogenic sources (Penner, 1991a; Dignon, 1992). A global map of spatially allocated  $\text{NO}_x$  emissions in Figure 4 illustrates a typical input used in the model. The model also predicts global wet and dry deposition of nitrogen species. Developing the capability to model  $\text{NO}_x$  from its

Increased emission	OH	O <sub>3</sub>	Lifetime (CH <sub>4</sub> , HCFC, HFC)
CH <sub>4</sub>	-	+	+
NO <sub>x</sub>	+	+	-
CO	-	+	+
NMHC	-	+	+

Figure 5. Precursor influences on atmospheric chemistry (derived from UNEP/WMO, 1991).

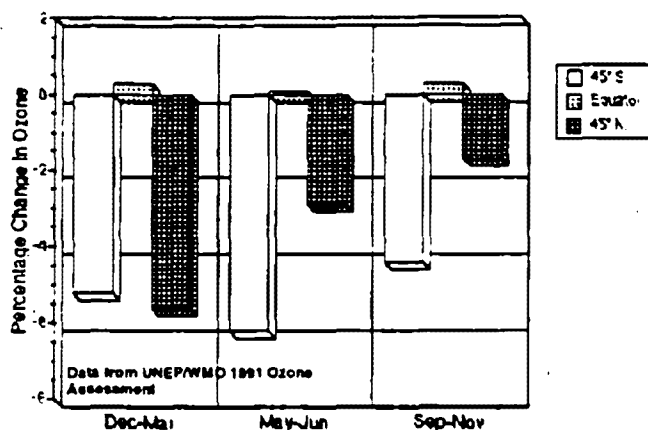


Figure 6. 1979-1991 total ozone column change (TOMS satellite data.)

WMO (1991) for the Total Ozone Mapping Spectrometer (TOMS) satellite. While this show substantial depletions, more recent data reported by NASA (1992) show much greater depletions, including in the tropics. In addition, measurements show record concentrations of ClO of 1.5 ppbv over northern New England in January 1992 as part of the Airborne Arctic Stratospheric Expedition (NASA, 1992). Abundance of chlorine monoxide (ClO) in the lower stratosphere at northern middle-latitudes is greater than predicted by models containing only gas-phase chemistry (UNEP/WMO, 1991).

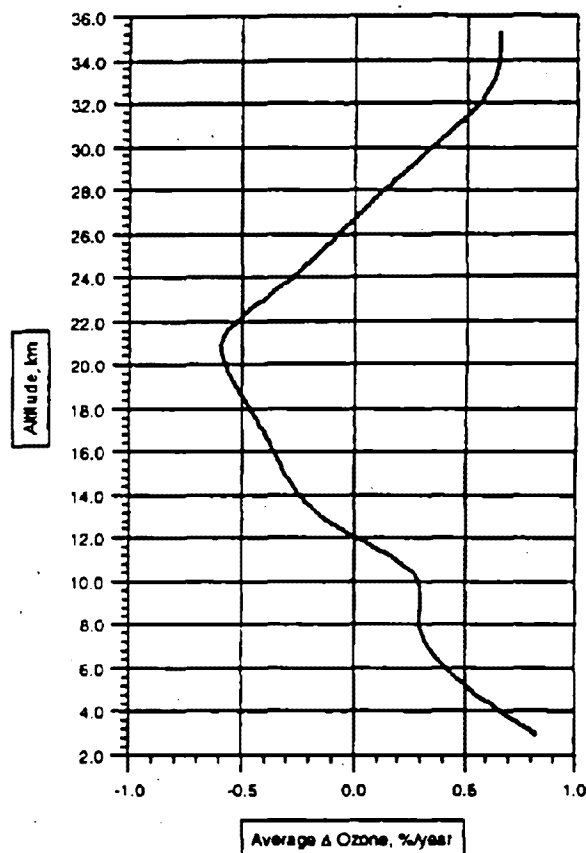


Figure 7. Ozone altitudinal trend estimates for the Northern Hemisphere (1970 - 1986).

Information on the vertical atmospheric distribution of ozone can be derived from ozonesonde, Umkehr, Stratospheric Aerosol and Gas Experiment (SAGE), and Upper Atmosphere Research Satellite (UARS) data. Unfortunately, most of the long-term measurements, particularly for the ozonesondes, are within the northern middle-latitudes. This hinders the development of reliable global vertical distributions for the Southern Hemisphere. There are concerns regarding calibration techniques for the long-term data from many of the northern ozonesonde stations. Nevertheless, the average percent per year change of ozone from 1970 to 1986 as a function of altitude for nine northern stations is shown in Figure 7 (UNEP/WMO, 1989). This historical ozonesonde record reveals that ozone appears to be increasing within the free troposphere and decreasing within the lower stratosphere. However, variations at individual stations show widely varying profile changes for different latitudes. Tropospheric ozone trends derived from ozonesonde data have accuracy limitations, but could be improved by expansion of monitoring capability (Prinn, 1988). Homogeneous chemistry 1-D models predict the ozone increases within the free troposphere but fail to predict the decreased ozone observed within the lower stratosphere. The change in the slope of the ozone profile that is observed in the troposphere below the tropopause may be due to the injection of ozone precursors by aircraft (Wuebbles, 1990; Kinnison, 1991). Tropospheric ozone trends continue to be measured at ozonesonde stations; however, measurements in the upper troposphere are sparse, and this is where ozone has its greatest radiative forcing effect.

Satellite data from the TOMS and the SAGE have been recently used to derive global maps of ozone within the troposphere and boundary layer (Fishman, 1991). Tropospheric ozone is derived as the residual or difference between the coincident TOMS and SAGE measurements between 50° S and 50° N. The residual, which is a relatively small difference between two larger values, represents the ozone column in Dobson units (ozone molecules per cm<sup>2</sup>) within the troposphere and boundary layer. Over a 10-year period the averaged seasonal depictions show the residual ozone to begin its formation in the Northern Hemisphere during March-May, reaching a maximum during June-August. In the Southern Hemisphere, ozone forms during the September-November season. What is so surprising is the size of the ozone plumes. The entire Northern Hemisphere is engulfed in an ozone plume that spans the Atlantic and much of the Pacific Ocean for the June-August season.

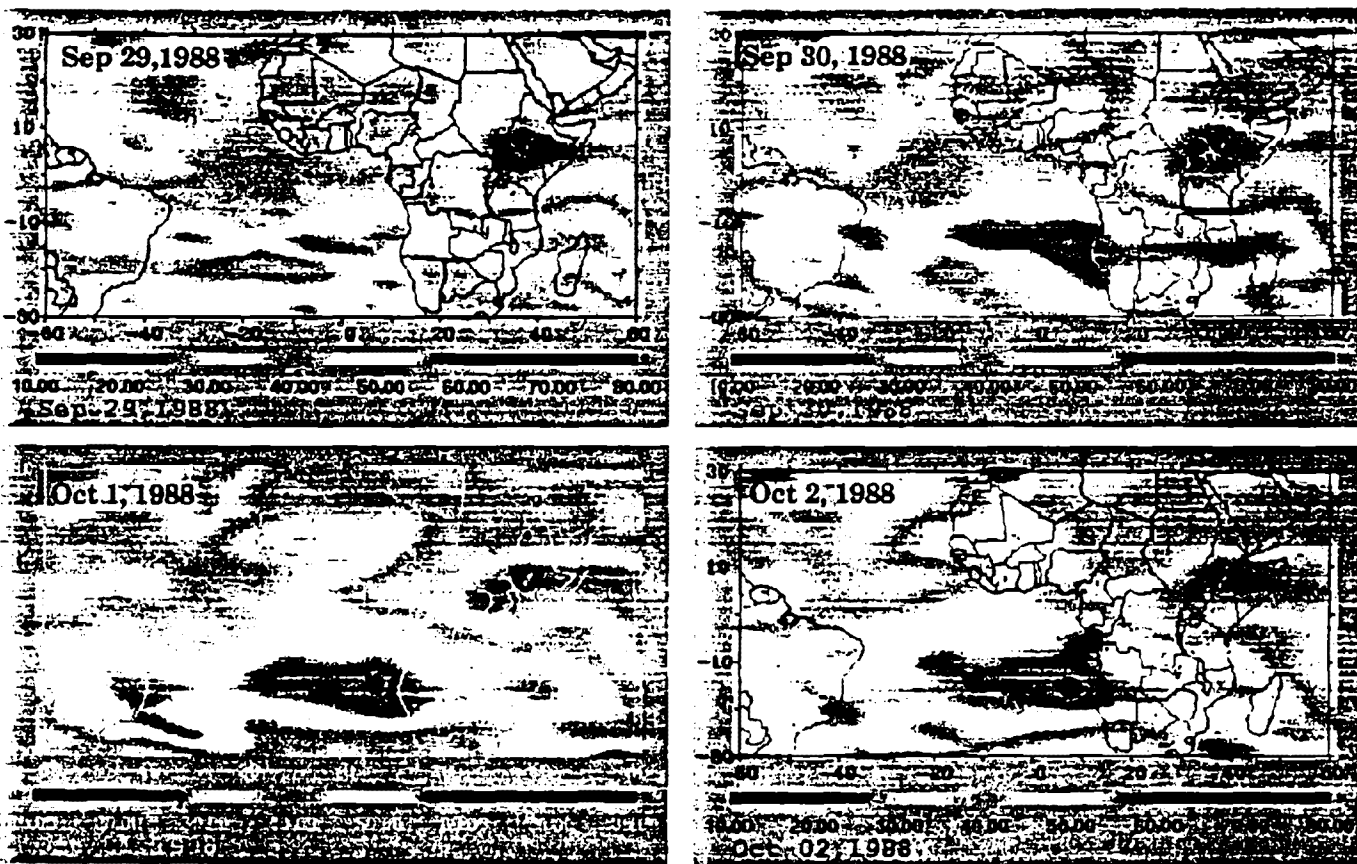


Figure 8. Satellite-derived tropospheric ozone residuals centered off the west coast of Africa.

In the Southern Hemisphere the ozone plume forms across lower Africa and tails across to Australia. It spans the Atlantic Ocean to South America. The formation of this plume appears to be associated with the biomass burning that occurs annually during the spring in the Southern Hemisphere. The formation of the observed ozone in the Northern Hemisphere is consistent with the photochemical production of ozone from its precursors during the spring and summer months.

Atmospheric scientists at NASA Langley Research Center are using the TOMS and SAGE data to derive daily residual maps for global tropospheric ozone for EPA. Since SAGE provides less than 5000 measurements per year, daily measurements are linearly interpolated from 60 day averages. The daily residual is obtained by subtracting the interpolated SAGE daily measurements from 3-day averages of the TOMS measurements and has a resolution of  $2.5^\circ$  latitude by  $5.0^\circ$  longitude. Computerized images of the daily residual from 1985 to 1990 are prepared by the EPA's Scientific Visualization Laboratory at RTP. A 4-day sequence for September-October 1988 is shown in Figure 8 that is believed to represent the formation of tropospheric ozone from the biomass burn in the springtime in the Southern Hemisphere. Scientists at NASA Langley Research Center are using the video computerized images to assist in the planning of the TRACER A Monitoring Program of the Biomass Burn in 1992. Scientists at EPA are comparing the satellite-derived daily residual  $O_3$  data for the Northern Hemisphere with ozone ground-based (AIRES), ozonesonde, and meteorological measurements. If the comparative analysis shows promising results, the satellite-derived ozone residuals will provide insight into the formation, transport, and fate of global tropospheric ozone, and may serve as a useful tool in the development of global chemical models that predict ozone concentrations from precursor emissions. EPA and NASA scientists are planning to develop another sequence of daily residuals using measurements from the Solar Backscatter Ultraviolet Spectrometer (SBUV) that flies on the Nimbus 7 satellite with the TOMS. Comparative analysis of the two daily residual data bases should provide insight into the techniques for deriving global tropospheric ozone from satellite data.



## Trends in Aerosols/Sulfates

It has been concluded that fossil fuel emissions over the past century have increased the tropospheric sulfate aerosol concentrations (UNEP/WMO, 1991). World total sulfur emissions are estimated to be 147 TgS with about 80 TgS coming mainly from fossil fuel combustion (IPCC, 1990). Husar (1989) shows a general correlation between sulfur emissions and extinction coefficient which is a function of visibility. Mayewski (1990) has determined, based on ice core data, that the anthropogenic sulfate loadings in remote areas of the Northern Hemisphere are now as high as or higher than the maximum loading from many past volcanic eruptions. Carbonyl sulfide (COS) is the most abundant sulfur-containing trace gas in the remote atmosphere and, with a lifetime of 2 to 6 years, is, via photolysis, a major source of aerosol sulfate in the stratosphere along with volcanic eruptions (UNEP/WMO, 1991). Sources of COS include anthropogenic activities, soils, biomass burning, and oxidation of carbon disulfide (UNEP/WMO, 1991). Long-term observational records show a 40-50% increase in stratospheric sulfate aerosols (UNEP/WMO, 1991).

## Trends in Ozone Precursors

Source emissions of  $\text{CH}_4$ ,  $\text{NO}_x$ , CO, and NMHCs have all been increasing. Figure 9 shows the IPCC predictions of future ozone precursor emissions. Atmospheric concentrations/distributions have been quantified for  $\text{CH}_4$  and CO, but are harder to do for the more reactive species,  $\text{NO}_x$  and NMHCs.

The atmospheric concentration of  $\text{CH}_4$  has been increasing at a rate of about 1% per year up to the last few years. Currently this growth rate appears to have fallen sharply with no completely satisfactory explanation. However, there is a possibility that OH is increasing at  $1.0 \pm 0.8\%$  per year (UNEP/WMO, 1991). The most recent data for methane, as taken from Khalil (1990), are given in Figure 10. Unfortunately, the data after 1988 are still not available. The data are undergoing quality assurance review, but should be available this summer in the journal

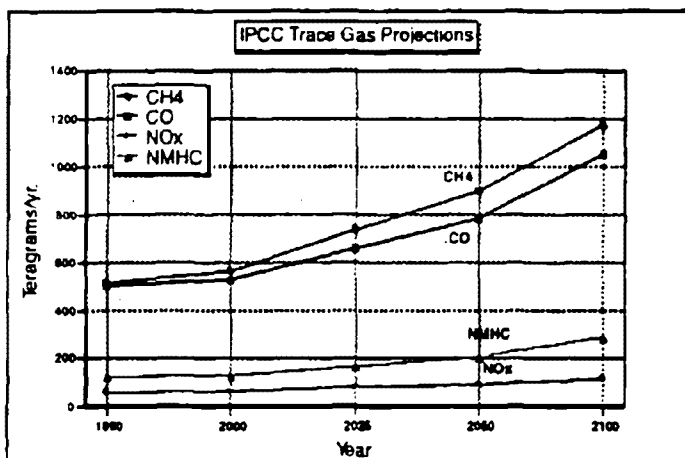


Figure 9. Projected ozone precursor emissions.

Chemosphere and a new book entitled *The Global Methane Cycle: Its Sources, Sinks, Distributions and Role in Global Climate Change*. Figure 11 represents 5 years of methane measurements from remote marine sites within the Geophysical Climate Change Sampling Network. The averaged atmospheric concentration of

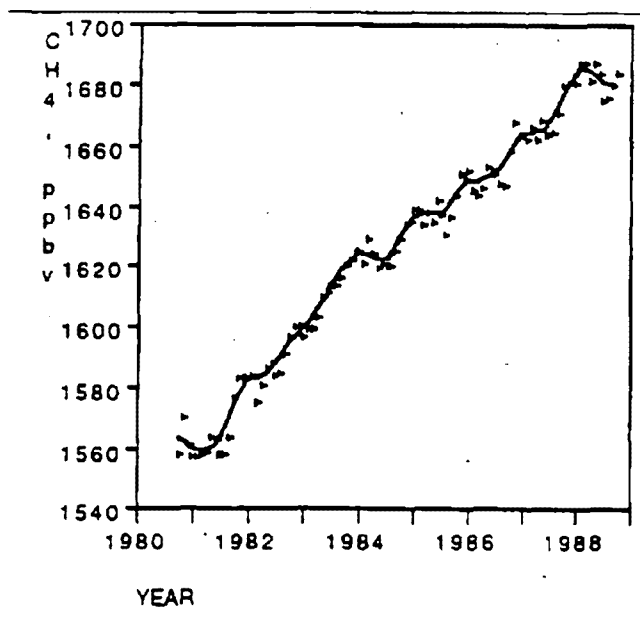


Figure 10. Atmospheric methane concentration.

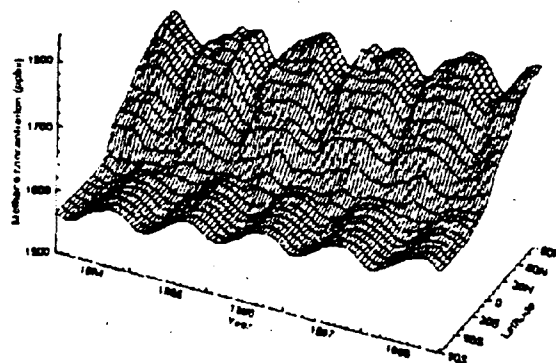


Figure 11. Hemispheric methane cycles with time. (IPCC, 1990; Reproduced with permission.)

methane is about 1.76 ppmv in the Northern Hemisphere and about 1.68 ppmv in the Southern Hemisphere. The seasonality is observed to vary with latitude and is repeatable over time in the hemispheres (IPCC, 1990). Note the increase in methane concentration right up to the arctic polar area. The primary emission sources of methane include: tundra/bogs/swamps, rice cultivation, biomass burning, livestock, coal mining, oil, and natural gas systems, landfills, and a variety of industrial processes (such as coke and petrochemicals production). Methane isotopic studies suggest that 20% of global methane is from fossil fuel and 10% is from biomass burning (UNEP/WMO, 1991).

The atmospheric concentration of carbon monoxide is increasing at about 1% per year in the Northern Hemisphere but is not increasing perceptibly in the Southern Hemisphere. The concentration is about 120 ppbv in the Northern Hemisphere and about 60 ppbv in the Southern Hemisphere for a hemispheric ratio of about 2 (Wuebbles, 1991). The primary sources of atmospheric CO are atmospheric oxidation of methane and nonmethane hydrocarbons, biomass combustion-related sources such as forest clearing, and fossil-fuel combustion (primarily transportation related).

Measurements of NMHCs are not adequate to establish trends with the exception of ethane (UNEP/WMO, 1991). Ehhalt (1991) has provided evidence of a trend for ethane over the Northern Hemisphere of  $0.9 \pm 0.3\%$  per year. Perhaps the best indicator of trend for NMHCs is the projected future emissions (see Figure 9). The primary sources of atmospheric NMHCs are biogenic in nature, including trees, oceans, and grasslands (UNEP/WMO, 1991). Anthropogenic sources include gasoline use, other petroleum-based solvents/chemicals, fuel wood use, biomass burning, and waste disposal (Watson, 1991). The reactivity and general variability of NMHCs in the atmosphere make it difficult to establish trends. NMHCs and their reaction by-products are found throughout the atmosphere. For example, the work of Greenberg (1990) indicates that many NMHCs may exist throughout the troposphere. Longer photochemical lifetimes, attributed to lower temperatures at high altitudes and latitudes, suggest to the investigators "that NMHCs may be present throughout the troposphere in many regions of the Northern Hemisphere." The more reactive NMHCs are generally found in smaller quantities relative to the less reactive compounds. Transport mechanisms such as cumulus clouds, dry convection, cold fronts, and flow of air over mountains are suggested as means for the substantial altitudinal dispersal in spite of atmospheric lifetime considerations. Figure 12 illustrates some of the data reported by Greenberg — in this case for total NMHCs at  $66^\circ$  N latitude. As can be seen, substantial NMHC mixing ratios are found high in the troposphere.

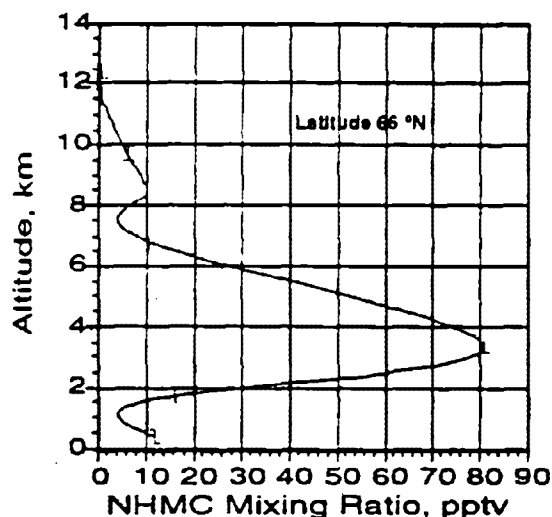


Figure 12. A total NMHCs profile for  $66^\circ$  N latitude from Greenberg (1990).

Penner (1991a) and Dignon (1992) have estimated sources and distributions globally of natural and anthropogenic emissions of  $\text{NO}_x$ . Northern Hemisphere anthropogenic sources are seen to be mainly fossil fuel combustion, and Southern Hemisphere anthropogenic contributions are seen to be a combination of fossil fuel emissions and biomass burning. Fossil fuel combustion, which consists of both stationary and mobile sources, is believed to account for about 50% of the estimated total emissions of global  $\text{NO}_x$ . If biomass burning is included, the total anthropogenic contributions become more like 75%. However, there is considerably more uncertainty in the emissions from biomass burning than from fossil fuel combustion in stationary sources. The NASA project (TRACER A) to characterize the 1992 biomass burn in the Southern Hemisphere should provide better quantification of the emissions. Natural sources include lightning, soil microbial activity, and input into the free troposphere from the photodissociation of  $\text{N}_2\text{O}$  in the stratosphere. Large uncertainties are also associated with the emissions from the natural sources. Sufficient atmospheric measurements of  $\text{NO}_x$  are not available to project global concentration trends. The best indication of  $\text{NO}_x$  concentration trends is from nitrate ( $\text{NO}_3$ ) measurements taken from ice cores. Analyses for  $\text{NO}_3$  in ice cores from Greenland and Switzerland show large increases in  $\text{NO}_3$  since the turn of the century (Neftel, 1985; Wagenbach, 1988).

## Radiative Forcing

Determining the radiative forcing caused by various trace substances is obviously difficult, with major questions still to be answered. Multiple effects for the same substance are possible in different parts of the atmosphere. Many of the complex questions arise from the indirect effects of trace substances. The recent IPCC (1990) report provided initial quantification of some of the indirect effects in terms of Global Warming Potentials (GWPs), especially for ozone and its precursors. But in later UNEP/WMO updates of the IPCC report, reservations have been expressed about the accuracy of the initial indirect GWPs. Also, the rather large negative-forcing indirect effect was identified for CFC-related ozone depletion in the lower stratosphere. GWPs are evolving with refinements taking into account such factors as sensitivity of the GWPs to the assumed background atmosphere (Wuebbles, 1992). Many of the indirect radiative forcing effects, for which indirect GWPs would be generated, require modeling to provide quantification, but for the most part the tropospheric models necessary to do the evaluation have not been fully developed and validated. EPA is collaborating with the Lawrence Livermore National Laboratory to identify, quantify, and refine potential indirect forcing effects for the various trace substances, especially as they relate to tropospheric ozone and its precursors.

As a greenhouse gas, the radiative properties or forcing for a given quantity of ozone is a function of altitude (Lacis, 1990). The radiative forcing of ozone has little effect within the boundary layer but maximizes within the free troposphere at the tropopause. In the lower stratosphere, the forcing is positive but diminishes with altitude. It is also a function of latitude. Hansen (1991) recently reported (at the 1991 AGU meeting in San Francisco) the impacts of atmospheric ozone on radiative forcing using the GISS GCM. When ozone between 10-20 km within the lower stratosphere was removed, the upper troposphere was found to cool by several degrees Celsius and the Earth's surface temperature cooled by 1-2° C. This simulation provides insight into the radiative effects of ozone removal that is believed to be now occurring by heterogeneous reactions in the lower stratosphere. When ozone above 35 km was removed in the model simulations, the stratosphere cooled, and a warming of about 2° C at the surface was observed. The warming of the surface in this case can be associated with an increase in radiant energy transmitted through the atmosphere. Increasing ozone in the free troposphere by a factor of 10 resulted in surface warming as a function of latitude. While the GISS GCM simulations point out the radiative importance of atmospheric ozone, the simulations also indicate a need for better ozone measurements in the troposphere and stratosphere to establish ozone profile trends. EPA scientists are also initiating studies to parameterize atmospheric transport processes between the boundary layer and free troposphere, such as cloud venting, for incorporation into global chemistry models. These processes inject ozone and its precursors into the troposphere. The atmospheric lifetime of ozone increases significantly in the troposphere where the temperature decreases with altitude up to the tropopause. These studies are intended to enhance model determination of global radiative influences due to changes in tropospheric ozone.

Table 1 illustrates some of the direct and indirect effects related to radiative forcing and their likely directional effects. This table is not provided as an accurate, comprehensive compilation of all potential important effects, but does attempt to show that there are many effects. Almost all the effects from the inorganic gases covered in Table 1 are directionally positive. Water vapor has a positive forcing effect in both the troposphere and stratosphere; however, there are also feedback effects related to water including clouds, snow cover, sea ice cover and precipitation. Hydrogen is also increasing in the atmosphere (Khalil, 1990) and can contribute water vapor to the stratosphere causing an indirect positive effect. CO has positive indirect effects associated with 1) production of ozone in the troposphere and 2) additional CO<sub>2</sub> as the final product of oxidation. Nitrous oxide is a direct acting greenhouse gas and might also cause positive forcing via its depletion of upper stratospheric ozone. NO<sub>x</sub> have a positive indirect forcing via production of tropospheric ozone. Radiative forcing of tropospheric ozone may be especially sensitive to NO<sub>x</sub> emitted by aircraft at cruise altitude (Wuebbles, 1990; Kinnison, 1991; Johnson, 1992). NO<sub>x</sub> may also have a negative forcing effect in the stratosphere via stratospheric ozone depletion. All of the effects identified for methane in Table 1 are positive. It has a direct effect, and it produces positive effects from ozone production in both the troposphere and the stratosphere. It has a positive effect via deactivation of active stratospheric halogens which destroy stratospheric ozone. It produces stratospheric water vapor, and it ultimately ends up as CO<sub>2</sub>, a greenhouse gas. All of the effects listed for NMHCs in Table 1 are also positive. NMHCs produce positive forcing from ozone formation in the troposphere and stratosphere. Longer-lived NMHCs that make it to the stratosphere would deactivate active Cl<sub>x</sub> and Br<sub>x</sub>, thus reducing stratospheric ozone depletion. NMHCs, like CO and methane, will also eventually oxidize to the greenhouse gas, CO<sub>2</sub>.

Halogenated organics would appear to cause both positive and negative forcing. CFCs such as CFC-11 and CFC-12 are strong absorbers causing direct greenhouse forcing in the troposphere. On the other hand such long-lived halogenated organics will cause stratospheric ozone depletion, thereby causing negative forcing. Aerosols constitute another set of forcing effects that are not well quantified and complex, but it would appear that their effects are mostly negative. Aerosols, such as sulfuric acid, can cause negative forcing through reflective scattering of solar radiation. They can also enhance cloud formation and reflectivity in the troposphere. Aerosols containing carbon black, on the other hand, may induce positive forcing via absorption of radiant energy. Finally, sulfuric acid aerosols in the lower stratosphere probably enhance ozone depletion via heterogeneous catalysis and destruction of sink species.

## Conclusions

Changes in several trace substances in the Earth's atmosphere are affecting global radiative forcing. Those substances which seem have the largest changes occurring now and projected into the future are CO<sub>2</sub>, ozone (and its precursors and depleters), and aerosols. It is conceivable that countervailing changes in the radiative forcing effects of these substances, especially ozone and aerosols, may be temporarily hiding or at least changing the "greenhouse signal." If in fact the greenhouse signal is being partially obscured at present, there is also potential for this effect's becoming less significant in the decades ahead because of 1) a continuation of increases in greenhouse gas emissions, 2) saturation of the tropospheric aerosol effect plus controls on SO<sub>2</sub> emissions, and 3) increasing tropospheric ozone. Recent findings by international scientists working toward more accurate assessment

of future forcing make it clear that indirect effects are playing an important role and are poorly quantified at present. The substantial complexities in factors affecting ozone and aerosols are discussed with emphasis on ozone and its precursors, including methane, NMHCs, CO, and NO<sub>x</sub>. A substantial number of potential forcing effects are identified along with an estimate of direction (sign). Quantifying radiative forcing and its sources are of substantial importance for future prevention and mitigation efforts, and to this end EPA is helping with efforts to enhance the ability to estimate both the direct and indirect factors contributing to forcing. Emphasis is being placed on better estimates of current and projected emissions and measures of radiative forcing such as Global Warming Potentials (GWPs). Research efforts are focused on enhanced emission/mitigation data and projections, improved data on global atmospheric trends, and enhanced capabilities for theoretical prediction via improved models.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

**Table 1. Partial listing of direct and indirect effects related to radiative forcing.**

<u>Inorganics (Mostly +)</u>	
H <sub>2</sub> O	H <sub>2</sub> O/Trop. (direct +) H <sub>2</sub> O/Strat. (direct +)
Hydrogen	H <sub>2</sub> /Strat. H <sub>2</sub> O (indirect +)
CO <sub>2</sub>	CO <sub>2</sub> (direct +) CO <sub>2</sub> /Strat. O <sub>3</sub> increase via strat. cooling (direct +)
CO	CO/Trop. O <sub>3</sub> (indirect +) CO/CO <sub>2</sub> (indirect +)
N <sub>2</sub> O	N <sub>2</sub> O (direct +) N <sub>2</sub> O/Strat. O <sub>3</sub> depletion (indirect +)
NO <sub>x</sub>	NO <sub>x</sub> aircraft/Upper trop. O <sub>3</sub> (indirect +) NO <sub>x</sub> /Strat. O <sub>3</sub> reduction (indirect -)
<u>Organics</u>	
CH <sub>4</sub> (all +)	CH <sub>4</sub> (direct +) CH <sub>4</sub> /Trop. O <sub>3</sub> (indirect +) CH <sub>4</sub> /Strat. O <sub>3</sub> (indirect +) CH <sub>4</sub> /Strat. O <sub>3</sub> increase via Cl <sub>2</sub> /Br <sub>2</sub> deactivation (indirect +) CH <sub>4</sub> /Strat. H <sub>2</sub> O (indirect +) CH <sub>4</sub> /CO <sub>2</sub> (indirect +)
NMHCs (all +)	NMHCs/Trop. O <sub>3</sub> (indirect +) Ethane, propane, etc. NMHCs/Strat. O <sub>3</sub> (indirect +) Ethane, propane, etc. NMHCs/Strat. O <sub>3</sub> inc. via Cl <sub>2</sub> /Br <sub>2</sub> deactivation (indirect +) Ethane, propane, etc. NMHCs/CO <sub>2</sub> (indirect +)
<u>Halogenated Organics (selected) (+ &amp; -)</u>	
	CFC-11 (direct +) CFC-12 (direct +) CFC-113 (direct +) CFC-22 (direct +) Cl <sub>2</sub> &Br <sub>2</sub> /Lower Strat. O <sub>3</sub> depletion (indirect -) Cl <sub>2</sub> &Br <sub>2</sub> /Upper Strat. O <sub>3</sub> depletion (indirect +) Halons (direct +) CH <sub>3</sub> Br (direct +)
<u>Aerosols (Mostly -)</u>	
	Aerosols/Strat./Trop. (direct -) Aerosols/Trop. (indirect -) Aerosols (Carbon black)/Trop. (direct +) Aerosols/SO <sub>4</sub> /Strat. O <sub>3</sub> depletion (indirect -)

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## Overview of Methane Energy and Environmental Research Programme in the United Kingdom

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### ABSTRACT

*The biofuels programme of research and development forms an important part of the UK Department of Energy's renewable energy programme.*

*This programme began in the mid 1970's as a response to the oil crisis of that time and was part of a much wider look at alternative energy supplies. The initial driving force for Biofuels and other renewables research was the prospect of greater diversity, and hence security of energy supply for the nation.*

*More recently, concerns over the environment and the need for 'sustainable' sources of energy, has added further strength to the case for using 'environmentally friendly' renewables.*

*This paper reviews the history of the biofuels programme, its present content and considers where future emphasis might lie.*

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## INTRODUCTION

### Biofuels: Status

Biofuels are any solid, liquid or gaseous fuels produced from organic materials which are derived either directly from plants or indirectly from industrial, commercial, domestic or agricultural wastes. They are amongst the most economically attractive sources of renewable energy offering significant potential and also environmental benefits locally, nationally and globally.

Estimates<sup>1</sup> suggest that some 14% of the world's energy (around 55EJ) is satisfied by the use of biofuels, making it by far the most important of the renewable sources. Renewable energy contribution in total is of the order of 20%. (See figure 1).

The most important use of biofuels is made by 'third world' or developing countries where use in rural areas often exceeds 90% of total energy requirements. In 'developed' countries use, as a proportion of total energy need, is much less, around 2-2.5% on average in the EEC and 4% in the USA. A recent survey of IEA nations participating in the Bioenergy Agreement observed that the highest level of contribution was no more than 15%. (See figure 2).

In the United Kingdom, use of biofuels amounted to a quarter of one percent of total primary energy needs in 1990, an estimated 23% of the total renewable energy supply. (See figure 3). Some of the reasons for the limited use of biofuels in the UK are:

- The UK is a fossil fuel rich nation and traditional sources of energy including coal, oil, natural gas (and also nuclear) are well established in the market place.
- Biofuels are very diverse in nature, disaggregated and (historically) satisfy only limited, local 'niche' markets.
- Biofuels are often bulky and less convenient to handle than traditional fuels
- Biofuels have a 'rustic' image and hence are often dismissed by large energy producers/users.
- Biofuels often appear uneconomic at the medium to large scale.
- Absence of large scale district heating networks that biofuels can 'plug' into.

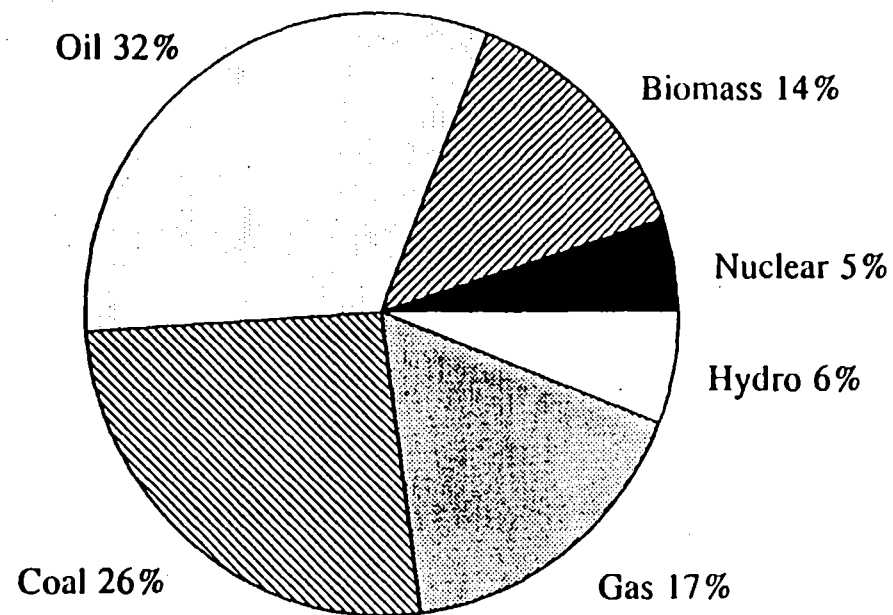
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or the Energy Technology Support Unit*

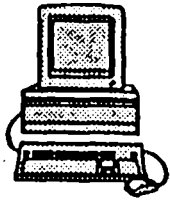
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<sup>1</sup> D O Hall "Biomass Energy" 1991 Butterworth-Heinemann Limited Energy Policy 19 (8) October 1991

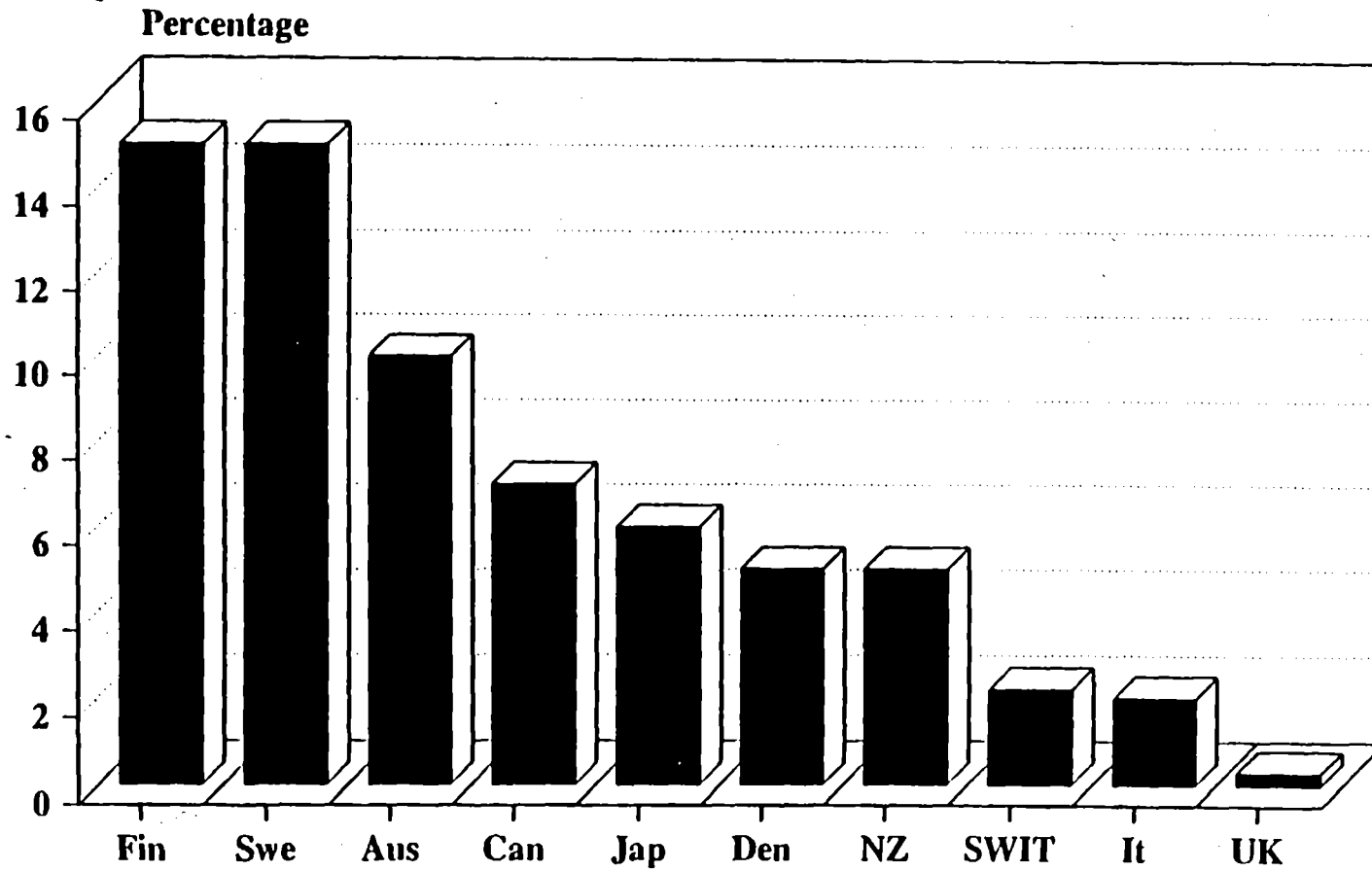


**Fig 1: World Energy Use**  
(World energy use: TOTAL 399EJ/9067mtoe)





**Fig 2 : IEA Countries  
Proportion of National Primary  
Energy Supplied by Biofuels**



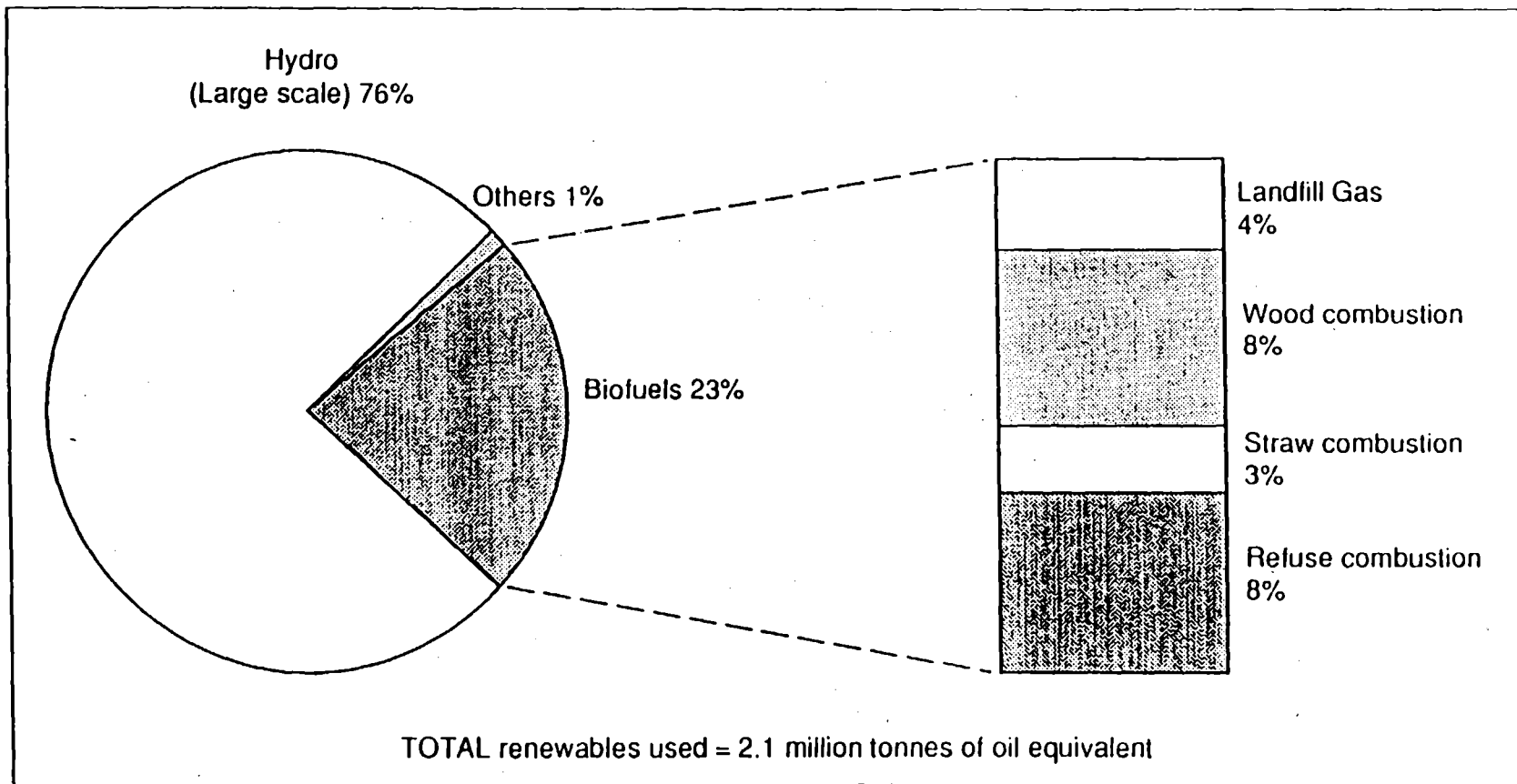


Figure 3. UK Renewable Energy Contribution (1990)

## THE UK DEPARTMENT OF ENERGY PROGRAMME

### General

The Department of Energy invests in a substantial programme geared towards harnessing 'environmentally friendly and commercially viable renewable sources of energy'. Renewables are recognised as offering diversity of energy supply and thus greater security of supply for the nation. Such sources are also viewed as 'sustainable' 'greenhouse gas' friendly (by recycling carbon through photosynthesis and by utilising methane) and clean (low in sulphur). As such they offer substantial environmental benefits over many traditional fuels.

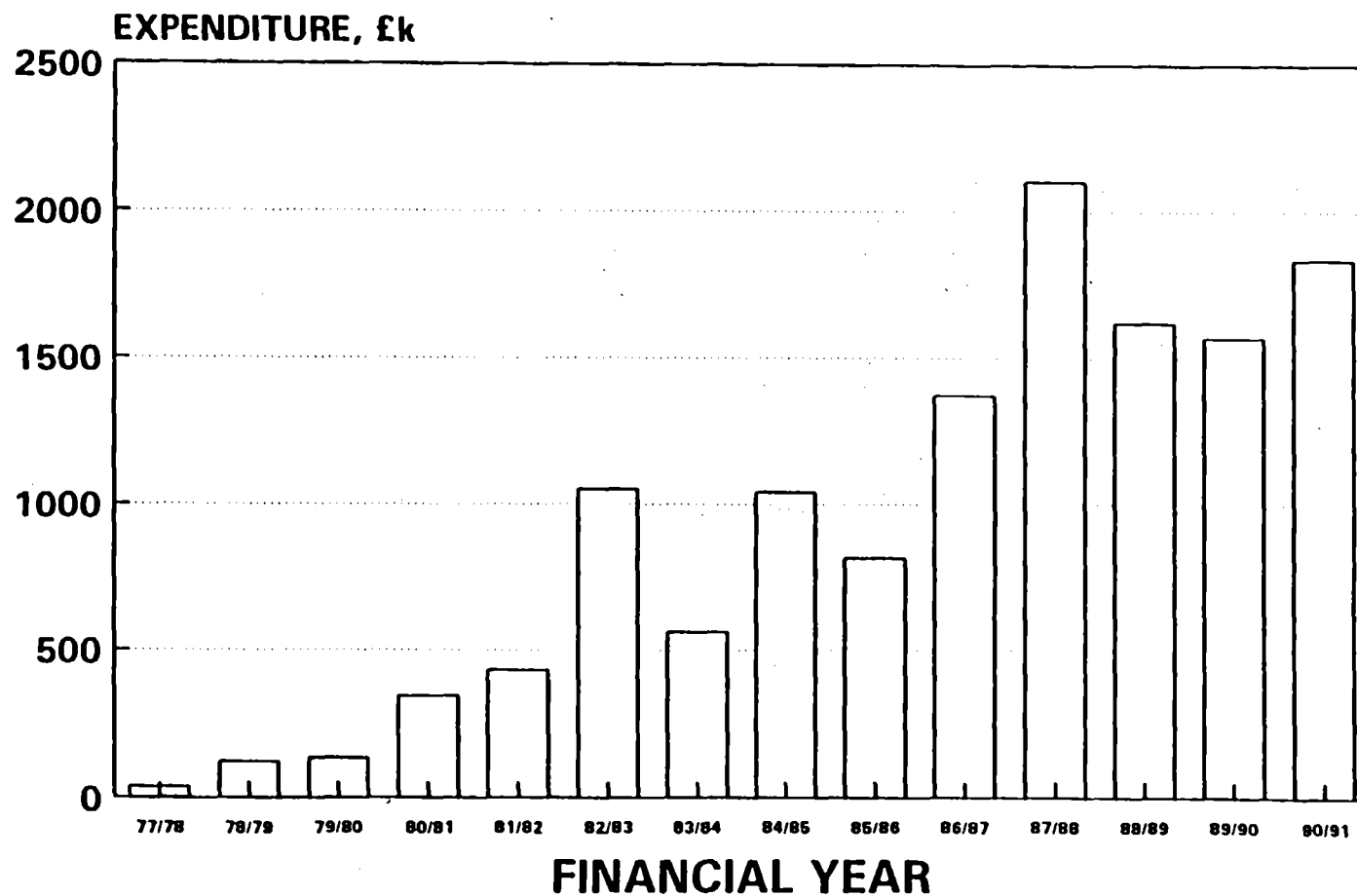
Government has so far invested a total of £180 million (since 1979) in renewable energy research and development projects, with approximately £13 million allocated to biofuels. The current renewable energy programme budget is running at £24 million per annum - a 20% increase on last financial year. Figure 4 indicates historic spend on biofuels.

Since its inception the Biofuels Programme has sought to define the size, nature and likely timing of the UK biofuels resource. This is a task which continues to this day with the progressive refinement of estimates and projections. The maximum accessible potential is believed to be very high, of the order of 200TWh/y which is equivalent to more than half the UK's current electrical needs. The bulk of the resource relates to crops - in particular short rotation coppice grown on land surplus to food growing needs. Some 50TWh/y can be produced from wastes and is available at up to 6 p/kWh.

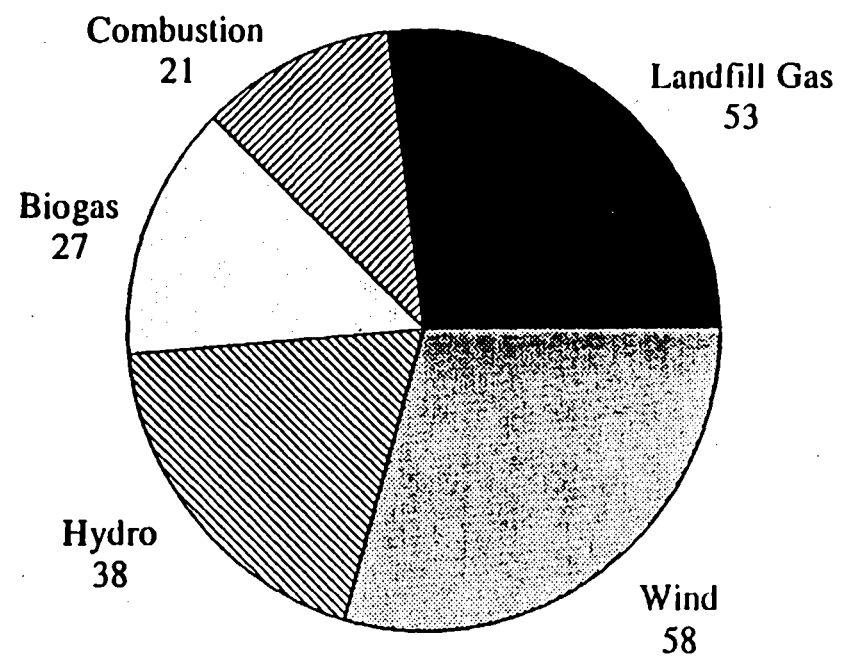
As already discussed, only a very limited use is currently made of biofuels - of the order of a quarter of one percent of the UK's total primary energy needs. Those fuels which are making a contribution include landfill gas, wood (from existing forestry), refuse and straw combustion. For these fuels the emphasis within the Programme is switching from more fundamental studies to work geared toward deploying the technologies. Hence, field trials and demonstrations are being worked up where these do not exist already. The detail of the Programme is explored in the central part of this paper. Maximum benefit is also being derived through monitoring projects which are proceeding as a result of the Non-Fossil Fuel Obligation (NFFO), a major market enabling measure for renewables. NFFO is an obligation placed upon Regional Electricity Companies to purchase a defined quota of renewable energy generating capacity. In order to secure the necessary capacity a premium price is paid to generators with the cost being met through a levy placed on consumers. So far it has resulted in more than 100 biofuels projects coming forward with a total installed capacity of more than 600MW<sub>e</sub> (See figures 5 and 6).

Apart from such technical measures great effort is also being placed on addressing other non-technical issues and barriers thought to be preventing the widescale adoption of technically mature biofuels. Matters which are of particular concern include uncertainty over environmental control and regulation of wastes, lack

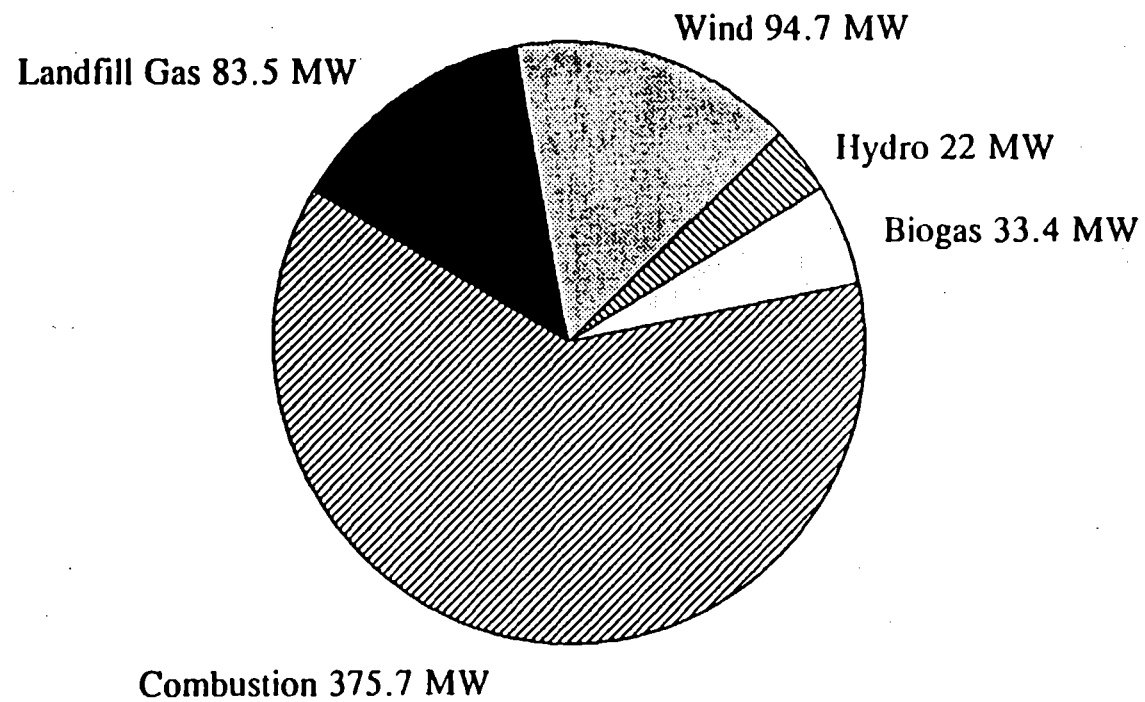
**Fig 4 :UK BIOFUELS PROGRAMME  
ANNUAL EXPENDITURE**



**Fig 5: Numbers of existing and planned  
NFFO Projects by Area**



**Fig 6: Declared Net Capacity of existing  
and planned NFFO projects**



of financing, credibility of certain technologies, planning, perception and the future of NFFO itself. In addition, for energy crops issues of land availability are central to any substantial biofuel production programme.

Less mature fuels and technologies still need a great deal of research and development effort as well as demonstration, if they are to yield the sought for energy benefits. Included in this category are wood and crops where in the past emphasis has been on growing the materials and not on use. The need within the Programme here is to demonstrate that such crops can not only be grown commercially but that they can also be used to produce both heat and electricity in a cost effective manner (initially with NFFO support). Gasification and advanced thermal processing is another area where considerable effort needs to be expended if significant advances are to be made.

The objectives of the current programme are to:

evaluate technically and economically the more important biofuel sources and conversion processes and identify those with most promise.

demonstrate and promote those which are cost effective, paying particular attention to environmental acceptability.

where appropriate, stimulate and support the development of better technology, particularly where such improvement is an essential prerequisite to commercial exploitation.

Four main areas now make up the Biofuels programme:

1. **Municipal Solid Waste:** Landfill Gas; Anaerobic Digestion; Combustion and Refuse Derived Fuel
2. **Dry wastes :** Dry wastes arising from industrial, commercial, agricultural and forestry operations in the UK excluded from the municipal solid waste category
3. **Wet Wastes :** Anaerobic digestion of aqueous organic wastes including sewage, food and drink processing effluents and animal slurries
4. **Crops :** Non food crops grown specifically as energy crops eg coppice

#### Programme Liaison

The Biofuels Programme interacts with many other organisations world-wide in order to both share and benefit from a much larger 'pool' of research effort. Such liaison also allows the programme to influence the debate on regulation and other vital non-technical issues which impact on the furtherance of renewable energy in the UK and elsewhere. In the United Kingdom the energy-from-waste aspects of the programme are closely coordinated with a complimentary programme, funded by the DoE. A co-ordinated approach has also been developed with other Government departments, including MAFF, particularly on the crops programme, DTI, Forestry Commission and the Departments of Health and Transport are also involved.



On the international scene, the UK, through the programme, participates fully in the IEA (International Energy Agency) Bioenergy Agreement. There is also a very active US/UK Bilateral Agreement to share information on biofuels and related environmental themes. Currently, several topics are being discussed by the four participating Government Departments (UK DEN and DoE; US Department of Energy and EPA) for collaborative action and a number of jointly sponsored conferences are being organised. There is also interaction with the CEC, particularly with the Directorates on Energy (DGXVII), Environment (DGXII) and Agriculture (DGVI).

## **THE DETAILED PROGRAMME BY AREA**

### **1. Municipal Solid Waste**

There are a variety of ways of utilising MSW and recovering energy. Within the current Department of Energy programme there are two key routes: landfill gas and combustion.

#### **1.1 Landfill Gas**

This area represents one of the most successful parts of the biofuels programme. The Department initiated the earliest work on landfill gas in the UK (in 1979), and remains in the vanguard of activities.

Approximately 50 million tonnes of municipal solid waste (encompassing household, civic amenity, commercial and industrial waste) is produced annually in the UK, with up to 90% currently disposed of to landfills (1991 figures). To date landfilling has offered a cheap and acceptable means of disposal, although more recently increased awareness of the environmental consequences of landfilling has led to closer scrutiny of procedures and a requirement for increased vigilance. Even allowing for greater use of incineration and municipal solid waste digestion it is generally considered that, for the foreseeable future, landfilling will continue to play a major role in the UK's waste management strategy. It is also thought that the potential for utilisable quantities of landfill gas to be generated from sites will increase if landfill practices continue to encourage fewer and larger sites, as observed since the 1980s. This being the case there is an opportunity to exploit the positive 'energy' feature of landfill gas generation and at the same time increase the environmental acceptability of the process.

The Department of Energy has long perceived the benefits, both in terms of energy and the environment, of harnessing landfill gas, and as such has had a programme of research, development and demonstration (RD&D) investigating all aspects of landfill gas, for the past 13 years. The programme has focused in particular on areas of uncertainty which may act as barriers to increased uptake of the technology aiming to encourage the development and use of landfill gas as a fuel and to publicise the potential of landfill gas as an economic energy resource. Six demonstration projects were established to validate the potential in schemes ranging

from electricity generation to kiln and boiler firing and played a key role in the development of this technology. These projects established landfill gas as a commercial technology in the UK.

It was also clear that a number of uncertainties remained and so a research programme has been underway since 1985, managed in two halves: A Field Studies and a Microbiology programme. Emphasis in particular is placed on the development of techniques for improving the yield of landfill gas whilst at the same time permitting improved environmental control. The Field Studies research programme is addressing well design, condensate removal, and the preparation of guidelines for landfill gas utilisation and control. The Microbiology programme aims to increase fundamental understanding in terms of the microorganisms responsible for landfill gas production, particularly cellulose degraders and methane producers.

#### Gas Utilisation Schemes in the UK.

The utilisation of landfill gas as an alternative energy resource is a proven technology, with schemes operational in a number of countries. There are three main options for gas exploitation :

- direct burning in kilns or boilers
- electricity generation
- gas upgrading

There are currently 37 landfill gas utilisation schemes underway in the UK (see Figs 7 and 8). Of these, 17 are direct use schemes such as use as landfill gas in kilns, driers or boilers; three are pre-NFFO electricity generation schemes and the remainder have come forward under NFFO. A further 36 schemes are planned, providing for 86.4 MW (DNC) from the NFFO supported schemes alone. It is hoped that further schemes will continue to come forward from sites where gas collection will be required in response to the recent legislation contained in the Environmental Protection Act (1990), where the revenue that can be obtained from the installation of a gas exploitation system may be seen as a means of offsetting some of the costs of installing a gas management system.

Figures 9 and 10 indicate the energy savings for the range of uses for landfill gas and also indicate the trend for utilisation options since 1986. The simplest option is direct use as this involves minimal capital investment and gas pre-treatment, but it is dependent upon the availability of a local user willing to take the gas. As this is not possible in many cases, electricity generation from the gas is the preferred option in the UK. This is further encouraged by the NFFO scheme previously discussed. Gas upgrading to pipe line quality is complex and expensive and most interest in this option has been shown by the United States where a number of purification plants have been constructed supplying considerable quantities of methane to local gas utility networks.

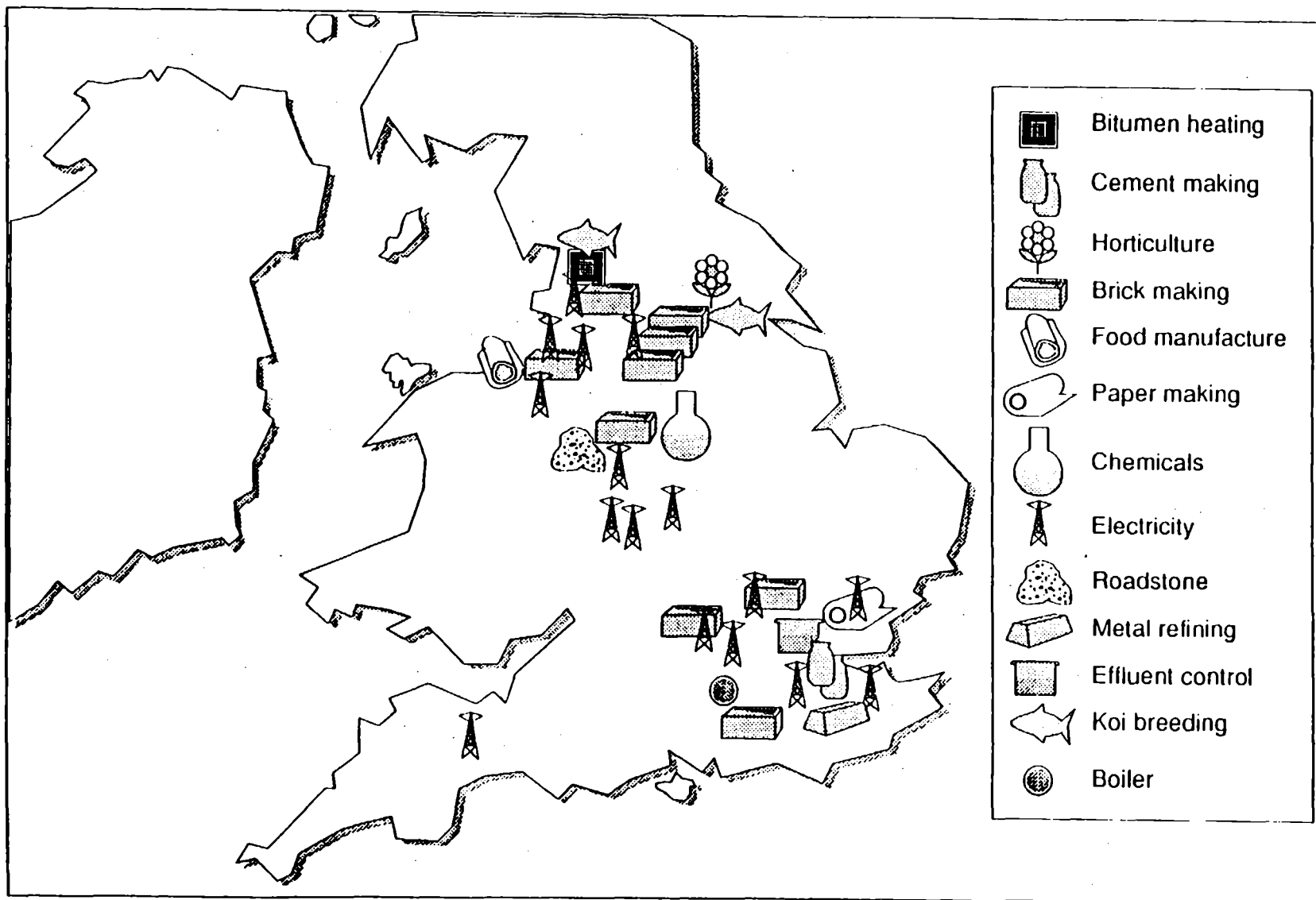


Figure 7. UK Landfill Gas Utilisation Schemes (1991)

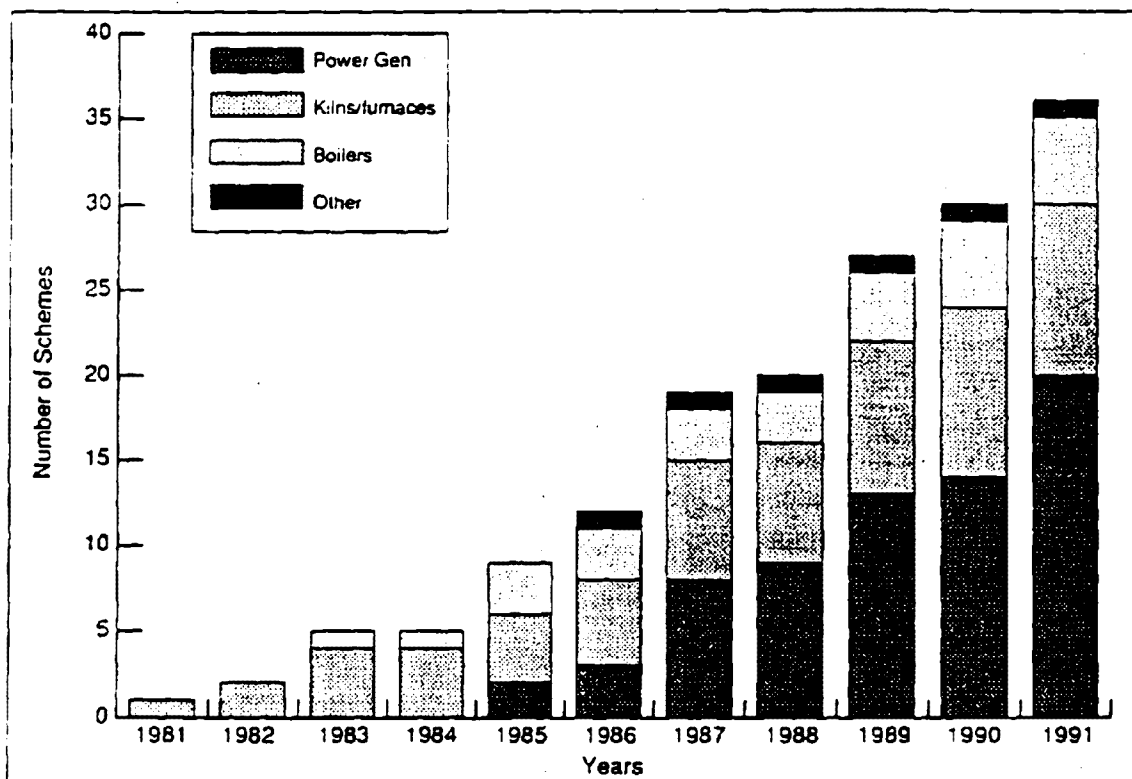


Figure 8 - LAMMCOS: Number of UK Landfill Gas Schemes

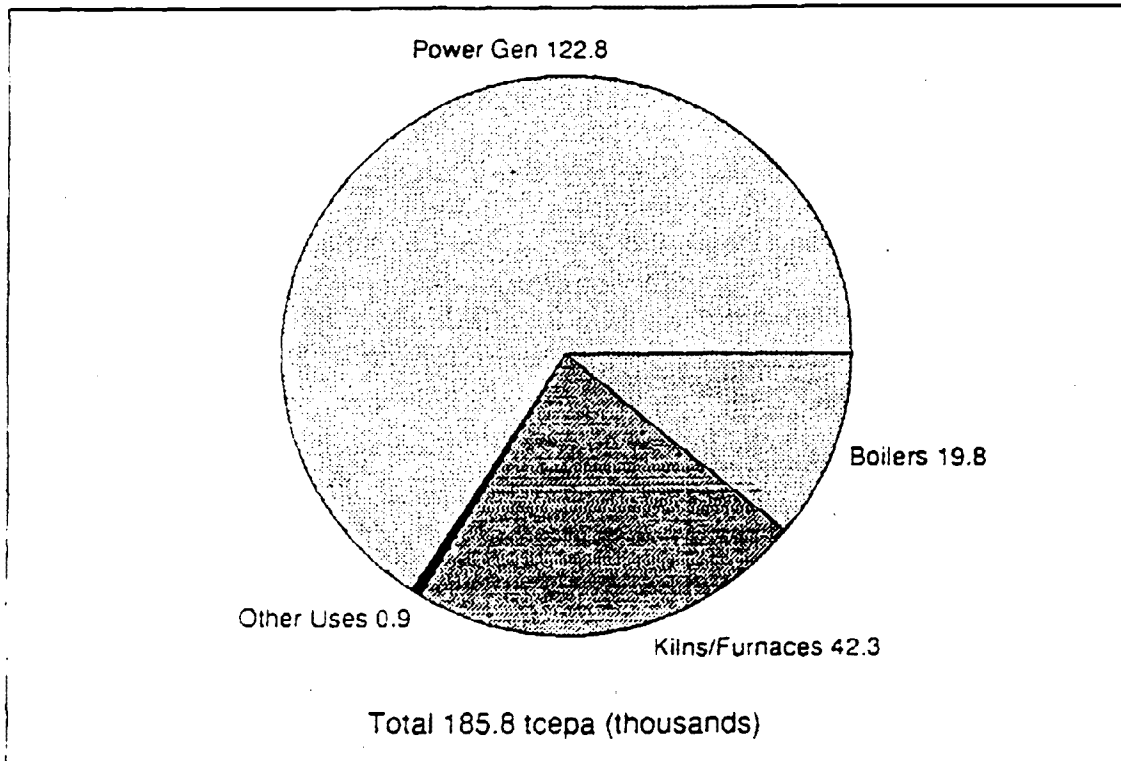


Figure 9. LAMMCOS: Total Energy Produced

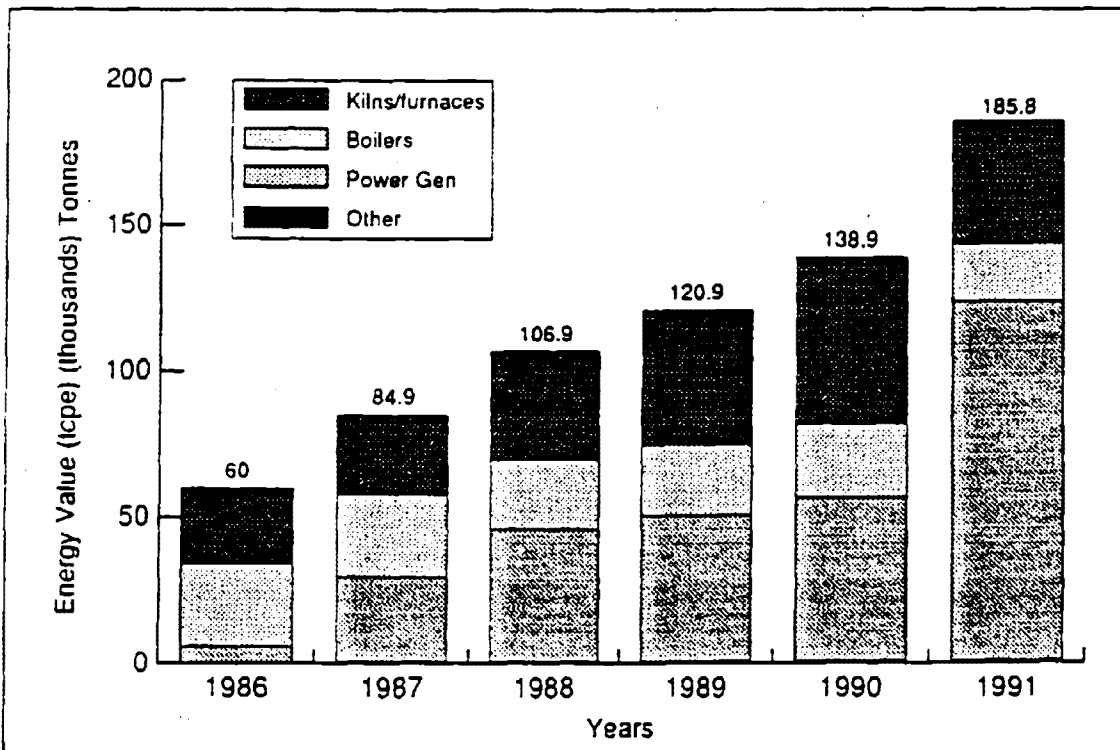


Figure 10. Use of Landfill Gas by Technology

## The Microbiology Programme

The disposal of organic waste material in holes in the ground and under circumstances where the environment rapidly becomes anaerobic, ie devoid of oxygen, will inevitably lead to microbial activity and the production of methane and carbon dioxide. Developing a greater understanding of the precise mechanisms involved and how they are influenced by the immediate environment is important if the maximum benefit is to be gained, safety standards upheld, and assessment procedures improved. Microorganisms are responsible for the degradation of biological material and so a programme aimed at understanding which organisms are responsible, what conditions they prefer, and how the landfill does or could satisfy these conditions has been running for 4 years, with a budget of just under £1 million. Seventeen projects have been initiated, with eleven already complete and further details and reports can be obtained from the Renewable Energy Enquiries Bureau at ETSU.

## The Field Studies Programme

The aims of the field studies programme are:

- to define with greater certainty the overall technical and economic potential of the UK landfill gas resource
- to establish an extended database for monitoring and use with the UK landfill gas resource model
- to investigate methods of landfill gas enhancement and optimisation
- to investigate more sophisticated and effective gas abstraction and treatment technology

There are currently 5 projects in this area and further details are available from the Renewable Energy Enquiries Bureau. Two of the nine energy efficiency projects previously mentioned will now be discussed in some detail to highlight how the projects have operated and what they achieved.

### Case History 1.

The feasibility of generating electricity for supply to the UK national distribution network, from landfill gas fuelled spark ignition engines was investigated at Stewartby landfill site, operated by Shanks and McEwan (Southern) Ltd, in 1987. The project aimed to show that remote or rural landfill sites without easy access to direct consumers of landfill gas could also capitalise upon the energy potential of landfill gas. The project cost £418,500 and achieved savings of £158,000 per annum offering a payback period of 2.4 years (1987 prices). The cost of the compressor was excluded from the investment cost because this would be needed anyway if the gas was simply flared. If gas control was not previously a pre-requisite and if existing gas collection and well systems were not in place a payback period of the order of 4.7 years (average exported tariff 2.75p/unit) was estimated.

Three 275 kW spark ignition engines fuelled by landfill gas coupled to air cooled generators were installed in a single -roomed engine house containing control

panels and the lubricating oil tank. Due to the lower calorific value of landfill gas, the rating quoted was 11% below the engine's normal rating when operating on natural gas. The units were designed to operate unattended, requiring comprehensive interlocks to trip the units in the event of low gas pressure, spit back in the carburettor, low oil pressure, high engine temperature or engine overspeed. All engine trip circuits were linked by telephone to a 24 hour call out system. Both vertical and horizontal wells were used to extract the gas and knock out drums for removal of water were located in polyethylene lines from the landfill site. Gas was compressed after filtration using a single constant displacement vane-type unit manufactured by Hammond Engineering and driven by a 45kW electric motor (rated to supply 680 m<sup>3</sup> /h) against 1.3 bar g. The compressed gas then passed through an aftercooler, baffle water separator, chiller and fine filters before being supplied to the adjacent engine house. Any surplus gas was flared.

Electricity was supplied at 415V for in-house use with the main export power stepped up to 6.6kV via a single transformer for use by the local London Brick Company. Any residual power was then exported to the local grid at 33kV.

Plant Performance. The plant operated almost continuously from February 1987. There were problems associated with a failure in the oil supply, resolved by a replacement pump, and also three compressor failures resulting from water getting through the water separation systems, requiring compressor rebuild or replacement in each case. Apart from two major service shut-downs the generators ran almost continuously, and most of the minor faults were electrical and resolved by adjustments to the equipment. Occasionally the units were tripped by low methane content. After 22,000 hours of service the engines were in generally good condition with only minor problems of wear.

#### Case History 2.

The second case history is the generation of electricity from landfill gas using gas turbines. A 3.65MW Centrax gas turbine (model CX350 KB5 powered by a General Motors Allison 501 KB5 single shaft gas turbine which runs at 14,250 rpm) was installed in 1987 to generate electricity for direct export to the local grid. At the plant the gas was scrubbed and then passed through a centrifugal blower before being compressed in two Belliss and Morcom WH56N compressors. Each compressor was rated at 55% duty, although each was capable of delivering 70% of the total gas requirement when operated with the blower. Before delivery to the turbine the gas was cooled and superheated to control condensation of hydrocarbons. The drive to the Brush 6.125 MVA generator was taken through a step down gearbox to 1,500 rpm. The generator output was exported to the local grid at 11kV via a 1.8 km underground cable.

Plant Performance. Start up of the system indicated many teething problems. During the plant acceptance trials the automatic condensate return valves were not functioning. Removal and cleaning rectified this problem. During commissioning one of the compressors failed as did the replacement unit. Consequently initial operation

was undertaken using only one compressor supplemented by the gas blower. Under these conditions it was possible to raise the turbine output to about 2.7MW. During early running of the compressor the cylinder head and valves suffered fouling by chloride salts and hydrocarbons, heavy corrosion also became apparent in the stainless steel flexibles connecting to the compressor. The probable cause was traced to the formation of hydrogen chloride through reaction of sodium hypochlorite with hydrocarbons. Sodium hypochlorite and sodium hydroxide were being added to the scrubber liquor to remove any traces of hydrogen sulphide present in the landfill gas. Dosing with sodium hypochlorite was subsequently stopped following advice from the manufacturers.

Problems of 'belling' had been reported on similar plant in the USA and so replacement ends of the turbine fuel manifold were manufactured. Due to fracture of the gas injection nozzles, all nozzles were replaced and subsequently redesigned. Problems were also encountered with the scrubber control panel and this was replaced. As a consequence of these problems the system operated with an availability of 85% and at a reduced average output of 58%. However during June 1989 - May 1990 the system ran with an availability of 95% while operating at 79% of rated output. All of the monitored exhaust emissions were lower than the limits allowed for municipal waste incinerators in the UK, except on one instance when the HCl level emitted marginally exceeded the limit of 250 mg/m<sup>3</sup>. The noise level at a distance of 50m was inaudible above the total background noise level, even at night.

The investment cost was £1.946 million (1986 prices) with savings of £176,780 giving a pay back period of 11 years. It should be recognised though that this is based on monitoring during the initial teething stage. It was estimated that if the plant had achieved target generation with the original electricity tariff the payback period would be reduced to 4.5 years.

#### Summary of Results From The Landfill Gas R&D programme

As previously mentioned several research projects are now complete. The following outlines a selection of the achievements:

1. Development of a computer model to estimate the UK national landfill gas resource.
2. Evaluation of well design concluding that horizontal wells were most effective in areas of high leachate levels.
3. Evidence to show that the application of a discontinuous polyethylene cap to previously uncapped areas increases the landfill gas content of the gas abstracted.
4. Demonstration of electricity generation from landfill gas using reciprocating engines and gas turbines.
5. Evidence to show that some of the bacteria involved in the landfill degradation process are specific to the landfill environment, endorsing the notion that we cannot just apply existing knowledge from similar systems eg anaerobic sewage sludge digestion.



6. Techniques for, and experience of, setting up laboratory scale model landfill systems.
7. Evidence to suggest that fungi do not play a major role in refuse degradation.
8. Evidence to show that some species of methane producing bacteria can be protected from external environmental fluctuations by co-existing within protozoa.
9. A comprehensive review of microbiological methods applicable to landfill studies and identification of areas of weakness.
10. A review document discussing the possible effects of recycling on waste composition and gas production.
11. A review of the potential for applying DNA technology to the study of landfills.

A number of projects are currently underway or at the final planning stages and it is hoped that information on the following will be available shortly:

1. Review of demonstrated prime mover engine technologies, mainly focusing on the UK but also looking overseas. The study will include corrosion, erosion and wear; the impact of legislation and emissions.
2. A feasibility assessment of the potential for developing a bioreactor cell rotation landfill.
3. An assessment of various enhancement techniques on the production of landfill gas at the Brogborough Landfill Test Cells.
4. An investigation into cellulose degradation in landfills.

## **1.2 Combustion of Municipal Solid Waste (MSW)**

Estimates of annual UK waste arisings (domestic, industrial, commercial and straw) suggest that the combustible fraction has an energy content equivalent to some 28 million tonnes of coal (Mtce) with an energy value in excess of £1000 million. Some 3.5 Mtce is estimated to be economically accessible at present energy prices, although less than 10% of this is currently realised.

In the UK Municipal waste combustion is dominated by mass burn incineration, with 34 plants providing a disposal route for 8-10% of UK arisings. These all date from the 1960s and 70s and were built by chiefly as a means of volume reduction prior to transport to landfilling. Energy was not an issue, and only 5 of the plants are equipped with energy recovery. Most of the plants are approaching the end of their serviceable life and, with the need to comply with recent comprehensive European air pollution regulations by 1996, it is anticipated that the majority will close rather than be retrofitted with the necessary abatement equipment.

Incinerators capable of meeting modern environmental requirements are considered to be proven technology. However, in the UK context of low cost landfill

they represent a high cost disposal option. DEN studies have therefore focused on the impact and maximisation of energy recovery to enhance project economics. CHP and district heating have been identified as preferred options. However, the UK markets for these are limited and hence, with the introduction of the Non-Fossil Fuel Obligation, the focus has moved to electricity production. Seven retrofit and new schemes have been proposed since the initial obligation was made in 1990, including a 1.5 Mte/yr 102 MW<sub>e</sub> plant for London (which will be the largest such scheme in Europe). In the absence of other fiscal measures, the NFFO is widely regarded as the major factor which will determine the future scale of mass burn incineration in the medium term.

In parallel with the economic studies, field trials have been undertaken at two of the existing heat recovery incinerators to evaluate the potential of mechanical screening to improve combustion and reduce the burden on the downstream gas cleaning equipment. Screening (at 50mm) was found to increase the calorific value (CV) by 30%, reduce the bottom ash by 30% and halve the carbon in ash losses. Energy recovery per tonne of sorted waste increased by over 40% compared with untreated refuse, reflecting both the increased CV and an overall improvement in boiler efficiency. Preliminary economic assessment indicates that pre-screening could yield a 20% saving on net disposal costs. Long term operational assessment is now required.

The principal aim of the programme, however, has been to assess alternative options to mass burn incineration for the typical scales of urban waste arisings (150-250,000 te/yr). This has concentrated on waste processing and the utilisation of refuse derived fuels (RDF), particularly the utilisation of high processed densified RDF as a substitute for lump coal on industrial solid fuel fired boilers.

#### Refuse Derived Fuel

The UK development of dRDF was initiated by the Department of Environment in the mid-1970s against the backdrop of a perceived energy crisis and a shortage of landfill capacity. Following initial development work a number of second generation dRDF plants were established in collaboration with Local Authorities, ostensibly as recycling centres with the RDF representing the reject paper fraction. In the event, markets for the recovered materials failed to develop and the dRDF became the principal product. DEN involvement in the utilisation of dRDF as an industrial fuel substitute commenced in 1981 with the sponsorship of a series of industrial user trials. Some 15 individual projects have since been initiated at a cost of £1.5 million. It rapidly became obvious that, due to the higher volatiles content, lower bulk calorific value and greater fouling potential of dRDF compared with coal, significant boiler modifications would be required in order to achieve fuel substitution. Much of the further work was aimed at understanding the fundamental combustion characteristics of dRDF, its handling and storage characteristics, the most suitable types of furnace for dRDF firing and the nature of the boiler modifications required. The chain grate stoker shell boiler was identified as particularly amenable to dRDF firing provided provision was made for over-fire air to ensure adequate burn-out of the volatile components and also for temperature control and soot blowing at the rear of the furnace to minimise boiler fouling. The programme was closed in mid-1991 when sufficient data for an

accurate assessment of the economics of dRDF production and utilisation had been amassed. The work showed that dRDF can now be produced and used without technical problems. However legislation requiring more comprehensive abatement of emissions from dRDF than from coal was introduced subsequent to the 1990 Environmental Protection Act. This renders the use of dRDF uneconomic against coal and other industrial fuels in most circumstances. However, four schemes have been accepted under the Non-Fossil Fuel Obligation and will commence electricity generation in 1991.

European policy is now that waste minimisation and materials recycling are preferable to incineration, with landfilling being a waste disposal option of last resort, and the UK has since introduced a recycling target equivalent to about 25% of municipal waste. Means of progressing towards this target are being investigated, including source separation and "blue box" systems. However, centralised processing for materials recovery, coupled with on-site energy production, may provide an economic option for waste disposal. Such integration, termed here Resource Recovery, is now being considered under a new programme strategy building on the success of the dRDF programme. Initial economic studies are currently underway in collaboration with major boiler manufacturers to assess the viability of this option, ahead of implementing the R,D&D elements of the programme, and will draw on the cRDF (coarse RDF) and MRF experience in the USA.

### Industrial and Commercial Wastes

It is estimated that industrial and commercial present the largest single waste energy resource, equivalent to 15.3 million tonnes of coal each year. This includes specialised wastes, produced as a result of a particular activity or process, for example scrap tyres and hospital waste. Most, however, is general industrial waste (GIW), made up largely of paper, cardboard, wood and plastics. This differs in composition from raw domestic waste and is an inherently better fuel, being generally less contaminated and with lower moisture and ash contents (both generally less than 10%).

In 1981 a review revealed that the vast majority of this waste is traditionally disposed of to landfill. A series of projects were therefore established under the Department of Energy's (DEn's) Energy Efficiency Demonstration (ED) Scheme to test out opportunities for their use as an industrial fuel. Reviews of the results revealed that the projects, especially those associated with GIW, had experienced many technical, organisational and contractual problems. Nevertheless a number of opportunities were identified for producing low-cost systems with improved characteristics which, if developed effectively, could prove attractive to industry. Subsequently, a strategy for industrial and commercial wastes as fuel was adopted by the Department of Energy under its Biofuels R&D Programme. The following summarises the main areas investigated:

Waste Preparation, Handling and Storage Technology. Demonstration projects have shown that shortcomings relating to the fuel processing, handling and storage have proved a major barrier to the uptake of this technology. The degree of processing

necessary for the use of industrial and commercial waste as fuel is largely determined by the requirements of the combustion system used. Major projects on waste handling, storage and preparation, together with shredder development studies and long term storage trials have therefore been undertaken.

Combustion Technology. For the 'on-site' market with outputs in the range of 1.5-3MW thermal, waste burning shell boilers, biomass pre-combustors or retrofit waste firing on existing boilers offer the best prospects.

In 'off-site' applications there is currently considerable interest in both CHP and power generation schemes. For this market, waste burning boilers, composite boilers or water tube boilers offer the best prospects.

Waste Burning Boilers. A 1 te/h waste-fired CHP facility is currently being evaluated under the DEN programme and large output installations can be built from a number of these units. The major limitation with currently available vertical shell units is that the maximum working pressure of the boiler is limited to 10bar. New designs operating at higher pressures are therefore being considered.

Composite boilers generally require only coarse waste preparation and operate at higher pressures than shell boilers, with the option to provide super heat giving improved power to heat ratios for CHP and Power Generation. Despite these inherent advantages, no systems are known to have been installed for waste firing.

Water Tube Boilers. Numerous combustion systems are available which, in principle, allow these boilers to deal with a variety of wastes (mass burn grates, fluidised beds, chain grates etc). A provisional design for a 5.5MW<sub>e</sub> power generation facility is currently being considered under the DEN programme. This is based on reciprocating grate technology with a bulk breaker, magnetic separation and a continuous belt storage bunker fuel handling system.

A particular problem exists with electricity production in small scale systems due to the relatively low performance of small scale steam turbine generators. A desk study of the potential of reciprocating steam engines and Sterling engines for electricity production is being undertaken as a complementary part of the programme, with a view to potential collaboration in longer term development.

## 2. Dry Wastes

Specialised Industrial Wastes (SIW). SIW includes hospital waste, waste wood, scrap tyres and many other opportunistic waste which may be utilised as an energy resource. Initially, the 'on-site' market was considered the most important for the utilisation of this resource, but more recently the potential for 'off-site' use has grown as major waste disposal companies have become interested in its exploitation. Notably, a 40 MW<sub>e</sub> private venture tyre-fired power station is now under development under NFFO, based on the US experience of multiple modular incinerator technology.

Hospital Waste. A major driver in the development of SIW utilisation has resulted from changing legislation affecting hospital waste incineration. Traditionally, this has been carried out 'on-site' at some 900 hospital locations in England and Scotland, mainly using rudimentary batch fired technology. Legislation introduced subsequent to the 1990 Environmental Protection Act now require such plant to meet strict performance standards. Further legislation proposed within the European Community may increase control yet further and few, if any, of the traditional incinerators could be retrofitted to comply with these requirements. New capacity will therefore be required, creating a potentially buoyant market. Health Authorities in particular are considering new group incineration schemes, financed internally, joint funded, or owned/operated by private waste contractors. Energy recovery is feasible but, because of the high disposal fees available is not a necessary prerequisite for economic viability. However, the market should prove fertile for the development of monitoring systems and advanced small scale pollution abatement technologies.

Straw. Annual straw production in the UK is estimated to be 17 million tonnes, of which up to 7 million tonnes are either burned in the field or ploughed in. The surplus straw, equivalent to 3.5 million tonnes of coal, is potentially available as a fuel and already some 02 M tonnes are consumed by farmers for farm heating, mainly based on simple batch fed whole bale burners. The potential for industrial and commercial use, however, is limited by the delivered cost of straw, which generally exceeds that of coal on a specific energy basis. Research towards reducing this cost have focused on densification of the straw to reduce transport costs. Other fundamental studies on the cohesion within a wafer and on the effect of variations in swath density are underway but it is now considered unlikely that a sufficiently robust system can be developed for in-field use. However, the basic system shows considerable promise as a static densifier for a wide range of organic and waste feedstocks.

Case Study: Poultry litter. Fibropower Ltd. are currently building a poultry litter fired power station at Eye in Suffolk. Construction of the power station began in Spring 1991 and it is to be commissioned in the Summer 1992. The project involves the collection of about 130kt/y of poultry litter within a 40km radius of the station which will be burnt to provide 12.6MW<sub>e</sub> of electrical power for export. The furnace ash and fly ash from the precipitator are high in phosphate and potash and will be removed from the site in bulk, for use as a base in the manufacture of agricultural fertilizers.

Originally, Fibropower planned to operate a CHP scheme generating about 5MW<sub>e</sub> but owing to commercial difficulties in selling the steam the Company decided to opt for an electricity only project. The project subsequently applied for, and was successful in obtaining, a contract under the first tranche of the NFFO. The project also received £750k from the European Commission, which included £12k to cover the cost of some of the specialised monitoring equipment. The DEn, provided £78k to cover the cost of monitoring which is being undertaken by FEC Consultants Ltd.

### 3. Wet Wastes

This part of the programme focuses on the potential for the production and utilisation of energy from biogas produced as result of the anaerobic digestion of wet waste, including sewage sludges; food and drink processing effluents; and animal slurries. Approximately 70,000m<sup>3</sup> of wet organic sludge is produced as an unwanted by-product of sewage treatment each day in the UK. Of this, 30% is disposed of untreated to farmland or landfill. The remaining 70% is disinfected, deodorised and stabilised by anaerobic digestion in large digesters before spreading on selective farmland or disposal at sea ( the latter permitted only until 1998). Such systems are commercially available and a proven technology with the sewage derived biogas generally used on site.

Food and drink processing effluents suitable for anaerobic digestion include both high solids food residues and dilute factory washwaters. A number of system designs are available, although digestion of such wastes is considered to be a developing technology in the UK.

Anaerobic digestion of farm slurries i.e. cattle, pig and chicken is still an emerging technology in the UK, with only one operational scheme recovering energy. The low uptake is a function of the economics of the process and the challenge in this area is to develop a low cost 'rugged' digester which farmers can afford to use.

### 4. Crops

#### Wood as a Fuel

The key part of the crops programme is "Wood as a Fuel". This work began in 1979 and considered a promising but uncertain technology for the future. From then until the present Department of Energy funded research, with a value of £1.7 million, has demonstrated the potential for wood fuel to become a major renewable energy resource in the UK, and the means by which this might be achieved. Fuel wood supply from conventional forestry operations have been considered from harvesting through to comminution, transport and storage pre- utilisation. The various technologies have been researched and the associated incurred costs determined, using a work study approach, enabling fuel wood strategies to be defined using a flexible computer programme. Fractionation of residue derived fuel chips to allow removal of higher value 'white' chips, to subsidise the production of lower grade fuel chips, is also being researched with the aim of lowering the costs of fuel production.

Research into arable energy forestry was limited to two projects during this time which demonstrated the potential for coppice derived fuel wood. During this period a single demonstration scheme was set up at the Tormore distillery where although the steam boiler based on wood fuel was a technical success, the company ceased operations.

The Wood as a Fuel programme has grown recently as a result of studies suggesting that fuel wood from conventional forestry operations might be possible at prices competitive with those of fossil fuels. This has coincided with the food over-production in the UK requiring farmers to diversify to non-food crops; planting grants being made available during 1991 and increasing concerns about local and global environmental issues raising the profile of producing and using wood as a fuel. Considerable effort is now being expended towards market development in particular enabling demonstrations of the relevant technologies for wood fuel uptake to be carried forward. It is considered that if a suitable market could be developed, the conventional forestry wood fuel source would initially be used to satisfy demand, with arable energy forestry coming on stream later, as the market expanded. Arable forestry though is seen as holding the greatest potential for wood fuel.

The aims of the Wood as a Fuel programme are to:

- take the research to the demonstration phase
- aid market development through demonstration
- assess the economics of wood fuel supply and use
- carry out underpinning research
- investigate the environmental implications of fuel wood provision and use.

For the purpose of this paper, wood fuel will be considered to be available from two main sources, existing "conventional" forestry operations, or short rotation coppice grown specifically as a fuel crop. Wood fuel derived from conventional forestry is considered as an additional available crop and not a residue or waste. Waste wood encompasses offcuts from manufacturing industry or timber from building demolition. They are considered separately for a number of reasons:

- the focus of the Wood as a Fuel programme is crop utilisation rather than waste recovery, and this has significant influence on the economics and supply infrastructure;
- waste wood is often chemically treated or otherwise contaminated leading to potential problems associated with emissions during utilisation;
- capital equipment is required to produce the fuel in a cost effective manner
- the resulting wood fuel can subsidise the production of the stem wood.

#### Fuel Wood from Conventional Forestry.

Forest management techniques are aimed at producing straight knot-free stemwood, which is achieved by planting trees closely together with thinning as required. In unmanaged woodland no thinning occurs and natural re-growth of young trees results leading to "derelict" woodlands. Trees tend to no longer grow straight due to, amongst other factors, light competition, and they also tend to grow at less than their maximum incremental rate. Consequently the standing value of the timber falls and utilisation options are limited. Wood for use as fuel can be derived from the operations required to bring such derelict woodland back into production, from essential forestry thinning operations and also from final harvests.

1. Final harvest The raw material available for production of fuel following British 'shortwood' final harvesting is the branches and small diameter tree tops (the 'brash'), which often account for more than 30% of the tree biomass, and is either left on site to rot or is removed prior to subsequent planting. Re-entering the site post harvest is obviously possible but involves doubling the wood handling. This obviously is not efficient and results in a high delivered price of fuel - £2.18 to £2.33/GJ. It does however mean that the only extra item of capital equipment required is the chipper.

Studies funded by the UK Department of Energy have demonstrated the increased efficiency of 'one pass' integrated harvesting operations, where the whole tree is removed from the forest after mechanical harvesting and subsequently separated to stemwood and fuel wood at the roadside. As the 'one pass' implies the material is only handled once and greater processor and chipper productivity is facilitated in the more stable environment of the roadside. The increased productivity and efficiency of operations reduces the delivered price of fuel wood to, in the best circumstances, £1.17/GJ. Increased productivity of stemwood also results, and since the cost of harvesting, transport and product separation are shared proportionately between the harvesting and the wood fuel operations, an effective subsidy of the costs of producing stemwood is achieved. The major drawback to such integrated harvesting though is the high capital equipment costs.

2. Essential Thinning The second potential source of fuel wood is from essential thinning operations, where whole tree chipping is the cost effective option. This approach has been demonstrated at Thetford forest in the UK and indicated high productivity with a delivered price of wood fuel in the region of £1.79/GJ. The capital equipment costs are once again high for this procedure.

3. Derelict Woodland Returning derelict woodland back to production may involve any combination of the above techniques, and it is likely that a fuel wood market would be the only one available to timber from badly neglected woodlands.

Whilst utilisation of the brash undoubtedly increases the efficiency of harvesting and thinning, the mechanical requirements lead to high capital costs and consequently will act as an impediment to adoption of these practices until a fuel wood market exists. The development of such a market will be dependent upon the production of fuel at a price competitive with fossil fuels which still remains a challenge. However when it does it should be long term and stable, permitting a return on capital expenditure, so offering a relatively attractive proposition.

One problem with using conventional forestry, not previously mentioned, is the fact that the amount of wood fuel available is constrained by the forestry resource, which is only 7% of UK land area. It is in tackling this issue that the role of arable energy forestry can have most impact.



### Arable Energy Forestry

In order to increase the amount of wood available, adoption of traditional coppicing methods for modern production is possible. Research has demonstrated that unrooted willow or poplar cuttings can be planted in closely spaced rows at approximately 10,000 trees to the hectare. The ground should be prepared and cleared of weeds in the autumn, planted in the spring and then harvested at two to five year intervals after initiation of coppicing. A crop yield of 10-15 dry tonnes of fuel per hectare per year has been demonstrated. Such plantations are best established on agricultural land and offers a good option for utilising land currently in food over-production. In the UK, coppice, as a designated non-food agricultural crop is eligible for 'set aside' payments (a scheme to encourage farmers to take land out of food production), and as added inducement is now included in the Forestry Commission's Woodland Grant Scheme which provides planting grants, as mentioned earlier. By using agricultural land in this way, as well as marginal areas, coppicing can provide an innovative and financially beneficial form of diversification and so arable coppice should not be seen as an alternative to forestry. A further attraction of arable coppice is the environmental acceptability of the process:

- The carbon dioxide given off during the burning of wood has previously been absorbed during the trees' lifetime, and so is a recycling process - there is not net gain in carbon dioxide levels.

- When compared with coal burning there is also the added benefit of reducing acid rain.

Poplar and willow were demonstrated to be the best two species for arable energy forestry in the UK, in agreement with research from other countries. Other species investigated gave poor establishment and high rates of failure on coppicing or poor yields. Until the canopy is large enough to cut out light and suppress growth on its own, or the root system is large enough to outcompete weeds for water, maintenance of a weed free plantation is essential. Prevention of rust disease which can cause premature defoliation leading to reduced crop yields is also important. At the end of the first growing season, the shoots produced are cut back to initiate coppicing, and because of the clonal nature of this crop, the shoots produced can themselves be used to produce cuttings for subsequent planting. By planting fields in rotation annual harvests and hence income can result. Harvesting is carried out in the winter any time after leaf fall (October/November) to leaf set (March/April) and a prototype tractor drawn harvester has been developed as part of the Department of Energy's research programme. This system uses contra-rotating augers to gather the stems which are cut close to the base by a circular saw. With further development it is anticipated that one hectare of three year old coppice per day could be harvested. Stems are collected in bales of 300kg and stored until required. Baled storage is important because this prevents microbial breakdown, in turn avoiding the need for expensive storage containers. A further advantage during the summer months is air drying of the bundles which leaves the wood more amenable as a fuel when it is ultimately removed for chipping and use. Another aspect of the Department's

programme is monitoring establishment, growth, harvesting, storage, combustion, and effect on the landscape in terms of environmental effects.

It has been estimated that the cut stool will remain in production for up to 30 years before replanting becomes necessary, although yields will decline towards the end of the life period. Although costings will vary on a case by case basis the basic costs associated with arable energy forestry encompass;

- fencing
- ground preparation
- cuttings
- harvesting
- chipping.

A project has been established (1992) in which a series of farmers are working together as a cooperative, producing wood fuel from arable energy forestry. Crop performance is being monitored, as are:

- the integration of the crop with other on-farm activities
- environmental effects and cash flow
- profitability

It is hoped that the project will help bring the product into the market, by assisting with crop production and its subsequent availability and sale.

#### Utilisation of Fuel Wood

Wood makes a good combustion fuel, however when burnt in open fires or wood burning stoves smoke and volatile pollution can be produced due to the batch feeding process involved. The preferred option therefore is for wood chips to be burnt in modern, refractory lined combustors with provision for secondary air which give a highly efficient and clean burn, if high combustion temperatures are maintained. Such wood chip fired plant can generate warm air, hot water for wet heating systems, or raise steam for process or electricity generating purposes. In the longer term thermal processing techniques to produce gaseous or liquid fuels from wood may well develop and become a UK option.

Wood combustion does have its problems though, the two main ones being size (wood has a low bulk density) and cost (typically twice that of equivalent coal fired plant, and three times that of oil or gas.) Consequently wood combustion is likely to be more suited to industrial or institutional users.

## FUTURE EMPHASIS

UK energy production is increasingly moving towards decentralised, low cost natural gas fuelled plant, particularly for power generation, and only in specific circumstances can biomass derived energy compete. Economics have traditionally represented a major barrier to the commercial development of renewable energy and so the creation of an internal market for renewables via NFFO, as an incentive to commercialise renewable energy technologies, has been an important aspect of the Government's energy policy. In the absence of large scale commercial heat or district heating networks, this emphasis has been on electricity generation. By using the proceeds of NFFO to pay higher tariffs for the electricity generated the financial viability of schemes from renewable and other non fossil fuel sources has improved. Since its inception a total of approximately 600MW<sub>e</sub> installed capacity has been contracted to supply (this figure includes electricity generated from hydro and wind farms).

The UK, in line with wider European policy, is focusing on waste minimisation, materials recycling and energy recovery, and tightened controls over waste disposal as a means of implementing its Integrated Pollution Control commitment. Consequently it is envisaged that industrial waste at source will be reduced and that recycling in the domestic and commercial sector will increase. In order to harness market forces to more effectively encourage waste minimisation, the Environmental Protection Act has established a strict environmental regime for the disposal of waste both to landfill and incineration, the two currently viable options for disposal. This will be manifested in increasing disposal costs which will provide a strong incentive for waste volume reduction. It is thought that landfilling costs, in particular, will rise relative to other forms of waste treatment and disposal so that incineration and 'resource recovery' centres will be less dis-advantaged. Although transfer stations enabling waste to be transported over long distances have increased in recent years it is still anticipated that incineration will increase in popularity, particularly in cities where available void is limited.

Refuse derived fuels were originally envisaged as offering an intermediary between landfill and incineration in terms of costs. Research concentrated on the production of pelletised or densified RDF (dRDF) which was targeted as a potential coal substitute for use on small scale boiler systems, either to generate process steam and/or provide space heating. It has failed to enter the waste disposal market at a significant level largely because of the failure to secure viable markets for the fuel, and its prospects are weak since recent emissions requirements have meant that any possible economic advantage of dRDF over conventional fuels has been eroded.

In order to promote greater recycling and reuse of materials the Governments aims are to encourage both the supply of, and demand for, recycled materials. In the domestic sector, where householders do not pay directly for the disposal of their waste, it is hoped that a system of 'recycling' credits will be introduced whereby the savings in landfill costs will be passed on to waste collection authorities and voluntary recycle organisations enabling recycling to become more profitable. Recycling in the

industrial sector is already more successful and the rising costs of waste disposal are likely to act as incentive to improve further.

In terms of energy recovery the increasing environmental pressures are generally acting as a spur. Although the anticipated increased costs of landfilling, legislative requirements and the decreasing availability of void is likely to lead to a reduction in landfilling and an increased role for incineration (particularly for large conurbations), for the foreseeable future landfill in the UK is likely to play a major, although less significant role than at present in waste management practice. The challenge therefore is to increase the control of gas production at sites thereby maximising both environmental control and facilitating effective energy recovery. Incorporation of an energy recovery component in the incineration and resource recovery processes will also be targeted. Anaerobic digestion of farm slurries and manures with energy production is still an emerging technology, in the UK, and so progress of the single scheme accepted under the first NFFO tranche will be eagerly followed.

A further possible boost to energy recovery ventures for other waste materials may result from recent legislation in the UK which has banned the disposal of sewage at sea after 1998, and also straw burning in fields effective this year, meaning that alternative disposal mechanisms will need to be found. However preliminary assessments so far suggest that this will make only a modest contribution.

No commercial projects currently exist in the United Kingdom for making use of energy crops although wood from conventional forestry is commonly used. However, the massive potential which could conceivably be derived from this resource is likely to encourage a substantial growth of interest. Longer term work on a range of energy crops and complementary technologies may be possible producing solid, liquid and gaseous fuels. In the short term, the Department of Energy's research programme is pioneering effort in terms of the growth, harvest and use of coppice wood fuel through a farming cooperative with the hope of providing market stimulus and incentive to producers and manufacturers. The effect of NFFO in this area has also been limited to date due to the technology being at the early development stage.

In summary the situation for commercialisation of electricity generating renewable energy schemes looks promising in the UK, and a contribution of 600MW<sub>e</sub> - 1000MW<sub>e</sub> by the end of the century looks attainable.

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Robert Dixon, Chairperson

5A

**THE CARBON BALANCE OF FOREST SYSTEMS: ASSESSING THE  
EFFECTS OF MANAGEMENT PRACTICES ON CARBON POOLS  
AND FLUX**

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**ABSTRACT**

Forests play a major role in the Earth's carbon cycle through assimilation, storage, and emission of CO<sub>2</sub>. Establishment and management of boreal, temperate, and tropical forest and agroforest systems could potentially enhance sequestration of carbon in the terrestrial biosphere. A biologic and economic analysis of forest establishment and management options from 94 nations revealed that forestation, agroforestry, and silviculture could be employed to conserve and sequester one gigaton (Gt) of carbon annually over a 50 year period. The marginal cost of implementing these options to sequester 55 Gt of carbon would be approximately \$10/ton.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

## INTRODUCTION

The accumulation of greenhouse gases in the atmosphere due to deforestation, fossil fuel combustion, and other human activities may have begun to change the global climate (12,26,38). Given our current understanding of global carbon sources and sinks, the prospect for managing the terrestrial biosphere to alter the carbon cycle and reduce the accumulation of greenhouse gasses appears promising (12,21,56).

Forest and agroforest systems play a prominent role in the global carbon cycle (26,47). Forests contain over 60% of the terrestrial above-ground carbon and approximately 45% of the terrestrial soil carbon (1,53). In addition, worldwide forests account for approximately 90% (90 gigatons, Gt) of the annual carbon flux between the atmosphere and terrestrial ecosystems. Based on preliminary estimates, application of forest management and agroforestry practices to stimulate biomass productivity on a global scale could potentially sequester or conserve several gigatons of carbon annually (12,21,56).

Agricultural systems also play a significant role in the global carbon cycle (7). They contain about 12% of the world's terrestrial soil carbon, and conservation of this pool is essential to sustained crop productivity and decreasing CO<sub>2</sub> emissions (7,26,27). Many agricultural practices have been shown to increase soil carbon content by increasing carbon sequestration and/or reducing the loss of carbon. Practices such as reduced tillage, crop residue incorporation, field application of manure and sludge, and rotations using cover crops or leguminous crops store more carbon than conventional technology (27).

Recognizing the prominent role of forest and agroforest biomes in global ecology and the global carbon cycle, participants at the United Nations Conference on Environment and Development (UNCED) developed a set of forest principles (20). The forest principles have several purposes including:

- \* slow deforestation
- \* protect biodiversity
- \* stimulate sustained forest management and productivity
- \* address threats to the world's forests

Of primary concern in shaping these objectives were several proposals in the past year for an international convention, charter, protocol, or other agreement to maintain, manage, or protect boreal, temperate, and tropical forests (31).

In 1989, delegates at the Noordwijk Ministerial Conference recognized the role of forests in transnational environmental issues, including global climate change, and stimulated interest in accelerated forestation and sustainable ecosystem management

options (35). The conference recognized the significance of the observed increases in atmospheric carbon dioxide and established a provisional net world-forestation goal 12 million hectares (ha) per year, which is to be reached by the year 2000.

The potential role of forest establishment to increase carbon sinks and stimulate sequestering of atmospheric carbon has been considered by a number of authors (2,16,17,22,44). These analyses have emphasized the major forest regions on a continental basis, especially within tropical latitudes. Though preliminary, these analyses have shown that forest and agroforest establishment and management appear to have significant promise for contributing to global carbon sequestration and conservation (38,54). At the same time, implementation of these practices has the potential to provide a continuous flow of forest-based goods and services (15,19).

Given the scope of the science-policy needs regarding global forests, the global carbon cycle, and climate change, two specific objectives were established in this assessment:

1. Identify promising technologies and practices that could be utilized at technically suitable sites to manage forest and agroforest systems to stimulate biomass productivity and sequester atmospheric carbon.
2. Assess economic potential, specifically costs at the site level, of establishing promising forest and agroforestry management practices.

## **MATERIALS AND METHODS**

### **DATA COLLECTION**

The assessment was based on a global database of biologic and economic information on forest and agroforest management options. Information regarding promising practices and initial costs at the site level within forested nations representing boreal, temperate, and tropical regions on six continents were collected using methods described by Dixon et al. (13) and Moulton and Richards (33). Regional and national biologic and financial data were collected in three major categories:

1. Forest growth or conservation, as measured by biomass accretion resulting from forest and agroforest management practices;
2. Associated costs for each management practice; and,
3. Area of land potentially suitable for each practice.

Data base methodology and scope were described previously (13,56). In a global review involving large amounts of technical

data from this assessment were considered the best available. When data on land productivity or biomass accretion were outside the bounds of the technical literature, the values were not used in the analysis.

## **FOREST GROWTH AND CARBON STORAGE**

Growth and yield of forests are normally expressed in terms of volume of stem wood. Thus, it was assumed that one cubic meter of stem wood is associated with 1.6 cubic meters of whole-tree biomass, which includes roots, branches, leaves, etc. (32,42,43). Whole-tree volume was multiplied by the density (i.e., specific gravity) of wood for each species to yield whole-tree biomass. Finally, it was assumed the carbon content of whole-tree biomass was 50% (8). Although below-ground carbon accretion is significant in forest systems, only above-ground accretion was considered in this assessment (5).

Graham et al. (16) and Schroeder (41) asserted that the relevant parameter in terms of carbon cycle calculations is the average amount of carbon on site over an indefinite number of rotations. If it is assumed that the system is sustainable and there is no yield reduction in later rotations, the result is the same as the average amount of carbon on-site over one full rotation. Because any number of biological, climatic, or social events could contribute to some level of yield reduction that cannot be predicted, the approach presented here may represent an upper bound (1,45). Carbon accretion and storage was calculated by summing the carbon standing crop for every year in the rotation and dividing by the rotation length. This approach assumes that, at or shortly after harvest, all stored carbon returns to the atmosphere (33).

## **COSTS OF MANAGEMENT PRACTICES**

The relative costs of promising management options used in this assessment were estimates of direct costs at the site level for labor, materials, transportation, and the initial infrastructure (for up to three years) to employ the options (13,33,56). Scaling of costs (between small and large projects) was not considered because previous analyses suggest this approach may be invalid (37,46). The cost of land was not included in the analysis, because: 1) land cost varies widely around the world; 2) land values are difficult to establish where land is held in common by communities or land is government-owned; and 3) no land market values exist (50).

Financial data are reported in 1990 US dollars. Costs for any reference year were adjusted based on the inflation and exchange rates for individual nations according to the International Financial Statistics (IFS) tables published by the



International Monetary Fund (25). A nation's inflation rate for the reference year, as measured by the Consumer Price Index, was extracted from the IFS tables. The reference year cost was then converted to a 1990 value and converted back to US dollars at the 1990 exchange rate (13).

Because forests are periodically harvested and replanted (1,45), the costs of initiating forest management or establishing plantations are recurring costs. In estimating costs, it is important to account for these additional investments that will occur at more or less periodic intervals in the future (10). The present value of future costs over a 50-year rotation period was computed for each practice or management option (13,56).

The net interest rate used was 5%. Cost per ton of carbon was calculated as the present value of all establishment costs over a 50 year period divided by mean carbon storage. Costs computed in this manner do not account for any financial benefits resulting from the initial investment (19,51).

#### **LAND AREA TECHNICALLY SUITABLE**

The carbon accretion and storage values were based on a per unit area basis (e.g., tons carbon per hectare). The technically suitable land area for each management practice is required to estimate a total amount of atmospheric carbon removal and storage. Both land area and carbon storage for different management practices were classified within nations by ecoregion following the system devised by Bailey (6). The broadest level of Bailey's classification was employed. This level, the domain level, contains four ecoregion subdivisions: boreal, humid temperate, dry, and humid tropical. A coarse distinction was recognized within each ecoregion between lowland and upland zones (e.g., site

quality). Forest establishment and management practices were qualitatively assigned to ecoregions for the purpose of tallying carbon sequestration potential (56).

Estimates of land available on which to implement forest establishment and management options are based on earlier assessments by Grainger (17,18), Houghton et al. (22), and Trexler (49). Within tropical latitudes, the assessment relies primarily on Advanced Very High Resolution Radiometer (AVHRR) analyses of land-use patterns by Houghton et al. (22). For the temperate zones, national inventories of land-use practice and patterns were consulted (21,33).

## STATISTICAL ANALYSIS

Non-parametric statistical analysis techniques (e.g., median and inter-quartile ranges) were employed to analyze biologic and economic data collected for various forest management practices (11). The Wilcoxon 2-Sample Non-Parametric Test (with continuity correction of 0.5) was used to test significant differences for each of the comparisons among boreal, tropical, and temperate median values.

## RESULTS

### MANAGEMENT OPTIONS

A wide range of promising forest and agroforest management practices and technologies were identified to promote carbon sequestering in the terrestrial biosphere (Figure 1). The assessment analyzed the opportunities to expand forest carbon pools across boreal, temperate, and tropical latitudes. Based upon the median values for carbon sequestration in tons of carbon per hectare, the following are the five most promising practice-region combinations, from high to low:

Natural regeneration in tropical latitudes (Figure 1c):

Management of humid tropical forests can result in storage of up to 195 tons of carbon per hectare (tC/ha). This reflects the great biomass productivity rates of natural ecosystems in the humid tropics (9). Estimates of forest growth rates and carbon accretion rates in tropical forests vary widely.

Afforestation in the temperate latitudes (Figure 1b):

The relatively high median value (120 tC/ha) likely reflects the growth rates of plantations established on marginal agricultural lands, which though medium to poor for agronomic crop productivity, are often quite suitable for forest plantation growth (1,23).

Establishment of agroforestry in tropical latitudes

(Figure 1c): If tree and agronomic crops are cultivated

together, carbon accretion ranges from 60 - 125 tons per hectare (t/ha). These practices have been employed by local peoples for centuries (19,30). These moderately high carbon sequestration values for agroforestry are encouraging because this practice is also one that will supply a sustained flow of goods and services to local populations (Gregerson et al. 1989).

Reforestation in the tropical latitudes (Figure 1c):

The high median value of this practice (65 tC/ha) supports the assertion that reforestation in the tropical latitudes has great potential to sequester and store carbon. Mean annual increments (e.g., up to 60 m<sup>3</sup>/ha/yr) for eucalyptus and caribbean pine for rotations of 20 years or less can rapidly store carbon. These plantation crops, however, may not always store the maximum amount of carbon over an extended period because short rotations limit biomass accumulation (42).

Reforestation in the temperate latitudes (Figure 1b):

At a median value of 56 tC/ha and an inter-quartile range of 32 - 96 tC/ha, this approach is the fifth highest on the list of promising practices for carbon sequestration. Forestation technology and expertise is well-developed among nations of temperate latitudes.

The lowest median values among management options evaluated were for silviculture practices (Figure 1). Silvicultural treatments, such as thinning and fertilization in plantations, will likely play a role in adapting forests to warmer, drier climates. Other investigators have reached the same conclusion (2,32,44).

Across boreal, temperate and tropical latitudes, biomass median estimates of the potential to sequester carbon through establishment and management of forest agroforest systems are 16 tC/ha, 68 tC/ha, and 66 tC/ha, respectively. The Wilcoxon non-parametric test indicates that the median values for the temperate and tropical latitudes were significantly greater than for the boreal and that the temperate and tropical median values are not significantly different ( $p \leq 0.05$ ).

## COST OF FOREST MANAGEMENT OPTIONS AT THE SITE LEVEL

Initial costs of forest establishment and management are least expensive in boreal regions. As management intensity increases in temperate and tropical regions, initial costs per hectare escalate accordingly (Figure 2). Natural regeneration, silvicultural treatment, agroforestry, and forestation are the least expensive practices within tropical latitudes (1,46,56).

Boreal latitudes: For boreal forest systems, natural regeneration practices and artificial reforestation could be implemented at a cost of \$90-325/ha (Figure 2a). At carbon storage values of approximately 17 t/ha and 39 t/ha, respectively, the initial cost of carbon sequestration for the two practices is \$5(\$4-11) and \$8(\$3-27)/ton (t). Silvicultural treatments are also a cost-effective means to manage boreal forest systems at \$74/ha. At a sequestration value of 10.5 tC/ha (Figure 1), the initial cost of carbon sequestration ranged from \$5-76/t. Dixon et al. (13) and Allan and Lanly (1) also reported that forestation and forest management practices in boreal systems can be sustained and provide a high rate of return on initial investment. The costs of forest establishment in Russia, which contains over 50% of the world's boreal forests, are a major determinant in calculating global biologic and economic potential to sequester atmospheric carbon (29).

Temperate latitudes: Within temperate regions, reforestation, afforestation, natural regeneration, and silvicultural practices are the least expensive forest management options for sequestering carbon (Figure 2b). Artificial reforestation median cost is \$350/ha. At a sequestration value of 56 tC/ha (Figure 2b), carbon is stored at an initial cost of \$6 (\$3-29)/t depending on site conditions, tree species, and management intensity. Afforestation can store about 120 tC/ha at a cost of \$260/ha or \$2(\$0.22-5)/tC. Natural regeneration can be implemented inexpensively at less than \$10/ha. At 9 tC/ha (Figure 2b), the carbon sequestration cost is less than \$1(\$0.01-0.43)/t. Intermediate silvicultural treatments (e.g., thinning and fertilization) enhance carbon storage in temperate forests at a median cost of about \$350/ha (Figure 1b). The initial cost is \$13(\$3-158)/tC. In temperate latitudes, establishment of agroforestry systems costs up to \$790/ha, and this practice stores carbon at 34 t/ha (Figure 1) for an initial cost of \$23(\$14-66)/t.

Tropical latitudes: The widest range of costs were reported for forest management options within tropical latitudes (Figure 2). Natural regeneration of forests and establishment of short-rotation fuelwood plantations and agroforestry systems can all be established for less

than \$500/ha (50 year basis) (Figure 2c). Reforestation and agroforestry can sequester carbon at less than \$10(\$2-26)/t because of high sequestration values, i.e., about 100 tC/ha (Figure 1c). Intermediate silvicultural treatments (e.g., thinning and fertilization) stimulate productivity and can sequester carbon at approximately (\$1.50-36)/t at a sequestration value of 59 t/ha (Figure 1c). Therefore, in the tropics, natural regeneration, agroforestry, reforestation, and silviculture sequester carbon at median initial costs of less than \$10/t. These initial costs per ton of carbon sequestered compare favorably to many non-forest options to sequester or conserve carbon that are \$30/t or more (34,38).

### **COST AND YIELD EFFICIENCY OF NATIONAL PROGRAMS**

The previous section revealed that establishment of plantations or agroforestry systems were cost efficient means of stimulating carbon sequestration compared to other options (34,38). A comparison of cost and yield efficiency for selected nations is presented in Figure 3. Costs of carbon sequestration in forestation programs were highest in Egypt, New Zealand, Zaire, and Venezuela. In contrast, costs were significantly lower in Australia, Brazil, China, Congo, Mexico, US, and Russia. The remaining nations surveyed were intermediate in reforestation costs. These calculated values for cost and yield efficiency of national forestation programs do not consider land rental costs, but are consistent with earlier estimates (2,3,38).

The efficiency and yield of specific practices (artificial reforestation and afforestation, natural reforestation, intermediate silvicultural practices, and agroforestry) for sequestering carbon are presented in more detail for Russia, US, and Brazil (Figure 4). These data represent a range of economic options (\$0.5-88/tc) to sequester carbon through forest management in representative boreal, temperate and tropical biomes. Collectively, these nations represent 30% of the earth's land area, and implementation of these practices on a large scale could stimulate significant carbon sequestration. Moulton and Richards (33) and Swisher (46) observed similar carbon

sequestration values and cost trends in their assessments of U.S. and Latin American forest management options, respectively.

A global synthesis of carbon sequestration and initial costs at the site level is presented in Figure 5a. Total initial cost rises gradually up to a carbon storage level of about 55 Gt. Beyond 55 Gt, the total cost begins to escalate at a more rapid rate. The marginal cost of sequestering carbon in global forest systems is approximately \$10/t (Figure 5b).

The distribution of technically suitable land among global ecoregions that would be required to achieve different levels of carbon storage is presented in Figure 6a. The analysis was completed by considering the area of land technically suitable for different practices in each ecoregion and the amount of carbon that those practices could store (17,22,49). The slope of the lines is relatively gradual up to 55 Gt indicating that relatively large increments of carbon can be stored on relatively small amounts of land. The slope becomes much steeper at 55 Gt as larger increments of land, and therefore higher establishment costs, are needed to store additional increments of carbon. More carbon could be stored, but it becomes less cost effective. The most productive and least expensive lands would likely be placed under management first (56).

A global total of approximately 570 million ha of land would be required to store 55 Gt of carbon (Figure 6a). Given current estimates of land suitability and availability, the distribution would be 190 million ha in the humid tropics, 220 million ha in dryland ecoregions within tropical and temperate latitudes, and 160 million ha in the humid temperate zones. Utilization of land in the boreal zone would only be considered at higher levels of carbon storage. Improved resolution of land availability estimates in the future could alter these estimates (22). Figure 6b illustrates the distribution of carbon storage between ecoregions (6). At the 55 Gt carbon level, 24 Gt would be stored in the humid tropics, 20 Gt in dryland ecoregions, and 11 Gt in the humid temperate zones.

Uncertainty is associated with estimates of land areas technically suitable and socio-economically available for forest establishment. For example, Trexler (49) estimated that social, demographic, political, and other factors could result in a 70% reduction in the available land estimates for tropical Africa and Asia that were reported by Houghton et al. (22). A sensitivity analysis was conducted to determine the possible effects of a 70% reduction in land available for forest establishment and management. A linear reduction in available land area evenly distributed over all nations and ecoregions would result in a reduction of total carbon storage potential to about 16.5 GtC.

Similarly, the technical suitability of ecoregions and site productivity varies widely within a nation or biome (42).

## DISCUSSION AND CONCLUSIONS

Past efforts to develop forest establishment and management cost estimates at the site level for sequestering and conserving carbon in the terrestrial biosphere have been preliminary (2,3,13). Site-level (13), regional (39), national (33,38b), and global (34,35,56) estimates have been calculated. The biologic and economic opportunity to conserve and sequester carbon in forest systems appears significant. This assessment suggests:

1. Forest establishment and management practices (e.g., natural regeneration, reforestation, afforestation, and agroforestry) can stimulate accretion of carbon in forest stands of boreal, temperate and tropical biomes;
2. Forest and agroforest establishment and management practices can be used to temporarily store carbon for less than \$30/tC, with median values ranging from \$1-8/tC.
3. Technically suitable land can be identified in boreal, temperate and tropical biomes of the world to implement forest management practices; and,
4. Potential carbon accretion and storage in forest systems may total up to 55 Gt over a 50 year period.

The current assessment of biologic and cost information from more than 90 nations worldwide represents the first attempt to develop a bottom-up global analysis of carbon sequestration potential in forest systems. The forest management practices identified here can be applied to a wide range of ecosystems in boreal, temperate, and tropical biomes (21). However, before practices can be widely and successfully implemented, more consideration must be given to the array of possible economic and socio-political constraints (49,51,55).

From the perspective of forest biomass productivity, afforestation in the temperate latitudes, agroforestry in the tropics, and reforestation in both the temperate and tropical latitudes are among the most promising options. When considering initial costs in dollars per ton of carbon, attractive options include natural and artificial reforestation in boreal latitudes; natural and artificial reforestation, afforestation and silvicultural practices in the temperate latitudes; and for the tropics, reforestation and agroforestry systems appear the most cost efficient (38). The cost estimates are preliminary and do not reflect benefits associated with goods and services that flow from forest sector. Moreover, rapidly changing labor costs in

Russia and developing nations significantly influence economic analysis of forest management options (19,29,36). The ultimate mixture of greenhouse gas reduction options for key nations and the global community (e.g., forest management, alternative fuels, conservation agriculture) will be driven by the socio-economic and political factors (4,14,15,19).

The costs of carbon sequestration options at the national level have been the focus of several recent research efforts in the United States (33), Germany (52), the Netherlands (401), Brazil (14), Costa Rica (46), and other nations (21). In addition, analyses of the impact of the Tropical Forest Action Plan on carbon sequestration have been completed for some nations and regions (1). The cost estimates of national carbon sequestration efforts in the current study suggest that programs could be effectively established in many of the major forested nations of the world (35,55).

Forest management programs and agroforestry programs have been implemented in several nations with a range of tree species, site conditions, and financial support (19,48,51). A number of the national forest-based programs are for the purpose of carbon sequestration and conservation. The ability of these programs to stimulate carbon sequestration varies (21). It must be stressed, that a key factor in successful forest management and agroforestry programs is the involvement and support of local populations in the planning and implementation phases (19,30,51).

Past and current analyses suggest the next step is micro- and macro-modeling of the biologic and economic potential of carbon conservation and sequestration efforts. Regional, national and global carbon budgets (anthropogenic and biogenic pools and flux) can be simulated with various process models (5,56). The menu of forest establishment and management options developed in this report can be used to define appropriate options to reduce accumulation of atmospheric greenhouse gases on regional, national and global scales. Ultimately, modeling efforts should link forest establishment and management costs with benefits that flow from the forest sector (e.g., goods and services) (5,33). Such an approach has been used for preliminary evaluations of forest sector policy options at national and global levels (2,3,4,38).

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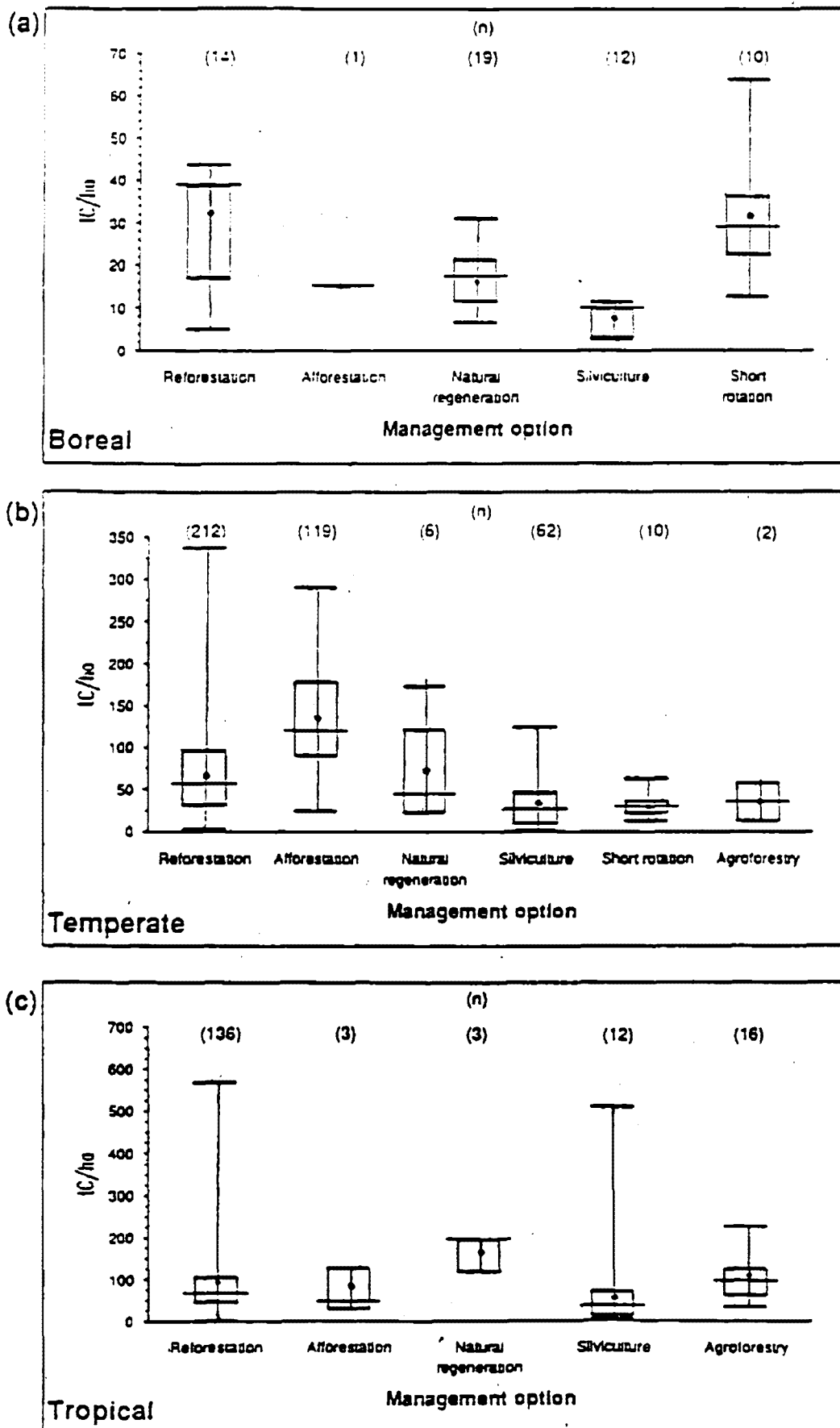
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#### ACKNOWLEDGMENTS

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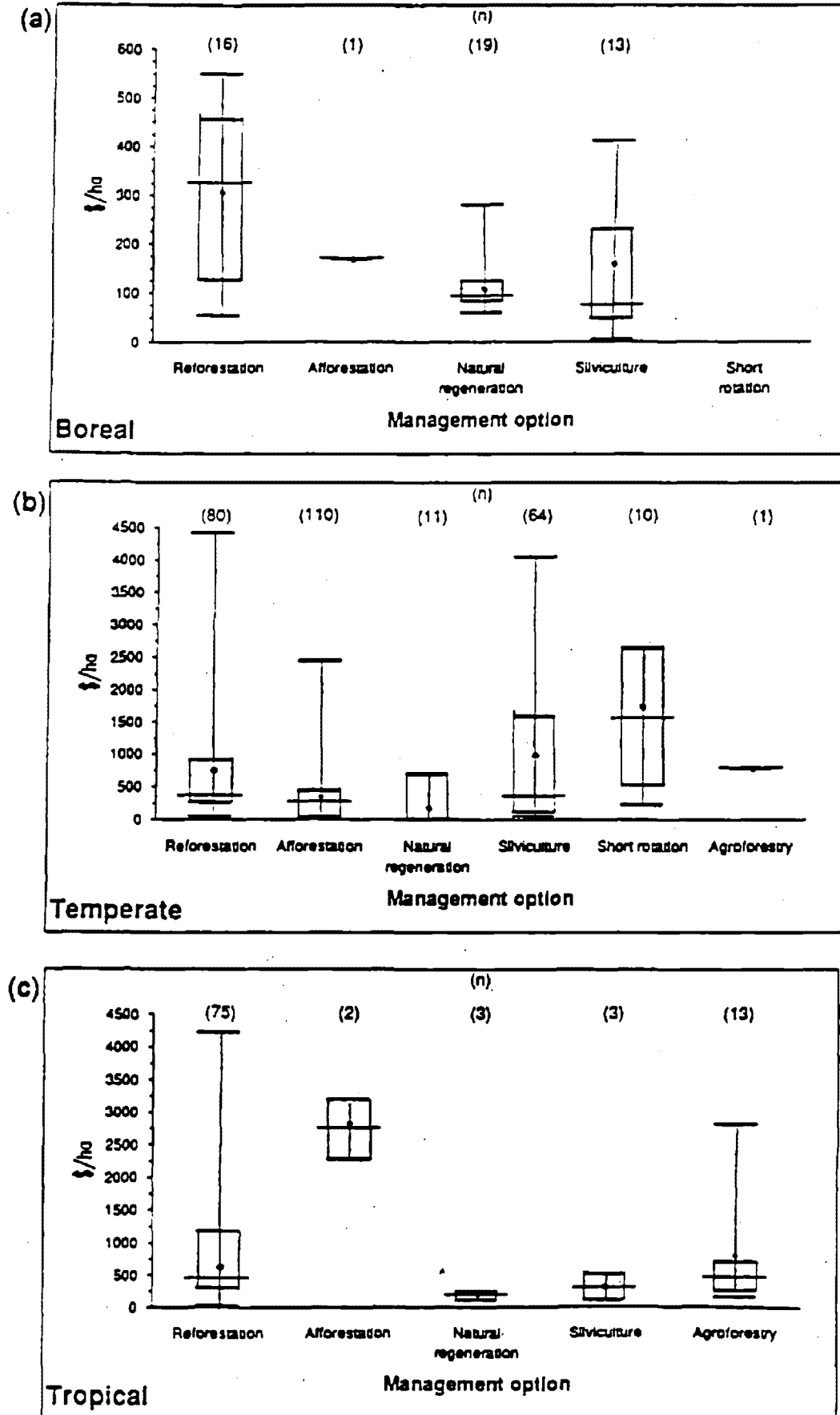
Figure 1

Carbon storage for forest management options for (a) boreal, (b) temperate, and (c) tropical biomes. Median values are indicated by the wide horizontal lines. Boxes represent interquartile ranges (middle 50% of observations), shaded circles are means and vertical lines indicate full range of data.

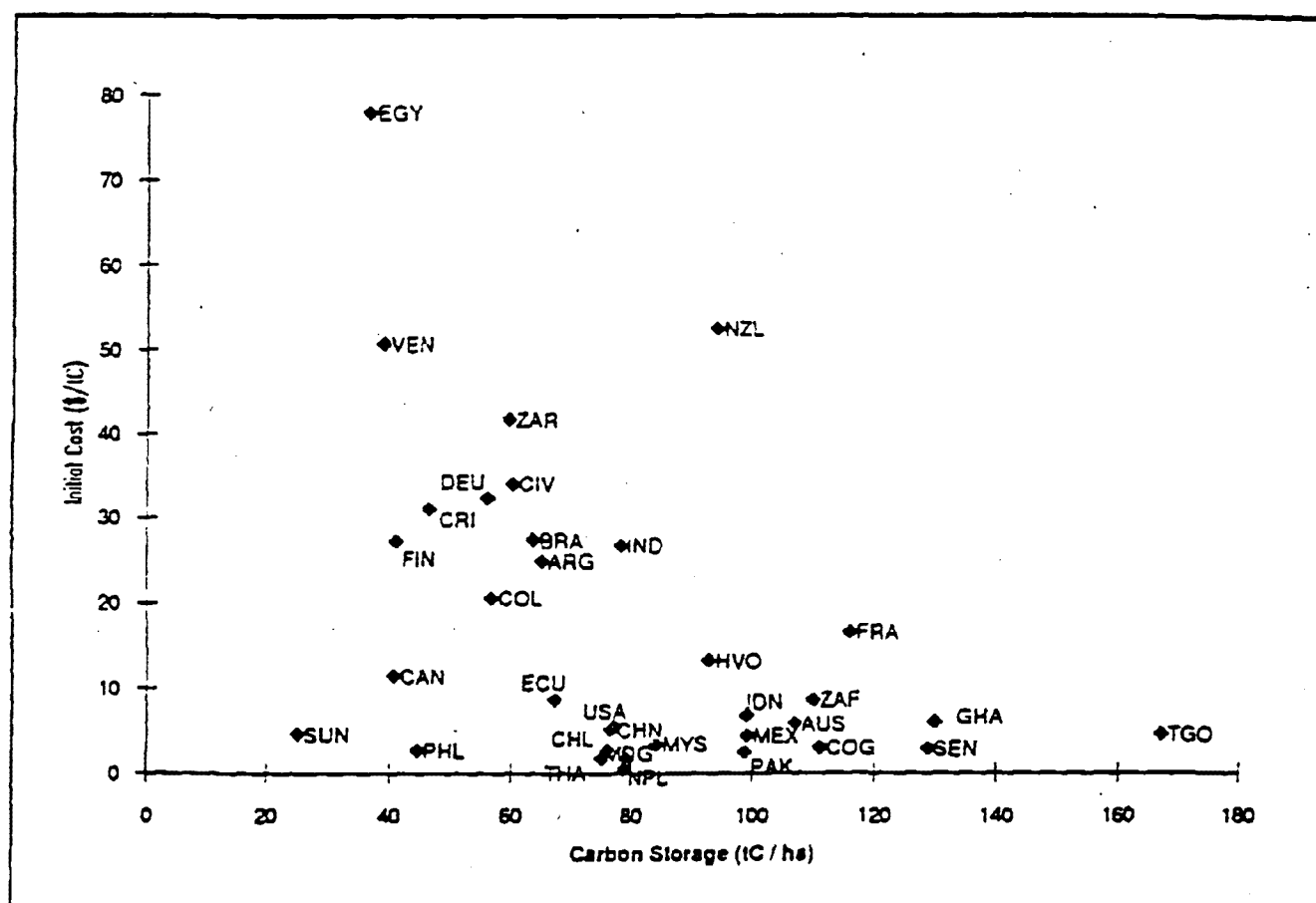


**Figure 2**

Initial costs for forest management options for (a) boreal, (b) temperate, and (c) tropical biomes. Median values are indicated by the wide horizontal lines. Boxes represent interquartile ranges (middle 50% of observations), shaded circles are means and vertical lines indicate full range of data.



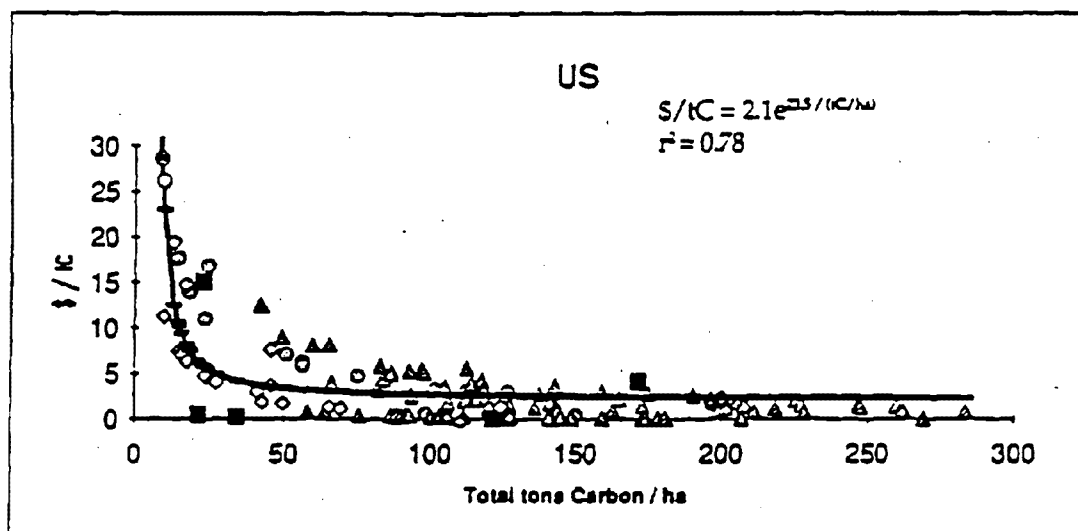
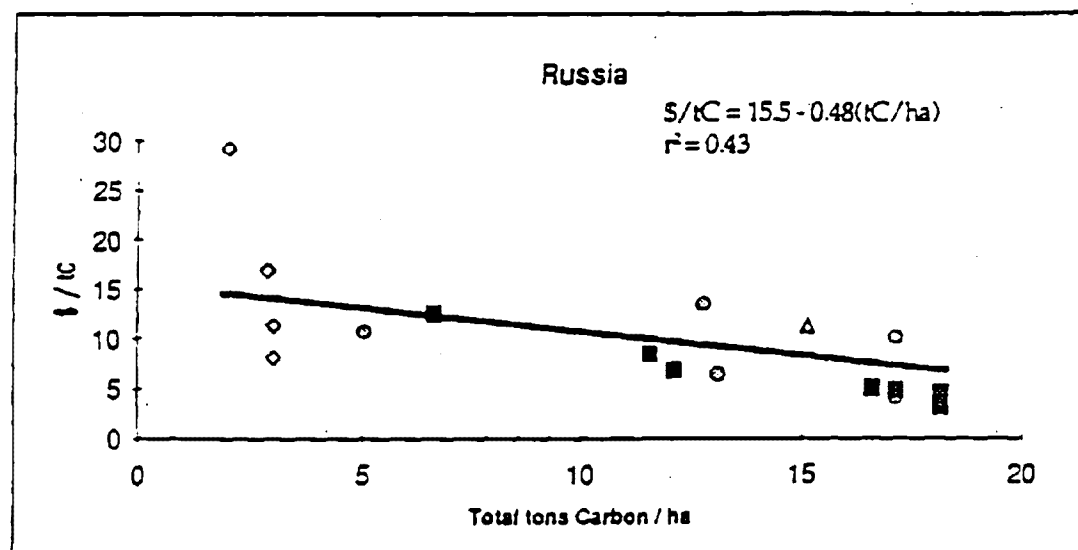
**Figure 3** Initial cost and carbon storage efficiency of national reforestation programs.



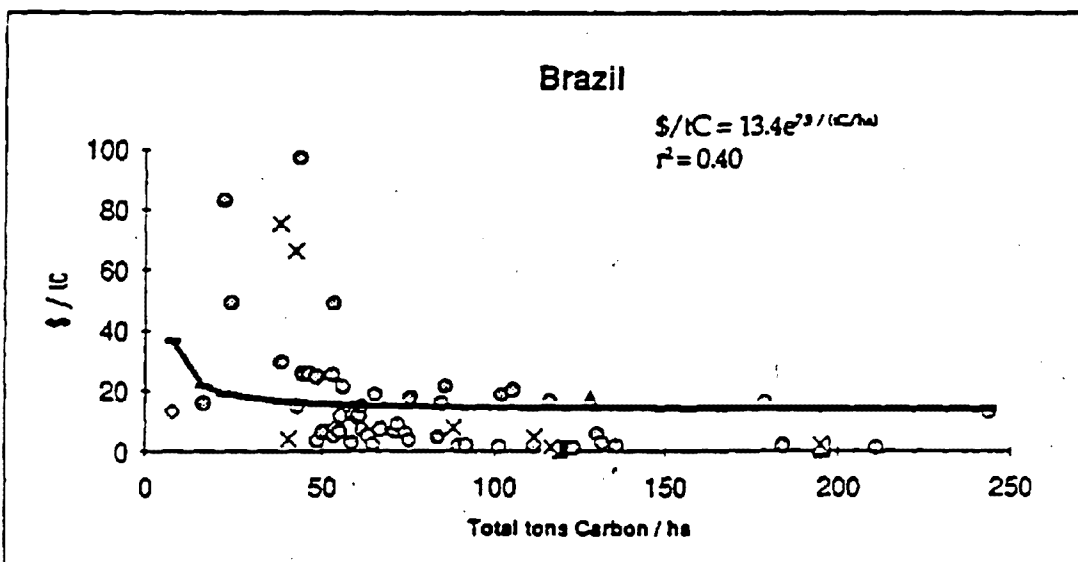
Code	Nation	tC/ha	\$/tC	Code	Nation	tC/ha	\$/tC	Code	Nation	tC/ha	\$/tC
ARG	Argentina	65.0	25.0	EGY	Egypt	36.5	77.9	PAK	Pakistan	98.8	2.5
AUS	Australia	107.0	5.9	FIN	Finland	40.9	27.3	PHL	Philippines	44.6	2.7
BRA	Brazil	63.5	27.4	FRA	France	115.9	16.6	ZAF	S. Africa	110.0	8.7
HVO	Burkina Faso	92.8	13.3	DEU	Germany	56.0	32.4	SEN	Senegal	128.8	2.9
CAN	Canada	40.7	11.5	GHA	Ghana	129.9	6.0	THA	Thailand	79.2	1.7
CHL	Chile	75.9	2.7	IND	India	78.0	26.8	TGO	Togo	167.0	4.6
CHN	China	76.3	5.2	IDN	Indonesia	99.0	6.8	USA	USA	77.0	5.5
COL	Colombia	56.7	20.6	MDG	Madagascar	75.0	1.8	SUN	USSR	25.0	4.6
COG	Congo	111.0	3.0	MYS	Malaysia	84.0	3.5	VEN	Venezuela	38.9	50.7
CRI	Costa Rica	46.3	31.0	MEX	Mexico	99.0	4.5	ZAR	Zaire	59.5	41.7
CIV	Cote d'Ivoire	60.2	34.1	NZL	N. Zealand	94.0	52.4				
ECU	Ecuador	67.2	8.7	NPL	Nepal	78.6	0.5				



**Figure 4** Efficiency and yield of reforestation, afforestation, natural regeneration, agroforestry and silvicultural practices in Russia, US, and Brazil.

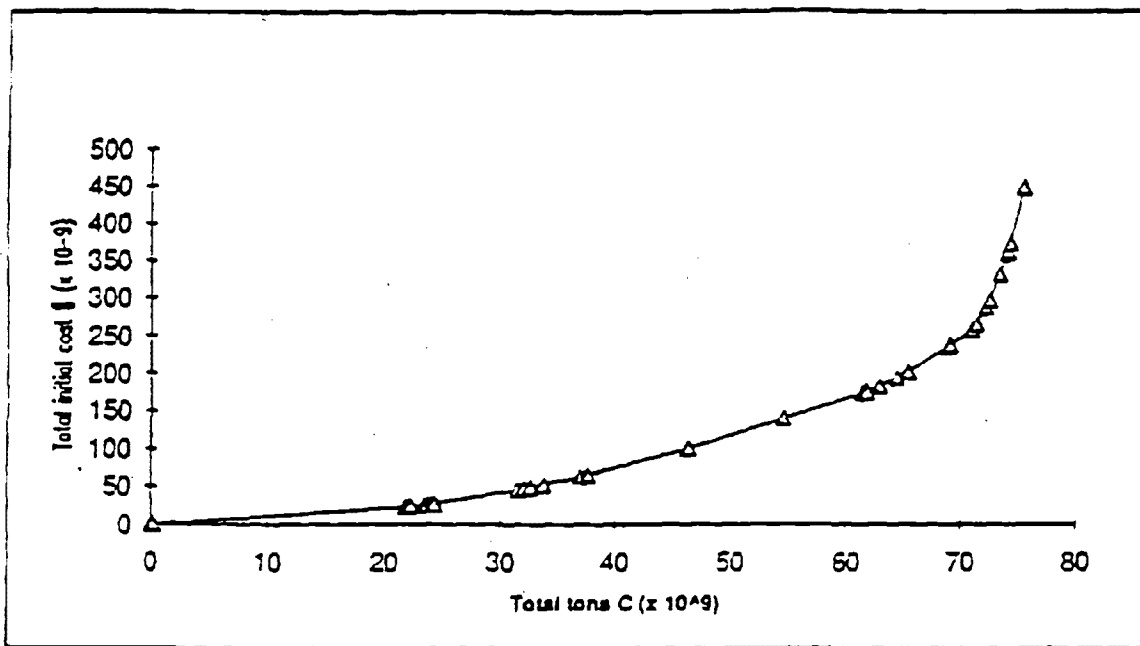


- Legend**
- Reforestation
  - △ Afforestation
  - Natural Regeneration
  - ◆ Silviculture
  - × Agroforestry



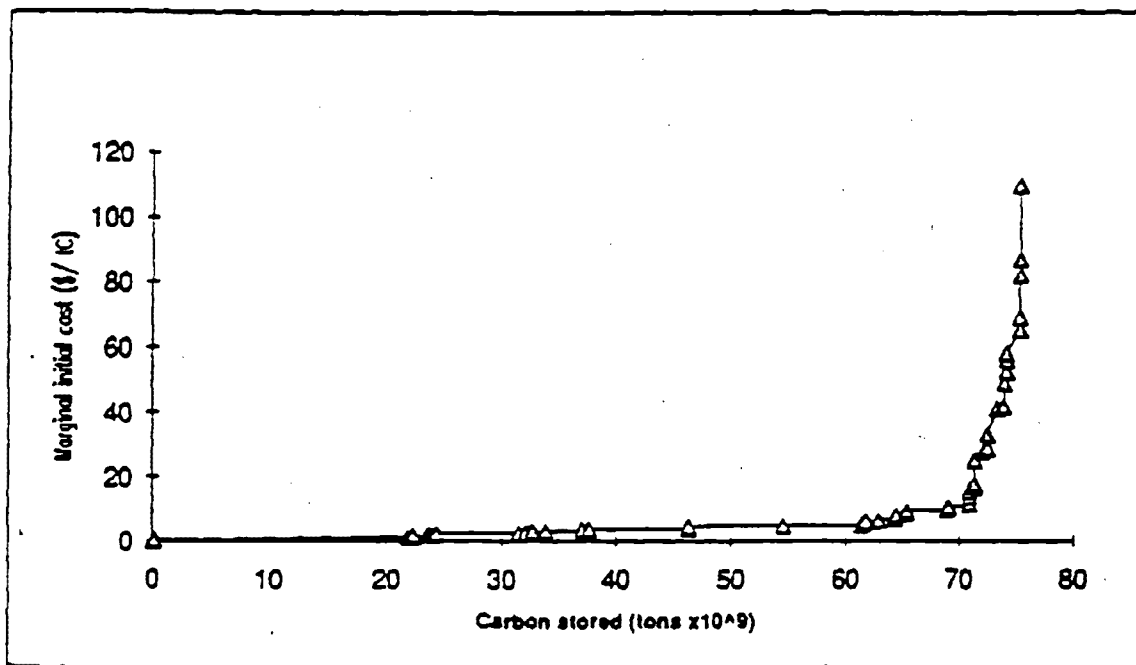
**Figure 5a**

Total initial global cost of sequestering carbon in forest systems employing forestation and forest management practices.



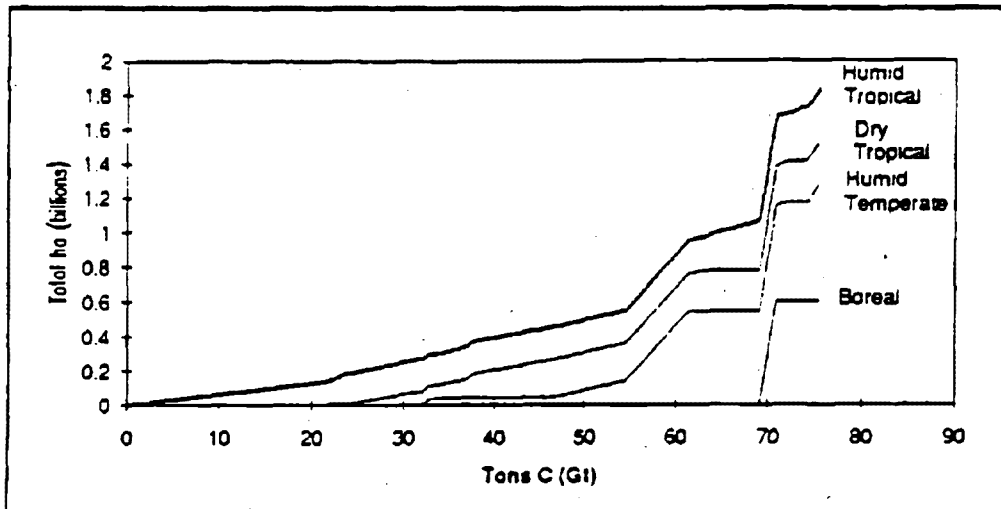
**Figure 5b**

Marginal initial costs of sequestering carbon in forest systems employing forestation and forest management practices.



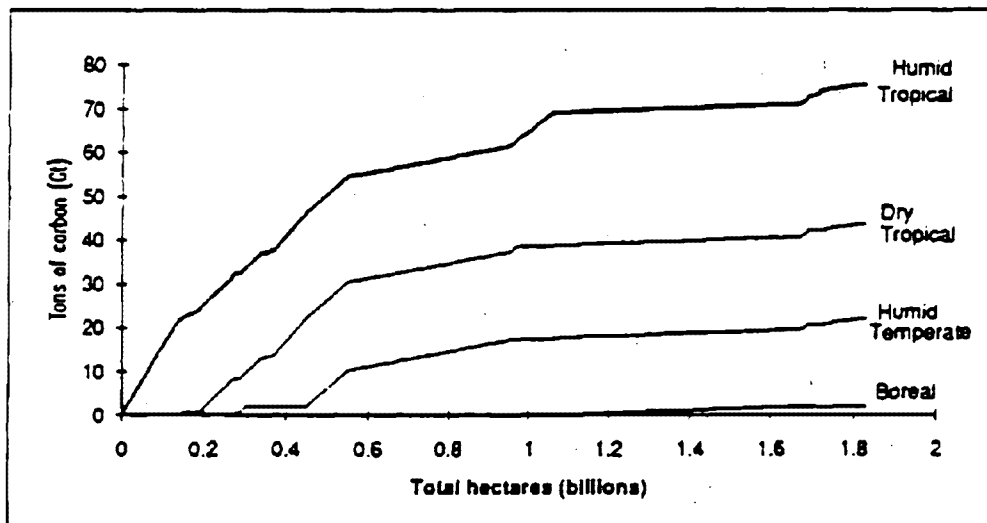
**Figure 6a**

Potential distribution of technically suitable land among ecoregions of key forest nations worldwide for different levels of carbon storage.



**Figure 6b**

Potential distribution of stored carbon among ecoregions of key forest nations worldwide for different levels of total carbon storage.





## **GLOBAL BIOME**

**(BIOspheric Mitigation and adaptation Evaluation)**

### **PROGRAM**

#### **Program Description**

**U.S. Environmental Protection Agency  
Office of Research and Development**

Robert K. Dixon and Jack Winjum  
U.S. Environmental Protection Agency  
Corvallis, OR

(This paper has been reviewed in accordance with the U. S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.)



**ORD/ERL-C**

Preliminary assessments suggest that forests and agroecosystems can be managed to conserve and sequester carbon, thereby reducing the accumulation of greenhouse gases in the atmosphere. Biomass utilization is a necessary component of a sustained terrestrial carbon sequestration effort. The Global BIOME (BIOSpheric Mitigation and adaptation Evaluation) Program will consist of: a) technical assessments of effectiveness of terrestrial biosphere management options and biomass fuel technology in reducing atmospheric accumulation of greenhouse gases, b) demonstration projects to assess the technical and economic feasibility of applying agricultural and forest management options and biomass fuel substitution, c) regional, national, and global assessments of effectiveness of terrestrial biosphere management and adaptation options, and d) assessment of practices and technologies which, if implemented, could facilitate adjustment of forest and agroecosystems to global climate change. The Global BIOME initiative is a component of EPA's Office of Research and Development national Global Change Research Program. The research is managed by the Agency's laboratories: ERL-A, ERL-C, AEERL, and AREAL. Research is conducted by EPA scientists in cooperation with universities, other federal agencies and laboratories, and contractors.

## PROGRAM GOAL

Evaluate the degree to which forest and agroecosystems can be technically managed or adapted, on a sustainable basis, to conserve and sequester carbon, and the degree to which biomass may be substituted for fossil fuels to reduce the accumulation of greenhouse gases in the atmosphere.

Emphasis will be placed on managed terrestrial ecosystems given their significant role in the global carbon cycle. Appropriate biologic management and adaptation technologies, costs and benefits, implementation procedures and environmental risks and benefits will be assessed.

### **POTENTIAL BIOLOGICAL GLOBAL CARBON MITIGATION** (above- and below-ground)

Sequestration	U.S.	Temperate (Gt C/yr)	Tropical	Boreal
Forestation	0.10	0.8	1.0	0.1
Agroforestry	0.05	0.1	0.5	—
Revegetation	0.05	0.2	0.2	0.2
Silviculture	0.03	0.1	0.1	0.1
Conservation				
Reduce deforestation	—	—	1.5	0.1
Halt desertification	—	0.2	0.2	—
Fire management	—	0.2	—	0.2
<b>Total</b>	<b>0.23</b>	<b>1.6</b>	<b>3.5</b>	<b>0.7</b>

Sources: Office of Technology Assessment (1984, 1987)  
Climate Institute (1991), Dixon, et al. (1991)

*A range of terrestrial biosphere management options which conserve or sequester carbon are available for utilization in the U.S. and biomes worldwide. Based on current estimates application of forest and agricultural management practices on global scale could potentially sequester and/or conserve 1-6 GtC annually. Many of these options have value added benefits beyond the reduction of greenhouse gases.*

## BACKGROUND

The accumulation of greenhouse gases in the atmosphere due to anthropogenic activities (e.g., deforestation, fossil fuel combustion) may have begun to change the global climate. Given our current understanding of global carbon sources and sinks, the prospects for managing the terrestrial biosphere to alter the carbon cycle to mitigate and adapt to climate change appear promising.

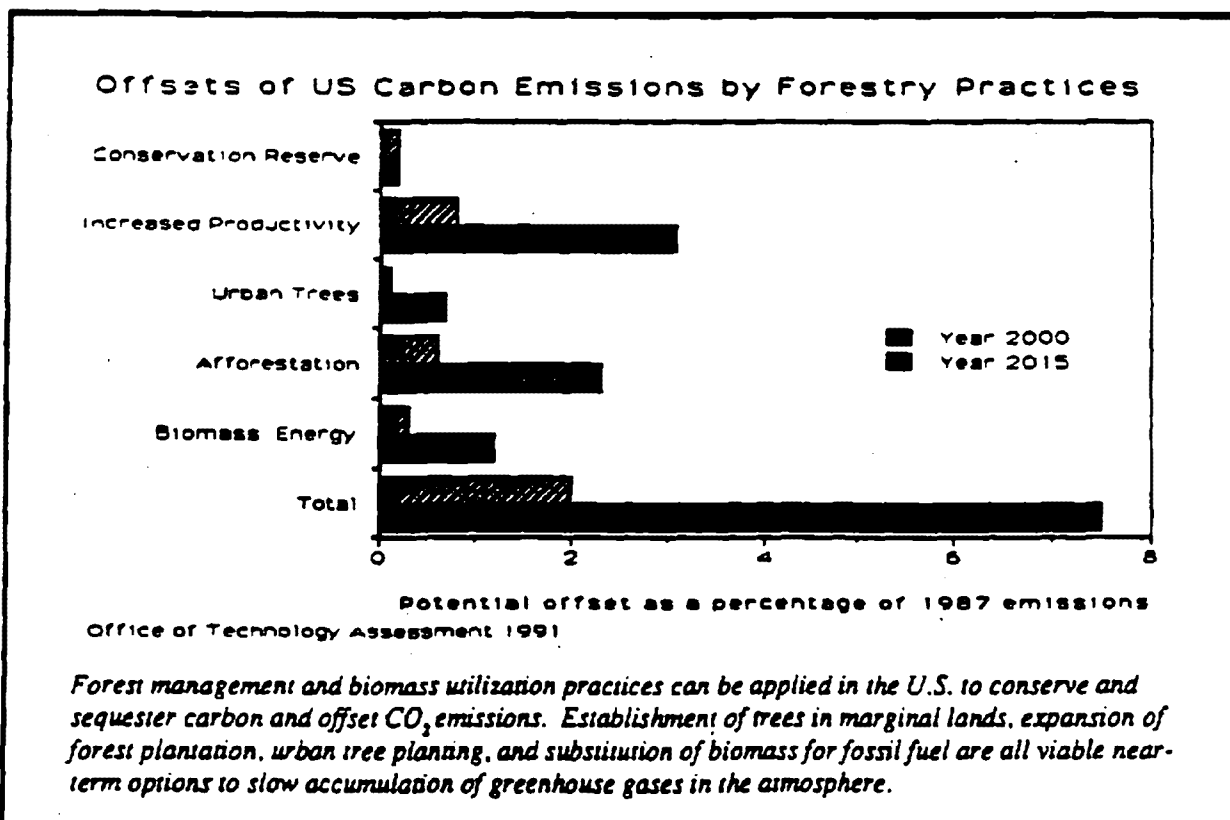
The Global BIOME Program was developed to answer the following policy question:

Can increases in the concentration of atmospheric CO<sub>2</sub> be effectively reduced or adapted to by increasing carbon sinks in forest and agricultural systems, and by the substitution of biomass for fossil fuels?

**Sequestration:** Forests and agroecosystems play a prominent role in the global carbon cycle. Forests alone contain an estimated 66% of terrestrial aboveground carbon, and approximately 45% of

the terrestrial soil carbon. Global forests account for some 90% (90 Gt) of the annually carbon flux to and from the atmosphere from terrestrial systems. Based on current estimates, application of forest and agroecosystem management practices on a global scale have the biological potential to sequester or conserve 1-6 GtC annually.

**Conservation:** Conservation efforts can be employed to retain carbon in the terrestrial biosphere. Slowing global deforestation could conserve over one GtC annually. Agroecosystems contain about 12% of the world's terrestrial soil carbon and conservation of this pool is essential to sustained crop productivity and decreasing CO<sub>2</sub> emissions. Some agricultural practices have been shown to increase soil carbon content by increasing carbon sequestration and/or reducing the loss of carbon. Examples include reduced tillage, crop residue incorporation, field application of manure and sludge, and rotations using cover crops or leguminous crops. Additional benefits from implementing forestry and agricultural practices that con-



serve soil carbon include increased soil water holding capacity, and nutrient availability, improved soil physical properties, and decreased soil erosion by wind and water. The Global BIOME Program will assess the forest and agroecosystem contribution to global carbon conservation.

**Fuel Substitution:** The potential exists to substitute biomass energy for some portion of fossil fuels to reduce the most significant anthropogenic factor in global warming, i.e., atmospheric additional cases of CO<sub>2</sub> from fossil fuel burning. The use of biomass would also encourage the establishment of agricultural and forest systems which will capture and sequester CO<sub>2</sub>. Utilization of biomass is a requisite for a significant carbon sequestration program since forestry and agricultural management options are finite and stored terrestrial carbon can eventually produce greenhouse gases. Currently, harvesting is responsible for 40% of total biomass costs. Preparation of biomass for various combustion processes may also be expensive. Technological advances in both of these areas should substantially reduce the cost burden and must be addressed.

**Adaptation:** The projected rate and magnitude of climate change impacts on forest and agroecosystems is unprecedented in recent geologic

history. Adaptation of terrestrial ecosystems to climate change will be necessary to maintain a flow of goods and services, as well as to conserve and sequester carbon. Biologic options to manage forest ecosystems to facilitate ecosystem adaptation to climate change, including forestation, thinning, and genetic manipulation will be evaluated. Similarly, adaptation of agroecosystems may be achieved through alternative cropping practices or land-use systems.

Recently, the G-7 countries, recognizing the prominent role of forest biomes in global ecology and the global carbon, agreed to develop a convention process to promulgate a **Global Forest Agreement**. The stated intent of this agreement includes:

- curb deforestation,
- protect biodiversity,
- stimulate sustained forest management and productivity, and
- address threats to the world's forests.

The Global BIOME Program will support this process by assessing the current distribution and extent of manageable forests, the suitability and availability of land for forest ecosystem management, and the state of practices which can be applied to forest management on a global basis.

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## PROGRAM ELEMENTS

Each Program Element and the scope of work to complete component tasks are presented below.

**ELEMENT I:** Regional and National Assessment of Effectiveness of Terrestrial Biosphere Management Options

**Rationale:** Evidence suggests the terrestrial biosphere can be managed to conserve and sequester carbon and facilitate adaptation to global climate change. An assessment of the capability to conserve and sequester terrestrial carbon requires knowledge of land suitability and availability, terrestrial systems management and adaptation, op-

tions, biomass utilization options, and ecoregional risk and benefits, in key regions and nations.

**Major program outputs:** Completion of tasks in Element I will provide a summary of options, and identify target/key countries for pilot demonstrations.

**Approach:** Five major tasks will be completed in the key country assessment:

**A. Carbon Pools and Flux:** Carbon budgets and models will quantify pools and flux for specific regions and nations. A detailed carbon budget for

the key countries, including *biogenic* and *anthropogenic* components will be constructed based on current data bases. These carbon budgets will be assembled by aggregating data for specific pools. Emphasis will be placed on biogenic components. Simulation models of anthropogenic and biogenic carbon pool dynamics will be developed. The models will be employed to evaluate effectiveness of various mitigation/adaptation strategies (e.g., tree planting *versus* emission reduction).

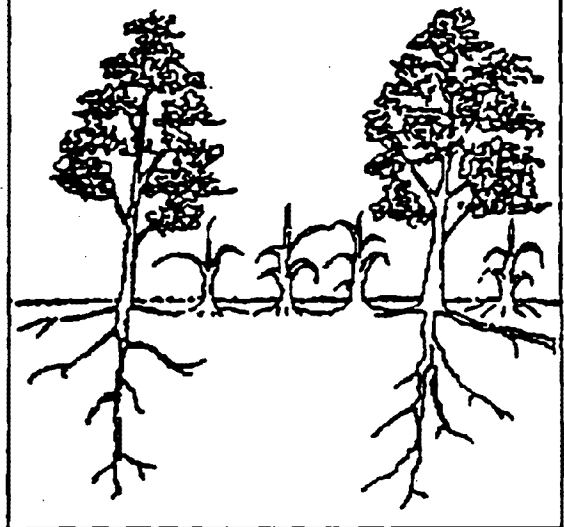
**B. Land Suitability and Availability Characterization:** Land-use practices and land availability will partially define opportunities to implement terrestrial biosphere management options. This assessment will assemble and evaluate all data on land technical suitability and availability for key nations. Technical suitability is defined as having edaphic, climatic, and biological conditions that permit the management of tree and/or agricultural crops on a sustainable basis for the purpose of conserving/sequestering carbon. Availability is based upon the social, political, and economic limitations of the countries with technically suitable lands. Further, an assessment of land-use practices and projected climate change on land suitability and availability is required.

**C. Forests and Agroecosystems' Adaptation Options:** Research will assess how shifts in forest distribution and productivity influence species survival and which species are most resilient in the face of altered climatic conditions. Management strategies and silvicultural practices will be identified which allow forest systems to adapt to warmer and drier environments. Options to be investigated include both *in situ* (e.g., nature reserves, migration corridors) and *ex situ* (e.g., zoos, botanical gardens) measures. Appropriate technology and management options will be ranked by: 1) carbon conservation and sequestration efficiency; 2) operational feasibility; and 3) socio-economic and eco-risk factors.

**D. Biomass Utilization Options:** Substitution of biomass for fossil fuels offers significant opportunity to reduce emissions of greenhouse gases. This

analysis will assemble and evaluate available data to rank the technological and economic feasibility of utilizing cultivated biomass from forestry and agricultural systems as a substitute for fossil fuels. The utilization of biomass will be viewed as a potential source of renewable energy, as feedstock for conversion to substitute fuels for transportation, or for use in durable products. This research will assess: 1) supplies of biomass from agricultural and forest residues; 2) the market potential for biomass energy technologies in the presence of alternative fuels; 3) biomass harvesting options; and 4) environmental and energy impacts of biomass combustion (conventional and advanced processes).

**E. Risk-Benefit Assessments:** The application of terrestrial biosphere management options will be dependent on social and environmental risks and benefits. Most of the management options to sequester and/or conserve carbon have collateral value-added benefits to society such as production of commodities, protection of biodiversity, and employment and income opportunities. A model framework will be developed for the examination



Agroforestry is a combination of trees and agronomic crops. A wide array of agroforestry systems are established and managed within temperate and tropical latitudes to produce food, fuel, and fiber. The net primary productivity of these systems is relatively high and the potential to sequester and conserve carbon is approximately 2 Gt, globally.



of trade-offs between: 1) ecological risks; 2) social and economic cost/benefits and effectiveness of decreasing atmospheric greenhouse gas emissions. Field assessments, literature reviews and model simulations will provide an assessment of the potential feasibility and benefits of terrestrial carbon adaptation/mitigation measures. The country-specific data collection, and analysis of the availability and technical suitability of lands for the sequestering of carbon in biotic systems requires careful scrutiny of management opportunities, socio-economic costs and benefits, and potential eco-risk.

#### **ELEMENT II: Pilot Projects to Assess Terrestrial Biosphere Management Options**

**Rationale:** Demonstration trials must be established in key regions and nations to determine effectiveness of terrestrial biosphere management options.

**Major program output:** Technological feasibility of management options and costs/benefits at site level will be characterized.

**Approach:** Pilot projects and demonstration trials will be established in key nations (e.g., U.S.A.,

Brazil, Mexico, Malaysia, Russia) to assess effectiveness of terrestrial biosphere management and adaptation options. The pilot projects will evaluate biosphere management technologies and logistics, including biomass utilization, in specific ecoregions/biomes. Research will provide defensible data and models for quantifying the carbon pools and dynamics for forestry and agricultural systems, critical soil and climate parameters, and the effects of management and adaptation approaches to conserve and sequester carbon. An assessment of social, economic and ecological risks and benefits will also be conducted at these field sites. The pilot projects will be long-term, intensive efforts to provide data for carbon budget and model development and calibration. Demonstration trials will be employed for technology transfer to various clients.

The pilot projects and demonstration trials will be established at extramural sites. Co-location and cooperation with U.S. Agency for International Development, U.S. Department of Energy, U.S. Department of Agriculture and others will be encouraged in the U.S.A. and abroad. In-country support will be a key to large-scale international pilot projects and demonstration trials.

### **SEQUESTRATION OF CARBON IN FORESTS**



Forests occupy approximately one-third of the Earth's land area and their vegetation and soils contain about 60% of the terrestrial carbon. The Earth's atmospheric CO<sub>2</sub> cycles through the terrestrial biota every seven years, and of this amount 70% cycles through forest ecosystems. These features suggest forest and agroecosystem management practices can be employed to mitigate the accumulation of greenhouse gases, such as CO<sub>2</sub>, in the atmosphere. Carbon sequestration rates in forest and agroforest systems range from 1-8 tC/ha/yr.

### **ELEMENT III: Global Assessment of Terrestrial Biosphere Management**

**Rationale:** Preliminary assessments suggest the global application of terrestrial biosphere management options have the potential to reduce the accumulation of greenhouse gases in the atmosphere and mitigate global change processes. The global effectiveness of these options will need to be evaluated by integration into large-scale models (e.g., GCMs or ESMs).

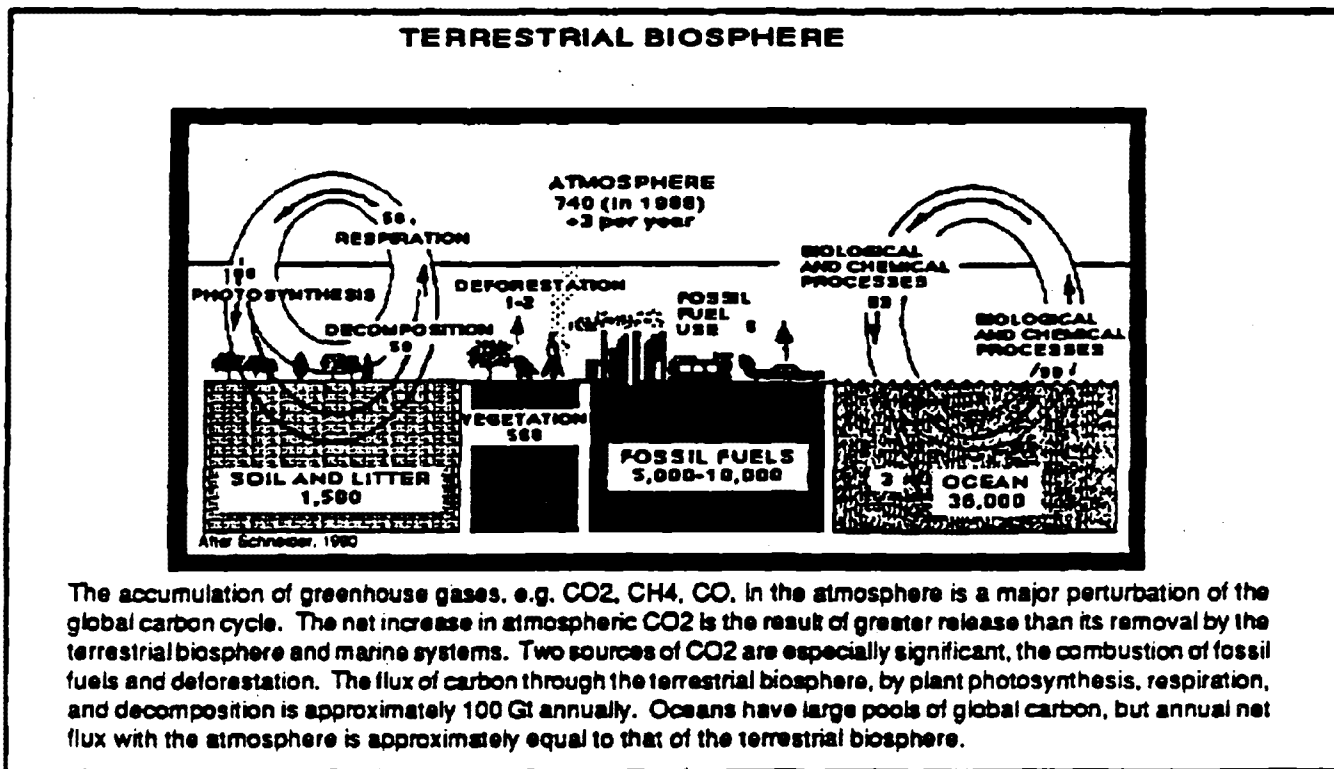
**Major Program Output:** A synthesis of the effectiveness of terrestrial biosphere management options to reduce greenhouse gas emissions to the atmosphere and mitigation of global climate change.

**Approach:** A synthesis of knowledge regarding the current potential for global terrestrial carbon conservation and sequestration will be provided. Carbon budget and modeling output from key national assessments and other data sources will be synthesized and evaluated on a global scale. An array of management and adaptation options (e.g., forestation, substitution of biomass for fossil fuels) will be examined. The global assessment will

include an evaluation and synthesis of anthropogenic and biogenic carbon pools and flux worldwide.

Biogeochemical and Earth System models of global carbon pools and flux will be employed to project future carbon flux rates to the atmosphere. The effectiveness of terrestrial biosphere management options to reduce carbon flux to the atmosphere will be examined. General circulation models, coupled with atmosphere-biosphere models, will be used to consider the responses and feedbacks of the terrestrial biosphere to project future climate change, given the application of carbon cycle management options.

The global synthesis will be completed in conjunction with complementary research activities in the U.S.A. and abroad. Cooperation with existing and emerging biogeochemical model and GCM programs will be essential. Econometric, social and environmental decision models for risk-benefit assessment of global management options will also be employed.



## REPRESENTATIVE PROGRAM OUTPUTS

Barnwell, T.O., R.B. Jackson, IV, E.T. Elliott, L.C. Burke, C.V. Cole, K. Paustaiian, E.A. Paul, A.S. Donigian, A.S. Parwardhan, A. Rowell and K. Weinrich. An approach to assessment of management impacts on agricultural carbon. *Journal of Water, Air & Soil Pollution* (in press).

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# AGRICULTURAL MANAGEMENT AND SOIL CARBON SEQUESTRATION: AN OVERVIEW OF MODELING RESEARCH

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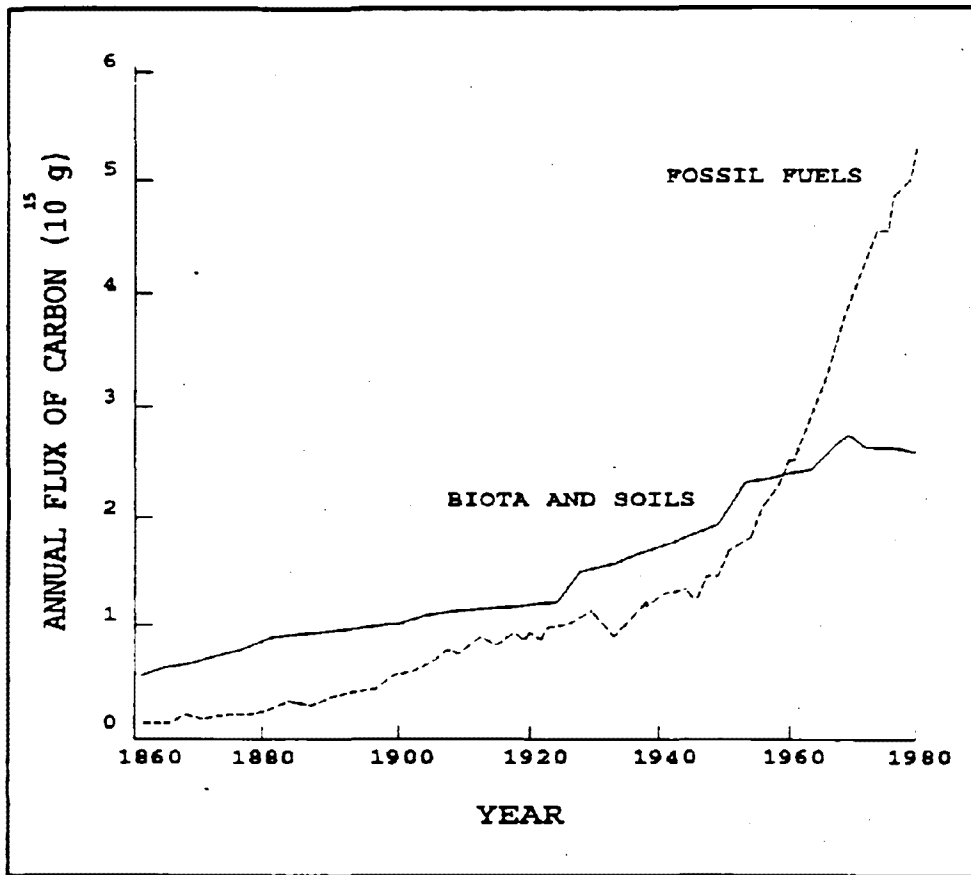
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**Abstract.** Soil carbon fluxes and pools are profoundly affected by agricultural management, which in turn is affected by national and international agricultural policies. This paper briefly describes the framework and some details of the soil and climate databases used in a computer modeling research strategy that is being implemented at the Environmental Research Laboratory, Athens, Ga. (AERL). The objective of the research is to determine the potential for U.S. agroecosystems to accumulate and sequester carbon as a means of slowing the global increase in atmospheric carbon dioxide.

## INTRODUCTION

The conversion of native ecosystems to agricultural lands in the central United States was perhaps the most extensive ecological disturbance known in North America during the past 150 years [Barnwell et al. 1991, Wilson 1978]. A major consequence of this land conversion has been a substantial loss of organic matter from soils across the regions [Haas et al. 1957, Campbell 1978, Barnwell et al., 1991]. Globally, soil C losses from land use change and agricultural management have been a primary anthropogenic source of atmospheric carbon dioxide (CO<sub>2</sub>), even exceeding fossil fuel CO<sub>2</sub> emissions until about 50 years ago (Figure 1) [Houghton et al. 1983]. Since soil carbon levels in most Great Plains and Corn Belt agricultural soils have been reduced to levels well below those existing prior to the establishment of agriculture, the potential should exist to increase them, thereby providing a sink for

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**Figure 1** Historical Terrestrial Carbon Emissions [Houghton et al., 1983]  
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atmospheric CO<sub>2</sub>. While pressures on agricultural management in the United States have been increasing in response to the environmental and economic costs of energy and chemicals (among others), many of the techniques designed to address these issues have also demonstrated a potential for increasing soil C levels above those maintained under conventional agricultural production systems. Such practices include increased use of green manure and animal manure [Vitosh et al. 1973], reduction in the proportion of bare fallow relative to crop in semiarid regions [Wood et al. 1991], and reduced or no-till management [Blevins et al. 1983, Dick 1983, Lamb et al. 1985]. However, the extent to which soil C levels can be regulated through the application of various combinations of these practices for different cropping systems, soil types, and climatic regions is not yet clear, particularly since agricultural management is driven by economics, which in turn, is greatly impacted by national and international agricultural policy.

To date there has been little systematic evaluation of how policies that encourage or discourage particular land uses or agricultural management practices affect regional soil C balances, and of what effect future policy shifts may have.

Data available from long term agricultural research sites have shown that the potential exists to increase agricultural soil carbon through management alone [Jenkinson et al. 1977 and 1987, Van der Linden et al. 1987]. The U.S. EPA is interested therefore, in assessing not only the agricultural management effects on soil carbon, but the policy implications driving the use of alternative agricultural management systems. To that end, we have developed a modeling framework that begins with the policies to be evaluated and their effects on agricultural economics; then includes the economy's subsequent effects on agricultural management through product demand, planted area and crop profit potential; and finally examines the effects of the resulting agricultural management scenarios on soil carbon (C) and nitrogen (N) fluxes and pools (Figure 2).

This year's research effort by AERL will analyze the central region of the United States (Figure 3). National and international agricultural policy scenarios are generated by EPA's Office for Planning and Policy Evaluation (OPPE). These policies then become inputs to the Comprehensive Environmental and Economic Policy Evaluation System (CEEPES) model known as RAMS [CARD 1992]. RAMS is an

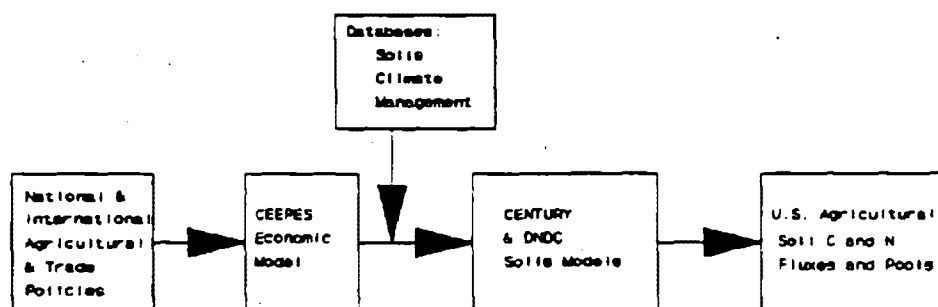


Figure 2 Modeling Framework for Assessing The Impact of Policy on Agricultural Management, and Agricultural Managements' Impacts on Soil C Fluxes.

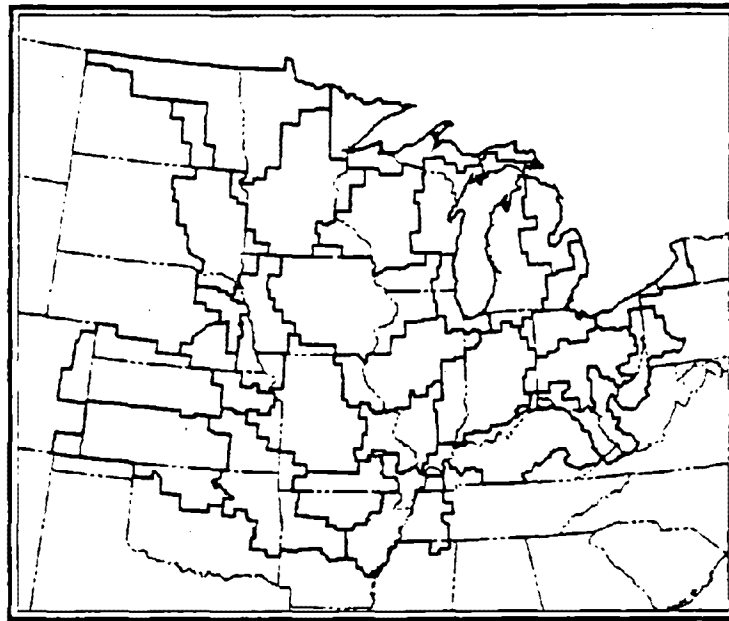


Figure 3 First Year Study Region Displaying Production Areas in bold (PA) and State Boundaries (Note: PAs follow county boundaries).

economic model maintained at the Center for Agricultural and Rural Development (CARD) at Iowa State University. The RAMS model divides the United States into production areas (PA) (Figure 3) for which crop areas and rotations are determined based initially on policy scenarios. CARD has tentatively specified twenty-seven PA's in our study area (Figure 3).

Twelve soil C models were reviewed before two were selected for our analysis [Barnwell et al. 1991]: the CENTURY model [Parton et al. 1983, Parton et al. 1987, Parton et al., 1988; Parton et. al. 1989] and the Denitrification Decomposition model (DNDC) [Li et al. 1992, Li et al. 1992a & b]. Among the numerous factors influencing soil C and N fluxes in both models are initial soil organic matter and nitrogen levels, climate (precipitation and temperature), crop type and yield, crop rotations, soil texture, tillage type and frequency, grazing, fertilizer applications, residue returns or removals, and irrigation frequencies and amounts. Both of the soil carbon models are site specific, which requires that for our purposes we develop a methodology for making regional assessments, in addition to performing model validations using site data.

## SITE DATA FOR VALIDATION

A workshop was held to assess the available databases for studying C and N fluxes and pools in North American agricultural soils [Barnwell et al. 1991]. The workshop helped to identify site field data for model testing, calibration and further validation. The "Soil Organic Matter (SOM) In Temperate Agroecosystems" workshop was held on February 18-21 1992 in Hickory Corners, Michigan. Presentations at the workshop included SOM data, as they relate to agricultural management, for more than 50 agricultural research sites in the United States and Canada. These data are currently being compiled into a conference proceedings and database [Paul and Elliot 1993]. We chose two sites for calibration and validation of CENTURY. These sites represented two of the primary crops grown in our study region -- corn and wheat.

## REGIONAL DATA FOR MODELING

### Soils.

CENTURY and DNDC require input data on soil texture (percent sand, silt, and clay) and on initial soil C and N levels. County resolution information was acquired for all of the soil data. These data were taken from three soils databases -- Data Base Analyzer and Parameter Estimator (DBAPE) [Imhoff et al. 1989], the 1982 National Resources Inventory (NRI) [Goebel and Dorsch 1982], and the 1987 NRI / Soils-5 database [Goebel 1987]. The soil texture information taken from the 1982 NRI Database was contained in the 1982 NRI / Soils-5 identification block (fields 76-78) in the 1982 NRI file. The file contained a code with which a texture could be determined from the National Soils Handbook [Soil Conservation Service 1983]. Both DBAPE and the 1987 NRI databases contained ranges of percent sand and clay. The high and low values from these ranges were averaged and their sum subtracted from 100 to obtain percent silt. This was done for each layer of soil for every soil type in the counties of the study region identified in DBAPE and the 1982 NRI databases. The soil texture values were averaged using depth weighting of percent sand, silt, or clay to a 20-cm depth from the surface of the soil.



The three databases were utilized independently, meaning that for any given county, only DBAPE data were used (Figure 4), or 1982 NRI data were used (Figure 5), or 1987 NRI / Soils-5 data were used (Figure 6). Thus combining the files entailed only the sorting of county federal information processing (fips) codes. The textures in the combined file were then reclassified into 1 of the 12 texture categories given in the Soil Conservation Service texture triangle. The format of the result was " County FIPS, Texture, Area " for all of the counties in the study region (i.e., each county could potentially have from 1 to 12 different soil textures). Finally, the soils were grouped into six texture classes based on the extent of different soil textures in the study region (Table 1).

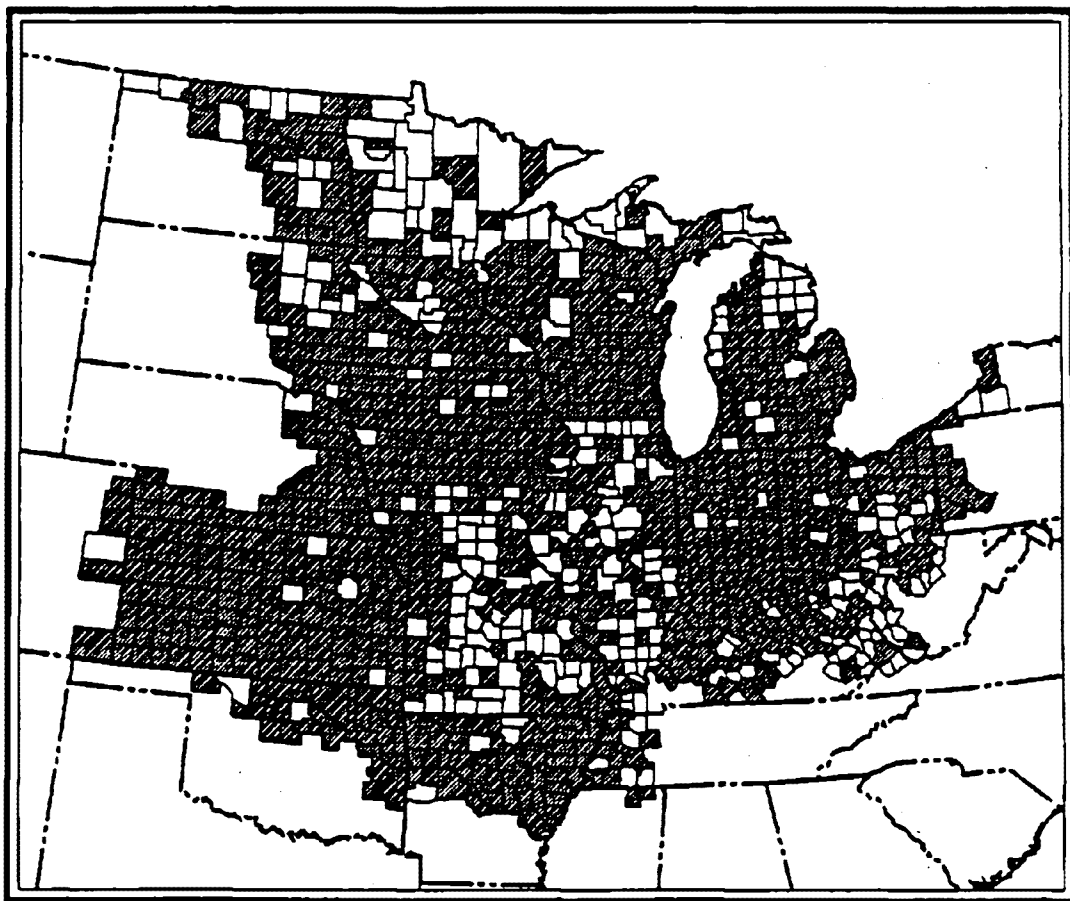


Figure 4 Counties for Which Soil Textures Were Taken From DBAPE.

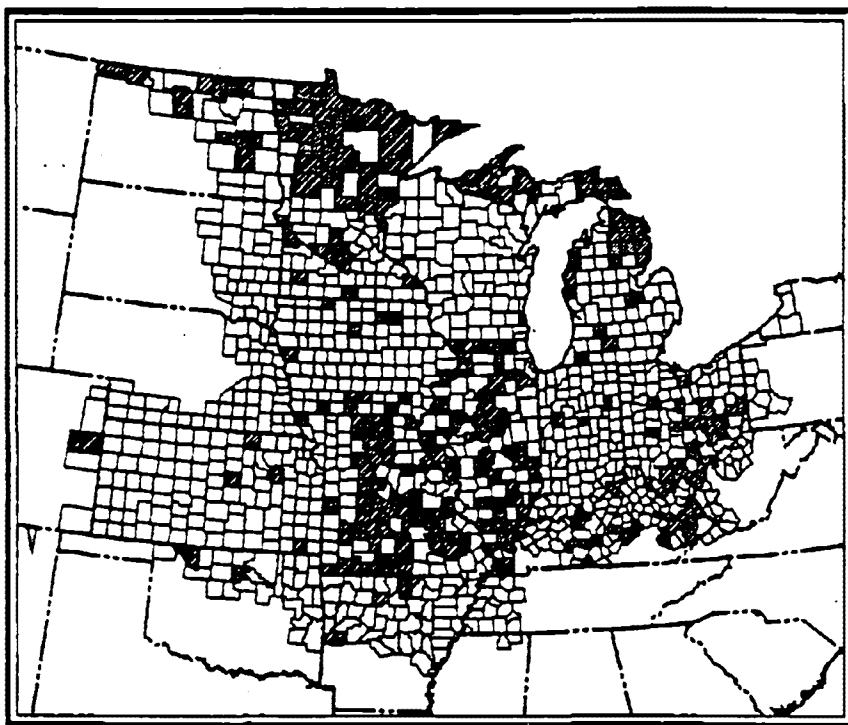


Figure 5 Counties for Which Soil Textures Were Taken From 1982 NRI.

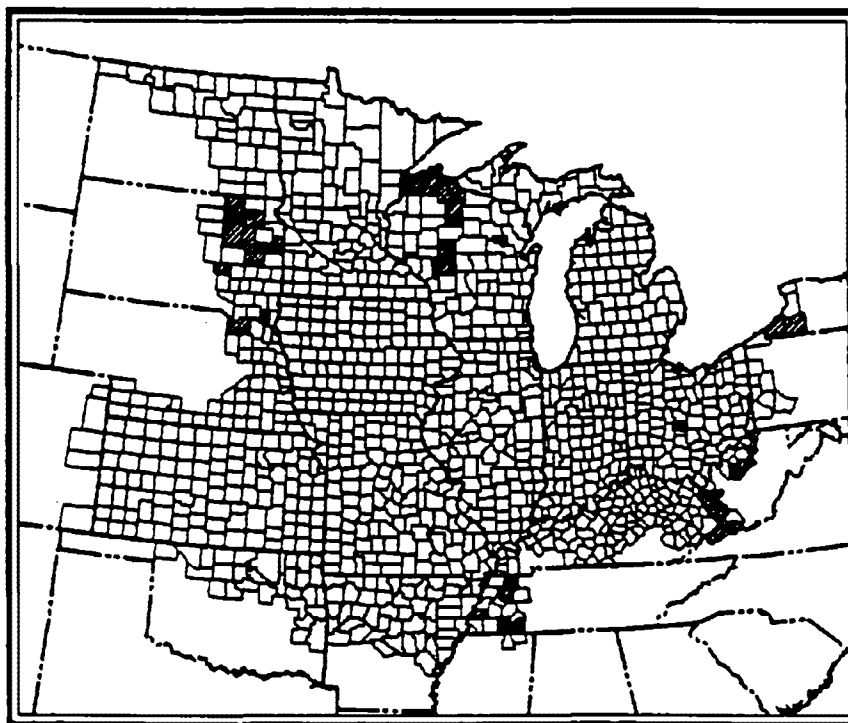


Figure 6 Counties for Which Soil Textures Were Taken From 1987 NRI.

Table 1 Texture Categories.

USDA Texture Categories	Combined Categories*
SAND	
LOAMY_SAND	SAND / LOAMY_SAND
SANDY_LOAM	
SANDY_CLAY_LOAM	SANDY_LOAM / SANDY_CLAY_LOAM
LOAM	LOAM
SILTY_LOAM	SILTY_LOAM
SILTY_CLAY	
SILTY_CLAY_LOAM	SILTY_CLAY / SILTY_CLAY_LOAM
CLAY	
CLAY_LOAM	CLAY / CLAY_LOAM

\* Note: SANDY\_CLAY and SILT were not found in the study area.

## Climate.

The models use monthly values for maximum and minimum temperature (CENTURY) or average temperature (DNDC), and total precipitation. These values can either be provided to the models as historically-recorded input from a user-supplied file, or the models can stochastically generate weather using mean and skewness values computed from a user-supplied data file or input by the user. A collection of historical climate data for the United States [Wallis et al. 1991] was used to obtain 41 years (1948-1988) of monthly maximum and minimum temperatures plus total precipitation data for 589 climate stations in the central United States (Figure 7). From these data, an average monthly maximum temperature value, and an average annual precipitation value was derived for each of the stations. A Geographic Information System (GIS) then was used to create contour maps of temperature (Figure 8) and precipitation (Figure 9). The temperature contours (2° C intervals) and precipitation contours (10-cm intervals) were then overlaid to produce areas of similar climate (i.e. Climate Divisions [CD]). The Climate Division (CD) boundaries were adjusted to coincide with county boundaries; primarily to simplify allocation to the CDs of crop and rotation area data from the RAMS model and the county level soils data.

Although this approach successfully identified subregions of like climate, some of the regions were not contiguous and varied greatly in size and shape. Therefore, while working with these GIS-created subregions, a new approach to defining the CD boundaries was employed. The CDs were overlaid with the PA boundaries and manipulated manually to follow and not cross PA boundaries, and to follow county boundaries within a PA. This resulted in each of the 27 PAs being divided into from two to six CDs producing a total of 80 CDs in the study region. Thus, each CD was comprised of counties for which soil properties information was aggregated to obtain soil data at the CD level.

To create a single climate data set for each CD, data from multiple climate stations (CS) were averaged. Initially, all of the CSs that fell within the boundary of a CD were allocated to the CD for data averaging. However, if there were not enough CSs in a CD, or if their locations were not geographically representative of the CD, one or more additional CSs were

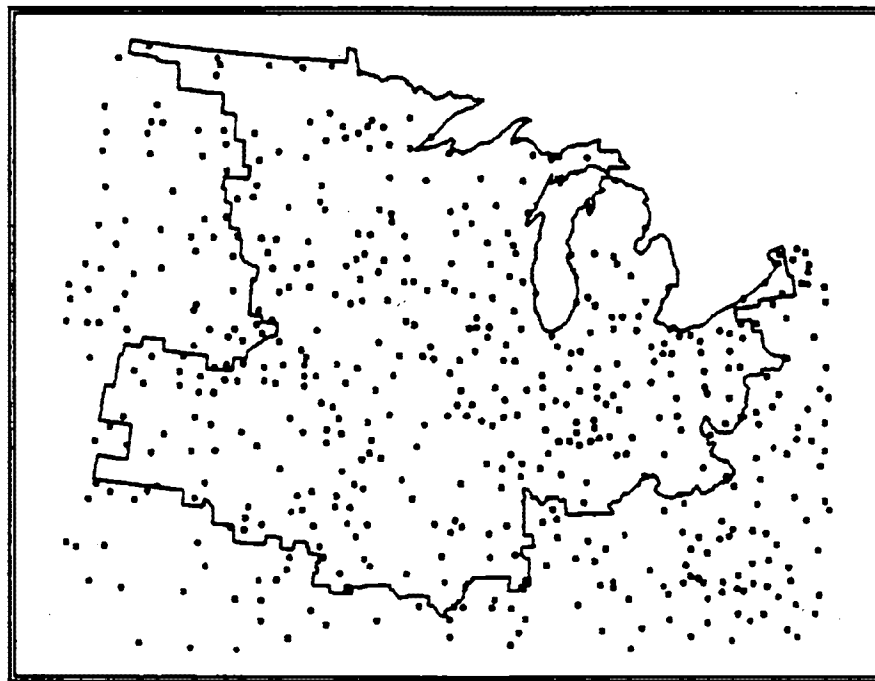


Figure 7 Climate Station Locations

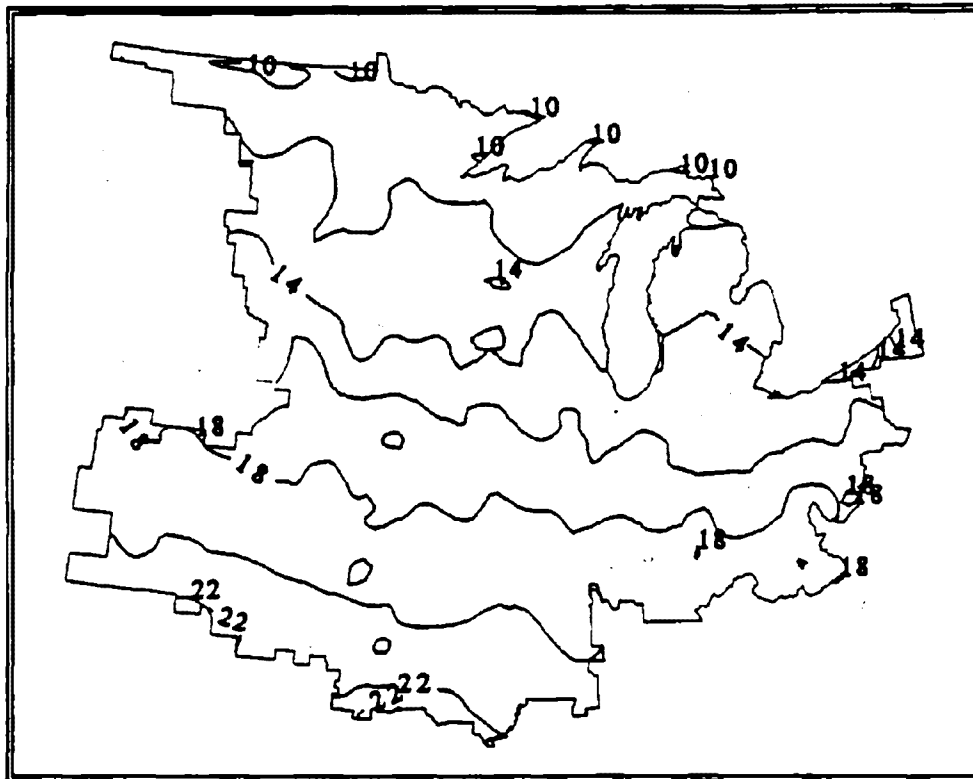


Figure 8 Average Maximum Temperature Contours [ $^{\circ}\text{C}$ ].

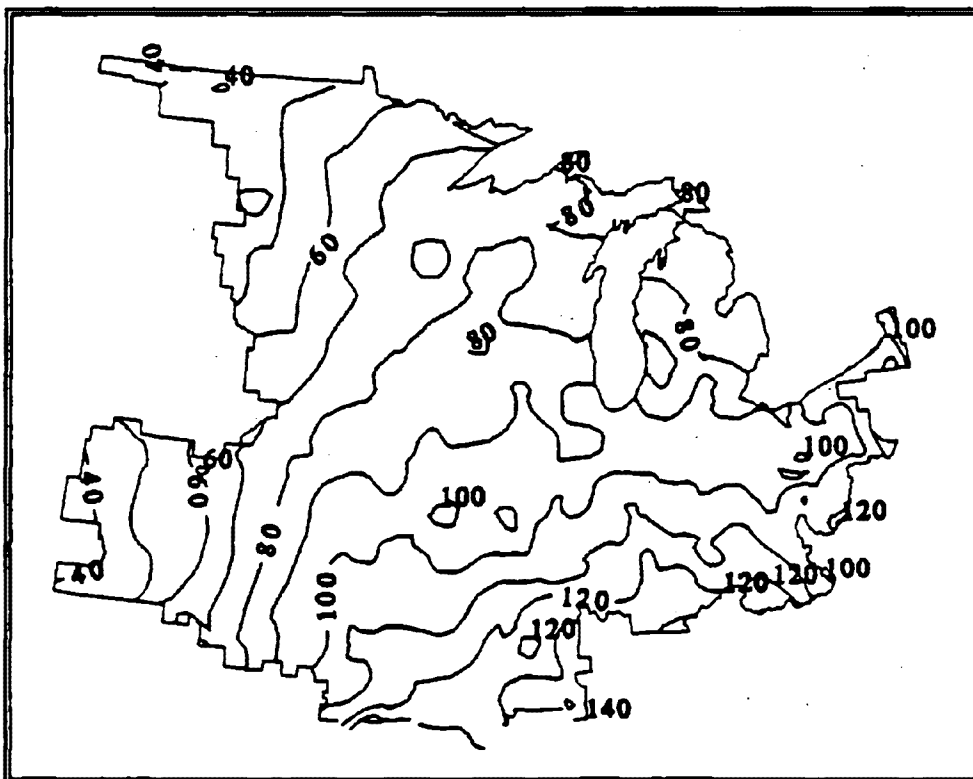


Figure 9 Average Annual Precipitation Contours [cm].

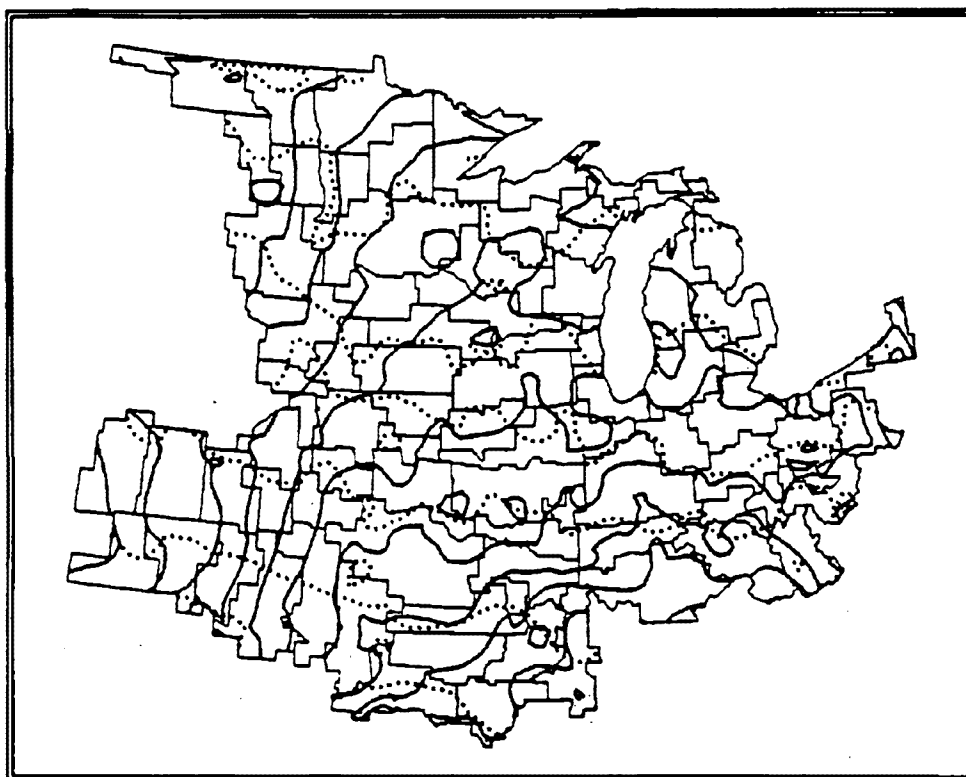


Figure 10 Overlay of Temperature Contours (····), Precipitation Contours (——) and Climate Divisions (CD).

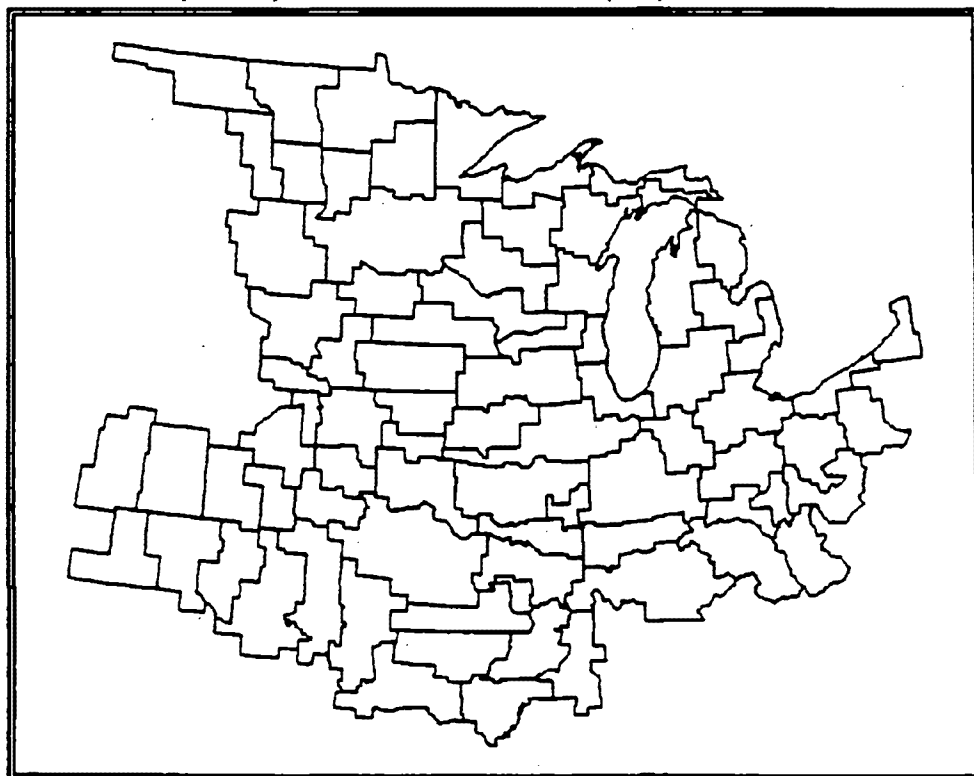


Figure 11 Climate Divisions (CD).

manually allocated. For each CD, the average of the monthly climate values from each of the allocated CSs were saved in a single file for input to the models.

### **Agricultural Management.**

The RAMS model produces, for each production area, crop rotations and the areas they occupy. Initially, 80 different crop rotations were identified in the region. Since we are currently able to model only corn, soybeans, wheat, hay (legume and non-legume), millet, and grasslands, and since we decided it was appropriate to group similar rotations and rotations that occupied less than 5% of the area in a PA, we were able to reduce the number of crop rotations to 35. This reduction was also required in order to reduce the number of model runs. Four tillage practices are considered -- conventional till fall plow, conventional till spring plow, reduced till, and no till. Irrigations and fertilizer applications will be added by the models as required by the crop physiology depending on the policy options being modeled. Further details of the modeling methodology and preliminary results of this initial assessment are discussed by Donigian and coworkers (1993).

### **SUMMARY**

For this work, climate divisions (CD) have been established as the most basic unit to be modeled (Figure 11). For each CD, soil textures and crop/rotation/tillage (C/R/T) scenarios have been identified. The next step is to determine the initial conditions of soil carbon and

nitrogen levels. Initial conditions will be established by making assumptions about the time extent of various C/R/T scenarios (from  $\approx$  1900 to 1988), and performing model runs under those scenarios for a sufficient time while matching historical crop yields through adjustments in crop, fertilizer, and tillage parameters. The results of the initial condition runs will consist of soil C and N values for each soil texture in the CD. The soil C values for each texture can then be weighted by their area distribution within the CD, and summed across all textures to obtain total C and N values. The results will then be compared with existing soil C and N data.

With initial conditions established, CARD specifies the existing spatial extent of C/R/T for each production area (PA). These values will be allocated to climate division (CD) C/R/Ts by multiplying them by the ratio of that CD's area to that PA's area. The base-case model results will represent a simulation time period of from 1989 to 1990. The model will then be used to predict soil C and N fluxes and pools to the year 2030, under a variety of policy alternatives which will include the status quo. The scenarios under consideration include: an increase in the area of Conservation Reserve Program (CRP) land, an increase in the use of cover crops, and an increase in the use of conservation tillage. A different policy scenario may generate new C/R/T practices from RAMS, which will then be used in CENTURY and DNDC to make model runs for predictions of soil C losses as  $\text{CO}_2$ , soil C storages, and total nitrogen losses. DNDC can also reliably distinguish  $\text{N}_2\text{O}$  emissions. Results from the two models can then be compared and assessments made about the effects of the policy on agricultural management, and about agricultural management's subsequent effects on soil C and N fluxes and pools [see Donigian et. al, 1993].



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## ASSESSMENT OF THE BIOGENIC CARBON BUDGET OF THE FORMER SOVIET UNION

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### ABSTRACT

A framework was created to quantify the natural terrestrial carbon cycle of the former Soviet Union (FSU). The organization of the carbon cycle parameter and georeferenced data base which support the framework and the calculations which are required to establish the carbon budget are performed with personal computer hardware and commercially available spreadsheet software. Based on the framework, net primary productivity (NPP) for the FSU was estimated at  $6.2 \pm 1.7$  GT ( $10^9$  tons) C/yr, the vegetation carbon pool at  $118.1 \pm 28.5$  GT C, the litter carbon pool at  $18.9 \pm 4.4$  GT C, and total soil carbon pool at  $404.0 \pm 38.0$  GT C. The components of the carbon budget obtained with the framework were in good agreement with estimates from other published sources. The framework will allow the role of the FSU in the global carbon cycle to be assessed. The extent of forest and agricultural ecosystems within the FSU that can be technically managed on a sustainable basis to conserve and sequester carbon may also be determined with the framework.

Although the research described in this article has been funded under U.S. Environmental Protection Agency Agreement CR17682-01 to Oregon State University, it has not been subjected to the Agency's review and, therefore, does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

### INTRODUCTION

The long-term ecological consequences of the change in the chemical composition of the atmosphere are not fully understood; however, a warmer global climate is highly probable (1). If  $\text{CO}_2$  concentrations were to double, the earth's temperatures may rise between 1 and  $5^\circ\text{C}$  (2). Climatic changes may be more pronounced in the Northern Hemisphere (3). Global warming may accelerate the rates of plant respiration (4) and decay of organic matter (5).

In view of the potential to significantly disrupt the equilibrium of the natural carbon cycle, it may be necessary to offset increased amounts of atmospheric  $\text{CO}_2$ . This will require the development of international strategies to reduce industrial emissions or manage terrestrial carbon stores. Before any international strategy can be formulated, policies aimed at maintaining a desirable carbon balance within national boundaries would be required. The determination of a carbon balance includes the quantification of the natural (biogenic) and

anthropogenic contributions to the carbon cycle within national boundaries. The quantification of the carbon cycle following an assessment of carbon pools and fluxes is generally referred to as the carbon budget. Carbon budgets recently have been established for Sweden (6) and the forest sectors of Canada (7) and the United States (8).

The former Soviet Union (FSU) was the largest country in the world. It occupied one-sixth of the land surface of the earth. An understanding of the carbon budget of the FSU is essential to the development of international strategies aimed at mitigation of the negative impacts of global climate change.

Anthropogenic carbon emissions in the FSU have recently been estimated at approximately 1 GT (9). Despite an abundance of Soviet data on carbon-cycle parameters in desert, tundra, forest and grassland ecosystems (10-18 and others), the national carbon budget of the FSU, specifically the natural component, has only recently been established, as described herein.

### THE PHYSICAL ENVIRONMENT OF THE FSU

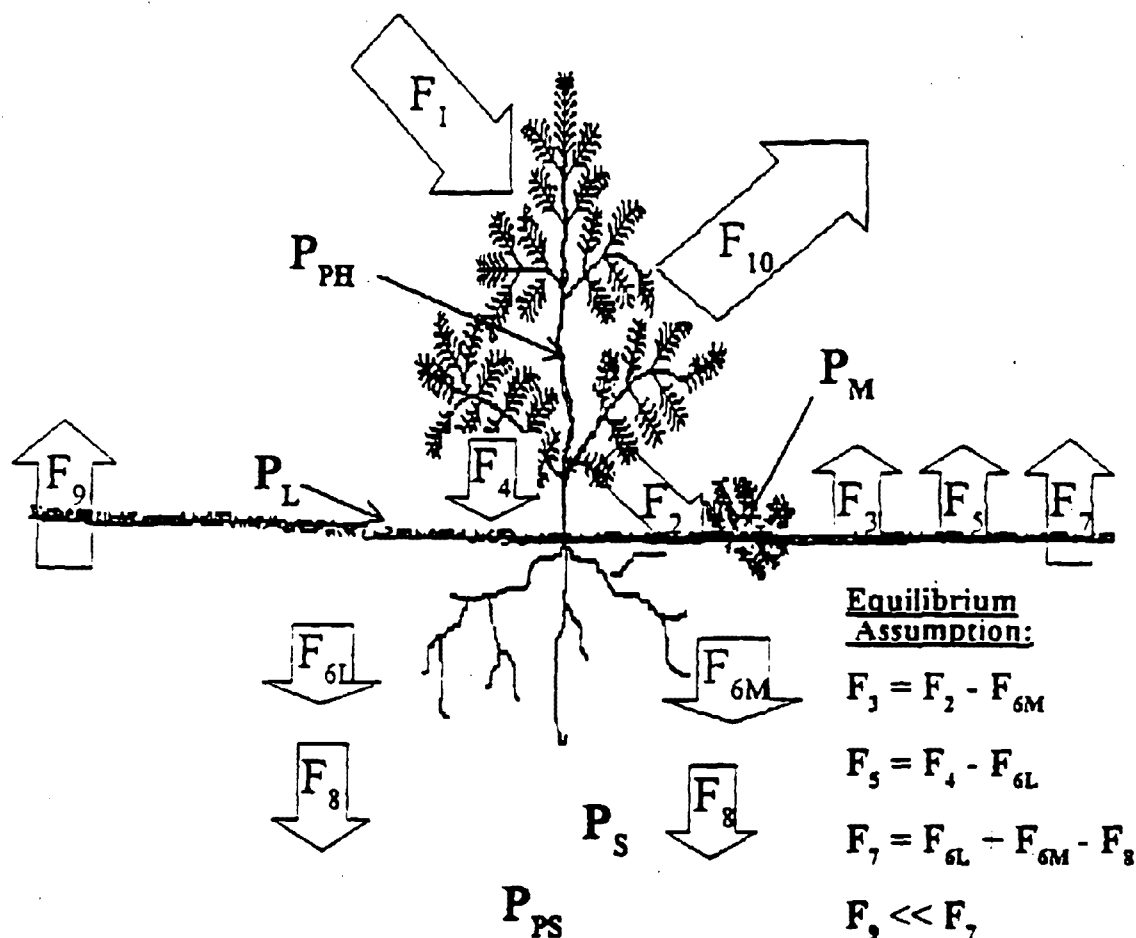
The territory of the FSU is represented by a variety of climate conditions. The major part of the territory is in the temperate climatic zone. The climate in the FSU changes from arctic and subarctic in the North to subtropical and desert in the South. From west to east, the climate makes a transition from maritime to continental to monsoon.

Matthews (19) identified eight principal types of vegetation in her global data base: forest, woodland, shrubland, grassland, tundra, desert, marsh/swamp and cultivated land. The vegetation of the FSU is represented by a variety of formations, including all of these major types. Arctic deserts and tundra formations are found in the northern regions of the FSU; deserts and semi-deserts occur in southern regions. A vast area, the largest of any country in the world, is occupied by forests and grasslands. The total area of forest zone under State supervision (in 1983) is 1,259 million ha (20), which is approximately 56.5 percent of the territory of the country. About 95 percent of the forest area is in Russia. Tundra and boreal forests store a significant amount of organic matter. Twenty-seven percent of the approximately 80 percent of terrestrial organic matter stored in soil is found in boreal ecosystems (21). Grasslands are also an important component of the terrestrial carbon cycle. Despite the fact that grasslands do not accumulate large quantities of plant mass (compared with forest ecosystems), they exhibit high net primary productivity (NPP) and, therefore, may influence the terrestrial carbon cycle.

Peat lands, which are wetlands where peat is accumulating, store a significant amount of carbon. Organic soil carbon content reaches 2,000 t/ha (22). The FSU has the greatest expanse of peat lands in the world (23). Wetlands are known to be a source of methane to the atmosphere (24-26). Although the atmospheric concentration of  $\text{CH}_4$  is much lower than the concentration of  $\text{CO}_2$ ,  $\text{CH}_4$  is 20 times more effective (per molecule) than  $\text{CO}_2$  as a greenhouse gas (27).

### THE NATURAL (BIOGENIC) TERRESTRIAL CARBON CYCLE

The natural (biogenic) terrestrial carbon cycle consists of a combination of carbon pools and fluxes as shown in Figure 1. The pools are carbon stores in soil and vegetation, including living vegetation (i.e., phytomass) and plant detritus (i.e., mortmass and litter). In the present study, the term mortmass was used to describe coarse above-ground and below-ground woody debris. The term litter was used to define the upper soil layer comprised of fine woody debris and leaves that are not completely decomposed. The effluxes



<u>Pools</u>		<u>Influxes</u>		<u>Effluxes</u>	
$P_{PH}$	- Phytomass	$F_1$	- Net Primary Productivity (NPP)	$F_3$	- Mortmass decomposition
$P_M$	- Mortmass	$F_2$	- Mortmass formation (stem, branch, & root detritus)	$F_5$	- Litter decomposition
$P_L$	- Litter	$F_4$	- Foliage formation (i.e. leaf litter fall)	$F_7$	- Unprotected Soil organic matter decomposition
$P_S$	- Soil	$F_{6ML}$	- Total formation of soil organic matter (from mortmass [M] and litter [L])	$F_9$	- Protected soil organic matter decomposition
$P_{PS}$	- Protected soil organic matter	$F_8$	- Formation of protected organic matter	$F_{10}$	- Autotrophic respiration
				$(F_1 + F_{10} = GPP)$	

Figure 1. Natural (biogenic) terrestrial carbon cycle.

are carbon emissions resulting from plant respiration and decomposition of organic matter. The processes of formation of new organic matter in soil and vegetation (i.e., humus and foliage formation) and NPP represent carbon influxes.

The NPP equals the difference between gross photosynthesis (GPP) and respiration of autotrophic organisms ( $R_A$ ). The  $R_A$  amounts to 44 to 52 percent (48 percent on average) (28) of GPP. Root respiration ( $R_{Ar}$ ) comprises one-third of the  $R_A$ . An ecosystem sequesters carbon during a specific phase of development (29). The parameter that characterizes this carbon storage is called net ecosystem productivity (NEP). The NEP equals the difference between NPP and the carbon loss resulting from heterotrophic respiration ( $R_H$ ).

Carbon fluxes can be measured or calculated. However, when carbon effluxes are measured, the contribution from different processes cannot be distinguished. For example, when soil carbon efflux is measured, it is difficult to distinguish between effluxes resulting from  $R_{Ar}$  and  $R_H$  (decomposition of litter, below-ground mortmass and soil organic matter). The quantitative method allows one to separate fluxes.

### METHODOLOGY TO ESTABLISH THE NATURAL (BIOGENIC) CARBON BUDGET

To establish the natural (biogenic) carbon budget, the geographic area within which it was quantified was isolated. The term ecoregion was applied to the boundaries and areal extent of the geographic area. The term ecosystem was applied to the combination of certain soil-vegetation formations within an ecoregion. The concept of an ecosystem is a broad one; its function is to emphasize obligatory relationships and interdependence (29). The term biome was applied to the complex of ecosystems within a climatic belt or subbelt. Nine biomes within the FSU were identified: polar deserts, tundra, forest-tundra/sparse taiga, taiga, mixed-deciduous forests, forest-steppe, steppe, desert-semi-desert and subtropical woodlands.

Two approaches may be used to identify ecoregions, namely, the use of: 1) maps with specific information, and 2) satellite imagery and remote-sensing techniques. A combination of these approaches may also be used. For example, ecoregions identified by map work may be validated with satellite imagery and remote-sensing techniques. At the present time (1991), several maps were used to isolate the ecoregions within which the natural carbon cycle was quantified. In the continuation of the research program, satellite imagery and remote-sensing methods will be used to validate the ecoregions defined for the FSU.

Carbon cycle parameters have been quantified by soil, agricultural and forest scientists, ecologists and botanists for several decades. The carbon cycle parameters may be expressed in terms of carbon content (for pools) or rate (for influxes or effluxes)/ha for a variety of soil-vegetation complexes. If the soil-vegetation complexes are related to the natural attributes identified on maps, which are used to isolate ecoregions, the carbon budget for an ecoregion can be established simply by multiplying the area of the ecoregion (in ha) by the carbon content(s) and flux(es). The carbon contents and fluxes for all the ecoregions may be summed to arrive at the carbon budget for a larger region, biome or nation.

Based on the preceding discussion, the framework shown in Figure 2 was created to assess a natural component of the carbon budget. Initially, maps were used to isolate ecoregions (Frames 1 and 2) and data bases, which contain natural carbon cycle parameters, were compiled (Frame 3). The areal coverage of the ecoregions was integrated with the carbon content and flux data bases to establish the carbon budget within the ecoregion (Frame 4). The organization of the carbon cycle parameter data base, the ha data for the ecoregions and the calculations that were required to establish the carbon budget were performed with personal computer hardware and commercially available spreadsheet software (30) in a Windows™ environment. The carbon budgets for the ecoregions were summed to establish the carbon budget for a biome

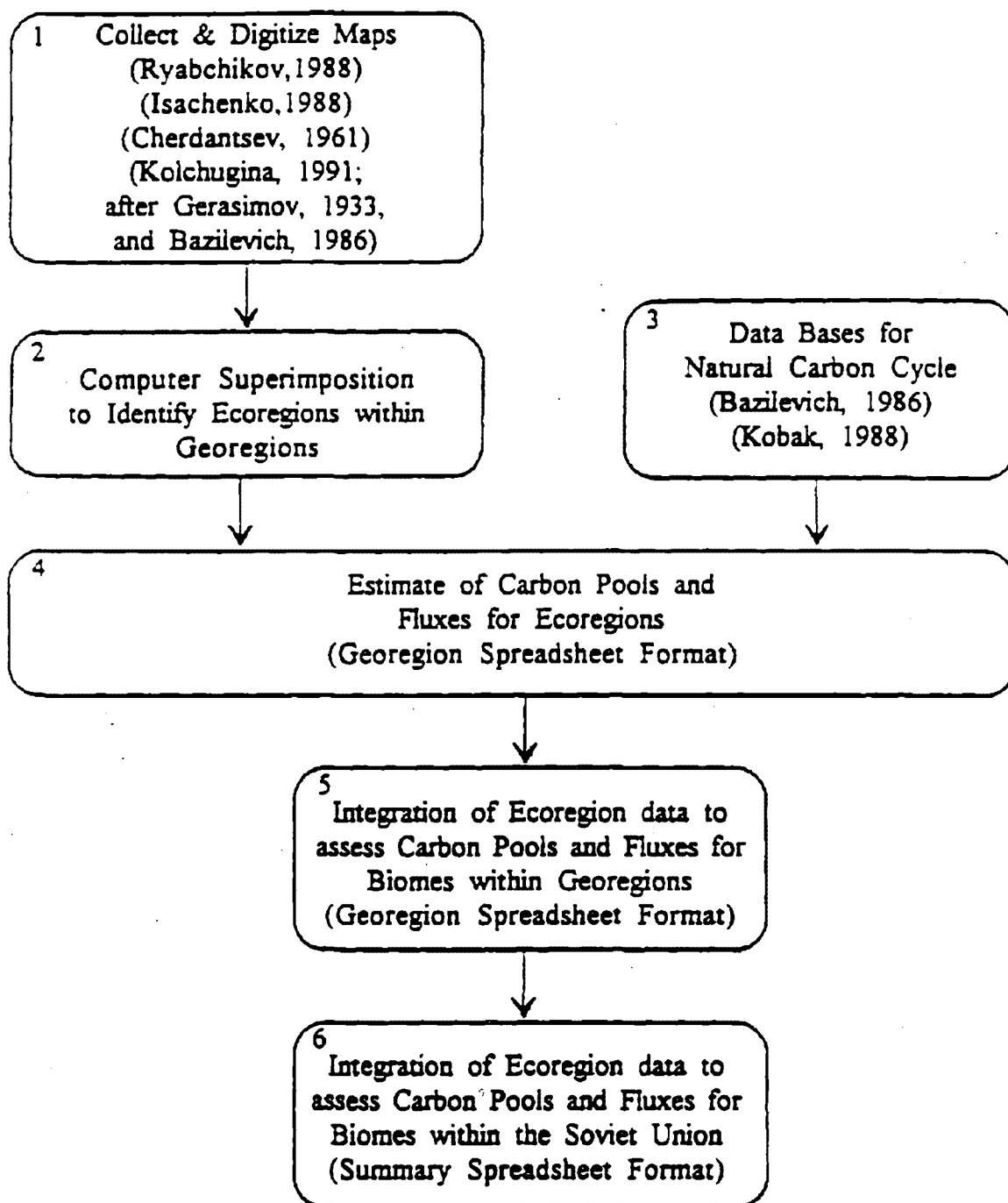


Figure 2. Framework to assess the natural (biogenic) component of the carbon budget



or the entire territory of the FSU (Frames 5 and 6). The specific activities related to the execution of these steps are discussed in the following paragraphs.

#### ISOLATION OF ECOREGIONS (FRAMES 1 AND 2)

About 95 percent of the territory of the FSU, including Russia, Ukraine, Belorussia, Kazakhstan and the Baltic states, was categorized by the soil-vegetation type of the ecosystem, the presence of wetlands and cultivation intensity. Maps containing information on the distribution of zonal soil-vegetation associations within the FSU (31), distribution of wetlands (32) and cultivation intensity of arable lands (33) were digitized and computer-superimposed with a geographical information system (GIS) (34). The map with the distribution of soil-vegetation associations (31) provided the basis for ecoregion isolation. In addition, eight georegions (Near Ocean; Eastern, Middle and Western Siberia; Eastern, Central and Western Europe; and Kazakhstan) were defined to accommodate geodependence of carbon accumulation (17,35). These georegions were also mapped, digitized and computer-superimposed with the GIS. After computer superimposition of the four maps noted above, more than 70 ecoregions related to different ecosystems (i.e., soil-vegetation associations) were identified. Wetland, floodplain, mountain ecosystems and arable land were isolated within these ecoregions. The ecosystems presented by Ryabchikov (31) were aggregated into nine biomes.

The map used to isolate wetlands (32) allows one to determine the total area of wetlands, but does not allow different wetland landscapes to be distinguished. There are at least three main classifications of mire systems in the FSU (36). According to the trophic conditions and the developmental stage, mires can be classified as eutrophic, mesotrophic or oligotrophic. According to the hydrological conditions, mires may be divided into minerotrophic (both ground and rain water supply) and ombrotrophic (rain water supply). According to the main layer of plant communities, mires can be divided into moss, graminoid, dwarf-shrub and shrub. Carbon accumulation differs depending on wetland type. Further studies will require the incorporation of maps that would allow one to isolate different types of wetlands. However, for the present, the superimposition of wetland and soil-vegetation maps allowed the determination of wetland type within a given ecosystem and the specification of carbon accumulation parameters.

#### DATA BASES FOR NATURAL CARBON CYCLE PARAMETERS (FRAME 3)

Bazilevich (17) compiled a data base on carbon accumulation in vegetation from studies of 1,500 vegetation complexes in the FSU. The data base is a comprehensive source of information on all vegetation formations in the FSU, namely, 13 polar desert and tundra, 40 forest, 57 grassland, 20 mire ecosystems and more than 50 desert-semidesert formations. These vegetation complexes were correlated to the ecosystems presented by Ryabchikov (31). The data base provides site-specific values for total phytomass content and phytomass productivity for all vegetation formations in the FSU. The data base allows the assessment of phytomass and phytomass increment allocation. Phytomass was categorized as green-assimilating, woody above- (stems and branches) and below-ground (roots and buried stems) parts of plants. Mortmass was categorized as woody above- (dead stems, branches, grass, windfall), and below-ground parts of plants and litter. Productivity of phytomass or NPP was categorized in the same manner as phytomass. The net carbon content of plant mass was assumed to be 50 percent (28). This percentage was used to calculate the net carbon storage and rates of carbon accumulation in vegetation.

Kobak's (28) data base was used to characterize the soil component of the carbon cycle. The data base resulted from the analysis of the published soil data. About 70 different Soviet and foreign sources were included (22,37-40, and others). Soil carbon cycle parameters for more than 40 soil types of polar, boreal and tropical belts represent the averages from the empirical data presented in different sources. However, in some cases, only certain data are taken into account. For example, the Soviet data are used to characterize

the carbon contents of podzol and chernozem soils. The data base includes carbon contents of soil (total and stable portion; in one-meter layer for inorganic soils and in all thickness for the bog organic soils), the annual rate of foliage and humus formation (total and stable portion), and  $\text{CO}_2$  efflux from soils.

Matthews and Fung (41) compiled a data base on methane emissions from natural wetlands. Three sources: 1) vegetation classified according to Matthews (19); 2) soil properties (42); and 3) fractional inundation from a global map survey of Operational Navigation Charts (ONC) are used to assess the global distribution of wetlands. Published data are analyzed to compile 1) typical methane emissions for wetland ecosystem type and 2) length of the active season (24,25,43,44, and others). Data on methane emissions from wetlands (41) were correlated to the data on wetland distribution within the nine biomes in the FSU.

#### CORRELATION OF DATA BASES TO MAPPED ECOSYSTEMS (FRAME 4)

The maps and data bases are not specifically designed for carbon cycle quantification. However, the names of soil-vegetation associations reported by Ryabchikov (31) corresponded well with the descriptions of vegetation formations given by Bazilevich (17) and soil types given by Kobak (28).

#### INTEGRATION OF ECOREGION AREAS AND CARBON DATA BASES (FRAME 5 AND 6)

Carbon pools and fluxes for natural ecosystems in the FSU were estimated by integrating the carbon data bases and the GIS analysis results (hectare data) within commercially available spreadsheet software (30). Productivity of green-assimilating parts of plants was used to characterize the rate of foliage formation. Data on carbon content in bog soils were integrated with ha data on the extent of wetlands within biomes. Low, mean and high estimates were made for each of the eight georegions by summing the contributions from each ecoregion. The carbon pools and influxes for the forest biomes in the FSU were obtained by summing the georegion totals for the nine biomes. Initially it was assumed that 1) natural ecosystems are presently in a state of equilibrium, (NEP) equals 0; 2) forests totally cover the area of ecosystems (excluding arable land) within forest-tundra/sparse taiga, taiga and mixed-deciduous forest biomes; and 3) forests occupy one-half of the area (excluding arable land) of the forest-steppe biome.

Carbon effluxes were calculated from the influxes assuming that all ecosystems were initially in an equilibrium state (NPP equal to  $R_H$ ). Mortmass decomposition was assumed to be equal to mortmass production. In turn, mortmass production was assumed to be equal to phytomass production (NPP and production of different parts of plants). Carbon efflux from litter decomposition was calculated as the difference between foliage formation (green-assimilating parts production) and the sum of total humus formation and peat accumulation. Carbon effluxes from soil organic matter decomposition were calculated as the difference between total and stable humus formation. Carbon efflux from  $R_{Ar}$  was calculated from the NPP, assuming that  $R_{Ar}$  comprises one-third of the total  $R_A$ , and  $R_A$  comprises 48 percent (on average) of the GPP; NPP equals the difference between GPP and  $R_A$ . The sum of  $R_{Ar}$  and  $R_H$  (below-ground mortmass, litter, and soil organic matter decomposition) may be compared with field measurements of the surface soil carbon efflux (28).

The estimates of carbon cycle parameters obtained in the present study were validated, where possible, with the help of other data bases. The global data base for the NPP of terrestrial ecosystems, compiled with the help of advanced very high resolution radiometer (AVHRR) data (45), was incorporated in the study. The NPP for natural (non-arable) ecosystems was calculated by dividing NPP totals for the ecoregion by the total number of ha and multiplying by the number of ha of natural ecosystems within the ecoregion.

## CARBON POOLS AND FLUXES IN THE FSU ... EXAMPLE RESULTS

The vegetation carbon pool of natural ecosystems in the FSU was estimated at  $118.1 \pm 28.5$  GT. The vegetation carbon pool included phytomass ( $91.0 \pm 22.0$  GT) and mortmass ( $27.1 \pm 6.5$  GT). The litter carbon pool was estimated at  $18.9 \pm 4.4$  GT. The soil carbon pool was estimated at  $404.0 \pm 38.0$  GT (including peat), with  $269.0 \pm 25.0$  in the stable form. Peatlands accumulated  $148.0$  GT C.

The total productivity of phytomass of the nine biomes was estimated at  $6.2 \pm 1.7$  GT C/yr. The productivity of green assimilating parts based on Bazilevich's (17) data was estimated at  $2.5 \pm 0.6$  GT C/yr. Humus formation was estimated at  $257.0 \pm 94.0$  MT ( $10^6$  t) C/yr ( $87.8 \pm 15.1$  MT C/yr in stable form). Methane production in peat lands was estimated at  $7.6 \pm 1.6$  MT C/yr. FSU biomes may be arranged in four groups based on the distribution of biomass (phytomass and mortmass): 1) polar-desert biome; 2) tundra and forest-tundra/sparse taiga biomes; 3) taiga, mixed-deciduous forest, forest-steppe and subtropical woodlands biomes; and 4) steppe and desert-semidesert biomes.

In the polar desert biome, mortmass was greater than phytomass and was distributed equally above and below ground. Above-ground phytomass was significantly greater than below-ground phytomass. In the tundra and the forest-tundra/sparse-taiga biomes, mortmass also exceeded phytomass. In the tundra biome, below-ground biomass was more developed. In the forest-tundra/sparse-taiga biome, phytomass and mortmass were distributed in equal proportions above and below ground.

In the forest biomes, phytomass was greater than mortmass. Above-ground parts were greater than below ground parts in both pools. Below-ground phytomass was approximately the same as above-ground mortmass. In the steppe and desert-semidesert biomes, phytomass and mortmass did not differ substantially. Below-ground parts were greater than above-ground parts in both pools. In the steppe biome, above-ground mortmass was greater than above-ground phytomass, while in the desert-semidesert biome, more living parts of plants were found above-ground.

The NPP of natural ecosystems estimated with the data base from Fung et al. (45) was compared with the estimate of phytomass productivity based on data given by Bazilevich (17). Total phytomass productivity ( $6.2$  GT C/yr) estimated from Bazilevich (17) was about 2.2 times higher than NPP ( $3.0$  GT C/yr) obtained from Fung et al. (45) (the polar desert biome represented one exception: NPP obtained from Fung et al. (45) was greater than phytomass productivity obtained from Bazilevich (17)). The NPP obtained from Fung et al. (45) corresponded well only with the productivity of green-assimilating parts given by Bazilevich (17). The discrepancy may be due to the fact that either root productivity or both root and above-ground woody phytomass productivity are underestimated by Fung et al. (45). Further, a discrepancy in the results could be related to the use of different methods to identify carbon-quantifiable regions. The rate of foliage formation estimated from Kobak's (28) data was  $3.6 \pm 0.6$  GT C/yr. The value was slightly greater than estimates based on data from Bazilevich (17).

The carbon efflux from the litter decomposition estimated from the equilibrium analysis was  $2.3$  GT/yr. Soil organic matter decomposition was  $0.2$  GT C/yr. The  $R_{A_r}$  was estimated at  $1.8$  GT C/yr. Below-ground mortmass decomposition was estimated at  $2.5$  GT C/yr.

The carbon efflux resulting from litter and soil organic matter decomposition ( $2.4$  GT C/yr) was less than the soil surface  $\text{CO}_2$  efflux ( $3.6 \pm 1.1$  GT C/yr) estimated for the nine biomes based on data reported by Kobak (28). The aggregated efflux from  $R_{A_r}$  and average efflux resulting from the decomposition of

below-ground mortmass, litter, and soil organic matter was estimated at 6.7 GT C/yr. This figure was 30 percent greater than the maximum CO<sub>2</sub> efflux (4.7 GT C/yr) estimated from Kobak's (28) data.

Based on Avogadro's number ( $6.028 \times 10^{23}$  molecules in a mole), methane emissions from peat lands were equivalent to  $3.8 \times 10^{35}$  molecules of CH<sub>4</sub>. The total efflux from below-ground mortmass, litter and soil organic matter decomposition was equivalent to  $3,437 \times 10^{35}$  molecules of CO<sub>2</sub>. Assuming CH<sub>4</sub> is 20-fold more active than CO<sub>2</sub> as a green-house gas, methane emissions represented approximately 2.2 percent of the soil surface efflux estimated in the present study.

#### AGRICULTURAL MANAGEMENT OPTIONS TO CONSERVE AND SEQUESTER CARBON

The cultivated area of the FSU was 211.5 million hectares in 1988 (46). This huge area is nearly twice the cultivated area of the United States. Clearly, the agricultural sector of the FSU may play a significant role in the global carbon cycle. The following technical management options to conserve and sequester carbon in the agricultural sector of the FSU have been identified by Gaston, et al. (47) and Rozhkov (48):

- Conservation tillage slows the loss of soil carbon by reducing erosion and by decreasing soil temperature and increasing soil moisture, thus reducing the oxidation of carbon. In substantial areas of the FSU, cold temperatures and high soil moisture may limit the use of this option.
- The addition of organic wastes has been shown to increase soil organic carbon (49). The potential to realize this option is related to the geographic distribution of livestock and current efficiency in returning manure to the soil.
- Cover cropping (or green manuring) improves soil structure and increases organic carbon content (50). Data which would allow the increase in carbon content by soil type and crop type is not available.
- The benefits of agroforestry (i.e., integrating trees with agricultural lands) are widely recognized. In the dry, windy conditions of the southern FSU the planting of tree belts (shelter belts) or hedges would enhance agricultural production, reduced soil erosion and, therefore, result in the direct sequestration of carbon.

#### FORESTRY MANAGEMENT OPTIONS TO CONSERVE AND SEQUESTER CARBON

A. Shwidenko (51) and Krankina, et. al. (52) have identified several management options that may increase the carbon storage or reduce the carbon source of forest ecosystems in the FSU, as follows:

- Reforestation of 95 million hectares of unforested area of the State Forest Fund (from 145 million hectares theoretically available for reforestation)
- Increased fire control and prevention would substantially reduce the 30 thousand forest fires which occur annually within the FSU. If the extent of forest fires could be decreased by 50 percent, a substantial amount of carbon would be sequestered.

- Enhanced forest productivity could be achieved mainly by reconstruction of low-stocked stands, partial replacement of deciduous stands with long-living coniferous, and replacement of climax stands.
- Enhanced disease and pest control includes the decrease and subsequent elimination of pests and diseased areas that presently comprise three million hectares, removal and selective cutting of dead and sick trees, etc.
- Reconstruction of the forest-industrial sector includes mainly a transition to ecologically-protective methods of wood harvesting that would allow rapid regeneration of forest stands, and an increase in efficiency of wood utilization from 50 (present assessment) to 70 percent.
- Increase in stand harvest age of main cuttings in the European part of the FSU is potentially interesting, theoretically realistic, and would result in substantial additional sequestration of carbon. However, high wood demand in the FSU and other countries might prevent the implementation of this option.

These options will depend on the forest policy of the republics of the FSU. To assess the additional amount of carbon that may be sequestered by implementation of these management options the trends in national forest policy should be known together with forest statistical data which reflects existing management practices for Soviet forests. Forest statistical data are available in the Forest Fund of the USSR (53).

## SUMMARY AND CONCLUSIONS

A framework was created to quantify carbon pools and fluxes in the FSU at the ecosystem, biome, georegional or national scales. The organization of the carbon cycle parameter and georeferenced data base which support the framework and the calculations which are required to establish the carbon budget are performed with personal computer hardware and commercially available spreadsheet software. The components of the biogenic carbon budget obtained with the framework were in good agreement with estimates from other published sources. The greatest advantage of the framework is that all elements identified may be easily updated and the carbon budget can be recalculated immediately thereafter. Sensitivity analyses may also be performed with the model. The framework will allow the role of the FSU in the global carbon cycle to be assessed. The extent of forest and agricultural ecosystems within the FSU that can be technically managed on a sustainable basis to conserve and sequester carbon may also be determined with the framework.

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# **HOUSEHOLD FUELS IN DEVELOPING COUNTRIES: GLOBAL WARMING, HEALTH, AND ENERGY IMPLICATIONS**

by

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## **ABSTRACT**

Although individually small, the widespread and daily use of household stoves with poor combustion efficiency in developing countries raises questions about possible global warming and other environmental implications of their airborne emissions. To explore the possible utility of efforts to measure the emissions from representative samples of these devices, a small pilot study of greenhouse gas emissions of biomass and fossil-fuel stoves was undertaken in Manila<sup>1</sup> (Smith et al., 1992a&b). The results, although based on only a few measurements, indicate that such stoves may have a significant role in global greenhouse gas inventories; be subject to substantial improvement through alternative technologies; and that policy measures should consider energy and health implications as well. As a consequence, a larger set of studies is being planned for India, China, Thailand, and Brazil.

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<sup>1</sup>Organized by the East-West Center, households were selected as part of a study of urban energy and air pollution funded by the International Development Research Center, Ottawa; physical sampling, laboratory analyses, and data reporting were supported by the U.S. Environmental Protection Agency; and additional data analysis and evaluation were funded by the Energy Sector Management Assistance Program, World Bank, and the United Nations Development Program. Collaborators included the College of Engineering of the University of the Philippines, the Oregon Graduate Institute, and Lawrence Berkeley Laboratory of the University of California. We greatly appreciate the contributions and suggestions of our colleagues in these institutions (Smith et al., 1992b).

## INTRODUCTION

It has been said that wood is the fuel that heats you twice, once when you chop it and again when you burn it. Like fossil fuels, however, biofuels also have the potential to heat you a third time as a result of enhanced greenhouse warming due to the gases released by combustion. It has generally been assumed that this potential is realized only when the biomass being burned is harvested on a non-sustainable basis. With sustainable harvesting, it is argued, an equivalent amount of carbon is recaptured by the regrowing biomass as released by combustion. Thus, the net greenhouse gas increment is zero. Even when this is true with regard to the number of carbon atoms, however, it may not be with regard to their greenhouse equivalence. In particular, photosynthesis captures only carbon dioxide ( $\text{CO}_2$ ) from the atmosphere, but actual biomass combustion emits other carbon-containing materials including molecules other than  $\text{CO}_2$  with atmospheric warming impacts (Levine, 1991).

These products of incomplete combustion (PICs) are also of concern because of their effects on human health. In many parts of the U.S., for example, smoke from wood-fired heating stoves is the principal cause of some types of ambient pollution during much of the year. For the nation as a whole, wood combustion is a major emissions source for some important air pollutants, such as particulates and polycyclic aromatic hydrocarbons.

Most of the world's woodfuel and other forms of biofuel, such as crop residues and animal dung, however, are burned not in metal heating stoves in developed countries, but in simple open cookstoves in developing countries. Approximately half the households in the world cook in this fashion. Measurements in village homes throughout the world have shown that health-impairing concentrations of PICs are often encountered where people use wood or other biomass for cooking or heating under poorly ventilated conditions (Smith, 1987).

These same PICs also represent lost energy and contribute to the low engineering efficiency with which meals are cooked in much of the developing world (Baldwin, 1987). This in turn increases pressure on biomass resources, which, along with land clearing and other factors, has been associated with deforestation and accompanying environmental problems in some areas.

The apparent opportunity for decreasing forest-stressing biofuel demand as well as reducing health-threatening smoke exposures has lured many local, national, and international organizations, both government and private, into programs to disseminate improved biomass stoves in poor countries. Although there have been major successes, such as the Chinese national improved stoves program, which has reached more than half the nation's rural households (>100 million stoves), only in recent years has the percentage of success been high for such programs (Barnes et al., 1992).

Recently, rising concerns about global warming from the buildup of  $\text{CO}_2$ , methane ( $\text{CH}_4$ ), and other greenhouse gases in the atmosphere have focused attention on worldwide biomass combustion. Emitting 2100-4700 Tg carbon/y compared to 5700 Tg C/y from fossil fuels, biomass burning plays important roles in the global carbon cycle (Crutzen & Andreae, 1990). Approaching 1000 Tg C/y, household biofuel, in turn,

accounts for a significant fraction of overall biomass combustion (Meyers & Leach, 1989). A question is thus raised: "Would alterations in household biomass combustion, such as might be brought about by improved stoves, have significant implications for global warming?"

This question can be divided into three parts:

1. At the global (macro) scale, what are the contributions of biomass-burning cookstoves in less-developed countries (here abbreviated BC-LDC) to global inventories of major greenhouse-related emissions?
2. At the project (micro) scale, what are the technical and economic potentials for reducing greenhouse-related emissions by changing BC-LDC technologies?
3. At the policy (meso) scale, what are the health, energy, and global warming implications of various policies affecting BC-LDC?

## THE PILOT STUDY

To explore these issues, it is essential to know the BC-LDC emission factors of all airborne species that have significant implications for energy, health, and global warming. Some of this information is already available, for in the 1980s a number of studies were undertaken to examine the energy efficiency and health implications of biomass stoves, both in developed and developing country situations (Smith, 1987). Although a significant amount of greenhouse-gas research has gone into studies of developing-country biomass burning at large scale (forest fires, swidden agriculture, savannah burning, etc.), however, relatively little attention has focused on the type of small-scale combustion found in BC-LDC (Levine, 1991).

Before attempting to fill this gap by embarking on a large-scale study of BC-LDC greenhouse-related emissions, we and our colleagues decided to conduct first a relatively small pilot study. This could serve the double purpose of:

- a. exploring whether the results were of sufficient interest to warrant conducting a larger study; and
- b. field testing some of the sampling and analysis techniques that might be used in the larger study.

With these goals in mind, a small study of cookstoves in Manila was undertaken. Monitored were emissions of more than 80 greenhouse-related and health-related gases (mostly non-methane hydrocarbons, NMHCs) from traditional cookstoves burning wood, charcoal, kerosene, and liquefied petroleum gas (LPG), which together account for the majority of all cooking in developing countries. Involving only a few stove/fuel combinations in each category, it is not possible to draw statistically valid global conclusions from this pilot study. Nevertheless, the measurements are quite suggestive, illustrating how more detailed studies of this type could be useful in answering the three questions posed above.

Table 1 summarizes the results of the sampling and analyses in terms of emission factors, grams of pollutant per kilogram of fuel for each of the major PICs<sup>2</sup>. The few data points argue that these results must be seen as tentative, until they can be verified at larger scale. Fuels are presented in order of increasing health effects and decreasing fuel carbon content.

TABLE 1. EMISSION FACTORS, GRAMS PER KILOGRAM DRY FUEL

	n	Fuel Carbon Content	CO <sub>2</sub>	CO	CH <sub>4</sub>	TNMOC	TSP
LPG	2	0.87	3190	25	0.01	3	0.10
Kerosene	7	0.86	3050	39	0.90	14	3.00
Charcoal	6	0.80	2570	210	7.80	4	1.70
Wood	9	0.50	1620	99	9.00	12	2.00

n = Number of data points.

TNMOC (Total Non-Methane Organic Compounds): Per carbon molecular weight taken as 18.

TSP (Total Suspended Particulates): Considered 75% carbon, see footnote 3.

## EVALUATION

A useful way to evaluate both the local and global effects of BC-LDC is to detail their impact on the carbon cycle. Shown as the framework to do so is the carbon flow common to Figures 1-3, which is derived for the composite wood-fired cookstoves in the Manila study. It follows the typical fate of the 500 g of carbon contained in 1.0 kg of wood burned in such stoves. About 88% of the carbon is emitted as CO<sub>2</sub> (weighing 1.6 kg) and the rest (60 g) is distributed as shown in Figures 1-3 among several kinds of PICs, which together weigh about 126 g.<sup>3</sup>

Such a framework allows an examination of this flow in the context of the three most important aspects of the emissions: energy, health, and global warming.

<sup>2</sup>These were determined by taking field samples from the flue stream of each above into stainless steel canisters that were sent back to the U.S. for laboratory analysis. The ratio of each PIC to CO<sub>2</sub> (net of background levels) was used to determine emission factors by taking literature values for the carbon contents of each fuel type and constructing the carbon balance for each stove. Details are found in Smith et al., 1992b.

<sup>3</sup>Particulates were not measured in the pilot study, so data from other studies were used in the figures (Smith, 1987; Joshi et al., 1989; Smith, 1990).

## The Cookstove Energy Cycle

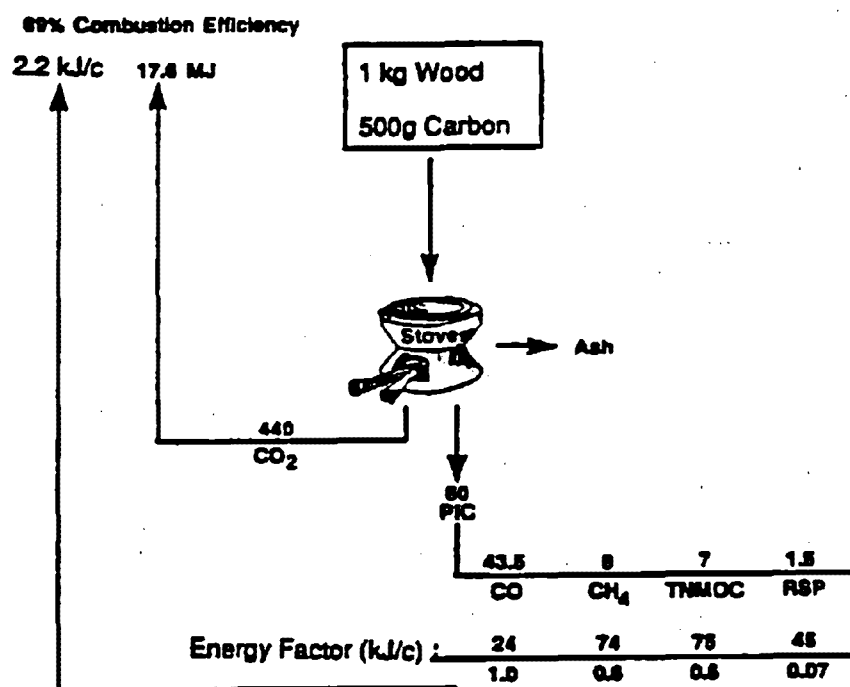


Figure 1. This shows the movement of fuel carbon through a traditional wood-fired cookstove as measured in the Phillippines (Smith et al., 1992a&b). Sixty grams of carbon was not combusted completely; i.e., was released as PICs. Based on the available energy in each PIC, if it had all been combusted completely, another 2.2 MJ would have been released as heat. The stove, therefore, has a combustion efficiency of about 89%. All the numbers refer to grams of carbon alone; e.g., the full mass of CO would be 28/12 (2.33) times larger. Here, total non-methane organic compounds (TNMOCs) are used instead of NMHCs. Respirable suspended particulates (RSPs) are used instead of TSP. Greater than 90% of TSPs are RSPs. NMHCs are about 94% of TNMOCs in this stove. Source of energy contents: Lelieveld & Crutzen (1992).

**Energy** - To put the PICs in an energy context, each constituent needs to be weighted by its energy content; i.e., the additional energy that could have been released if it had been burned all the way to CO<sub>2</sub>. As shown in Figure 1, the result is that the PICs contain about 11% of the energy originally in the wood; i.e., the combustion efficiency is about 89%. In other words, compared to a stove with near 100% combustion efficiency, this stove requires about 12% more fuel (1/0.89).

This inefficiency is part of the reason that traditional stoves use more fuel than it seems they should. The other major technical reason, of course, is low heat transfer efficiency (the fraction of heat released from the fuel that is taken into the cooking utensil).

**Health** - As well as representing an energy loss, the 126g of PICs represent the main health-damaging air pollutants from wood combustion. One way they can be aggregated and compared is by use of the Relative Hazard Index (RHI). This is simply the amount of air it would take to sufficiently dilute each pollutant until it reached the relevant health-based concentration standard (Smith, 1987). With standards as shown, the total RHI of the PICs is about 120,000 m<sup>3</sup>. CO<sub>2</sub> is not much of a health hazard, as shown by the relatively small RHI, 1800 m<sup>3</sup>. (Obviously, application of different standards (e.g., from different countries) would result in different weightings for the pollutants.)

A practical use of these dilution volumes would be to estimate what fraction of the needed dilution might actually be achieved in a typical cooking situation. If, to be generous, a village kitchen is 40 m<sup>3</sup> and its air exchange rate is equivalent to about 25 air changes per hour (Smith, 1987), the kitchen has access to about 1000 m<sup>3</sup> of dilution air each hour. A typical burn rate for a woodstove is about 1 kg/h, producing each hour the amount of PICs shown in Figure 2. Even in this fairly well-ventilated situation, the available dilution air would seem to be far below (40-70 times) what is needed to keep total non-methane organic compounds (TNMOCs)<sup>4</sup> and respirable suspended particulate (RSP) concentrations from exceeding the standards (the latter being more important for health), a prediction consistent with many village measurements in developing countries. In fact, it is not uncommon for indoor concentrations to reach 100 times the standard for RSP during cooking (Pandey et al., 1989; Smith & Ahuja, 1990).

Two of the PIC categories shown (TNMOC and RSP) are composites containing a vast array of mostly organic chemicals. Many of these individually are known to be health-threatening (e.g., benzene in TNMOC and polyaromatic hydrocarbons in RSP). Thus, if RHIs were calculated for each in turn, the total would be much larger than the RHIs for the general categories.

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<sup>4</sup>Strictly speaking, TNMOC is the appropriate category for following carbon flows and NMHC for global warming implications. Since they are both about equal in size (NMHC are about 93% of TNMOCs in this stove), however, we have not tried to maintain the distinction throughout the text.

## The Cookstove Health Cycle

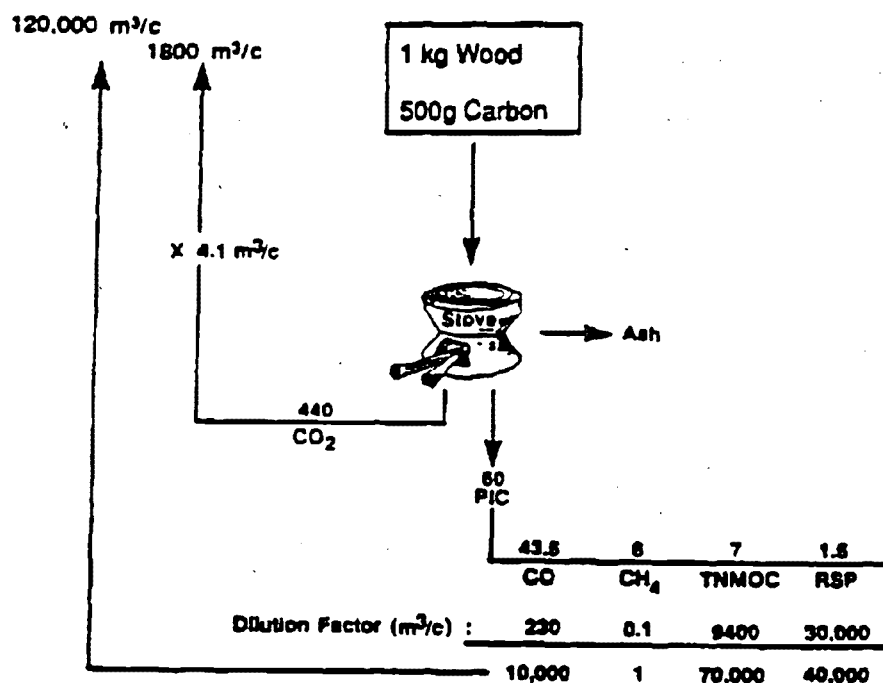


Figure 2. Starting with the same fuel carbon flows as Figure 1, this figure weights the PICs not on the basis of energy, but on the basis of how many cubic meters of air would be necessary to dilute the emission to meet U.S. air pollution standards. Where there is only an occupational standard, an appropriate safety factor (10) has been used to establish a public standard. The following standards were used (in mg/m³): CO<sub>2</sub>=900; CO=10; CH<sub>4</sub>=11,000 (asphyxiation); NMHC=0.16; RSP=0.05. The dilution factors shown in the figure are on a per-carbon-atom basis. Although the NMHC standard was actually set to prevent the formation of ozone, it represents a much less stringent standard than would be applied if certain individual hydrocarbons were used as the basis of the dilution factor. The benzene in NMHC from these woodstoves, for example, would require 40 times more dilution than shown.

**Global Warming** - Figure 3 evaluates the same PICs in terms of their greenhouse gas potential. To do this, it is necessary to apply some index so that the impacts of the different gases can be combined (Smith & Ahuja, 1990). This is so because the gases have different heat-trapping abilities, lifetimes, and interactions with other gases in the atmosphere. Here, we have used the Global Warming Potentials (GWPs) developed by the Intergovernmental Panel on Climate Change (IPCC, 1990; Smith et al., 1991). These are given as a ratio to CO<sub>2</sub> (either per molecule or per carbon atom), and thus can be interpreted as the degree to which the total warming of each compares to CO<sub>2</sub>. Since the gases have different atmospheric lifetimes, the relative impact (GWP) depends on the chosen time horizon. Shown here are the results for time horizons of 20 and 100 years. In general, shorter time horizons make the non-CO<sub>2</sub> gases look more important relative to CO<sub>2</sub>, since CO<sub>2</sub> is the longest lived of this group.<sup>5</sup>

The result is that, depending on the time horizon chosen, the non-CO<sub>2</sub> GGs (i.e., the PICs) have a total GWP 20-110% as much as the CO<sub>2</sub> itself. This implies that looking only at the CO<sub>2</sub> emissions of cookstoves may not give a good picture of their global warming implications. It also implies that improvements in combustion efficiency could result in much larger reductions in total GWP than would be indicated simply by changes in CO<sub>2</sub> emissions.

**Biomass-Stove PICs - Relative Weights.** From all three perspectives, energy, health, and global warming, PICs are to be avoided. As shown in Table 2, however, the three perspectives do not weight the individual PICs in the same way relative to one another. Note that the weights are much more skewed for the health column than the others; i.e., a factor of 41 between NMOC and CO, down by an additional factor of 230 to the minor hazard of CO<sub>2</sub>, and then another factor of 10 down to the insignificant health hazard of CH<sub>4</sub>. Both the energy and global warming viewpoints, in contrast, hold CH<sub>4</sub> and TNMOC to have similar relative weights, and none of the differences are as large as for health.

## GLOBAL IMPACTS

Using these preliminary data, it is instructive to note how large BC-LDCs might appear to loom in the global picture for each perspective.

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<sup>5</sup>These GWPs are not known with certainty and changes can be expected as knowledge improves. Indeed, in its 1992 supplement, the IPCC (IPCC, 1992) suggested that indirect effects (chemical interactions affecting other greenhouse gases) of the non-CO<sub>2</sub> gases were not well enough known to be used in policy discussions; i.e., the values for the CH<sub>4</sub> GWP would decrease to 13, 4, and 1.5 (by time horizon) and those for CO and NMHC would be 1.0 at all times. The report states, however, that "(t)he carbon cycle model used in these calculations probably underestimates both the direct and indirect GWP values for all non-CO<sub>2</sub> gases." Given this caveat and that our purpose here is principally illustrative, we have not modified the GWPs from those recommended originally by the IPCC (IPCC, 1990). We have, however, used the updated estimates for the total effects of CH<sub>4</sub> as presented by Lelieveld & Crutzen (1992).



## The Cookstove Carbon Cycle

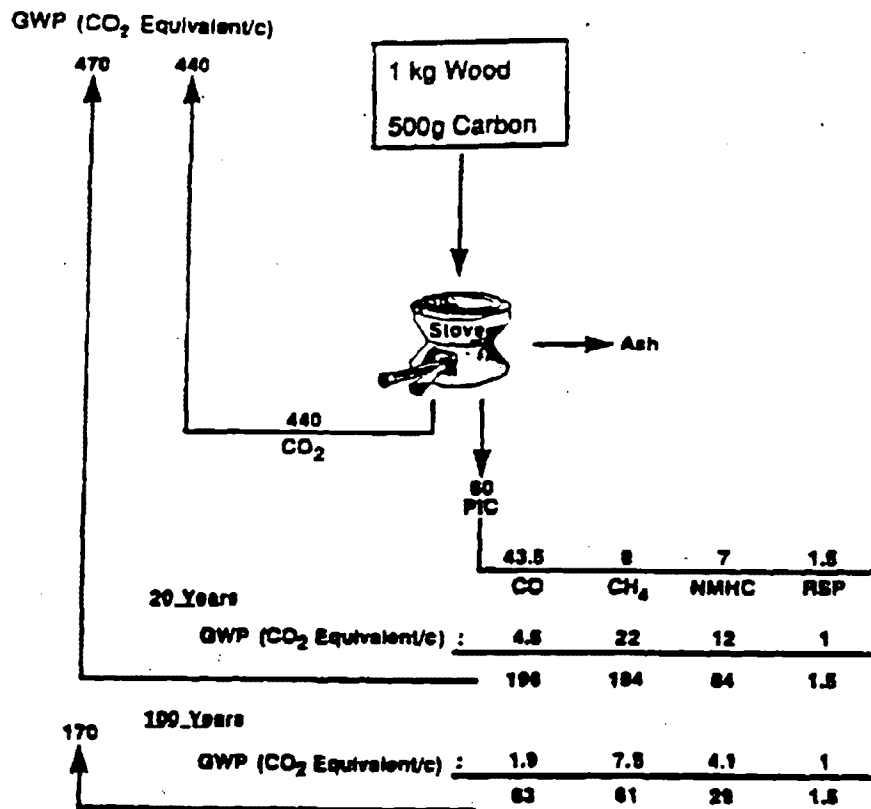


Figure 3. The same carbon balance for the woodstove is shown as in Figures 1 and 2. In this case, the PICs are weighted by the Global Warming Potentials (GWPs) appropriate for 20-year and 100-year time horizons. Note that the PIC GWP is about equal to that of the CO<sub>2</sub> for a 20-year time horizon. Sources: Smith et al. (1992a&b); Smith et al. (1991); IPCC (1992); Lelieveld & Crutzen (1992); Joshi et al. (1989).

TABLE 2. RELATIVE IMPORTANCE FOR PICs  
UNDER DIFFERENT REGIMES

	Energy	Health	Global Warming Index Time Horizon (years)		
			20	100	500
CO <sub>2</sub>	1.0	1	1.0	1.0	1.0
CO	0.8	230	4.5	1.9	1.3
CH <sub>4</sub>	1.6	0	22.0	7.5	3.2
NMHC	1.8	9400	12.0	4.1	2.3
RSP	1.3	30000	1.0	1.0	1.0

All values are shown relative to CO<sub>2</sub> on a carbon basis; i.e., NMHC is 9,400 times worse than CO<sub>2</sub> for health.

Sources: GWPs from IPCC (1990); Smith et al. (1991) as corrected by Lelieveld & Crutzen (1992). Energy data from Culp (1979).

### Energy

Although humans in some way utilize perhaps 40% of world net biomass production (Vitousek et al., 1986), as shown in Table 3, that proportion used directly for fuel accounts for only about 15% of direct human energy use. Even so, biofuel in the form of wood, crop residues, brush, and animal dung, is today still the chief form of energy for most humanity, just as it has been since the discovery of fire (Hall & Rosillo-Calle, 1991). In developing countries, biofuels constitute about 35% of total energy use, and in rural areas of developing countries, some 75%. In the poorest developing countries, however, biomass fuels make up 80-90% of all energy use (Smith, 1987). Based on the pilot study, therefore, the loss of energy represented by the PICs from BC-LDC is roughly 1% of total human energy use and could approach 10% for some countries.

### Health

In the case of health, particulate exposures from biomass use could be responsible for approximately 50% of the total global human exposure. Most of this occurs indoors in rural areas of developing countries, although there are significant exposures in cities and outdoors as well. The vast preponderance of research, regulation, and control of particulate air pollution is still focused on urban outdoor developed-country situations, which, however, account for rather a small overall fraction of global exposures (Smith, 1988).

TABLE 3. GLOBAL IMPORTANCE OF PIC FROM BIOMASS-FIRED COOKSTOVES

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**Energy**

Biomass makes up about 14% of all direct human energy use.  
It is about 33% of energy use in developing countries.  
It is about 75% of energy use in rural areas of developing countries.  
It is the most important fuel for the majority of humanity.

Sources: Smith (1987); Meyers & Leach (1989); Hall & Rosillo-Calle (1991)

**Health**

Cause of up to 50% of total human exposure to RSP.  
Second largest occupational group, after farm workers (cooks).  
Known risk factor for most important killer of developing-country children (pneumonia).

Sources: Pandey et al. (1989); Smith (1988)

**Global Warming**

Human biofuel consumption: 20-40% of all biomass combustion.  
1-5% of all CH<sub>4</sub> emissions.  
6-14% of all CO emissions.  
8-24% of all NMHC emissions.  
1-3% of all human-generated global warming.

Sources: Smith et al. (1992b); Ahuja (1990)

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These high exposure levels are due not only to high particulate concentrations, but also to the large populations involved. Indeed, after farmworkers, cooks represent the largest occupational group in the world.<sup>6</sup>

It is important to note that the emissions from biomass fuels need not be high compared, for example, to those from coal-fired industrial and power facilities in order for the human exposures to be substantially greater. This is because a much larger proportion of pollution released in household reaches people, compared to that from centralized facilities. The impact per unit emissions tends to be greater for distributed releases, and few things are more distributed than cooking, which occurs in every household, every day.

**Greenhouse Gases** - Based on the few measurements taken in Manila, it would seem possible that biomass stoves could account for fairly significant proportions of global emissions of the three greenhouse gas categories -- CO, CH<sub>4</sub>, and TNMOC (Table 3). For

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<sup>6</sup>These stoves are undoubtedly responsible for a large fraction of global exposures to a range of other pollutants as well; e.g., CO, polycyclic aromatic hydrocarbons, formaldehyde, and benzene.

CO and CH<sub>4</sub>, the percentages in Table 3 translate into contributions to overall global warming from biomass-fired cookstoves of 0.4-0.9% and 0.1-0.5%, respectively. These are in same range as estimated by Ahuja (1990) for all biomass stoves, who also estimates that the overall contribution of biomass stoves to global warming is about 2%. In addition the contribution due to PICs is estimated to account for about 15% of net deforestation and, thus, about 1.5% of net human CO<sub>2</sub> additions to the atmosphere (1.1% of total warming).

## CONTROL MEASURES

Assuming people will continue to need to cook and are well versed in operating their stoves, there are basically two ways to reduce PIC emissions from biomass-fired cookstoves: change the fuel or change the stove. With new information of the kind made available by the Manila study, it is possible to make further judgments about these options.

### Fuel

One objective of household energy policy can be to encourage people to move up the energy ladder sooner than they otherwise might. This can be done through fuel and stove pricing or other ways to make new stove/fuel combinations relatively more attractive. In most parts of the developing world, the first step beyond unprocessed biomass is charcoal or kerosene, followed by LPG. In some areas, Thailand, for example, little kerosene is provided and the first step after charcoal is LPG. In China, it is often coal, followed by LPG. Movement up the ladder generally results in substantially fewer health-damaging PIC (RSP and CO) emissions per meal (Smith, 1990).

With a switch from biomass to fossil fuels, however, a global warming penalty might at first seem inevitable because fossil rather than contemporary carbon would be emitted. Because biomass combustion leads to a high amount of PICs with a large GWP (Figure 3), however, the picture is substantially more complicated.

Based on the pilot study results, consider the benefits of switching from wood to charcoal, kerosene, or LPG as summarized in Table 4.<sup>7</sup> From a health standpoint, a shift from wood to LPG reduces the overall health impact by a factor of 100. Kerosene, on the other hand, results in a reduction by a factor of six. Use of a charcoal stove results in an improvement by more than a factor of four.

From a global warming standpoint, the impact depends on how the biomass is harvested; i.e., whether the CO<sub>2</sub> is recycled. Table 4 shows the range between the extremes; i.e., assuming totally sustainable harvesting and complete deforestation (no regrowth). It is perhaps not surprising that, with complete deforestation, LPG and kerosene are better than wood, 9 and 6 times, respectively. Even with sustainable harvesting, however, because of the significant amount of PICs released by the woodstove, kerosene and LPG stoves release, respectively, 2.6 and 1.7 times less GWP per meal cooked.

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<sup>7</sup>The values in Table 4 have been derived by taking into account the differences among the stove/fuel combinations in overall cooking efficiency and energy per fuel carbon atom.

TABLE 4. RELATIVE PIC EMISSIONS, HEALTH EFFECTS, AND GLOBAL POTENTIALS OF LPG, KEROSENE, CHARCOAL, IMPROVED BIOMASS, AND WOOD COOKSTOVES

	Stove Eff.	Biofuel Use	CO	CH <sub>4</sub>	TNMOC	RSP	Health	20-YEAR WARMING	
								Deforest	Regrow
LPG	0.70	0.00	0.02	9.30E-05	0.02	0.01	0.01	0.11	0.39
Kerosene	0.50	0.00	0.05	0.01	0.13	0.17	0.16	0.17	0.61
Charcoal	0.30	1.60	0.73	0.30	0.10	0.25	0.22	0.91	0.29
IBC									
wood	0.25	1.60	0.20	0.20	0.20	0.20	0.20	0.20	0.20
outdoor			0.40	0.40	0.40	0.40	0.04	0.40	0.40
Wood	0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Note: Except for the first, all the columns are normalized such that the impact of the traditional wood-fired cookstoves is set to 1.0. Where appropriate, the impacts of the improved wood-fired cookstove with flue are divided between those that occur indoors and outdoors. Elimination of indirect effects for CO and TNMOC (NMHC) as suggested by IPCC (1992) changes the relative magnitudes, but does not change the conclusions that these fossil-fuel cookstoves produce less GWP than this woodstove even with renewable harvesting.

These values are somewhat misleading, however, because they exclude PIC contributions from elsewhere in the fuel cycles for these fuels. The releases at oil fields and refineries for kerosene and LPG, however, are likely to be less than 10% of those at stoves (Smith et al., 1975). For locally harvested wood, they should be even lower, although there may be some wastage during harvesting, transport, and storage.

For charcoal manufacture, however, the contribution is likely to be quite large. Although there are few emissions data from the charcoal kilns commonly used in developing countries, even relatively modern kilns apparently emit rather large amounts of PICs (Foley, 1986). Based on an extrapolation from emissions measurements of a U.S. Missouri kiln (USEPA, 1986) operating at 33% efficiency (mass charcoal/dry wood), Figure 4 shows the possible carbon flow in a kiln operating at 20% efficiency, which is common in developing countries (Foley, 1986; Katyega and Kjeilstrom, 1991). Note that nearly 35% of the carbon in the wood put in the kiln is released as PICs. Thus, the 20-year GWP ratio of PICs/CO<sub>2</sub> for the kiln is about 7.6; i.e., the PICs produce more than seven times as much GWP as the CO<sub>2</sub> (4.8 times the 100-year GWP).

If the 64 million tonnes of wood made into charcoal each year in developing countries (Joshi et al., 1989) was charged to kilns like the one in Figure 4, charcoal making might be responsible for releasing 1.5 Tg/yr of carbon as CH<sub>4</sub>. This source may be significant but direct measurements would help develop reliable estimates for the types of the kilns typically in use.

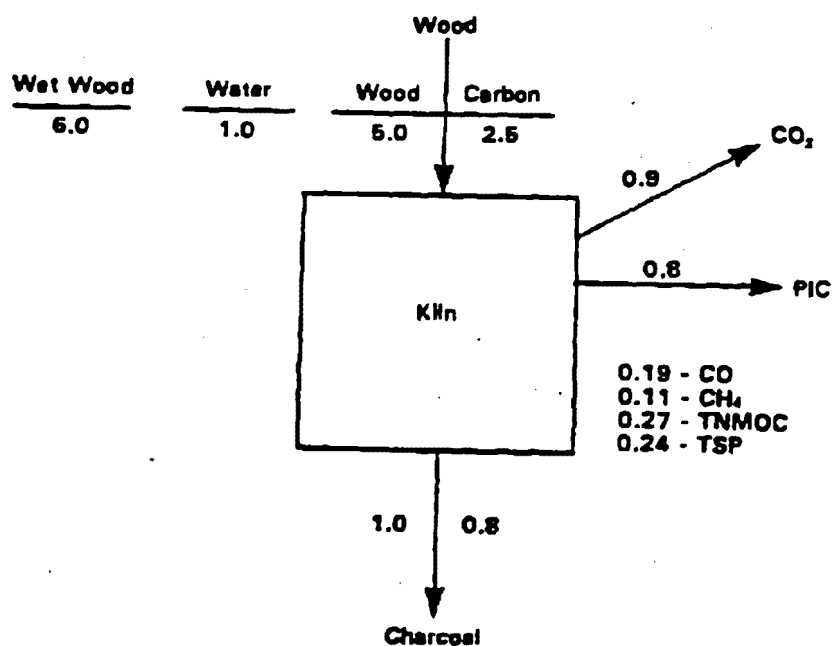


Figure 4. Carbon flows for hypothetical charcoal kiln used in developing countries. Based on measurements reported in U.S. EPA's Compilation of Air Pollutant Emission Factors, 1986 (U.S. EPA, 1986) for a Missouri kiln with 33% production efficiency. This has been modified to a 20% efficient kiln, which is more typical in developing countries, by assuming that the difference in efficiency does not alter the ratio of PICs to CO<sub>2</sub>. TNMOC=total non-methane organic compounds (vapor); TSP=total suspended particulates (aerosol).

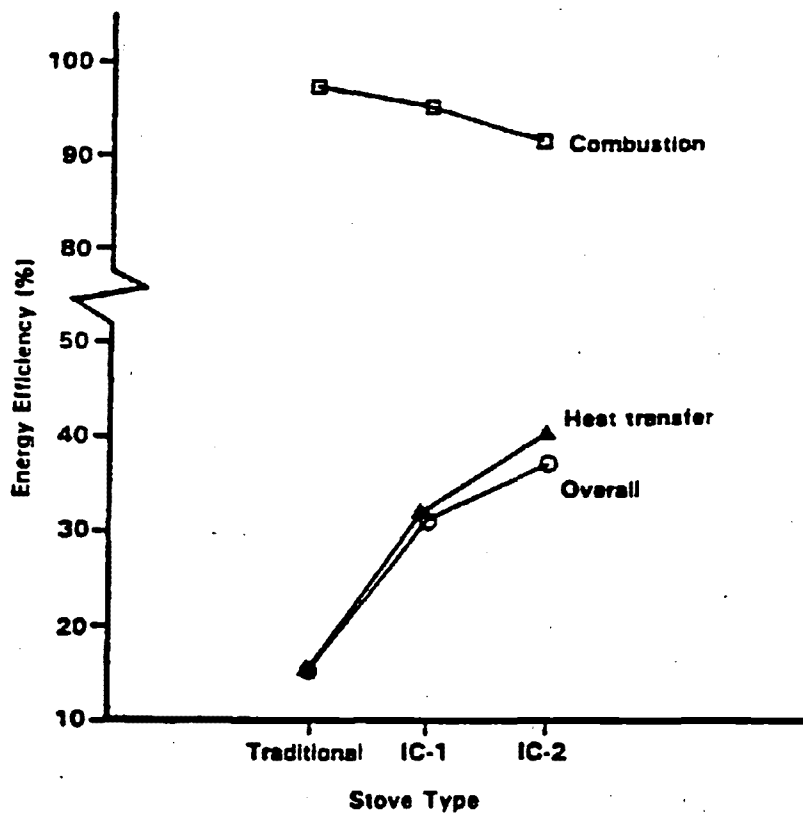


Figure 5. The differences among overall and internal efficiencies in three metal wood-fired cookstoves without flues. Note that, although both improved stoves achieve substantially more overall energy efficiency than the traditional stove, combustion efficiencies are less. Thus, IC-2 produces 4 times more PICs per unit energy delivered than the traditional stove  $(100-92)/(100-98)$ . Thus, though its energy use per meal is 2.5 times less  $(15/40)$ , the overall result is that about 60% more PICs are produced per meal. The original investigators measured only CO and particulates (Joshi et al., 1989). The remaining PICs have been assumed to appear in the same ratios as measured in the Manila pilot study.

## Stoves

The first-level approach to improved biomass cookstoves (IBCs) is shown in Table 4. The IBC uses 40% less fuel and releases about 35% of its PICs into the kitchen, the rest going outdoors where it is assumed to have only 10% as much health impact per gram as emissions released indoors. (These changes are based on results found in field measurements of improved stove programs (Pandey et al., 1990; Ramakrishna et al., 1989; Reid et al., 1986). Improvements measured in the laboratory can be much greater.) Note that, due to lack of data, there is no change considered in global warming impact other than that 40% less fuel is used; i.e., the same fraction of the carbon is released as PICs of the same composition.

To understand how changes in stove design and operation actually affect PIC emissions, it is important to recognize that overall stove efficiency ( $E_t$ ) is a function of two internal efficiencies -- combustion efficiency ( $E_c$ ) (i.e., the amount of chemical energy in the fuel that is converted to heat) and heat-transfer efficiency ( $E_h$ ) (i.e., the amount of heat that reaches the food in a cooking stove or reaches the room in a heating stove):

$$E_t = (E_c) \times (E_h) \quad (1)$$

In general, emissions per meal of PICs and  $\text{CO}_2$  are an inverse function of overall efficiency in that, all else being equal, the less fuel used for a given cooking task, the less PICs will be released. Thus, improvements in fuel efficiency should lead to lower greenhouse gas (GHG) emissions.

Changes in stove operation and design, however, often affect the two internal efficiencies in quite different ways. In particular, thermal transfer efficiency can be increased at the expense of combustion efficiency. Design and operation changes that improve overall fuel utilization, therefore, sometimes actually increase one internal efficiency at the expense of the other.

Although few data are available for biomass cookstoves, Figure 5 illustrates this effect in a study of particulate and CO emissions of one traditional and two improved wood-fired metal cookstoves (Pandey et al., 1989). Overall efficiency rose from 15% to 31% and 37% in the two improved stoves, greatly decreasing potential fuel demand for cooking. In the process, however, PIC emissions per meal actually increased by 8% because combustion efficiency dropped from 97% to 92%.

It might be thought that there is little net GHG impact from changes in combustion efficiency. In other words, the fuel carbon that is not oxidized all the way to  $\text{CO}_2$  will be released as PICs. The smaller the fraction of carbon released as  $\text{CO}_2$ , the more as PICs and vice versa.

In rough terms, this trade-off is true for carbon mass and number of carbon atoms. It may not be true for the net greenhouse impact, however, because these different molecules have different greenhouse impacts. Thus it is necessary to keep track not only of the total carbon emissions but also of their form.



The PICs/CO<sub>2</sub> ratio can vary dramatically even at constant overall efficiency, depending on the relative contribution of heat transfer and combustion efficiencies. CO<sub>2</sub> emissions are in general less dependent than PICs on combustion efficiency. For example, a shift from 90% to 80% combustion efficiency results in a near doubling of PICs but only about 10% less CO<sub>2</sub>. (More dramatically, a change in combustion efficiency from 99% to 98% would result in less than a 1% loss of total efficiency but a near doubling of PICs.)

Since PICs emissions are a stronger function of combustion efficiency than they are of total efficiency, emissions can sometimes increase along with total efficiency. A popular means by which fuel utilization of traditional cookstoves has been raised, regrettably, is simply to reduce airflow by enclosing the fire, thereby greatly increasing the heat transfer efficiency to the pot, but also lowering the combustion efficiency. The end result, therefore, can be a net increase in fuel utilization and a consequent reduction in CO<sub>2</sub> emissions, but a rise in the PICs/CO<sub>2</sub> ratio or even an increase in absolute PIC emissions per cooking task, as shown in Figure 5.

The GHG implications of stove emissions depend strongly not only on the PICs/CO<sub>2</sub> ratio, of course, but also on the particular mixture of PIC molecules. Each mixture will have a different greenhouse equivalence weighting depending on the relative amounts of the different constituents.

The radiatively active PIC molecules, such as CH<sub>4</sub>, and the molecules that play a part in their atmospheric chemistry before turning into CO<sub>2</sub>, such as CO and NMHC, have total (direct and indirect) GWPs above 1.0; i.e., greater than CO<sub>2</sub>. Indeed, it would seem that all organic molecules must have a GWP per carbon atom of at least 1.0 because once released they would relatively soon be oxidized to CO<sub>2</sub>, the rating of which, by definition, is 1.0. Only elemental carbon particles might have a GWP less than 1.0, if they are assumed not to be oxidized within a relevant time period.

Although there do not seem to be sufficient theory or data to predict the exact relationship between design changes and the PICs/CO<sub>2</sub> ratio, we do have rough estimates of typical GWPs of PICs. The PIC GWP of the woodstoves in Manila varied from 1.7 to 7.8, depending on the time horizon.

Thus, efficiency improvements to the Manila woodstove that allowed combustion efficiency to drop in exchange for increased heat-transfer efficiency could actually lead to significant increases in PICs with their health and greenhouse impacts.

Final decisions with regard to fuel and stove changes will of course depend on relative economics and other non-environmental issues (Smith, 1992). Nevertheless, the carbon flow framework made possible by the monitoring data would be a valuable grounding for these further analyses.

## CONCLUSION

Putting aside for the moment the few actual measurements involved, the information available from the Manila pilot study has allowed us to make substantial progress toward answering the three questions posed at the beginning:

1. The contribution to global inventories;
2. Advantages and disadvantages of various technical options (stove/fuel combinations); and
3. Policy implications because of interactions among energy, health, and global warming objectives.

As we indicate above, it would be extremely useful to have sufficient data to resolve the carbon balances of such small combustion devices as stoves. Five characteristics make such devices attractive for this kind of research:

- a. The devices are (or are operated in a way to be) substantially different from those in developed countries, which have been subject to much research already;
- b. They have widely varying, but generally poor, combustion efficiencies, leading to significant amounts of PICs;
- c. Although individually small, they are widely used, leading potentially to emissions significant on the global scale;
- d. There is substantial scope for technical improvement; and
- e. Of interest, although not of direct concern from the standpoint of global warming, they are evenly dispersed with the population, making their PIC emissions more likely to produce ill health.

Stoves fill this bill, as do other ubiquitous combustion devices such as motor vehicles.

Based on these encouraging, but preliminary findings, we are planning to embark on a more extensive study of cooking and heating stoves. This will be undertaken jointly with colleagues in India and China, which not only contain about 65% of the population in developing countries, but where a wide range of stove/fuel combinations are in use. Because of the potentially, but little studied, significance of charcoal kiln emissions, we also plan to study the emissions of a wide range of kilns in Thailand and Brazil.

We also hope to examine more closely a set of greenhouse-gas sources in developing countries that have potential for rather large contributions to global inventories. These are garbage dumps around large cities where not only is there significant anaerobic decay, but also smoldering spontaneous combustion, low-tech incineration, and intentional burning by scavenger communities to recover metals.

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## The Potential for Energy Crops to Reduce Carbon Dioxide Emissions\*

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Energy crops are herbaceous or woody plants grown specifically to produce biomass for combustion and production of electricity or for conversion to fuels such as ethanol. When grown intensively such crops can yield up to 43 dry Mg biomass/ha/yr in the temperate zone although yields of 10 to 20 Mg are more typical.

By substituting sustainably-grown biomass for fossil fuels, CO<sub>2</sub> emissions from energy consumption can be reduced significantly. Although biomass fuels are net emitters of CO<sub>2</sub> because fossil fuels are used in the production of energy crops (e.g., fertilizers, transportation), biomass fuels emit much less CO<sub>2</sub> than fossil fuels per unit of energy produced. A hectare of U.S. farmland on the average could produce sufficient biomass to reduce annual CO<sub>2</sub> emissions by 5 Mg C if such biomass was used to produce electricity that would otherwise be produced with coal.

Within the U.S. there are at least 131 million hectares of farmland that could support energy crop production. Much of this land lies in the midwest although the southeast also contains considerable acreage. More acreage can support herbaceous energy crops than woody crops as there are herbaceous crops that can tolerate drier conditions than any woody crop.

The potential for energy crops to reduce CO<sub>2</sub> emissions will depend on how much land can be profitably dedicated to energy crops. Farmers will adopt energy crops when it is economically advantageous for them to do so. Power companies will adopt biomass energy when the cost of energy from fossil fuels exceeds the cost of energy from biomass. Government policies and regulations affect both these relationships. Currently biomass crops must compete with subsidized agricultural crops thereby inflating the price of biomass to an energy facility. On the other hand, pollution regulations can favor energy crops as a fuel source since biomass crops can burn cleaner than coal.

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(NOTICE: Although the following paper was not presented at the Symposium, it was provided by principal author Graham as being equivalent to the presentation made there and representative of the related research.)

THE POTENTIAL FOR SHORT-ROTATION WOODY CROPS  
TO REDUCE U.S. CO<sub>2</sub> EMISSIONS\*

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## Abstract

Short-rotation woody crops (SRWC) could potentially displace fossil fuels and thus mitigate CO<sub>2</sub> buildup in the atmosphere. To determine how much fossil fuel SRWC might displace in the United States and what the associated fossil carbon savings might be, a series of assumptions must be made. These assumptions concern the net SRWC biomass yields per hectare (after losses); the amount of suitable land dedicated to SRWC production; wood conversion efficiencies to electricity or liquid fuels; the energy substitution properties of various fuels; and the amount of fossil fuel used in growing, harvesting, transporting, and converting SRWC biomass. Assuming the current climate, present production, and conversion technologies and considering a conservative estimate of the U.S. land base available for SRWC ( $14 \times 10^6$  ha), we calculate that SRWC energy could displace  $33.2$  to  $73.1 \times 10^6$  Mg of fossil carbon releases, 3-6% of the current annual U.S. emissions. The carbon mitigation potential per unit of land is larger with the substitution of SRWC for coal-based electricity production than for the substitution of SRWC-derived ethanol for gasoline. Assuming current climate, predicted conversion technology advancements, an optimistic estimate of the U.S. land base available for SRWC ( $28 \times 10^6$  ha), and an optimistic average estimate of net SRWC yields (22.4 dry Mg/ha), we calculate that SRWC energy could displace  $148$  to  $242 \times 10^6$  Mg of annual fossil fuel carbon releases. Under this scenario, the carbon mitigation potential of SRWC-based electricity production would be equivalent to about 4.4% of current global fossil fuel emissions and 20% of current U.S. fossil fuel emissions.

## Introduction

Biomass energy is one of several renewable energy sources that could be used to displace fossil fuel energy and thus reduce fossil fuel CO<sub>2</sub> emissions to the atmosphere. Among the renewable energy technologies, biomass is unique in that it can be a source of not only electricity but also liquid or gaseous fuels. Thus biomass energy is the one renewable energy source that can directly displace such petroleum products as gasoline and diesel fuel.

Renewable biomass feedstock can come from either herbaceous or woody crops. In this paper we will focus on wood feedstocks and in particular wood from tree crops grown under short rotations (4-12 years) in an agricultural production system hereafter referred to as short-rotation woody crops (SRWC). SRWC have been promoted as a possible source of significant amounts of renewable woody feedstock and a technology that could offer landowners an attractive alternative use (rather than food production) for marginal to good cropland.

The objective of this paper is to estimate the potential for SRWC technology to reduce the U.S. CO<sub>2</sub> emissions in view of both current and future technologies. To make this estimation, a series of linked questions must be addressed. First, how much SRWC energy feedstock could be produced annually in the United States? Second, how much electricity or fuel could that feedstock produce? Third, how much fossil fuel could that wood-derived electricity or fuel displace? Fourth and finally, what would be the net carbon mitigation benefit to the atmosphere of that displacement? The links among these questions are outlined in the following equations.



Amount of feedstock =

$f_1(\text{number of hectares, yield/ha, harvest \& storage losses})$

Energy produced =

$f_2(\text{amount of feedstock, conversion efficiency})$

Fossil fuel carbon displaced =

$f_3(\text{energy produced, fuel substitution properties, carbon contents of fossil fuels})$

Net carbon mitigation =

$f_4(\text{fossil fuel carbon displaced, carbon input to SRWC feedstock})$

We will briefly discuss factors affecting feedstock amount, energy production, fossil fuel displacement, and net carbon mitigation benefit. Then preliminary estimates of the possible carbon mitigation benefit of growing SRWC for energy production in the United States will be presented on the basis of current and future technologies and two levels of land availability.

#### Amount of Feedstock

To determine the amount of wood feedstock that might be produced by growing SRWC, it is necessary to know the wood yield per hectare of SRWC and

the amount of land available and suitable for SRWC. Yields and land availability will be addressed separately.

### Yield Potentials

In considering SRWC yields, several questions must be posed. First, what yields are currently and potentially attainable? Second, what yields are necessary for SRWC energy to be competitive with other energy types? And third, what technology and site conditions are needed to produce competitive yields?

SRWC yields in research field trials have steadily risen over the past 12 years as SRWC technology has improved. Yields as harvestable woody biomass in the range of 9-15.7 (dry) Mg/ha/year are now common in production research trials (Wright et al., 1992). (Yield is defined as "the standing aboveground woody biomass of the SRWC crop divided by the crop's age" and is analogous to the forestry term mean annual increment, or MAI.) If a concerted research effort is maintained, yields of 15.7-29.1 (dry) Mg/ha/year are believed attainable by the year 2010 on moderate to good cropland. To date, the maximum observed experimental yield from a temperate climate SRWC is 43.3 (dry) Mg/ha/year (Table I) (Wright and Ehrenshaft, 1990).

To be competitive with other energy sources at current prices in the U.S. market, delivered SRWC energy feedstock must cost less than \$1.90/GJ [\$37/((dry) Mg) in U.S. dollars (Ranney et al., 1987). This would permit biomass-to-ethanol production costs to match current gasoline production costs. The cost rate translates to a yield of roughly 16-22 (dry) Mg/ha/year on sites having moderate annual land rents (\$100-\$148/ha). Current delivered

SRWC costs are roughly \$1.90-\$2.85/GJ [\$37-\$56/(dry) Mg] when relatively good cropland is used, moisture is not limiting, and the best available SRWC techniques are practiced (Wright and Ehrenshaft, 1990). These cost figures assume that chips are used as the raw feedstock. If whole trees could be burned as has been proposed (Ostlie, 1989), the feedstock costs would be significantly less. The economic attractiveness of wood as an energy feedstock is, of course, highly dependent on the cost of alternative energy sources. Taxes on fossil-carbon-emitting sources or increases in oil import prices would improve the competitiveness of SRWC as an energy source. However, currently high SRWC production costs and low fossil fuel prices combine to make SRWC-derived energy noncompetitive in most situations.

SRWC yields are a function of genotype, cultural practices, and site quality. Silver maple (Acer saccharinum), sweetgum (Liquidamber styraciflua), American sycamore (Platanus occidentalis), black locust (Robinia pseudoacacia), poplars (Populus spp. and hybrids), and eucalypts (Eucalyptus spp.) have been identified as potential species for SRWC in the United States and are currently the subject of SRWC research. Hybrid poplars and eucalypts have shown the greatest potential thus far for attaining exceptionally fast growth rates in the United States. Good cultural practices are critical if promising genotypes are to express their growth potential. Site preparation is especially important. SRWC must be established under the same conditions as almost any other agricultural crop, and fertilization is needed for most SRWC species approximately every other year to maintain rapid growth and sustain fertility of the land. To obtain high SRWC yields at reasonable costs, agricultural cropland is required [land in U.S. Department of

Agriculture (USDA) cropland classes IV or better] (Wright et al., 1992). The establishment of SRWC crops on cut-over forested sites has been tested, but results have shown that growth was relatively poor compared with that of cropland under cultivation or recently abandoned (Wright et al., 1989). For example, sweetgum and sycamore yields on an old-field site in coastal Alabama were more than double those on an adjacent cut-over forested site. Thus, from both an economic and a carbon mitigation perspective, the conversion of forested land to SRWC is generally not desirable.

Harvesting and handling technology can affect both net yield from the site and feedstock costs. Harvest losses are commonly assumed to be between 5 and 10% of the aboveground wood standing in the field at the time of harvest, and storage losses are estimated at 10 to 15% (Wright et al., 1992). Harvesting costs are difficult to project because harvesting equipment suitable for the unique conditions of SRWC are under development and have not been widely tested. Smaller equipment than is commonly used in conventional forestry is more cost effective, however (Stokes et al., 1986).

#### Land Availability

The land base that might be dedicated to growing SRWC in the future is a function of land quality, agricultural product demands, U.S. agricultural policy, and environmental considerations. Of these four factors, land quality can be discussed with the most certainty. An analysis of the U.S. nonfederal land base suggests that there are 159 million hectares of cropland or potential cropland that could under current conditions support SRWC without the use of irrigation (Wright et al., 1992). Ninety-one million of these

hectares might support SRWC yields in excess of 11 Mg/ha/year. The average yield on these lands was projected to be 14 dry Mg/ha/year.

Projections of land needed for current and future food production in the United States suggest that putting existing U.S. cropland into energy-crop production may be both feasible and economically desirable (USDA/SCS, 1990). In 1982,  $62 \times 10^6$  ha of the approximately  $200 \times 10^6$  ha potentially suitable for crop production were either fallow or used for pasture or range (USDA/SCS, 1987). In addition to the land normally used for range and pasture, varying amounts of productive cropland are idled each year. For any 1 year during the 1980s,  $4.5 \times 10^6$  to  $32 \times 10^6$  ha of productive cropland were idle. Thus, a significant portion of the U.S. crop base is not used for food production.

This underutilization of the U.S. cropland base has received government attention. A report requested by the U.S. Secretary of Agriculture (New Farm and Forest Products Task Force, 1987) proposed a national goal of "developing and commercializing within 25 years, an array of new farm and forest products, utilizing at least 150 million acres [ $60 \times 10^6$  ha] of productive capacity, to meet market needs representing net new demand for agriculture and forestry production." SRWC would appear to be such a "new product," assuming energy markets develop for SRWC feedstocks. Such markets are, however, unlikely to develop unless biomass feedstocks become more competitive with fossil feedstocks.

Furthermore, current institutional factors would inhibit the conversion of land to SRWC production even if energy markets did develop. Present U.S. agricultural policies provide incentives to keep resources in traditional agricultural practices, and lending institutions would require a stable and

long-term assured market for energy crops before financing became available. To encourage adoption of SRWC, agricultural producers would probably require assurances that commodity program hectares on their farm would not be affected and SRWC markets are stable and permanent. To produce under the current institutional structure, the price for the SRWC feedstock would need to incorporate significant incentives to overcome the institutional factors as well as the cost of producing the SRWC feedstock.

Changes in U.S. farm policies are beginning to occur. In 1985 the Food Security Act incorporated provisions of the type needed to begin establishment of wood energy crops. The act initiated the Conservation Reserve Program (CRP), which targeted  $16 \times 10^6$  ha of highly erodible land for long-term retirement from food crop production. Land eligibility is limited to predominantly highly erodible cropland, filter strips, certain woodland areas, and fields having evidence of scour erosion. As of 1989,  $12 \times 10^6$  ha had been set aside under this program. SRWC grown on 9- to 12-year rotations would appear to be suitable for some of these lands because the establishment of SRWC accomplishes the goal of reducing soil erosion yet is also not as permanent a land-use conversion as conventional forestry. SRWC is potentially profitable today on this land base if government CRP subsidies are included (Lothner et al., 1988).

### Energy Production

To determine the amount of energy in the form of electricity or fuel that can be produced from a hectare of land or a megagram of biomass

feedstock, it is necessary to understand the status of conversion technologies, particularly the efficiency of conversion. Today's biomass conversion technologies tend to have relatively low energy-conversion efficiencies, but considerable potential exists to improve the overall process efficiencies and make these processes more economically favorable (DOE/BMSTD, 1988).

### Electricity Production

Most conventional wood-to-electricity generating plants (10-50 MW<sub>e</sub>) operating today have an energy-conversion efficiency of about 25%, largely because of the high moisture content of the wood feedstock. However, the use of low-moisture-content wood feedstocks with high-pressure and high-temperature turbines and boiler systems could result in wood-to-electricity conversion efficiencies of 33-35% (Gary Elliot, president, Fitchner USA, and Dave Ostlie, president, Energy Performance Systems, personal communication, Spring 1990). Supercritical pressure plant cycle efficiencies as high as 40% have been demonstrated (Combustion Engineering, 1981). Larson and Williams (1989) and Larson and Svenningsson (1990) have proposed the use of aeroderivative gas turbines [steam-injected gas turbines (STIG) and intercooled steam-injected gas turbines (ISTIG)] coupled with biomass gasifiers to generate electricity. Efficiencies for STIG and ISTIG, using coal as the feedstock, have been documented at 35.6 and 42.1%, respectively. Because biomass should gasify more easily than coal, Larson and Svenningsson (1990) feel that biomass should have at least as high an overall cycle

efficiency as coal if the gasifier system is specifically designed for biomass.

### Ethanol Production

Using an ethanol conversion facility model developed at the National Renewable Energy Laboratory, researchers found that a dry megagram of wood can produce about 344 L of ethanol with a conversion-process efficiency of 41% (Hinman et al., 1991). The ethanol is produced from the hemicellulose and cellulose in the wood. The lignin and unfermented carbohydrates of the wood are burned to provide energy for the conversion process. The wood-to-ethanol process differs from the more conventional corn-to-ethanol production in which the starch in the corn grains converts to ethanol and the process energy is generally provided by coal (Marland and Turhollow, 1991).

The ethanol conversion model also indicates that current wood-to-ethanol technology would produce a surplus 184 kWh of electricity per dry megagram of wood processed to ethanol. Actually, the process would generate 495 kWh of electricity, but 311 kWh would be used in processing the feedstock. With improvements in both feedstock composition and the conversion process (e.g., fermentation efficiencies and enzymes used for hydrolysis of cellulose), a dry megagram of wood could produce about 503.3 L of ethanol and a surplus of about 101 kWh of electricity. This represents a wood-to-ethanol conversion-process efficiency of 60%. The reduced electricity production under the future technology analysis is a result of more efficient use of the wood in the ethanol conversion process and, consequently, less wood residue for combustion.



## Gross Fossil Fuel Carbon Displacement

The gross amount of fossil fuel carbon that could be displaced per unit of wood feedstock is a function of fuel substitution properties, the amount of energy or fuel produced per unit of wood, and the amount of carbon released per unit of fossil fuel energy. Because fuel substitution properties vary considerably between ethanol and coal, the two will be discussed separately.

### Coal Displacement

The relative amount of electricity produced per dry Mg of wood or coal feedstock is a function of the process-conversion efficiency and the relative energy content of the two feedstocks. The energy contents of both wood and coal per unit of delivered weight vary considerably. An average energy content of wood is 19.8 GJ/(dry) Mg, whereas an average energy content of coal is about 27.2 GJ/Mg as delivered (Turhollow and Perlack, 1991; Marland and Turhollow, 1991). These values, together with the assumed conversion efficiencies of wood and coal combustion, determine the relative raw energy levels of each feedstock required to produce the equivalent kilowatt hours of electricity. The raw energy levels of wood and coal required to produce a kilowatt hour of electricity are obviously the same if the conversion efficiencies are the same.

Once the energy level of the coal equivalent (to the wood burned) is determined, the calculation of carbon offset is straightforward because the carbon content of coal per joule is nearly constant over a wide range of coal types. That carbon level in coal is 24.12 kg/GJ if carbon released in the

mining and transportation of coal is not considered and 24.65 kg/GJ if the additional carbon emissions are considered (Marland, 1983). The gross fossil-carbon offset for substituting wood for coal is therefore 488.1 kg C/Mg wood, assuming equal coal- and wood-conversion efficiencies (19.8 GJ/Mg wood \* 24.65 kg C/GJ coal). The carbon offset per unit wood is not sensitive to improvements in process conversion efficiencies because it is assumed the same improvements would occur for coal conversion.

### Gasoline Displacement

The calculation of gross fossil fuel displacement in the wood-to-ethanol fuel pathway includes consideration of both relative substitution rates of ethanol for gasoline and any electricity produced or fossil carbon released in operation of the conversion facility. Liquid fuels derived from biomass do not necessarily substitute for conventional fuels on a one-to-one energy content basis. Even though a liter of ethanol contains only about two-thirds the energy content of a liter of gasoline, it can be burned more efficiently. Therefore, a liter of ethanol can substitute for 0.8 L of gasoline (Lynd et al., 1991). Much of the energy in the wood used to produce ethanol is needed to provide process energy and thus is not available to displace gasoline. Consequently, it takes about two units of wood energy to displace one unit of energy in gasoline. This is in contrast to coal displacement for electricity generation in which a unit of wood energy is equivalent to a unit of coal energy.

Because the carbon content of gasoline is 20.76 kg/GJ (0.723 kg/L) if the energy costs of refinement and transportation are included (Marland and

Turhollow, 1991), the gross ethanol carbon offset per dry Mg of wood is 199 kg C under current conversion technology (i.e.,  $344 \text{ L ethanol/Mg wood} * 0.8 \text{ L gasoline/L ethanol} * 0.723 \text{ kg C/L gasoline} = 199 \text{ kg C/Mg wood}$ ). The gross offset is 291 kg C under future conversion technology. If one then includes the carbon savings associated with the surplus electricity production, the total carbon offset is 236 kg C/Mg wood for current technology and 307 kg C/Mg wood for future technology. These values incorporate the assumption that 75% of the electric substitution would be from fossil fuel and the other 25% from renewables so the kilowatt-hour carbon savings is 0.2 kg C/kWh for current technology and 0.16 kg C/kWh for future technology (Turhollow and Perlack, 1991).

#### Net Carbon Benefits

The calculation of net carbon benefits requires some assumptions of yield and SRWC management practices because they will determine the amount of fossil fuel used to produce a unit of SRWC-derived energy. For purposes of this discussion and for assessing the U.S. potential for SRWC-derived energy, we assume that current technology will produce average standing yields of 14 Mg dry wood/ha/year, future technology will produce average standing yields of 22.4 Mg dry wood/ha/year, and in both scenarios there is a 5% harvesting loss and a 15% (current) to 13% (future) transportation and storage loss. As noted previously, 14 Mg/ha/year was the average yield calculated for all U.S. lands that could support SRWC with yields greater than 11 Mg/ha/year. The 22.4 Mg/ha/year yield under future technology was chosen to reflect current

expectations for the future (Wright et al., 1992). Conversion efficiencies must also be assumed to calculate the gross fossil fuel carbon offset. For our current scenario, we assume electric production efficiencies of 33% for both wood and coal and an ethanol conversion efficiency of 41% (344 L of ethanol plus 184 kWh of electricity per megagram of wood). For our future scenario, we assume electric production efficiencies of 42% for both wood and coal and an ethanol-conversion efficiency of 60% (503 L of ethanol plus 101 kWh of electricity per megagram of wood).

The combustion of wood or ethanol (products of SRWC) does emit carbon into the atmosphere, but these emissions are balanced by the carbon taken up by the SRWC energy plantations, provided there are no soil carbon changes. However, fossil-carbon inputs are currently required in the production, harvesting, and transportation of SRWC feedstocks. Soil carbon changes are difficult to predict because they strongly depend on the former land use and SRWC management practices. If there was no irrigation and the former land use was conventional crop production, some increase in soil carbon might occur in SRWC production as a result of the reduction in tillage and the unharvested root systems of SRWC. However, data to document the level of sequestering in soil and roots are not yet available, the sequestering would not continue indefinitely, and the stored carbon might be released if the site were to be converted back to food crop production. Growing SRWC on land previously forested or in pasture or irrigating SRWC would most likely cause a net loss of soil carbon. For purposes of this analysis, soil carbon is assumed not to change, and all carbon inputs to the production, harvesting, and transportation of SRWC are assumed to be carbon emissions that reduce the

benefit derived from fossil fuel displacement. The following discussion briefly describes the types and levels of carbon inputs and calculates, by conversion technology - current and future, electricity and ethanol - the net benefit derived from displacement of fossil-carbon feedstocks with SRWC. A detailed discussion of these carbon inputs can be found in Turhollow and Perlack (1991).

#### Carbon Inputs to SRWC Feedstock Production

Carbon inputs to the production, harvest, and delivery of short-rotation woody feedstocks are a function of expected management practices and expected yield. Energy requirements for each operation (site preparation, weed control, fertilizer, pesticides, harvest, transport, and storage) must be estimated by fuel type (diesel as a proxy for all petroleum liquids, natural gas, and electricity) and then converted to carbon equivalents. For our analysis of the potential for SRWC production in the United States, electricity is assumed to be generated 75% from coal and 25% from nonfossil sources. Management practices are assumed the same for both scenarios and are described in greater detail in Turhollow and Perlack (1991) in their description of hybrid poplar production. Harvest is assumed to occur on a 6-year cycle, with two coppice harvests, for a stand life of 18 years.

Establishment of the plantation requires an application of a contact herbicide and disking in the fall followed by a disking and application of pre-emergent herbicide prior to spring planting. Herbicides are applied only the first and second years of the stand life. Phosphate and potash are applied the first year of each cycle, nitrogen is applied every other year,

and insecticides and fungicides are applied on the average every 5th year in the 6-year cycle. The pesticide-use estimates in these scenarios are probably high. Actual pesticide use in operational SRWC poplar stands has been much less (Don Rice, James River Company, personal communication, Spring 1991). With an exception of harvest, transport, and storage operations, fossil-fuel use in SRWC production is calculated on a per hectare basis and is insensitive to yield. Harvest, transport, and storage operations are assumed to use diesel fuel at a rate of 1.1 GJ/(dry) Mg of wood delivered to the conversion facility; thus, diesel use is sensitive to yield.

For current technology, production of an average annual (after loss) yield of 11.3 (dry) Mg/ha requires per hectare inputs of 270 L of diesel fuel, 77 m<sup>3</sup> of natural gas, and 84 kWh of electricity, which results in carbon emissions of about 0.29 Mg C/ha/year or 25.8 kg C/Mg of wood delivered to the conversion facility. With future technology, production of an average annual (after loss) biomass yield of 18.5 dry Mg/ha requires per hectare inputs of 401 L of diesel fuel, 77 m<sup>3</sup> of natural gas, and 84 kWh of electricity, which contributes carbon emissions of about 0.40 Mg/ha/year or 21.9 kg C/Mg wood. The difference in diesel-fuel usage results from more wood per hectare being harvested, transported, and stored.

#### Net Carbon Benefit from Conversion of Wood to Electricity or Ethanol

The net carbon mitigation benefit of using SRWC to produce electric power and/or ethanol is simply the carbon displacement of the fuel substitution minus the carbon emissions from SRWC production. Tables II and III outline these calculations on a per hectare basis. By substituting wood

for coal, the gross carbon offset is about 5.51 and 9.03 Mg C/ha/year using available and future technologies, respectively. After subtraction of the carbon emissions associated with SRWC production, harvesting, and transportation, the net offset of carbon is about 5.22 and 8.63 Mg C/ha under available and future technologies, respectively. The net carbon offset by conversion of SRWC to ethanol to be used for gasoline substitution amounts to about 2.37 and 5.28 Mg/ha for currently available and future technology, respectively (Table III). The offset of carbon is about twice as high for electricity from SRWC as it is for ethanol from SRWC.

#### U.S. Potential Carbon and Energy Benefit

The potential carbon mitigation and energy supply benefits of SRWC are a function of (1) the land base dedicated to the production of SRWC crops and (2) the advancement of SRWC and associated energy-conversion technologies. To evaluate the U.S. potential, two SRWC adoption scenarios are considered.

The first is a "current conditions" scenario. Table IV gives the assumptions on land base and yield used in this scenario. The land base selected ( $14 \times 10^6$  ha) is the amount of land currently eligible for CRP in SRWC-suitable regions. As noted previously, SRWC is potentially profitable today on this land base if government CRP subsidies are included (Lothner et al., 1988). The selected yield is the same as previously stated; the projected U.S. average of all lands capable of SRWC yields in excess of 11 Mg/ha/year. The previously described current energy-conversion technologies are also assumed. Under these assumptions, the annual carbon

offset by SRWC-based energy production is  $33.2 \times 10^6$  Mg C/year if the wood is used to produce ethanol and  $73.1 \times 10^6$  Mg C/year if the wood is used for electricity.

The second scenario is a "future" scenario. The assumptions include a doubling of the SRWC-dedicated land base to  $28 \times 10^6$  ha and targeted improvements in SRWC and associated conversion technologies (Table IV). Under these assumptions, the total U.S. carbon benefit (offset) would be  $148 \times 10^6$  Mg/year with ethanol production, or  $242 \times 10^6$  Mg/year with combustion and electricity generation (Table IV). This is about 13 or 20% of the current U.S. fossil fuel carbon emissions (ethanol or electricity, respectively) and 2.9 or 4.4% of global fossil fuel carbon emissions.

#### Discussion

The results of our analysis suggest that SRWC have significant potential to offset annual U.S. fossil fuel carbon emissions. But these results must be considered in light of our assumptions. In both scenarios we assume a considerable land base in the same order of magnitude as is currently dedicated to corn or soybeans. A land use change of this magnitude would have profound effects on local economies and perhaps on national agricultural markets. The important point is that large amounts of agricultural quality land are needed if SRWC technology is to significantly contribute to U.S. energy needs and carbon dioxide mitigation. Such shifts in land use have occurred in the recent past. In the early 1950s soybeans were an



insignificant part of the U.S. agricultural sector; in 1988 soybeans were planted on 24 million hectares.

We also assume that average yields of 14 to 22 Mg/ha/year can be obtained on large acreages in the United States without irrigation. This would appear plausible given the research experience under current climatic conditions, but if the Midwest becomes drier as a result of greenhouse warming, the acreage of land that could support reasonable SRWC yields without irrigation would dramatically decrease.

Although this paper addresses the use of SRWC to provide biomass feedstock, we would be remiss if we did not acknowledge the importance of such other sources of biomass as crop and forestry residues and herbaceous energy crops. Forestry residues are widely used throughout the forest industry to supply power to pulp and paper facilities and mills. Existing forests are being harvested to support power plants in northern New England. Because of the much lower yields in most natural forests (typically 2-4 Mg/ha/year), the use of traditional natural forests to supply wood feedstock on a sustainable basis would require a much larger land base than would SRWC. The environmental and societal impacts of using existing forests could also be considerable, although with careful management the New England experience appears to have been fairly positive (Hudson and Mullett, 1987).

Herbaceous energy crops have advantages and disadvantages relative to SRWC. Herbaceous energy crops can probably be used over a wider range of sites because some of the crops can be grown on drier and steeper settings than SRWC. Herbaceous energy crops also are more similar to conventional agricultural crops and thus easier for farmers to integrate into their

existing operations. Herbaceous energy crops will also provide an economic return to the farmer much more quickly than SRWC.

Disadvantages of herbaceous energy crops include higher erosion potential (if the energy crop is sorghum or corn), higher inputs of fertilizers, greater harvest/transportation/storage losses (if handled as a hay crop), and lower energy content per unit of dry matter [17.4 GJ/Mg vs 19.8 GJ/Mg (Turhollow and Perlack, 1991)].

The carbon offset per unit of land dedicated to herbaceous crops will be less than if that land was dedicated to SRWC unless the herbaceous yields are higher. Using the production scenarios and fossil carbon inputs for SRWC, sorghum, and switchgrass presented in Turhollow and Perlack (1992), assuming identical gross yields (14 dry Mg/ha), and burning the feedstock for electricity at equal conversion efficiencies, we calculate that on a per hectare basis, switchgrass could displace 3.81 Mg C/ha/year; sweet sorghum, 4.65 Mg/ha/year; and SRWC, 5.22 Mg C/ha/year (Table V). Undoubtedly, in some (and perhaps most) situations herbaceous energy crops would be preferable to SRWC but the preference would be strongly affected by potential yield, the existence of an infrastructure for handling SRWC, and the motivations for growing the crops.

The per hectare carbon savings of a corn-to-ethanol energy strategy are relatively low compared with a SRWC-to-ethanol energy strategy. This is because the fossil energy inputs required to grow corn and convert it to ethanol are quite high. Using information from Marland and Turhollow (1991) on carbon inputs in corn production and conversion to ethanol and the substitution properties of ethanol for gasoline, we calculate that an average

hectare yielding 7.47 Mg corn/ha/year would produce 2,783 L of ethanol and give a net carbon displacement of 0.54 Mg C/ha/year if most of the processing energy was coal-generated electricity (as is the case now) and 1.3 Mg C/ha/year if all the processing energy was derived from biomass (Table V). Both these estimates include the backing out some of the energy inputs to processing in recognition of the byproducts of corn-to-ethanol production (analogous to our electricity credits in the ethanol scenarios) and the substitution of ethanol for gasoline. In comparison with a hectare of SRWC, a hectare of corn would produce 71% of the ethanol and 23% of the carbon savings, assuming current technology for both SRWC and corn. From an environmental perspective, corn production for ethanol is also probably less desirable compared with either SRWC or switchgrass because of the greater input of fertilizer and pesticides and the greater erosion potential.

In summary, our analysis suggests that the use of SRWC to produce electricity or ethanol could make an important contribution to the U.S. energy sector and to the reduction of U.S. fossil fuel carbon emissions. However, that contribution depends on the dedication of a significant fraction of the U.S. agricultural land base to energy crops and continued improvements in SRWC production technology and biomass-energy- conversion technologies.

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TABLE I: Short-rotation woody crop yields by U.S. region - current and future expected yields for operational conditions and maximum observed values (Wright et al., 1992)

Region	Yields (dry) Mg/ha/year		
	Current	Goal	Maximum observed
Northeast	9.0	15.7	15.7
South/Southeast	9.0	17.9	15.7
Midwest/Lake	11.2	20.2	15.7
Northwest	15.7	29.1	43.3
Subtropics	15.7	29.1	27.6



TABLE II: Annual carbon offset per hectare by electricity produced from short rotation woody crops (SRWC)

Assumptions and results	<u>Technology status</u>	
	Available	Future
Biomass yield (before losses), (dry) Mg/ha/year	14.0	22.4
Biomass yield (after losses), (dry) Mg/ha/year	11.3	18.5
Conversion efficiencies assumed		
wood-to-electricity (%)	33	42
coal-to-electricity (%)	33	42
Electricity production, MWh/ha/year*	20.5	42.7
Gross carbon offset by fuel substitution, (Mg/ha/year)**	5.51	9.03
SRWC production carbon emissions, Mg/ha/year	0.29	0.40
Net carbon offset, Mg/ha/year	5.22	8.63

\* Assumes wood energy content of 19.8 GJ/dry Mg

\*\* Assumes coal carbon content of 24.65 kg C/GJ.

TABLE III: Annual carbon offset per hectare by short rotation woody crops (SRWC) ethanol production

Assumptions and results	Technology status	
	Current	Future
Biomass yield (before losses), (dry) Mg/ha/year	14.0	22.4
Biomass yield (after losses,) (dry) Mg/ha/year	11.3	18.5
Wood-to-ethanol conversion efficiency (%)	41	60
Ethanol yield: L/(dry) Mg biomass	344	503
L/ha	3889	9312
Electricity yield : kWh/(dry) Mg biomass	184	101
: kWh/ha	2079	1868
Carbon offset by fuel substitution, Mg/ha/year		
ethanol substitution*	2.25	5.39
electricity substitution*	0.41	0.29
SRWC production carbon emissions, Mg/ha/year	0.29	0.40
Net carbon offset, Mg/ha/year	2.37	5.28

\* Assumes the carbon content of gasoline is 0.723 kg/L and one liter of ethanol can substitute for 0.8 L of gasoline.

# Assumes 1.0 kWh of biomass-derived electricity substitutes for 0.75 kWh of coal-derived electricity, a coal conversion efficiency of 33% (current) and 42% (future), and a carbon content of coal of 24.65 kg/GJ.

TABLE IV: U.S. production scenarios - land and yield assumptions: carbon offset, ethanol, and electricity generation; comparison to U.S. fuel and electricity consumption; and comparison to U.S. and global carbon emissions from fossil fuel

	Short rotation woody crop energy scenarios			
	Current ethanol	Current electricity	Future ethanol	Future electricity
Net Yield, (dry) Mg/ha/year	11.3	11.3	18.5	18.5
U.S. land base, $10^6$ ha	14	14	28	28
Ethanol generated, $10^9$ L/yr	54.3	-	260.7	-
Electricity generated ( $10^6$ MWh)	29.1	287.1	52.4	1196.6
Percentage of current U.S. gasoline consumption	10.4	-	49.7	-
Percentage of U.S. electric power consumption	1.1	10.7	2.0	44.5
Carbon offset, $10^6$ Mg/year	33.2	73.1	148	242
Percentage of U.S. fossil fuel carbon emissions	2.9	6.0	13.2	19.9
Percentage of world fossil fuel carbon emissions	0.6	1.3	2.9	4.4

Table V: A comparison of short rotation woody crops (SRWC) derived energy with other forms of biomass energy. Combustion of SRWC is compared with combustion of sweet sorghum or switchgrass. Differences in net yield are a function of differences in harvesting and transportation losses. Differences in fossil carbon inputs are a function of differences in crop management (e.g., fertilizer use, tillage, pesticides). Conversion of SRWC to ethanol using current technology is compared with conversion of corn grain to ethanol using current technology and assuming current use of coal for process energy or assuming use of biomass for process energy

	Gross yield	Net yield	Electricity or ethanol production	Gross fossil carbon displacement	Fossil carbon inputs	Net carbon savings
Combustion	Mg/ha/year	Mg/ha/year	Mwh/ha/year*	Mg C/ha/year	Mg C/ha/year	Mg C/ha/year
SRWC	14	11.3	20.5	5.51	.29	5.22
Sweet sorghum	14	11.8	18.8	5.06	.41	4.65
Switchgrass	14	9.64	15.4	4.13	.32	3.81
Ethanol production	Mg/ha/year	Mg/ha/year	L EtOh/ha/year	Mg C/ha/year	Mg C/ha/year	Mg C/ha/year
SRWC	14	11.3	3882	2.66	0.29	2.37
Corn grain**	-	7.47	2783	1.61	1.07	0.54
Corn grain***	-	7.47	2783	1.61	0.31	1.30

\* Assumes a conversion efficiency of 33%.

\*\* Assuming 75% of electricity needed for process energy is derived from coal combustion.

\*\*\* Assuming all electricity needed for process energy is derived from combustion of biomass.

Robert Williams, Chairperson

## ROLES FOR BIOMASS ENERGY IN SUSTAINABLE DEVELOPMENT

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### INTRODUCTION

Biomass (plant matter) has been used as fuel for millenia. In the 18th and 19th centuries it was widely used in households, industry, and transportation. In the US, as late as 1854, charcoal still accounted for nearly half of pig iron production, and throughout the antebellum period wood was the dominant fuel for both steamboats and railroads [1]. Biomass dominated global energy consumption through the middle of the 19th century [2]. Since then biomass has accounted for a diminishing share of world energy, as coal and later oil and natural gas accounted for most of the growth in global energy demand. Today biomass is not much used by industry, though it is still widely used for domestic applications in developing countries--especially in rural areas [3]. Still, biomass accounts for about 15% of global energy use, only slightly less than the share of global energy accounted for by natural gas (*see Figure 1*).

Although the trend has been away from biomass as an energy source, there are strong reasons for revisiting biomass energy:

- o Dependence on liquid hydrocarbon transport fuels has led to urban air pollution problems in many areas that cannot be solved simply by mandating further marginal reductions in tailpipe emissions. California has adopted a policy mandating the phased introduction of low- and zero-emission transport vehicle/fuel systems, and many other US states and some other countries are likely to pursue similar policies [4]. Some biomass-based transport energy options could effectively address this challenge [5,6].
- o The prospect of declining future production of conventional oil in most regions outside the Middle East [7] once more raises concerns about the security of oil supplies. Fluid fuels derived from biomass substituted for imported oil can help reduce energy security risks [5].
- o Responding to concerns about global warming may require sharp reductions in the use of fossil fuels [8]. Biomass grown sustainably and used as a fossil fuel substitute will lead to no net buildup in atmospheric carbon dioxide, because the CO<sub>2</sub> released in combustion is compensated for by the CO<sub>2</sub> extracted from the atmosphere during photosynthesis.
- o A major challenge facing developing countries is to find ways to promote rural industrialization and rural employment generation, to help curb unsustainable urban migration [9]. Low-cost energy derived from biomass sources could support such activities [5].
- o There are large amounts of deforested and otherwise degraded lands in tropical and subtropical regions in need of restoration [10]. Some of these lands could be restored by establishing biomass energy plantations on them. Part of the revenues from the sale of biomass produced on such lands could be used to help pay for these land restoration efforts [3,5].
- o In industrialized countries, efforts to provide food price and farmer income stability in the face of growing foodcrop productivities have led to a system of large-scale agricultural subsidies. Despite mounting economic pressures to reduce or eliminate such subsidies, so doing is difficult politically [11]. However, converting excess agricultural lands to biomass production for energy would both provide a

new livelihood for farmers and make it possible to phase out such subsidies [3,5].

Because of such considerations, and because of good prospects for providing competitive energy supplies from biomass using modern energy conversion technologies, it was projected in a recent study exploring the prospects for renewable energy that biomass can have major roles as a renewable energy source [5]. In a renewables-intensive global energy scenario constructed for that study it was estimated that renewable energy could provide about 45% of global primary energy requirements in 2025 and 57% in 2050, with biomass accounting for about 65% of total renewable energy in both years (*see Figure 2*). For the US, the corresponding renewable energy shares of total primary energy were projected to be similar to the renewable shares at the global level, with biomass accounting for 55-60% of total renewable energy in this period (*see Figure 3*).

In the renewables-intensive global energy scenario, biomass supplies are provided mainly by biomass residues of ongoing agricultural and forest product industry activities (*e.g.*, sugar cane residues and mill and logging residues of the pulp and paper industry) and by feedstocks grown on plantations dedicated to the production of biomass for energy purposes. In the present analysis, the discussion is focussed on plantation biomass, which accounts for about three-fifths of global biomass supplies in the period 2025-2050 [5].

### THE CHALLENGES POSED BY BIOMASS ENERGY

The notion of shifting back to biomass for energy flies in the face of conventional wisdom. Bringing about such a shift would require overcoming strong beliefs held by many people that biomass is inherently unpromising as an energy supply source. It is widely believed that:

- o Biomass is an inconvenient energy carrier and thus inherently unattractive for modern energy systems.
- o The use of land to grow biomass for energy conflicts with land needs for food production.
- o Large-scale use of biomass for energy would create environmental disasters.
- o The energy balances associated with biomass production for energy are unfavorable.
- o Biomass energy is inherently more costly than fossil fuel energy.
- o Resource constraints will limit biomass to a minor role in a modern global energy system.

In what follows each of these concerns is dealt with in turn.

### ATTRACTING CONSUMER INTEREST BY MODERNIZING BIOMASS ENERGY

Biomass is often called "the poor man's oil" [9]. This characterization arises in part from the low bulk density of biomass fuels. Freshly cut wood typically has an energy density of about 10 GJ per tonne--compared to 25 to 30 GJ per tonne for various coals and more than 40 GJ per tonne for oil; it is thus both difficult and costly to transport biomass fuels long distances; in rural areas of developing countries women and children spend considerable time gathering fuelwood for cooking. Wood cookstoves also pollute--generating in rural kitchens of developing countries total suspended particulates, benzo-a-pyrenes, and other pollutants--often at levels far in excess of ambient air quality standards [12].

Also, as incomes rise, consumers' preferences shift to energy carriers of higher quality. The higher the quality of the fuel, the more convenient it is to use and the less the pollution generated--hence the more desirable it is. This phenomenon is well-known for cooking fuels: charcoal is preferred to wood; kerosene is preferred to charcoal; and clean gaseous fuels such as liquid petroleum gas (LPG) are preferred to kerosene [12].

It is often argued that the existence of this "energy ladder" shows that consumers will shift away from

biomass fuels, as they are able to afford energy carriers of higher quality. Data on the global patterns of biomass use for energy support this contention: while biomass accounts for 38% of energy use in developing countries, where it is used mainly by poor people in rural areas, it accounts for less than 3% of energy use in the industrialized countries (see Figure 1).

However, this argument concerns not biomass *per se* but rather the energy carriers used by the consumer. Biomass can be used directly as a low-quality solid fuel (e.g. fuelwood), it can be upgraded into a higher quality solid fuel (e.g. charcoal), or it can be converted into gaseous or liquid fuels or electricity. In short, biomass can be utilized as an energy source with a wide range of energy carriers. Thus biomass would be an acceptable energy source at higher income levels if it could be converted into energy carriers deemed desirable by consumers with higher incomes.

## ADDRESSING THE FOOD VS. FUEL CONTROVERSY

The renewables-intensive global energy scenario developed in [5] calls for establishing worldwide some 400 million hectares of biomass plantations for energy by the second quarter of the 21st century--a land area that is not small compared to the nearly 1500 million hectares now in cropland [13]. Because the world population is expected to nearly double by that time, the potential for conflict between biomass production for food and biomass production for energy warrants careful scrutiny. Because land is needed to grow food, but energy can be provided in many ways, food production should have priority. The key questions are: How much land is needed for food production? And how does this need compare with the arable land resource? In addressing these questions it is useful to consider the industrialized and developing country situations separately.

### *Industrialized Countries*

Because their population growth is slow and food yields have been increasing, the amount of land needed for food production is declining in industrialized countries.

In the US, more than one-fifth of total cropland, some 33 million hectares, was idled in 1990, either to support crop prices or to control erosion. Furthermore, the Soil Conservation Service of the U.S. Department of Agriculture projects that the amount of idle cropland will probably increase to 52 million hectares by 2030 as a result of rising crop yields, despite an expected doubling of exports of maize (corn), wheat, and soybeans in this period [14]. The urgency of addressing the challenge of excess agricultural lands was the major theme of the 1987 report of The New Farm and Forest Products Task Force to the Secretary of Agriculture [15]:

"The productive capacity of US agriculture is greatly underutilized. The country today has carryover stocks of between six months and one year's production of major commodities, with productivity continuing to increase at a faster rate than demand. Estimates of land in excess of production needs to meet both domestic and export market demand range as high as 150 million acres [61 million hectares]--with about one third of that already available from the Conservation Reserve Program. This represents an enormously wasted national asset which, if transformed into a more productive one through new products, would have a profoundly positive impact on the Nation's economy."

In the European Community more than 15 million hectares of land will have to be taken out of farming by 2000 if surpluses and subsidies associated with the Common Agricultural Policy are to be brought under control [16]; a study carried out by the Netherlands Scientific Council for Government Policy projects that the land needed for food projection in the Community could be 50 to 100 million hectares less in 2015 than at present [17].

While the conversion of excess cropland in the industrialized countries to energy plantations presents an opportunity to make productive use of these lands, such a conversion cannot be easily accomplished under present policies. In many countries farmers are deterred by a subsidy system that specifies what crops the farmer can produce in order to qualify for a subsidy; and energy crops are not allowed. Conversion to profitable

biomass energy production will make it possible eventually to phase out many of these agricultural subsidies (see *Appendix A*). However, this will not be accomplished overnight, because of the economic dislocations that would result; today these subsidies total about \$300 billion per year for countries of the Organization for Economic Cooperation and Development (OECD) [11]. As long as a system of subsidies continues, however, the bias against energy crops should be removed.

### *Developing Countries*

For developing countries the situation is quite different. Because of expected population growth and rising incomes, it is likely that more land will be needed for food production. The Response Strategies Working Group of the Intergovernmental Panel on Climate Change has projected that the land in food production in developing countries will increase 50% by 2025 from the present level of about 700 million hectares (see *Table 1*) [18]. The demand can be compared to potential supply--that is, land physically capable of supporting economic crop production, within soil and water constraints. Potential cropland was estimated for 91 developing countries in a 1991 Food and Agriculture Organization (FAO) study [19]. For these countries potential cropland was estimated to be about 2055 million hectares--nearly three times present cropland (see *Table 1*).

Looking to the year 2025 and assuming cropland requirements in developing countries increase 50% by then, there would still be a substantial surplus potential cropland of nearly 1,000 million hectares in these countries (see *Table 1*). There would be substantial regional differences, however, with major surpluses totalling more than 1,100 million hectares in Latin America and Africa, and a 110 million hectare deficit in Asia. (China was not included in the FAO analysis.) Thus it appears that substantial amounts of land suitable for energy plantations may be available in both Latin America and sub-Saharan Africa, even with major expansions of cropland to feed the growing population. But in Asia, with its high population density, conflicts with food production could become significant.

The extent of the potential conflict in Asia, however, depends sensitively on future food crop productivities. It is possible that apparent food/fuel conflicts could instead prove to be synergistic, if some of the energy produced in biomass plantations were used to help make agriculture more productive. Increasing food production on the better lands, while growing trees or perennial grasses for energy on marginal lands, would generally be environmentally preferable to increasing agricultural output by bringing marginal lands into food production. Detailed assessments are needed, on a country-by-country basis, to understand the prospects for productivity gains with more intensive agricultural management and the extent of food/fuel conflict if the agricultural sector is more intensively managed.

Unfortunately, the FAO study does not clarify where new cropland would come from. To be sure, some forestlands are involved. Clearly, it would not be desirable to cut down virgin forests in favor of intensively managed biomass plantations. Cutting down virgin forests could be avoided, however, by targeting for biomass plantations lands that are deforested or otherwise degraded and that are suitable for reforestation. Large land areas have been degraded. One estimate is that 2,077 million hectares of tropical lands are degraded, of which 758 million hectares are judged suitable for reforestation (see *Table 2*).

Outside of Asia the amount of degraded land suitable for reforestation (excluding degraded lands in the desertified drylands category, one-fifth of which is estimated to be suitable for reforestation--see *Table 2*) is substantial (see *Table 2*)--some 156 million hectares in Latin America (49% of the total degraded land area in Latin America) and 101 million hectares in Africa (12% of the total degraded land area in Africa). In Asia, such land areas are also large--some 169 million hectares (18% of the total degraded land area); however, for Asia, country by country assessments are needed to determine the extent to which its degraded lands will be needed for food production or other purposes warranting higher priority than energy. China, despite its high population density, has a goal of increasing forest cover by 52 million hectares by 2000 (compared to the mid-1980s) and by an additional 93 million hectares over the longer term [20].

The main technical challenge of restoration is to find a sequence of plantings that can restore ground temperatures, organic and nutrient content, moisture levels, and other soil conditions to a point where crop yields



are high and sustainable. Successful restoration strategies typically begin by establishing a hardy species with the aid of commercial fertilizers or local compost. Once erosion is stabilized and ground temperatures lowered, organic material can accumulate, microbes can return, and moisture and nutrient properties can be steadily improved. This can lead to a self-regenerating cycle of increasing soil fertility [21,22].

If it is feasible to overcome this technical challenge and various other socioeconomic, political and cultural challenges [3], plantation biomass in developing regions could make substantial contributions to world energy without serious conflict with food production. In sub-Saharan Africa and Latin America, where potential land areas for plantations are especially large, biomass could be produced by the second quarter of the 21st century in quantities large enough to make these regions major exporters of biomass-derived liquid fuels (see *Figure 4*), offering competition to oil exporters and bringing price stability to the global liquid fuels market [5].

Converting such large areas of degraded lands to successful commercial plantations would be a formidable task. Research is needed to identify the most promising restoration techniques for all the different land types and conditions involved. Yet the fact that many of the successful plantations in developing countries have been established on degraded lands [3] suggests that it may be feasible to deal with these challenges, with adequate research and commitment. And interest in restoring tropical degraded lands is high, as indicated by the ambitious global net afforestation goal of 12 million hectares per year by the year 2000 set forth in the Noordwijk Declaration at the 1989 Ministerial Conference on Atmospheric and Climate Change in Noordwijk, The Netherlands [23].

## **MAKING BIOMASS PRODUCTION FOR ENERGY ENVIRONMENTALLY ATTRACTIVE**

Throughout the 19th and 20th centuries, there has been substantial deforestation worldwide, as a result of both land clearing for agriculture and the non-sustainable mining of the forests for forest products. The more simplified landscape resulting from this deforestation is unable to support the diversity of species that once flourished there. Moreover, modern intensive agricultural management practices have created other serious environmental problems--including the loss of soil quality as a result of continual mining of the soil with plant harvesting, erosion as a result of intensive cultivation practices, and contamination of runoff with nitrates and other chemicals arising from the use of fertilizers, herbicides, and pesticides. A major concern is that such problems would be aggravated by a major shift to biomass energy.

There is no doubt that biomass can be grown for energy purposes in ways that are environmentally undesirable. However, it is also possible to improve the land environmentally through the production of biomass for energy. The environmental outcome depends sensitively on how the biomass is produced.

Consider first the challenge of sustaining the productivity of the land. Since the harvesting of biomass removes nutrients from the site, care must be taken to ensure that these nutrients are restored. In various ways this challenge can be dealt with for energy plantations more easily than is feasible in agriculture or in industrial fiber production, largely as a result of the fact that energy markets allow flexibility in the choice of biomass feedstocks, so that choices can be made to better meet environmental objectives. This is especially true for biomass conversion technologies that begin with thermochemical gasification (which will often be the preferred approach for providing modern energy carriers from biomass feedstocks [5]); such processes can accommodate a wide range of alternative feedstocks.

With thermochemical gasification it is feasible to recover all mineral nutrients as ash from the gasifier at the biomass conversion facility and to return the ash to the plantation site for use as fertilizer. Of course, fixed nitrogen lost to the atmosphere at the conversion facility must be replenished. However, there are several ways this can be accomplished in environmentally acceptable ways. First, when trees are the harvested crop, the leaves, twigs, and small branches, in which nutrients are concentrated, can be left at the site to reduce nutrient loss. (So doing also helps maintain soil quality and reduce erosion through the addition of organic matter to the soil.) Also, nitrogen-fixing species can be selected for the plantation or for interplanting with the primary plantation species to eliminate or reduce to low levels the need for artificial fertilizer inputs. The promise of

intercropping strategies is suggested by 10-year trials in Hawaii, where yields of 25 dry tonnes per hectare per year were achieved without nitrogen fertilizer when *Eucalyptus* was interplanted with nitrogen-fixing *Albizia* trees [24]. Biomass production for energy allows much more flexibility than is possible with agriculture in meeting fixed nitrogen requirements this way. In agriculture, the market dictates the choice of feedstocks with a narrow range of acceptable characteristics, but the conversion technology usually puts few restrictions on the choice of biomass feedstock for energy systems, aside from the requirement of high productivity, which is needed to keep costs at acceptable levels.

Energy crops also offer flexibility in dealing with erosion and with chemical pollution from herbicide use. These problems occur mainly at the time of crop establishment. Accordingly, if the energy crop is an annual crop (e.g., sweet sorghum), the erosion and herbicide pollution problems would be similar to those for annual row-crop agriculture. The cultivation of such crops should be avoided on erodible lands. However, the choices for biomass energy crops also include fast-growing trees that are harvested only every 5 to 8 years and replanted perhaps every 15 to 24 years and perennial grasses that are harvested annually but replanted perhaps only once in a decade. In both cases erosion would be sharply reduced, on average, as would the need for herbicides.

A major concern about agriculture is water pollution from nitrate runoff associated with the excessive use of chemical fertilizers. Where it would not be practical to deal with this problem by planting nitrogen-fixing plantation species as an alternative to chemical fertilizers, runoff pollution could be controlled instead by planting fast-growing trees having low nitrogen-use efficiency in riparian zones [25]. In the future it will also be possible to use "designer" fertilizers whose release is timed to match the temporal variations in the plant's demand for fertilizer [26,27].

Another concern is chemical pollution from the use of pesticides to control the plantation crop against attack by pests and pathogens. While plantations in the tropics and subtropics tend to be more affected by disease and pest epidemics than those in temperate regions, experience with plantations in these regions shows that careful selection of species and good plantation design and management can be helpful in controlling pests and diseases, rendering the use of chemical pesticides unnecessary in all but extraordinary circumstances. A good plantation design, for example, will include: (i) areas set aside for native flora and fauna to harbor natural predators for plantation pest control, and perhaps (ii) blocks of crops characterized by different clones and/or species. If a pest attack breaks out on one block, a now common practice in well-managed plantations is to let the attack run its course and to let predators from the set-aside areas help halt the pest outbreak [3].

Biomass plantations are often criticized because the range of biological species they support is much narrower than for natural forests. While this is generally true, the criticism is not always relevant. It would be relevant if a virgin forest were replaced with a biomass plantation. However, it would not be relevant if a plantation and associated natural reserves were established on degraded lands; in this instance, the restored lands would be able to support a much more diverse ecology than was possible before restoration. If biomass energy crops were to replace monocultural food crops, the effect on the local ecology would depend on the plantation crop species chosen, but in many cases the shift would be to a less ecologically simplified landscape [28].

As already noted, establishing and maintaining natural reserves at plantations can be helpful in controlling crop pests while providing local ecological benefits. However, preserving biodiversity on a regional basis will require land-use planning in which natural forest patches are connected via a network of undisturbed corridors (riparian buffer zones, shelterbelts, and hedgerows between fields), thus enabling species to migrate from one habitat to another [28].

While major expansions in research are needed to provide a sound analytical and empirical basis for achieving and sustaining high biomass yields in environmentally acceptable ways, there is time for this research and extensive field trials, because major bioenergy industries can be launched using as feedstocks primarily residues from the agricultural and forest products industries [5]. If substantial commitments are made to biomass plantation research in the near term, plantation biomass could start to make contributions to energy when residue

supplies are no longer adequate to meet the needs of the growing biomass energy industry, near the turn of the century or shortly thereafter [3].

## **ACHIEVING FAVORABLE ENERGY BALANCES IN BIOMASS PRODUCTION FOR ENERGY**

For biomass energy systems to be viable, the net energy balance must be favorable--i.e., the useful energy produced must be greater than the fossil fuel energy inputs required to provide the biomass energy. Concerns about net energy balances have been widely voiced in the case of fuel ethanol from maize (corn), which is produced in the US under subsidy at a rate of 3 billion liters per year. In this case the net energy balance is often marginal, and in some instances, the fossil fuel inputs to the system are greater than the alcohol energy produced [29]. Maize, however, is a feedstock intended primarily for use as food, not fuel, and its production system is especially energy-intensive among biomass crops.

There are many alternative biomass energy systems characterized by favorable net energy balances. For example, the production of fuel ethanol from sugar cane in Brazil (where production at a level of 12 billion liters per year provides nearly one-fifth of total transport fuel requirements) is characterized by an energy balance in which the energy content of the produced alcohol averages about 6 times the fossil fuel inputs required to grow, harvest, and transport the cane and convert it to alcohol [30]. Moreover, the net energy balances are also favorable for many energy plantation crops that might be grown in temperate climates. Table 3 shows that with present plantation technology, the energy content of the harvestable biomass would be in the range 11 to 16 times the fossil fuel energy needed to provide the biomass [31], and that this ratio is expected to increase with advanced technology. This harvested biomass could be used with near-term technology to produce methanol via thermochemical gasification at an overall efficiency of about 63% [32], so that overall the amount of energy that can be produced in the form of methanol is 7 to 10 times the fossil fuel input to the biomass energy production system.

In general, energy systems having good prospects for becoming economically competitive tend to be characterized by favorable net energy balances, while systems with poor economic prospects may have unfavorable energy balances.

## **ACHIEVING ATTRACTIVE ECONOMICS BY MODERNIZING BIOMASS ENERGY**

The planting, cultivation, and harvesting of biomass is generally more labor-intensive and costly than recovering coal or other fossil fuels from the ground. Thus, per unit of contained energy, biomass tends to be the more costly, especially where there are abundant indigenous fossil fuel resources. This primary energy cost comparison does not imply that biomass energy systems cannot be cost-competitive with fossil fuel energy systems, however. A more meaningful measure of economic performance is the cost of the energy services provided by the biomass and alternatives, taking into account the technologies for converting biomass into modern energy carriers (electricity and gaseous or liquid fuels) and the energy end-use systems in which these energy carriers would be used. On a cost-of-service basis the economic outlook for biomass can be favorable if modern conversion and end-use technologies are used.

### ***Biomass Electricity***

Today biomass, mainly in the form of industrial and agricultural residues, is used to generate electricity with conventional steam-turbine power-generators. These biomass power systems can be cost-competitive where low-cost biomass fuels are available, in spite of the fact that steam-turbine technologies are comparatively inefficient and capital-intensive at the small sizes required for biomass electricity production. The US currently has more than 8,000 MW<sub>e</sub> of generating capacity fueled with such feedstocks, most of which was developed in the 1980s. Electricity production based on this existing technology will not expand much in the future, however, because unused supplies of low-cost biomass residues are rapidly becoming unavailable.

Biomass power generation involving the use of more costly but more abundant feedstocks could be made cost-competitive by adapting to biomass advanced-gasification technologies originally developed for coal

for use with gas turbine-based power systems [33]. Biomass is a more attractive feedstock for gasification than coal because it is easier to gasify and has a very low sulfur content, so that expensive sulfur removal equipment is not needed. Biomass integrated gasifier/gas turbine power systems with efficiencies of 40% or more will be demonstrated in the mid-1990s and will probably be commercially available by 2000. These systems offer high efficiencies and low unit capital costs for baseload power generation at relatively modest scales of 100 MW, or less and will probably be able to compete with coal-fired power plants in many circumstances--even with relatively costly biomass feedstocks. By 2025 conversion efficiencies as high as 57% may be feasible, using advanced biomass gasification/ fuel-cell technologies, based on similar technologies (involving molten carbonate and solid oxide fuel cells) being developed for coal [33].

The electric power industry is beginning to appreciate the importance of biomass for power generation. In an assessment by the Electric Power Research Institute of the potential for biomass-based power generation, it is projected that biomass could be used to support 50,000 MW<sub>e</sub> of electric capacity in the US by 2010 and probably twice that amount by 2030 [34].

### *Transport Fuels from Biomass*

Unlike the auspicious near-term outlook for biomass-derived electricity, very large increases in the world oil price are required before biomass-derived transport fuels could compete in cost with gasoline on a cost-per-unit-of-fuel-energy basis. Nevertheless, because of ongoing changes in the transport sector, the prospects are auspicious that biomass fuels will be able to compete in providing transport services at world oil prices near the present low level. This prospect will be illustrated here for methanol and gaseous hydrogen fuels derived from biomass via thermochemical gasification.

Based on the use of gasification technology<sup>1</sup> that could be commercialized before the turn of the century<sup>2</sup> it should be feasible to produce either methanol or gaseous hydrogen delivered to the consumer at a cost that is 40 to 50% higher than the price of gasoline near the turn of the century [6,32], when gasoline is expected to have a pump price (exclusive of retail taxes) of \$1.25 per gallon (\$0.33 per liter). Even though these fuels are likely to be more costly to produce than gasoline, the prospects are good that they would be able to compete on a *lifecycle cost basis* (cents per km driven) with gasoline, if the biomass derived fuels were used, not in internal-combustion-engine vehicles, but in fuel-cell vehicles.

Biomass-derived fuels are likely to be cost-competitive with the same fuels derived from coal even when the biomass feedstock is more costly than coal [32], both because biomass contains much less sulfur (the removal of which is costly) and because biomass is much more reactive and thus easier to gasify than coal. In both cases the first step is thermochemical gasification aimed at producing a nitrogen-free synthesis gas (a gaseous mixture consisting largely of carbon monoxide and hydrogen, with some methane). The relatively high reactivity of biomass makes it possible to produce this synthesis gas with steam gasification at the relatively low temperatures achievable in indirectly heated gasifiers (*see footnote 1*). However, because of coal's much lower reactivity, much higher temperatures are required for efficient gasification--temperatures achievable only by burning some of the coal in place with oxygen, in an "oxygen-blown" gasifier. The high cost of the required oxygen plant more than offsets the lower cost of the coal feedstock.

While the internal combustion engine has dominated road transportation since the automobile was introduced, the long-term outlook for this engine in transportation is clouded by growing concerns about urban

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<sup>1</sup> The most promising technology involves an indirect gasifier, such as the indirectly heated gasifier being developed by the Battelle Columbus Laboratory, in which biomass is gasified in steam at relatively low temperatures (compared to coal), using an external heat source to provide the heat needed to drive the endothermic reactions involved [29,32].

<sup>2</sup> All technological components required to produce either methanol or hydrogen other than the gasifier are already well-established commercially.

air quality. It is already becoming apparent in southern California that air quality goals cannot be met simply by mandating further incremental reductions in tail-pipe emissions of new vehicles and that a shift to very-low- or zero-emission vehicles is needed in order to reach these goals. Accordingly, the State of California has mandated that 10% of new cars purchased in 2003 must be zero emission vehicles--a requirement that may be adopted by many Eastern US states as well [4].

This California air-quality initiative has led to a substantial industrial effort to commercialize the battery-powered electric car. While the battery-powered electric car is a zero-emission vehicle, this technology will probably be limited to a modest fraction of the automotive fleet market in the long term, without major advances in battery technology that make it feasible to overcome the long (several-hour) recharging time required for batteries [5,6].

A zero-emission vehicle alternative to the battery-powered electric car is the fuel cell car operated on compressed hydrogen. As in the case of the battery-powered electric car, electric motors provide the mechanical power that drives the wheels. But in this case the electricity to run the motors is provided not by a battery but rather by a fuel cell that converts energy stored in compressed hydrogen gas canisters directly into electricity. Unlike the battery-powered electric car, the hydrogen fuel cell car need not be recharged but can be refueled in a time comparable to that for a gasoline-fueled internal-combustion-engine-powered car. Moreover, the lifecycle cost of owning and operating a fuel cell car (in cents per km) operated on hydrogen derived from biomass would probably be less than for a battery-powered electric car [5, 6, 32]. Although biomass-derived hydrogen is likely to be about 50% more costly than gasoline and although the hydrogen fuel cell car may cost 40% more than an internal-combustion-engine car of comparable performance, on a lifecycle cost basis the hydrogen fuel cell vehicle is likely to also be less costly--mainly because the fuel cell car is expected to be three times as energy-efficient and because, like the battery-powered electric car, it is expected to have lower maintenance costs; the energy conversion unit has fewer moving parts than in an internal-combustion-engine car and does not have to be designed to contain explosions of fuel/air mixtures.

A drawback of the hydrogen fuel cell option is the requirement of a hydrogen gaseous fuel infrastructure. This difficulty could be circumvented by using instead methanol as a hydrogen carrier: the methanol would be reacted with steam under the hood of the car and thereby converted into a mixture of carbon dioxide and hydrogen--thereby providing the hydrogen needed to operate the fuel cell. There are three advantages of using methanol instead of hydrogen: the fuel delivered to the consumer would be slightly cheaper because, unlike hydrogen, the fuel does not have to be delivered pressurized; the car would be less expensive because costly high-pressure hydrogen storage canisters would not be needed; and it is easier to establish an infrastructure for marketing a liquid fuel like methanol than for a gaseous fuel like hydrogen. The drawbacks of the methanol fuel cell option are: the energy conversion efficiency is less (the car is likely to be only 2.5 times as energy-efficient as the gasoline internal-combustion-engine vehicle it would replace, owing to the energy requirements for "reforming" methanol with steam); the onboard reformer is an added complication to the system; and a methanol fuel cell vehicle would not qualify as a zero-emission vehicle, because of the modest air pollution emissions associated with the operation of the methanol reformer--although its emissions would be much less than for an internal-combustion-engine vehicle. On balance, the methanol fuel cell vehicle may be slightly less costly on a lifecycle cost basis than the hydrogen fuel cell vehicle [6,32].

The ability of the biomass fuels to compete arises from the fact that both hydrogen and methanol can be used in technologically superior fuel cell vehicles, but gasoline and other hydrocarbon fuels cannot--at least for first-generation fuel-cell vehicles.<sup>3</sup>

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<sup>3</sup> Over the next couple of decades the most likely candidate fuel cell for automotive applications is the so-called proton-exchange-membrane fuel cell, which operates at a modest temperature of 25 to 120 °C. At such a low operating temperature it is practical to reform methanol fuel, but the costs involved in reforming other fuels would be prohibitive. In the longer term, if high-temperature fuel cells (e.g., the solid oxide fuel cell, which would operate at 1000 °C) prove to be practical for vehicular applications, it may be feasible to reform a wide range of hydrocarbon or alcohol fuels under the hood of the car.

The prospect that biomass-derived methanol used in fuel cell vehicles will be able to compete with gasoline used in internal-combustion-engine vehicles implies that liquid-fuel importing countries should be indifferent to the choice between oil and biomass-derived methanol imports on narrow economic grounds. And since methanol derived from biomass and coal feedstocks should also be roughly competitive on narrow economic grounds while biomass would be favored on environmental grounds, biomass-derived methanol could become a major energy carrier in international commerce in a world that is sensitive to environmental values. This is the basis for the world trade pattern for liquid fuels shown in Figure 4 for a renewables-intensive global energy scenario [5], with trade levels equal for oil and biomass-derived methanol in the period 2025-2050.

## CREATING MAJOR ENERGY ROLES FOR BIOMASS WITH LIMITED LAND RESOURCES

Because the photosynthetic process is a relatively inefficient way of converting solar energy into chemical fuel energy, large land areas are required if biomass is to make major contributions to energy supply. For example, displacing fossil fuels in the US with the energy equivalent amount of biomass grown on plantations at the average productivity of US forests (4 dry tonnes per hectare per year) would require a plantation area of 1 billion hectares--approximately the total US land area. This "back-of-the-envelope" calculation suggests that biomass can never become a significant energy source. While it is certainly true that biomass resources are not large enough to enable biomass to provide all energy needs, the role of biomass nevertheless can be substantial, if modern technologies are used for biomass production and conversion.

The land constraints on biomass production can be reduced in part by intensively managing the biomass plantations. With modern production techniques, biomass productivities far in excess of natural forest yields can be realized. A reasonable goal for the average harvestable yield on large-scale plantations in the US is 15 dry tonnes per hectare per year [3]--corresponding to a photosynthetic efficiency of about 0.5%. The amount of land that might be committed to biomass energy plantations in the US could be over 50 million hectares--the amount of excess cropland projected by the US Department of Agriculture to be available by the year 2030 [14]. However, for the purposes of the present discussion, it is assumed that by that time the amount of land in the US committed to biomass plantations is a more modest 30 million hectares--approximately the amount of excess cropland in the US at present. Potential biomass production on this much land at 15 tonnes per hectare per year would amount to about 9 EJ per year.

The land constraints on biomass production can also be eased by exploiting for energy purposes biomass residues (urban wastes and residues of the agricultural and forest-product industries) that can be recovered in environmentally acceptable ways. It has been estimated that such residues in the US could amount to about 6 EJ per year [28].

The biomass energy potentially available from these two sources, some 15 EJ per year, could probably be produced in the US in environmentally acceptable ways without running up against significant land-use constraints. This is equivalent to 19% of total US primary energy use, exclusive of biomass, in 1987. It does not follow, however, that these potential biomass supplies would displace 19% of conventional US energy. The extent to which conventional energy would be displaced depends sensitively on the conversion technologies deployed.

Consider, for example, the two energy activities often targeted for replacement by biomass energy--the generation of electricity from coal and the running of light-duty vehicles (automobiles and light trucks) on gasoline. In the US these activities in 1987 accounted for some 30 EJ of primary energy and about half of total CO<sub>2</sub> emissions from fossil fuel burning. If these two activities (at 1987 activity levels) could be replaced by biomass grown renewably, the result would be a 50% reduction in US CO<sub>2</sub> emissions.

Suppose first that biomass were used with commercially available technologies: (i) replacing coal-based steam-electric power plants with biomass-based steam-electric power plants having a 20% average efficiency and (ii) replacing gasoline-fired internal-combustion-engine light-duty vehicles having 1987 average fuel economies, with the internal-combustion-engine vehicles operated on methanol derived from biomass (using commercially available technology designed to make methanol from coal but modified to accommodate biomass), assuming no

improvement in the fuel economy of the vehicles other than what would be inherent in a shift from gasoline to methanol (gasoline-equivalent fuel economies of 23 mpg for autos and 16 mpg for light trucks). The amount of biomass needed for this conversion would be about 49 EJ per year (*see Figure 5*)—far more biomass than is likely to be available for energy purposes.

By the turn of the century, the first generation of biomass-integrated gasifier/gas turbine technology will probably be commercially available, making it possible to roughly double the efficiency of biomass power generation [33]. In this time frame more energy-efficient biomass-to-methanol conversion technologies may well be available [32]. Moreover, it is feasible and cost-effective to introduce light-duty vehicles operated on methanol having much higher fuel economies (gasoline equivalent fuel economies of 39 mpg for autos and 26 mpg for light trucks). Using these technologies the total biomass required to displace all coal power generation and oil use by light-duty vehicles at 1987 activity levels would be reduced to 23.5 EJ per year (*see Figure 5*).

During the second decade of next century, even more energy-efficient fuel cell technologies are likely to be available, both for power generation (57% efficient biomass-integrated gasifier/fuel cell systems employing molten-carbonate or solid-oxide fuel cells) and for motor vehicle applications (proton-exchange-membrane fuel cell vehicles that are 2.5 times as energy-efficient as comparable gasoline-fired internal-combustion-engine vehicles). Using these technologies the total biomass required to displace all coal power generation and oil use by light-duty vehicles at 1987 activity levels would be reduced to about 14 EJ per year, which is comparable to the above estimate of potential supplies from plantations and residues (*see Figure 5*).

Thus with advanced technologies biomass can play major roles in the energy economy, despite the low efficiency of photosynthesis.

## CONCLUSION

As a potential energy source for modern energy economies, biomass is unusual in that biomass production and use would interact with a far wider range of human activities than any other energy source. In part this is due to the fact that biomass energy is rooted in photosynthesis, without which human life would not be possible. Yet agriculture and forestry are also based on photosynthesis, and biomass energy seems to have the potential for even stronger interactions with human society than either of these other activities.

If biomass energy systems are poorly managed, they could provide some societal benefits, but the benefits may not outweigh the social costs involved. But if biomass is well managed, it is very likely that all the major concerns people have about biomass energy could be turned into a wide range of net societal benefits. Successfully developed, biomass energy could provide:

- o competitively priced modern energy carriers for a substantial fraction of human energy service requirements, if advanced conversion and end-use technologies are used,
- o the opportunity to reduce CO<sub>2</sub> emissions at zero incremental cost, through the displacement of fossil

fuels by competitive biomass energy,<sup>4</sup>

- o the opportunity to introduce biofuels that are compatible with zero-emission or near-zero-emission fuel-cell vehicles, for combatting urban air pollution problems,
- o the opportunity to bring competition, price stability, and energy security to the world fuels market through the development of a large-scale world biofuels industry,
- o a strong basis for rural development in developing countries,
- o the opportunity to pay for the restoration of many tropical and subtropical degraded lands through their conversion to biomass plantations for energy,
- o the opportunity for sub-Saharan Africa and Latin America to become major world economic powers as large-scale biofuels exporters,
- o a new livelihood for farmers in industrialized countries, and
- o the opportunity to phase out agricultural subsidies in the industrialized countries, thereby strengthening the economies of these countries while leveling the playing field in world trade for farmers in developing countries.

But these benefits cannot be realized without a new public policy that promotes and coordinates activities aimed at:

- o eliminating the biases in current policies (subsidies, tax incentives, regulations) against biomass energy systems,
- o learning how best to produce biomass for energy sustainably under a wide range of conditions, while preserving biological diversity and respecting a wide range of other environmental values,
- o revitalizing and creating new economic opportunities for rural regions where biomass would be grown for energy applications,
- o establishing new biomass energy industries that can both produce and market modern biomass energy carriers efficiently,
- o carrying out the research, development, and demonstration needed to facilitate a continuing flow to the market of innovative biomass energy conversion and end-use technologies,
- o transferring resources needed to ensure access to advanced biomass energy technologies in developing

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<sup>4</sup> In addition, some carbon would be sequestered in the steady-state inventory of biomass plantations. Neglecting changes in soil carbon associated with establishing plantations and considering only the average inventory associated with biomass that will be harvested, the sequestering capacity of 400 million hectares of plantations would be about 9 billion tonnes of carbon (assuming an average rotation length of 6 years between cuts), corresponding to 3 years of buildup of CO<sub>2</sub> in the atmosphere from fossil fuel burning.

Changes in soil carbon should also be taken into account. Some recent experimental evidence suggests that the soil carbon content will increase at average rates in excess of one tonne of carbon per hectare per year during the first 18 to 20 years of an unharvested hybrid poplar stand established on land previously managed for row crops; this was determined by comparisons of the carbon contents of the soils in the hybrid poplar stand and the adjacent land in row crops. The experimental data are inadequate, however, to determine how long this buildup might persist or the extent to which harvesting at intervals of about 6 years would affect the rate of carbon turnover in the soil [35].



countries,

- o establishing environmental guidelines that both give impetus to the development and commercialization of clean biomass energy technologies and safeguard against environmentally undesirable approaches to biomass energy development.

The set of required new measures is broad, reflecting the broad range of benefits that could flow from successful biomass energy development.

Five years ago, the required policy change would have been deemed unrealistic, even unthinkable. But today this is no longer the case. A global consensus is emerging that the only acceptable development is sustainable development. This was the underlying theme of the United Nations Conference on Environment and Development in Rio de Janeiro, in June 1992. It is now realized that the only way to achieve sustainable development is to shift from one-dimensional policymaking to holistic approaches that deal with all direct and indirect impacts of a given economic activity, making concerted efforts to avoid adverse impacts before they occur.

Thus, though it is unfamiliar or at least not yet well understood by most people, biomass energy will get focussed attention in the forthcoming sustainable development debates--both because of potentially disastrous consequences of ill-planned biomass energy development efforts and because of the enormous overall benefits in support of sustainable development goals that would arise from the proper development of biomass energy.

The timing of these debates could not be better for the biomass energy community. Because modernized biomass energy plays a negligible role in the world energy economy at present, the future shape of the biomass energy industry can be molded by the sustainable development debates, before the industry becomes well established.

It is a rare event in modern history that the big concerns about potential adverse impacts of human technological prowess are aired before people have had a chance to demonstrate this prowess by changing the world. And rarer still is the possibility that these concerns can be reflected in timely changes of course that avoid the problems of concern.

## **ACKNOWLEDGMENTS**

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Table 1. Present <sup>a</sup> and Potential <sup>b</sup> Cropland for 91 Developing Countries (million hectares)								
	Present Cropland	Potential Cropland						
Region		Low Rainfall	Uncertain Rainfall	Good Rainfall	Natural Flooded	Problem Land	Desert	Total
C. America	37.6	2.2	13.3	18.5	5.7	31.4	3.5	74.6
S. America	141.6	26.0	37.5	150.3	105.7	492.7	2.8	815.0
Africa	178.8	73.4	96.8	149.3	71.3	358.1	3.8	752.7
Asia (excl. China)	348.3	59.8	67.0	67.4	80.5	117.6	20.3	412.5
Total	706.3	161.4	214.7	385.5	263.1	999.7	30.4	2054.9

Notes to Table 1

<sup>a</sup> Source: [13].

<sup>b</sup> As estimated by the Food and Agriculture Organization (FAO) in 1990 [19]. Potential cropland is defined by the FAO as all land that is physically capable of economic crop production, within soil and water constraints. It excludes land that is too steep or too dry or having unsuitable soils.

Table 2. Geographical Distribution of Tropical Degraded Lands and Potential Areas for Reforestation <sup>a</sup> (million hectares)					
Region	Logged Forests	Forest Fallow	Deforested Watersheds	Desertified Drylands	Total
Latin America	44.0	84.8	27.2	162.0	318.0
Africa	39.0	59.3	3.1	740.9	842.3
Asia	53.6	58.8	56.5	748.0	916.8
Total	136.5	202.8	86.9	1650.9	2077.1
Area Suitable for Reforestation	137	203	87	331	758

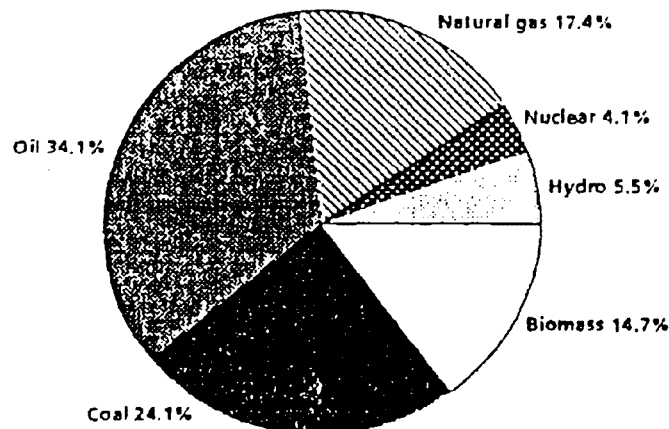
Notes to Table 2

<sup>a</sup> Source: [10].

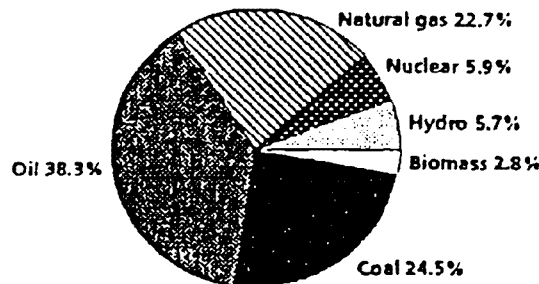
Table 3. Energy Balances for Biomass Production on Plantations <sup>a</sup>						
	Hybrid Poplar		Sorghum		Switchgrass	
	1990	2010	1990	2010	1990	2010
Energy Inputs (GJ/hectare)						
Establishment	0.14	0.14	1.29	1.29	0.39	0.39
Fertilizers	3.33	3.33	8.87	12.69	5.26	7.38
Herbicides	0.41	0.41	1.82	1.82	-	-
Equipment	0.17	0.17	-	-	-	-
Harvesting	7.31	11.69	3.72	8.24	5.47	8.41
Hauling <sup>b</sup>	2.40	3.07	3.81	6.90	2.79	3.60
Total	13.8	18.8	19.5	30.9	13.9	19.8
Energy Output (GJ/hectare)	223.7	366.3	232.8	528.5	157.5	252.0
Energy Ratio	16.3	19.5	11.9	17.1	11.3	12.7

#### Notes to Table 3

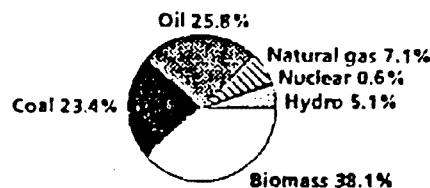
- <sup>a</sup> Source: [31].
- <sup>b</sup> The energy required to transport the biomass 40 km to a biomass processing plant.
- <sup>c</sup> Yields net of harvesting and storage losses for 1990 (2010) production technology are assumed to be 11.3 (18.5) tonnes per hectare per year for hybrid poplar (with a heating value of 19.8 GJ/tonne), 13.3 (30.2) tonnes per hectare per year for sorghum (heating value of 17.5 GJ/tonne), and 9.0 (14.4) tonnes per hectare per year for switchgrass (heating value of 17.5 MJ/tonne).
- <sup>d</sup> The energy ratio = energy output/energy input.



World  
Total = 373 exajoules  
Population = 4.87 billion  
Energy use per capita = 77 gigajoules



Industrialized countries  
Total = 247 exajoules; 66 percent of world total  
Population = 1.22 billion; 25 percent of world total  
Energy use per capita = 202 gigajoules

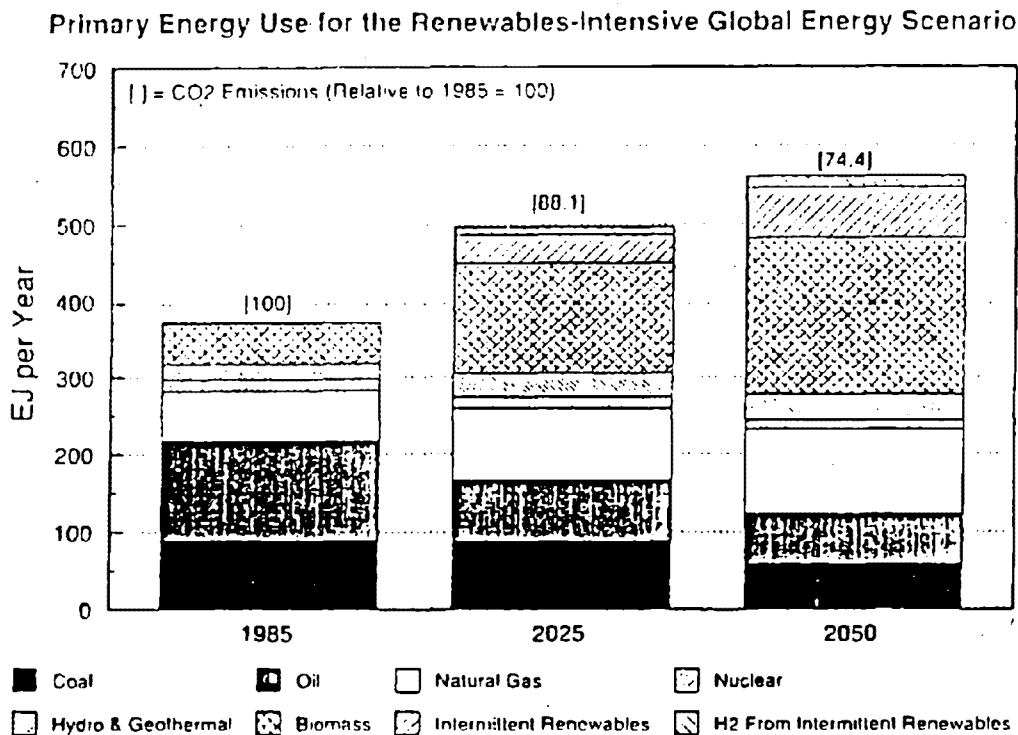


Developing countries  
Total = 126 exajoules; 34 percent of world total  
Population = 3.65 billion; 75 percent of world total  
Energy use per capita = 35 gigajoules

Figure 1. World Primary Energy Consumption by Energy Source and by World Region

Primary energy consumption is shown for the world (top), industrialized countries (middle), and developing countries (bottom) in 1985. Data for all energy sources except biomass are from [5]. Biomass energy data are estimates based on surveys, from [3].

The primary energy associated with electricity produced from nuclear and hydroelectric sources is assumed to be the equivalent amount of fuel required to produce that electricity, assuming the average heat rate (in MJ per kWh) for all fuel-fired power-generating units.



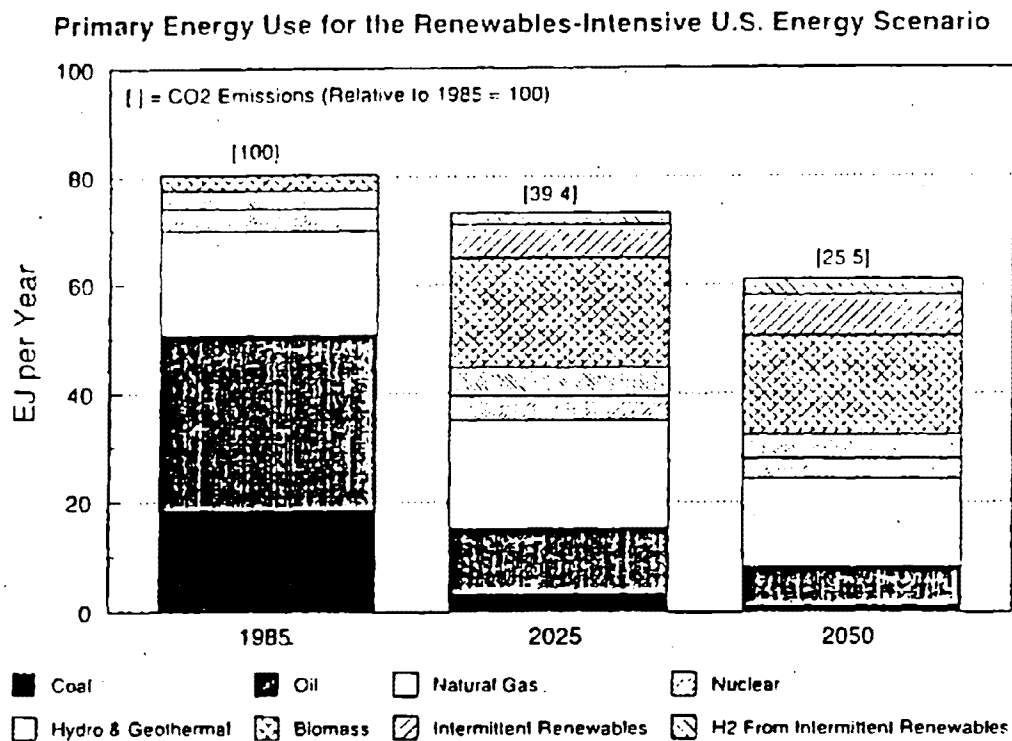
**Figure 2. Global Primary Energy Requirements for a Renewables-Intensive Global Energy Scenario**

This figure shows global primary energy requirements for the renewables-intensive global energy scenario developed in [5] in an exercise carried out to indicate the future prospects for renewable energy for each of 11 world regions. In developing this scenario, the high economic growth/high energy efficiency demand projections for solid, liquid, and gaseous fuels and electricity developed by the Response Strategies Working Group of the Intergovernmental Panel on Climate Change [36] were adopted in [5] for each world region. For each region a mix of renewable and conventional energy supplies was constructed in [5] to match these demand levels, taking into account relative prices, regional endowments of conventional and renewable energy sources, and environmental constraints.

The primary energy associated with electricity produced from nuclear, hydroelectric, geothermal, photovoltaic, wind, and solar thermal-electric sources is assumed to be the equivalent amount of fuel required to produce that electricity, assuming the average heat rate (in MJ per kWh) for all fuel-fired power-generating units in a given year. This global average heat rate is 8.05 MJ per kWh in 2025 and 6.65 MJ per kWh in 2050.

For biomass-derived liquid and gaseous fuels the primary energy is the energy content of the biomass feedstocks delivered to the biomass energy conversion facilities.

Primary energy consumption in 1985 includes 50 EJ of non-commercial biomass energy [3]. It is assumed that there is no non-commercial energy use in 2025 and 2050.



**Figure 3. Primary Energy Requirements for the US in a Renewables-Intensive Global Energy Scenario**

This figure shows primary energy requirements for the US in the renewables-intensive global energy scenario developed in [5] in an exercise carried out to indicate the future prospects for renewable energy for each of 11 world regions, one of which is the US. In developing this scenario, the high economic growth/high energy efficiency demand projections for solid, liquid, and gaseous fuels and electricity developed by the Response Strategies Working Group of the Intergovernmental Panel on Climate Change [36] were adopted in [5]. For the US and other industrialized countries, this demand scenario involves a slow decline in primary energy demand as the economy expands, as a result of the emphasis given to improved energy efficiency. The mix of renewable and conventional energy supplies shown was constructed in [5] to match these demand levels, taking into account relative energy prices, endowments of conventional and renewable energy sources, and environmental constraints.

The primary energy associated with electricity produced from nuclear, hydroelectric, geothermal, photovoltaic, wind, and solar thermal-electric sources is assumed to be equivalent to the amount of fuel required to produce that electricity, assuming the average heat rate (in MJ per kWh) for all fuel-fired power-generating units in a given year. The US average heat rate is 8.07 MJ per kWh in 2025 and 6.42 MJ per kWh in 2050.

For biomass-derived liquid and gaseous fuels the primary energy is the energy content of the biomass feedstocks delivered to the biomass energy conversion facilities.

## Interregional Fluid Fuel Exports in Renewables-Intensive Global Energy Scenario (millions of barrels of oil-equivalent per day)

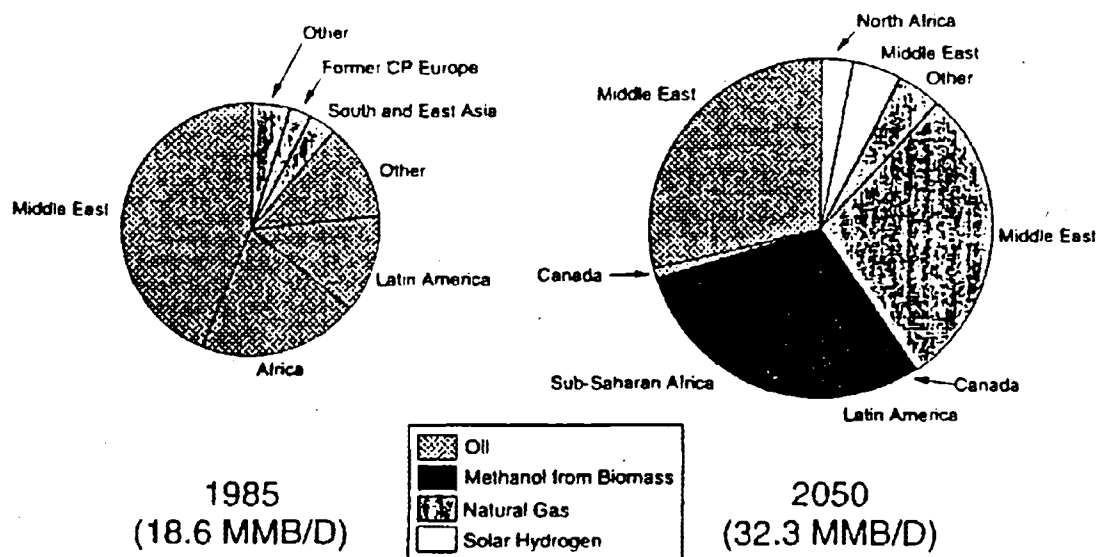
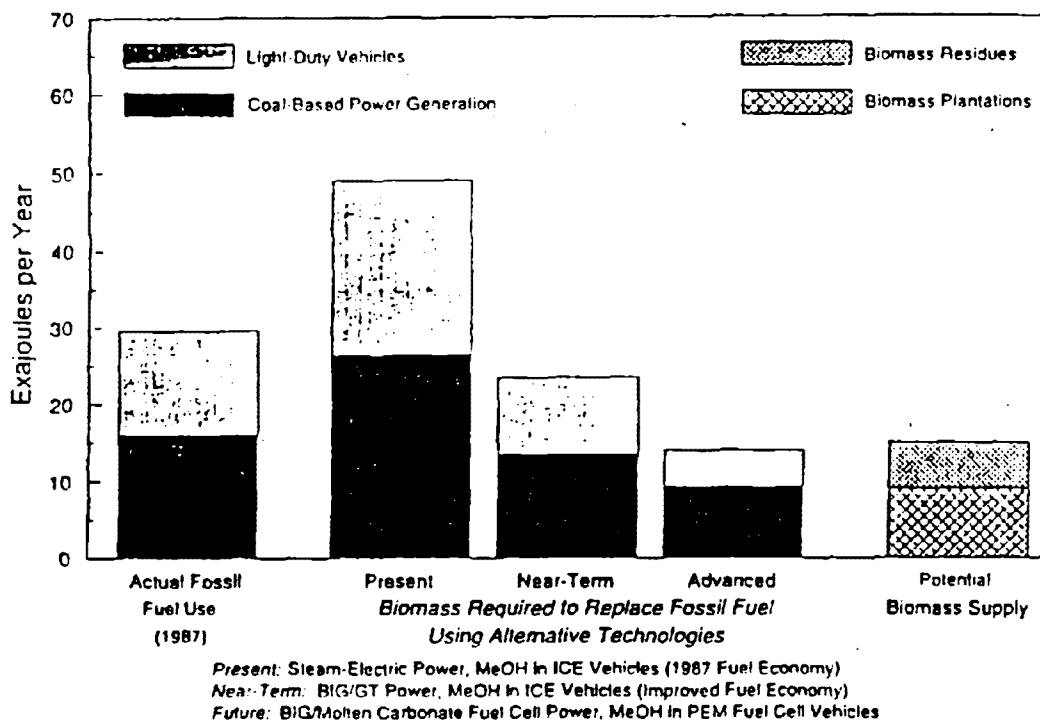


Figure 4. Interregional Fuels Flows for a Renewables-Intensive Global Energy Scenario

The importance of world energy commerce for the renewables-intensive global energy scenario developed in [5] and for which global primary energy consumption is shown in Figure 2 is illustrated here. The figure shows that by the middle of the next century there would be comparable interregional flows of oil, natural gas, and biomass-derived methanol, as well as small flows of hydrogen derived from renewable sources. This diversified supply mix is in sharp contrast to the situation today, where oil dominates international commerce in liquid and gaseous fuels.

Most methanol exports would originate in sub-Saharan Africa and in Latin America, where there are vast degraded areas suitable for revegetation that will not be needed for cropland (*see Tables 1 and 2*). Growing biomass on such lands as feedstocks for producing methanol (or other biomass fuels) would provide a powerful economic driver for restoring these lands.



**Figure 5. Energy for Light-Duty Vehicles and Power Generation in the US**

Shown here are the biomass primary energy requirements for displacing all petroleum used by light-duty vehicles (automobiles and light trucks) and all coal-fired power generation in the US, at the 1987 activity levels, with alternative biomass technologies, in relation to potential biomass supplies.

The bar on the left shows fuel actually consumed in 1987 by light-duty vehicles and by coal-fired power plants. The second bar shows the biomass primary energy requirements if light-duty vehicles and coal-fired power plants at 1987 activity levels were replaced by biomass energy systems that are commercially available today. The third bar shows biomass requirements if technologies likely to be available in the year 2000+ time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. The fourth bar shows the biomass requirements if technologies likely to be widely available in the 2020 time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. The bar on the right shows potential biomass supplies from plantations on 30 million hectares of excess agricultural lands plus residues (urban refuse plus agricultural and forest product industry residues) that are recoverable under environmental constraints.

For details see Endnote for Figure 5.



## ENDNOTE FOR FIGURE 5

The bar on the left represents fuel consumed in 1987 by light-duty vehicles and by coal-fired power plants. Automobiles and light trucks, with average fuel economies of 19.1 mpg and 12.9 mpg, respectively, consumed 103 billion gallons of gasoline. In 1987 coal-fired power plants, operated with an average efficiency of 32.9%, produced 1464 TWh of electricity.

The second bar shows the biomass primary energy requirements if light-duty vehicles and coal-fired power plants at 1987 activity levels were replaced by biomass energy systems that are commercially available today. With present biomass gasification technology (adapted directly from coal gasification) methanol can be produced from wood at 50% efficiency (HHV basis). Operated on methanol, cars and light trucks would have gasoline-equivalent fuel economies of 22.9 mpg and 15.5 mpg, respectively, some 20% higher than gasoline vehicles, because of the higher thermal efficiency of internal combustion engines when operated on methanol [29]. The net result is that the biomass feedstock requirements to support the 1987 level of light-duty vehicles would be  $1/(0.5 \cdot 1.2) = 1.67$  times the amount of gasoline used by light-duty vehicles in 1987. The present average efficiency of biomass power plants operating in California is about 20%, so that the biomass plants would require  $32.9/20 = 1.65$  times as much fuel to make electricity as the coal plants they would displace.

The third bar shows the biomass primary energy requirements if biomass technologies likely to be available in the year 2000+ time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. It is cost-effective to increase the average (on-the-road) fuel economy of new cars and light trucks to about 33.6 and 22.7 mpg (76% higher than in 1987), respectively, if operated on gasoline, and to 40.3 and 27.2 mpg of gasoline-equivalent energy (20% higher than on gasoline), respectively, if operated on methanol. Such a shift could be achieved over the next couple of decades. During this period it would be feasible to introduce methanol production technology involving indirect biomass gasification, for which the overall biomass-to-methanol conversion efficiency is 63% [32]. With these technologies biomass fuel input requirements would be  $(1/1.76)/(0.64 \cdot 1.2) = 0.74$  times as large as the petroleum required in 1987. If electricity were produced from biomass using biomass integrated gasifier/gas turbine technology that could be introduced commercially in this time frame, the efficiency of power generation would be 39%, nearly double that of existing biomass power plants, so that the biomass plants would require  $32.9/39 = 0.84$  times as much fuel to make electricity as the coal plants they would displace.

The fourth bar shows the biomass primary energy requirements if biomass technologies likely to be available in the 2020 time frame were used to replace all oil used for light-duty vehicles and all coal-based power generation, at 1987 activity levels. By the end of the second decade of the 21st century, biomass-derived methanol could be routinely used in proton-exchange-membrane fuel-cell vehicles at gasoline-equivalent fuel economies that are 2.5-times the fuel economies of gasoline-powered internal-combustion-engine vehicles of comparable performance [5, 6]. With these technologies biomass fuel input requirements would be  $(1/1.76)/(0.64 \cdot 2.5) = 0.355$  times as large as the petroleum required in 1987. Also, by that time, biomass integrated gasifier/fuel cell systems (using molten carbonate or solid oxide fuel cells) for stationary power generation could well be available with biomass-to-electricity conversion efficiencies of perhaps 57% [33], for which fuel requirements would be  $32.9/57 = 0.577$  times coal requirements for power generation in 1987.

The fifth bar shows potential US biomass supplies, consisting of (i) 9 EJ per year of plantation biomass grown on 30 million hectares of excess agricultural lands at an average productivity of 15 dry tonnes per hectare per year and a heating value of 20 GJ per dry tonne of biomass, plus (ii) 6 EJ per year of those residues (urban refuse, agricultural residues, forest product industry residues) that are estimated to be recoverable under environmental constraints [28].

## **APPENDIX A: PHASING OUT AGRICULTURAL SUBSIDIES IN INDUSTRIALIZED COUNTRIES BY CONVERTING EXCESS AGRICULTURAL LANDS TO BIOMASS PRODUCTION FOR ENERGY**

Public policies provide subsidies to agricultural producers both via monetary transfers from taxpayers through government budgets and from consumers through higher prices for agricultural commodities. These subsidies are large--amounting in 1987 to \$295 billion for all countries of the Organization for Economic Cooperation and Development (OECD) and to \$81 billion (some \$330 per capita) for the US alone [11]--equivalent to about one-fifth of total retail expenditures on energy in the US [37]--see *Table A1*.

These subsidies were a focus of the May 1987 ministerial level meeting of the Council of the OECD. The communique issued at this meeting declared [11]:

"Boosted by policies which have prevented an adequate transmission of market signals to farmers, [agricultural] supply substantially exceeds effective demand. The cost of agricultural policies is considerable, for government budgets, for consumers, and for the economy as a whole. Moreover, excessive support policies entail an increasing distortion of competition on world markets; run counter to the principle of comparative advantage which is the root of international trade and severely damage the situation of of many developing countries. This steady deterioration...creates serious difficulties in international trade, which risk going beyond the bounds of agricultural trade alone...This deterioration must be halted and reversed..."

The communique included as recommended agricultural policy reform principles:

- "a) The long-term objective is to allow market signals to influence by way of a progressive and concerted reduction of agricultural support, as well as by all other appropriate means, the orientation of agricultural production; this will bring about a better allocation of resources which will benefit consumers and the economy in general."
- "f) The adjustment of the agricultural sector will be facilitated if it is supported by comprehensive policies for the development of various activities in rural areas. Farmers and their families will thus be helped to find supplemental or alternative income."

Despite the commitment to reform made in 1987, as of 1991 there was no fundamental reform of agricultural policy for the OECD as a whole, as shown by time series data (*see Table A1*).

This stalemate could be ended and both of the above reform principles of the OECD ministerial communique could be satisfied if policies were adopted to convert excess agricultural lands to biomass production for energy purposes.

Principle "f" could be satisfied by eliminating the bias in current policies against energy crops. (In many countries public policy specifies what crops the farmer can produce to qualify for a subsidy; and energy crops are not allowed.) As the energy crop production industry becomes well established it would be feasible to begin phasing out many of the subsidies, thus satisfying principle "a."

Table A1. Transfers to Agricultural Producers Associated with Agricultural Policies of OECD Countries<sup>a</sup>

	1987		1988		1989		1990		1991	
	A <sup>b</sup>	B <sup>c</sup>	A <sup>b</sup>	B <sup>c</sup>	A <sup>b</sup>	B <sup>c</sup>	A <sup>b</sup>	B <sup>c</sup>	A <sup>b</sup>	B <sup>c</sup>
Australia	0.6	38	0.6	35	0.7	39	1.1	67	1.2	70
Austria	3.8	501	3.5	465	2.9	379	4.1	532	4.1	534
Canada	8.6	335	8.7	334	8.3	315	9.8	369	9.5	353
EC-12	119.4	369	120.8	372	101.2	311	138.3	401	141.8	409
Finland	4.4	894	4.9	997	4.9	994	6.0	1208	5.9	1173
Japan	65.5	537	70.7	577	65.8	534	60.4	489	63.2	510
N. Zealand	0.1	35	0.2	57	0.1	29	0.1	25	0.1	19
Norway	3.3	793	3.5	825	3.3	790	4.2	993	4.2	987
Sweden	3.2	377	3.0	357	3.1	362	3.5	404	3.6	416
Switzerland	5.3	803	5.6	842	5.0	750	6.2	916	6.4	925
US										
from taxpayers	51.6		44.2		47.8		44.2		51.8	
from consumers	30.8		26.0		23.7		29.7		29.9	
Tariff revenues	- 1.4		- 1.1		- 0.7		- 0.9		- 1.0	
Subtotal	80.9 <sup>d</sup>	332	69.2 <sup>d</sup>	281	70.8 <sup>d</sup>	285	73.0	290	80.8	318
OECD										
from taxpayers	119.6		121.8		119.5		129.4		142.9	
from consumers	190.6		187.6		161.0		190.4		195.4	
Tariff revenues	- 15.2		- 18.6		- 14.4		- 13.1		- 17.6	
Total	295.2	361	290.7	353	266.1	321	306.8	367	320.7	380

<sup>a</sup> Source: [11].<sup>b</sup> A = total transfers, in billion US dollars per year.<sup>c</sup> B = transfers per capita, in US dollars per capita per year.<sup>d</sup> For comparison, retail expenditures on energy in the US totalled \$394 billion in 1987, \$408 billion in 1988, and \$437 billion in 1989 [37].

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This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

**AN ANALYSIS OF THE HYDROCARB PROCESS  
FOR METHANOL PRODUCTION FROM BIOMASS**

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**ABSTRACT**

A pilot plant is being designed to evaluate the technical feasibility of producing transportation fuel from biomass by the Hydrocarb process. As a basis for that design, computer simulations and experimental studies have been carried out to establish optimum process conditions for a range of feedstocks that are anticipated for pilot plant tests. This paper discusses the results of simulations to determine the operating parameters and performance when using urban wastes such as greenwaste and sewage sludge as feedstocks. The simulations were used to configure the process steps for maximum fuel (methanol) production, to determine feed rates, and to estimate thermal efficiency. The results indicate that about 77 kg of methanol can be produced from 79 kg of dry greenwaste when sludge and digester gas are fed as co-feedstocks in a ratio of 0.2. The optimum system pressure is found to be 50 atm (5 MPa). Temperatures of 900°C for gasification and 1000°C for methane pyrolysis are recommended on the bases of thermodynamics, kinetics, and the limitations of materials of construction. Thermal efficiency at these conditions is estimated to be 74 percent.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

## INTRODUCTION

Thermodynamic calculations suggest that the Hydrocarb process<sup>(1,2)</sup> might produce carbon black, hydrogen, and/or methanol from fossil fuels or virtually any other carbonaceous materials and might do so with high thermal efficiency. Potential feedstocks include coals of all ranks, residual oil, oil shale, woody biomass, sewage sludge, and municipal wastes. This innovative process consists of three essential reactions: (1) hydrogasification of the carbonaceous feedstocks to produce a methane-rich gas, (2) thermal decomposition of methane to carbon and a hydrogen-rich gas which is recycled, and (3) catalytic conversion of the carbon monoxide (CO) and hydrogen contained in the recycled gas to produce methanol. The mix of process products is optional: a clean solid fuel (carbon black), a liquid fuel (methanol), slurry fuel mixtures of carbon and methanol, or gaseous fuels (hydrogen and methane) can be produced by changing the order of the reaction steps.

Since the process operates without additional steam and oxygen--and because the oxygen in the feedstocks is removed mainly in the form of methanol and water--the carbon dioxide (CO<sub>2</sub>) emission is significantly reduced in comparison to traditional fossil fuel conversion processes involving steam/oxygen gasification<sup>(3)</sup>. When biomass is used as a co-feedstock with fossil fuel to produce methanol and the carbon is sequestered, the CO<sub>2</sub> greenhouse gas emission can be significantly reduced and even eliminated<sup>(4,5)</sup>.

## PRELIMINARY ANALYSES

In order to attain a better understanding of the potential of the Hydrocarb process, particularly as a means of producing a clean transportation fuel from biomass, the U.S. Environmental Protection Agency (EPA) developed an interagency agreement with the Brookhaven National Laboratory to perform detailed process analyses and related experimental studies of biomass hydrogasification and methane pyrolysis. The process was analysed using a computer simulation model developed by Hydrocarb Corporation that performs complete mass and energy balances for various process configurations, feedstock options, reactor types, and operating conditions. Initial results of the simulations were published by the EPA in 1991<sup>(3)</sup>; a follow-up report is in preparation.

EPA's independent assessment of the biomass/natural-gas option of the Hydrocarb process as a technology for production of alternative transportation fuels<sup>(6)</sup> confirmed that it can, theoretically, produce methanol at a cost that is competitive with petroleum fuels. Most importantly, it concluded that methanol may be produced and utilized in the transportation sector with a 70 percent reduction in CO<sub>2</sub> emission relative to gasoline at no incremental cost and may achieve 100 percent CO<sub>2</sub> reduction at marginal incremental cost. Other potential advantages derive from its higher yield of fuel energy compared to other processes for producing alternative fuels from biomass or from natural gas by the conventional steam reforming process. The Hydrocarb approach therefore has potential for mitigating CO<sub>2</sub> emissions from mobile sources in a more effective manner than current alternatives. Since the transportation sector accounts for at least 24 percent of total CO<sub>2</sub> emissions, any means of reducing that source will have to be considered when assessing options for dealing with the global warming problem.

## PILOT PLANT EVALUATION

Because of methanol's potential role in reducing urban air pollution, the South Coast Air Quality Management District (SCAQMD) of California is seeking new technologies for domestic methanol production, especially from urban wastes, and has agreed to co-sponsor with the EPA a pilot plant evaluation of the Hydrocarb process. Preliminary design of that pilot plant is now in progress. The objectives are: (1) to demonstrate the technical feasibility of producing methanol from woody biomass and natural gas by the Hydrocarb process, and (2) to evaluate its performance using sewage sludge, digester gas, and greenwaste as alternative feedstocks. If successful, the results will be used to establish more comprehensive cost estimates and provide a basis for decisions regarding further development. Prior analyses<sup>(3,5,6)</sup> have considered the use of woody biomass and natural gas as feedstocks. This paper focuses on the design of a pilot plant that will utilize 50 lb/hr (23 kg/hr) of urban wastes as feedstock.

## LABORATORY STUDIES

### KINETICS OF BIOMASS HYDROGASIFICATION

The hydrogasification of biomass in the form of poplar wood having particle size less than 150  $\mu\text{m}$  in diameter was investigated in a 25 mm ID and 2.5 m long tubular reactor facility described in detail elsewhere<sup>(7,8)</sup>. The tests were conducted at temperatures up to 800°C and pressures between 30 and 50 atm. The experiments were performed in two modes depending upon the heatup rate. In the low heatup mode, the biomass was first loaded in the reactor at room temperature. Hydrogen was then introduced into the system until the desired initial pressure was established. The reactor was slowly heated at a rate less than 10°C/min while the change of pressure in the reactor and the composition of the effluent gas were monitored with time. In the higher heatup mode, the reactor was first heated to the desired temperature and pressurized with hydrogen before introducing the biomass. From the variation of pressure and gas composition versus time, the rates of reaction and degree of conversion were determined. The high-heatup-rate experiments showed that 88 to 90 wt percent of biomass could be gasified at residence times in the order of 15 minutes<sup>(7)</sup>. The number of moles of gas formed, as calculated from the pressure change, varies with time as shown in Figure 1.

### METHANE PYROLYSIS

The rate of thermal decomposition of methane was investigated using the same reactor facility at temperatures ranging from 700 to 900°C and pressures of 28 to 56 atm<sup>(8)</sup>. In these experiments, methane was continuously fed into the reactor. On-line gas analyses were taken upstream and downstream of the reactor to determine the reaction rate. The variation of methane concentration with residence time at different operating conditions, shown in Figure 2, indicates that a gas residence time of about 2 min is required for the reaction to reach equilibrium composition at 50 atm and 900°C. The activation energy is found to be 31.3 kcal/mol. By extrapolating it to higher temperatures, the residence time would be 41 sec at 1000°C and 12 sec at 1140°C.



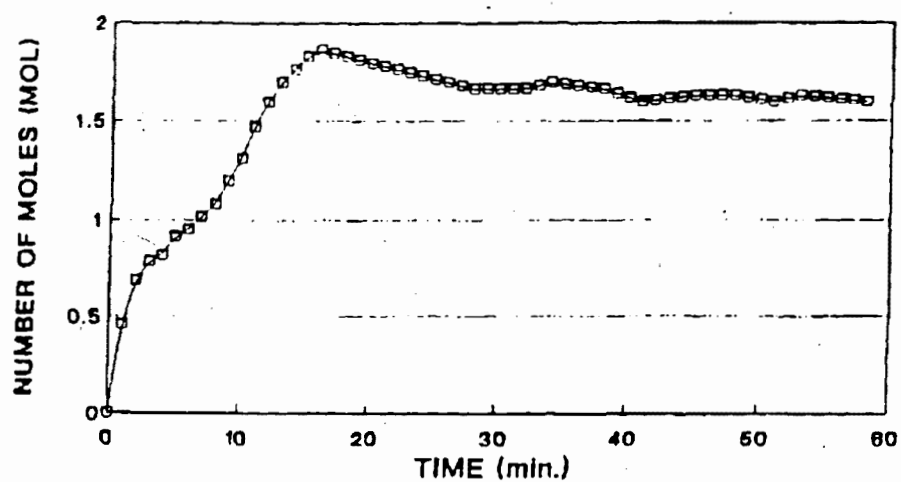


Figure 1. The change in number of moles in the reactor with time at 800°C and 5.24 atm of initial hydrogen pressure. Run No. 1152

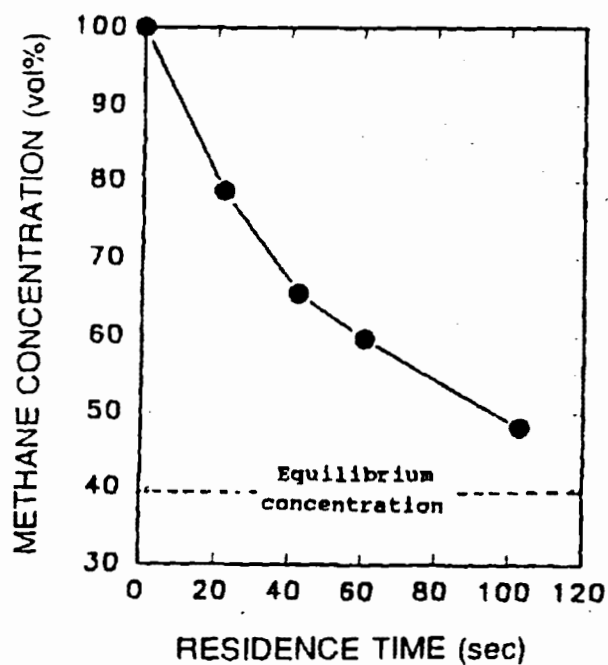


Figure 2. Methane concentration vs. gas residence time. (56.1 atm and 900°C)

## PROCESS SIMULATION STUDIES

### REACTION SEQUENCE

There are two possible configurations for the Hydrocarb process, according to the sequence of the three reactor steps involved. One of these configurations, Cycle 1, is designed so that the process gas flows successively from the hydrogasification reactor (HPR) through the methane pyrolysis reactor (MPR), the methanol synthesis reactor (MSR), and the methanol condenser (COND). The gas leaving the condenser is recycled back to the HPR after withdrawing a small purge gas stream. The other configuration, Cycle 2, directs the process gas formed in the HPR to the MSR and condenser, then to the MPR, followed by recycle to the HPR. Figures 3 and 4 illustrate these configurations.

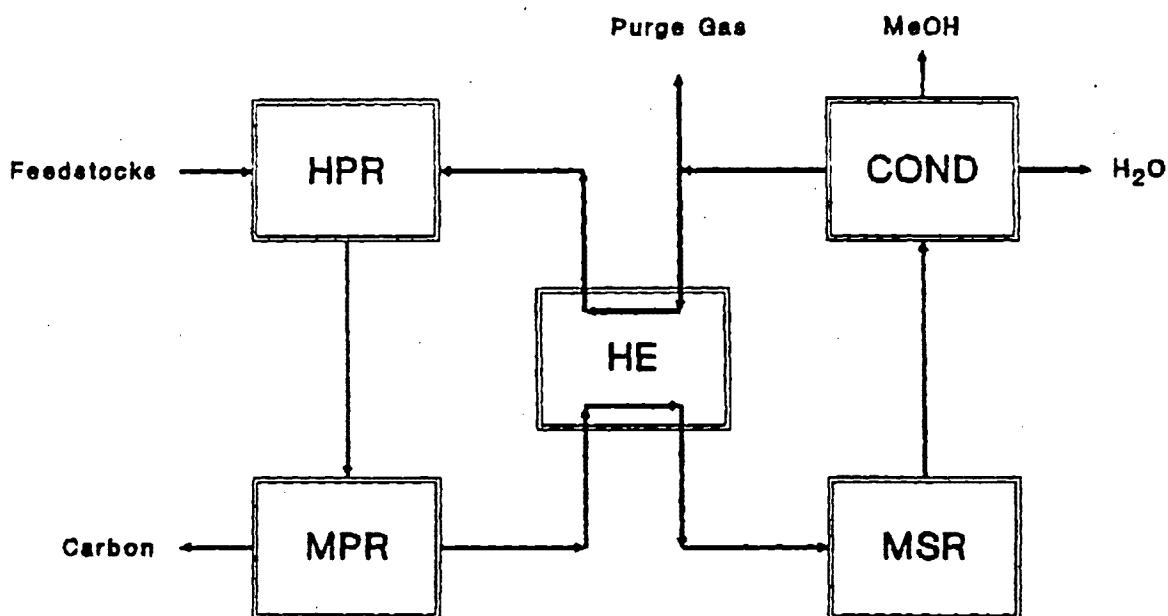


Figure 3. Cycle 1 of the Hydrocarb process.

In Cycle 1, the process gas from the MPR is cooled from the temperature of that reactor down to the MSR reaction temperature, 260°C, and this recovered energy is used to heat the process gas from the condenser, operating at 50°C, up to about the temperature of the HPR. From an energy balance on the HPR (assumed to be a fluidized bed), the temperature of the recycled process gas fed into it is adjusted until the reaction heat generated in the HPR is balanced by the enthalpy difference of inlet and outlet gas streams. In Cycle 2, two gas/gas heat exchangers are used: one cools the gas stream from the temperature of the HPR to the temperature of the MSR by heating the gas stream from the condenser; and before entering the MPR, the process gas is further heated in the second heat-exchanger by the hot gas stream from the MPR.

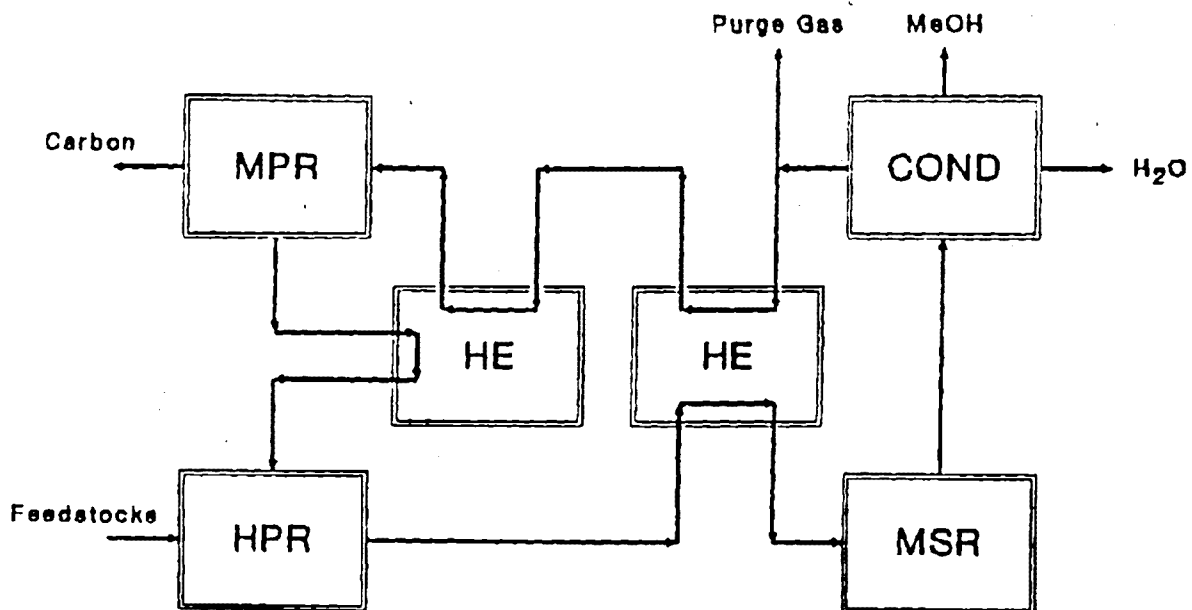


Figure 4. Cycle 2 of the Hydrocarb process.

The primary interest of SCAQMD and EPA is to produce a maximum amount of methanol from biomass. With this in mind, computer simulations were made with the process model to compare the above cycles and determine which is better suited to that objective. The feedstocks assumed for this comparison are representative of urban wastes obtained from a California wastewater treatment plant (sewage sludge and digester gas) and other sources (greenwaste). The compositions of these materials are listed in Table 1. Included in Table 1 are the higher heating values (HHVs) of each fuel, given on a moisture-free basis (MF), and the heat of formation, which is expressed on a moisture-and-ash-free basis (MAF).

#### Performance Criteria

Several important performance criteria are used to compare the two cycles and also to assess the performance of Hydrocarb with alternative feedstocks. They include: minimum methane feed per unit of biomass feed, production ratio of methanol to carbon black, carbon efficiency, thermal efficiency, and gas circulation rate. Thermal efficiency is defined here as the total heating value of methanol, carbon black, and net purge-gas production (i.e., that which is not used to heat the MPR) divided by the total heating value of biomass, natural gas, and any external fuel source that is used to heat the MPR or close the energy balance. Similarly, carbon efficiency is the ratio of total carbon in all of the products to the carbon in all of the feedstock materials including the fuel used for MPR heating.

TABLE 1. PROPERTIES OF THE FEEDSTOCKS USED  
IN THE STUDY

Feedstock	Green- waste	Methane CH <sub>4</sub>	Sewage Sludge	Digester Gas
Molecular Formula	CH <sub>1.4</sub> O <sub>0.54</sub>	CH <sub>4</sub>	CH <sub>1.7</sub> O <sub>0.42</sub>	CH <sub>2.5</sub> O <sub>0.74</sub>
Composition (wt%)				
C	49.11	-	28.55	-
H	5.85	-	4.09	-
O	35.41	-	16.03	-
H <sub>2</sub> O	5.00	-	9.82	-
Ash	3.34	-	36.53	-
S	0.16	-	1.36	-
N	1.13	-	3.62	-
CH <sub>4</sub>	-	100	-	36.81
CO <sub>2</sub>	-	-	-	61.82
High Heating Value (Btu/lb-MF) <sup>a</sup>	-8670	-23881	-5510	-8792
(kcal/kg-MF) <sup>b</sup>	-4817	-13267	-3061	-4884
Heat of Formation (kcal/kg-MAF)	-1386	-	-1770	-

<sup>a</sup> 1 Btu/lb = 2 kJ/kg

<sup>b</sup> 1 kcal/kg = 4 kJ/kg

Using the above performance criteria, Table 2 compares Cycles 1 and 2 under the same operating conditions when the feedstocks are greenwaste and natural gas. The comparison is based on a capacity of 100 kg/hr of greenwaste containing 5 wt percent moisture. The HPR is assumed to be a fluidized bed in which 90 percent of the carbon content of the biomass is gasified (an assumption justified by the experimental work discussed above). The material balances calculated for the two cycles show that a minimum natural gas feed equivalent to 10 wt percent of the biomass feed is required for Cycle 1 and 6 percent for Cycle 2.

TABLE 2. COMPARISON BETWEEN CYCLE 1 AND CYCLE 2  
WITH BIOMASS AND NATURAL GAS AS FEEDSTOCKS  
(50 atm, HPR = 900°C, AND MPR = 1000°C)

Cycle	1	2
Greenwaste (5% H <sub>2</sub> O) (kg/h)	100	100
CH <sub>4</sub> Rate (kg/h)	10	10
Burning CH <sub>4</sub> for MPR (kg/h)	12.8	11.6
Methanol (kg/h)	58.0	31.6
Carbon Black (kg/h)	29.7	35.6
MeOH/C (kg/kg)	1.95	0.89
Carbon Efficiency (%)	77.8	75.1
Thermal Efficiency (%)	72.0	64.4
Gas Recycle (kgmol/h)	46.4	43.6

Table 2 compares the results of process simulations of the two cycles under the same operating conditions using greenwaste and natural gas as co-feedstocks. It can be concluded that Cycle 1 provides the higher methanol production and greater thermal efficiency; moreover, it requires only one heat exchanger. Thus, Cycle 1 is the configuration that will be used for pilot plant evaluation.

## FEEDSTOCK SIMULATIONS

### Greenwaste Moisture

As shown in Table 2, 100 kg of greenwaste containing 5 percent moisture should produce 58 kg of methanol when Hydrocarb is operated in the Cycle 1 configuration. The moisture content of the feedstock was found to have an influence on process performance as illustrated for greenwaste in Table 3. The basis for these calculations was 95 kg/h of moisture-free greenwaste to which varying amounts of water are added. The reaction temperature was 900°C for the HPR and 1000°C for the MPR. The table shows that the minimum methane feed ratio, which is the weight ratio of methane to greenwaste fed into the HPR for hydrogasification, increases with moisture content of the greenwaste in order to maintain material balance in the system. Table 3 also indicates that the methanol yield and the thermal efficiency improve with increasing moisture content of greenwaste. However, as the moisture in biomass fed into the HPR increases, the exothermic heat generated in the reactor decreases, resulting in the requirement of a higher temperature of the process gas recycled into the HPR in order to keep its reaction temperature constant.

**TABLE 3. EFFECT OF MOISTURE IN GREENWASTE  
ON THE PERFORMANCE OF THE PROCESS  
(based on 95 kg/h MF greenwaste)**

H <sub>2</sub> O/MF-GW (wt. %)	5.26	10.5	15.8	21.1
Min. CH <sub>4</sub> /MF-GW (kg/kg)	0.1	0.12	0.14	0.16
T of PG into HPR (°C)	892	910	927	944
Methanol (kg/h)	58.0	65.5	73.1	80.8
Carbon Black (kg/h)	29.7	28.4	27.0	25.5
MeOH/C (kg/kg)	1.95	2.31	2.71	3.17
Carbon Efficiency (%)	77.8	77.8	77.7	77.7
Thermal Efficiency (%)	72.0	72.8	73.4	74.1
Gas Recycle (kgmol/h)	46.4	47.5	48.6	49.8

When the weight ratio of moisture to greenwaste reaches 21.1 percent, the temperature of the process gas recycled to the HPR is required to be 944°C. If the moisture of greenwaste is further increased, the overall reaction heat in the HPR will become endothermic. Therefore, there is an optimum moisture content of the feedstock for maximum methanol yield. For greenwaste, that optimum is 21 percent (Table 3), which yields about 81 kg of methanol for every 95 kg of dry biomass. Biomass moisture contents can be adjusted to the optimum value by water addition or by external drying using waste heat from the MPR heater or from the methanol converter.

## Sewage Sludge and Digester Gas

Additional simulations were made assuming the feedstocks to be sewage sludge and digester gas, supplemented by greenwaste and natural gas. These comparisons are based on a fixed capacity of 100 kg/h of total solid feedstocks including sludge and greenwaste. For these calculations, both the greenwaste and sludge were assumed to be dried to 5 percent moisture before entering the HPR. The process performance of Cycle 1 at 50 atm and 900°C for the HPR and 1000°C for the MPR is summarized in Table 4 assuming various feed ratios of sludge to greenwaste. The methane feed was 15 percent of the greenwaste rate for all cases, while the ratio of digester gas to sludge was 0.5, based on the gas generating capacity of the sewage plant. A maximum allowable sludge feed ratio of 0.4 (sludge/greenwaste) was found in the calculation; if this ratio is further increased, the HPR becomes endothermic and an additional heat source would be needed for the HPR.

**TABLE 4. THE EFFECTS OF SLUDGE/GREENWASTE FEED RATIO ON THE PROCESS PERFORMANCE (50 atm, HPR = 900°C, and MPR = 1000°C)**

Sludge/Greenwaste	0	0.1	0.2	0.3	0.4
Greenwaste (kg/h) <sup>a</sup>	100.0	90.90	83.33	76.92	71.43
Sludge (kg/h) <sup>a</sup>	0	9.10	16.67	23.08	28.57
CH <sub>4</sub> (kg/h)	15.00	13.61	12.50	11.53	10.69
Digester Gas (kg/h)	0	4.54	8.33	11.53	14.26
Limestone (kg/h) <sup>b</sup>	1.43	2.47	3.32	4.07	4.66
Methanol (kg/h)	56.44	57.73	58.92	59.91	60.62
Carbon Black (kg/h)	31.99	31.32	30.83	30.38	29.94
MeOH/C (kg/kg)	1.76	1.84	1.91	1.97	2.02
Carbon Efficiency (%)	79.65	79.62	79.59	79.57	79.55
Thermal Efficiency (%)	72.30	72.65	72.94	73.19	73.40

<sup>a</sup> 5% moisture content in greenwaste and sludge.

<sup>b</sup> Molar feed ratio of limestone to total sulfur in feedstocks is assumed to be 2.0.

The data in Table 4 show that the thermal efficiency and the product ratio are only slightly affected by the sludge/greenwaste ratio. This indicates that sludge can be processed with greenwaste by the Hydrocarb process to produce considerable amounts of methanol and carbon black. Calculations also found that there is an optimum moisture content for each sludge/greenwaste feed ratio. As shown in Table 5, increasing the moisture content of sludge/greenwaste feeds increases the product ratio of methanol to carbon black and the thermal efficiency of the process. Since the maximum allowable ratio of sludge to greenwaste is 0.4, the pilot plant design took a sludge/greenwaste ratio of 0.2 as a representative data base. The optimum flow rate and composition of each stream for the feed ratio (sludge/greenwaste) of 0.2 is shown in Figure 5. When feeding digester gas, it is interesting to note that part of the CO<sub>2</sub> component of that gas reacts in the HPR with carbon in the greenwaste to form CO and methane and the rest of that CO<sub>2</sub> is converted to CO in the MPR. This results in an increase in the CO

mole fraction of the process gas from 2.24 to 5.79 percent in the HPR and from 5.79 to 7.82 percent in the MPR. The CO is then converted to methanol in the MSR. Some waste CO<sub>2</sub>, as well as waste biomass, is thus recycled to a clean fuel.

TABLE 5. OPTIMUM MOISTURE CONTENT FOR  
SLUDGE/GREENWASTE FEEDSTOCKS

Sludge/Greenwaste	0.2	0.4
Dry greenwaste (kg/h)	79.16	67.86
moisture (kg/h)	14.08	9.96
Sludge (kg/h)	15.84	27.14
moisture (kg/h)	1.72	2.96
CH <sub>4</sub> (kg/h)	12.50	10.69
Digester Gas (kg/h)	8.33	14.26
Limestone (kg/h)	3.26	4.66
Methanol (kg/h)	76.86	73.90
Carbon Black (kg/h)	25.85	26.35
MeOH/C (kg/kg)	2.97	2.80
Carbon Efficiency (%)	77.88	78.28
Thermal Efficiency (%)	74.17	74.30

## OPERATING CONDITIONS

The pressure and temperature at which the HPR and MPR are operated affect the performance of the Hydrocarb process. With regard to the HPR, the temperature is established by the requirement for desulfurization, especially in the case of sewage sludge, which is to be partially accomplished by limestone addition. Given the CO<sub>2</sub> partial pressures in the HPR, the active hydrogen sulfide sorbent, calcium oxide, can exist only at temperatures above 850°C. For that reason, and the fact that gasification rate and carbon conversion increase with temperature, an HPR temperature of 900°C is established.

### Temperature

The effect of temperature in the MPR was investigated at 50 atm pressure when the HPR temperature is fixed at 900°C. The results shown in Table 6 indicate that increasing the MPR temperature will improve the methanol production and reduce the process gas circulation rate. However, the temperature in the MPR is limited by the thermal and structural properties of the materials of construction. When a MPR temperature of 950°C is assumed, the HPR is no longer energy neutral: it becomes endothermic. For these reasons, 1000°C is the recommended temperature for the MPR.

## Pressure

The influence of pressure is also presented in Table 6. The methanol production rate is found to increase with decreasing system pressure. However, as pressure decreases, the thermal efficiency is reduced and the gas circulation rate (which affects capital cost of the plant) increases significantly. Since catalytic methanol converters normally require at least 50 atm pressure, some simplification is achieved if the other two process steps that produce the synthesis gas are conducted at the same pressure.

From this study it is concluded that the most favorable operating conditions for co-processing biomass and methane are 50 atm system pressure, and temperatures of 900°C in the HPR and 1000°C in the MPR.

**TABLE 6. EFFECTS OF PRESSURE AND TEMPERATURE ON THE PROCESS PERFORMANCE (100 kg/h GW,  $\text{CH}_4/\text{GW} = 0.15$ , HPR = 900°C)**

P atm	T/MPR °C	MeOH/C kg/kg	C Eff %	Ther Eff %	Recycle Gas kgmol/h
50	1000	1.76	79.7	72.3	47.5
50	1050	2.31	78.1	72.3	34.4
50	1100	2.65	77.3	72.3	27.4
50	1200	2.96	76.4	71.9	20.4
60	1000	1.55	80.9	72.7	44.7
50	1000	1.76	79.7	72.3	47.5
40	1000	2.06	77.9	71.2	53.7
30	1000	2.31	74.8	67.9	68.3

## **PILOT PLANT DESIGN**

Based on the above process analysis and kinetics experiments, design specifications are being developed for the HPR and MPR of a 50 lb/h Hydrocarb pilot plant utilizing biomass feedstocks. The energy balance simulations are based on fluidized bed reactors which will be used for both the hydrogasification of biomass and the decomposition of methane. The reaction temperature in the HPR is controlled by adjusting the temperature of the inlet process gas from the gas heat exchanger which recovers the heat in the hot process gas from the MPR.

The heat required for the MPR is to be provided by circulating alumina particles between the fluidized bed MPR and a riser combustor. Other fuels such as methane or by-product carbon are burned in the riser to heat the alumina particles. The hot particles then enter the MPR where their sensible heat is transferred to the entering gas. The cooled particles are then returned to the riser combustor for reheat. Detailed design specifications for the HPR, MPR, reheater, and other equipment for the pilot plant are being developed.



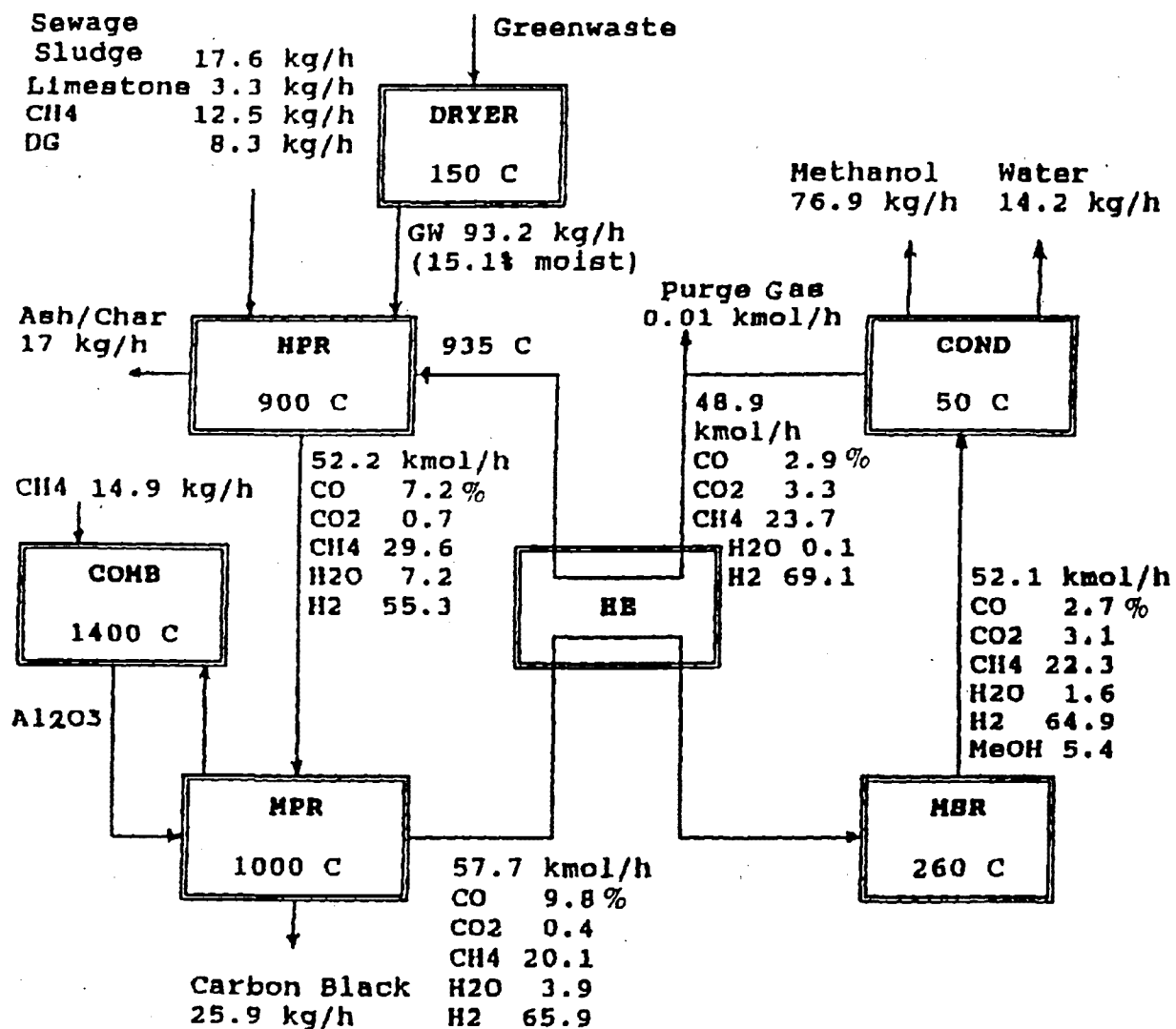


Figure 5. Rates and compositions of various streams for the optimum conditions with greenwaste (GW), sludge (SL), CH<sub>4</sub>, and digester gas (DG) as feedstocks (50 atm, SL/GW = 0.2).

## SUMMARY AND CONCLUSIONS

The process design and analysis as well as experimental work on the kinetics of hydrogasification of biomass and methane decomposition for a pilot plant using the Hydrocarb process to produce methanol from biomass are reviewed. The hydrogasification kinetic experiments showed an overall conversion of 88 to 90 wt percent of biomass in the HPR. The gas residence time required for the reaction in the MPR to reach an equilibrium composition was found to be 2 min at 50 atm and 900°C. Process simulations show that a process having the flow sequence from the HPR to the MPR to the MSR to the condenser, produces more methanol and provides a higher thermal efficiency than the alternative cycle. A minimum methane co-feed is required for processing greenwaste, and depends on the moisture content of the greenwaste. Sewage sludge and digester gas from a municipal sewage treatment plant can be co-processed with greenwaste by the Hydrocarb process. The CO<sub>2</sub> in digester gas is converted to CO in the HPR and MPR so that more methanol can be produced in the methanol synthesis reactor. The optimum process conditions were determined to be a pressure of 50 atm in the total system and temperatures of 900 and 1000°C in the HPR and MPR, respectively.

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## ALTERNATIVE FUELS FROM BIOMASS

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### ABSTRACT

Substitution of biofuels derived from cellulosic biomass for conventional fuels would reduce the accumulation of carbon dioxide in the atmosphere and the possibility of global climate change, improve our energy security and trade deficit, revitalize rural and farm economies, and address urban air pollution and waste disposal problems. The major fractions of biomass, cellulose and hemicellulose, can be broken down into sugars that can be fermented into ethanol. Through technology advances for producing ethanol, the projected cost at the plant gate has been reduced from about \$3.60/gallon ten years ago to \$1.27/gallon, and opportunities have been identified to further drop the price to \$0.67/gallon, a price competitive with gasoline from oil at \$25/barrel, within ten years. Through anaerobic digestion, a consortium of bacteria can break down cellulosic biomass to generate a medium-Btu gas that can be cleaned up for pipeline-quality methane. The cost of this methane has been reduced to about \$4.50/MBtu ( $10^6$  Btu) for municipal solid waste (MSW) feedstocks, and technology advances could drop the price to about \$2.00/MBtu. Algae could consume carbon dioxide from power plants and produce lipid oil that can be converted into a diesel fuel substitute. Projected costs for this biodiesel have dropped from almost \$18.00/gallon to about \$3.50/gallon now, with a target of \$1.00/gallon. Biomass can also be gasified to a mixture of carbon monoxide and hydrogen for catalytic conversion into methanol. Currently, methanol from biomass is projected to cost about \$0.85/gallon, and with improved technology, a cost of \$0.50/gallon could be realized. Catalytic processing of pyrolytic oils from biomass produces a mixture of olefins that can be reacted with alcohols to form ethers such as methyl tertiary butyl ether (MTBE) for use in reformulated gasoline to reduce emissions. Costs could be competitive today for olefins from MSW. Because biofuels technologies require little if any fossil fuel inputs, carbon is recycled through their use, reducing substantially the net amount of carbon dioxide released to the atmosphere.

## INTRODUCTION

The United States contributes about 25% of the carbon dioxide (CO<sub>2</sub>) released from fossil fuels to the atmosphere, with transportation fuels accounting for about 27% of that amount (1). Carbon dioxide is believed to be the most important greenhouse gas, trapping nearly 50% of the radiation that could lead to global climate change (2), and significant benefit would be gained by development of fuels that do not contribute to the buildup of CO<sub>2</sub> in the atmosphere. Because significant air pollution problems are attributed to gasoline and other conventional fuels, alternative transportation fuels are of particular interest for reducing carbon monoxide and smog in our cities.

In addition to concern about the effects of fuel use on the environment, the U.S. economy depends strongly on unstable sources of imported petroleum. As a result, the nation experienced several oil price shocks as foreign producers controlled supplies of oil in the 1970s. In 1990, the price of oil and gasoline increased again because of the Iraqi invasion of Kuwait, reminding us that oil and natural gas represent the weakest links in the U.S. energy supply. The United States imports about half of the petroleum it uses annually, and even though natural gas imports are now less than 6% of usage, gas and oil imports in the year 2000 are predicted to rise to 11% and 56% of the 23.6 and 37.2 quads of consumption, respectively. Furthermore, petroleum imports are responsible for about 40% of the trade deficit of the United States (3). About 97% of the energy consumed by the transportation sector is derived from petroleum, making this important segment of our economy particularly vulnerable to disruptions in unstable sources of oil.

Fuels known as biofuels can be produced from many plant materials and waste products such as agricultural wastes and municipal solid waste (MSW) that together are called biomass. Several oxygenated biofuels such as ethanol reduce carbon monoxide emissions when blended with gasoline. A number of biofuels can be substituted directly for conventional transportation fuels to reduce urban air pollution. Biofuels can also be used in the residential, industrial, and utility sectors. Substantial improvements have been made in the technology for producing the liquid and gaseous biofuels that this nation needs most, and these fuels now have the opportunity to make a strong impact on our fuel use.

This paper focuses on the progress of and prospects for promising biofuels produced by both biological and thermal reactions. First, the possible contribution of biofuels to our energy supply will be presented. Then, the technologies for producing biofuels will be summarized, and some of their important characteristics discussed. The potential benefits of biofuels for mediating CO<sub>2</sub> buildup will be illustrated.

## BIOFUELS PRODUCTION TECHNOLOGIES

### BIOMASS AVAILABILITY AND COST

Plants use the sun's energy to convert CO<sub>2</sub> and water into simple sugars through photosynthesis. These sugars can be stored directly in plants such as sugar cane or combined to form starch for plants such as corn. All plants join sugars together to form the structural carbohydrate polymers cellulose and hemicellulose, which together with lignin

support the plant. The cellulose, hemicellulose, and lignin components represent the largest fractions of plant matter and can be termed cellulosic biomass or just biomass. When we burn biomass, the stored energy from the sun is released. The energy content of biomass can also be thermally or biologically transformed to liquid or gaseous fuels that integrate well with our existing fuel distribution and use infrastructure.

Although the outward appearance of the various forms of cellulosic biomass such as wood, grasses, municipal solid waste (MSW), and agricultural residues is different, all of these materials are quite similar in composition. Cellulose is generally the dominant fraction, representing about 40% to 50% of the material by weight, while the hemicellulose portion represents 20% to 40% of the material. The remaining fraction is predominately lignin with lesser amounts of substances called extractives. The cellulose polymer is composed of glucose sugar while arabinose, mannose, xylose, glucose, and other sugars make up hemicellulose. Although most forms of cellulosic biomass are low in cost, the historical costs of conversion to liquid and gaseous biofuels have been too high to allow economic application of these technologies on a large scale.

It is estimated that about 190 million acres of land could be used to grow energy crops dedicated for the production of biofuels. For an average productivity of 9 tons/acre/year, about 1.7 billion tons of cellulosic biomass could be harvested each year (4). If accessible underutilized wood, agricultural residues, and MSW are included, about 2.5 billion dry tons per year of cellulosic biomass could be produced at prices from \$18 to \$65 per dry ton (1,5,6). As a perspective on the size of this resource, about 250 billion gallons of liquid fuels could be produced from this quantity of biomass compared to the approximately 115 billion gallons of gasoline used in the United States.

## FUEL ETHANOL

More than 3 billion gallons of ethanol produced from sugar cane is used in Brazil each year. However, U.S. sugar prices are controlled at about \$0.20/pound, a price that is too high for fuel production. Instead, about 1 billion gallons of ethanol are made from corn in the United States each year. Ethanol from corn currently sells for about \$1.20 to \$1.30/gallon and is competitive with state and federal tax incentives. Ethanol blends from starch and sugar crops comprised as much as 8% of the U.S. gasoline market in 1987, up from less than 1% in 1981. There are about 50 U.S. fuel ethanol manufacturing facilities that use corn and other grains as feedstocks.

Over the years, several processes have been studied for conversion of cellulose-containing biomass to ethanol catalyzed by dilute acid, concentrated acid, or enzymes known as cellulases. In each option, the feedstock is pretreated to reduce its size and open up the structure. The cellulose fraction is hydrolyzed by acids or enzymes to produce glucose sugar, which is subsequently fermented to ethanol. The soluble xylose sugars derived from hemicellulose are fermented to ethanol as well, while the lignin fraction can be burned as fuel to power the rest of the process, converted into octane boosters, or used as a feedstock for production of chemicals.

Dilute acid systems typically have low ethanol yields of 50% to 70%. Concentrated sulfuric or halogen acid options achieve the high yields required, but the acids must be recovered at a cost substantially lower than the cost at which these inexpensive materials are produced in the first place, a difficult requirement. Enzyme-catalyzed options provide the high yields of ethanol necessary for economic viability, under mild conditions, with low concentrations of enzyme. In addition, enzyme-catalyzed processes have tremendous potential for technology improvements that could bring the selling price of ethanol down to levels competitive with those of existing fuels. Enzymes are also biodegradable and environmentally benign. At this time, the simultaneous saccharification and fermentation (SSF) enzyme-based process has emerged as the favored route to achieve low-cost fuel ethanol production within a reasonable time frame (7).

In the SSF process, the cellulosic biomass is first pretreated to open up the biomass structure and facilitate subsequent processing. Several options have been considered for biomass pretreatment including steam explosion, acid catalyzed steam explosion, ammonia fiber explosion, and organosolv, but the dilute acid option appears to have the best near-term economic potential. In this process, about 0.5% sulfuric acid is added to the feedstock, and the mixture is heated to around 140° to 160° C for 5 to 20 minutes. Under these conditions, most of the hemicellulose is broken down to form xylose and other sugars, leaving behind a porous material of primarily cellulose and lignin that is more accessible to enzymatic attack.

Following pretreatment, a portion of the pretreated biomass is used in an enzyme production vessel to support growth of a fungus that produces cellulase enzyme. Then, the cellulase enzyme is added to the bulk of the pretreated substrate along with yeast or other fermentative microorganisms. The enzymes catalyze the breakdown of the cellulose by the so-called hydrolysis reaction to form glucose sugar; the yeast or other suitable microbe ferments the glucose to ethanol. The presence of yeast along with the enzymes minimizes sugar accumulation in the vessel, and since the glucose produced during breakdown of the cellulose slows down the action of the cellulase enzymes, higher rates, yields, and concentrations are possible by consuming the sugar as it is released. Additional benefits are that this process reduces the number of fermentation vessels to about half that for separate hydrolysis and fermentation steps and that the presence of ethanol makes the fermentation mixture less likely to be invaded by unwanted microorganisms. Finally, the ethanol is separated from the rest of the fermentation broth in a purification step.

The xylose and other sugars released from the hemicellulose polymers are often predominantly five-carbon sugars that are not as readily converted to ethanol as glucose, and until recently, these sugars had to be discarded. However, several options have been developed for using xylose. At this time, the most promising option appears to be the use of genetically engineered bacteria (8,9) or some new yeast strains for ethanol production.

Because lignin represents a significant fraction of cellulosic biomass, it is important to derive value from lignin. Lignin has a high energy content and can be used as a boiler fuel. Generally, the amount of lignin in most feedstocks is more than sufficient to supply all the heat and electricity required for the overall ethanol production process, as well as to generate excess heat or electricity. Thus, additional revenue can be derived from

electricity exports from the plant (10). The electricity sold for current plant designs is equivalent to about 8% to 10% of the energy content of the ethanol product, and greater revenues are likely as the technology is improved to require less process heat and electricity. Alternatively, lignin could be converted into chemicals or octane boosters such as methyl aryl ethers.

Progress on the enzyme-catalyzed processes to convert cellulosic biomass into fuel ethanol has been substantial over the last ten years, with projected selling prices dropping from about \$3.60/gallon in 1980 (11) to only about \$1.27/gallon (12). This selling price reduction is due to improvements in enzymes to achieve higher rates, yields, and concentrations with lower loadings, proper selection of fermentative microbes, and advances in xylose fermentations through genetic engineering.

Significant opportunities still exist to lower the selling price of ethanol from cellulosic biomass at the plant gate to \$0.67/gallon. Key target areas include improved glucose and xylose yields from pretreatment, increased ethanol yields to 90% or greater from cellulose and xylose fermentations, decreased stirring and pretreatment power requirements, better productivities through continuous processing, low-cost production of octane enhancers or chemicals from lignin, increased ethanol concentrations, and reduction of fermentation times. Feedstock costs are a significant fraction of the final product selling price, so improvements in feedstock production, collection, and genetics could provide additional cost reductions through economies of scale for larger ethanol plants, decreased feedstock costs, and less non-fermentable feedstock. Many of these goals have been met individually and the evidence that the rest can be achieved is great; the primary need is to meet them simultaneously. Fortunately, there are enough options for lowering the selling price of ethanol so that not all the technical goals must be achieved to reach the target.

## BIODIESEL FROM MICROALGAE

Microalgae are single-celled plants that contain photosynthetic machinery driven by the sun's energy to combine CO<sub>2</sub> and water to form a variety of products. Algae are particularly unique in their ability to produce a high fraction of their total weight (about 60% or more) as lipid oils or triglycerides. Lipids are hydrocarbons with a higher energy density than that of the carbohydrates plants typically produce. Although these algal oils can be used directly in diesel engines, they can also be readily converted into esters that more closely match diesel fuel properties and burn more cleanly (13). Diesel fuel currently supplies about 17% of the energy used for transportation in the United States. Production of diesel fuel from algae complements ethanol manufacture from cellulosic biomass in that as ethanol displaces the fraction of petroleum converted into gasoline, substitutes must be found for the fraction now used to manufacture diesel fuel.

Microalgae grow well over a wide range of temperatures in high-salinity water that is unsuitable for other purposes. Therefore, it may be possible to use the abundant high-salinity water in aquifers coupled with inexpensive flat land available in the Desert Southwest to grow microalgae to produce biodiesel. Shallow uncovered ponds or raceways could be created to produce algae with slowly rotating paddle wheels used to circulate the water and provide mixing. Carbon dioxide from power plant flue gas would be injected into

the ponds to promote algal growth. The rapidly growing microalgae would be harvested, and the lipid oils would be extracted for conversion into ester fuels (13).

Microalgal ponds are very efficient in their uptake of  $\text{CO}_2$ , recovering about 90% of the gas injected into a pond. Thus, they provide an effective means of  $\text{CO}_2$  recovery from power plants. Of course, when ester fuels are burned, the  $\text{CO}_2$  captured by the algae is released to the atmosphere, but almost twice as much energy is produced for a given amount of  $\text{CO}_2$  released as would be possible without the use of algal ponds. As a result, a coal-burning power plant coupled to an algal pond would contribute far less  $\text{CO}_2$  to the atmosphere than a conventional gas-fired plant on a total energy released basis (14). Of course, similar benefits could be provided to a gas-fired power plant. If the lipid oils were converted to a chemical for production of durable goods, the carbon could be sequestered for a longer term, reducing the impact of fossil fuel use on  $\text{CO}_2$  accumulation. Use of biodiesel also has a low sulfur impact on the environment.

Progress on technology for producing oil from microalgae has been considerable. A number of strains have been collected that are tolerant to high salinity, high light intensity, wide temperature variations, and extreme temperatures. Many of these strains grow rapidly and produce about 60% of their weight as lipids when they are deprived of key nutrients such as silicon for diatoms or nitrogen for green algae (15). The enzyme acetyl Co-A carboxylase (ACC) has been identified as a key catalyst in lipid oil synthesis (15,16), and research is now focused on developing techniques to genetically enhance lipid oil synthesis by controlling the genes responsible for ACC production.

The projected price of biodiesel production from algae has dropped from approximately \$18/gallon in the early 1980s to around \$3.50/gallon now. Opportunities have been identified to reduce the price to about \$1.00/gallon. The primary need is to enhance the growth rate of algae while achieving high lipid oil concentrations. However, these estimates are based on commercial prices for  $\text{CO}_2$ , which represents a major share of the oil production cost. If fines were levied for  $\text{CO}_2$  releases into the atmosphere,  $\text{CO}_2$  prices would drop drastically or users might be paid to accept this gas, and algal oil production could be cost competitive much sooner.

## BIOGAS

Natural gas, which is primarily methane, is considered an environmentally clean and economically attractive fuel with a high energy content. It is widely used for industrial, residential, and utility applications. It also has potential merit for transportation markets, but it is nonrenewable. Biogas, a mixture of approximately equal portions of methane and  $\text{CO}_2$ , is a medium-Btu gas formed by a biological process called anaerobic digestion, in which complex organic compounds are decomposed by microorganisms. Anaerobic digestion has been used in the United States since early in the twentieth century to stabilize and reduce the volume of municipal sludge before disposal. In typical installations, the biogas produced in the process was flared rather than recovered as an energy source. Anaerobic digestion is also used to remove soluble wastes from chemical plant effluents. However, although the anaerobic digestion processes now operating are effective in meeting waste disposal requirements, current systems were not designed for cost-effective energy production



and are not well suited to utilization of solid cellulosic biomass. In sanitary landfills, naturally occurring anaerobic bacteria break down the biodegradable fraction of the MSW buried there to form biogas although the gas production rates and yields vary widely. Only a small percentage of that gas is now being economically recovered.

In the anaerobic digestion process, one group of bacteria breaks down cellulose and other complex molecules enzymatically into simple sugars and other monomers. Then, other types of bacteria digest these products, producing organic acids that are in turn broken down to form still smaller molecules of acetate, formate, hydrogen, and  $\text{CO}_2$ . Finally, specialized bacteria, called methanogens, use these compounds to produce methane and  $\text{CO}_2$ . When  $\text{CO}_2$  is removed from biogas, the methane-rich product is a high-Btu gas that can be directly substituted for natural gas. Thus, this biological pathway directly converts organic matter into a gas that can be used directly in a boiler or processed to be compatible with the existing distribution infrastructure.

If MSW is employed as the substrate, anaerobic digestion also provides an environmentally sound disposal method. In the anaerobic digestion of MSW, the solid waste is shredded and ferrous materials are removed. Generally, it is also necessary to separate the extra-fine and oversized materials for landfill disposal. The mixture is fed into digesters, and the microbial process converts about half the solid waste into a gas composed of about equal fractions of methane and  $\text{CO}_2$ . The solids left after digestion is complete are dewatered for disposal. For a tipping fee of \$20/ton for the MSW processed, a methane selling price of about \$4.50/MBtu ( $10^6$  Btu) is estimated for established technology.

Several improvements have been made in the anaerobic digestion process. Stratified operation of the digester can result in higher solids concentrations and achieve 10% higher methane yield than a conventional vessel. Technology has also been demonstrated to enrich the methane content of the product gas from an anaerobic digester to near pipeline quality by recirculating a leachate stream from the digester through an air stripping unit or other  $\text{CO}_2$  desorption process. Novel anaerobic digestion units have been operated at 35% to 40% solids concentrations with gas generation rates of 7 to 9 times those possible with conventional devices, which are limited to 6% to 10% solids levels (17). Such devices reduce the volume of the containment vessel and thus decrease vessel costs per amount of methane generated.

Continued research could result in further reductions in methane cost to approximately \$2.00/MBtu (18). Research is needed to identify the organisms present in anaerobic digesters and clarify their complex interactions. Specific organisms can then be selected for genetic breeding and manipulation to allow operation of anaerobic digesters at optimal conditions. Feedback and control mechanisms should be developed to maintain stable operation of digesters (19). Engineering efforts should be undertaken to develop large-scale reactor designs that can process high concentrations of solids to decrease the cost of biogas production. Work is also needed on landfill gas recovery to understand the effect of atmospheric conditions on gas flow, evaluate microbial populations that produce landfill gas, and improve gas generation and capture methods.

## METHANOL FROM BIOMASS

Biomass can be thermally gasified to produce synthesis gas (syngas) rich in carbon monoxide and hydrogen; syngas can then be catalytically converted to methanol. Methanol production includes steps for feed preparation, thermal gasification, methanol synthesis, and gas conditioning and cleanup. Feed preparation typically employs well developed equipment for biomass drying, size reduction, and feeding. Methanol synthesis from carbon monoxide and hydrogen is a well established technology. In order to achieve commercial application of methanol production from biomass, low-cost technology is needed for thermally gasifying the biomass to carbon monoxide and hydrogen and preparing the gas stream for catalytic formation of methanol.

The gasification step can be carried out by controlled direct addition of air or oxygen to the gasifier to produce heat and drive the breakdown of biomass to form carbon monoxide and hydrogen. In such processes, part of the biomass is burned to provide the heat required to drive the formation of the target gases. Alternatively, indirectly heated gasifiers rely on transfer of heat from an external source through a heat exchange device to break down biomass (20,21). Indirect gasifiers may have some cost advantages relative to units that are directly fed air or oxygen. However, further engineering evaluations and economic studies are needed to establish the relative merits of the alternative processes.

Although the raw syngas is rich in carbon monoxide and hydrogen, it cannot be directly processed in the catalytic synthesis unit because it contains significant amounts of impurities including particulate matter, methane, tar, and various light hydrocarbons. In addition, the ratio of carbon monoxide to hydrogen must be adjusted to that required for methanol synthesis. Research has shown that the gas can be cleaned up and the composition adjusted for methanol synthesis. However, further work is required to determine the fate of organic impurities and methane; establish the effect of hydrogen, carbon monoxide, and  $\text{CO}_2$  on tar and methane removal; estimate useful catalyst life; and demonstrate the ability of catalysts to destroy tars and reduce methane under realistic operating conditions with various feedstocks.

Currently, methanol is estimated to cost about \$0.85/gallon from biomass feedstocks costing about \$42/ton. Several opportunities have been identified that would make methanol from biomass competitive with gasoline as a neat fuel. Direct syngas conditioning in one step would replace expensive quenching and scrubbing operations to remove tars and subsequent reheating and steam reforming to reduce excessive levels of methane. We need to develop catalysts that meet lifetime requirements, as well as better gas cleanup systems. Concepts must also be tested at a reasonable scale to establish operational parameters and commercial potential. Improvements in feedstock costs, as discussed for ethanol production, would also benefit methanol economics. Successful demonstration of these improvements could drop the cost of methanol to about \$0.50/gallon, a price competitive with gasoline from oil at \$25/barrel.

## REFORMULATED GASOLINE COMPONENTS (RGCs)

Concerns about urban air pollution have led to enactment of legislation such as the Clean Air Act Amendments of 1990, which require measures be taken to improve air quality. Use of neat fuels such as ethanol and methanol are one way to reduce emissions of unburned hydrocarbons and carbon monoxide, which contribute to smog formation. In addition, gasoline compositions are being changed or "reformulated" to reduce their contribution to air pollution. Oxygenates such as ethanol and ethers are added to gasoline to improve fuel combustion and reduce the release of smog-forming compounds as well as carbon monoxide. The Clean Air Act Amendments of 1990 mandate the use of 2.7% oxygen in fuels for several ozone and carbon monoxide non-attainment regions, thus causing a large demand for oxygenates such as ethanol and methyl tertiary butyl ether (MTBE). Ethers such as MTBE and ethyl tertiary butyl ether (ETBE) are made by reacting the appropriate alcohol (i.e., methanol or ethanol, respectively) with isobutylene. Currently, isobutylene is derived from fossil sources, but these compounds can also be made by fast pyrolysis of biomass followed by catalytic reaction of the pyrolysis products to form olefins. The olefins in turn can be reacted with alcohols to form RGCs such as ETBE and MTBE.

Fast pyrolysis rapidly heats the biomass to temperatures at which the predominant pyrolysis reactions form oxygenated crude oil vapors, rather than char, water, or gases. A vortex reactor forces biomass particles to slide along the externally heated reactor wall, and the close contact between the particles and the wall produces high rates of heat transfer. As a result, the surface of the biomass particle is pyrolyzed and removed, but the bulk of the particle is still unheated through an ablative pyrolysis phenomena (22,23).

The oxygenated crude pyrolysis oil vapors produced in the vortex reactor are converted into olefins and other products through a thermal cracking operation. Extensive studies of these reactions have typically shown that some olefins and other hydrocarbons of interest result but in yields that are not high enough to be economically interesting. However, zeolite catalysts such as HZSM-5 used to convert methanol to gasoline crack the pyrolysis oil vapors with dramatically higher olefins production. Researchers have identified operating conditions with this zeolite catalyst in a slipstream reactor, and low coke yields and relatively high yields of high-octane alkylated aromatics and gaseous olefins were achieved. These products give a very high octane blending stock for use with reformulated gasoline (23,24).

The offgas from the catalytic cracking reactor contains a considerable amount of gaseous olefins. Catalytic conversion of these olefins to larger hydrocarbon molecules in a secondary catalytic reactor has been studied to facilitate condensation and recovery of these materials. A compressor pressurizes the gases that enter the secondary catalytic reactor. Primarily isoparaffins boiling in the gasoline range have been generated from the gaseous olefins. Changes in the catalysts, coreactants, temperatures, and pressures selected could change the products from the secondary reactor.

Preliminary evaluations of the economics of the combined pyrolysis and catalytic conversion process are encouraging, especially when refuse-derived fuel (RDF), a low-cost feedstock derived from MSW that gives enhanced yields of olefins compared to those from

wood, is used as the feedstock. Research on novel catalysts will increase both the olefin yields and the selectivity toward olefins versus aromatics. Initial catalyst screening in the laboratory has already identified some promising candidates, and the results suggest that yields could be improved substantially.

Preliminary process evaluations of the advanced catalytic process suggest that mixed ethers could be produced for \$0.67/gal while they would cost about \$0.96/gal based on existing technology (25). However, the vortex reactor represents a new technology, which carries a considerable risk because of the lack of current industrial experience. Therefore, further research is required in areas such as selectivity and catalyst life. In addition, the ability to scale up the fast pyrolysis of biomass to produce condensable pyrolysis vapors must be demonstrated.

## IMPACT OF BIOFUELS ON CARBON DIOXIDE ACCUMULATION

In this section, the impact of using biofuels on CO<sub>2</sub> accumulation and the potential for global climate change will be discussed. An example will be presented based on ethanol production from cellulosic biomass, but the concepts are applicable to any of the biofuels that have been presented here.

Carbon dioxide released during fermentation and ethanol combustion is recycled back to grow new biomass, replenishing that harvested for ethanol manufacture. In addition, the lignin in the feedstock can be burned to provide all the process heat and electricity needed to drive the conversion process, and some heat or electricity is left to sell for added revenue. Thus, provided new trees or other biomass are planted to replace those that are harvested for energy, CO<sub>2</sub> provides the key link between the fuel and the biomass resource, and CO<sub>2</sub> does not accumulate in the atmosphere. Fossil fuels used in the production and transport of biomass and ethanol are the only sources that can lead to CO<sub>2</sub> accumulation.

Considerable controversy and confusion exists about the amount of fossil energy required to produce ethanol and the interpretation of this information for energy efficiency and the impact on potential global climate change. Energy inputs must be properly accounted for and the performance of ethanol must be properly compared to that for fossil fuels if comparisons are to be made between fuels.

## ENERGY USE

Figure 1 summarizes energy flows for the production of ethanol from cellulosic biomass (1). Modest energy inputs are required to produce cellulosic biomass because cultivation and fertilizer needs are not large. In addition, no process energy input is shown because the lignin contained in the feedstock can be used as a boiler fuel, and the amount of energy contained in the lignin is sufficient to produce process heat and electricity for the overall process. In addition, the equivalent of 8% of the ethanol fuel value can be sold as electricity (9), thereby displacing about 3 times that amount of fossil energy inputs for electricity production by power companies.

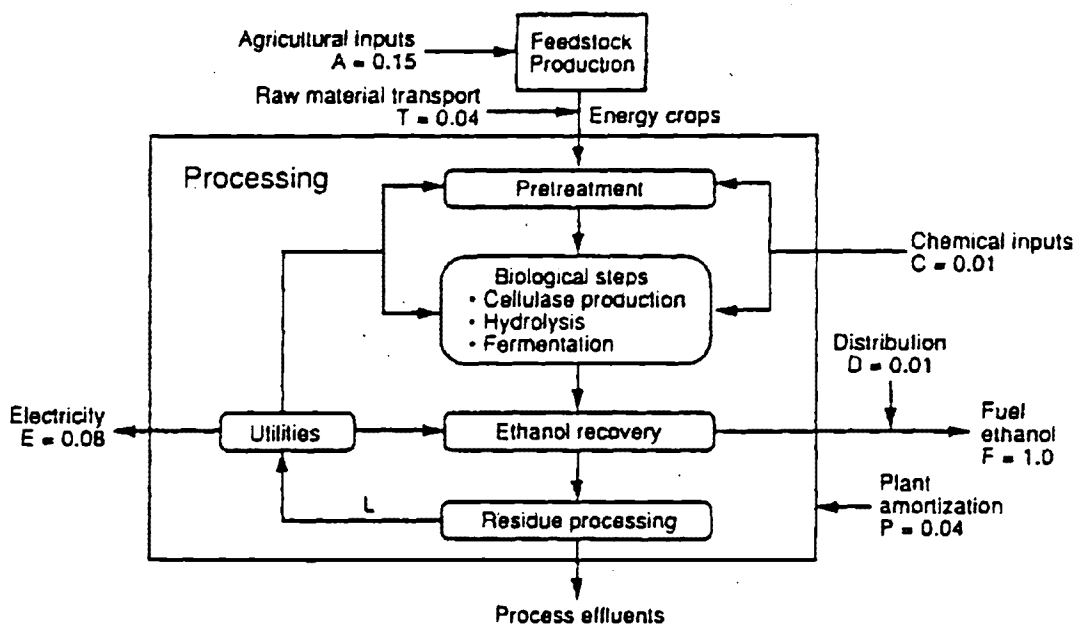


Figure 1. Energy requirements and outputs for production of ethanol from cellulosic biomass based on one unit of ethanol energy output

If we add the total amount of fossil energy inputs, about 19,000 Btu/gallon of ethanol are required for ethanol production from cellulosic biomass. Alternatively, 3 times the electricity produced could be subtracted from the fossil fuel requirements to account for the fossil fuel that would be used in any event for producing that quantity of electricity (26). In this case, the net amount of fossil fuel use, as shown in Table 1, is only about 800 Btu/gallon of ethanol. For comparison, production of gasoline requires about 14,000 Btu/gallon of gasoline produced. Gasoline has a lower heating value of about 115,000 Btu/gallon, compared to ethanol at 76,000 Btu/gallon.

## CARBON DIOXIDE RELEASED

An estimate of the contribution of ethanol production to  $\text{CO}_2$  accumulation in the atmosphere can be performed by weighing the quantities of fossil fuels used according to the amount of  $\text{CO}_2$  released by each. For the purposes of this discussion and with reference to Figure 1, natural gas is assumed to be the fuel source for agricultural ( $A$ ), chemical ( $C$ ), and plant amortization ( $P$ ) inputs; petroleum is assumed for transportation ( $T$ ) and distribution ( $D$ ). Combining  $\text{CO}_2$  release data for these sources with the energy requirements presented in Figure 1 gives the results presented in Table 1 for ethanol derived from cellulosic biomass. Only  $\text{CO}_2$  is included that is produced by combustion of fossil fuels since  $\text{CO}_2$  generated during fermentation of biomass cellulose and hemicellulose and combustion of lignin and ethanol can be recycled to grow new biomass to replace that harvested for energy production.

It is interesting to note that if the fossil equivalent for production of electricity is subtracted from the fossil fuel sources for ethanol production from cellulosic biomass, a negative  $\text{CO}_2$  contribution results (Table 1). This outcome is due to the low usage of fossil fuels for conversion of cellulosic biomass to ethanol and the displacement of electricity in

TABLE 1. CARBON DIOXIDE RELEASED IN ETHANOL PRODUCTION FROM CELLULOSIC BIOMASS

Process	Feedstock Production	Raw Material Transport	Chemical Inputs	Process Energy	Plant Amortiza- tion	Fuel Distribu- tion	Total Fossil CO <sub>2</sub>	Coproduct Displacement of CO <sub>2</sub>	Net Fossil CO <sub>2</sub>
Assumed Fossil Fuel	Natural Gas	Petroleum	Natural Gas	None	Natural Gas	Petroleum	--	--	--
Btu/Gallon Ethanol	11,400	3,000	800	--	3,000	800	19,000	(18,200)	800
Carbon Dioxide Released lb/gallon	1.5	0.5	0.1	--	0.4	0.1	2.6	(4.6)	(2.0)

Note: Calculated on the basis of the exported electricity displacing coal-generated electricity, which was generated at 33% efficiency

the grid. To produce an equivalent amount of electricity from fossil resources such as coal would actually produce more CO<sub>2</sub> than the total released during ethanol production, and subtracting the amount of CO<sub>2</sub> that would have been released anyway for generation of that quantity of electricity gives a net credit of 2 pounds of CO<sub>2</sub>/gallon of ethanol produced.

From the data in Table 1, it appears that production of ethanol from cellulosic biomass would be a minor contributor of CO<sub>2</sub> to the atmosphere. This is because all of the process heat is produced by combustion of lignin, a renewable feedstock. In addition, few fossil fuel inputs are needed to produce cellulosic biomass. Biomass sources of fuels and fertilizers could be substituted for the fossil fuels assumed in this analysis, resulting in no net CO<sub>2</sub> release for ethanol from cellulosic biomass. By way of comparison, gasoline use releases a total of 190 pounds of CO<sub>2</sub>/MBtu or 21.8 pounds/gallon of gasoline.

## FUEL UTILIZATION

In the United States, ethanol is currently blended with gasoline at 10% concentrations. As mentioned earlier, the energy content of ethanol is 76,000 Btu/gallon; gasoline contains about 50% more energy at 115,000 Btu/gallon. By accounting for each of these components, the energy content of the blend is about 111,000 Btu/gallon. If we assume that the range of a vehicle is proportional to the energy density of the fuel, then 1.036 gallons of blend would be required to travel the same distance as one gallon of gasoline. On the other hand, data from Southwest Research Institute have shown that there is no statistically significant difference in the mileage for a 10% blend versus that of regular gasoline. In effect, this evidence suggests that the ethanol blended with gasoline has an energy density equivalent to 115,000 Btu/gallon.

Use of neat ethanol can also be considered in at least two different ways. First, the amount of one fuel needed to travel the same distance as for another fuel can be determined by the ratio of the lower heating values of the two fuels. Thus, about 50% more ethanol would be required than for gasoline to give the same service. For an engine designed for gasoline use with only modifications in timing and air:fuel ratio to allow combustion of ethanol, ethanol fuel would give such a range. However, because ethanol has more favorable fuel properties such as a higher octane and heat of vaporization than gasoline, an engine optimized for ethanol can be 20% to 30% more efficient than a gasoline engine (1,6). Assuming the latter results in a ethanol driving range of about 80% of that of gasoline.

## COMPARISONS OF FOSSIL FUEL USE AND CARBON DIOXIDE RELEASE

Table 2 presents a comparison of the fossil fuel requirements for ethanol from cellulosic biomass and gasoline. Consideration is given to both blends and neat fuel use and to comparison of the amount of ethanol required based on lower heating value and performance. The lower end of the range shown is with credit given for fossil fuel displacement for electricity production, while the higher end does not account for excess electricity production. Blends of ethanol from cellulosic biomass with gasoline always yield lower fossil fuel use than gasoline. Furthermore, for neat fuel markets, ethanol production from cellulosic biomass requires one-fifth or less fossil fuel input than gasoline, depending

**TABLE 2. FOSSIL FUEL USE AND CO<sub>2</sub> RELEASED FROM CELLULOSIC BIOMASS**

<b>Form of Fuel Use</b>	<b>Fossil Fuel Used (Btu/gal of gasoline equivalent)</b>	<b>CO<sub>2</sub> Released (lb CO<sub>2</sub>/gal of gasoline equivalent)</b>
<b>Blends Based on Lower Heating Value</b>		
Ethanol	120,400 - 122,200	20.1 - 20.6
<b>Blends at Same Range as Gasoline</b>		
Ethanol	116,200 - 118,000	19.4 - 19.9
<b>Neat Fuel Based on Lower Heating Value</b>		
Ethanol	1,200 - 28,700	-3.0 - 3.9
<b>Neat Fuel Based on Improved Efficiency</b>		
Ethanol	1,000 - 23,800	-2.5 - 3.2
Gasoline	129,000	21.8

on the accounting given for electricity production and the assumed efficiency of ethanol utilization.

Also presented in Table 2 is the amount of CO<sub>2</sub> released when a vehicle is propelled the same distance by ethanol as gasoline. Again, based on the low use of fossil fuels in production of ethanol from cellulosic biomass, this fuel scores very well in minimizing CO<sub>2</sub> emissions that could contribute to global climate change. If we subtract the CO<sub>2</sub> emissions that would have resulted from fossil fuels to generate the amount of electrical energy produced in the ethanol plant, the net effect is that ethanol removes CO<sub>2</sub>. It may be more appropriate to assign the CO<sub>2</sub> released to both electricity and ethanol based on the relative energy contributions and compare each to the alternative, but the benefits would still be substantial.

## CONCLUSIONS

A wide range of fuel products, which can reduce our vulnerability to disruptions in fuel supplies and improve our balance of trade deficit, can be produced from biomass, a renewable, abundant feedstock. These products include ethanol, methanol, methane gas, biodiesel, and olefins for production of RGCs. All of these biofuels can be used in the transportation sector, some as gasoline additives to reduce emissions of carbon monoxide and smog-forming compounds and others as substitutes for fossil fuels. Some can also be employed for residential, utility, and industrial applications. Substantial progress has been made in reducing the price of biofuels production, and goals have been defined to further reduce that cost. Many of these fuels are now ready for introduction into our energy sector



for selected applications, and their use would improve our environment significantly from a viewpoint of both local air pollution and the potential for global climate change. Because only modest amounts of fossil fuels would typically be used to produce biofuels, the net release of CO<sub>2</sub> to the atmosphere would be small. Furthermore, for cellulosic biomass, all of the energy inputs in the overall process could ultimately be derived from renewable feedstocks, thereby avoiding any net release of CO<sub>2</sub>.

The work reported is funded by the Biofuels Systems Division of the U.S. Department of Energy. The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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## COPRODUCTION OF METHANOL AND POWER

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### ABSTRACT

Integrated Coal Gasification Combined Cycle (IGCC) is one of the emerging technologies for electric power generation from coal. Under contract with Florida Power & Light (FPL) and Electric Power Research Institute (EPRI), Bechtel is to design an IGCC/methanol coproduction plant that is suitable for utility operation of a base loaded power plant. The potential benefits of methanol coproduction in a IGCC plant are identified and quantified.

Shell and Dow gasifiers are selected for this study only to illustrate the potential effects of the dry-feed and slurry-feed gasification process on methanol production. The combined cycle power plant features the GE Model MS-7001F gas turbines, HRSG with steam reheat, and duct firing. The fuel-grade methanol plant design is based on Chem Systems' Liquid Phase Methanol (LPMEOH\*) Process. Two operating modes of the methanol plant are considered: the recycle mode (RM) and the once-through mode (OTM).

Results from cases with the slurry-feed gasifiers and OTM plant are presented in this paper. They have indicated that methanol coproduction can increase the equivalent availability of an IGCC plant to that for a natural gas fueled combined cycle plant. Methanol coproduction can also reduce the risk of the lower than anticipated gasifier availability.

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\* A trademark of Chem Systems Inc.

## INTRODUCTION

The Research & Development Department of Bechtel Group Inc. is conducting a site-specific study for the coproduction of electric power and clean by-product fuel in an IGCC plant. This study is being performed for the Florida Power & Light (FPL) Company and the Electric Power Research Institute (EPRI).

The major objectives of this study are to first design a base case IGCC plant that is representative of a base-loaded power plant, and then to identify and to quantify the potential benefits of a spare gasifier, fuel-grade methanol, and liquid hydrogen coproduction as additions to the base case plant. This is significantly different than previous methanol coproduction IGCC studies which have assumed cyclic operation of the power block with undersized coal gasification capacity (1).

FPL's Martin Site, located near the eastern shore of Lake Okeechobee, Florida provides the site data for this study. The major components of the proposed IGCC plant are: slurry-feed (DESTEC) gasifiers, GE advanced gas turbine (Model MS7001F), methanol plant based on Liquid Phased Methanol (LPMeOH) process.

The performance, process design, and cost data for the slurry-feed gasifier were prepared by DESTEC. GE's Turbine Technology Department estimated the performance of the latest GE MS7001F gas turbine. This latest gas turbine unit, fully-loaded with syngas, is capable of generating 192 MW power at an ambient temperature of 45°F. Chem Systems prepared the design package for the once-through methanol (OTM) plant which features a slurry reactor design (LPMeOH). Detail description of the LPMeOH process is available in various publications (1, 2, & 3).

The results for the power and methanol coproduction are presented in this paper while the results on the liquid hydrogen coproduction are reported in a separate paper (4).

## SCREENING STUDY

A screening study was first conducted to define the study cases that would best illustrate the potential benefits of a spare gasifier and methanol coproduction. Some of the key factors considered were: plant equivalent availability, maximum utilization of the spare gasifier, methanol plant size, usage of methanol produced, and overall plant performance. Two of the cases developed are summarized here to illustrate and to quantify the benefits of coproducing methanol and power: (1) a base-loaded IGCC plant without a spare gasifier as the base case, and (2) a base-loaded IGCC plant with a spare gasifier and an OTM plant. The block flow diagrams for these two cases are shown in Figures 1 and 2.

These cases are chosen in order to achieve the maximum plant equivalent availability with an IGCC plant. As shown in Figure 3, the plant equivalent availability of a base-loaded IGCC plant is determined to be 86%. A spare gasification train increases the IGCC plant equivalent availability to 90%. The gasification plant scheduled and forced outage rates are higher than those of the gas turbine cycle. If sufficient amount of methanol is produced for backup fuel, the power block can be operated on methanol when one or more gasification trains are not available. The resulting plant equivalent availability will be similar to that in a natural gas-based combined cycle plant (93%).

## PROCESS DESCRIPTION

The base case IGCC plant consists of four slurry-feed gasifiers generating sufficient medium-Btu syngas to fully load four GE gas turbines at 95°F ambient temperature. The design coal rate is 7412 short tons per day (stpd). The oxygen purity is 95% to take advantage of lower power requirement in the oxygen plant compared to that required to produce 98+% oxygen purity.

The IGCC/OTM plant includes a spare gasifier and an OTM plant. Since the spare gasifier is also operated at its design capacity, the design coal feed rate is increased to 9296 stpd. The acid gas removal unit is revised in order to meet the more stringent sulfur requirement of the catalyst in the methanol plant. The design of the OTM plant is based on the LPMeOH process. The OTM plant is sized so that the gasifiers can be operated year-round at the design capacity. Daily fluctuation of syngas demand from the power block is met by varying the amount of syngas for duct firing in the HRSG.

About two-thirds of the syngas from the Coal Gasification Unit is diverted to the OTM plant. About 30% of the combined carbon monoxide and hydrogen in the syngas is converted to methanol in the LPMeOH slurry reactor. The unconverted syngas is expanded to recover some of the energy before it is combined with the remaining syngas in the Water Saturation Unit feeding the gas turbines.

## RESULTS AND DISCUSSION

### PLANT PERFORMANCE

The performance of the IGCC base case plant and the IGCC/OTM plant at an ambient temperature of 75°F is shown in Table 1. The net power outputs from the IGCC and the IGCC/OTM plant are 927 and 994 MW, respectively. The heat rate for the IGCC plant is 8832 Btu/Kwh. The heat rate for the IGCC/OTM coproduction plant is estimated to be 9125 BTU/Kwh. However, heat rate is not a good indicator for the thermal efficiency in power generation from the IGCC/OTM plant because it is highly integrated with the associated OTM plant. Duct firing in the power block further reduces the meaningfulness of using the heat rate as the indicator for the IGCC coproduction plant performance.

The OTM plant produces 978 stpd (100 million gallons per year) methanol. The OTM plant consumes approximately 50% of the syngas output from a gasifier. As shown in the latter part of this paper, sufficient amount of methanol can be produced as backup fuel for the power block.

### COST OF ELECTRICITY

As shown in Table 2, the plant investments for the IGCC base case and the IGCC/OTM plant are estimated to be \$1440 and \$1592 per Kw, respectively. The plant investment includes the costs of startup, inventory, owner's costs, and AFUDC. As shown, the methanol plant cost is about three percent of the total plant investment.

EPRI's economic model for an investor-owned utility (IOU) scenario was used to determine the cost of electricity (COE) for the IGCC base case and the IGCC/OTM plant. The key financial assumptions are shown in Table 3. The

COEs for the IGCC base case and the IGCC/OTM plant are 37.0 and 34.6 mills per Kwh, respectively. As expected from its relatively low capital investment cost for the OTM plant, methanol coproduction lowers the COE of the IGCC plant.

As shown in Figure 4, methanol coproduction does not have any negative impact on the COE of the IGCC plant if the methanol price is at \$0.35 per gallon escalated merely at the inflation rate of 6%.

## BENEFITS OF METHANOL COPRODUCTION

The immediate benefits of the methanol coproduction scheme to the IGCC plant can be illustrated in two scenarios. In the first scenario, when a gasifier is down unexpectedly, syngas can be diverted to the power block so that power generation is not interrupted. In this case, the backup fuel is the syngas. Thus, overall plant thermal efficiency remains the same as the base IGCC plant and is not decreased as would be the case if methanol or another form of "stored energy" were employed as backup fuel.

The second scenario involves the planned shutdown of a gasification train. Because the gasification train has to be shut down for a longer period of time than the combined cycle plant for planned maintenance, stored methanol can be used in the power block when syngas is not available. The combined effect of these two scenarios is to raise the plant equivalent availability of the power block to 93%, the same availability as the natural gas-based combined cycle plant. The amount of backup methanol fuel is estimated to be about 24 million gallons per year.

The methanol coproduction concept can also reduce the potential technical risk of the gasifier, a relatively new technology for power generation industry. The gasifier risk abatement can be best illustrated by examining the effect of gasifier component availability on the annual methanol production rate and the overall IGCC plant equivalent availability. The gasifier component availability is the probability that the gasifier is in operating condition at any given time. In this study, the design value for the gasifier component availability is 96%.

As shown in Figure 4, the IGCC plant equivalent availability is directly proportional to the gasifier component availability. The IGCC/OTM plant equivalent availability is 90% when the gasifier component availability is 96%. In the unlikely event, the gasifier component availability should be 84%, the IGCC plant equivalent availability should be 86%. If 61 million gallons of methanol is available annually as backup fuel, the IGCC/OTM can

be operated at the same equivalent availability (93%) as that of a natural gas-based combined cycle plant.

## CONCLUSIONS

An IGCC/OTM coproduction plant design has been developed according to actual FPL dispatched utility operation. With the most pessimistic methanol price forecast, results of this study indicate that methanol coproduction can offset the cost of a spare gasifier and increase the new power output of an IGCC plant with the same number of working gasifiers and gas turbines.

The proposed IGCC/OTM plant configuration can increase the IGCC plant equivalent availability from 86% to 93%, the equivalent availability of a natural gas-based combined cycle plant.

The methanol produced can also help to reduce the risk of lower than expected gasifier availability. If the gasifier component availability were decrease from 96% (the design basis) to as low as 84%, sufficient methanol would be available to maintain the combine cycle plant operation at its 93% plant equivalent availability.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.



Table 1

## IGCC Plant Performance Summary (Slurry-Feed Gasifier)

	<u>IGCC Base Case</u>	<u>IGCC with the OTM plant</u>
Ambient Temperature, °F	75	75
Number of Gasifiers (Total/Spare)	4/0	5/1
Number of GT/ST/HRSG	4/2/2	4/2/2
Coal Feed Rate, stpd	7412	9296
Products:		
Fuel-grade methanol, stpd (as 100% methanol)	0	978
Gross Power, MW	1035	1158
Net Power Output, MW	927	994
Heat rate, Btu/Kwh (HHV)	8832	9125 (Note)

Note: The estimated heat rate only includes the equivalent amount of syngas for electrical power generation

Table 2

IGCC Plant Cost Summary (Slurry-Feed Gasifier)  
(1st Qt. 1990 \$/Kw)

	<u>IGCC Base Case</u>	<u>IGCC with OTM Methanol Plant</u>	
Net Power Output, MW	926.7	993.6	
<u>Plant Units</u>			
Coal Gasification Unit	295	320	(20 %)
Air Separation	144	188	(12 %)
Power Block	422	449	(28 %)
Methanol Plant	0	52	(3 %)
General Facilities	214	178	(11 %)
Startup, Inventory, Owner's Cost	87	99	(6 %)
AFUDC	278	306	(20 %)
	<hr/> 1440	<hr/> 1592	<hr/> (100 %)

Table 3  
Financial Assumptions

<u>Source Of Capital</u>	<u>Capitalization Ratio</u>	<u>Cost</u>
Common Equity	45%	13.4%
Preferred Stock	10%	10.0%
Debt	45%	10.0%
Federal & State Income Taxes	38.0%	
Book Life, Years	30	
Tax Life, Years	20	
Initial Year Of Design & Construction		1990
Beginning Of Commercial Operation		1995
Allocation Of PFI Over Design/Construction Yeras		
	15%, 25%, 35%, and 25%	
PFI Escalation	6.0% Per Year	
General Inflation	6.0% Per Year	
Coal Cost/escalation	\$45/ton, 6.8% per Year	
Methanol Credit/escalation	\$0.35/gallon, 9% per Year	

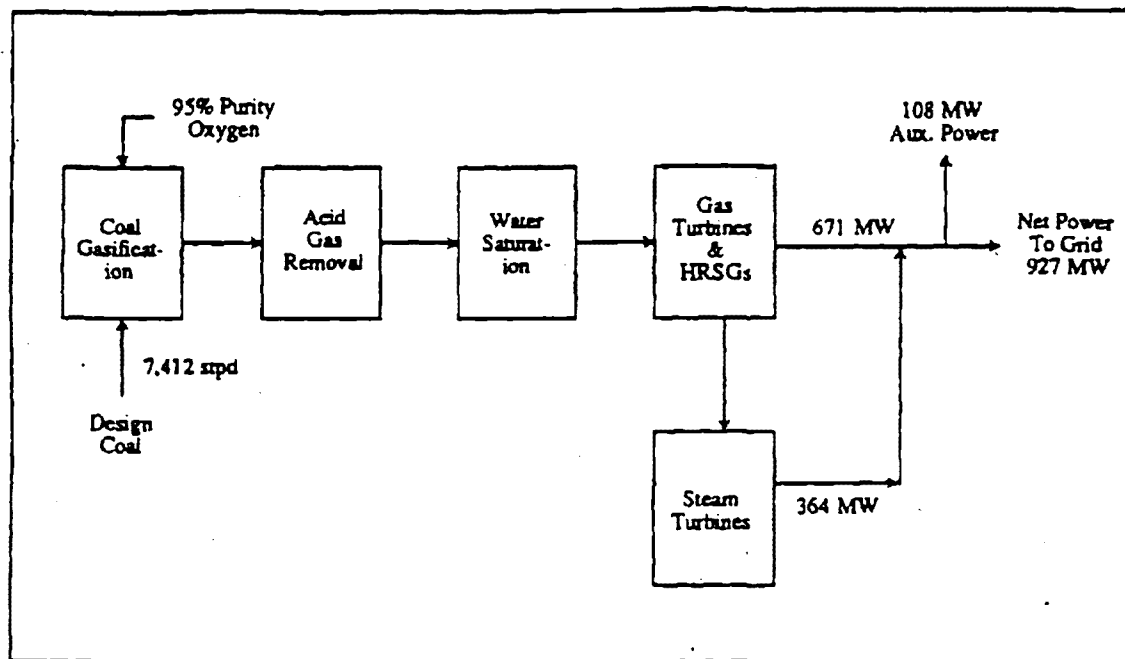


Figure 1  
Block Flow Diagram Showing an IGCC Plant Without Spare  
Gasifier or Methanol Plant (Slurry-Feed Gasifier)

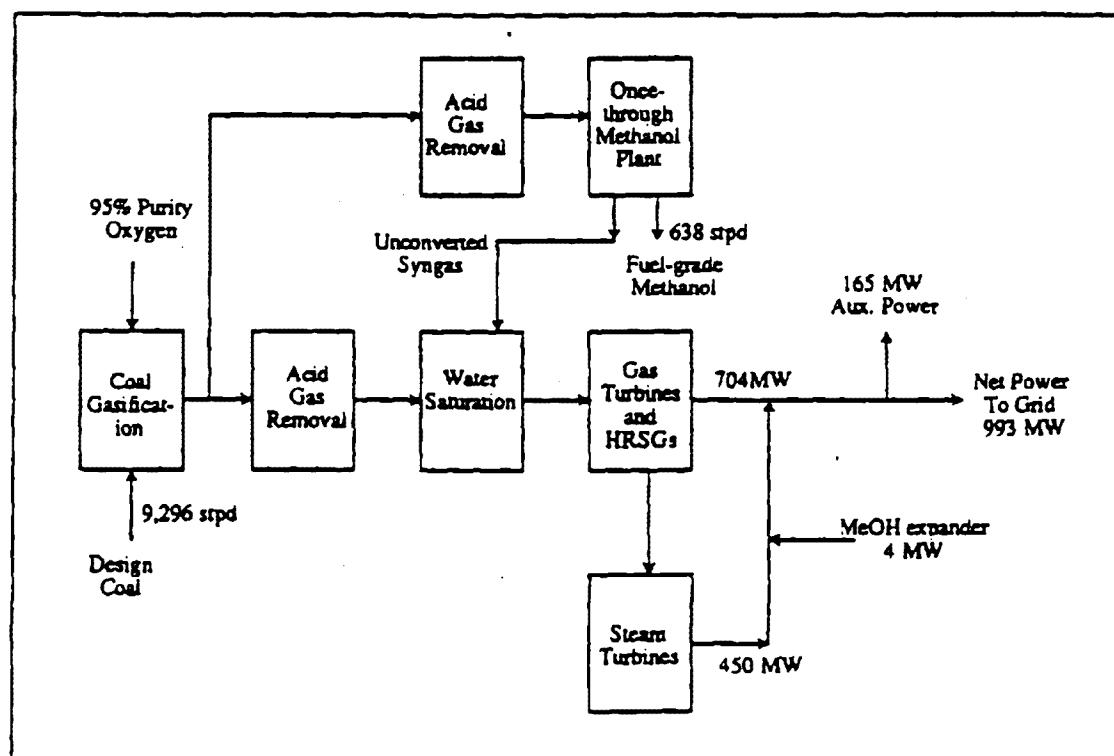


Figure 2  
Block Flow Diagram Showing an IGCC/OTM Plant  
Slurry-Feed Gasifier

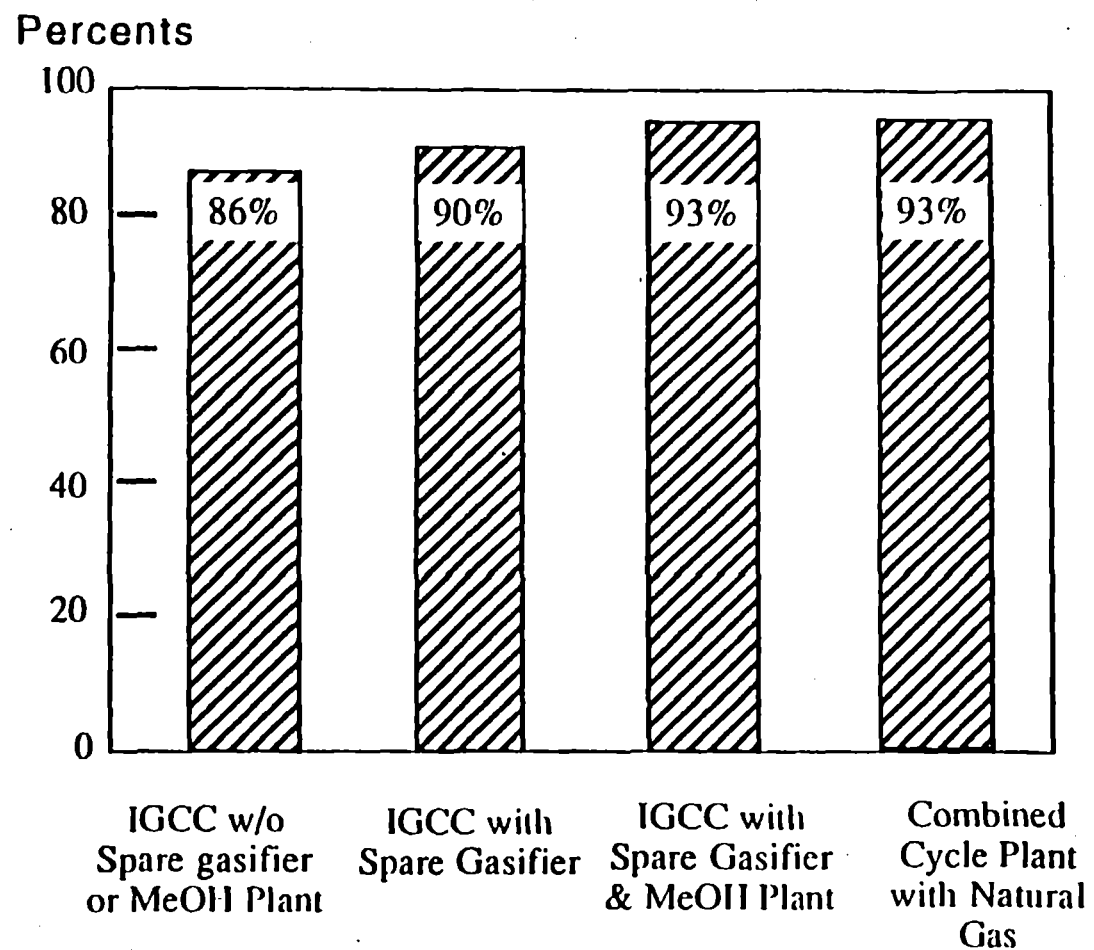


Figure 3 Plant Equivalent Availability

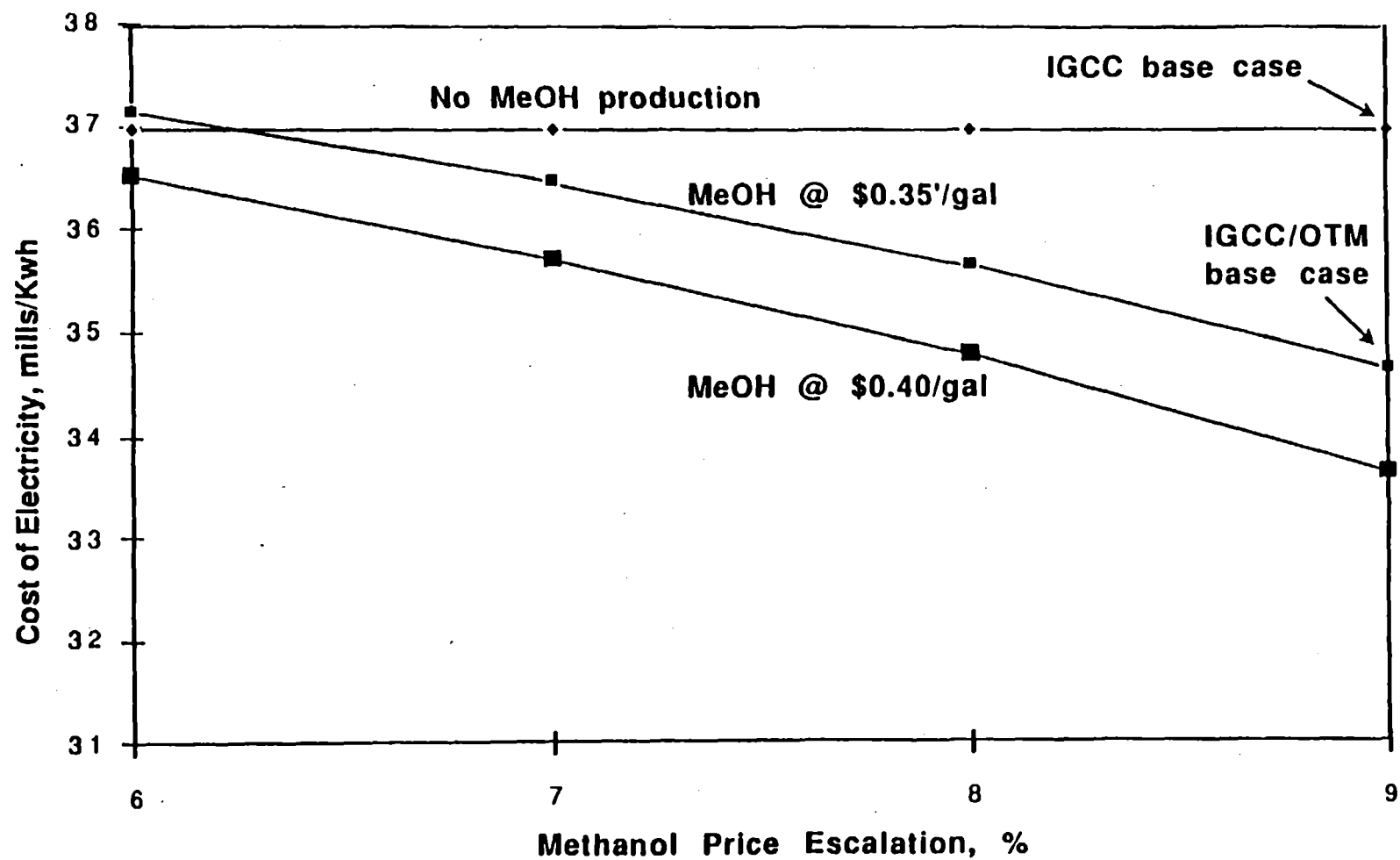


Figure 4 Effects of Methanol price and Escalation on COE

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EPA'S COST-SHARED SOLAR ENERGY PROGRAM

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ABSTRACT

The objective of this program is to establish and demonstrate solar energy cost-shared commercialization projects to demonstrate how they can be used to displace fossil fuels. The program will also have a major impetus to validate the ability of solar energy to be used as a pollution mitigation technology. Further, the demonstrations will assist in removing obstacles to the marketplace for solar technologies by assisting in quantifying environmental concerns. This paper discusses a project which has just commenced in the area of photovoltaic demand-side power supplies. Additional discussion is provided relative to future projects which are being contemplated.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.



## INTRODUCTION

Growing use of fossil fuels has generally contributed to environmental degradation including such problems as acid rain and the greenhouse effect (the buildup of global warming gases such as carbon dioxide, carbon monoxide, and methane). It is, therefore, imperative to investigate technologies that have potential to prevent or mitigate these environmental problems and also make sense from energy, engineering, and economic viewpoints. Solar energy technologies meet these criteria. Because of solar energy's huge potential and the clear environmental benefits from its usage, EPA intends to establish and demonstrate the practical potential of solar energy applications that are close to being commercialized and thereby provide added impetus to their commercialization and, at the same time, utilize the technology as a pollution reduction strategy or to comply with potential environmental concerns.

The general goal of the program is to demonstrate the technical and economic feasibility of solar technologies as a pollution mitigating energy replacement of fossil fuels. The general approach is to install and monitor solar energy systems at different geographic locations in the United States for users of retail electricity who are interested in having such systems on their premises. These systems should supply electrical power directly to the user, where they have to compete only with the retail cost of electricity. These systems would be monitored for performance and reliability using on-line remote monitoring all tied into a central facility at EPA's Air and Energy Engineering Research Laboratory (AEERL) at Research Triangle Park, NC. Participants in the demonstration projects will be required to have considerable experience in the selected technology, to select an appropriate solar energy system, to determine the requirements for the technical and economic aspects of the technology to be a pollution mitigating energy strategy, to select appropriate host sites, to conduct the required demonstration activities, and to cost-share at least 50% of the project (at least 30% for companies qualifying as small businesses).

## PHOTOVOLTAICS (AN EPA PROSPECTUS)

Within the solar area, perhaps the most promising and potentially ubiquitous energy option is based upon photovoltaic (PV) conversion, the transformation of solar radiation directly into electric power. Tremendous opportunities exist for solar PV technologies to assist in meeting the energy needs of the 1990's and beyond. The costs have come down dramatically (about 68% per decade) since solar cells were first used in space. The current levelized cost of energy for PV is around 30 to 35¢/kWh, with costs expected drop to the 4 to 7¢/kWh range by the year 2010 [1]. Thus, in the domestic bulk power markets, head-to-head competition with gas- and coal-fired plants before 2010 will be tough. However, even at today's costs there is an untapped remote (off-grid power supplies) world market of perhaps 200-300 MW.

For grid-connected applications, nearer term opportunities appear to be on the customer (retail) side of the meter, where load growth could be met with PV demand-side and distributed power supplies. For example, summer peaking rates can range from 11 to 44¢/kWh which would imply that for demand-side power supplies to shave peaking loads on buildings could be cost effective today in some locations. The utility companies or customers could own the on-site PV power generators.

Another near term possibility for grid-connected PV is distributed power sources for standby generation and dispatchable power for the utility grid. For load centers where demand growth has strained local transmission and distribution capabilities, PV distributed power supplies could be an option to upgrading a substation or constructing a new substation. In fact, it has been reported [2] that current PV systems could be marginally competitive today in certain locations. For these sites, avoided utility costs would accrue due to savings in equipment capacity additions/upgrades (generation, transmission, and distribution) and in increased reliability of customer service. That study also found that, while costs somewhat exceeded benefits today, by 1995 the benefits provided by PV distributed systems would exceed costs. This projection, of course, assumes that the levelized cost of energy for PV will decline.

With the potential increase of electric vehicles (EVs) in the near future, solar PV carports are expected to provide daytime recharging for EVs. The primary recharging stations for EVs will be the users' homes, with batteries charged at night. These daytime recharging stations could also be grid-connected to provide solar-generated electricity to buildings when the vehicles are not plugged-in. There is a good match between the peak electricity provided by the recharging station and daytime recharging needs of the EVs. Of course, the number of recharging stations will depend on how many EVs are ultimately on the road and how inexpensive PV units become.

The future environmental impact of PVs is difficult to estimate at this time. The U.S. Department of Energy (DOE) [1] has projected that PV market penetration in the U.S. by the year 2010 could range from approximately 6 to 27 GW. Using a 27.5% capacity factor for PV and offsetting emissions from electric power generation using a coal-fired plant, it can be shown that for each gigawatt of PV generating capacity, approximately 2.2 million tonnes less of carbon dioxide (CO<sub>2</sub>) is emitted to the atmosphere per year. Thus, if these market projections are correct, by the year 2010 a yearly reduction of emissions of CO<sub>2</sub> could be achieved by PV on the order of 13 to 59 million tonnes.

Thus, EPA's R&D efforts will tend to be in the PV systems application development arena, where DOE traditionally has not allocated much funding. EPA's future activities are likely to be in: demand side power supplies, distributed power

supplies, integrated building applications, daytime recharging stations for EVs, and advanced control systems for PV/hybrid systems.

#### CURRENT PROJECT (DEMAND-SIDE MANAGEMENT)

Demand-side management (DSM) activities by utilities have been around for a while. Most utilities conduct their own DSM programs, but some have turned to energy service companies to acquire load management capabilities. Usually, peak demand reduction is their primary goal, but energy reduction has also been targeted. However, most utilities have been somewhat reluctant to commit to demand side power supplies, especially new and emerging technologies, as a means for load control (DSM). To fill that void, EPA has embarked on a project to install and monitor PV energy systems in several geographical locations in the U.S. for retail-end users of electricity. The goal of the project is to investigate how PV technology may be used as a pollution mitigating energy replacement of fossil fuels by reducing electrical demand by commercial and residential buildings. The project requires that the PV systems:

- be located on the user's premises;
- supply electric power directly to the user;
- reduce the electrical demand by commercial and/or residential buildings;
- compete only with the retail cost of electricity;
- be modular and replicable;
- be capable of generating 5 to 15 kW at each site; and
- obtain performance data over a complete heating and cooling season and transmit the data to EPA.

In August, 1992, a contract is expected to be awarded to Ascension Technology, Lincoln Center, MA, to conduct the study. Additionally, Ascension Technology has 10 utility partners that will provide significant co-funding, along with in-kind support. Seventeen PV systems (eight commercial buildings and nine residences) will be installed and monitored at various sites in the U.S. The actual site selections have not been finalized yet. The total PV power involved is 116 kW. Applying the previously stated yearly emissions reduction potential of PV (1 GW reduces CO<sub>2</sub> emissions by 2.2 million tonnes), this project will produce a reduction of 255 tonnes of CO<sub>2</sub> per year.

The total environmental benefits of DSM using PV power supplies could be significant. For example, if 50 million residential users in the U.S. installed 4 kW rooftop PV generators to produce daytime electricity, the electricity produced could displace 200 GW of central station generated electricity. This calculation assumes that this offset electricity is produced from coal to estimate an upper value for the pollution reduction potential of PV power supplies in a DSM role. Obviously, the offset

electricity could be produced by a complicated mix of gas, oil, coal, and nuclear plants. With this assumed, over 400 million tonnes less CO<sub>2</sub> would be emitted yearly.

#### **FUTURE PROJECT (PHOTOVOLTAIC - ELECTRIC VEHICLE RECHARGING STATIONS)**

Electric vehicles (EVs) are rapidly becoming a focus of public attention [3]. Legislation has been passed in California and Massachusetts, and is pending in 10 other states, to require a specified percentage of automobile sales in these states to be EVs by 1998. The impetus behind this legislation is that EVs offer the promise of cleaner air to cities. In the United States today there are 185 million gasoline fueled vehicles on the road with an additional 7 million added annually. Total vehicle kilometers traveled doubled in the last two decades from approximately 1.6 trillion in 1970 to 3.2 trillion in 1990, and current estimates predict another doubling by the year 2000. The number of cars on American roads and the kilometers they travel are increasing much faster than the human population. Although the United States has the most stringent emission regulations in the world, motor vehicles account for approximately 35% of total volatile organic compound (VOC) emissions, 40% of total nitrogen oxides (NO<sub>x</sub>) emissions, and over 65% of total carbon monoxide (CO) emissions.

Adoption of EVs by the public would necessitate changing production (car manufacturers) and buying (consumer) patterns. Several recent legislative policies may provide catalysts for these changes. For example, the California plan does mandate EVs: 2% of all cars sold in California in 1998, rising to 10% by 2003. If the eight Northeast States for Coordinated Air Use Management adopt the California plan, between 250,000 and 300,000 EVs could be on U.S. roads by 2003. Also, several large automobile manufacturers (e.g., GM, Ford, Chrysler, Nissan, and BMW) have major EV projects ongoing. The GM Impact has changed the vision of EV performance to that of high performance sports cars [3]. It is anticipated that a significant increase in EV sales could begin as early as 1995.

The environmental benefits from EVs are difficult to quantify at this time. A study conducted by the South Coast Air Quality Management District [4] showed that by replacing 5% of conventional gasoline fueled vehicles with EVs in the South Coast Air Basin would reduce yearly VOC and NO<sub>x</sub> emissions by approximately 8950 and 6600 tonnes, respectively. However, California would probably benefit more than other states because their electricity is produced primarily by natural-gas fired steam plants. In other areas, there could be an increase in emissions associated with a growth in electricity consumption and production. However, many of the power plants may be located in less environmentally sensitive geographical locations, and if EV recharging occurs at night, emissions will be produced at off-peak ozone forming hours.

It is generally assumed that most EV batteries will be charged at night when demand for electric power is low. However, it is almost a certainty that some infrastructure must exist for daytime recharging, especially for commuter vehicles. If EVs are bought in large numbers, driving patterns are likely to be similar to internal combustion vehicles, which will require daytime "refueling." EVs charged with power from PVs would truly be zero emission vehicles.

EPA is currently contemplating a PV recharging scenario for EVs. While no decision has currently been reached, the likely approach will be to install two or three PV recharging stations in non-attainment ozone metropolitan areas. One year's data would be gathered to demonstrate that EVs and a PV recharging facility can be a transportation option to reduce greenhouse gases.

## CONCLUSION

EPA has embarked on a study to determine the environmental benefits potential of DSM using PV. The R&D focus will be in the systems application development area as a pollution reduction strategy.

## REFERENCES

1. The Potential of Renewable Energy: An Interlaboratory White Paper, U.S. Department of Energy, SERI/TP-260-3674, DE 90000322, March 1990.
2. Benefits of Distributed Generation in PG & E's T&D System: A Case Study of Photovoltaics Serving Kerman Substation, Pacific Gas and Electric Company, GM 663024-8, August 1991.
3. Fischetti, M., Here Comes the Electric Car - It's Sporty, Aggressive, and Clean, Smithsonian, Vol. 23, pp. 34-43, April 1992.
4. Long Range Strategies for Improving Air Quality, South Coast Air Quality Management District and the Southern California Association of Governments, September 1985.

## PHOTOVOLTAIC DEVELOPMENTS

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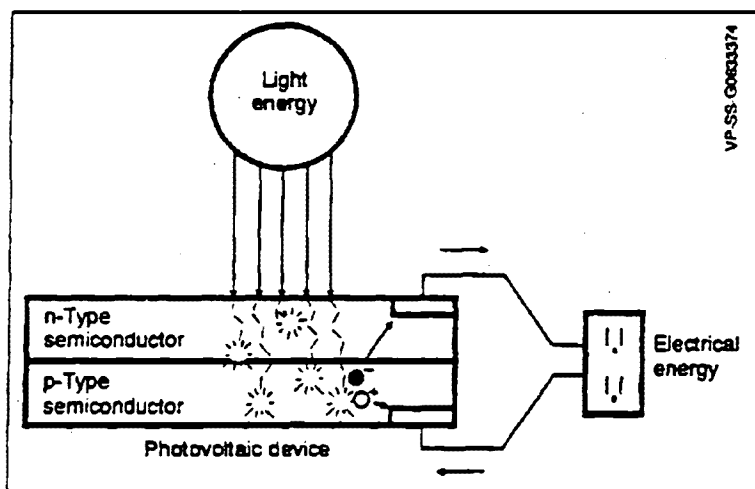
### ABSTRACT

Photovoltaics, the direct conversion of sunlight to electricity, is an environmentally pristine, renewable energy option currently used in a large number of international applications, principally non-grid-connected in remote locations. Examples include water pumping, communications, vaccine refrigeration, and village power. Over the past 15 years, a very aggressive research and development program carried out by the U.S. Department of Energy has continued to improve photovoltaic performance and reliability and has contributed to lower production costs. Along with these improvements have come a large number of new, cost-effective uses, including larger power installations in a utility environment. This technical and economic progress will be reviewed to represent the current status of this renewable energy option. Near-term plans for large-scale installations in the United States will be discussed along with the required costs for competitiveness with conventional electricity generation options.

Photovoltaics (PV) is the technology by which sunlight is converted directly into direct current (dc) electricity. The technology utilizes many of the same techniques common to solid-state electronic devices such as integrated circuits. PV involves no moving parts, so there is nothing to wear out, and it is environmentally benign during operation. PV is modular in that individual solar cells are combined in series and parallel combinations to synthesize the desired design voltages and currents (hence power) to form multiple solar cells into what are known as modules. Multiple modules are further wired in series-parallel combinations to form larger powered arrays. Using these various combinations, PV systems can literally be built in sizes ranging from less than a watt to many megawatts. Depending on the application, the dc power can be converted to alternating current (ac), allowing it to interface directly to the electric utility grid.

## INTRODUCTION

Figure 1 shows the basics of the solar cell. Essentially, the PV device is a battery like those commonly used in many applications. It has two terminals but no consumables to be replaced. Instead, the PV "battery" is fueled entirely by sunlight. The inherent energy of the sunlight is transferred to the material from which the PV device is fabricated (typically a semiconductor such as silicon). The energy is transferred through an absorption process. In the process, electrons and holes in the semiconductor are liberated by the sunlight and are able to move under the influence of a built-in electric field created by the positive/negative (pn) junction that is fundamental to the operation of the device.



**Figure 1.** In the typical PV cell, photon energy frees electrical charge carriers, which become part of the current in an electrical circuit. A built-in electrical field provides the voltage needed to drive the current through an external load.

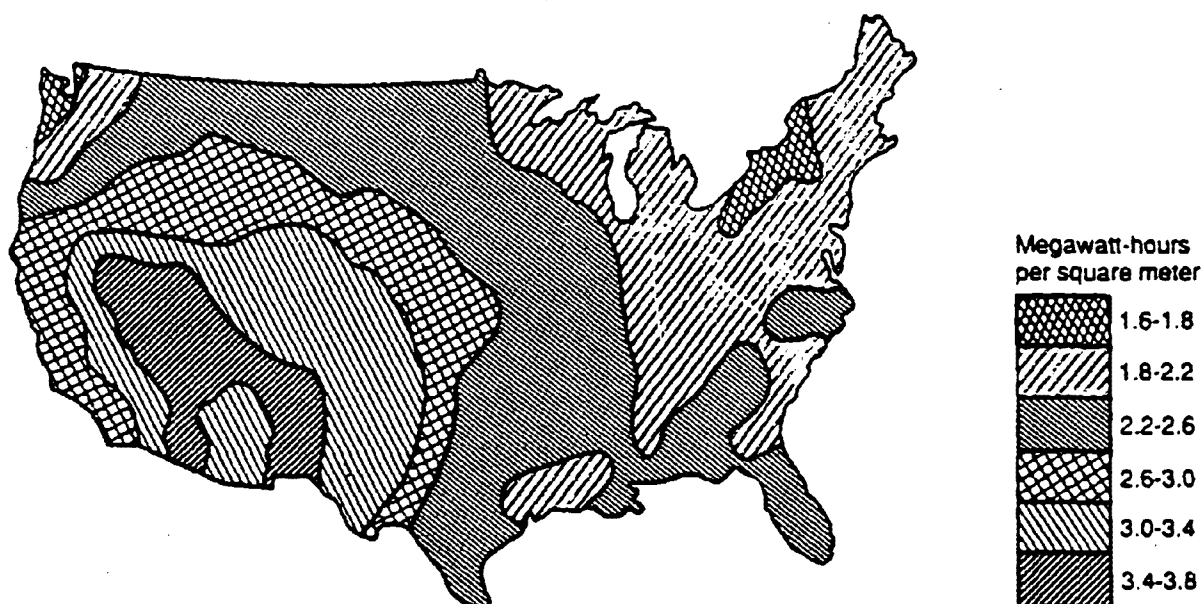
If all of the solar energy were converted to electricity, each square meter of PV cell would produce 1000 watts. The efficiency of conversion is, however, limited by physical processes to less than 100%. Typically, PV devices convert from about 5% to 35% of the available solar energy depending on the type of semiconductor material used. As will be shown later, the higher the efficiency of the module, the more that can be afforded for the module.

There are two fundamental types of PV systems. The first is the "flat plate" system, and the second is the concentrator system. Flat-plate systems are typically mounted in a fixed position relative to the sun. They can, however, be tracked to follow the sun in both its hourly

movement and its seasonal change in position. The concentrator uses either mirrors or lenses to focus the sunlight onto a small area. The concentration raises the power density by a factor of 10-1000 over a typical flat-plate module. Both approaches have their own economical parameters that influence the ultimate cost of PV-produced electricity. In addition, concentrators can be used effectively only in geographical areas where the so-called direct component of sunlight is plentiful. An example would be the desert southwest in the United States. Typically, flat plates can be used in almost all geographic areas.

## THE SOLAR RESOURCE

There is a common misunderstanding that the United States has inadequate sunlight to allow significant energy to be generated by photovoltaics. Actually, the energy available is about  $10^{17}$  kilowatt-hours per year, about a million times as much energy as the United States consumes on a yearly basis. The map shown in Figure 2 indicates that the average yearly solar resource varies from 1.6 megawatt-hours per square meter per year at the least desirable regions to 3.8 megawatt-hours per square meter per year in the best areas. Therefore, flat-plate collectors can operate well whether in Seattle or Phoenix. This is because the solar spectrum consists of a direct and a diffuse component, and flat plates use the total spectrum whereas concentrators can concentrate only the direct component. The direct component is significantly reduced by clouds, dust, and other airborne particles. Therefore, concentrators will find application primarily in the desert southwest, where the direct component is more available.



**Figure 2.** Average annual solar radiation for the United States

Sunlight has a color spectrum varying from the long-wavelength infrared to the short-wavelength ultraviolet. Depending on the semiconductor used to fabricate the solar cells, its sensitivity will vary with the color of the spectrum. The maximum theoretical efficiency is limited to approximately 30%–35% for flat-plate solar cells. Concentrated sunlight allows the cells to operate at higher efficiencies, perhaps as high as 40%–45%.

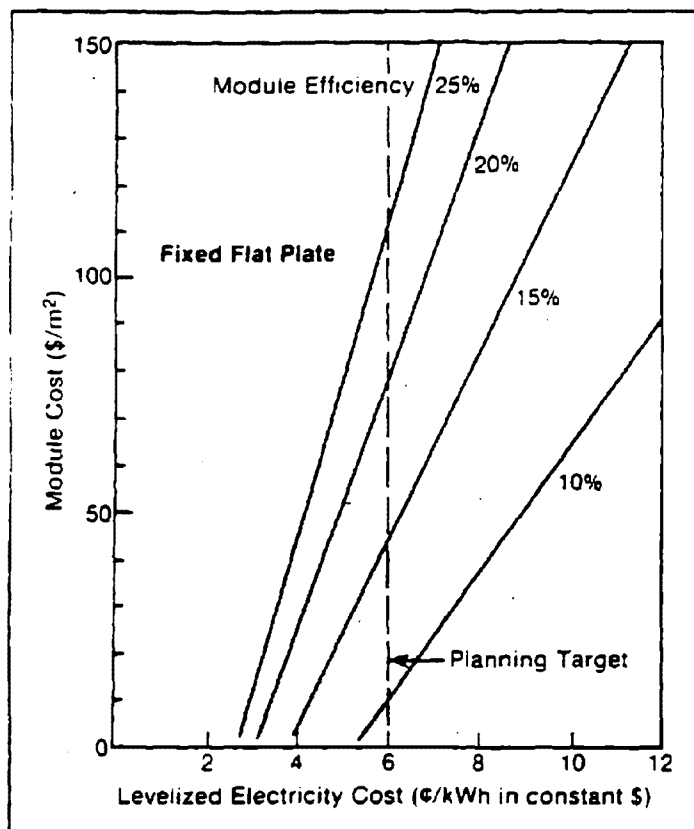
## ECONOMICS OF PHOTOVOLTAICS

For PV to be widely used, the costs must be competitive with those of conventional forms of electricity. In the United States, average prices for electricity are 6–7 cents per kilowatt hour. Today's PV generates electricity at 20–30 cents per kilowatt hour, so these costs must be reduced by about a factor of five. A number of factors influence PV energy costs. Foremost are the module efficiency, lifetime, and cost on an area basis. Several economic factors, principally the cost of money, also factor into the



equation to determine the energy cost. The U.S. Department of Energy (DOE) chose, as a target, 6 cents per kilowatt hour. Figure 3 indicates the module costs and module efficiency that combine to produce the 6-cent goal. The figure assumes a module lifetime of 30 years. It is evident, from the figure shown for flat-plate systems, that lower efficiencies require lower module costs. In fact, module costs can be traded off against efficiency. Similar curves exist for concentrators, which require higher efficiencies to

offset the higher costs of the required trackers and lenses to follow and concentrate the sun.



**Figure 3.** Module costs and efficiencies vs. 30-year levelized electricity costs for flat-plate photovoltaic systems (fixed flat plate)

## CURRENT MARKETS AND APPLICATIONS

The worldwide market for PV today is approximately 50 megawatts. Of this amount, the United States has about a one-third market share; the rest is sold primarily by Japan and Europe. Much of the market is concentrated in remote applications and consumer products. Remote applications include water pumping, communications, vaccine refrigeration, cathodic protection, and small village home power. The technology used in these applications is primarily crystalline and polycrystalline silicon. Consumer applications include small products such as calculators, watches, and small battery chargers. Most of these products are fabricated from amorphous silicon. In all cases, the applications are considered to be high value and are competitive with the alternatives such as diesel power, batteries, and kerosene. As the cost of PV is reduced, more of these applications will be available for PV to fill. Eventually, larger applications will become cost effective, including residential and commercial building demand-side-management projects and

larger bulk power stations. The industry is currently caught in a "catch-22" situation. That is, as the production plant sizes increase, prices are reduced through economy of scale. However, to justify the capital expenditures for plant construction, sustainable markets must be identified. And, lower costs are necessary to generate these sustainable markets. Markets are currently growing at about 20% per year. This evolutionary approach to market growth will delay the construction of the larger, cost-effective production facilities. To accelerate this process, DOE instituted activities to identify cost-effective applications within the electric utility industry that can be aggregated to form larger, sustainable markets. Under consideration are applications such as PV in lieu of line extensions, system upgrades, and transmission and distribution controls such as sectionalizing switches. As an example, power applications that are more than one-half mile from the utility grid are many times less expensive when provided by

PV/battery systems instead of by extending the utility grid. In fact, in Colorado, the utility regulators require the utility to provide the customer with an analysis of the use of PV when the monthly kilowatt hour usage divided by the distance to the utility line is less than 1000 (the so-called "Rule 31"). Most planners forecast a massive growth in PV systems when the price of PV-generated electricity reaches about 10 cents per kilowatt hour.

## STATUS OF PV TECHNOLOGIES

It is difficult to track the technical progress of PV. The most generally accepted figure of merit is the device or module efficiency. Compounding the problem is the fact that different organizations measure efficiency under a variety of test conditions. To allow a comparison of different technologies between different laboratories, the National Renewable Energy Laboratory (NREL) provides efficiency measurements under carefully controlled test conditions. The accompanying tables list the most current results for a wide variety of materials and device configurations. The numbers represent the best devices that NREL has measured but may not represent the best reported in the technical literature. As indicated in the tables, the measurement uncertainty is estimated to be  $\pm 2\%$  for single-junction cells and  $\pm 5\%$  for multiple-junction cells.

Crystalline or polycrystalline silicon continues to be the material of choice for high-efficiency, highly reliable PV modules. However, to reach the ultimate low costs, there is a growing consensus that a thin-film technology will be required that uses less semiconductor material in highly automated production facilities. Currently, industry is pursuing a variety of approaches and materials, including amorphous silicon deposited by glow discharge, thin-film polycrystalline silicon grown from solution, copper indium diselenide ( $\text{CuInSe}_2$ ) deposited by sputtering of the metal followed by in-situ selenization, and cadmium telluride ( $\text{CdTe}$ ) either spray-deposited or grown by close-spaced sublimation. All of these techniques are making excellent progress and have a high probability of success. Several of the approaches have been used to fabricate modules and are undergoing evaluation in a utility test demonstration at the Photovoltaics for Utility-Scale Applications (PVUSA) site in Davis, California.

## THE FUTURE

Future progress in the widespread use of PV can take several paths, depending on market development or market pull scenarios. One possibility is a business-as-usual or evolutionary growth path continuing to expand at 20% or more a year. Such a track will push off into the future, perhaps to the year 2010, any serious investment in larger, cost-effective production facilities. The second track is a more revolutionary market expansion through growth in competitive high-value applications, coupled perhaps with government policy changes (possibly driven by environmental concerns), and U.S. utility usage of PV. In the near term, the international market will continue to be a major user of PV. Consumer interest in PV buildings applications (demand-side management) could also allow market expansion. Clearly, the technological progress to date indicates a technology readiness to meet market demand. Economic factors, rather than technical ones, are now the major forces controlling PV's future.

## FURTHER READING

The interested reader is referred to the following list of publications for additional information. The technical level varies from low to highly technical.

1. *Fundamentals of Solar Cells*, A.L. Fahrenbruch and R.H. Bube, Academic Press (1983), a very complete reference book with a high degree of technical detail.
2. *Solar Cell Device Physics*, S.F. Fonash, Academic Press (1981), a highly technical coverage of device physics.
3. *Solar Energy Conversion: The Solar Cell*, R.C. Neville, Elsevier (1978), a medium technical level of the technology.
4. *Solar Cell Array Design Handbook*, H.S. Rauschenbach, Van Nostrand Reinhold (1980), a good reference on systems-related issues.
5. *Solar Cells*, edited by C.E. Backus, IEEE Press (1976), a collection of historical technical paper reprints.
6. *Basic Photovoltaics Principles and Methods*, Solar Energy Research Institute, Van Nostrand Reinhold (1984), very general for readers without extensive technical background.
7. *Harnessing Solar Power: The Photovoltaics Challenge*, K. Zweibel, Plenum Press (1990), a very good introduction to PV technology.

In addition, three international conferences meet every 18 months (spaced 6 months apart) for which proceedings are published. These range from highly technical to general overviews. The conferences are the IEEE Photovoltaic Specialists Conference (the United States), the EC Photovoltaic Solar Energy Conference (European), and the Photovoltaic Science and Engineering Conference (Far East).

## ACKNOWLEDGEMENT

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# Amorphous Silicon

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
ARCO	1/17/89	3.960	874	15.62	71.3	9.7	a-Si
Advanced PV Sys	1/31/91	0.998	872	16.54	71.2	10.3	a-Si
Brookhaven	4/30/86	0.023	832	14.60	66.3	8.1	a-Si
Chronar	10/18/90	1.060	864	16.66	71.7	10.3	a-Si
	1/4/88	0.980	2510	7.20	64.8	7.4	a-Si/a-Si/a-Si:Ge
	3/20/89	1.000	1706	7.31	68.5	8.6	a-Si/a-Si:Ge
	3/10/86	0.284	878	14.40	65.9	8.3	Photo CVD a-Si
ECD	2/16/88	0.268	940	15.20	69.4	9.9	ITO/a-Si/ss
	6/13/89	0.269	1875	7.43	73.6	10.3	ITO/a-Si/a-Si/ss
	2/16/88	0.268	1640	10.10	69.6	11.6	ITO/a-Si/a-Si:Ge/ss
	2/16/88	0.268	739	19.80	59.6	8.7	ITO/a-Si:Ge/ss
	2/16/88	0.268	2541	6.96	70.0	12.4	ITO/a-Si/a-Si/a-Si:Ge/ss
IEC	11/7/87	0.284	862	17.60	65.8	10.0	Photo CVD a-Si
Glass Tech	5/4/90	1.017	852	17.26	69.8	10.1	a-Si (20Å/s depos.rate)
	9/15/89	0.986	886	17.46	70.4	10.9	a-Si
	12/13/89	0.989	1711	8.45	71.6	10.4	a-Si/a-Si
3M	1/22/87	0.140	874	13.80	64.7	7.8	a-Si on Kapton
Solarex	4/16/87	1.077	879	18.80	70.1	11.5	a-Si
	10/1/87	0.758	1685	9.03	68.1	10.3	a-Si/a-Si:Ge
	6/16/89	0.256	2300	6.68	57.7	8.9	a-Si/a-Si/a-Si:Ge
Spire	12/9/86	0.099	878	16.60	72.2	10.5	a-Si
	6/5/85	0.102	1586	6.90	57.4	6.3	a-Si/a-Si:Ge

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators in the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL ((303) 231-1032).

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
UPG	1/4/88	1.010	876	13.80	69.6	8.4	a-Si
Vactronics	11/11/86	0.256	822	11.40	60.5	5.7	a-Si
NREL	10/10/88	0.049	841	16.90	66.8	9.5	a-Si

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators in the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL [(303) 231-1032].

# AlGaAs, GaInP, GaInAsP, GaInAsGaAs, InP

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
ASEC	3/6/89	4.003	1036	27.57	85.3	24.3	GaAs, GaAlAs window
Kopin	11/13/89	4.000	1011	27.55	83.8	23.3	GaAs Cleft (separated)
	6/3/88	1.000	1208	18.20	85.5	18.8	1.75 eV GaAlAs
	3/12/90	3.910	1022	28.17	87.1	25.1	GaAs, GaAlAs window
	4/16/90	16.00	4034	6.55	79.6	21.0	5mm Cleft GaAs, sub module
SMU	7/23/85	1.009	822	19.70	62.2	10.1	Thin Film GaAs/Ge/graphite (direct)
Spire	3/6/89	0.250	1029	27.89	86.4	24.8	GaAs, GaAlAs window
	4/21/92	16.14	1055	26.86	85.4	24.2	GaAs
	3/7/89	0.250	1018	27.56	84.7	23.8	GaAs(MBE) Purdue
	4/30/86	0.250	1200	16.20	82.6	16.0	1.75 eV GaAlAs
	4/26/90	4.015	878	29.29	85.4	21.9	InP
	4/24/87	0.249	1213	17.60	83.0	17.7	1.69 eV GaAsP
	9/22/88	0.250	891	25.50	77.7	17.6	GaAs on Si
	11/25/88	0.250	1190	23.80	84.9	24.1	GaAs/Ge Tandem
Varian	3/8/89	0.500	2403	13.96	83.4	27.6	Two-terminal tandem
	—	0.500	1402	13.92	86.8	16.0	1.93 eV GaAlAs top cell
	—	0.531	1000	13.78	83.0	11.3	GaAs bottom cell
	—	—	—	—	—	27.3	Three-terminal tandem
	8/6/87	4.000	1244	16.00	84.6	16.8	1.75 eV GaAlAs
	7/9/87	2.932	730	17.40	78.7	10.0	1.15 eV GaInAs bottom cell under 1.75 eV GaAlAs
	3/8/89	4.000	1045	27.60	84.5	24.4	GaAs, GaAlAs window

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators is the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL [(303) 231-1032].

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
NREL	8/24/90	0.0634	973	1416	83.8	22.9	InP tope cell, 50 suns direct
	—	0.0663	445	1321	75.7	<u>8.9</u>	0.75 eV GaInAs bottom cell, 50 suns direct
	—	—	—	—	—	31.8	3-terminal InP/GaInAs tandem
	10/11/90	0.0511	1096	990.3	83.5	23.1	GaAs top cell, 39.5 suns direct
	—	0.0534	626	556.7	80.7	<u>7.1</u>	0.95 eV GaInAsP under GaAs top cell
	—	—	—	—	—	30.2	4-terminal mechanically stacked tandem
	—	—	—	—	—	—	39.5 suns, ASTM E891 direct
	8/13/90	0.310	876	28.70	82.9	20.9	InP top cell
	—	0.312	337	21.94	72.1	5.3	0.75eV GaInAs bottom cell
	—	—	—	—	—	26.2	InP/GaInAs 3-terminal tandem
	2/20/91	0.0746	899	6343	82.5	27.5	1.15 eV GaInAsP, 171 suns, direct
	8/21/89	0.250	2292	13.61	87.4	27.3	GaInP/GaAs 2-terminal tandem
	12/18/89	0.173	1038	28.70	86.4	25.7	GaInP/GaAs ,with aperture
	9/13/89	0.249	1050	27.80	85.6	25.0	GaAs, GaInP window
	1/18/91	0.0746	959	1509	87.3	24.3	InP homojunction 52 suns ,direct
	12/10/90	0.0746	901	2588	79.3	21.0	Heteroepitaxial InP on GaAs, 88 suns, ASTM E891 direct
	—	—	—	—	—	—	ITO/InP
	8/19/88	0.108	813	27.97	82.9	18.9	1.75 eV GaAsP
	4/11/85	0.100	1254	13.10	85.8	14.1	1.24 eV InAsP
	11/3/88	0.108	760	20.20	80.9	12.4	0.95 eV GaInAsP under a GaAs filter, 30.6 suns, ASTM E891 direct
	10/14/90	0.160	658	531.8	82.0	9.4	

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators is the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL [(303) 231-1032].

# **Mono and Multi-Silicon**

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
EMC	9/3/85	4.100	592	31.50	79.1	14.8	Ribbon
Spectrolab	6/5/85	15.470	595	36.70	76.9	16.8	mono crystal Si
Spire	10/28/85	4.020	634	36.30	81.6	18.8	mono crystal Si
Stanford	6/3/86	0.152	681	41.00	78.4	21.9	Point-contact cell
	9/20/88	8.525	702	40.70	77.7	22.2	mono crystal Si
Oak Ridge	10/3/86	4.000	657	36.00	81.6	19.3	mono crystal Si
Astro-Power	10/30/89	1.000	583	30.70	80.2	14.4	100 μm thinned mono-Si
	12/1/88	1.020	600	33.00	79.2	15.7	Thin film poly on ceramic Sandia measurement
Westinghouse	5/8/85	1.017	602	31.60	80.7	15.4	Web; Direct, 28°C
	11/29/84	24.500	598	30.40	79.5	14.5	Web; Direct, 28°C
	4/11/85	1.004	637	33.70	76.2	16.5	mono crystal Si
Univ. of New	12/14/89	4.024	700	40.33	81.3	23.0	mono-crystal Si, aperture
South Wales	9/25/85	4.120	608	35.70	73.1	17.3	multi-crystal Si (Wacker)
	4/7/87	0.801	628	41.50	79.6	20.8	mono-crystal: Conc.
	7/23/87	11.980	629	37.30	79.1	18.6	mono-crystal: Large area
ISE Germany	10/16/91	4.023	675	39.57	77.8	20.8	mono-crystal

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators in the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL [(303) 231-1032].



# **CuInSe<sub>2</sub> and CdTe**

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
ARCO	6/17/88	2.400	464	38.50	65.4	11.7	ZnO/[Cd,Zn]S/CuInSe <sub>2</sub>
Boeing	12/30/86	1.074	509	30.40	66.0	10.2	CdS/CuInGaSe <sub>2</sub>
	9/8/88	0.987	555	34.20	65.7	12.5	ZnO/[Cd,Zn]S/CuInGaSe <sub>2</sub>
	1/2/92	3.990	532	31.88	67.9	11.5	ZnO/[Cd,Zn]S/CuInGaSe <sub>2</sub>
	7/1/92	0.990	546	36.71	63.4	13.7	ZnO/[Cd,Zn]S/CuInGaSe <sub>2</sub>
IEC	9/2/87	1.028	445	35.00	64.6	10.1	ZnO/[Cd,Zn]S/CuInSe <sub>2</sub>
	5/18/89	0.105	729	18.95	69.0	9.5	Glass/ITO/CdS/CdTe/Cu
	10/22/91	0.191	790	20.10	69.4	11.0	Glass/ITO/CdS/CdTe/Cu/Au
ISCT	1/3/91	0.994	483	35.60	66.7	11.5	ZnO/CdS/CuInSe <sub>2</sub> /Mo/Glass
NREL	6/12/85	1.033	446	35.30	65.3	10.3	CdS/CuInSe <sub>2</sub>
	2/10/92	0.096	682	21.66	55.3	8.2	Glass/SnO <sub>2</sub> /CdS/CdTe/Cu
Photon Energy	5/19/89	0.313	783	24.98	62.7	12.3	Glass/SnO <sub>2</sub> /CdS/CdTe
	5/2/91	0.300	788	26.18	61.4	12.7	Glass/SnO <sub>2</sub> /CdS/CdTe
"SMU, Chu"	4/14/88	1.022	736	21.90	65.7	10.6	Glass/SnO <sub>2</sub> /CdS/CdTe/HgTe/Ag
U.S. Florida	5/24/91	1.197	840	21.93	72.6	13.4	Glass/SnO <sub>2</sub> /CdS/CdTe/C/Ag
	11/19/91	1.080	850	24.41	70.4	14.6	MgF <sub>2</sub> /Glass/SnO <sub>2</sub> /CdS/CdTe/C/Ag
	7/26/92	1.047	843	25.09	74.5	15.8	MgF <sub>2</sub> /Glass/SnO <sub>2</sub> /CdS/CdTe/C/Ag
AMETEK	10/19/89	1.068	767	20.93	69.6	11.2	Glass/SnO <sub>2</sub> /CdS/CdTe/ZnTe/Ni

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators is the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL [(303) 231-1032].

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
Georgia Tech.	5/17/91	0.080	714	24.19	59.8	10.3	Glass/SnO <sub>2</sub> /CdS/MOCVD CdTe/ZnTe
	6/28/91	0.080	745	22.10	66.0	10.9	Glass/SnO <sub>2</sub> /CdS/MOCVD CdTe
U. Toledo	10/29/91	0.080	790	17.75	60.2	8.4	Glass/SnO <sub>2</sub> /CdS/Laser ablated CdTe/Cu/Au

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators is the area designed to be illuminated. The total estimated uncertainty for single junction cells is  $\pm 2\%$ . The estimated uncertainty for multiple-junction cells is  $\pm 5\%$ . This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL ((303) 231-1032).

# Mechanically Stacked 4-Terminal PV Devices

Source	Date	Total Area (cm <sup>2</sup> )	V <sub>oc</sub> (mV)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)	Comments
ARCO	6/17/88	2.400	430	17.10	66.1	4.9	ZnO/[Cd,Zn]S/CuInSe <sub>2</sub> under a-Si
	—	2.400	871	15.62	71.25	9.7	a-Si top cell
	—	—	—	—	—	14.6	4-terminal tandem: a-Si on CuInSe <sub>2</sub>
Boeing /Kopin	11/13/89	4.000	1011	27.55	83.8	23.3	GaAs Cleft stacked on
	—	—	360	12.11	57.8	2.5	ZnO/[Cd,Zn]S/CuInSe <sub>2</sub>
	—	—	—	—	—	25.8	4-terminal tandem, GaAs on CuInSe <sub>2</sub>
NREL	10/11/90	0.0511	1096	990.3	83.5	23.1	GaAs top cell, 39.5 suns direct
	—	0.0534	626	556.7	80.7	7.1	0.95 eV GaInAsP under GaAs top cell
	—	—	—	—	—	30.2	4-terminal tandem GaAs on GaInAsP
	—	—	—	—	—	—	39.5 suns, ASTM E891 direct

All measurements performed at NREL, 1000Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition used for nonconcentrator cells is the total area, the area for concentrators in the area designed to be illuminated. The total estimated uncertainty for single junction cells is ±2%. The estimated uncertainty for multiple-junction cells is ±5%. This table was printed on Tuesday, July 14, 1992. For further information contact Keith Emery at NREL [(303) 231-1032].

## Summary of Thin-Film Amorphous Silicon Module Efficiencies

Cell Structure	Source	Date	V <sub>oc</sub> (V)	I <sub>sc</sub> (mA)	FF (%)	P <sub>max</sub> (W)	Aperture Area (cm <sup>2</sup> )	Efficiency (%)
a-Si	ARCO	06/16/88	42.83	277	67	7.9	844	9.4
a-Si	ARCO	10/11/88	22.61	2102	71	33.5	4939	6.8
a-Si	ARCO	2/21/90	44.79	826	65	24.1	3962	6.1
a-Si	Chronar	3/10/88	23.87	1154	64	17.5	2625	6.7
a-Si	Chronar	10/23/89	57.98	1697	63	61.8	11344	5.2†
a-Si	Chronar	4/6/90	61.03	1848	66	74.4	11904	6.2††
a-Si	Chronar	5/10/90	24.26	403	76	6.6	873	7.6
a-Si	APS	9/17/91	55.7	1980	70	77.8	12129	6.4†††
a-Si	Glasstech Solar	10/16/89	22.14	368	66	5.4	880	6.1
a-Si	Glasstech Solar	10/16/89	12.01	2008	63	15.2	2703	5.6
a-Si	Solarex	4/6/87	25.38	410	68	7.1	1006	7.1
a-Si	Solarex	4/20/88	25.12	1352	66	22.5	3882	5.8
a-Si	Solarex	11/15/89	42.32	300	67	8.5	936	9.1
a-Si	Solarex	2/1/90	42.35	337	64	9.2	933	9.8
a-Si	Utility Power Group	10/16/89	16.08	479	64	4.9	750	6.5

The module efficiencies are received prior to any light induced degradation

- † Measured outdoors in Golden, CO, 1044 W/m<sup>2</sup> total irradiance, 38°C module temperature
- †† Measured outdoors in Golden, CO, 1004 W/m<sup>2</sup> total irradiance, 33°C module temperature
- ††† Measured outdoors in Golden, CO, 1006 W/m<sup>2</sup> total irradiance, 29°C module temperature

All measurements performed at NREL, 100 Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition for modules is the minimum rectangular aperture that can be placed over the module without affecting the photo-current or the inside frame area. The total estimated uncertainty for single junction modules is ±5%. The estimated uncertainty for multiple-junction modules is ±10%. This table was printed on Tuesday, July 14, 1991. For further information contact Keith Emery at NREL [(303) 231-1032].

# Summary of Thin-Film Multiple-Junction Module Efficiencies

Cell Structure	Source	Date	V <sub>oc</sub> (V)	I <sub>sc</sub> (mA)	FF (%)	P <sub>max</sub> (W)	Aperture Area (cm <sup>2</sup> )	Efficiency (%)
a-Si/a-Si	Advanced PV Systems	1/28/91	48.8	183	65	5.8	942	6.6
a-Si/a-Si	Chronar	1/22/88	22.95	1119	59	15.1	2547	6.0
a-Si/a-Si	Chronar	1/30/89	47.75	191	65	5.9	842	7.0
a-Si/a-Si	Chronar	9/10/90	46.73	548	64	16.4	2555	6.4
a-Si/a-Si	Glasstech Solar	10/16/89	7.49	858	60	3.9	888	4.4
a-Si/a-Si	Solarex	9/06/88	48.78	193	61	5.8	1007	5.7
a-Si/a-Si	Sovonics	4/12/88	22.76	1558	67	23.9	3646	6.6
a-Si/a-Si	Sovonics	5/10/89	21.58	1671	67	24.0	3864	6.2
a-Si/a-Si	Sovonics	4/21/88	22.20	2656	62	36.6	6634	5.5
a-Si/a-Si	Sovonics	4/12/88	22.76	1558	67	23.9	3646	6.6
a-Si/a-Si	United Solar Corp. (USSC)	12/28/90	23.45	1883	61	27.1	3676	7.4
a-Si:C/a-Si:Ge	Solarex	10/24/88	49.85	234	60	7.0	1007	7.0
a-Si/a-Si/a-SiGe	Solarex	11/15/89	62.65	174	61	6.7	936	7.1
a-Si/a-Si:C/a-Si:Ge	Solarex	2/1/90	65.48	189	68	8.3	936	8.1†
a-Si/a-Si/a-Si:Ge	Solarex	10/9/90	66.75	206	63	8.7	940	9.3
a-Si/a-Si/a-Si:Ge	Solarex	3/12/91	57.34	242	66	9.1	937	9.7
a-Si/a-Si/a-Si:Ge	Sovonics	10/6/88	17.01	555	64	6.0	838	7.2
a-Si/a-Si/a-Si:Ge	Sovonics	12/5/88	17.02	609	66	6.8	868	7.9

The module efficiencies are received prior to any light induced degradation

† Measured outdoors in Golden, CO, 1097 W/m<sup>2</sup> total irradiance, 24°C module temperature

All measurements performed at NREL, 100 Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition for modules is the minimum rectangular aperture that can be placed over the module without affecting the photo-current or the inside frame area. The total estimated uncertainty for single junction modules is ±5%. The estimated uncertainty for multiple-junction modules is ±10%. This table was printed on Tuesday, July 14, 1991. For further information contact Keith Emery at NREL [(303) 231-1032].

### Summary of Thin-Film CuInSe<sub>2</sub> and CdTe Module Efficiencies

Cell Structure	Source	Date	V <sub>oc</sub> (V)	I <sub>sc</sub> (mA)	FF (%)	P <sub>max</sub> (W)	Aperture Area (cm <sup>2</sup> )	Efficiency (%)
CdS/CdTe	AMETEK	10/24/88	9.63	125	57	0.68	100	6.8
CdS/CdTe	AMETEK	1/3/90	7.05	118	49	0.40	103	3.9
CdS/CdTe	Photon Energy	3/23/88	21.07	395	57	4.8	808	5.9
CdS/CdTe	Photon Energy	10/24/88	20.49	519	57	6.1	838	7.3
CdS/CdTe	Photon Energy	11/2/89	20.75	453	58	5.4	930	5.8
CdS/CdTe	Photon Energy	9/3/91	~21	573	~55	6.7	832	8.1†
CdS/CdTe	Photon Energy	3/25/92	35.6	893	50	15.9	3630	4.2††
ZnO/CdZnS/CuInSe <sub>2</sub>	ARCO	5/30/91	24.01	244	64.4	36.7	3883	9.7
ZnO/CdZnS/CuInSe <sub>2</sub>	ARCO	1/23/89	23.04	2461	60	33.8	3985	8.5
ZnO/CdZnS/CuInSe <sub>2</sub>	ARCO	6/16/88	25.38	637	64	10.4	938	11.1
ZnO/CdZnS/CuInSe <sub>2</sub>	Boeing	12/3/86	1.78	774	63.9	0.88	97.0	9.1

† Measured outdoors in Golden, CO, 1013 W/m<sup>2</sup> total irradiance, 33°C module temperature, under continuous maximum power tracking to minimize voltage shift

†† Measured outdoors in Golden, CO, 1053 W/m<sup>2</sup> total irradiance, 22°C module temperature, under continuous maximum power tracking to minimize voltage shift

All measurements performed at NREL, 100 Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition for modules is the minimum rectangular aperture that can be placed over the module without affecting the photo-current or the inside frame area. The total estimated uncertainty for single junction modules is ±5%. The estimated uncertainty for multiple-junction modules is ±10%. This table was printed on Tuesday, July 14, 1991. For further information contact Keith Emery at NREL ((303) 231-1032).

# **Concentrator Cell Efficiencies Verified at Sandia with Respect to the Standard Concentrator Reporting Conditions**

Source	Illuminated Area (cm <sup>2</sup> )	Efficiency (%)	Concentration (suns)	Materials System
Univ. New South Wales	20.0	22.6	20	float-zone Si
Solarex	38.4	20.2	20	Czochralski Si
Solarex	39.5	17.5	20	multi-crystalline Si
Astropower	39.6	17.8	20	Czochralski Si
Stanford Univ.	0.15	28.2	140	float-zone Si
Univ. New South Wales	1.58	25.2	125	float-zone Si
SERA	0.065	23.9	65	float-zone Si
Solarex	1.58	21.5	150	float-zone Si
Varian	0.126	28.1	403	GaAs
Varian	0.126	29.2	206	GaAs
Spire	0.317	28.7	200	GaAs
Sandia, Varian and Stanford	0.317	31.0	500	GaAs stacked on Si, 4-terminal tandem
Boeing	0.053	34.2	100	GaAs stacked on GaSb 4-terminal tandem

All measurements performed at NREL, 100 Wm<sup>-2</sup>, 25°C, ASTM E892 global unless noted otherwise. The area definition for modules is the minimum rectangular aperture that can be placed over the module without affecting the photo-current or the inside frame area. The total estimated uncertainty for single junction modules is ±5%. The estimated uncertainty for multiple-junction modules is ±10%. This table was printed on Tuesday, July 14, 1991. For further information contact Keith Emery at NREL [(303) 231-1032].

ADVANCED ENERGY SYSTEMS FUELED FROM BIOMASS

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ABSTRACT

The concentration of carbon dioxide (CO<sub>2</sub>), a greenhouse gas, is increasing by an estimated 0.5 percent per year. CO<sub>2</sub> emissions from fossil fuel combustion quadrupled between 1950 and 1980. Conversion of renewable biomass to energy is CO<sub>2</sub> neutral and produces lower sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) emissions than fossil fuel combustion.

The U.S. Environmental Protection Agency/Air and Energy Engineering Research Laboratory is studying two biomass conversion technologies: conventional combustion in a boiler coupled with a steam turbine system and gasification in a gasifier coupled with an aeroderivative turbine system. In-house research is addressing the problems encountered in conventional systems with regard to emissions, tube fouling, bed agglomeration, and low thermal efficiency. Extramural research is addressing the problems of advanced systems with regard to fixed/fluidized-bed gasifiers, alkali/particulate cleanup, gas compatibility with turbines, and system efficiency. The results will provide data for owner/operators to improve system performance and for designer/developers to demonstrate advanced systems. This research will help promote biomass-for-energy as a global warming mitigation strategy by focusing on a need to maximize biomass resources through increased utilization efficiency.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.



## INTRODUCTION

The leading culprit in the greenhouse gas arena is carbon dioxide ( $\text{CO}_2$ ), and its concentration is increasing by an estimated 0.5 percent per year [1]. Anthropogenic activities are responsible for the unwanted buildup of  $\text{CO}_2$  in the atmosphere.  $\text{CO}_2$  emissions from fossil fuel combustion quadrupled between 1950 and 1980 alone; therefore, reducing fossil fuel  $\text{CO}_2$  emissions is an obvious place to start mitigation activities [1]. The efficient use of biomass is  $\text{CO}_2$  neutral and can reduce pollution by lowering sulfur dioxide ( $\text{SO}_2$ ) and nitrogen oxides ( $\text{NO}_x$ ) emissions. Figure 1 is a simple representation of the biomass closed carbon cycle and the fossil fuel (oil, coal, and gas) open carbon cycle.

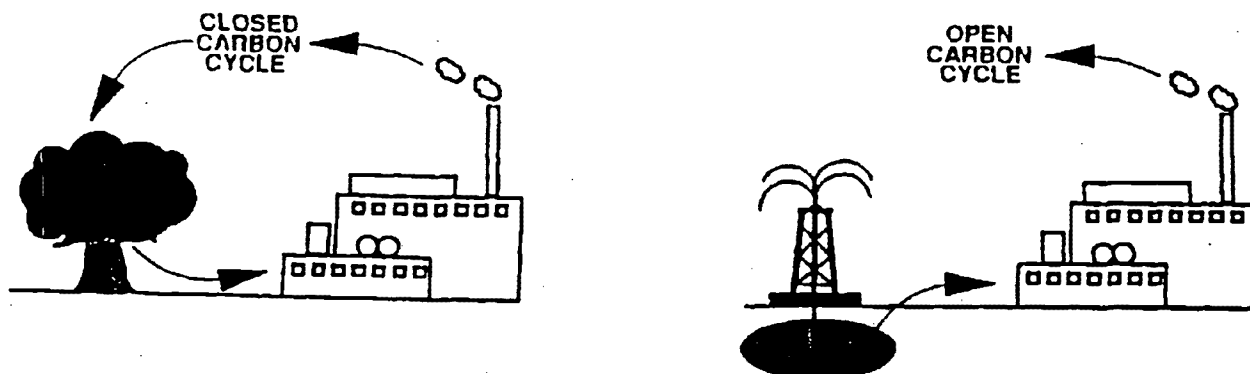


Figure 1 - Carbon Cycles

Biomass is the principal single source of energy for 75 percent of the world's population [2]. It provides about 14 percent of the world's energy; 35 percent of the total energy supply in developing countries, and 3 percent of the total energy supply in developed countries (see Figure 2) [3]. This energy contribution is equivalent to 35 million barrels ( $5.6 \times 10^9$  L) of oil per day globally [2]. Some analyses suggest that the amount of energy contributed by biomass could be increased by a factor of 13 [2]. By the second quarter of the 21st century, biomass could provide 25-35 percent of the total global power generation capacity [4]. In 1990, the United States had 9,000 MW of biomass-fueled electric capacity, 36 times the capacity in 1980, due to the Public Utilities Regulatory Policies Act of 1978 (PURPA) [4].

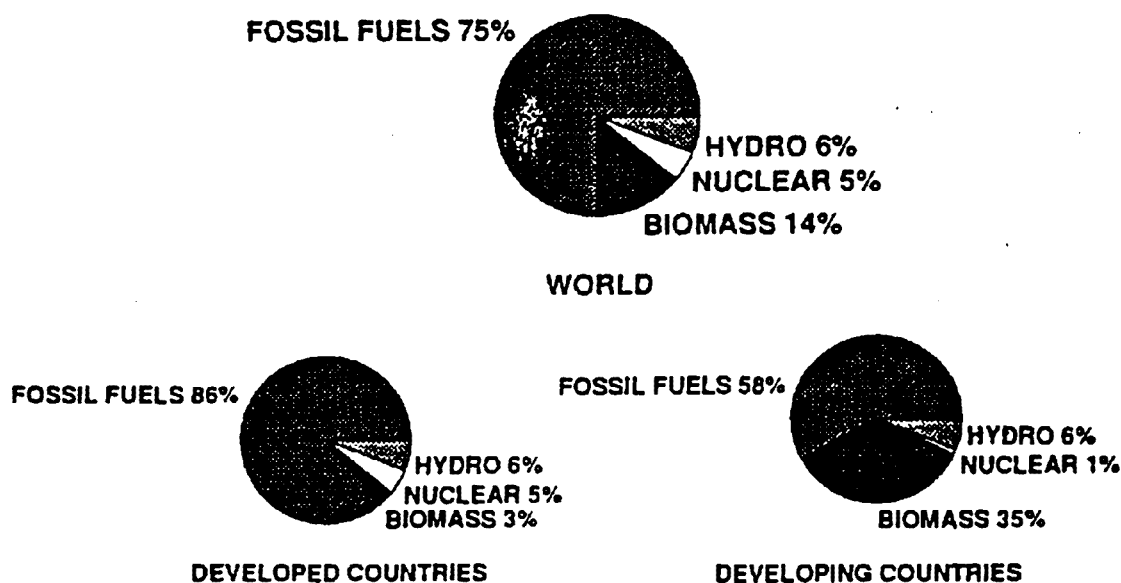


Figure 2 - Energy Use Distribution

Increasing biomass availability on a sustainable basis may not be viewed as a high priority in developing countries and what is appropriate in one country might not work as well in another. But energy demands will increase in all countries and all countries have forestry and agricultural wastes and the potential for energy crops. Therefore, greater use of industrial wood wastes, agro-processing wastes, and agricultural residues will have the greatest near term impact. The potential for the use of existing biomass resources in the world is  $65,381 \times 10^6$  GJ;  $41,068 \times 10^6$  GJ in developing countries and  $24,313 \times 10^6$  GJ in developed countries [3]. The development and commercialization of small, residue-fueled facilities should fill the needs of rural communities and biomass industries as well as developing countries.

Promotion of carbon sequestration and biomass utilization requires research on various issues including land use, forest management, production, harvesting, reforestation, urban reforestation (carbon sequestration and mitigation of the urban heat island effect), displacement of fossil fuels with biomass-based electricity and liquid fuels, and increased use of wood products. The U.S. Department of Agriculture (USDA)/Soil Conservation Service, USDA/Forest Service, U.S. Department of Energy (DOE)/Office of Conservation and Renewable Energy, U.S. Environmental Protection Agency/Air and Energy Engineering Research Laboratory (EPA/AEERL), National Renewable Energy Laboratory, and Oak Ridge National Laboratory are some of the domestic organizations studying these issues.

## CONVERSION TECHNOLOGIES

In ethanol production from woody energy crops, 75 percent of the energy ultimately produced can actually count toward fossil fuel displacement. When woody crops are directly converted to electricity, this figure can increase to 90 percent [1]. This 15 percent increase indicates that the conversion technologies with the greatest near term potential will focus on direct biomass-to-energy production. This near term production should occur through utilization of residues in small stand-alone energy production facilities.

EPA/AEERL's goal is to promote activities to achieve renewable production, provide modern energy carriers, develop high-efficiency conversion processes, develop high efficiencies for end use, and develop technologies that have favorable economics on a small scale.

EPA/AEERL's program is studying two conversion technologies: conventional combustion in a boiler coupled with a steam turbine system and gasification in a gasifier coupled with an aeroderivative turbine system (see Figure 3).

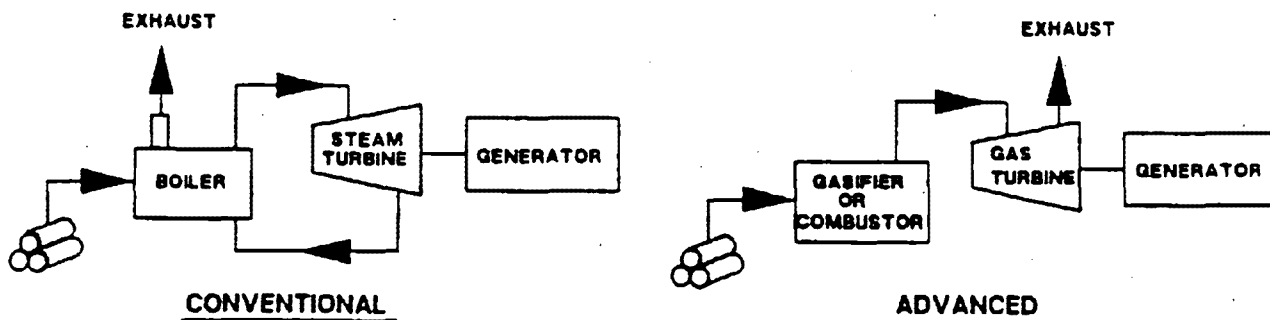


Figure 3 - Cycle Flow Diagrams

### Combustion

Throughout the world, process heat/steam and electricity generated from biomass fuels are almost entirely a result of direct combustion. Direct combustion technologies fueled with biomass include dutch ovens, spreader-stokers, total or suspension fired combustors, and fluidized or circulating bed combustors. Since these technologies are firmly established, they are readily transferable to biomass energy applications throughout the developed and developing world.

In applying these technologies to biomass fuels, problems are often encountered with regard to unacceptable, uncontrolled emissions, boiler tube fouling, bed agglomeration, and less than optimum thermal efficiency. These problems arise as a result of the combustor's inability to respond to rapid variations in certain properties of the fuel feed (moisture content, particle size, and inorganic content).

In-house research at EPA/AEERL is addressing the above problem, and by doing so, will provide data to owner/operators of biomass combustion systems for the purpose of improving system performance through modifications to the combustion process. This research will help promote biomass-for-energy as a global warming mitigation strategy by focusing on a need to maximize biomass resources through increased utilization efficiency.

The approach of the research is to burn different biomass fuels (sawdust briquettes, bagasse pellets, and switch grass briquettes) in a pilot-scale stationary grate combustor. A first series of tests is to use fuels with relatively uniform properties. Standard thermal and chemical analyses will be performed to quantify fuel properties. Data obtained from this series of tests will establish a baseline and characterize relationships between fuel properties and system performance. In a second series of tests, fuel properties will be measurably altered (by increasing moisture content or inorganic fraction, for instance) and the system will be monitored and adjusted to optimize combustor performance under adverse operating conditions. The purpose of performing this series of tests will be to minimize emissions of criteria and non-criteria pollutants -- carbon monoxide (CO), NO<sub>x</sub>, particulate matter (PM), and volatile organic compounds (VOCs) -- and fouling of heat transfer surfaces while maximizing thermal efficiency by controlling air flows, combustion air temperature, etc. Techniques for controlling the combustion process will be developed so that they can be applied by operators of biomass combustion systems. Testing is anticipated to begin in June 1993 when construction of the combustor facility is complete.

### Gasification

Gas turbines fueled with biomass gas offer a great advantage in the 10 to 50 MW range. Net plant conversion efficiencies could exceed 50 percent, especially if the turbine exhaust is used in a heat recovery steam generator or an air bottoming cycle [4]. Aeroderivative gas turbines (i.e., gas turbines derived from aircraft jet engines) offer high efficiency, low unit capital costs at modest scales, and low maintenance due to their compact modular nature.

#### Fixed-bed Gasifiers

Temperatures of the gas exiting the gasifier are expected to be 500-600°C for the fixed-bed updraft design. Within this temperature range, the alkali compounds (formed primarily from potassium and sodium in the feedstock) appear to condense on PM and can be controlled by particulate collection devices. The temperature is high enough that the tars formed will remain in the vapor phase and actually boost the heating value of the gas. It would be desirable to have the gasifier and gas turbine close-coupled to eliminate any condensation problems [4].

The State of Vermont was funded by EPA/AEERL, DOE, and U.S. Agency for International Development to evaluate the compatibility of gasified biomass feedstocks with an aeroderivative gas turbine power generation system. The EPA/AEERL is also

funding Vermont to perform a feasibility study on demonstrating this technology. The compatibility evaluation was performed at the General Electric Corporate Research and Development (GE CR&D) coal gasification pilot plant. The objectives of the study were:

- to determine the composition of the product gas and gasification rate,
- to determine the nature of the contaminants in the gas that might have a detrimental effect on the gas turbine,
- to measure the contaminants in the gas that might have a negative environmental effect, and
- to determine the effectiveness of cyclones for particulate removal.

The gasification plant consisted of a feed system, a fixed-bed updraft gasifier, and a cyclone (see Figure 4). The State of Vermont provided 83.8 tons (76 tonnes) of dried wood chips and Winrock International provided 42.5 tons (39 tonnes) of bagasse pellets.<sup>1</sup> These highly reactive biomass fuels were gasified at 20 atm (2.03 MPa). The biogas product had a higher heating value than coal gas and was compatible with gas turbine combustors. The particulate carry over and the alkali metal contained in the particles indicated that a single cyclone was not sufficient for cleanup. The sulfur emissions were lower than for coal combustion facilities equipped with flue gas desulfurization systems, and fuel bound nitrogen levels were lower than for coal [5].

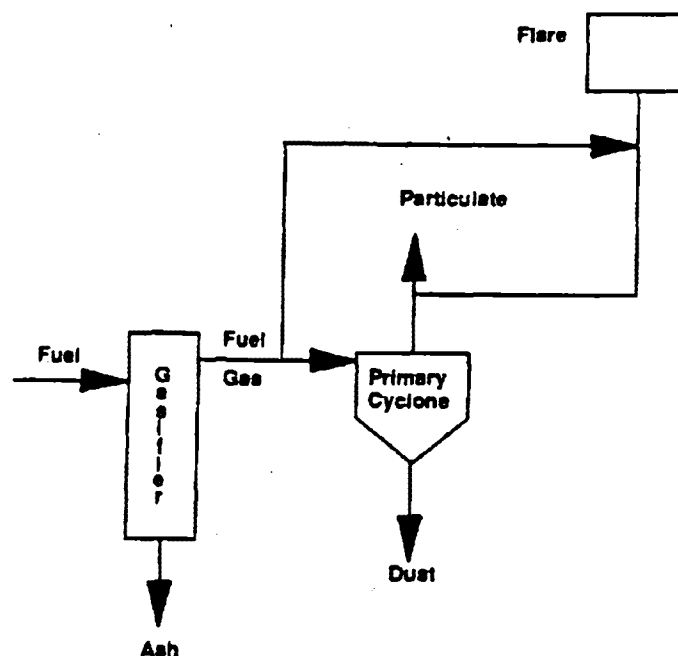


Figure 4 - GE CR&D's Equipment Flow Diagram

<sup>1</sup>Pelletized switch grass was the third fuel considered but the pellets crumbled in shipping. Briquetting Marketing and Services, Inc. was able to produce a switch grass briquette per the GE size specification on a demonstration briquettor. This demonstration size briquettor had a small throughput that would not produce the quantity required for the test in the time allowed prior to testing.

## Fluidized-bed Gasifiers

The most promising long-term prospect for biomass gasification is the use of fluidized-bed gasifiers that can accommodate a wide variety of feedstocks. Fluidized-bed gasifiers have higher throughput capabilities and greater fuel flexibility than fixed-beds, including the ability to handle low-density feedstocks like undensified crop residues or sawdust. Gas quality control with fluidized-bed gasifiers may require different treatment for two reasons. First, the exit gas temperatures are higher, 800-900°C, which may result in the vaporization of alkalis. Second, there is more particulate carry-over, which cyclones alone will not handle, that will require ceramic or sintered-metal barrier filters [4].

EPA/AEERL plans to cooperate with a researcher in the development of a system consisting of a pressurized feed system, a fluidized-bed gasifier, and a filter for gas cleanup. All components of the system have been designed to operate on biomass fuel with minimal preparation and produce a gas suitable to fuel an aeroderivative turbine. Testing of the system will begin in late '92.

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PROGRAMS AND POLICY IMPACTS ATTRIBUTABLE TO REGIONAL

BIOMASS PROGRAM WOOD STOVE RESEARCH EFFORTS

ABSTRACT

The decision by the CONEG Policy Research Center in the spring of 1985 to embark upon a field evaluation of wood stoves led to an ambitious and sophisticated six-year research program which has had profound impacts on the evolution of the industry. The initial interest in exploring the claims of manufacturers about the efficiency, particulate emissions, and creosote build-up in catalytic, catalytic add-on, and noncatalytic "high tech" woodstove models readily expanded to undergird much of the conceptual thinking which informed the EPA's participatory regulations negotiations process engaging the industry, the agency and environmentalists. Since the publication of the EPA certification standards in 1987 and the laboratory testing methodology utilized to support the standard, the NRBP-sponsored research has moved on to test the field durability of certified stoves. The early, disappointing findings in that field testing identified structural, design and materials flaws which have directly contributed to improved stove designs in the second generation of certified stoves.

The story of the Regional Biomass Program research is punctuated by these impacts:

1. The equipment and field testing methodology developed for particulate emissions in the original study set the standard for all field testing in North America for the next half-decade.
2. The findings in the original studies in the Northeast and Northwest influenced at least three specific aspects of the New Source Performance Standard (NSPS) established for wood stoves in 1987: the separate emissions levels for catalytic and noncatalytic stoves; the burn rate and fuel cycle conditions for testing; and the enforcement procedures related to physical inspections of the newly manufactured stoves.
3. Unprecedented collaboration among US and Canadians in embracing this research, improving the quality and aiding comparability of testing in both countries.
4. Successful leveraging of funding from a second federal agency, two state agencies, and the manufacturer's trade association for four-six successive research projects.
5. The assembling of Project Advisory Committees of researchers, government officials, regulators, and manufacturers for a frank exchange on both research and policy issues.
6. The direct impact on stove designs following a public meeting with stove manufacturers during the summer of 1989.
7. The new emphasis in the industry and concern among regulators about durability of stoves certified since 1988; and the development of a reliable research instrument and testing methodology to simulate field results are direct impacts of the research.

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## Introduction

Over the last twelve years, significant amounts of research and dialogue have been undertaken regarding wood stove technology and its environmental impact. Beginning with the first study in 1982 in Ohio and New York, presented by Stockton G. Barnett of OMNI Environmental Services to the Energy from Biomass and Wastes Symposium, concerns were raised regarding wood stove performance and related particulate emissions, fluepipe creosote accumulation, and overall efficiency. These concerns were particularly evident in areas of the United States, such as the Pacific Northwest, where wood stove emissions contributed a large percentage of environmental particulate emissions, heightening additional health and safety concerns simultaneously as the wood stove manufacturing industry experienced tremendous growth. Ski areas in Colorado and river towns in New England subjected to air inversions also experienced problems with woodburning.

In early 1984, the state of Oregon promulgated the first wood stove particulate emissions regulations in the nation. These regulations allowed a phase-in period and set separate standards for catalytic and non-catalytic stoves based primarily on laboratory testing results. Two benchmark field studies were launched between 1985-1987: 1) the 1985-87 Northeast Cooperative Wood Stove Study (NCWS), often referred to as the "CONEG" study (Coalition of Northeast Governors)<sup>1</sup>; and 2) the 1986-87 Whitehorse, Canada study. While the final results of both of these studies were not available to the U.S. Environmental Protection Agency until late 1988, the EPA was actively involved in setting up a "regulatory/negotiation" (commonly referred to as "reg/neg") process to seek input and comments from a wide range of industry, research, and government actors on proposed regulations to limit particulate emissions within the wood stove industry by setting certification standards for new equipment. The interim results from the NCWS and Whitehorse studies contributed significantly to the conclusions and discussions in the "reg/neg" process. Since the promulgation of these regulations, phased in over two periods between 1988 and 1990, additional continued testing of wood stoves has been conducted to compare laboratory and field test results and to identify equipment degradation problems and operator practice issues.

Several factors indicate the importance of both the research and its management on a number of key areas within the evolution of wood stove manufacturing:

- 1) the initial research goal of improving wood stove design has led to a significant amount of available data on different emissions impacts of variously designed stoves, and the technology transfer resulting from this research has led to design improvements in the wood stove manufacturing industry;
- 2) the testing methodology developed for this research, the "Automated Wood Stove Emission Sampler" (AWES) and a data-logger, has set the industry standard for such testing throughout the past ten years, and has most recently been adapted for masonry heater and fireplace emissions studies;

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<sup>1</sup>The Northeast Cooperative Wood Stove Study is commonly known as the "NCWS" study, the "Northeast Study", and the "CONEG" study. Since much of the research literature and public awareness of this study refers to the "CONEG" study, this terminology is widely used in this report.



- 3) the process used in planning and monitoring the early wood stove studies brought together a unique group of industry and government representatives prior to the promulgation of regulations, leading to important regulatory compromises that produced a sense of "livable" regulatory action;
- 4) the testing methodology and results led to active interest and cooperation between two national governments (the U.S. and Canada) and among a number of different U.S. government agencies and industry representatives; and,
- 5) continued testing of laboratory/field conditions raises future concerns not only about stove design but also about the importance of operator-controlled conditions and the on-going need for consumer education and training by manufacturers and industry representatives. The current focus of testing on stove durability issues has stimulated a creative tension between manufacturers, who fear additional regulations, and other parties concerned about a steady increase in emissions as certified stoves age.

#### **Summaries of Significant Research Efforts**

##### **• The CONEG Study, 1985-87**

The first major study of wood stove emissions and efficiency was conducted for the Coalition of Northeast Governors (CONEG) Policy Research Center, and sponsored by CONEG, the New York State Energy Research and Development Authority (NYSERDA), and the U.S. Environmental Protection Agency (EPA). This study, known as the CONEG study or the Northeast Cooperative Wood Stove Study (NCWS), was begun in the spring of 1985 and continued in various phases throughout the next six years.

The purpose of the first CONEG study, conducted by OMNI Environmental Services of Beaverton, Oregon (the firm originally involved in the laboratory testing for the state of Oregon DEQ), was to determine the effectiveness of both catalytic and non-catalytic new technologies in reducing wood use, creosote build-up, and particulate emissions. Sixty-eight homes in Waterbury, Vermont, and Glens Falls, New York, were involved in the testing over two heating seasons, 1985-86 and 1986-87. The study measured emissions, creosote build-up, efficiency, and wood use for both conventional technology wood stoves, which provided the baseline, and the new technology stoves. The study was the first major field research activity to determine if field performance of the new technology could out perform conventional technology and meet laboratory expectations.

An important facet of the CONEG study was the field introduction of a sampling technology that would set the standard for almost all future wood stove emissions testing. OMNI Environmental Services developed the Automated Wood Stove Emissions Sampler (AWES) specifically to sample residential wood stove emissions. This sampler draws flue gases through a probe which samples from the center of the flue pipe one foot above the flue collar. The sample then passes through an XAD-2 resin trap that collects semivolatiles and remaining particulates. Flue gas oxygen concentrations, used to determine flue gas volume,

are measured by an electrochemical cell.<sup>2</sup> The sampling period can be varied. The promised development of the AWES by OMNI was a major reason the firm was selected over five competitors when the CONEG contract was awarded in the late spring of 1985.

The AWES was accompanied by the "Data LOG'r", a programmable microprocessor/controller capable of measuring a large number of variables including date and time for recording periods, daily date and time in five-minute intervals, flue gas averages over five-minute periods, ambient temperature in fifteen-minute intervals, wood weights, oxygen measurements when the AWES unit was sampling, and AC power status, measured at five-minute intervals (see Exhibit 1 and Exhibit 2 for a pictorial representation of the AWES and data LOG'r systems).

After obtaining the baseline conventional stove data, three advanced technology stove types were tested: catalytic stoves, add-on or retrofit devices (attached to conventional airtight stoves at fluepipe), and low-emission non-catalytic stoves. Special emphasis was placed on testing the effectiveness of the catalytic combustors.

Results of the CONEG study were published in November, 1987. Generally, the CONEG study did indicate that the low-emission non-catalytic stoves and the catalytic stoves had lower emissions and creosote accumulation than the conventional stoves. However, the range of performances and the number of variables involved prevented definitive conclusions about stove design and performance. In all cases, however, the advanced technology episodically demonstrated lower emissions under the field conditions. The average emissions rates for the stove types were 20.1 g/h for conventional stoves, 17.9 g/h for retrofits, 16.4 g/h for catalytics, and 13.4 g/h for the low-emission non-catalytic stoves. Unfortunately, while the new technology stoves did show decreased emissions, the reductions were not as great as anticipated given the laboratory testing. The study was unable to point to any single factor dominant in all stoves that affects emissions.

The CONEG study did raise several important issues: 1) it indicated the potential for overall emissions reductions with new technology stoves; 2) it identified the issue of catalyst performance/degradation over time (a major issue in the next round of testing); 3) it set the standard accepted methodology and technology for field testing; 4) it raised the question of operator practice as a potential factor affecting stove performance; and 5) it pointed out the need for continued field and laboratory testing of both design and performance.<sup>3</sup>

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<sup>2</sup> This description of the OMNI AWES and Data LOG'r systems is compiled from the numerous OMNI wood stove reports cited in the reference section of this report.

<sup>3</sup> A year after the CONEG study began, the Northwest Regional Biomass Program conducted its own complementary research in Portland, Oregon. Since the findings from these studies were presented after the EPA regulations were published, they are discussed in Part B.

• The Whitehorse, Canada Study, 1986-87

In 1986-87 the City of Whitehorse, Yukon, Canada, conducted a study funded by the Canadian Department of Energy, Mines and Resources. The findings of the study were presented in September, 1987. The study was designed to assess the effectiveness of new stove technologies in reducing emissions, reducing the risk of chimney fires, and improving overall efficiency. The new technologies studied included integral catalytic wood stoves, catalytic "add-on" retrofit devices, and low-emission non-catalytic stoves. In addition to undertaking the testing as a means of determining whether laboratory predictions could be fulfilled in the field, the study evaluated operator practices in the home, type of wood, and flue pipe creosote build-up.

This study used the same AWES, Data LOG'r equipment as was used in the CONEG study. Emission samplings were taken over a nine-week period in fourteen homes; four one-week sampling periods involved conventional stoves, and five one-week sampling periods involved the new technology stoves.

While the basic types of stoves tested in the Whitehorse study were similar to those tested in the CONEG study, the actual models differed. However, the results of the Whitehorse study were similar to those of CONEG: conventional wood stoves exhibited particulate emissions of 21.8 g/h, catalytic retrofit stoves averaged 16.2 g/h and integral catalytic stoves averaged 12.1 g/h, and low-emission non-catalytic stoves averaged 14.3 g/h. These are emissions levels more than twice as high as those achieved in laboratory certification tests. While the CONEG study could not be statistically verified among the technologies with a significant confidence level, the Whitehorse study did prove at a statistically significant level that all of the advanced technology categories performed better than the conventional stoves (even though the differences among the various advanced technology categories were not as apparent).

The Whitehorse Study also pointed to major differences in creosote build-up in sealed and vented double wall flue pipes. Within three days of the testing, the vented type of double wall flue pipe was clogged with creosote and emissions rates actually increased. With the sealed pipe, emissions decreased and the creosote problem was abated. Additionally, the Whitehorse Study indicated a possible link between chimney length and high emissions (straight, short chimneys with a mix of flue diameters may cause higher emissions), and raised the importance of firebox size and burn rates in emissions testing.

Two key factors raised in the CONEG study were corroborated by the Whitehorse study: 1) the hypothesis of the CONEG study that the advanced technology stoves could perform better than conventional stoves in the field, providing better emissions control and efficiency, was confirmed statistically in the Whitehorse study; and 2) both studies indicated that field results of the advanced technology stoves did not match the Oregon certification levels, even when using stove models certified in laboratory testing to those levels.

Both studies also raised issues of equipment degradation and operator influence as being important factors in emissions control. As neither of these issues could be verified with data, they were not as immediate at the time as the importance of determining stove design factors that could reduce emissions and increase overall stove efficiency.

- The 1988-89 Northeast Cooperative Wood Stove Study in Glens Falls, NY

After the promulgation in 1988 of the EPA regulations setting standards for emissions for wood stoves, to be phased-in during 1988 and 1990, the CONEG Policy Research Center, the EPA, NYSERDA, and the Canadian Combustion Research Laboratory embarked on another round of research aimed at further quantifying the field performance of new technology stoves. As the previous studies had demonstrated that advanced technology stoves were not performing in the field up to the laboratory certified standards, additional field testing was needed not only to further quantify field performance but also to determine the factors influencing emissions, including operator practice and equipment failure. All of the new technology stoves involved in this research were required to meet the Oregon 1988 standards, to pass a lab stress test, to have adequate draft and sizing, and to be used by experienced wood stove operators. The stoves were considered to be 1990 EPA-certifiable. Three catalytic stoves and two non-catalytic stoves were tested in twenty-five homes in Glens Falls, New York, over five week-long testing periods from January - March, 1989.

The crucial finding of this study was that the average overall emissions rate was 9.4 g/h for these stoves, a 55-60% reduction from the EPA designated conventional stove rate of 21.3 g/h. This finding was a statistically valid (95% confidence level) indication that the technology for the new stoves had dramatically improved over conventional stove levels. However, there was still a large variance among the stove types in emissions levels, and two of the three catalytic stoves did not perform well in the field. EPA lab certification levels were within reach for at least one of the catalytic stoves, but most of the stoves tested were found to be about twice as high in emissions in the field as in laboratory tests. One of the catalytic stove models had serious emissions problems in four of the five stoves after only three months of field use. The catalyst in one stove was found to be the cause of degradation. A second catalyst failed after two seasons. Warping of the bypass systems in one stove was found to contribute to leaks around the catalyst and elevated emissions. It was determined that the lack of flame impingement shielding and the high internal catalyst temperature were factors contributing to the increased emissions.

In the noncatalytic stoves, loose bypasses and some oxidation of the baffles and bypass support mechanisms were noted; however, there was no indication that these problems had caused emissions degradation. A computer model was generated for the noncatalytic stoves which indicated that emissions are lowest when wood moisture is low and burn rates are high.

This study proved that design was a crucial factor in developing high technology stoves and in influencing emissions. For the first time in the field studies, a catalyst was removed for further testing and a definitive finding was reached -- that catalysts do fail and that bypasses and supports must be of sufficiently heavy construction to resist warping and oxidation caused by the high temperatures. The study noted that, for the non-catalytic stoves, those without bypass mechanisms actually performed better, although this was not necessarily a cause and effect situation. These findings indicated that stove design should consider not only emissions reduction, but also other factors such as heat exchange, sensitivity in performance to variations in burn rates, and wood moisture.

The Glens Falls study was the first to indicate with surety that operator practices also contribute heavily to emissions performance. It noted that, at least in the non-catalytic stoves, high stack temperatures and high excess air levels resulted in a net efficiency that was not much higher than conventional stoves. While it could not be proven at this point without additional testing, the study noted that variables such as wood moisture, burn rate, and draft could also be important in reducing emissions and improving overall efficiency. The study pointed to sizing and installation factors which affect draft and burn rate as well as operator factors (wood moisture, other fuel factors).

Several important issues were raised by the Glen Falls study: 1) research activities to date had focused on the importance of design factors in reducing emissions, but these findings were primarily laboratory findings; in the field, it appeared that not only design, but also operator practices were contributing to emissions levels and efficiency; 2) laboratories had not yet been able to predict significant "stress testing" design issues; i.e., how stoves perform over time under field conditions (particularly in light of the catalyst degradation and bypass problems); and 3) if operator practices were also important factors, further testing would be needed to isolate the specific operator-controlled factors, such as wood moisture, burn rate, and draft, that affected emissions and efficiency the most.

• **The 1990 Second Season Glens Falls, NY, Study**

In 1990 the Canadian government sponsored a second season follow-up study on the Glens Falls, New York, stoves that were part of the 1988 study. This study was conducted to measure the degree of equipment degradation after two seasons in the field. As in the previous studies, the OMNI testing procedures using the AWES and the Data LOG'r were used to measure field performance; additionally, the study conducted a laboratory analysis of two failed catalysts.

Emissions in three of the four catalytic stoves (all one model) demonstrated no increase in the second season. However, the one catalytic stove that showed elevated emissions after one season continued to exhibit increased emissions throughout the second season. One of the other stoves actually performed at 2g/h for both seasons, indicating the importance of stove design and proper sizing with regard to longevity of emissions reductions. All five of the other model catalytic stoves had elevated emissions after the second season.

The two failed catalysts were evaluated in the laboratory and performed almost identically to the field results. An important facet of this study was the reliability of the "simulated real world emissions test" in the laboratory in predicting field performance. The laboratory test was able to simulate field performance by reproducing a number of field variables, such as wood type, wood moisture, diameter, weight, loading pattern, stack draft, and some operator procedures (such as burn rates).

The project determined that the best performing wood stove was used at a lower burn rate than is typical for average New York winter weather. The stove was "oversized" and did not burn hot. These findings suggested that the catalytic burning technology might be cleanest in a warm climate where burn rates are usually lower but used in combination with a strong draft to assure quick catalyst lightoff.

- On-going Stress Testing

After finding that equipment degradation was a major factor contributing to emissions elevation in catalytic wood stoves, the Northeast Stove study group continued to sponsor further laboratory testing to simulate the experience of wood stoves under field conditions. Sponsored jointly by CONEG, NYSERDA, EPA, the Canadian Combustion Research Laboratory, the Wood Heating Alliance, and the Oregon Department of Environmental Quality, this ongoing research used OMNI Environmental Services to develop and test a stress methodology which could simulate in days a minimum field experience of one season.

As described by OMNI, the test includes a cold start, air controls set at maximum, keeping the loading door open for a few minutes and never completely closing it thereafter, an opened bypass for the first ten minutes of operation, fuel reloading when stack temperatures fall back to 500 degrees F., and a 24-hour continuous burn cycle for a period of 10 to 25 days. Early 1991 results indicated that stress tests matched closely the field degradation findings of catalytic stoves in which degraded catalysts and metal warping occurred in the lab conditions. For the non-catalytic stoves, oxidation of the baffle occurred. Additional testing procedures are focusing on the causes of catalyst degradation and the design changes that can be made to improve long-term operation. The linking of the laboratory and field results was a significant product of this research.

- 1988-90 Field Testing in Crested Butte, Colorado

In the summer of 1988, the Town of Crested Butte, Colorado, initiated a wood stove replacement program as an attempt to reduce particulate matter from wood stoves. Colorado has seven areas of non-attainment with the 1987 EPA ambient air quality standards for PM-10 (particulate matter of 10 microns or smaller). The Town of Crested Butte, a former mining town with high wood burning usage, had adopted in 1982 a stringent ordinance prohibiting wood stove or fireplace installation in new construction unless certain insulation and "R-value" standards were in place. This was followed in 1986 by a voluntary stove replacement program to provide incentives for replacement of conventional wood stoves with newer models certified to either EPA or state of Colorado standards. With a high level of public consciousness about the wood stove emissions problem and the replacement program in place, Crested Butte offered a unique site for the EPA, the Wood Heating Alliance (WHA), and the state of Colorado Department of Health to sponsor a study on wood stove emissions before and after installation of certified model appliances.

The Town contracted the research to Dennis R. Jaasma, of the Virginia Polytechnic Institute, to determine particulate emissions and carbon monoxide and dioxide levels attributable to conventional and certified stoves. This field study was the first to use a new sampling technique, developed by the Virginia Polytechnic Institute, for on-site determination of particulate emissions. This type of sampling technique allows emissions results of both particulate matter and CO to be obtained within 72 hours of the sampler retrieval.<sup>4</sup>

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<sup>4</sup>The Crested Butte study was the first to use the Virginia Polytechnic Institute sampling technique; almost all of the other wood stove studies have been conducted using the AWES Data LOG'r technique. Both techniques correlate well with EPA Methods 5G and 5H; the results of the VPI sampling are available on-site, while the OMNI testing incorporates additional data

For this study, thirteen stoves were monitored during the first winter (1988-89), two of which were certified catalytic models and eleven of which were conventional stoves. In the following season (1989-90), twenty-four stoves were monitored, including seven conventional, twelve catalytic, and five non-catalytic stoves. The certified stoves were both EPA and Colorado certified. Wood was weighed on-site prior to use and operators were instructed to use the "designated wood pile" during the study.

The conventional stoves were found to exhibit 47% higher particulate matter emissions than the 15g/kg value recommended by EPA for airshed modelling. On average, the certified stoves reduced particulate matter by 53% and CO by 49%, although there were significant differences in performance among the various models of certified stoves. The two non-catalytic stoves achieved levels of 71% lower particulate matter and 48% lower CO in one model, and 44% and 19% lower in the other model. Proper sizing and adequate burn rate were deemed crucial to the lowered emissions and efficiency of the non-catalytic stoves. Another related finding of this study was that catalytic function over time, as in the previous studies, was a crucial factor contributing to increased emissions in some models of catalytic stoves; replacing the catalyst as soon as this data developed contributed to an immediate decrease in emissions.

#### **Research Findings Influencing the EPA "REG/NEG" Process and Final 1988 Regulations**

During the EPA "reg/neg" process, only the initial findings of the first phases of research on wood stoves were available. Given that Oregon was the only state to have issued regulations on wood stoves, and to have some research testing data to back up their emissions policies, the EPA was seeking input primarily on the design factors contributing to reduced wood stove emissions. As the improved technologies were just emerging in response to the need for cleaner-burning stoves, the EPA was interested in the results from catalytic add-ons, retrofits, and new stoves.

The first CONEG study was being conducted as the "reg/neg" process was underway. Preliminary indications from this study can be identified as having a major influence on at least three aspects of the final New Source Performance Standards: 1) the setting of different standards for catalytic and non-catalytic stoves; 2) the requirement that quality assurance testing be conducted; and 3) the consideration of burn rate and fuel cycle conditions for the testing methodology, as well as the field testing protocol.

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obtained from the LOG'r. Some interviewees noted that the VPI sampling technique, while faster and less costly, may lose resolution of mass over time, causing it to be less accurate when measuring emissions of 6g/hr or less.

### • Equipment Auditing and Adaptation

Given that an entire series of research activities were using the same OMNI AWES and Data LOG'r methodology and technology, the EPA was prompted to test the equipment numerous times for quality assurance and correlation with its own Methods 5G and 5H. The overall result of this monitoring was improved technology and increased public confidence in the testing results. A major evolution of the equipment occurred in 1989 with the on-set of the Glens Falls study, when an EPA audit uncovered certain deficiencies within the AWES system. In January, 1989, the oxygen cell was discovered to be unreliable during the field testing, and was replaced with a new cell which has proved to be extremely reliable since then. As a result of the on-going EPA equipment auditing, functional adaptations were made in the equipment which made the results much more reliable over time.

Over the last ten years, only one wood stove emissions study (the Crested Butte Co. Study) has been conducted without using the OMNI equipment. As a result of its widespread effectiveness and accepted authority in this area, the OMNI technology continues to be used in more recent stress testing (sponsored jointly by the Canadian Combustion Laboratory, CONEG, the EPA, and the Oregon DEQ). It has also attracted the attention of the Bonneville Power Administration in Portland, Oregon, in researching the emissions for advanced technology small-scale biomass combustors relative to wood stoves. OMNI continues as well to research health impacts and costs resulting from smoke in EPA non-attainment areas, such as Oregon. Additionally, OMNI has assisted the California Air Resources Board and the Denver Brown Cloud Study in chemical balance modelling as a direct result of its experience with burn cycles gained from wood stove research. Finally, OMNI's adaptation of its equipment to provide data for pellet stove and masonry fireplace research continues to set the standard for wider use of emissions testing technology, including the possible setting by EPA of an "AP-42" number for masonry fireplaces.

### • Future Considerations

Generally, the first two rounds of research through the time of the Wood Heating Alliance 1989 forum in Chicago, provided the wood stove industry with sustained and valid technological data to support design and quality control efforts. While there continues to be mixed reaction to the stress testing, there has been positive feedback from the industry regarding the support provided by testing for the field performance of new equipment in particular. At a March, 1992, trade show, Jim Hermann, from Earth Stove and incoming Chairman of the Hearth Products Association, remarked that "we now have the technical data to support the performance of new technologies in the field." Research efforts brought the wood stove manufacturing industry into a positive relationship with government and other consumer groups, particularly since the relationship was not just defined by regulatory action, but also by "research which could assist the design".<sup>5</sup>

The next ventures in testing will focus on continued durability concerns, particularly in areas designated by the EPA as "non-attainment" areas in terms of the Clean Air Act requirements. These areas include parts of Oregon and Colorado as well as certain river towns in New England that experience the "air inversion" quality problem. Regulatory pressure will be sustained by the durability testing as discount rates for catalytic technology and emissions trading by utilities lead to increased efforts to "trade" various cleaner burning technologies.

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<sup>5</sup> Noted by Skip Hayden of the Canadian Combustion Research Laboratory.



Additionally, the CONEG/EPA collaborative that has been advanced by the wood stove research will lead to new venues as the field of air toxics continues to be researched. The transferability of the wood stove testing technology, already evidenced by the masonry fireplace and heater testing, will lead to even more collaboration efforts which may impact future Clean Air Act statutory changes.

While the federal funding for regionally sponsored biomass program research has remained steady over the last five years, some areas are continuing to support on-going stress-testing as well as broadening the emissions testing to include formerly exempt heaters such as the masonry heaters or the pellet stoves. Some states have used Oil Overcharge funding to provide wood stove replacement loans or grants, particularly on behalf of low income households. The EPA non-attainment areas in particular are continuing efforts to reduce particulate emissions, and these efforts vary from the use of "smoke police" in Oregon to detect concentrations of wood stove emissions to setting opacity limits in Klamath Falls. The state of Colorado and several western localities have passed laws to mandate that new homes may only accept certified stove installations.

Much of the continued testing appears to be generated in areas where non-attainment of clean air is an issue. Oregon has six non-attainment areas, and one interviewee noted that a 20-40% reduction in wood stove emissions resulting from equipment changeouts could significantly impact this problem. Financing for such programs, however, is limited. Last year, a dedicated tax on cordwood almost passed the state legislature with the backing of large industry, the wood stove industry, and the environmental community in a unique coalition.

With the continued use of wood for heating purposes, particularly in the non-attainment areas, reduced emissions will remain an important goal. The 1990 census indicated, surprisingly to a number of wood stove representatives, that the use of wood as a primary heating source for all households increased from 17% in 1980 to 21% in 1990. Given this increase, and the need to bring the non-attainment areas into EPA compliance, there is a continuing need for sustained production and/or updating of cleaner-burning wood stove equipment.

Building on the findings of the later research which indicated the importance of operator practices in reducing wood stove emissions, one of the current endeavors of the northeast regional biomass programs will be a focus on increased consumer awareness and education about the benefits of clean wood burning. This campaign, the "Lessons Learned" project, will promote various public relations efforts designed to address the benefits of wood heating in the northeast relative to other heating sources, the need to use certified wood burning appliances, how to burn wood correctly, and how to maintain wood burning appliances.

With increased public focus on responsible wood burning techniques and technology, wood stove use can be viewed as a valid domestic renewable and cost-effective resource, particularly in areas of the United States such as the northeast which continue to rely heavily on foreign-provided fossil fuels.

6-110

EXHIBIT 1  
Schematic of AWES/Data LOG'r System

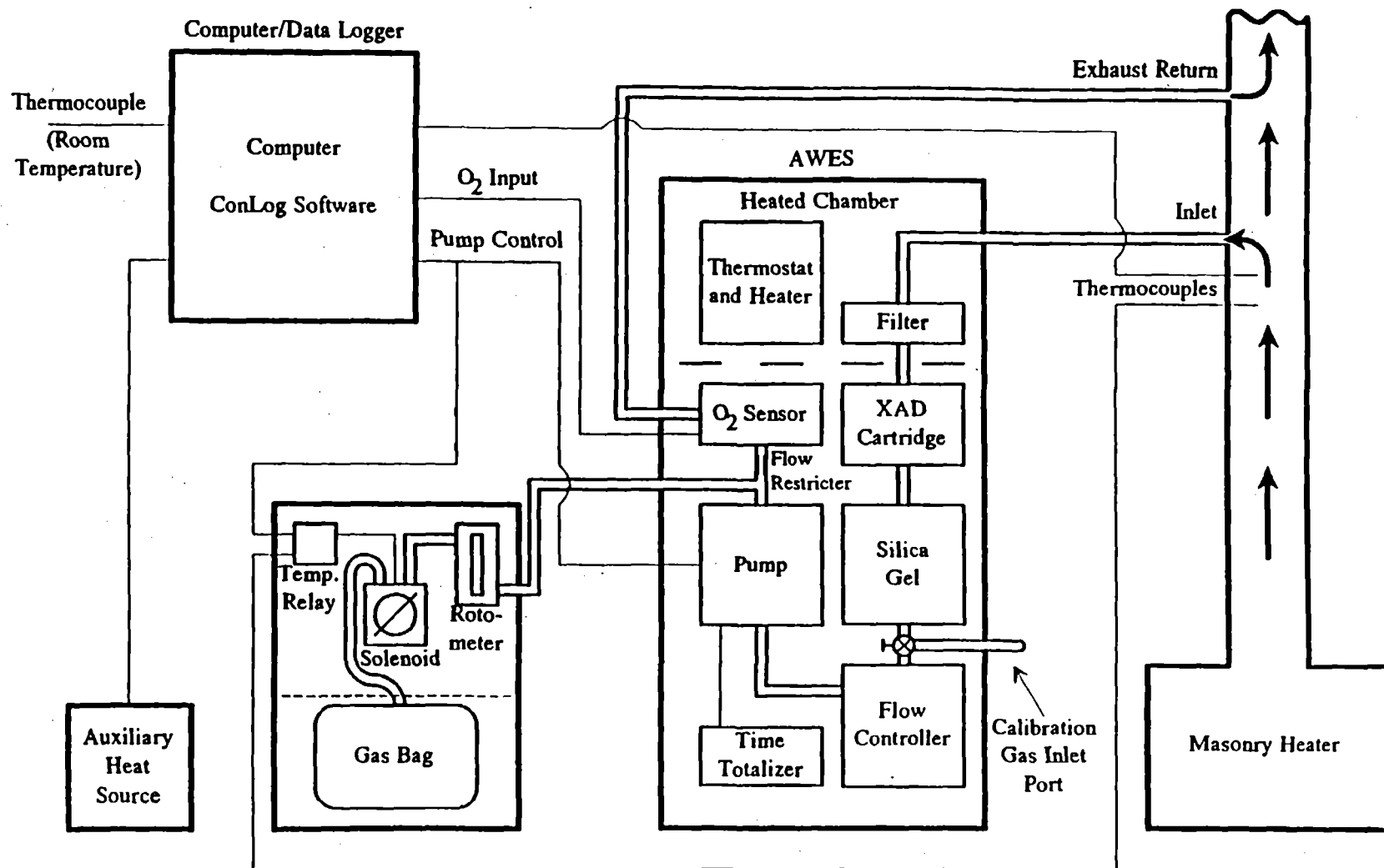


Figure 1. Schematic of AWES/Data LOG'r system.



OMNI  
Environmental  
Services, Inc.

Not to Scale

Project No.: 80119.01

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Drawing: 80119-01.DRW

**EXHIBIT 2**  
**CHRONOLOGICAL LIST OF WOOD STOVE STUDIES**

**I. 1985-86**

- o Northeast Cooperative Wood Stove Study (CONEG study), Vermont and New York
- o Bonneville Power Administration, Portland, Oregon

**II. 1986-87**

- o Northeast Cooperative Wood Stove Study (CONEG study), Vermont and New York (2nd season)
- o Whitehorse Efficient Woodheat Demonstration, Whitehorse, Yukon Territory, Canada
- o Emission Sampling Systems Comparability Study, Portland, Oregon
- o Catalytic Retrofit/Add-on Devices Evaluation, Portland, Oregon

**\*\*\* EPA Regulations Promulgated February 26, 1988**

**III. 1988-89**

- o Northeast Cooperative Wood Stove Glens Falls First Year, Glens Falls, New York
- o B.E.S.T. Project, Medford, Oregon

**IV. 1989-90**

- o Northeast Cooperative Wood Stove Glens Falls 2nd Year, Glens Falls, New York
- o B.E.S.T. Project, Medford, Oregon (Phase 2)
- o Klamath Falls Study, Klamath Falls, Oregon (Canadian Combustion Research Laboratory and WHA)
- o On-going Stress Testing, Oregon
- o Crested Butte, Colorado, Colorado Dept. of Health, WHA

**V. 1990-92**

- o Crested Butte, Colorado, 2nd Season
- o Pellet and Masonry Heater Testing, Western Clay Products Assn.
- o Diversified Fuels Study, Bonneville Power Administration and Oregon Department of Energy
- o EPA Stress Test Continuation

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16. ABSTRACT The report documents the 1992 Greenhouse Gas Emissions and Mitigation Research Symposium, held in Washington, DC, August 18-20, 1992. The symposium provided a forum of exchange of technical information on global change emissions and potential mitigation technologies. The primary objectives of the meeting were dissemination of technical information and education in recent research. Oral papers along with an international panel discussion, overheads, slides, and a GloED demonstration provided for lively exchanges in the following areas: activities in EPA, U.S. Department of Energy (DOE), and Electric Power Research Institute (EPRI) on greenhouse gas emissions and mitigation research, and EPA/AEERL's global emissions and technology databases; international activities of selected industrialized and developing countries; carbon dioxide (CO <sub>2</sub> ) emissions and their control, disposal and reduction through conservation and energy efficiency, and carbon sequestration including utilization of waste CO <sub>2</sub> ; methane (CH <sub>4</sub> ) emissions and mitigation technologies including such topics as coal mines, the natural gas industry, key agricultural sources, landfills and other waste management sites, and energy recovery by fuel cells; biomass emission sources and sinks, including cookstove emissions and control approaches; and solar and renewable energy sources.			
17. KEY WORDS AND DOCUMENT ANALYSIS			
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Gases	Solar Energy	Stationary Sources	07D 03B
Greenhouse Effect	Wood	Greenhouse Gases	04A 11L
Emission	Stoves	Woodstoves	14G 13A
Carbon Dioxide	Earth Fills		07B 13C
Methane	Fuel Cells		07C 10B
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