

EPA-600/2-74-002

March 1974

Environmental Protection Technology Series

Control of Environmental Impacts from Advanced Energy Sources



**Office of Research and Development
U.S. Environmental Protection Agency
Washington, D.C. 20460**

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CONTROL OF ENVIRONMENTAL IMPACTS
FROM ADVANCED ENERGY SOURCES

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Contract No. 68-01-0483
Program Element 1AB013
Roap/Task PEMP 22

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ABSTRACT

The technology and the environmental effects associated with the production of energy from some new or advanced sources are reviewed. These include solar, geothermal, oil shale, solid wastes, underground coal gasification, and hydrogen energy sources. Projections to the year 2000 of the levels of energy production from the first four of these sources are presented. Environmental impacts on air quality, water quality, and land uses are derived per unit of energy produced. Levels of pollutant emissions and other environmental effects of the development of these advanced energy sources are projected. Impacts likely to require control measures are identified. Subjects for research and development directed toward control of environmental impacts are recommended. These recommendations are incorporated into a research and development plan. Approximate priority assignments derived from consideration of the timing of development and the importance and degree of definition of the identified environmental effects are given.

This report was submitted in fulfillment of Contract 68-01-0483 by Stanford Research Institute under sponsorship of the Environmental Protection Agency. Work was completed as of March 1974.

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UNITS OF MEASURE

Conversion of U.S. units of measure to the metric system is now proceeding rapidly. Several agencies of state and federal governments now call for the use of metric units (e.g., the geothermal group of the California Division of Oil and Gas). The Environmental Protection Agency has required the use of metric units in this report.

SRI has, therefore, employed the International System of Units (SI), which is based upon the meter, kilogram, and second as the basic measures of length, mass, and time. Within this system, energy units are derived combinations of the basic units. The preferred unit for energy is the joule. However, the kilowatt hour, a hybrid unit, is more widely understood at this time and has been used frequently in this report, sometimes outside the context of electric power. (Among those seeking to institute global uniformity in the use of units, the kilowatt hour is considered to be less acceptable than the joule, and the use of the kilowatt hour may ultimately be discarded).

During the period of changeover to metric units, a certain amount of confusion must be expected--especially since energy is measured in such various units as kilocalories, barrels of oil equivalent, kilowatt hours, therms, and so on. To minimize this confusion, SRI has expressed energies in joules or multiples of the watt hour and made sparing use of hybrid units, such as metric ton and the engineering units of the English system. The prefixes kilo, mega, and tera are sometimes used in accordance with standard SI practice. The following listing summarizes the most common conversion factors that readers may want to have available while reading this report.

Further information on the International System of Units can be found in Special Publication 330, National Bureau of Standards, Department of Commerce.

Energy

$$\begin{aligned}1 \text{ Btu} &= 1.055 \times 10^3 \text{ joule (J)} \\1 \text{ Btu} &= 2.929 \times 10^{-4} \text{ kilowatt hour (kWh)} \\1 \text{ kWh} &= 3.600 \times 10^6 \text{ joule (J)} \\1 \text{ kcal} &= 4.186 \times 10^3 \text{ joule (J)}\end{aligned}$$

Length

$$\begin{aligned}1 \text{ inch} &= 2.540 \times 10^{-2} \text{ meter (m)} \\1 \text{ inch} &= 2.54 \text{ centimeter (cm)} \\1 \text{ foot} &= 0.3048 \text{ meter (m)} \\1 \text{ yard} &= 0.9144 \text{ meter (m)} \\1 \text{ mile} &= 1.609 \text{ kilometer (km)}\end{aligned}$$

Mass

$$\begin{aligned}1 \text{ pound} &= 0.4536 \text{ kilogram (kg)} \\1 \text{ ton (short)} &= 9.072 \times 10^2 \text{ kilogram (kg)} \\1 \text{ tonne} &= 1 \text{ metric ton (MT)} \\1 \text{ metric ton} &= 10^3 \text{ kilogram (kg)}\end{aligned}$$

Area

$$\begin{aligned}1 \text{ acre} &= 0.407 \text{ hectare (ha)} \\1 \text{ acre} &= 4.047 \times 10^3 \text{ square meter (m}^2\text{)} \\1 \text{ square foot} &= 9.290 \times 10^{-2} \text{ square meter (m}^2\text{)} \\1 \text{ square mile} &= 2.590 \times 10^6 \text{ square meter (m}^2\text{)} \\1 \text{ square mile} &= 2.59 \text{ square kilometer [(km)}^2\text{)}\end{aligned}$$

Volume

$$1 \text{ cubic foot} = 2.832 \times 10^{-2} \text{ cubic meter (m}^3\text{)}$$

$$1 \text{ gallon} = 3.785 \times 10^{-3} \text{ cubic meter (m}^3\text{)}$$

$$1 \text{ barrel (oil)} = 0.1590 \text{ cubic meter (m}^3\text{)}$$

Pressure

$$1 \text{ pound per square inch} = 6.895 \times 10^3 \text{ Pascal (Pa)}$$

$$1 \text{ bar} = 10^5 \text{ Pascal (Pa)}$$

$$1 \text{ atmosphere} = 1.013 \times 10^5 \text{ Pascal (Pa)}$$

$$1 \text{ Pascal} = 1.0 \text{ newton/m}^2$$

Equivalents

<u>Factor</u>	<u>Prefix</u>	<u>Symbol</u>
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^1	deka	da
10^2	hecto	h
10^3	kilo	k
10^6	mega	M
10^9	giga	G
10^{12}	tera	T

ACKNOWLEDGMENTS

The following members of the professional staff of SRI contributed directly to this study:

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I CONCLUSIONS

Six emerging energy technologies have been examined: solar energy, geothermal energy, oil shale development, energy from solid wastes, underground coal gasification, and hydrogen as an energy carrier.

Three of these six new energy sources require immediate attention from EPA because they are expected to be deployed soon and have been found to have significant direct environmental effects. These three are: geothermal energy, oil shale, and energy from solid waste.

Major problem areas associated with geothermal energy technology are: hydrogen sulfide emissions, disposal of saline waters, land subsidence, and land use guidelines.

Major problem areas in oil shale development are: emissions from retorts, disposal of waste waters, disposal of processed waste shale, rehabilitation of lands, and consumptive use of scarce water.

Major problems in obtaining energy from solid wastes are: emissions of exotic pollutants, ash disposal, and treatment of process water.

None of these three technologies is expected to produce a major share of U.S. energy in either the near or long term, but their environmental effects could become acute in local areas.

Solar thermal energy for heating and cooling may be deployed soon, but, in general, this energy source has environmental effects that are indirect, less severe, and more easily controlled by existing technologies and statutes.

The environmental effects of using hydrogen as an energy carrier are similar to those of solar energy in that they are primarily indirect, associated with materials processing.

The environmental effects of in-situ gasification of coal are difficult to foresee because no practical technological system has been developed.

Such conclusions have led to the assignment of priorities and the formulation of recommendations as summarized in the next section of this report.

II RECOMMENDATIONS

For the three new energy technologies assigned highest priority--geothermal, oil shale, and solid wastes--EPA should initiate at once programmed research directed toward the demonstration of control strategies and technologies, and the enunciation of operating standards and guidelines in the areas of air quality, water quality, and land use practices.

The following types of research and development are needed for one or more of the new energy sources:

- Background studies leading to enunciation of standards or guidelines.
- Development of control technologies.
- Stimulation of new technologies.
- Further research to better define some potential problems.

Priorities within the EPA program of research and development for control of environmental impacts from new energy sources should be assigned on the basis of the nearness of deployment of the various technologies, with consideration given to the expected magnitudes of the energy production and environmental effects, and to the degree of definition of the problem.

Specific recommendations for elements of a research and development program are given in Section VI of this report; priorities are assigned on the basis recommended above.

III INTRODUCTION: FRAMEWORK FOR ANALYSIS

A. Background

In March 1973, Stanford Research Institute (SRI) began a series of discussions with representatives of the U.S. Environmental Protection Agency (EPA) that resulted in this report in support of EPA's energy-related program planning activities. The purpose of the report is to provide the technical background and data necessary for EPA to evaluate alternative research and development programs to achieve control of pollutants associated with development of nonconventional energy sources. The effort was intended to provide partial source material to assist EPA in formulating its research program strategy and recommendations for prospective research projects addressed to priority topics. A draft final report was submitted to EPA late in 1973. Some revisions were incorporated into the report early in 1974.

The main text of the report summarizes information on advanced sources of energy and serves as a concise introduction to the principal conclusions and recommendations. The first part, therefore, is convenient for those who need to be familiar with essential factors of advanced energy sources and associated environmental effects, but who do not require extensive, detailed data.

The appendices present more detailed descriptions of individual advanced energy sources and their environmental effects. This material, which was the major data leading to the study team's conclusions and recommendations, is intended to serve as a convenient reference for those who are more directly concerned with advanced energy sources and control of their environmental effects.

Abundant domestic supplies of conventional, low-cost energy to meet projected demands are no longer taken for granted in the United States. The range of choice of conventional energy sources is narrowing, and attention to new energy sources is required. Increased demand for energy, in many respects, is incompatible with public concern over the environmental impact from the operations of energy production and consumption. Yet, it is apparent that the conflict between energy need and environmental quality must be reconciled if the nation is to achieve progress in and maintain a style of living that offers each individual opportunities to realize his or her potential and participate fully in a dynamic society.

It is apparent that the present energy crisis faced by the United States features severely restricted options. The ability of domestic supplies to meet demands while we conserve environmental quality is the difficulty. Unless a coordinated and comprehensive effort is initiated to provide new options for meeting the nation's energy needs and environmental goals, the possibility of one or more of the severe energy and environmental crisis scenarios looms greater.

The importance and visibility of the energy situation make it imperative that government agencies charged with responsibility in energy development have access to accurate and complete information addressed to their special requirements. Often, however, such information is lacking, or at best is incomplete; information is especially lacking on the environmental impacts of energy production and utilization. Past activities were frequently undertaken to emphasize efficient and economical energy development, and minimum consideration was given to resulting environmental effects. Previous activities did not necessarily require

data on environmental effects because they were external to market calculations. With respect to advanced energy sources, John Kenneth Galbraith^{1*} has observed that it is especially important to avoid "... substitut[ion] of new forms of pollution to which people are not accustomed for those to which they have become reconciled." Galbraith goes on to note that "instead of eliminating [pollution], one natural recourse is to urge the public that it is imaginary or benign or is being eliminated by actions that are imaginary."

Positive actions to deal with pollution control of advanced energy sources require detailed information, but in many respects the requisite data are incomplete. As the environmental effects from energy production processes have become matters of intense national concern. Considerable efforts have been expended to quantify the levels of emissions, effluents, and solid wastes produced by existing or planned energy production facilities employing fossil or nuclear fuels. Further, strenuous efforts to formulate pollution control strategies and upgrade control technologies have been undertaken by public and private organizations. Although there are certain exceptions, most pollution control technology is being applied to existing energy generation facilities. This is natural because the energy production technology originated first, but it represents a substantial investment that can be modified only with considerable difficulty and great cost. However, the impetus for pollution control is beginning to show positive results in improved air and water quality at many places around the nation. That even small environmental quality improvements are being realized in the face of rather formidable odds is a rather remarkable achievement.

Clearly, it would have been more efficient and economical if pollution control technology had been incorporated in facilities at the time of their

*References are listed at the end of the report, before the appendices.

design and construction, or in the case of some processes, if production of pollutants had been suppressed from the beginning. This important lesson learned from experience with conventional energy systems can be applied both to new developments using fossil fuels and to advanced energy sources. An increasing body of data is being developed for potential improvement in conventional energy systems. But it is the purpose of this report to provide information important to the research and development stages of advanced energy systems, to support the planning activities of the Environmental Protection Agency.

B. Selection of Energy Sources

As used in this work, the term "advanced energy sources" refers to those resources or technologies that produce energy or fuel through systems that are different in concept and in operation from those in common use at present. This definition is intentionally broad to encompass a variety of advanced energy sources. However, in order to concentrate on those advanced energy sources of greatest development and environmental impact potential, only those that may become operational in the period from 1980 to 2000 were included in this analysis. These advanced energy sources may be categorized broadly into (1) resource-based sources and (2) technology-based sources. Resource-based sources are those in which some naturally occurring resource material not presently employed for energy production would be developed and processed in some way to extract its energy or fuel. Technology-based sources are those that feature the application of new technological methods or systems that concentrate the energy content of diffuse or disaggregated sources. Table 1 lists, for these categories, the advanced energy sources included in the present study.

Many of these advanced energy sources may be further subdivided into several subtypes. These are dealt with in Section IV and in the several appendices to this report.

Table 1

ADVANCED ENERGY SOURCES STUDIED

Category	Advanced Energy Source
Resource-based	Geothermal energy Oil shale Solid wastes Underground coal gasification
Technology-based	Solar energy Hydrogen

C. Analysis of Each Energy System

Advanced energy sources include an array of diverse technologies and systems. Such systems are commonly developed to deal with special problems posed by the advanced sources and often lack counterparts in other, more conventional systems. Hence, attempts at analysis based on technical factors alone are infeasible. Accordingly, the present study was structured around the development stage of each advanced energy source, and its resulting environmental impact. The study included investigation of the relative significance of the impact, its general implications for EPA, and specific research and development needs. The approach used in analyzing each of these factors is described separately below.

1. State of the Art

A concise account of the present state of development of technology for energy production from advanced sources was prepared from available information. This account included, where appropriate, discussion of subtypes of advanced sources (e.g., dry steam and hot water subtypes of geothermal resources). The discussion also included examination of the

several stages of operations required for the development of advanced energy sources (e.g., mining, crushing, transportation, retorting, and upgrading of oil shale). Although drawn from the technical literature, these data were compiled to serve as a basis for further analysis as well as a ready reference for those nontechnical readers who require information about advanced energy sources and the manner in which they may be utilized.

2. Resulting Environmental Impacts

The environmental impact resulting from advanced energy source development was quantified to the extent possible from available data compiled during the preparation of the description above. The impact on air and water quality was expressed in units of pollutant per unit of energy produced (e.g., weight of SO₂ per megawatt). Also, units of solid wastes and land requirements were similarly quantified. Although the estimated environmental impact from advanced energy sources derived from such work may be somewhat uncertain because of the generally imperfect state of knowledge about such systems, such quantification, nevertheless, serves a useful purpose in providing some idea of the dimensions of the impact likely to be experienced.

3. Relative Significance of the Impacts

Quantification of environmental impact on a unit energy basis permits calculation of the total pollution load associated with development of various energy capacities. This will enable planners to calculate, in advance of development, the apparent uncontrolled environmental impact from developments of varying size. When compared against measurements of ambient environmental quality in the vicinity of projected developments or environmental quality standards established by cognizant

regulatory agencies, the resulting data can yield an assessment of the relative significance of the impacts. Such information is needed in determining the degree to which available control technology can contain the pollutants emitted.

4. General Implications for EPA

As the nation's need for energy increases, it will become necessary to employ advanced energy sources to a great degree. Should these sources approach becoming important contributors to regional or local energy supply, it will be essential for the EPA to be prepared to implement appropriate measures to safeguard environmental quality from the outset of development. Knowledge of the characteristics of advanced energy technologies and the resulting environmental impact is of clear importance in the definition of future environmental quality standards and pollution control requirements.

5. Specific Research and Development Needs

The analysis of each advanced energy system included an identification of specific research and development areas where further work appears necessary. This information is essential in formulating the requisite program plans for accomplishing improvements in energy production with less pollution as well as in attaining more effective control technology for present systems.

D. Formulation of a Research and Development Plan

The detailed information resulting from the analysis of each advanced energy system was used in formulating a broad plan for advanced energy research and development, a plan addressed to improved control of environmental impact. This plan was based on a common framework for identifying

research and development needs and an approach to setting priorities. Each of these factors is detailed separately below and followed by a description of its use in formulation of the overall research plan presented in Section VI of this report.

1. Identification of Research and Development Needs

The individual analyses of advanced energy sources resulted in identification of cases where potentially important environmental impacts may occur. In these cases, regardless of the information available from previous research, additional work is needed either to define the environmental effects more precisely or to determine the means to secure their control. In short, therefore, the analysis of research needs and assessment of their significance varies according to the state of knowledge about the advanced energy sources themselves.

2. Priorities

The research and development needed to control environmental impact is broad in scope. So much needs to be done, that it will be impossible to undertake all the necessary work concurrently. It is apparent that research and development priorities will have to be established by EPA as it formulates its programs and that the priorities will depend on many determinants. This study is only one input to the planning process.

In order to make the results of this study most useful to EPA decision makers, the following guidelines for establishing research priorities were employed in compiling detailed recommendations given in Section VI of this report:

- The estimated times of development of advanced energy sources form primary guidelines for establishing research priorities. It is apparent that, when preliminary analyses suggest environmental impacts of some importance from advanced energy

sources, the scope of research for control technology will need to be greatest for those sources that are projected to reach operational status at the earliest date.

- Where two advanced energy sources are estimated to reach operational status at about the same time and the apparent environmental impacts are identified with comparable precision, then research and development should be directed toward control of the most severe environmental impact.
- Where two advanced energy sources are estimated to become operational at about the same time and their impacts are of equal severity, then research and development should be directed toward the best defined problems.

3. Approach to Research and Development Planning

The approach to research and development planning in this work was to employ tables that relate estimated energy development from advanced sources to projected environmental effects. The estimated energy production levels from these sources, at five-year intervals until the year 2000, were compiled from available sources and supplemented by original SRI projections as necessary. Using the scaling factors relating unit impact to unit of energy produced, derived from the detailed analyses of individual sources, the project team calculated the expected impact in particular years. The relationship of uncontrolled environmental impacts to present levels of control standards was analyzed where applicable. These data are contained in Section IV of the report. These data were then employed to recognize classes of problems requiring research efforts. A matrix classifying the efforts by type of research and medium of impact was constructed and used to formulate the plan for research and development presented in Section VI.

With the foregoing description of the framework for analysis employed in this study as background, it is now appropriate to turn to examination in the next section of the projected environmental impact from advanced energy sources.

IV SUMMARIES OF ADVANCED ENERGY SOURCES

This section presents summary information on each advanced energy source analyzed in this study. Tables that present projected energy production and environmental impact are also included in this section. Further information on each source is given, for those who desire greater detail, in several appendices at the end of the report.

A. Overview of the Advanced Energy Sources

A summary of total amounts of energy projected to be derived from advanced sources during the remaining years of the present century is presented in Table 2. The table shows that advanced sources begin to reach appreciable levels of energy production only in the middle or late 1980s. These estimates are conservative in that no crash programs to develop new technologies are taken into account. Some conservation is warranted by the long lead times inherent in design, construction, testing and de-bugging of facilities before they can be relied upon to support routine operations at high output levels. These lead times would be long regardless of the environmental effects and controls that are of primary concern to this study. Although it may be argued by some that requirements for environmental control would cause serious delays in realizing energy production from advanced sources, detailed data reviewed in the course of this work led to the general conclusions that such delays (if any) would be small in comparison with the time required to resolve more fundamental technical, institutional, or economic problems. There would, in short, be sufficient opportunity to deal with environmental control considerations while dealing with energy production technology research and development. No significant time constraint is foreseen.

Table 2

SUMMARY OF TOTAL PROJECTED ANNUAL ENERGY PRODUCTION LEVELS
FROM ADVANCED SOURCES
(10^{15} joules per year)

Source	1970	1975	1980	1985	1990	1995	2000
Solar*	0	0	0	400	2,500	4,000	12,000
Geothermal†	1.8	14	72	180	360	720	1,400
Oil shale‡	0	0	610	2,000	2,700	3,400	4,000
Solid wastes§	0	10	55	300	950	3,000	10,000
Total■	1.8	24	740	2,900	6,500	11,000	27,000
U.S. demand♦	70,000	83,000	98,000	120,000	140,000	170,000	200,000
Percent of U.S. demand filled by above sources	3×10^{-3}	3×10^{-2}	0.8	2	5	6	13

* Data from Table 3.

† Data from Table 5.

‡ Data from Table 7.

§ Data from Table 13.

■ Totals may not check because figures are rounded.

♦ Assuming continued exponential growth, 20-year doubling time.

A key question about advanced energy sources relates to their potential contribution to overall energy supply. The projections in Table 2 suggest that even the greatly increased amounts of energy from these sources by 1990 will be only about 5 percent of the total demand estimated for that year. Clearly, although not a major fraction of the national energy consumption, advanced energy sources could be quite significant factors in regional or local energy supplies. Similarly, environmental impact from advanced energy source development, although likely to be small in terms of the national pollution load, may well be severe on local levels. Analysis of the problems posed by such situations requires a detailed examination of the environmental baselines of regions where advanced energy sources may be developed. Such examination is beyond the scope of the present study.

B. Solar Energy Summary

There are many technologies for using solar energy. For direct collection of solar radiation, photovoltaic solid-state materials may be used to generate electric power directly, thermal systems can be used to generate electric power or to provide space conditioning, and crops can be grown and harvested to fuel boilers or provide a feedstock for biological production of gaseous fuels. There are many situations where joint use of photovoltaic and thermal collection systems offer special benefits; these range from building rooftop collectors to large installations comparable in output to modern nuclear fission power plants. In addition, an earth-orbiting satellite-borne photovoltaic collector transmitting power to earth by a microwave beam is conceptually feasible. Moreover, solar energy can be extracted from natural geophysical reservoirs by tapping the winds or taking advantage of temperature differences in the ocean to drive turbines.

Because solar energy is such a dilute resource, large collection areas are required, which implies the need for a large investment in collector hardware. As a consequence, scientific and engineering feasibility is far ahead of economic feasibility for all solar energy technologies. Currently, small-scale thermal collection and special-use photovoltaic collection are economically feasible. The National Science Foundation is launching a major effort to achieve commercial realization (within the next decade) of small-scale thermal collection for the heating and cooling of buildings. Since the use of crops grown specifically for their fuel value represents an extension of well-developed agricultural and forestry practice, this approach could probably be commercialized within a decade also, but it is not receiving similar priority. Table 3 shows the annual energy production estimated by the NSF/NASA solar energy panel if their research and development schedule is followed. It is rather likely that the funding priorities administered by the NSF will be the dominant factor influencing the rate of solar energy development.

1. Environmental Consequences

Although solar energy is widely reported to be pollution free, this represents an oversimplification of the situation. For all solar energy technologies, vast collection areas are required, and enormous quantities of materials would be consumed to produce the necessary hardware. Although most solar energy installations would be nearly benign to the environment at the site, traditional environmental consequences would be caused where the materials were mined, refined, and formed into solar energy collectors. The neglect of these indirect, but nevertheless cumulatively important, environmental consequences of solar energy utilization should not continue.

Although design considerations are tentative, it is possible to compile data on the emissions that are likely to result directly from

Table 3

SOLAR ENERGY: ESTIMATED ANNUAL ENERGY PRODUCTION (in units of 10^{18} joule)*

	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>	<u>1995</u>	<u>2000</u>
Thermal collection							
Buildings [†]	0 [‡]	0	0	0.1	0.5	1.0	2.0
Central electric	0	0	0	0	0	0	0.8
Photovoltaic							
Central electric	0	0	0	0	0	0	0
Satellite borne	0	0	0	0	0	0	0.8
Buildings	0	0	0	0	0	0	0.8
Ocean thermal gradients	0	0	0	0	0	0	0.8
Wind power	0	0	0	0	0	0	0.8
Energy plantations							
Combustion	0	0	0	0	0	0	0.8
Conversion to chemical fuel (mainly methane) [§]	0	0	0	0.3	2.0	3.0	5.0

* These estimates are based largely upon Table 3 in "An Assessment of Solar Energy as a National Resource," NSF/NASA Solar Energy Panel, December 1972, and reflect current national R&D spending priorities for development of solar energy collection.

[†] The comparatively early emergence of this technology reflects the vigorous governmental R&D support currently being supplied by the National Science Foundation.

[‡] Entries of zero indicate that this technology will achieve less than 1% penetration of this market it is intended to serve. However, demonstration experiments and pilot plants of significant size can be expected, often with considerable publicity.

[§] The comparatively early emergence of this technology reflects the present state of the art, the great national demand for methane, and the rapidly declining availability of methane from natural gas.

the fabrication of rooftop thermal energy collectors of the type envisioned by the NSF/NASA Solar Energy Panel. These data are displayed in Table 4 and compared with emissions related to materials production or emissions from activities that the installation of this solar energy technology may displace. Clearly some tradeoffs in the quantities and species of pollutants are involved in reaching a judgment of whether this solar energy technology will improve overall air quality. However, if the control technologies now available are rigorously applied to the industries producing materials required for rooftop thermal solar energy collectors, this technology could achieve a significant reduction of energy resource consumption and air pollution in urban areas.

Unfortunately, as Table 3 illustrates, the lead time for other solar energy technologies is so long and the technology (design, materials requirements, future materials production methods) is so uncertain that a compilation of air pollutants similar to that in Table 4 for other solar energy technologies cannot be justified at this time.

There are some special environmental problems related to solar energy collection. For example, substantial quantities of biocides would probably be necessary to prevent fouling of the flow-through passages in the boilers of installations designed to tap ocean thermal gradients; local climate modifications might result from altered heat balances caused by large-scale insolation collection installations; aesthetic problems would arise from new architectural design constraints for buildings equipped with solar energy collectors; the legal problem of "sun rights" would emerge; and questions of land use in arid, but sunny parts of the United States would become important. Additionally, there would be a subtle pressure for population redistribution towards locations where solar energy could provide power at low cost.

Table 4

AIR POLLUTANT EMISSIONS: MATERIALS FOR PRODUCTION OF THERMAL SOLAR
ENERGY COLLECTORS FOR BUILDINGS, MATERIALS, AND ACTIVITIES DISPLACED, 1985*
(10⁴ kg)

	Total Particulates	Fluorides	Sulfur Oxides	Carbon Monoxide	Hydrocarbons	Nitrogen Oxides
Materials consumed						
Glass (soda lime)	30	60F [†]	--	--	--	--
Alternative metals						
Aluminum (best controls, most common process) [‡]	48 [§]	1.0	0.091 [§]	2.6 [§]	0.15 [§]	91 [§]
Copper (controlled) [‡]	5.8	--	1800	--	--	--
Material displaced						
Asphalt roofing	0.88	--	--	1.2	2.0	--
Activity displaced per year						
Natural gas combustion for domestic space conditioning (uncon- trolled)	15	--	0.49	16	6.5	65

* This information is abstracted from Table 4 in Appendix A.

[†] The variable "F" represents the weight percentage of fluoride input to the furnace.

[‡] Existing installations generally do not achieve this degree of control, although the control technologies are currently available.

[§] Includes emissions arising from the production of electric power (from natural gas) for the electrolysis process.

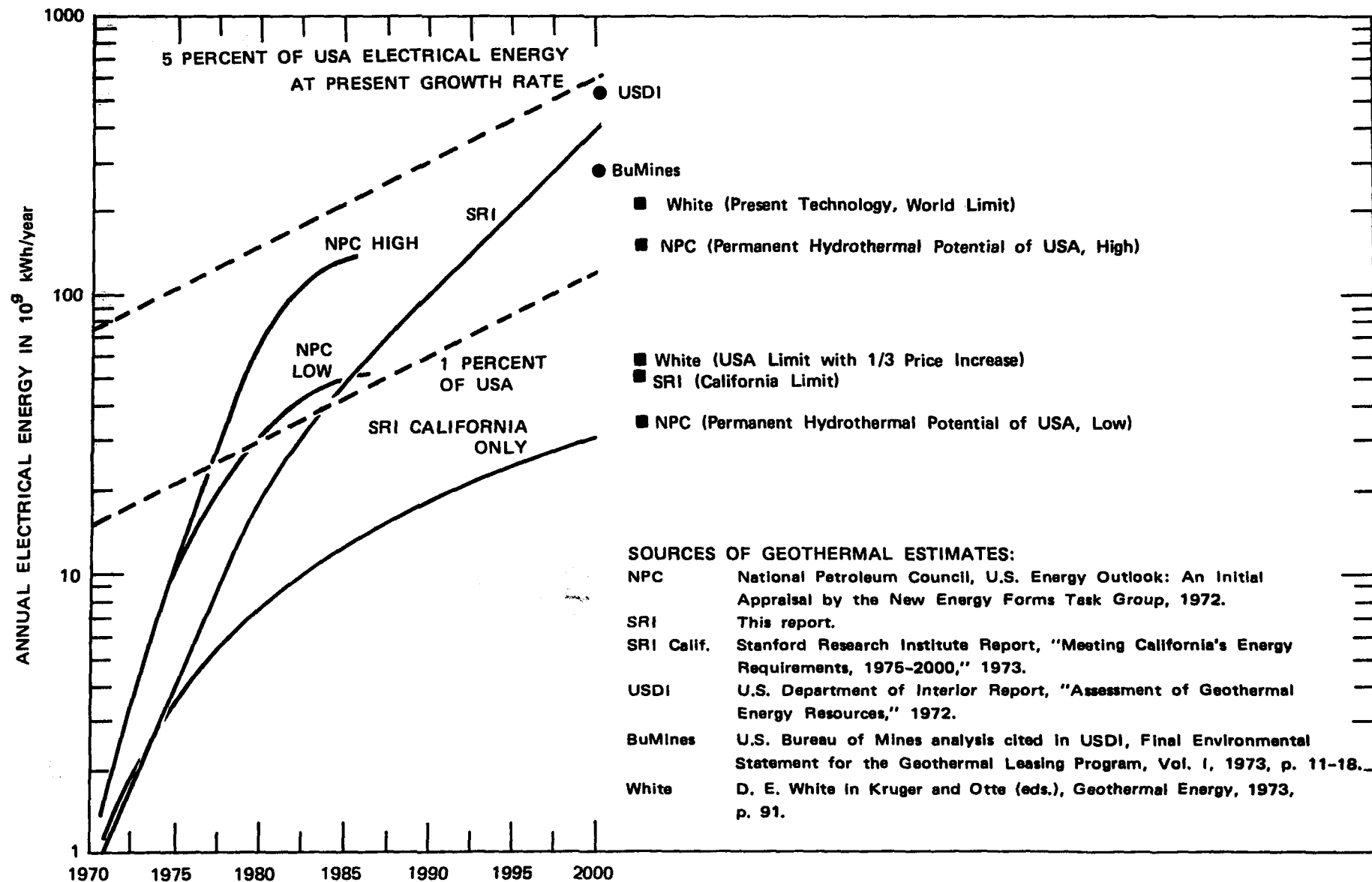
2. Recommendations

The Environmental Protection Agency should establish a modest program to maintain awareness of evolving solar energy technology and liaison with those who work on solar energy and major interest groups. By continually refining the forecast of both the direct and indirect environmental consequences, EPA would be able to keep developers informed and influence the development of hardware and systems design. Thereby, EPA can seek to lessen any detrimental environmental consequences and achieve full exploitation of environmental benefits. This suggested program is described more completely in Appendix A.

C. Geothermal Energy

Geothermal energy already is a source of commercial electric power in the United States. Power production at The Geysers in California should produce over 3 billion kWh from about 500 MW of installed capacity in 1975. While the ultimate level of production of electricity from geothermal energy is extremely uncertain, it is clear that the present level of production is a small fraction of what is possible. The steam reservoir now being tapped at The Geysers is representative of only one type of geothermal resource, the vapor-dominated hydrothermal convection source, which is the least abundant type but the type most easily tapped for electric power production. Most of the uncertainty as to the ultimate energy production from geothermal resources derives from the fact that the technology and the costs required for the exploitation of other types of geothermal energy reservoirs are so undetermined.

Projections of the annual electric energy production from geothermal energy sources are presented in Figure 1. The figure shows two projections from a National Petroleum Council (NPC) study² and two projections by SRI, one for California alone³ and the other adopted for this report. Also



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FIGURE 1 PROJECTED GROWTH OF GEOTHERMAL ELECTRICITY

shown are various estimates of levels of ultimate or year 2000 production. The relative significance of the projected levels of geothermal energy production is indicated by the straight lines showing 5 percent and 1 percent of total U.S. electricity production based on projecting the 1970 level with a 10-year doubling time (i.e., a 7 percent annual growth rate). The production level adopted as the definition of "significant" in Appendix B is 33 billion kWh and occurs near the intersection of the SRI projection and the one percent line.

The kWh, the usual unit of electrical energy, has been chosen to measure the level of geothermal energy development. This choice reflects the judgment that virtually all exploitation of geothermal energy will be for the production of electricity. Significant use of geothermal energy for space heating is ruled out by the fact that the heat can't be transported to structures beyond the field itself. Use of geothermal energy for process heat is unlikely because of the relatively low temperatures of geothermal reservoirs, as indicated in Table B-5 in Appendix B on geothermal energy.

Another judgment reflected in the projections of geothermal energy production shown in Figure 1 concerns the time scales for development of different types of geothermal energy. Neither the SRI nor the NPC projections anticipate the use of geothermal resources other than the hydrothermal convective type prior to 1985. A hydrothermal convective reservoir exists where water and an abnormally high rate of heat flow coincide naturally. A well drilled into the reservoir yields both hot water and steam (a wet geothermal field), or, rarely, as at The Geysers, steam alone (a dry geothermal field). The technology for producing electricity from such geothermal fields exists. This technology is at the commercial stage for dry fields (The Geysers) and at the demonstration (Cerro Prieto) or pilot (Niland) stages for wet fields. The technologies for exploiting the other types of geothermal resources mentioned in Appendix B

(stimulated dry hot rock, geopressured, and magmatic) are largely conceptual at present. The first attempts to demonstrate the extraction of energy from dry hot rock are planned to take place after 1975.

The projection adopted in this report does assume that some energy will be derived from geothermal sources other than the hydrothermal convective ones before the end of the century. Table 5 contains an estimate of 50 billion kWh from such sources in the year 2000, but this value is only a fraction of the range of estimates given for that year in Figure 1. The more than usually speculative nature of projections of the development of these new forms of geothermal energy can be emphasized by quoting D. E. White, a geothermal specialist of the U.S. Geological Survey: "I am reluctant to offer estimates of geothermal resources that are now sub-marginal but that may be utilized with appropriate technological breakthrough; adequate cost data are completely lacking."⁴

A final point to be made regarding the timing and the magnitude of geothermal resource exploitation is that both are tied directly to the research and development effort mounted by government and industry. It is generally agreed that the potential of geothermal energy is vastly increased if technical breakthroughs allow the exploitation of geopressured, magmatic, and dry rock sources. As White goes on to say, "However, major geothermal contributions [greater than 10 percent of our energy needs] could result from such breakthroughs."⁴ The development now underway is projected in Figure 1 to make geothermal energy a resource of local importance, but it is not likely to make it a source for more than 5 percent of the national consumption of electrical energy.

A number of the quantifiable environmental effects of generating electricity from geothermal energy are summarized in Table 5. The projected levels of geothermal energy development and the factors for scaling

Table 5

PROJECTED ENVIRONMENTAL IMPACTS OF GEOTHERMAL ENERGY

Item	Unit	1975	1985	2000	Scaling Factor
Geothermal electricity					
Energy from dry hydrothermal	10^9 kWh/yr	4	30	50	
Energy from wet hydrothermal	10^9 kWh/yr	0	20	300	
Energy from other reservoirs	10^9 kWh/yr	<u>0</u>	<u>0</u>	<u>50</u>	
Total geothermal energy	10^9 kWh/yr	4	50	400	
Total geothermal power capacity	GW	0.5	7	60	
Waste heat					
Heat rejected at plant sites	10^{15} J/yr	72	900	7,200	18 MJ/kWh (16 percent efficiency)
Air pollutants					
Hydrogen sulfide	10^6 kg/yr	18	220	1,800	4.5 g/kWh
Ammonia	10^6 kg/yr	24	300	2,400	6.0 g/kWh
Methane	10^6 kg/yr	18	220	1,800	4.5 g/kWh
Land requirement					
Area of geothermal fields	sq km	15	200	1,800	30 sq km/GW
Water					
Liquid brought to surface	10^9 kg/yr	8	900	14,000	40 kg/kWh (wet), 2 kg/kWh (dry)
Total dissolved solids brought to surface	10^9 kg/yr	0	10	150	0.5 kg/kWh (wet), zero (dry)
Solid waste					
Volume of TDS brought to surface after evaporation of the water	10^6 m ³ /yr	0	5	90	0.5 m ³ /1000 kg

environmental effects to those levels are given explicitly in the table. The scaling factors are taken from the discussion of environmental effects in Section II of Appendix B and are derived explicitly from properties of two hydrothermal convective fields: The Geysers (dry) and Cerro Prieto (wet). They should be as applicable to geothermal sites in general as single factors can be from single geothermal sites. The thermal efficiency, which determines the waste heat load, is typical of the best hydrothermal convective fields. The factors for emissions to the air are from average values at The Geysers. The hydrogen sulfide level in some wet geothermal wells is appreciably higher⁵ (by a factor of 5), so further experience with wet geothermal resources may suggest a larger scaling factor for these uncontrolled emissions. The land use factor was also derived from experience at The Geysers, in this case, experience with steam production rates, transport distances, and depletion effects. The scaling factors for water, total dissolved solids, and solid waste are characteristic of the Cerro Prieto geothermal water, which has a salinity somewhat below 2 percent.

One method to estimate the degree of control needed to bring the effects quantified in Table 5 to within some acceptable limits is to determine the effect on ambient environmental quality of the projected level of emissions or other impact and to compare the resulting indicator of ambient quality with an appropriate environmental quality standard. This method is used in Appendix B to estimate that something like 98 percent control may be in order for hydrogen sulfide emissions at The Geysers and that more than 90 percent control of total dissolved solids would be needed for a geothermal field like Cerro Prieto producing energy on a significant scale and discharging geothermal fluid into a fresh water stream that has one-tenth the mean annual flow of the Colorado River. This method requires the use of a model for calculating ambient quality, given a production level and a scaling factor.

Another method for estimating the need for control of an environmental effect is to compare the directly expressed emission or effluent or the land-use factor with a comparable standard associated with a similar industry or process (rather than with an ambient quality standard). This method would result in a control requirement independent of the production level, because the standard is applied directly to quantities like the scaling factors in Table 5. The need for control of hydrogen sulfide emissions is estimated according to this method, by comparing them to the standards for sulfur dioxide emissions from the fossil fuel alternatives to geothermal power plants. The fact that hydrogen sulfide is oxidized to sulfur dioxide in the atmosphere within 2 to 48 hours suggests that the comparison is appropriate.⁶ Table 6 presents the quantitative comparison. The conclusion suggested by Table 6 is that, on a per kWh basis, where the geothermal plant suffers from its 16 percent efficiency (as compared to the 40 percent efficiency of the best fossil fuel plants), the emission of sulfur as hydrogen sulfide at the Geysers plant is comparable to the emission of sulfur as sulfur dioxide from a coal-fired plant meeting the EPA standards for a new source. Both are within 50 percent of the value of 3 grams of sulfur per kWh. By way of further comparison, the burning of 1 percent sulfur coal to produce electricity at 40 percent thermal efficiency also results in an emission factor of 3 grams of sulfur per kWh if the coal has a heating value of 30 MJ/kg (13,000 Btu/lb). The control requirement estimated on the basis of this comparison can be anywhere from zero to nearly 90 percent, the high requirement resulting from a situation where the hydrogen sulfide content of the geothermal fluid is about five times the average at The Geysers.

The control requirements for materials dissolved in the geothermal fluids are being met at The Geysers and at Niland by reinjection of the fluids into the subsurface geothermal reservoir after the heat energy

Table 6

EMISSION FACTORS FOR GEOTHERMAL PLANTS COMPARED
WITH EMISSION STANDARDS FOR FOSSIL FUEL POWER PLANTS

Description	Form of the Emission	Emission in Grams of Sulfur per Megajoule of Heat		Thermal Efficiency (percent)	Emission in Grams of Sulfur per Kilowatthour of Electricity	
		Factor	Standard		Factor	Standard
Geothermal						
Typical case at The Geysers	H ₂ S	0.2	--	16	4	--
Bad case in Imperial Valley	H ₂ S	1.0	--	16	20	--
Fossil fuel*						
Coal-fired plant	SO ₂	--	0.26	40	--	2.3
Oil-fired plant	SO ₂	--	0.17	40	--	1.5

* EPA standards from The Federal Register, 23 December 1971.

has been extracted at the power plant. This procedure has the additional environmental virtue of decreasing the probability and the magnitude of subsidence caused by depletion of the reservoir. Reinjection introduces another possibility that geothermal brine will contaminate a fresh water aquifer by leakage through a well casing, but this threat must be dealt with anyway in the wells bringing the brine to the surface. In the semi-arid western United States, where most of the hydrothermal convective resources are to be found, the only environmentally sound alternative to reinjection of spent geothermal fluids is extensive treatment and mineral recovery. This alternative is being investigated to determine its technical and economic feasibility.⁷

Other environmental effects of generating electricity from geothermal energy are identified in Appendix B. The most important ones have been presented in Table 5. and in this summary. The recommendations for research and development to control the adverse effects and to realize the advantages of geothermal energy are presented in Section VI of this report.

D. Energy from Oil Shale

1. State of the Art

Oil shale is not shale, and it does not contain oil; it is instead, a fine-grained, compact, laminated sedimentary rock that contains kerogen, an organic, high molecular weight mineraloid of indefinite composition. Kerogen can be extracted from oil shale by retorting that results in a hydrocarbon liquid akin to natural crude oil that in turn can be processed and refined much as petroleum. Attention is directed to oil shale as an advanced energy source because certain deposits (especially in Colorado, Utah, and Wyoming) are relatively rich in kerogen that, if recoverable, could represent an important source of supplementary refinery feedstocks or substitute for natural gas.

Only those portions of oil shale deposits containing the richest kerogen content and occurring in thick beds can be considered as reserves for prospective developments. Still, these reserves are approximately equivalent to a giant oil field, estimated at about $5.2 \times 10^9 \text{ m}^3$ (33 billion barrels) of oil. More than ten times as much shale oil is estimated to occur in lower grade and thinner beds, but it is improbable that these resources will experience development in this country.

Table 7, based largely on the work of the U.S. Department of the Interior, shows the amounts of shale oil projected to be developed by the year 2000. Rapid development is projected, reaching $16 \times 10^6 \text{ m}^3$ (100 million barrels) per year by 1980 and increasing more than sixfold by the end of the century. Most of the shale for processing is estimated to be derived from mining, with small amounts from in-situ development in later years.

The alternate approaches to oil shale utilization are shown in Figure 2. According to projections, most future oil shale development will start with mining followed by crushing, retorting, refining, and

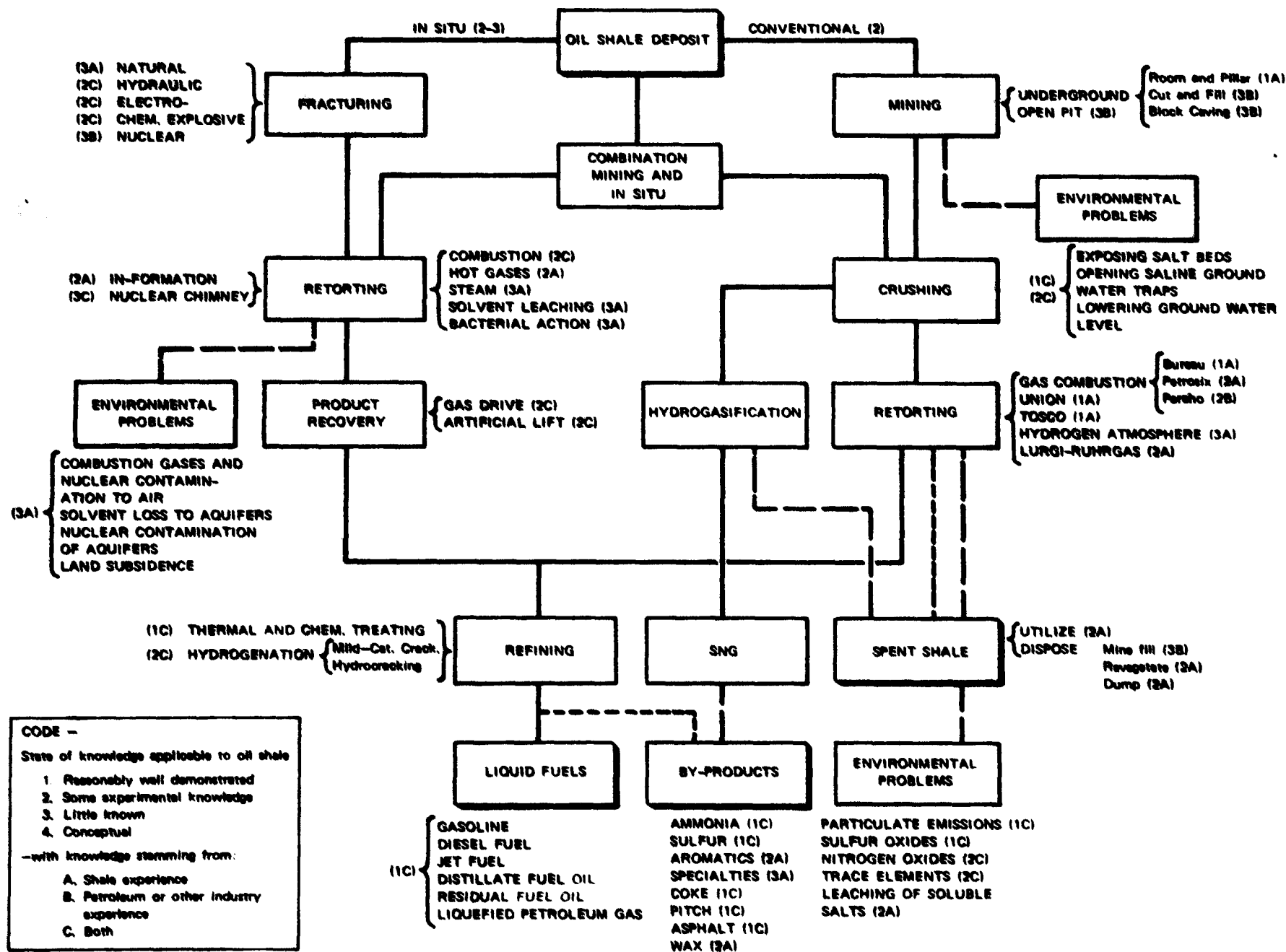
Table 7

PROJECTED ANNUAL FUEL PRODUCTION FROM OIL SHALE DEVELOPMENT

 (10^6 m^3)

	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>	<u>1995</u>	<u>2000</u>
Total estimated oil production	0	0	16	52	70	87	105
Underground mining	0	0	8	24	32	40	48
Surface mining	0	0	8	24	32	40	40
In-Situ	0	0	0	4	6	7	17

Source: Stanford Research Institute, using data from U.S. Department of the Interior, "Final Environmental Impact Statement for the Prototype Oil Shale Leasing Program" in four volumes, 1973, Volume I, "Regional Impacts of Oil Shale Development". Data presented here calculated on the assumption of 330 days of plant operation per year.



SOURCE: Based on original figure in H. Perry, "Prospects for Oil Shale Development," U.S. Department of Interior, 1968.

FIGURE 2 OIL SHALE UTILIZATION — PROCESSES, ENVIRONMENTAL EFFECTS, AND STATE OF KNOWLEDGE

disposal of processed shale. Mining of oil shale has been performed on a pilot basis, but never at the scale anticipated for full-size operations. For example, one $8 \times 10^3 \text{ m}^3$ (50,000 barrel) per day plant would require approximately $5.7 \times 10^7 \text{ kg}$ (62,500 tons) of mined oil shale per day. Many plants of this size are projected. Clearly, there are a number of operational problems to be addressed in undertakings of such magnitude.

Mined shale is crushed and transported to a plant where it is retorted. Several retorting processes have been developed at various times. The processes differ in their method of heat transfer to the shale for kerogen recovery. The two retorting approaches most likely to be developed are those that employ heat transfer either by (1) burning combustion gases generated in the retort or (2) introduction of hot solids into the retorting bed. Each of these methods results in environmental impacts that will need to be controlled.

2. Environmental Consequences

Oil shale development may result in a number of adverse environmental consequences unless proper steps are taken to achieve pollution control. Environmental impact will include dust, sulfur dioxide in flue gases, nitrogen oxide in combustion products formed by burning crude shale oil, and sour water decanted from the product oil. Retorting shale produces a strong odor characteristic of organic nitrogen compounds, and it may be dispersed widely. Additionally, shale processing required significant amounts of water consumption and also results in large amounts of processed shale that will need disposal and management to avoid creation of long-standing sources of significant pollutant amounts.

The analysis in the present study, based on work done by the U.S. Department of the Interior and other sources, quantified the following environmental consequences and projected impacts from oil shale development to the year 2000:

- **Water Use.** Availability of water is recognized as a principal constraint upon oil shale development because the deposits are located in arid regions. Table 8, in which the overall industry size is limited to 3.2×10^5 m³ (2 million barrels) per day because of the availability of water, shows the total annual consumptive water requirements for each type of mining. This amount of water consumption would preempt other potential uses and thereby contribute indirectly to environmental impacts associated with oil shale development.
- **Land Requirements.** Land is required for oil shale production facilities, but by far the largest land disturbance in oil shale development is related to surface disposal of processed shale. Table 9 shows the projected annual land requirements for oil shale production until the year 2000.
- **Water Quality.** Oil shale development could lead to degradation of water quality in the vicinity of developments. Although effluents from processing plants will require obvious controls, a major source of water pollution will be from surface disposal of processed oil shale. Table 10 shows estimated leachate, salinity, sediment, and heavy metals produced from weathering and erosion of processed shale disposed of at the surface near oil shale developments in the Piceance Basin region of Colorado.

Control of these potential pollutants will require treatment of processed shale disposal areas. Materials that may be leached from disposal piles must be contained and prevented from leaving the disposal site. Ideally, research to find alternative uses for processed shale, which would obviate the need for its surface disposal, would be perhaps the most effective means of realizing control over the potential water quality effects of oil shale development.

Table 8

PROJECTED ANNUAL WATER REQUIREMENTS - OIL SHALE

	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>	<u>1995</u>	<u>2000</u>
Total estimated oil production, 10^6 m^3	0	0	16	52	70	87	105
Recurring annual water consumption							
(a) Underground mine production, 10^6 m^3	0	0	8	24	32	40	48
Water consumption (@ $4.1 \text{ m}^3/\text{m}^3$ oil)	0	0	33	98	130	160	
(b) Surface mine production, 10^6 m^3	0	0	8	24	32	40	40
Water consumption (@ $4.0 \text{ m}^3/\text{m}^3$ oil)	0	0	32	96	130	160	
(c) In-situ production, 10^6 m^3	0	0	0	4	6	7	17
Water consumption (@ $2.1 \text{ m}^3/\text{m}^3$ oil)	0	0	0	8.4	13	15	
TOTAL ANNUAL WATER CONSUMPTION, 10^6 m^3	0	0	65	200	270	340	41

(Totals may not check because of rounding.)

Source: SRI calculations based on U.S. Department of the Interior, "Final Environmental Statement for the Prototype Oil Shale Leasing Program," Vol. I, 1973, pp. III-9,34.

Table 9

PROJECTED ANNUAL LAND REQUIREMENTS - OIL SHALE

	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>	<u>1995</u>	<u>2000</u>
Total estimated oil production, 10^6m^3	0	0	16	52	70	87	105
Recovery annual land requirements, ha [*]							
Underground mine production, 10^6m^3	0	0	8	24	32	40	48
Disturbance, ha (@ 11 ha/ 10^6m^3 oil) [†]	0	0	88	260	350	440	530
Surface mine production, 10^6m^3	0	0	8	24	32	40	40
Disturbance, ha (@ 17 ha/ 10^6m^3 oil)	0	0	136	410	540	680	680
In-situ production, 10^6m^3	0	0	0	4	6	7	17
Disturbance, ha (@ 7 ha/ 10^6m^3 oil)	0	0	0	28	42	49	120
TOTAL ANNUAL DISTURBANCE, ha	0	0	220	700	930	1200	1300
(Totals may not check because of rounding)							

* Assumes 76m (250 ft) average depth of spent shale disposal.

† Assumes no spent shale returned to mine.

Source: SRI calculations based on U.S. Department of the Interior, "Final Environmental Statement for the Prototype Oil Shale Leasing Program," Vol. I, 1973, pp. III-12,14,17.

Table 10

PROJECTED ANNUAL WATER QUALITY EFFECTS FROM SURFACE DISPOSAL OF PROCESSED OIL SHALE

	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>	<u>1995</u>	<u>2000</u>
Total estimated oil production, 10^6 m^3	0	0	16	52	70	87	105
Surface disposal of processed shale, 10^9 kg (@ 40% of total processed shale, $3.4 \times 10^3 \text{ kg/m}^3$)	0	0	54	180	240	300	360
Area required for disposal, ha (@ $1.3 \text{ ha}/10^9 \text{ kg}$ processed shale)*	0	0	72	230	310	385	465
Leachate produced, 10^4 kg (@ $17 \times 10^2 \text{ kg/ha}$)†	0	0	120	390	530	650	790
Dissolved solids produced, 10^3 kg (@ 150 kg/ha)	0	0	12	39	54	66	81
Sediment produced, 10^3 m^3 (@ $4.8 \text{ m}^3/\text{ha}$)	0	0	0.3	1.1	1.5	1.8	2.2
Heavy metals, 10^6 kg (@ $0.086 \text{ kg/m}^3 \text{ oil}$)	0	0	1.4	4.5	6.0	7.5	9.0

* Assumes 76m (250 ft) average depth of spent shale disposal.

† Assumes the top 10cm (4 in) of spent shale is leached.

Source: SRI calculation based on U.S. Department of the Interior, "Final Environmental Statement for the Prototype Oil Shale Leasing Program," Vol. I, 1973, pp. III-14, 88, 90, 99.

- **Air Quality.** Development of the western oil shale deposits will result in a decline of general air quality through emissions of chemical compounds and particulate matter to the atmosphere. Table 11 shows estimated sulfur oxide and nitrogen oxide emissions associated with projected levels of oil shale development. The data indicate that uncontrolled SO_x emissions will greatly exceed maximum EPA standards unless control measures are employed. Uncontrolled NO_x emissions, on the other hand, will be less than the maximum standard level, and unless the standard is altered, they would not appear to require special control procedures at this time. It must be remembered, however, that this initial analysis does not consider the possible adverse environmental impact resulting from the cumulative effects of such emissions from many sources in an air basin. This potentiality, which needs to be examined by further research and analytical work, could lead to the need for NO_x control.

In addition to chemical emissions, oil shale development promises to be inherently dusty, and significant amounts of particulates could be produced as indicated in Table 12. The table shows that uncontrolled dust levels associated with oil shale development are in excess of the EPA standard. This will require some measure of dust control to bring these emissions within the limits established by present standards. Dust control will be required at several stages of oil shale development, especially in mining, crushing, transportation, and disposal. It is clear that the degree to which dust control can be realized will vary greatly in the different stages. A key question is whether each stage must be within established standards, or whether the standard applies only to the overall operation.

Table 11

PROJECTED ANNUAL CARBON EMISSIONS - OIL SHALE

	1970	1975	1980	1985	1990	1995	2000
Total estimated oil production, $10^6 m^3$	0	0	16	52	70	87	105
Sulfur Oxides							
(a) SO_x emissions, $10^6 kg$ (@ $5.7 kg/m^3$ oil)*	0	0	91	300	400	500	600
(b) SO_x emissions, $10^6 kg$ (@ $11 kg/m^3$ oil)*	0	0	170	550	740	920	1100
(c) SO_x emission level at maximum EPA standard, $10^6 kg$ (@ $0.2 kg/m^3$ oil)	0	0	3.2	10	14	17	21
(d) Excess SO_x emissions over standard at minimum emission rates (a), $10^6 kg$	0	0	88	290	390	480	580
(e) Total SO_x emissions at 90% control level for (a), $10^6 kg$	0	0	9.1	30	40	50	60
Nitrogen Oxides							
(a) NO_x emissions, $10^6 kg$ (@ $0.46 kg/m^3$ oil)	0	0	7.4	24	32	40	48
(b) NO_x emissions, $10^6 kg$ (@ $0.68 kg/m^3$ oil)	0	0	11	35	48	59	71
(c) NO_x emission level at maximum EPA standard, $10^6 kg$ (@ $0.57 kg/m^3$ oil)	0	0	9.1	30	40	50	60
(d) (Deficit) NO_x emissions compared to standard at minimum emission rate (a), $10^6 kg$	0	0	(1.7)	(6.0)	(8.0)	(10.)	(12)

* Assuming the sulfur is emitted as SO_2 .

Source: ERI calculations based on U.S. Department of the Interior "Final Environmental Statement for the Prototype Oil Shale Leasing Program," 1972, Volumes I and III.

Table 14

PROJECTED ANNUAL PARTICULATE EMISSIONS - OIL SHALE

	<u>1970</u>	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>	<u>1995</u>	<u>2000</u>
Total estimated oil production, 10^6 m^3	0	0	16	52	70	87	106
Uncontrolled dust level, 10^6 kg (@ 0.054 kg/m^3)	0	0	0.9	2.8	3.8	4.7	5.7
"Typical" dust level, 10^6 kg (@ 34 g/m^3)	0	0	0.55	1.8	2.4	3.0	3.6
Dust emission levels at standard, 10^6 kg/m^3 [Std= 80 g/m^3 (.028 lb/bbl)]	0	0	1.3	4.2	5.6	7.0	8.4
Excess dust emissions compared to standard at uncontrolled emission rates, 10^6 kg	0	0	0.5	1.5	2.1	2.6	3.2

Source: BRI calculations based on U.S. Department of the Interior, "Final Environmental Statement for the Prototype Oil Shale Leasing Program," Vol. I, 1973, p. III-192.

3. Recommendations

The magnitude of potential oil shale developments, their location in virtually undeveloped, arid regions of the American West where substantial amounts of public lands occur, and the apparent impacts on air and water quality and land use are strong points in the argument that the Environmental Protection Agency undertake a program of research and development. The suggested program is described in Section VI of this report and in Appendix C.

E. Energy from Solid Wastes

The energy equivalent of 2 million barrels of oil per day (the national energy consumption equivalent is 35 million barrels of oil per day) is the estimate given in Appendix D for the energy potential of both urban and agricultural wastes in the United States. The assumptions made to arrive at this estimate are (1) that total wastes are 30 kg per person per day, (2) that population is 200 million people, (3) that energy content of wastes is 8 MJ/kg (4000 Btu/lb), (4) that efficiency of collection and conversion to energy is 25 percent, and (5) that energy equivalent of a barrel of oil is 6 GJ. According to this estimate, solid wastes could supplement the national energy supply by six percent. The greatest uncertainty in this energy supply assessment is in the choice of the fraction of the total wastes that are assumed to be converted to energy. A 25 percent recovery rate is optimistic under present circumstances, where only about a sixth (5 kg per person per day) of the total solid waste is urban refuse (the most easily collected component). Other estimates of the energy potential of solid waste, based on present waste collection patterns, are closer to 1.5 percent of national energy consumption.^{8,9}

With even the most advanced of the solid waste conversion processes only now moving from the demonstration toward the commercial stage, an initial growth rate for the new technology is not established and a pattern of growth toward some ultimate limit cannot be extrapolated. For the sake of projecting the increasing emission levels from a growing use of this energy resource, this report assumes that energy from solid waste will amount to five percent of total U.S. energy in the year 2000 and will reach that level at a growth rate characterized by a doubling time of two years during the 1975 to 1985 decade and of three years during the remainder of the century. This assumption leads to the energy production levels presented in Table 2 and Table 13.

Energy recovery can be achieved by incineration of urban or "dry" agricultural wastes. Process heat or power produced in steam or gas turbines are the usable products. Energy can also be recovered from gases produced through pyrolysis. The gases can be burned at the facility to produce power, or they can be transmitted elsewhere for use. If used as synthesis gas, the pyrolysis gas substitutes for gas made from other fossil resources. Anerobic digestion can be used for urban refuse disposal if these urban wastes are mixed with "wet" materials such as sewage. The digestion process produces a methane containing gas suitable for combustion or purification for transport. Anerobic digestion is the most likely method for disposal of agricultural wastes, especially in those locations and situations that produce large quantities of readily collectable manure and food processing wastes.

All the processes of energy recovery from waste disposal have an advantage over sanitary landfill through minimization of land requirements, elimination of putrescible materials, and simplification of disease and vector control. However, extensive energy recovery operations increase the potential for air pollution. In tests at the Chicago incinerator, a

particulate emission rate of approximately 0.4 kilogram per tonne of urban refuse processed has been achieved. These emissions met the requirements of no more than 0.183 grams per cubic meter (0.08 grains per SCF). An urban population of 175 million (estimated for the mid-1980s) will produce approximately 262 million tonnes of refuse. If 75 percent of this refuse were incinerated under proper controls, the pollution resulting would be about 100,000 tonnes of particulates per year. This should be compared with the 1.4 million tonnes of particulates from uncontrolled combustion of solid wastes or the 25 million tonnes of particulates that comprise the estimated annual air burden of the United States. Pyrolysis process will produce similar or smaller particulate loads ranging downward from 100,000 to perhaps 10,000 tonnes. Anerobic digestion should produce relatively little particulate contamination.

The experience at the Combustion Power Inc. pilot plant in Menlo Park, California, provides the data for determining emission factors applicable to gaseous, as well as particulate, air pollutants. This plant incinerates solid waste in a fluidized bed combustor and generates electricity by passing the combustion products through a gas turbine. The emission factors are shown in Table 13. The emission factor for particulates at the Chicago incinerator, used in the estimate of the previous paragraph, is somewhat more than half of the one adopted in Table 13, an indication of the accuracy of the emission factors used. It should be noted that the factor of five as the emission level advantage of pyrolysis over incineration referred to in Appendix D may be decreased substantially when the subsequent burning of the fuel produced by pyrolysis is included as part of the energy production system. The emission factors given in Table 13, therefore, are useful as upper limits for estimates of emission levels from both incineration and pyrolysis. The time scale for development of energy-producing solid waste facilities presented in Table 13 is not quite

Table 13

PROJECTED ENVIRONMENTAL IMPACTS OF ENERGY FROM SOLID WASTES

<u>Item</u>	<u>Unit</u>	<u>1975</u>	<u>1985</u>	<u>2000</u>	<u>Emission Factor</u>
Energy					
Annual production	10^{15} J/yr	10	300	10,000	
Fraction of U.S. total	percent	0.01	0.2	5	
Air Pollutants					
Particulates	10^6 kg/yr	1	30	1,000	0.1 kg/GJ
SO ₂	10^6 kg/yr	1	30	1,000	0.1 kg/GJ
NO ₂	10^6 kg/yr	2	60	2,000	0.2 kg/GJ
CO	10^6 kg/yr	0.4	12	400	0.04 kg/GJ
HCl	10^6 kg/yr	1	30	1,000	0.1 kg/GJ

Note: The present annual national emission levels are approximately

- Particulates, $20,000 \times 10^6$ kg/yr
- SO₂, $30,000 \times 10^6$ kg/yr
- NO₂, $20,000 \times 10^6$ kg/yr.

as short as the one for the projection just cited. The result is that the particulate emission level of hundreds of thousands of tonnes is projected for about the year 1990 rather than the mid-1980s.

The small fraction of total emissions likely to be attributable to these solid waste processes is due to the extremely small amount of energy now being produced from solid wastes. Even at the rapid growth rate projected, a doubling every two years until 1985 and every third year thereafter, the start from a mere 5,000 tonnes per day in a few demonstration plants in 1975 does not lead to even a tenth of a percent of the national energy consumption until after 1982. Under these conditions, the small fraction of national pollutant levels accounted for by solid waste energy processes has no implication regarding the quality of the emission control technology. An indication of the need, if any, for lower emission levels from solid-waste energy plants must be sought by considering the maximum production to be reached sometime after the year 2000 or by comparing the emission factors given in Table 13 with those from similar processes for which standards exist.

The maximum possible production of energy from solid waste, if virtually all the waste is converted to energy, is 25 percent of total national energy consumption. With total collection being uneconomical and unlikely, the six percent value cited at the start of this section is a better estimate of the ultimate level of energy production from solid wastes. This suggests that emission levels quite comparable to those given in Table 13 for the year 2000 are likely to constitute the ultimate level of emissions if current technology for producing energy from solid waste is fully used.

Table 14 presents another approach for estimating a control requirement. The emission factors adopted here on the basis of experience with pilot and demonstration plants are compared with emission standards for

Table 14

EMISSION FACTORS FOR ENERGY FROM SOLID WASTE
COMPARED WITH FOSSIL FUEL EMISSION STANDARDS*

<u>Pollutant</u>	<u>Type of Plant</u>	<u>Emissions</u>	
		<u>Factors</u> <u>(kg/GJ)</u>	<u>Standards</u> <u>(kg/GJ)</u>
Particulates	Solid waste [†]	0.1	0.1 [‡]
	Coal	--	0.04
	Oil	--	0.04
SO ₂	Solid waste [†]	0.1	--
	Coal	--	0.52
	Oil	--	0.34
NO ₂	Solid waste [†]	0.2	--
	Coal	--	0.30
	Oil	--	0.13
	Gas	--	0.09

* All standards are taken from The Federal Register of 23 December 1971.

† The emission factors for energy from solid wastes are based on measurements made on the CPU-400 system of Combustion Power, Inc.

‡ The emission standard for particulates from a solid waste energy plant is derived from the published standard for incinerators (0.18 g per standard cubic meter at 12 percent CO₂) by assuming that the combustible fraction of the solid waste is 55 percent of the total and has a composition given by C₃₀H₄₈O₁₉. The heat value assumed is 15 MJ per kg for the combustible fraction, i.e., 8 MJ/kg for the total.

fossil-fuel fired, steam generating plants. The implication of Table 14 is that little additional control is needed. More information on the status of control technology and the degree of control required is presented below in Section IV-H.

Hazardous chemicals can be emitted from any of the disposal processes. Most heavy metal and carcinogens will be associated with particulates and, as a first approximation, hazards from these special sources can be taken as being in proportion to the total particulate emissions from the various processes. Volatile chemicals, such as mercury and many organic compounds, will also be emitted. The organic chemical substances are not expected in quantities large enough to be of environmental concern.

Residues from the energy producing processes, such as ash and waste waters, can produce undesirable effects. Ash deposits must be handled in a way that prevents unacceptable levels of leaching by underground streams and rain water, which would transfer acid, alkali, or heavy metal residues and pollute natural waters. Quench and scrub waters must be treated to control similar effects, but the treatment is standard, and present controls appear to be adequate to prevent adverse effects.

Anerobic digestion may pose special problems in disposal of treated residues. Urban wastes may still have substantial volume after anerobic digestion and, therefore, continue to require considerable land for disposal. In addition, if the bacterial processes are poisoned, the "stuck" digester will be filled with a vile, smelly, difficult-to-handle product.

F. Underground Coal Gasification

The underground gasification of coal is as yet a commercially unproven concept. Decades of development in the USSR, England, the United States, and other countries have failed to produce a viable process. The

two current underground gasification programs under development in the United States face immense technical problems. There is a substantial risk that the current programs will likewise fail to demonstrate a viable process. However, the economic impact of successful development of the concept as a substitute for gasifying strip-mined coal is potentially large. The environmental impact of large-scale commercial development of underground coal gasification, vis-à-vis strip-mined coal gasification, may also be large, depending upon:

- Failure of current efforts to devise acceptable means of reclaiming stripped arid land.
- Demonstration that there are no unacceptable environmental effects of underground coal gasification.

No support by the EPA of the current development programs is recommended at this time. However, the EPA should follow the progress of the current programs and retain the option of reconsidering this decision at a later date.

G. Hydrogen as an Energy Carrier

1. State of the Art

Currently, hydrogen is produced mainly from methane or by steam reforming processes driven by fossil fuels. In the long term, when fossil fuels become scarce, hydrogen is a likely energy carrier for use in mobile applications. Such hydrogen could be produced by electrolysis using electric power from any basic energy resource or, perhaps, by closed cycle thermochemical decomposition of water using high temperature heat from a nuclear reactor. As petroleum and gas become less available, hydrogen will be needed in large quantities if coal is to be gasified to methane and liquefied to other hydrocarbons. However, hydrogen also might be utilized as a fuel directly. Hydrogen is also seen as an important option

for energy storage somewhat analogous to pumped hydrostorage. It has been determined that, in some circumstances, transmission of energy in the form of hydrogen conveyed by pipeline can be more effective than overhead electric transmission. Moreover, because of the variability in insolation many solar energy technologies may not be viable without an energy storage mechanism such as hydrogen.

Experience with gaseous hydrogen in Europe and liquid hydrogen in the U.S. space program has contributed greatly to the understanding of handling and storage techniques. Considerable information has been gained about the embrittlement of metals in a high-purity hydrogen environment. The safety record with hydrogen has been impressive; it suggests that the widespread belief that hydrogen is intrinsically less safe than more familiar fuels is probably not warranted.

Except for thermochemical decomposition of hydrogen, nearly every aspect of the prophesied hydrogen energy economy has shown scientific and engineering feasibility. In many applications, economic feasibility is near. Furthermore, engineering improvements, together with the expected rise in price of competing fossil fuel energy carriers, are almost certain to increase the economically attractive uses of hydrogen.

2. Environmental Consequences

Research has demonstrated that internal and external combustion engines can be operated easily and more cleanly on hydrogen. Hydrocarbon and carbon monoxide emissions are reduced to those stemming from lubricating oils, and nitrogen oxides are also greatly reduced. Consequently, hydrogen used as a fuel in transportation systems offers the potential of cleaner urban air. (However, many logistic and engineering hurdles impede such application.)

Used for energy storage and energy transmission by electric utilities, hydrogen could lessen many of the aesthetic impacts and emotional reactions associated with overhead electric transmission lines and pumped hydro storage. If provided from independent sources, the use of hydrogen in coal gasification or liquefaction would greatly improve the utilization of coal resources and thereby reduce the annual amount of land disspoilment or disruption.

Today's hydrogen energy technologies are not without their own environmental problems, however. The electrolyzers now in operation emit asbestos particulates and employ nickel catalysts. Since asbestos is a known carcinogen and nickel is in short supply, health hazards and resource limitations will probably require new technical approaches to electrolysis. The addition of a hydrogen production step in the energy economy suggests that a lower overall system efficiency is to be expected. An increased thermal discharge to the environment would, therefore, follow. To make up for the net decrease in efficiency, more basic energy resources would be needed.

H. Application of Control Technology

Identification of the environmental impacts associated with advanced energy sources is of primary importance to formulation of strategies for research and development leading to control over adverse effects. It is also useful to consider the degree to which existing types of control technology might be applied to pollutants released from advanced sources. Although, as the preceding discussion in this section (further documented in greater detail in the Appendices) shows, the advanced energy sources differ significantly from conventional sources, they do produce pollutants that are generally similar to those released by more ordinary energy sources. As a result, it is natural to inquire about the adequacy or

inadequacy of existing control technology applied to these advanced energy sources. Full examination of such technology would be a major undertaking clearly beyond the scope of this initial planning study. Nevertheless, an initial appraisal of the nature of the problem in direct application of existing control technology to advanced energy sources and a preliminary assessment of emission control technology from these sources is presented below as an aid to program planning. It is followed by specific recommendations for further work in this regard.

1. Nature of the Problem

The application of existing pollution control technology to reduce environmental impacts from advanced energy sources is a multifaceted problem. Clearly, an important consideration is the degree to which technologies developed for some other application can be employed directly or modified for use with advanced energy sources. In some cases, even if existing control technologies might be adapted to advanced energy sources, it is not apparent that their efficiencies would be comparable to those achieved in more common uses.

Critical as they may be, however, technological considerations in application of pollution control technology cannot be separated from economic factors. In other words, even the most attractive adaptation of existing pollution control technology to advanced energy sources will fail if it leads to unacceptable costs for installation and operation. The record of the recent past illustrates that there exist technologies to control a wide variety of combinations of pollutants and sources. [See, for example, "Compilation of Air Pollutant Emission Control Factors," U.S. Environmental Protection Agency Report No. AP-42, Second Edition (April 1973)]. The degree to which the most efficient technology has been deployed, however, is determined by economic factors, and such deployment is

certainly not universal. Further limitations on technology applications are existing rules and regulations specifying equipment and procedures. These institutional constraints also influence both economic and technical activities. Difficult to define for conventional energy sources, these are even more a deterrent to ready application to advanced energy sources. The nature of the problem in assessment of existing control technology, therefore, is that the utility of this technology is determined by many complexly interrelated technical, economic, and institutional factors. Consequently, a definitive account of the adequacy of existing control technology for application to advanced energy sources is beyond the scope of this report. Such an account would require that the control efficiency be expressed as a function of cost. This report can, however, provide an example of the needed research and a preliminary assessment of emission control technology for advanced energy sources. This is given below, followed by recommendations for a comprehensive examination of the topic as a part of planning for R&D undertakings.

The approach to assessment of existing emission control technology as applied to advanced energy sources may be formalized and systemized through reference to a simple equation:

$$E = (P)(ef)(1 - C_c \cdot C_t)^*$$

Where

E = total emissions for a source, kg/yr

P = national production level of the industry, GJ/yr

ef = emission factor for uncontrolled source, kg/GJ

* Adapted from: "Particulate Pollutant System Study: Volume III-Handbook of Emission Properties," Midwest Research Institute (1 May 1971).

C_c = average efficiency of control equipment used in the industry for the specific source

C_t = amount of application of control in the industry (on a production capacity basis) for the specific source

For the present application to advanced energy sources, the following general comments and qualifications are in order:

- (a) P will be locally significant, but will be small in relation to overall national energy production out to the end of the century.
- (b) P times e_f , the national uncontrolled emission of the pollutant, could become locally important, even though small in comparison with other sources nationwide.
- (c) C_c is obtained from some advanced energy pilot plant experience and from some industrial processes that are similar to the advanced energy processes.
- (d) C_t is zero in cases where pilot plants for new energy technologies have not applied any controls. However, the concern of this report is the level of emissions accompanying operation on a significant scale. Since the installations for significant scale operations have yet to be built, it is assumed that all of them will include controls and C_t is taken to be unity in the projections presented here.

It is clear that early goals of future R&D on advanced energy sources should be (a) to reduce uncertainty on emission controls (and other pollution suppression), and (b) to demonstrate the economical installation and operation of these controls from the outset in energy source development. In this way, those who contemplate ventures for production of energy from these sources will have technical guidance and encouragement

in incorporating optimum control technology into their plans. Coupled with economic incentives, this could lead to widespread application of effective pollution control technology from the outset of developments.

2. Preliminary Assessment of Existing Emission Control Technology

In illustration of the nature of the problem discussed above, a preliminary assessment of the application of existing emission control technology to advanced energy sources was performed. This assessment is limited to consideration of the technology of the problem, and does not attempt to provide coverage of the vital economic and institutional factors that will largely determine the deployment and operation of the technology. The foregoing indicates that such work needs to be carried out, but it is incorporated here only to the extent that the present use of a control system implies that its cost is not prohibitive in its present application. It is expected that the costs of installing control technology as a part of new plants would be a smaller proportion of total plant cost than is their present application. However, as indicated above, the technical effectiveness of the control when applied to a new energy technology is an important unknown.

The illustration presented below is based on emission control technology because (a) many advanced energy sources yield pollutants to the atmosphere, often in substantial quantities, (b) these pollutants could, if uncontrolled and concentrated in sufficient magnitude in a restricted area, result in adverse effects or hazards, and (c) there are several standard reference works available to guide such an assessment. Still, it must be recognized that the assessment suffers from several serious weaknesses:

- (a) The actual control technology for advanced energy sources is not established and that used in the assessment often is drawn from more conventional processes judged to be similar. This assumption may not be valid upon deeper examination.
- (b) The efficiencies of existing technologies may be degraded when applied to advanced energy sources owing to different operating conditions (e.g., saline waters of geothermal reservoirs and high metal content of solid waste fuel). This needs to be investigated in detail.
- (c) Ambient environmental conditions in the vicinity of advanced energy sources may be different in degree or in character from those present at more conventional sites, requiring more stringent controls to safeguard or maintain environmental quality (e.g., salinity in Colorado River Basin from oil shale development).
- (d) Standards for emission control for advanced energy sources may not be identical to those employed for other analogous conventional sources and therefore the estimated control requirements may be misleading. As pointed out in Section V, however, it is likely that new technologies can be brought into compliance with standards too strict for achievement by existing technologies.

Despite these inherent limitations in analysis, it is useful to have some idea of the capabilities and the applications of existing control technology to advanced energy sources as a guide to program planning.

Therefore, a preliminary assessment has been carried out. Three tables present the results of this initial assessment for energy from geothermal, oil shale, and solid waste sources. These advanced energy sources are included because their direct emissions could become locally important in coming years; solar energy is omitted because its effects are largely indirect. The tables illustrate the following points:

- (1) Geothermal Energy--No need for control of NH_3 or CH_4 emissions has been established, so the focus is on H_2S control. Table 15 presents some data relevant to the control of hydrogen sulfide from geothermal energy sources. Because refinery techniques to control H_2S are not applicable to a gas flow that is mostly steam, the operators of The Geysers power plant have had to try alternative means to remove the H_2S from the gas streams vented to the atmosphere. The 90 percent control indicated in the table has been achieved in tests at The Geysers but has not yet been applied to routine operations. Thus, the method of H_2S removal by catalyzed precipitation of sulfur is one developed explicitly for geothermal energy, but is not yet a completely demonstrated method. There is also reason to believe that the degree of control obtainable by this method may not be adequate to achieve the strict California standard for ambient concentrations of H_2S . While there are solid grounds for optimism regarding the eventual success of this control at The Geysers, there is no guarantee that it can be transferred to the more abundant, but less developed, wet geothermal resources.

Table 15

EMISSION AND CONTROL OF HYDROGEN SULFIDE IN GEOTHERMAL ENERGY PRODUCTION*

Case	Emission [†] Factor kg/GJ	Percent Control	Projected [‡] Annual Emissions 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
1. Comparison standard--one-half the mass of SO ₂ permitted from an oil-fired steam generator ¹	0.17	NA	1500	NA	NA	Coal fired comparison standard is 0.26 kg/GJ; ¹ Meeting California ambient H ₂ S standard may require emissions as low as 0.004 kg/GJ ²
2. Uncontrolled emission of H ₂ S at The Geysers ³ (dry)	0.2	0	1800	None	NA	
3. Emission of H ₂ S with control being developed at The Geysers ⁴	0.02	90	180	Scrubbing in cooling tower using iron or nickel to catalyze precipitation of sulfate as sulfur	May not meet ambient standard for H ₂ S ²	Final tests early in 1974; Commercial operation on new unit late in 1974; Solid product must be sold or sent to landfill
4. Uncontrolled H ₂ S from high sulfur wells in Imperial Valley ⁵ (wet field)	1.0	0	9000	None	NA	
5. H ₂ S from high sulfur well with some control ⁶	0.1	90	900	Scrubbing similar to that developed for dry steam at The Geysers	Transferability of control technology not assured	Serious effort on sulfur control awaits demonstration of power plant feasibility; Over 90 percent control could be required ²

NA = Not applicable

*Sources and notes are referred to by the superscripted numbers and are listed below.

[†]Emission factors are in kilograms per 10⁹ joules of thermal energy brought to power plant. Multiplication by 2.3 gives the factor in lb per 10⁶ Btu. Conversion from kilowatthours of electricity to gigajoules of thermal energy assumes a heat rate of 22 MJ/kWh (21,000 Btu/kWh or 16 percent thermal efficiency) for a geothermal plant. Table 6 shows how geothermal emission factors compare to fossil fuel emission factors on both a per unit heat and per unit electricity basis.

[‡]Total emissions of H₂S are projected on the basis of 4 x 10¹¹ kWh of electricity produced at about 16 percent efficiency from 9 x 10⁹ GJ of geothermal energy delivered to generating plants. This level of production is predicted for the year 2000 in Figure 1 and Table 5.

SOURCES AND NOTES:

1. Emission standards set by EPA for SO₂ from fossil fuel steam generators. Published in The Federal Register, 23 December 1971.
2. Appendix B of this report estimates a control requirement of 98 percent based on a comparison of a box model calculation of the ambient concentration of H₂S emitted by a 4500 MW geothermal generating capacity and the California ambient air quality standard for H₂S.
3. Calculated in Appendix B from data given by J. P. Finney, "Design and Operation of The Geysers Power Plant," in P. Kruger and C. Otte (ed.), Geothermal Energy: Resources, Production, Stimulation, p. 148 (Stanford University Press, Stanford, California 1973).
4. G. W. Allen and H. K. McCluer of Pacific Gas and Electric Company in "Fifth Progress Report to the Public Utilities Commission of the State of California: Geysers Hydrogen Sulfide Emissions Abatement Program" (28 December 1973).
5. M. Goldsmith, "Geothermal Resources in California--Potentials and Problems" EQL Report No. 5, p. 32, California Institute of Technology, Environmental Quality Laboratory (December 1971).
6. Assumes successful application of The Geysers control system to wet geothermal field.

- (2) Oil Shale--As indicated in Table 16, emission of SO_x , NO_x , and particulates are expected from oil shale operations. All retorting methods result in the formation of H_2S , and it is conceivable that sulfur will be emitted in this reduced form when it occurs in a gas of low heating value, as is the case in all but the indirectly heated (Class IV) retorts. Similarities between oil shale production and other industrial processes suggest the possible application of either desulfurization plants used in refineries or stack gas sulfur dioxide scrubbing plants envisioned for boilers. In either case, 90 percent control can be anticipated and may be adequate. However, both the performance and the adequacy problems regarding sulfur emissions from oil shale require further study.

Adequacy of the control depends on the comparison standard adopted. While the Interior Department environmental statement referenced in Tables 11 and 16 suggests some difficulty in meeting the relevant Colorado emission standards for sulfur, the EPA standards for fossil fuel boilers cited for comparison in Table 16 are not far from the uncontrolled emission factors. However, Table 16 should not be taken as an indication that there is no serious problem. In addition to the Colorado standards, there are two other criteria that suggest a substantial control need: (1) The calculation of ambient air quality cited as Source 10 in Table 16 implies that both substantial emission control and a very tall stack may be needed to meet the EPA primary ambient air quality

Table 16

EMISSIONS AND CONTROLS FOR AIR POLLUTANTS FROM OIL SHALE PRODUCTION*

Case [†]	Emission Factor [‡] kg/GJ	Percent Control	Projected [§] Annual Emissions 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Hydrogen Sulfide (H ₂ S):						
1. Comparison standard-- see comment	0.01	NA	40	NA	NA	SO ₂ emission standard for oil-fired steam generator ¹ divided by 2 for mass correction and by 17 to reflect more stringent odor standard for one- hour ambient concentration of H ₂ S ²
2. Uncontrolled Class II retort, internal com- bustion ³	0.08	0	320	None	NA	
3. Uncontrolled Class II retort, high temperature internal combustion ³	0.15	0	600	None	NA	
4. Uncontrolled in-situ retorting ⁴	0.2	0	800	None	NA	
5. Uncontrolled Class IV retort, indirectly heated ³	0.3	0	1200	None	NA	Off gas from this retort will not be emitted without combustion or desul- furization ⁵
Sulfur Oxides as SO ₂ :						
6. Comparison standard-- oil-fired steam generator ¹	0.35	NA	1400	NA	NA	Coal-fired comparison is 0.52 kg/GJ
7. Uncontrolled Class II retort, internal com- bustion ³	0.15	0	600	No desulfurization, only combustion converting H ₂ S to SO ₂	NA	
8. Proposed control of above Class II retort ⁶	0.015	90 ⁷	60	Stack gas scrubber after burning H ₂ S to SO ₂	Reliability and cost problems currently associated with stack gas SO ₂ scrubbers ⁸	Assumes adaptability of one of the SO ₂ scrubbing systems currently being developed or demonstrated ⁹
9. Uncontrolled Class II retort, high temperature internal combustion ³	0.3	0	1200	No desulfurization, only combustion converting H ₂ S to SO ₂	NA	
10. Proposed control of preceding Class II retort ⁶	0.03	90 ⁷	120	Stack gas scrubber after burning H ₂ S to SO ₂	Reliability and cost problems currently associated with stack gas SO ₂ scrubbers ⁸	Assumes adaptability of one of the SO ₂ scrubbing systems currently being developed or demonstrated ⁹
11. Uncontrolled in-situ retorting ⁴	0.4	0	1600	No desulfurization, only combustion converting H ₂ S to SO ₂	NA	

Table 16 (Continued)

Case [†]	Emission Factor [‡] kg/GJ	Percent Control	Projected [§] Annual Emissions 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Sulfur Oxides as SO₂ (Continued):						
12. Proposed control of preceding in-situ retort ⁵	0.04	90 ⁷	160	Stack gas scrubbing after burning H ₂ S to SO ₂	Reliability and cost problems with stack gas SO ₂ scrubbers ⁸	Assumes adaptability of one of the SO ₂ scrubbing systems currently being developed or demonstrated ⁶
13. Uncontrolled Class IV retort, indirectly heated ³	0.6	0	2400	No desulfurization, only combustion converting H ₂ S to SO ₂	NA	
14. Moderate desulfurization of Class IV retort off gas ⁹	0.06	90	240	Removal of H ₂ S prior to combustion to SO ₂	None identified	High (5 percent) H ₂ S content of off gas should make this level of control readily attainable; ⁹ This case, with tall (250 m) stack, is calculated to meet ambient SO ₂ standards ¹⁰
15. Colony Oil Co. design for desulfurization of Class IV retort off gas ¹¹	0.006	99	24	Low-pressure MEA (mono-ethanolamine) process to remove H ₂ S prior to combustion to SO ₂	Not yet demonstrated	Potentially an environmental advantage of Class IV retorts
Nitrogen Oxides as NO₂:						
16. Comparison standard--gas-fired steam generator ¹	0.09	NA	360	NA	NA	Oil-fired comparison is 0.13 kg/GJ; Coal-fired is 0.30 kg/GJ ¹
17. Maximum uncontrolled emission level ¹²	0.020	0	80	None	NA	
18. Maximum emissions, low control ¹²	0.016	20	64	Lime-slurry scrubbing	Insignificant degree of control	Not yet applied to oil shale
19. Minimum uncontrolled emission level ¹²	0.013	0	50	None	NA	
20. Minimum emissions, high control ¹²	0.003	75 ¹⁴	12	Combustion modification, especially two-stage combustion ¹⁴	Potential for causing incomplete combustion	Bureau of Mines tests on coal furnaces; ¹⁴ not yet applied to oil shale
Particulates:						
21. Comparison standard--fossil fuel steam generator ¹	0.04	NA	160	NA	NA	
22. Uncontrolled ¹⁵	0.1	0	240	None	NA	Hypothetical case
23. Minimum emission from anticipated processes other than TOSCO II retort ¹⁶	0.003	97 ¹⁷	12	Wet scrubbing, bag filters, dust suppression with water, separators integral to the oil production ¹⁸	None identified	

Table 16 (Continued)

Case [†]	Emission Factor [‡] kg/GJ	Percent Control	Projected [§] Annual Emissions 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Particulates (Continued):						
24. Maximum emission from anticipated processes other than TOSCO II retort ¹⁶	0.015	85 ¹⁹	60	Wet scrubbing, bag filters, dust suppression with water, separators integral to the oil production ¹⁸	None identified	
25. Maximum emission from anticipated processes including use of the Class IV TOSCO II retort with fluid-bed preheater ¹⁶	0.03	70 ¹⁹	120	Wet scrubbing, bag filters, dust suppression with water, separators integral to the oil production	Likely to be inadequate degree of control	

NA = Not applicable

*Sources and notes are indicated by the superscripted numbers and are listed below.

[†]The classes of retorts are those described in Appendix C.

[‡]Emission factors are in kilograms per 10⁹ joules. Multiplication by 2.3 converts the factor to lb/10⁶Btu. The energy unit in the denominator of the emission factor refers to the heating value of the oil produced, which is taken to be 40 GJ/m³ or 6 million Btu/bbl. The commercial plant size assumed throughout the Interior Department's environmental impact statement is 50,000 bbl/day, which amounts to an energy output in the form of oil equivalent to 13,000 GJ/hr. It should be noted that the comparison emission standards are expressed as mass per unit of energy input to a steam generator. A possible air pollution guideline for the oil shale industry would be to limit emissions at the production stage to a small fraction of those permitted at the combustion of the fuel.

[§]Projected annual emissions are based on the production level of 105 × 10⁶m³/yr (about 2 million bbl/day) given in Table 7 as an estimate for the year 2000. This is 4 × 10¹⁸ joules/yr as given in Table 2.

SOURCES AND NOTES:

1. EPA new source standards given in The Federal Register, 23 December 1971.
2. S. Williamson, Fundamentals of Air Pollution, p. 390 (Addison-Wesley Publishing Co., Reading, Mass., (1973) gives California ambient standard for one hour averaging time as 0.5 ppm for SO₂ and 0.03 ppm for H₂S.
3. U.S. Department of the Interior, "Final Environmental Statement for the Prototype Oil Shale Leasing Program," Volume I, p. I-18 (1973).
4. ibid., p. I-40.
5. ibid., p. I-19.
6. ibid., p. III-134.
7. Refinery experience indicates that 90 percent control cannot be achieved unless the tail gas from the desulfurization or sulfur recovery plant is itself cleaned by a separate process, probably SO₂ scrubbing. Reference: C. S. Russell, Residuals Management in Industry: A Case Study of Petroleum Refining, p. 165 (Resources for the Future, Johns Hopkins University Press, Baltimore, Maryland, 1973).

Table 16 (Concluded)

8. R. S. Greeley, "Status of Stack Gas Sulfur Dioxide Control," The MITRE Corporation (January 1973).
9. U.S. Dept. of Interior, op. cit., p. III-136.
10. ibid., p. III-146.
11. ibid., p. III-126.
12. ibid., p. III-129.
13. ibid., p. III-128.
14. G. A. Mills and H. Perry, "Fossil Fuel: Power and Pollution," Chemtech, January 1973, pp. 53-63.
15. Estimated to be over 30 times the controlled emission cited as Case 23. The reference of Case 23 gives no estimate of an uncontrolled emission factor.
16. U.S. Dept. of Interior, op. cit., p. III-133.
17. Reference 16 gives the emission factor, not the percent control. The percent control given here is an estimate based on expected performance of the controls described in Reference 16. This assumption is the basis for the uncontrolled emission factor given as Case 22.
18. U.S. Dept. of Interior, op. cit., pp. 122-123, 132.
19. Derived from ratio of this emission factor to that adopted in Case 22 as the uncontrolled emission factor.

standard for SO_2 ; (2) It is reasonable to expect that emissions from the production of a fuel can be reduced to only a fraction (perhaps a tenth) of the sulfur emitted by the burning of the fuel.

Table 16 indicates that the control needs for emission of NO_x and particulates are not as critical as those for sulfur emissions. By any emission criterion, even the requirement that emissions at the production stage be less than a tenth those at the combustion stage, the control technology indicated for NO_x in Table 16 will be adequate, if it is transferable to oil shale production processes. In the case of particulates, there appears to be a need for some reduction of the emission factor from the TOSCO II retorting process.

(3) Energy from Solid Wastes--The emission factors given above in Tables 13 and 14 were based on experience at the Combustion Power Inc. pilot plant and include the effects of the controls in use there. Table 17 presents a more general survey of both controlled and uncontrolled emissions from other methods of processing solid wastes. As far as air pollution is concerned, the Union Carbide pyrolysis process looks very promising. Also, the transferability of some incinerator control technology would be an asset. Appropriate demonstrations and tests of these technologies and their transferability merit immediate consideration.

3. Elements of a Research Program for Assessment of Control Technology

Based on the work performed during this study, the elements of a recommended research program for assessment of pollution control technology for advanced energy sources can be identified. These include the following:

- (1) Refining the estimates of control requirements for emissions, effluents, solid wastes, and land use by taking into account the characteristics of the regions where advanced energy sources will be developed.

Table 17

EMISSIONS AND CONTROLS FOR AIR POLLUTANTS FROM PROCESSES PRODUCING ENERGY FROM SOLID WASTES*

Case	Emission [†] Factor kg/GJ	Percent [‡] Control	Projected [§] Annual Emissions, 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Sulfur Oxides as SO ₂ :						
1. Comparison standard-- oil fired steam generator ¹	0.35	NA	1400	NA	NA	Coal fired comparison would be 0.5 kg/GJ ¹
2. Uncontrolled municipal incinerator ²	0.15	0	600	None	NA	Usually no SO _x control employed
3. Combustion Power Inc. gas turbine ³	0.1	33	400	Fluidized bed combustor	None	Easily meets standard because municipal refuse is a low-sulfur fuel
4. Garrett pyrolysis pro- duction of fuel oil ⁴	0.35	0	1400	None	NA	Emission factor, 0.1 kg/GJ at pyrolysis plant and 0.25 kg/GJ at combustion of oil; ⁴ assumes no control at the combustion of the oil; product oil is 0.3 percent sulfur by weight. ⁵
5. Union Carbide pyrolysis production of fuel gas ⁶	0.007	95	28	Scrubber with basic aqueous solution	None identified	Plant waste water requires treatment
6. New York City, tests ⁷ at 73rd St. incinerator	0.04	75	160	Medium energy wet venturi scrubber	None identified	Demonstration experiment, preliminary results
7. British incinerator experience ⁸	0.06	60	240	Wet collectors	Corrosion can be caused by HCl in the gas stream	
Nitrogen Oxides as NO _x :						
8. Comparison standard-- gas-fired steam generator ¹	0.09	NA	360	NA	NA	Other possible comparisons ¹ : oil-fired, 0.13 kg/GJ; coal-fired, 0.30 kg/GJ
9. Uncontrolled municipal incinerator ²	0.15	0	600	None	NA	Usually no NO _x control attempted
10. Combustion Power Inc. gas turbine ³	0.2	0	800	Fluidized bed combustor	Inadequate control	Model tests had indicated better NO _x control than demonstrated here
11. Garrett pyrolysis production of fuel oil ⁴	0.2	0	800	Liquid scrubber integral to the pyrolysis system; None at combustion of the oil	Inadequate control at combustion stage	Emission factor at pyrolysis plant is only a tenth of total (0.02 kg/GJ)
12. New York City, tests at 73rd St. incinerator	0.003	98	12	Medium energy wet venturi scrubber	None identified	Emission factor for N increased by factor of ten if emissions in reduced form as NH ₃ are included; preliminary results
13. British incinerator experience ⁸	0.05	67	200	Not indicated	Not indicated	Worst case has twice this emission factor

Table 17 (Continued)

Case	Emission Factor, kg/GJ	Percent Control	Projected Annual Emissions, 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Hydrocarbons as CH ₄ .						
14. Comparison standard--none exists		NA		NA	NA	Generally combustion is so complete that emissions from stationary sources are negligible
15. Uncontrolled municipal incinerator ²	0.08	0	320	None	NA	
16. Combustion Power Inc. gas turbine ³	0.015	80	60	Fluidized bed combustor	None	
Carbon Monoxide:						
17. Comparison standard--none exists		NA		NA	NA	Generally combustion is so complete that emissions from stationary sources are negligible
18. Uncontrolled municipal incinerator ²	2	0	8,000	None	NA	
19. Combustion Power Inc. gas turbine ³	<0.04	>98	<160	Fluidized bed combustor	None	
Chloride as HCl:						
20. Comparison standard--a British recommendation ⁶	0.2	NA	800	NA	NA	Maximum HCl content in flue gases recommended by The Alkali Inspector in Britain
21. Uncontrolled municipal incinerator ⁹	0.4	0	1600	None	NA	HCl emissions depend primarily on polyvinyl chloride content of the refuse
22. Combustion Power Inc. gas turbine ³	0.1	75	400	Fluidized bed combustor	None	Alkaline content in waste is presumed to absorb some HCl during the combustion
23. New York City, tests at 73rd St. incinerator ⁷	0.01	97	40	Medium energy wet venturi scrubber	None identified	Preliminary results
24. British incinerator experience ⁸	0.05	87	200	Wet collectors	Corrosion unless alkaline solution used	

Table 17 (Continued)

Case	Emission Factor, kg/GJ	Percent Control	Projected Annual Emissions, 10 ⁶ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Particulates:						
25. Comparison standard-- fossil fuel steam generator ¹	0.04	NA	160	NA	NA	Incinerator standard of 0.18 g/m ³ at 12 percent CO ₂ would mean a comparison standard of 0.08 kg/GJ ¹
26. Uncontrolled municipal incinerator ²	2	0	8000	None	NA	Most incinerators control 60 percent of this through settling chamber and water spray ²
27. Combustion Power Inc. gas turbine ³	0.08	96	320	Baffled settling chamber followed by two stages of cyclone separation, 6-inch and 3.5-inch	Clogging by molten ash deposits; inadequate control of fine particulates; this is best, not typical, control	Clogging alleviated by water injection; control of fine particulates in a high temperature (>700°C) gas stream is a significant problem in this and other processes
28. Garrett pyrolysis production of fuel oil ⁴	0.06	97	240	Cyclone separator followed by liquid scrubber are integral to pyrolysis system; bag filter used on cooled gas emitted at pyrolysis plant; control at oil combustion not specified	None identified	Emission factor at pyrolysis plant is 0.02 kg/GJ (99 percent control); oil combustion assumed to meet 0.04 kg/GJ steam generator standard
29. Union Carbide pyrolysis production of fuel gas ⁵	0.012	99.4	48	Electrostatic precipitator followed by scrubbing with basic aqueous solution	None identified	Pyrolysis furnace itself credited with 96 percent control; leaks at pyrolysis plant assumed negligible; emission only when cleaned product gas is burned
30. Chicago Northwest Incinerator ¹⁰	0.04	98	160	Electrostatic precipitator of 96.8 percent design efficiency	Somewhat lower flue gas temperature could result in corrosion of precipitator by condensed acids ¹¹	Electrostatic precipitator has potential for adequate control when temperature and content of flue gas permits its use
31. New York City, tests at 73rd St. incinerator ⁷	0.07	96.5	280	Settling chamber and medium energy wet venturi scrubber	None identified	Preliminary results
32. Coventry, England, incinerator ¹²	0.2	90	800	Electrostatic precipitator said to be 96.5 percent efficient	Inadequate control	
33. British incinerator experience ⁸	0.1	95	400	Usually electrostatic precipitators of 97 percent efficiency; A few cases of cyclone separators	Inadequate control	Mechanical collectors said to be 80 percent efficient and wet collectors 92 percent

Table 17 (Continued)

Case	Emission Factor, kg/GJ	Percent Control	Projected Annual Emissions, 10 ³ kg	Control Technology	Problems with the Control Technology	Comment/R&D Implication
Fine Particulates (<5 μ m):						
34. Comparison standard--none exists		NA		NA	NA	
35. Uncontrolled incinerator with a typical high fraction of fine particulates	0.5	0	2000	None	NA	Assumes 25 percent of mass consists of particulates < 5 μ m; consistent with British experience ^a and BAHCO analysis ¹³
36. Combustion Power Inc. gas turbine ³	0.08	84	320	Baffled settling chamber; 6-inch cyclone; 3.5-inch cyclone	Clogged by molten ash unless water injected	Represents best performance, typical may be only 60 percent control
37. SRI calculation	0.07	86	280	Two stages of 6-inch multicyclone	NA	Based on size distribution of case 35 and collection efficiencies cited by EPA ¹⁴

NA = Not applicable

* Sources are referred to by the superscripted numbers and are listed below.

[†]Emission factors are in kilograms per 10⁹ joules. Multiplication by 2.3 gives the factor in lb per 10⁶ Btu. The factors given have been calculated from values given in the references cited by assuming that each kg of solid waste is one-fourth carbon by weight and has a heat value of 9 MJ (4000 Btu/lb). It happens that the common incinerator emission unit of 1 gr/scf at 12 percent CO₂ converts to almost exactly 1 kg/GJ.

[‡]Percent control is calculated here by comparison to the uncontrolled emission given as the second case under each pollutant category. Actual measurements preceding and following the control devices used in the various cases cited would generally give a different value for control efficiency due to differences between each source and the average uncontrolled emission adopted.

[§]The total energy value of the solid wastes processed to recover energy is taken here to be 4×10^{18} J/yr. This is about 5 percent of present annual energy consumption in the United States and about 2 percent of that projected for the year 2000. Table 13 gives the energy value of solid waste expected to be processed for energy in 1975 as only 0.01×10^{18} J/yr.

SOURCES:

1. EPA emission standards for fossil fuel fired steam generators published 23 December 1971 in The Federal Register.
2. EPA, Office of Air Quality Planning and Standards, Compilation of Air Pollutant Emission Factors, Second Edition, p. 2.1-3 (April 1973).
3. R. H. VanderMolen, "Energy from Municipal Refuse through Fluidized Combustion: The CPU-400 Pilot Plant," paper presented at 66th Annual Meeting of AIChE, November 1973.
4. SRI study of the Garrett process.
5. R. W. Borio, "Combustion and Handling Properties of Garrett's Pyrolytic Oil," Final Report of Combustion Engineering, Inc., Project 900127, December 1972.

Table 17 (Concluded)

6. Private communication from R. S. Paul of Union Carbide Corporation.
7. E. F. Gilardi and H. F. Schiff, "Comparative Results of Sampling Procedures Used During Testing of Prototype Air Pollution Control Devices at New York City Municipal Incinerators," Proc. 1972 National Incinerator Conference, ASME, pp. 102-110 (1972).
8. R. H. Watson and J. M. Burnett, "Recent Developments and Operating Experience with British Incinerator Plant," ibid., pp. 155-165.
9. E. R. Kaiser and A. A. Carotti, "Municipal Incineration of Refuse with 2% and 4% Addition of Four Plastics," Department of Chemical Engineering, New York University, New York (June 1971).
10. G. Stabenow, "Performance of the New Chicago Northwest Incinerator," ibid., pp. 178-194.
11. F. R. Rehn, discussion of Stabenow paper, Discussions 1972 National Incinerator Conference, ASME, pp. 25-26 (1972).
12. N. Rayman and P. J. Scott, "Design of a Refuse Incineration Plant for the City of Coventry, England," Proc. 1972 N.I.C., op.cit., pp. 166-177.
13. Midwest Research Institute, "Particulate Pollutant System Study, Volume III-Handbook of Emission Properties," p. 523 (May 1971).
14. EPA, Office of Air Quality Planning and Standards, op.cit., p. A-3.

- (2) Surveying the existing control technologies that may be appropriate to the environmental impacts identified for the advanced sources.
- (3) Specifying the technical problems and limitations associated with these existing control technologies in new applications.
- (4) Analyzing the economics of the transferability of those control technologies from their present uses to advanced sources and the impact upon overall energy production costs.
- (5) Preparing detailed research and development program plans for control of pollutants from advanced energy sources.

V GENERAL RECOMMENDATIONS FOR CONTROLLING ENVIRONMENTAL IMPACTS FROM ADVANCED ENERGY SOURCES

A. Introduction

EPA is involved in research and development related to new energy technology in order to ensure that the goal of an adequate national energy supply is achieved with acceptable impact on the environment. From its extensive experience in observing, regulating, and ameliorating the adverse impacts of the several energy technologies currently dominant, EPA recognizes the considerable advantages of incorporating environmental protection measures into developing technologies rather than taking remedial steps after a technology is in use on a large scale. This consideration is especially important in the context of energy technology, because huge investments in long-life capital equipment are required. Although EPA is not in a position to develop the clean energy sources desired, it can ensure that those responsible for development give adequate consideration to environmental protection measures so that an environmentally acceptable product results.

The standard-setting authority of EPA has been essential to control the pollution from existing facilities and technologies. This authority, however, should not be reserved only for present pollution problems; it is perhaps even more useful in guiding the development of future technology. Experience with regulations concerning use of a retrofit device or an add-on process has shown that this approach is extremely expensive and usually achieves rather limited pollution abatement. Given appropriate and timely advance standards set by EPA, the producer of an energy technology can utilize his expertise to find the optimum way to meet the standards.

Provided that the standards reflect a proper balance between technological feasibility and environmental quality, the virtues of the early setting of a standard are apparent. Through monitoring, modeling, and studies of health effects, EPA is improving its knowledge of environmental quality requirements. Knowledge of the frontiers of relevant technology is required for the proper weighing of technical feasibility. One purpose of this report by SRI is to help meet the EPA need for such knowledge.

The contribution of EPA toward the goal of an adequate supply of clean energy goes beyond the setting of standards. Through projects concerned with the technology of the future, EPA has seized the opportunity to influence technological feasibility in the realm of pollution control. While standards are necessary to guide the design of energy technology, they can be expected to change with developing technology. One factor bringing about such change is EPA support for projects that may demonstrate the technical and economic feasibility of significantly higher standards.

B. Support for Improved Technology

It is within the mission of the Environmental Protection Agency to support research and development efforts to improve technology for the control of pollutants emitted by advanced energy sources. The subjects recommended in the next section (see Section VI-C-2) for inclusion in a research and development program involve such support, particularly where the present study has identified environmental impacts that are likely to be unacceptable if no more than current control measures are employed.

Support for the improvement of technology not designed primarily as control technology can also be justified as part of the mission of EPA when the new technology has the potential for improving environmental quality by supplanting a more polluting technology. Therefore, some of our recommendations call for supporting the development of certain elements of energy production technology that offer environmental advantages; those

in Section VI-C-3 pertaining to geothermal energy development fall in this category. Because the development of geothermal technology is also within the mission of other federal agencies (such as the Atomic Energy Commission and the National Science Foundation), further investigation by EPA may reveal that environmental goals are already being adequately served without the need for direct EPA involvement at the present time.

Recommendations given in Section VI-B pertaining to solar energy, underground coal gasification, and hydrogen as an energy carrier, have implications for eventual EPA support of new energy production technologies.

C. Support for Demonstration of Economic Viability

Although the technical work on advanced energy sources and control of associated environmental impacts is important, it is equally important to demonstrate conclusively the economic viability of technical accomplishments. It would be of little use to prove that some technique, apparatus, or material would result in complete pollution control if the related costs are so great that they preclude deployment.

To overcome the uncertainties of the costs of a particular pollution control scheme, a demonstration in an operational situation is often necessary. While no economic demonstration activity is explicitly recommended in Section VI, such demonstrations would logically follow the technical work suggested. Of course, the government or its contractors should not replace the private sector in determining the economic viability of a new process. However, it seems apparent that EPA can and should bring some technologies to the stage where the private sector has a clear incentive to pursue the demonstration of economic feasibility. An incentive could be supplied through enunciation of standards, but in many cases, legal or practical considerations may, instead, lead EPA to support some demonstrations of economic viability prior to the setting of standards.

D. Use of Standards at Various Stages of New Technology

The use of standards that set the limits of allowable pollutants resulting from industrial activities is widespread and enforcement of these standards provides the major incentive for industry to undertake environmental protection measures. Thus, through the use of standards, EPA is indirectly bringing the expertise of industries to bear on solution of their own pollution problems. This approach, therefore, multiplies the effort going into the development of environmental protection technology.

Some specific areas where new or revised standards could be useful in reducing adverse effects of energy production are listed in Section VI-C-1. To stimulate successful environmental protection measures effectively, the standards must be formulated sufficiently early that improvements can be incorporated efficiently into the design of technologies. The standards must also be strict enough to prevent undesirable effects when a small industry scales up to become a mature industry fully exploiting the available resources. There is, of course, no guarantee that technologies compatible with existing technologies will also be adequate to prevent undesirable effects from eventually occurring. However, the chance of achieving both goals is greater for a completely new technology than for one already frozen in a particular pattern. The earlier the interaction between the requirements of environmental quality and the technical constraints, the more likely that a successful resolution will occur. Recommendations in Section VI-C-1 call for the initiation of the studies needed to set adequate environmental protection standards. As the advanced energy technologies proceed through the anticipated stages of their development towards deployment, somewhat different considerations (indicated in the sections that follow) will prevail.

1. Development

During the development stage of the technology to obtain energy from advanced sources, it is appropriate to use existing standards applicable to related industries as guidelines. This procedure will avoid both the premature constriction of a new technology and the waste of EPA resources on insignificant sources of pollution. Such comparisons to formal standards for related processes are made at various points in this report.

A key purpose of development operations should be to determine the species and quantity of pollutants released so that approaches to their control can be devised. Some of the recommendations for further research, listed primarily in Section VI-C-4, are directed toward this goal.

Formal guidelines or standards are desirable to facilitate the incorporation of environmental protection into the design and cost assessment of developing energy technologies. But the need for an early enunciation of the standard sometimes conflicts with the need to avoid the establishment of a misleading guideline. Erroneous standards, if too strict, can unduly discourage promising techniques or, if too lenient, unduly encourage an environmentally unsound technology. Until the data can give confidence that the right balance between environmental, economic, and technical considerations can be struck, extrapolations from existing standards provide the best guidelines.

2. Early Commercial Operation

The term "commercial" implies that a technology has developed to the point that an operator has decided to deploy the technology in the belief that it will prove economically feasible. Whenever deployment results in undesirable environmental consequences that cannot be mitigated

without the imposition of an economic penalty that destroys the feasibility of the project, it can be concluded that there has been a failure in the environmental management at the technological development stage. In recognition of its responsibility to help prevent this kind of failure, EPA is pursuing studies such as this one.

Reaching the early commercial stage implies that technical and economic uncertainties have been overcome sufficiently to attract some investment capital. Uncertainties regarding environmental impact also should have been reduced substantially by experiments performed during the development stage. These experiments can provide a basis for further reducing environmental and economic uncertainties and for the setting of specific standards to be met by the new technology. However, the fact that the deployment of the new technology is still very limited at this stage makes it possible to allow the first commercial plants to temporarily exceed the standards that will eventually be needed to accommodate a mature industry based on the new technology. To minimize uncertainty at this stage, promulgation of a standard based on present feasibility for the early commercial installations is needed together with some formal indication of the standard that is expected to be met by the eventual full sized industry. Subjects recommended for standard setting activities are listed in Section VI-C-1.

3. Significant Scale Operation

The advanced energy sources considered in this report will not be major contributors to the national energy production before the end of this century (see Section IV). However, local or regional environmental effects of the new energy technologies will be appreciable during the 1980's. During the decade of the 1980s, EPA will most probably be concerned with setting standards applicable to new energy technologies

operating at significant scales of production. As a result of anticipating attention to the development of these new technologies, EPA may find that the requirements of environmental protection are consistent with technical and economic feasibility.

E. Strategy for Dealing with Indirect Impacts

Besides direct impacts, there can be many indirect environmental consequences. Most recommendations in Section VI are in response to identified direct environmental impacts. However, as emphasized in the summary of solar energy (Section IV-A), most of the environmental impacts of that technology are indirect. The distinction can be put as follows:

- Direct impacts result from activities comprising the sequence of operations leading to energy production (e.g., mining, crushing, retorting, and disposing of oil shale).
- Indirect impacts have their environmental effect at the site of other activities required to support the advanced energy development (e.g., emissions from the smelting of copper to be used in the construction of rooftop collectors of solar energy).

Recommendations for research and development related to the control of indirect impacts appear primarily in Sections IV-A and VI-B-1. These recommendations include a suggestion for the establishment of communications links with the developers of solar energy technology and for viewing existing new source standards as controls on the indirect impacts of solar energy.

Through communication with the developers of solar energy, EPA can work to minimize the indirect impacts of the eventual technology by directing attention to the environmental effects of activities such as the production of materials and shifts in population. The existing liaison between EPA and NSF, the federal agency with principal responsibility for

solar energy development, has already been used to initiate such communications. Recommendations in Section VI include calls for communication with developers of technology for the use of hydrogen and underground coal gasification, but these activities have a lower priority than solar energy.

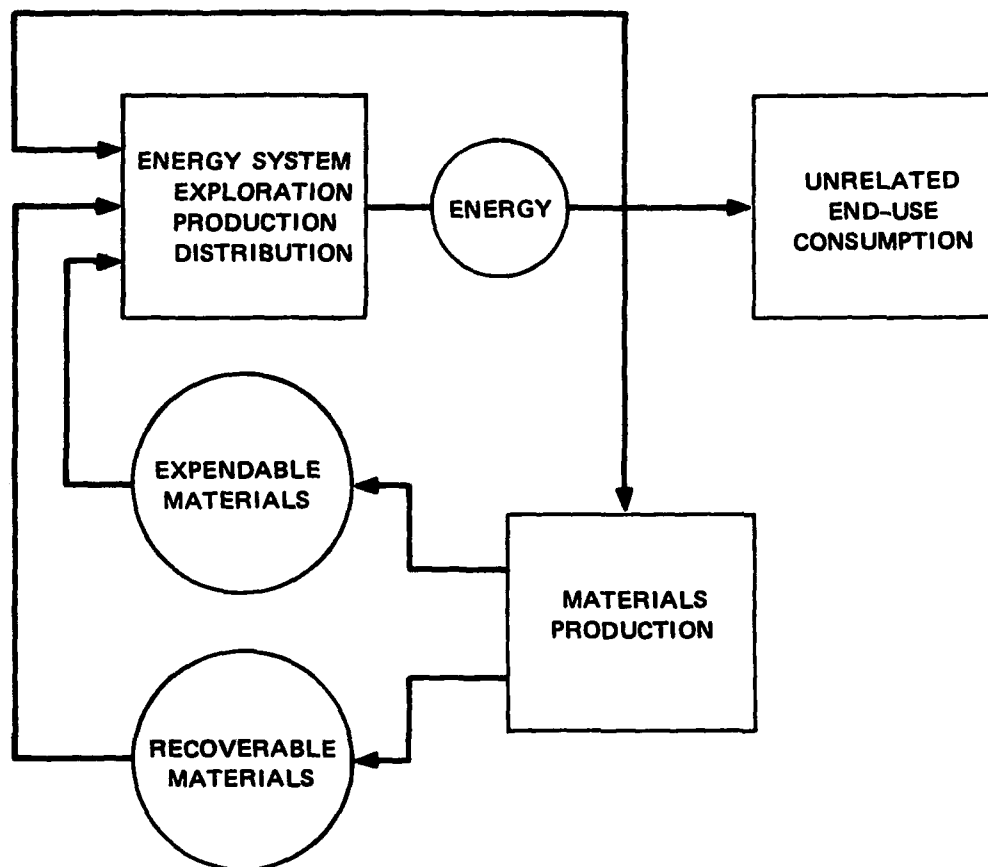
Through the formulation and enforcement of standards for new sources of emissions and effluents, EPA has a means of controlling indirect, as well as direct, impacts of new energy technology. To cite again the solar energy example, the deployment of solar energy collectors on a significant scale will appreciably increase the demand for certain materials and will therefore necessitate the expansion of the industries producing these materials. Appreciable expansions are subject to the standards for new sources of pollution, once EPA has promulgated them for a particular industry or process.

A third recommendation for dealing with the indirect impacts of advanced energy technologies is presented in the separate section below. This is the recommendation regarding the use of the energy efficacy concept.

F. Energy Efficacy as an Indicator of Environmental Impact

1. The Concept

Except for acts of philanthropy, the economic system is based on the concept of profit; only those endeavors that generate monetary return in excess of investment are pursued. This principle has an analog in energy economics; in order to remain viable, energy systems must generate more net energy than they themselves consume in all the steps of their operations. The use of energy by an energy resource system is illustrated in Figure 3. As long as mankind is capable of locating and extracting



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FIGURE 3 ENERGY SYSTEM

fossil fuels, it is not difficult to maintain an apparent status of net energy gain in return for exploration, development, extraction, and refining activities. This situation, however, is somewhat analogous to withdrawing money from the bank and pretending it is wages. Nature has stored energy resources upon which mankind is now drawing.

In anticipation of the future, when mankind may be forced to draw upon an "income" energy resource (such as solar), it is important to develop an index that reveals whether an energy collection technology is generally worthy of development, an index that takes into account all direct and indirect impacts.

Energy efficacy, defined here as the ratio between the net usable energy output and the sum of all required energy inputs, can be used to evaluate the value of a given technology. The greater the energy efficacy coefficient, the greater the profitability of the technology (measured in energy terms). The energy efficacy equation is

$$\text{Energy efficacy} = \frac{\text{Energy available for unrelated use}}{\text{Energy consumption related to energy system}} .$$

Technological options should obviously be pursued among only those technologies with an energy efficacy index greater than 1.0 (the break-even point). If it were found, for example, that a certain solar energy technology system were to require an expenditure of more energy in its production and operation than it could collect and make available during its lifetime, then it could be concluded, justifiably, that the technology must be improved or abandoned.

In the computation of the energy efficacy coefficient, it is essential to draw the system boundaries realistically enough to include all the truly important energy inputs. A complete vertical analysis is required. For example, if an energy technology consumes steel, then it is important to include not only the energy required for steel making and metal forming, but also the energy expended in mining and transporting the necessary iron ore, coking coal, and limestone. Vertical analyses generally reveal that the indirect energy consumption greatly exceeds the obvious direct energy consumption.^{10,11} For instance, although Alcoa reports¹² that present day aluminum production requires about 22 kWh/kg, a vertical analysis has shown that the total energy input into aluminum is about 80 kWh/kg.¹⁰

It may seem that evaluation in energy units would be redundant to an evaluation in monetary terms and that to determine the energy efficacy of a given technology would require only the application of a conversion factor. Unfortunately, there are at least two reasons why no simple conversion is possible. First, the amount of labor required for different technological systems varies widely. For example, a petroleum refinery exhibits a high degree of automation, while silicon solar cells currently require manual assembly. Second, there are major differences throughout the economy in the price of energy;¹³ these depend upon the type of energy, the volume of purchase, corporate arrangements, and regulatory factors. Consequently, the apparent redundancy between monetary and energy measure is, in fact, largely illusory. In fact, the lack of proportionality between monetary and energy measurement scales can obscure the potential of some energy technologies that appear too expensive in monetary terms, but which actually yield a good return on energy investment.

It has, nevertheless, recently been possible to convert the monetary input/output matrix of the U.S. economy (for 1963) into an energy input/output matrix by giving attention to the complicating factors mentioned.¹³ The energy input/output matrix currently available can be used to trace the flow of energy between energy sectors of the economy. An energy sector submatrix of the U.S. economy is shown in Table 18. From these numbers and ancillary information,¹³ it is possible to determine roughly the energy efficacy of three of the most important contemporary basic energy resource technological systems--coal, petroleum, and gas (see Table 19). The efficacies for these contemporary technologies are surprisingly low, especially for petroleum and gas. The reasons behind these low efficacy figures are difficult to itemize fully. However, much of the energy consumed by these energy systems goes to functions that are easily overlooked, such as the function of providing ventilation in

Table 18

ENERGY INPUT/OUTPUT SUBMATRIX OF THE U.S. ECONOMY*
(1963)

<div>Seller Buyer</div>	Coal Mining	Petroleum Refining	Electric Utilities	Gas Utilities
Coal mining	9.7	2.7	1.4	2.0
Petroleum refining	41	250	14	200
Electric utilities	90	35	47	49
Gas utilities	6.8	15	1.9	150

* All energy is expressed in units of TWh (10^{12} Wh) to two significant figures.

Source: Herendeen¹³

Table 19

ENERGY EFFICACY COEFFICIENT FOR CONVENTIONAL
TECHNOLOGICAL SYSTEMS

System	Efficacy	Comment	Source
Coal mining	42	Excludes energy required for delivery to final demand.	Reference 13
Petroleum refining	4.8	Excludes energy required for delivery to final demand.	Reference 13
Gas utilities	5.9		Reference 13
Nuclear fission reactors (LWR)	< 32	Based entirely upon energy consumed by gaseous diffusion isotopic enrichment of fuel.	References 14, 15

underground coal mines. The situation is likely to be similar for underground oil shale mines.

The energy input into materials expended in resource recovery is even more easily overlooked. For example, steel casings routinely used by the petroleum industry to line oil wells or geothermal wells represent a sizable investment in an energy intensive material that is often unretrievably expended. An analogous situation can be found in underground coal mining where steel bolts designed to prevent roof collapse are frequently left behind after the deposit has been mined out. A representative, but incomplete listing of important energy inputs to conventional energy industries is given in Table 20. Of course, an important distinction must be made between materials that are consumed by the energy system in a fashion that does not allow their ultimate recovery for recycling or reuse (such as the steel casings in an oil well) and materials that are recoverable in the future (such as the steel in an oil refinery). It is therefore significant, for example, that in terrestrial solar energy installations, there will be only a negligible amount of material expended irretrievably. In a sense, therefore, the vast materials demands of solar energy collectors are "deposits in a materials bank" that could possibly be withdrawn later for reuse.

Data sufficient to determine the energy efficacy coefficient for nuclear fission is apparently uncollected, but an upper limit is readily obtained by consideration of only the isotopic enrichment of uranium in the nuclear fuel cycle. This limit is shown in Table 19.

One of the most important uses of the energy efficacy coefficients for conventional energy resources will be as a conceptual design guideline for the development of new energy technologies. The American economy can clearly function using energy efficacy indexes as low as about five (see Table 19). Thus, new energy technologies should ultimately

Table 20

ABBREVIATED LIST OF IMPORTANT USES OF ENERGY
AND ENERGY INTENSIVE MATERIALS IN CONVENTIONAL
ENERGY TECHNOLOGY SYSTEMS

System	Energy Use	Materials
Coal (underground)	Elevators Ventilators Conveyors Crushers Boring machines Hauling	Steel for roof control Steel for rails
Petroleum	Drilling (includes dry holes) Crude oil pumping Pipeline pumping Hauling Refinery process heat	Steel for well casings Drilling clays Tetraethyl lead
Nuclear fission reactors (LWR)	Uranium mining Isotopic enrichment Pumping of heat- transfer fluid Pumping of power- plant coolant	Fuel rod cladding Isotopic separation membranes Radioactivated materials used in processing and structures

be viable and the general economy should be sustainable if they can meet or exceed the indexes of petroleum and gas. As an example, upper limits to the energy efficacy index for the various forms of solar energy have been estimated, based upon the considerations given elsewhere in this report. These are given in Table 21. Although it must be emphasized that the true efficacy will be lower than these estimates because many factors have been neglected, it can be concluded that a satisfactory performance for certain solar energy technologies is probably attainable.

Table 21

ESTIMATED UPPER LIMITS TO THE ENERGY EFFICACY
COEFFICIENT FOR SOLAR ENERGY TECHNOLOGIES*

System	Energy Efficacy Coefficient [†]	Comment [†]
Energy plantations	< 3	Electric output. American Southwest. Assumes three crops per year, field drying, and combustion to generate electricity. Energy costs of providing inter basin water transfer for irrigation are included.
Ocean thermal gradients	< 15	Electric output. Considers only energy input into material (aluminum) for boiler, condenser, and cool water intake conduit.
Photovoltaic system (large satellite)	< 6	Electric output. Published projections revised to account for indirect energy inputs into materials.
Photovoltaic system (large terrestrial)	< 27	Electric output. Considers only total energy input to aluminum support structure for solar cell array.
Thermal system (large plant)	< 55	Electric output. Considers only total energy input to aluminum support structure (which may form part of collector) and double glazed glass cover.
Thermal system (small plant, on buildings)	< 56	Heat output. Considers only total energy input to copper rooftop collector and double glazed glass cover.

* Thirty-year installation lifetimes are assumed.

[†] Consideration of additional energy inputs necessarily reduces the energy efficacy coefficient.

2. Environmental Implications

It is now clearly discernable that energy extraction, transportation, processing, storage, distribution, and consumption activities are the most significant sources of environmental degradation in the United States. This fact, unfortunately, is not widely appreciated; dissemination of the recent document entitled "Energy and the Environment--Electric Power" by the Council on Environmental Quality¹⁶ is intended to convey this message to the public.

Besides its obvious utility as a measure of the value of new energy technologies, the energy efficacy coefficient should prove to be an important indicator of environmental impact. The evidence is abundant (but disorganized and dispersed) that the path of least energy consumption is also the path of least disruption and insult to the environment. Cognizance of this principle is implicit in an Oak Ridge National Laboratory analysis of the resource recovery issue in waste management that pointed out the many concomitant opportunities for energy conservation and environmental quality preservation raised by well designed recycling programs.¹⁷ The principle should be no less true for energy technologies themselves.

By use of the energy efficacy coefficient, for example, one could infer that solar energy technologies will create significant, although indirect, environmental impacts irrespective of the often-cited claims to the contrary articulated by solar energy advocates. Besides its use as a macroscopic indicator that could be used to rank the desirability--in environmental terms--of new energy technologies, the very same vertical analysis categorizing the energy inputs necessary for the derivation of the energy efficacy coefficient would provide a firm base for the compilation of indirect environmental consequences. Considerable further work is required, however, in order to perfect the concept and permit it to be employed as an analytical tool to guide decision making.

3. Implications for EPA Activities

As part of its evolution to an agency that anticipates events and influences developments important in the environmental arena, EPA might find it worthwhile to sponsor further research to determine the energy efficacy coefficient for present and future energy technologies. In addition, EPA could detail the relationship between impairment of environmental quality and energy utilization, and thereby document the usefulness and significance of the energy efficacy concept as an indicator of environmental impacts. EPA could develop a methodology to incorporate the energy efficacy concept into the planning process. Success in this endeavor would logically be followed by development of an analogous "energy utilization" coefficient that would be applicable to any existing or proposed technological system. Use of this latter coefficient could be expected to yield results important for the ordering of EPA priorities and environmental quality control.

VI RECOMMENDATIONS FOR ADVANCED ENERGY RESEARCH AND DEVELOPMENT PLANNING

The analyses of advanced energy sources (summarized in Section IV and detailed in the Appendices) resulted in a number of specific recommendations for further research and development. These recommendations are compiled in this section and classified by type and priority. They can be used to define the elements of a future research and development program.

A. A Listing of Control Requirements

This study of advanced energy technology has led to the identification of some areas where controls should be required to prevent unacceptable effects on the environment. These areas are listed below under the energy sources in the order in which the sources appeared in Section IV.

1. Solar Energy

Because solar energy technologies appropriate for large-scale use are currently less clearly defined than others under consideration, and, moreover, because their environmental impacts are generally indirect, the following items are not strictly analogous to the entries in other categories. Control requirements should include:

- Development of design guidelines concerning materials likely to be used in solar energy collections to ensure
 - Minimum consumption.
 - Avoidance of materials that may release toxic substances when eroded by long exposure to the natural environment.

- Selection of materials that require the least energy in their production.
- Avoidance of the use of scarce elements (e.g., Ga).
- Choice of materials that can be recycled easily upon normal retirement or breakdown.
- Development of operations guidelines and initiation of legislation or precedent-setting case law in areas concerning
 - Land use.
 - Solar energy collection in international waters.
 - Releases of hazardous materials in accidents (especially for ocean thermal gradient installations).
 - "Sun rights" (analogous to mineral rights).

2. Geothermal Energy

Control requirements for geothermal energy should include :

- Substantial reduction of hydrogen sulfide emissions from dry steam field at The Geysers.
- Isolation of geothermal brine by means of closed-cycle generating systems.
- Prevention of ground-water contamination during reinjection of geothermal fluids.
- Treatment or reclamation of saline geothermal waters.
- Reduction of need for fresh cooling water in dry regions.
- Land use consistent with noise, subsidence, construction, and depletion associated with development of a geothermal energy field.

3. Oil Shale

Control requirements for energy production from oil shale should include:

- Rehabilitation of spent shale disposal sites to a state consistent with land-use plan and by means consistent with water supply.

- Isolation of process water from fresh-water system (realizing "zero-discharge").
- Sulfur dioxide control: emission of the gas itself and possible leaching if it is absorbed in shale residue in Union A or Lurgi-Ruhrgas retorts.
- Reduction of oxides of nitrogen emissions according to need determined by final forms of both air quality standard and retort technology.
- Reduction of effluents and emissions that are also produced in conventional refineries to levels consistent with standards for refineries.
- Minimization of consumptive use of water.

4. Energy from Solid Wastes

Control requirements for energy production from solid wastes should include:

- Monitoring or treatment to control pH and other content of leachate from ash residue.
- Removal of gaseous sulfur compounds to meet emission standards comparable to requirements that sulfur content of coal be significantly below one percent.
- Monitoring and possibly reducing emission of vapors and volatiles such as hydrogen chloride, mercury, and partially oxidized organic compounds.
- Removal of particulates from exhaust stream as required to meet standards.
- Reduction of particulate surface area available to adsorb carcinogens and other toxic substances.
- Removal of hydrogen sulfide produced in anaerobic digestion processes.
- Disposal of sour digester residue.
- Conventional control of dust, noise, and odor.
- Treatment or dilution of quench water.

5. Underground Coal Gasification

Control requirements for energy production from solid wastes should include

- Prevention of water pollution similar to acid mine drainage caused by entrance of ground water into coal seam depleted by gasification.
- Assurance that land use and structures are consistent with possible subsidence of surface above depleted seams.
- Removal of hydrogen sulfide from gas stream at surface.
- Protection of adjacent mineral resources from explosive fracturing proposed in some concepts.
- Location of deep seams unquestionably isolated from air and ground water.

6. Hydrogen as an Energy Carrier

Before use of hydrogen as a fuel increases substantially, significant changes in production and consumption technologies are likely. Control requirements should include:

- Establishment of emissions and effluent standards covering the materials suggested for use in high efficiency electrolyzers, high temperature thermal decomposition of water, and fuel cells.
- Establishment of design guidelines to steer development away from selection of materials that require large amounts of energy or that have large known detrimental environmental impacts during their production processes.

B. Subjects for Research and Development

The control requirements imply the need for various types of research and development. SRI has identified a number of such needs as a result of this study. They are listed below, again organized under the energy technologies presented in this report.

1. Solar Energy: Continuous Review of Solar Energy Development

A continuing effort should be made to influence the course of development of solar energy technologies so that they conform to EPA guidelines (suggested above in the list of control requirements) established to minimize the need for remedial measures.

2. Geothermal Energy

Subjects for research and development should include:

- (a) Emission standard for hydrogen sulfide. Environmental impact analysis (including modeling and comparisons) should be continued in order to set and justify an emission standard for hydrogen sulfide from geothermal power plants.
- (b) Hydrogen sulfide emission control technology. Experiments on hydrogen sulfide control at The Geysers should be continued. Problems encountered in two attempted processes--catalyzed solution as sulfate and catalyzed precipitation as elemental sulfur--should be identified and new techniques should be devised.
- (c) Closed-cycle geothermal plants. A binary cycle generating plant employing heat exchange from the geothermal brine should be developed because of its potential for using high salinity sources without producing effluents and emissions.
- (d) Turbogenerators driven by liquid geothermal brine. The exploitation of hot water and geopressured resources would be facilitated by the existence of a turbine using both the pressure and heat energies of both the liquid and steam supplied by hot water dominated geothermal reservoirs.
- (e) Geological site survey techniques. The methods now used to determine the geological structure and resources of a site should be studied to assess their adequacy for environmental protection and to identify ways to decrease the cost of adequate surveys.
- (f) Reinjection of geothermal brine. The potential for contamination of ground or surface waters during reinjection operations should be assessed. Ways to improve this vital technology should be identified.
- (g) Treatment and reclamation of saline water. Nearly all geothermal fluids will contain too heavy a burden of dissolved solids to be injected into a local water stream. Because it represents an alternative to reinjection and a potential source of water and minerals, the technology for treating saline geothermal water should be investigated.

- (h) Cooling systems for semi-arid regions. The low thermal efficiency of geothermal power plants, the relatively low condenser discharge temperature, the high salinity of most geothermal liquids, and the limited fresh water supply at most western geothermal sites combine to complicate the disposal of waste heat from a geothermal power plant. Existing technology and new concepts should be studied, both as an aid in the development of the energy resource and as an important step in the control of adverse environmental impacts.
- (i) Standards (guidelines) for land use. Environmental effects due to the noise, land subsidence, construction, and eventual retirement of facilities associated with geothermal power production can best be controlled through wise land use planning. The criteria for such planning should be formulated.

3. Oil Shale

Subjects for research and development should include:

- (a) Rehabilitation of disposal areas. The land used for disposal of spent shale wastes should be rehabilitated in a way consistent with water supply limits and land use criteria. Additional study is recommended.
- (b) Water pollution from shale wastes. Monitoring and modeling work is needed to quantify the effects of various shale disposal techniques on water quality.
- (c) Treatment and reclamation of saline water. Both runoff water from shale disposal areas and process water from oil production may be subjects for treatment. The available techniques should be evaluated.
- (d) Evaluation of the zero-discharge criterion. It is said that oil shale will be produced by methods that prevent process water from reentering the fresh water system. Before development proceeds much further, the practicality and the necessity of this zero-discharge assumption should be tested.
- (e) Emissions from in-situ retorting. Some in-situ methods may prove viable. These methods should be identified, their emission factors determined, and the control need and potential studied.

- (f) Sulfur dioxide control. Methods of controlling sulfur dioxide emissions from oil shale retorts must be demonstrated. An intermedia effect that needs study is the possible leaching of sulfur dioxide absorbed in the shale residue in some retorts.
- (g) Refinement of estimates of emission factors for retorts. To determine control requirements, more accurate knowledge of emission factors for the most promising retorts is needed.
- (h) Application of refinery pollution control techniques. The transferability and the adequacy of applying conventional refinery emission and effluent control techniques to the upgrading of crude oil from shale should be investigated.
- (i) Application of control techniques from coal processing. The potential for applying methods used to control wastes and emissions in coal processes, especially coking and gasification, should be assessed.
- (j) Alternatives to consumptive use of water. There will be economic incentives for the oil shale industry to avoid a production limit set by water availability. Therefore, EPA should be aware of the alternatives to consumptive use of water and evaluate the environmental assets and liabilities of these alternatives.
- (k) Geological site survey techniques. Knowledge of the geology of the site is a crucial element in protecting the environment from potential adverse impacts from any in-situ process.

4. Energy from Solid Wastes

Subjects for research and development should include:

- (a) Data on exotic pollutants. An assessment should be made of the possibility that incineration and pyrolysis of man-made materials can result in unacceptable emissions of exotic pollutants--metals, hydrogen chloride, carcinogenic compounds--for which no emission standards exist. Upper limits of the emission factors for such pollutants should be determined by measurements of the quantity and composition of emissions from existing demonstration plants.

- (b) Determination of emission factors. The adequacy of the data on emissions now being obtained at demonstration plants for converting solid waste to energy should be assessed. If monitoring of the emissions at these plants is inadequate to lead to the setting of standards and control requirements, monitoring programs should be revised.
- (c) Emission standard for fine particles. The facts that (1) smaller particulates have greater surface area per unit of mass, (2) most heavy molecules of low volatility (the metals and carcinogens) pass into the atmosphere adsorbed to the surface of particulate matter, and (3) the smaller particles are more effective per unit mass in decreasing visibility, suggest the need to consider a standard tied to the surface area of particulate emissions.
- (d) Water pollution from ash disposal. The local conditions determining the water pollution potential of leaching from incinerator ash residue should be identified and quantified.
- (e) Treatment of process water. The assumption that standard water treatment (secondary) should be adequate to control pollution from quench and scrub water should be verified. The implications for choosing sites for solid-waste energy facilities should be made explicit.
- (f) Cleaning the pyrolysis gas. The economic and environmental consequences of scrubbing pyrolysis gas before it is mixed with air for combustion should be determined. The emission factors for combustion of pyrolysis gas, at or away from the site of the pyrolysis, should be measured and correlated with the scrubbing process used.

5. Underground Coal Gasification

Subjects for research and development should include:

- (a) Geological site survey techniques. The prevention of pollution from an in-situ process requires knowledge of the geology of the site. The methods now used to determine the geological structures and resources of a site should be studied to assess their adequacy for environmental protection and to identify ways to decrease the cost of adequate surveys.

- (b) Eventual monitoring of tests. After initial tests on site have confirmed the promise of an in-situ gasification technique, monitoring of emissions at the surface and effects on water quality underground should be carried out in order to set standards and determine control requirements. Some baseline data at the site will be required for a proper monitoring program.
- (c) Periodic review of the technology. To ensure that adequate environmental protection measures are incorporated in the development of underground coal gasification, a periodic review of this development should be carried out. Should environmental or economic attractiveness imply a more rapid move toward deployment of some in-situ technology, a continuing review would be desirable.

6. Hydrogen as an Energy Carrier: Periodic Review of the Technology

To ensure that adequate environmental protection measures are incorporated in the development of hydrogen for energy storage and transportation, a periodic review of this development should be carried out. Should environmental or economic attractiveness imply a more rapid move toward deployment of hydrogen technology, a continuing review would be desirable.

C. Classification of the Recommendations

The subjects just listed call for several types of research in support of several different methods of improving environmental quality. It follows that actions related to the research needs listed here will not be the responsibility of any one division within EPA. In order to facilitate the channeling of these recommendations within EPA and to make explicit the different categories of these recommendations as envisioned by SRI, the subjects for research and development are listed below according to the nature of the recommendation and the media (air, water, or land) most directly involved. It should be noted that some environmental effects defy the air-water-land categorization and that virtually all

environmental problems have intermedia aspects. In this listing by type, each title is followed by an indication of the primary medium involved and the subsection designation [1, 2(a), 2(b)] from Section VI-B.

The recommended subjects for research and development are classified below according to the type and goal of the research.

1. Formulation of Performance Standards or Guidelines

This work involves the derivation of quantitative standards for emissions, effluents, or land use on the basis of (1) considerations of environmental quality, and (2) anticipated levels of development of the sources of environmental impacts. Such standards would be based solely on environmental impact analysis and, therefore, as pointed out in Section V-A, would be subject eventually to considerations of technical and economic feasibility.

The following is a list of the titles and section numbers of the recommendations that call for information and analysis leading to the formulation of standards or guidelines:

- An emission standard for hydrogen sulfide from geothermal power plants [AIR, 2(a)].
- Standards (guidelines) for land use in geothermal fields [LAND, 2(i)].
- Rehabilitation of disposal areas for spent oil shale [LAND, 3(a)].
- Evaluation of the zero-discharge criterion for oil shale processing [WATER, 3(d)].
- Sulfur dioxide control in oil shale retorting [AIR, 3 (f)].
- Emission standards for fine particles from solid waste energy producing processes [AIR, 4(c)].
- Continuous review of solar energy development [ALL MEDIA, 1].

2. Development of the Technology to Control Certain Emissions and Effluents

The preliminary analysis carried out as part of the present study has identified certain environmental impacts of advanced energy sources as likely to be unacceptable and, therefore, as requiring a higher degree of control than now being employed. These are areas where promising control technologies should be identified and their development supported.

The following recommendations by SRI are directed toward the realization of adequate control technology:

- Develop hydrogen sulfide emission control technology for geothermal power plants [AIR, 2(b)].
- Develop treatment and reclamation of saline water associated with both geothermal and shale-oil energy production [WATER, 2(g) and 3(c)].
- Develop sulfur dioxide control in oil-shale retorting [AIR, 3(f)].

3. Development of New Energy Technology Having Apparent Environmental Advantages.

The technologies listed under this heading are not simply for the control of emissions or effluents but are essential parts of energy production systems. They are presented as candidates for EPA support on the grounds that they have potential for becoming part of new energy systems that are particularly attractive on environmental grounds. The recommended technologies are:

- Closed-cycle geothermal power plants [WATER, 2(c)].
- Turbogenerators driven by liquid geothermal brine [WATER, 2(d)].
- Cooling systems for geothermal power plants in semi-arid regions [WATER, 2(h)].

4. Further Analysis of Effects on Air and Water Quality

Most of the recommended subjects for research and development fall into this category. These are areas where environmental effects of advanced energy technology have been identified as being important but have not been analyzed to the point of recognizing definite needs for controls or standards.

Further study of the effects of advanced energy technology on air and water quality is needed in the following areas:

- ReInjection of geothermal brine [WATER, 2(f)].
- Water pollution from shale wastes [WATER, 3(b)].
- Emissions from in-situ retorting of oil shale [AIR, 3(e)].
- Refinement of estimates of emission factors for retorts used in oil shale processing [AIR, 3(g)].
- Application of refinery pollution control techniques to oil shale processing [MULTIMEDIA, 3(h)].
- Alternatives to consumptive use of water in oil shale processing [WATER, 3(j)].
- Data on exotic pollutants from energy producing solid waste disposal [MULTIMEDIA, 4(a)].
- Determination of emission factors for solid-waste energy processes [AIR, 4(b)].
- Water pollution from ash disposal from solid-waste energy processes [WATER, 4(d)].
- Treatment of process water from energy-producing solid-waste disposal [WATER, 4(e)].
- Cleaning the pyrolysis gas in solid-waste energy processes [AIR, 4(f)].
- Eventual monitoring of tests of underground coal gasification processes [MULTIMEDIA, 5(b)].

5. Further Analysis of General Environmental Effects of Advanced Energy Technologies

The recommendations not adequately described in the above categories are listed here. What they have in common is an applicability to the full range of media and to intermedia effects. The recommendation for study of geological site survey techniques is of special significance because, in addition to its multimedia implications, it has applications in three of the advanced technologies studied. The solar energy recommendation is repeated in this category because of its implications beyond standards or guidelines.

The following further studies of the environmental effects of advanced energy technology are recommended by SRI:

- Geological site survey techniques for use in establishing environmental control requirements at the sites of geothermal energy production, in-situ oil shale retorting, and underground coal gasification [MULTIMEDIA, 2(e), 3(k), and 5(a)].
- Continuous review of solar energy development [MULTIMEDIA, 1].
- Periodic review of the technology for underground coal gasification [MULTIMEDIA, 51 (c)].
- Periodic review of the technology for using hydrogen as an energy carrier [MULTIMEDIA, 6].

6. Matrix Summary of the Ordering by Type and Media

The classification just presented can be summarized in matrix form, as shown in Table 22. This matrix indicates the classifications by type of recommendation and by type of environmental impact.

Although there are several key recommendations relating to standards and technology development, most of the recommendations pertain to the need for further research to better define the nature of advanced energy systems and their resulting environmental impacts. These impacts are estimated to have principal effect on air and water quality

Table 22

**CLASSIFICATION MATRIX FOR RESEARCH
AND DEVELOPMENT RECOMMENDATIONS**

Classification by Type of Recommendation	Classification by Type of Impact			
	Air Quality	Water Quality	Land Use	Other
Develop a standard	2(a)* 3(f) 4(c)	3(d)	3(a) 2(i)	1
Develop control technology	2(b) 3(f)	2(g) and 3(c)		
Support promising energy technology		2(c) 2(d) 2(h)		
Conduct further research	3(e) 3(g) 3(h) 3(i) 4(a) 4(b) 4(f) 5(b)	2(f) 3(b) 3(h) 3(i) 3(j) 4(a) 4(d) 4(e) 5(b)		2(e), 3(k), and 5(a) 1 5(c) 6

* Recommendations appear here according to their subsection numbers in Section VI-B.

unless research and development is successful in suppressing release of pollutants or in achieving control over them.

The structure of Table 22 reflects a judgment regarding the nature of recommendations and character of environmental impacts. Perhaps the best known systems and impacts are those for which research and development is concerned with development of standards and control technology. Lesser known systems need research and development for quantification of the environmental impacts and discovery of the nature of pollutants produced from these sources. With respect to type of impact, Table 22 reflects the view that the environmental media that may disperse pollutants most widely or may be the means of transmitting such pollutants to other media require most intensive work. This classification is valuable in establishing priorities for conducting the necessary research and development work.

D. Assignment of Priorities

The scope and complexity of the research and development programs identified to control environmental impacts from advanced energy sources are such that all the desirable work cannot be performed concurrently; priorities must be employed. In the final analysis, the EPA bears the responsibility for determination of the priorities and ranking criteria for the research and development programs that it administers or conducts. This study, while it can offer support to the EPA's process of program planning, is no substitute for these activities.

There are many factors involved in setting priorities. These include (1) estimated costs, (2) work to be done, (3) anticipated classes of results, (4) interactions with other activities, and (5) the time results are required to guide further actions. Identification of work to be done has already been covered in earlier sections.

If limited to the projected time scale for development of advanced research sources, the ranking of research and development priorities for advanced energy could be listed as follows:

<u>Priority Ranking</u>	<u>Advanced Energy Source</u>	<u>Main Determinations Needed</u>
1	Geothermal dry steam	Air quality impacts
2	Oil shale	Air and water quality impacts
3	Solid wastes	Air and water quality impacts
4	Solar thermal	Indirect impacts
5	Geothermal hot water	Water quality impacts
6	Solar energy plantation	Land use and wastes impacts
7	Underground coal gasification	Water quality impacts
8	Solar photovoltaic	Indirect impacts
9	Other geothermal	Water quality impacts
10	Hydrogen	Indirect impacts

This listing reflects the principle that research and development should be done first on those advanced energy sources expected to be deployed at the earliest dates. Such priorities enhance the prospect that control approaches will be available at times when sizable energy production from these sources is expected.

However, it is incomplete to base priorities solely on the expected timing of development. As indicated in the classification approach described in the previous section, the several research and development recommendations for individual advanced energy sources can be categorized according to type of work and expected impact. Accordingly, it would be worthwhile to assign higher priority to those research and development efforts expected to contribute to more than one advanced energy source (e.g., saline water treatment for geothermal and oil shale developments) and to those expected to contribute to the solution of problems beyond the advanced technologies dealt with in this report (e.g., control of fine particulate emissions). Additionally, it is clearly more important

to address the control of identified environmental impacts from soon-to-be-developed advanced energy sources than it is to pursue further research, although such further research is recognized as both desirable and essential.

With these additional factors in mind, another ranking of priorities for research and development is given in Table 23. This table ranks the specific research topics by affected environmental media. Items listed at the top of the table are those with the highest priority. The ranking, somewhat subjective, still reflects considerations of timing, magnitude of impact, and degree of definition of the problem. The table suggests that research and development is required at an early date to address environmental impacts associated with development of geothermal resources, oil shale developments, and energy production from solid wastes. This research and development is required to demonstrate practical pollution control strategies and technologies to achieve applicable operating standards for air quality, water quality, and land-use practices. Solar thermal energy warrants attention soon, but attention of a different nature because of the indirect effects involved. Research and development for control of environmental effects from other forms of solar energy production, underground coal gasification, and hydrogen as an energy carrier is also desirable, but the need for research and development is not as urgent because these sources are estimated to require more time to develop.

Priority ranking of the types of research and development required for control of environmental impacts from advanced energy sources represents an important part of the overall planning process. Clearly, however, essential cost factors and overall agency requirements also will need to be considered by EPA in arriving at a final plan for efforts in the energy sector.

Table 23

PRIORITIES OF RESEARCH AND DEVELOPMENT RECOMMENDATIONS*

Ranking	Air	Water	Land	Other
Highest	2(b)	2(g), 3(c)	3(a)	
	2(a)	3(d)		
		3(b)		
		2(c)		
	3(f)			1
		2(d)	2(i)	
	4(c)	2(h)		2(e), 3(k), 5(a)
		2(f)		
	3(e)			
	3(g)			
	3(h)	3(h)		
	3(i)	3(i)		
		3(j)		
	4(a)	4(a)		
	4(b)	4(d)		
	4(f)	4(e)		5(c)
Lowest	5(b)	5(b)		6

* Recommendations appear here according to the subsection numbers of Section VI-B.

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Appendix A

SOLAR ENERGY

by

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I SOLAR ENERGY: STATE OF THE ART

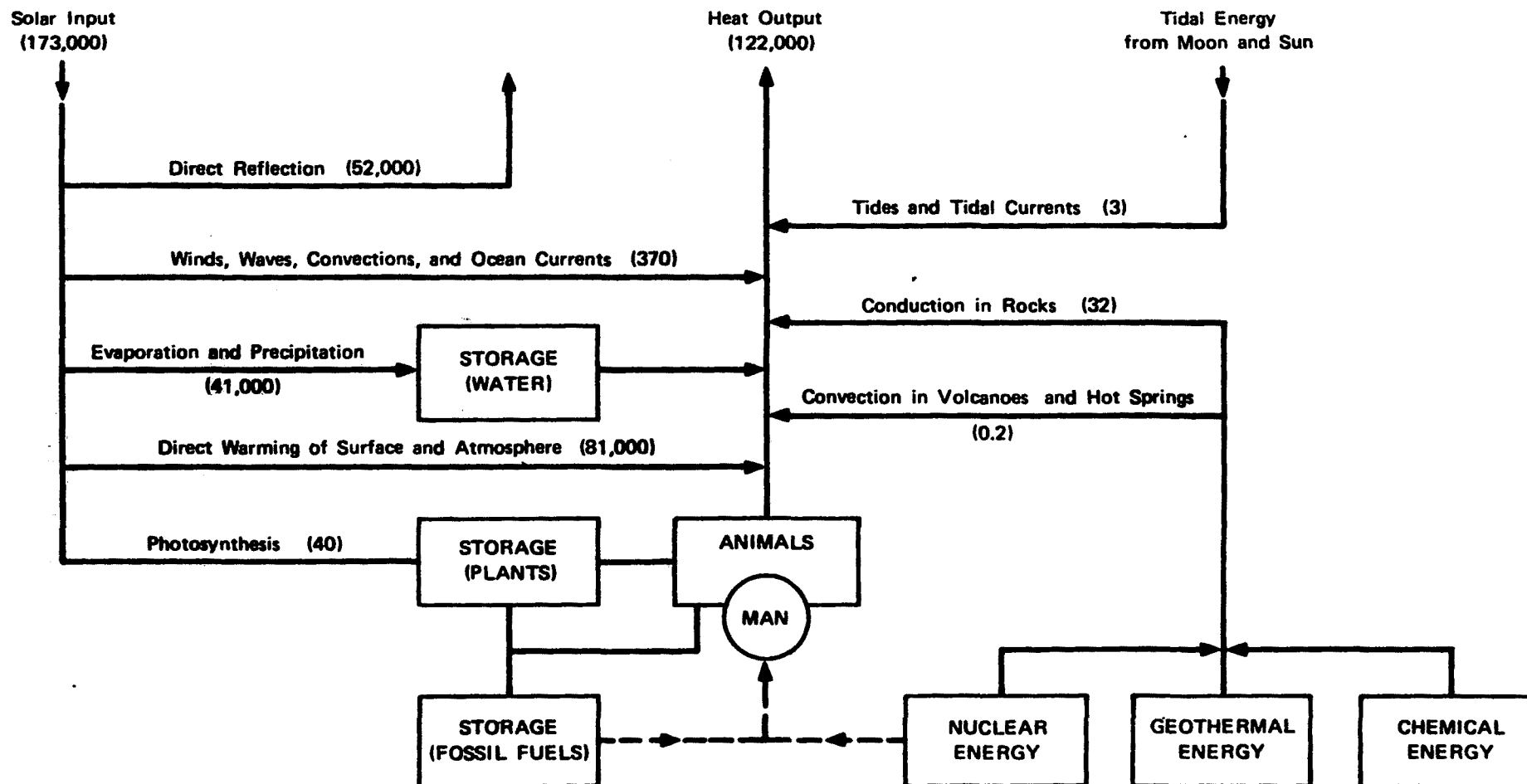
A. Introduction

Energy received from the sun represents by far the most significant component of the thermal balance of the earth. As indicated in Figure 1, solar energy not only warms the earth but also drives the winds, the ocean currents, the hydrologic cycle, and is responsible for photosynthesis in plant materials.^{1*} Historically, mankind has used all these aspects of solar energy, although in the industrialized nations, the last century has seen almost total reliance on hydropower and the photosynthetic energy stored over geologic time in the form of coal and oil. Recently, however, attention has been drawn to the possibility, and impending need, to utilize solar energy more directly. Although the energy density of solar radiation reaching the surface of the earth is rather low (about 0.8 kW/m^2 during the brightest six to eight hours of the day in the relatively cloudless deserts of the U.S. Southwest),² solar radiation has the advantage of being available everywhere--at least during certain parts of the year. Opportunities for increased solar energy utilization can be classified in three broad categories:

- Thermal energy
- Electrical energy
- Synthesis of renewable chemical fuels.

Naturally, these categories are not mutually exclusive, and all include four basic system elements: collection or extraction, conversion, storage,

* Numbered references are listed on page 1 at the end of Appendix A.



NOTE: Numbers in parenthesis are terawatts (10¹² watts).

SOURCES: M. King Hubbert, "Energy Resources of the Earth" *Scientific American*, September 1971, pp. 61-70.
John Holdren and Philip Herrera, *Energy* (Sierra Club, San Francisco), 1971.

FIGURE 1 POWER BALANCE FOR THE EARTH

and distribution. Among the various solar energy systems possible, different combinations of these elements assume dominant importance. These basic elements are defined briefly below as a prelude to discussion of various systems.

Collection and Extraction--Solar energy can be exploited by extracting momentum from winds, falling water, and ocean currents; by oxidation of organic materials; by utilization of thermal differences in the oceans to drive heat engines; by thermal capture of solar radiation; and by generation of electricity from photovoltaic cells exposed to incident radiation. Since the density of energy available in many of these sources is rather low, facilities for collection or extraction generally require large areas of exposure or contact.

Conversion--The form of energy obtained from the collection or extraction process is frequently inappropriate for direct use, distribution, or convenient storage. Consequently, conversion of energy between thermal, electrical, and chemical forms is usually a prerequisite for a solar energy system.

Storage--Geographical, diurnal, seasonal, and meteorological variations in insolation provide a major constraint in the application of solar energy because human activity patterns and, consequently, demand for energy do not coincide with the availability of sunshine. Since storage of large quantities of energy in electrical form is difficult, storage in a large thermal reservoir or in chemical compounds is usually considered the most attractive.

Distribution--Once collected or extracted, it is necessary to transfer the energy to its point of use. Over short distances, heat

exchange fluids can be effective, but over large distances electrical or chemical distribution is more efficient. Electrical distribution can be accomplished by fairly conventional methods. Chemical distribution is especially convenient if the energy has been stored in liquid or gaseous chemical compounds because this facilitates transmission by pipeline or bulk carriers.

B. The Technological Systems

1. Thermal Energy Collection from Insolation

In the simplest solar energy systems, suitable for heating or cooling a small building, the collection of solar energy results directly in a temperature rise in a heat exchange fluid, which in turn is used to warm space, heat water, or cool space by use of an absorption refrigeration cycle.^{3,4} In these systems, collection and storage considerations dominate, since no conversion is required and transmission is minimal. Numerous tests have demonstrated the engineering feasibility of heating and cooling buildings in the appropriate climate.^{3,5} Because about 22 percent of all energy currently consumed in the United States is used for space conditioning and water heating,⁵ thermal solar energy systems for use in buildings are especially beguiling. Indeed, a recent NSF/NASA report suggests that 50 years from now such systems could provide about 35 percent of the country's space conditioning energy requirements.⁶ Studies of insolation have shown that large areas of the United States, especially the Southwest, are well suited for this application.⁵

Present systems usually use flat plate collectors and often use water as the heat transfer and storage fluid. Although engineering feasibility has been demonstrated,^{3,5,6} economic feasibility remains elusive, and experience has revealed several remaining engineering challenges:

- Ensured durability, and long, low maintenance lifetimes for low cost collectors and plumbing
- Increased thermal exchange and storage efficiency
- Integration with the existing energy utility network to provide supplemental energy as needed

Large scale centralized thermal solar energy installations have been envisioned to provide the thermal energy required for the generation of electricity using conventional Rankine cycles. For these large installations, efficient distribution of thermal energy within the array of collectors presents a formidable problem, requiring the pumping of enormous quantities of heat exchange fluids or the use of advanced-concept "heat pipes." To store enough heat to keep the generators in operation during periods of low collection and throughout the night, enormous* thermal storage reservoirs are necessary.^{3,7,8} To provide energy storage adequate to buffer seasonal variations, the thermal storage must be supplemented with chemical or mechanical storage (such as pumped storage of water). Hydrogen obtained from the electrolysis of water during periods of peak power is frequently regarded as the logical choice for chemical storage.^{9,10,11}

Vast quantities of hydrogen are required to buffer the energy output of a large solar energy installation. Storage as a cryogenic liquid at 20.4°K is technically feasible,¹² although the liquification process consumes energy and thereby lowers the overall system efficiency. Metal hydrides, such as MgH_2 , offer an alternative hydrogen storage capability since they exhibit very high atomic densities of hydrogen, and the diffusion of hydrogen through the magnesium is relatively rapid at convenient temperatures.¹³ Procedures to process the vast amounts of

*About 300 metric tons of eutectic salts are required per day of reserve energy for an electric power output of 1 MW.

metal hydride that would be required have not been detailed. When needed, electricity could be regenerated either by combustion of the hydrogen in conventional power plants or by fuel cells. It is believed to be likely, moreover, that reversible fuel cells suitable for both electrolysis and recombination can be devised.

Other storage mechanisms widely considered to be feasible involve exploitation of the heat of fusion of eutectic mixtures of salts,⁷ although there has not been agreement on the most appropriate substances. A cycle employing Al burned to Al_2O_3 which is then recycled to Al by using peak period electrical power has been mentioned.⁷

Unlike thermal approaches to the heating and cooling of buildings with solar energy, the system feasibility of a large scale thermal process solar energy installation has not been demonstrated. Relevant research and development has been concentrated on the following topics to improve overall system efficiency:

- Suitable energy storage mechanisms, especially eutectic salt mixtures.
- Selective optical coatings that are highly absorptive in the visible portion of the spectrum, but that have low emissivity in the infrared portion. The coatings must be durable at elevated temperatures and must have long lifetimes.
- Inexpensive and durable focusing devices, such as plastic cylindrical Fresnel lenses to concentrate the incident radiation on thermal transfer fluid piping.
- Efficient heat transfer fluids and materials with acceptably low corrosion potential.

2. Electrical Energy

a. Photovoltaic Conversion

Many semiconductor materials have been found that absorb photons from the solar flux and thereby generate an electrical current.

The materials most exploited for photovoltaic "solar cells" have been cadmium sulfide, CdS, and high purity single crystal silicon.¹⁴ Recent developments have suggested that Schottky diodes¹⁵ and gallium arsenide (GaAs)¹⁶ may also possess substantial potential for application. In addition, recent research has shown that chlorophyll can be used as an electron donor to semiconductors, thus opening the possibility of a symbiotic chlorophyll-semiconductor solar cell.¹⁷ At the present time, CdS solar cells are relatively easy to make, but silicon cells are expensive and almost entirely handmade by cottage industry methods,¹⁴ and almost entirely consumed in the U.S. Space program. Degradation of performance after environmental exposure is one of the lingering difficulties with all solar cells. Ironically, since most of the applications to date have been in space probes, more is known about damage caused by environmental exposure in space than on earth. Except for meteorite damage, the space environment is more benign for solar cells than the terrestrial environment. Efficiencies with which the various cells convert incident solar energy to electricity are summarized below. (For comparison, fossil fuel electrical power generation plants typically operate at 30 percent efficiency.)

	Approximate Efficiencies		
	<u>Usual</u>	<u>Observed</u>	<u>Theoretical</u>
Cadmium sulfide	6%	8%	--%
Silicon single crystal	13	16	22
GaAs	--	18	26
Schottky diodes	--	6	22

The intermittent nature of sunlight on earth poses a special problem to all schemes to utilize photovoltaic collection of solar energy. At present, it is awkward and costly to store large quantities of energy in electrical form, thus making it difficult to

envision a large solar energy plant with electrical storage sufficient to buffer variations in supply and demand.^{3,7} Consequently, one of the key issues in the development of solar electrical power is the identification and evaluation of an efficient and economical energy storage capability. Since the energy is made available in electrical form, again electrolysis of water to make hydrogen for storage and later combustion is widely believed to be a suitable strategy.^{9,10,11}

Although photovoltaic collection of solar energy is not usually associated with the heating and cooling of buildings, the electrical output can be used to operate a heat pump (these usually have an "effective" efficiency of 200 to 300 percent) to accomplish the necessary heat transfer. One analysis¹⁸ has indicated that in Phoenix, Arizona, a home using solar cells, hydrogen generation for energy storage, and fuel cells for dark period electrical generation could be energetically self-sufficient. Indeed, an annual excess hydrogen generation was projected. Research and development related to terrestrial photovoltaic solar energy is currently concentrated on

- Discovery of new materials exhibiting photovoltaic properties at suitable energy conversion efficiencies.
- Improved solar cell efficiency, fabrication techniques, durability, and lifetime, all at lower cost.
- Electrolysis and fuel cells with improved efficiencies and greater durability (including the possibility of a dual-purpose reversible cell).

Because the earth's atmosphere reflects and absorbs much of the incident solar energy, serious suggestions have been made to construct an extensive satellite borne array of solar cells in synchronous earth orbit.^{6,19,20,26,27,28} A satellite station would receive about ten times as much incident energy as is available on earth and would be

able to operate around the clock. The electrical energy generated by the satellite could be beamed to earth as microwave radiation and thereafter converted to electricity in conventional form for distribution. In spite of the obvious difficulties of construction in space, problems associated with the variability of insolation on earth would be considerably alleviated.

A satellite solar power station, SSPS, capable of providing about 10 GW on earth would require placing about 25 million kilograms of material into orbit.⁶ This would require an estimated 300 to 1,000 flights of a second generation space shuttle.⁶ The SSPS would presumably be assembled in orbit from prefabricated modular elements. The SSPS is envisioned to consist of two large arrays of photovoltaic solar cells, each with an area of about 16 square kilometers feeding a 1-km diameter phased array of microwave generators acting as a transmitter. On the earth, a special antenna about 7 km in diameter would intercept the microwave beam, rectify the current, and enter the received energy into a fairly conventional electrical distribution network.⁶ Although such an SSPS might generate 10 GW of electrical energy, this amount would be only about 3 percent of the 1970 installed U.S. electrical generating capacity and less than 1 percent of the capacity believed necessary by 1990.²⁹

Many problems remain to be solved before an SSPS could become a reality, and most of the current research is devoted to establishing the feasibility of the concept.

b. Wind Power

Extraction of mechanical energy from winds was prevalent many years ago (as evidenced by picturesque windmills in much of Europe); however, interest in wind power had almost completely waned 60 years

ago.⁵ Since then, applications have been mainly in rural areas, and even these have decreased with rural electrification. However, some operational experience was gained in the United States during World War II from the operation of a wind power generator at Grandpa's Knob, Vermont; the 1.3-MW generator operated sporadically between 1941 and 1945.³⁰ Since wind power is variable in most locations, energy storage mechanisms, similar to those discussed above, are necessary to make wind power significantly more convenient to use. Research and development in the area of wind power has been almost nonexistent, although the recent NSF/NASA solar energy assessment⁶ is rekindling interest and there is now some slight governmental funding (NSF/NASA).³¹ Work is especially needed in the areas of:

- Materials development for lightweight high strength turbine blades.
- Windmill structures using contemporary materials.

c. Hydropower

The extraction of energy from falling water is, like wind power, a very old technology. In the United States very little unexploited potential remains for hydropower development--especially without arousing substantial controversy on environmental, recreational, and aesthetic grounds. Consequently, hydropower is seldom regarded as a beckoning opportunity to extract stored solar energy. Nevertheless, several technological research and development activities currently in progress may improve the effectiveness of hydropower including:

- Pumped storage for peak shaving of electrical generation
- Superconducting electricity generators
- Weather modification to increase flows in appropriate rivers.

Although, strictly speaking, hydropower is a stored form of solar energy,¹ the nearly complete exploitation of its potential suggests that it should receive no further attention in this study.

d. Thermal Differences in the Sea

A vast quantity of solar energy is stored in the heat capacity of the oceans. Year-round absorption of incident radiation warms surface waters in the tropics. Solar energy driving the winds and the precipitation cycle annually builds up polar snowpacks that melt in the spring, giving rise to cold subsurface currents.⁶ Because of convection on a global scale, the warm surface waters move poleward and the cool subsurface waters move toward the tropics. In some areas, warm surface waters override (by a few thousand feet) significantly colder waters. In the temperate zones, this creates a significant opportunity to operate a heat engine between the effectively infinite warm and cool heat reservoirs that exist in the sea.^{6,21,22,23,32,33}

Enormous quantities of warm and cool sea water circulated past efficient heat exchangers could drive a conceptually simple heat engine at relatively low thermodynamic efficiency. However, by processing very large quantities of water, this engine nevertheless could yield significant quantities of energy in electrical form. For plants of this nature, efficient heat transfer and energy transmission to the shore and to distant inland locations become the dominant considerations. Because these plants extract energy from essentially continuous sources, the problem of energy storage can be neglected.

Although this concept is not new, few attempts have been made to demonstrate engineering feasibility. Two successful demonstrations succumbed to mechanical failure after only short periods of operation.⁶ Interest in this concept of solar energy extraction is increasing,

and several serious engineering studies are now in progress. Some of the major explorations yet to be accomplished include:

- Consideration of mechanical design and construction strategies
- Refined identification of optimal sites
- Evaluation of alternative energy transmission technologies suited for land-sea links.

3. Renewable Fuels

Once collected or extracted, solar energy can be stored chemically in synthetic fuels, such as hydrogen obtained from electrolysis. Processes have been suggested to go a step further and to collect CO_2 from the atmosphere for combination with the electrolytic H_2 to synthesize organic molecules such as methane, methanol, and gasoline suitable for use as fuel.²⁴ Since virtually the sole products of combustion of the fuels are water and CO_2 ,^{*} the process would be a closed cycle with nature supplying the return path. The chief advantages of the synthetic fuels approach to solar energy utilization are that mismatches in solar energy and supply can be buffered more easily, the fuel can be stockpiled or distributed by conventional means to areas remote from the solar energy installation, and the fuels can be used in mobile applications such as in aircraft. Inorganic chemical cycles in which the depleted chemicals are returned to the solar energy installation for recharging are also possible, including $\text{Al}-\text{Al}_2\text{O}_3$ or $\text{Mg}-\text{MgH}_2$ cycles.^{8,13}

Quite another approach to generation of renewable fuels is to use natural photosynthesis to generate organic molecules in a plantation devoted to growing plants solely for the purpose of energy production.²⁵

* Some nitrogen oxides may be formed if combustion occurs in air at high temperatures.

Under optimal conditions, some plants are able to fix about two percent of the incident sunlight. Grown and harvested completely, without the usual agricultural regard for segregation into product and waste, the total plant can be used either to fire conventional electric generators or to be chemically converted, refined, and concentrated into organic molecules suitable for use as fuels.⁶ Some of this reduction process may be accomplished organically by fermentation processes. These conversion processes can also intercept and utilize organic materials from the urban, agricultural, and livestock waste streams.⁶ Although photosynthetic utilization of solar energy has long been a major feature of human culture, the following issues are being studied as a prelude to the possible application of the concept of an energy plantation.

- Determination of the known plants that not only fix sunlight efficiently but also are easily harvested and processed.
- Identification of necessary processes to maintain a closed system, such as returning nutrients to the soil.
- Analysis of the energetics of the complete system to ascertain the net energy gain.
- Genetic alteration of plants to maximize their photosynthetic efficiency to yield maximum biomass per unit area cultivated.

II SOLAR ENERGY: ENVIRONMENTAL IMPACTS

A. Introduction

In the popular literature (and most of the professional literature as well), solar energy is depicted as a "pollution free" source of energy, ideally suited to a culture in which environmental quality is held in high regard. It is true that solar energy installations will not be sources of air pollution, and because they will consume energy cleanly delivered in the form of electromagnetic radiation from the sun, they will not be directly responsible for creating a demand for strip-mined coal or oil from offshore wells. Nor, in many cases, will solar energy installations be responsible for thermal pollution of streams or other bodies of water used to provide cooling water for stream driven electric generating plants. However, it is not true, and it is extremely naive and shortsighted to maintain, that no adverse environmental effects would result from the harnessing of solar energy.

It is extremely important to appreciate that not all the pollution associated with any given energy source occurs at the site of energy conversion or final utilization. For example, it has long been recognized that environmental damage resulting from coal mining is a consequence and one of the societal costs of the generation of electrical energy by conventional coal-fired generating plants. The environmental disruption associated with the mining and with production of the steel that is used to fabricate the actual generation plant, with the railroads or barges that deliver the coal, and with the machinery at the mines is likewise a consequence of this form of energy utilization. However, relatively few people have extended their thinking far enough to include consideration

of these ancillary parts of the system that delivers energy from its basic source to the final user. In its evaluation of environmental effects associated with various energy technologies, it is essential that EPA take the larger view and consider the entire energy system along with the various component technologies.

Seen in this way, it is clear that utilization of solar energy simply cannot be pollution free--that is only a cliché. Indeed, it is inherent in the nature of solar energy as a widespread, but dilute source of energy that utilization invariably requires collection devices that cover a large area and therefore consume vast quantities of materials. It is in the extraction, production, and processing of these materials that many of the environmental impacts of solar energy utilization lie. Certainly, deployment of alternative forms of energy production facilities also consume materials with attendant environmental disruptions. A major problem facing policy-makers in the energy resource and environmental quality arenas is the comparative evaluation of alternative energy systems.

One general and pervasive aspect of solar energy utilization that also indirectly affects environmental quality results from the uneven geographic availability of insolation suitable for capture of solar energy. Should solar energy become an economically viable resource, all accounts indicate that the arid areas of the Southwest will be the most attractive geographical location to utilize this resource by direct capture of sunshine. Depending on the development of other energy resources elsewhere in the nation, it is possible that in the future energy may be available in the Southwest at lower prices than in other regions. This, together with a climate many people regard as attractive, would lead to an inexorable, although slow, migration of the industry, employment opportunities, and population to the Southwest much as has been occurring in the last two decades toward the southeastern states.³⁴ Inasmuch as most of the Southwest is arid and, as experience in Arizona has shown, prone

to air pollution problems, exploitation of solar energy could result in a significant increase in urban-related environmental problems in the southwestern states.

The following sections consider the magnitude of the major, most obvious materials demands created by the various forms of solar energy outlined in the previous sections. Other environmental effects are also considered, such as possible adverse effects on local or regional climates, biota, land use, and water or air resources.

B. Specific Solar Energy Technologies

1. Thermal Collection of Insolation

a. Electric Energy Generation from Large-Scale Solar Energy Collection

Installations envisioned for the large-scale collection of insolation by thermal means are discussed in two basic forms. The first entails a system of simple reflectors or inexpensive, low precision optical lenses to focus direct sunlight on a conduit through which a heat transfer fluid is pumped. The incident energy heats the fluid, and this captured energy is continually removed as the pumped fluid passes by a heat exchange element that forms the high temperature reservoir for a boiler (water need not be the working fluid) driving a conventional thermodynamic electric generation plant. To enhance the buildup of heat, the conduit is generally colored black and is enclosed in a glass or plastic greenhouse-like environment; to inhibit the loss of energy by convection, the enclosure can be evacuated.

Conceptually, this scheme is very old; however, modern thinking has added, either on the collecting conduit or on the protective cover, a thin film selective coating that is transparent to electromagnetic radiation in the visible part of the spectrum (in which most of

the solar radiation lies) but is opaque in the infrared part of the spectrum (in which most of the reradiation from the hot conduit lies). An important limitation of this form of collector is the inability of a mirror or lens concentrator to focus the indirect or diffuse solar radiation that results from radiation scattered from molecules of the gases composing the air, particulates, the earth's surface, clouds, and so forth. Moreover, focused collectors need continued reorientation to follow the sun, at least in its seasonal excursions to be effective. Since diffuse radiation is a substantial fraction of the sunshine normally received (often about 20 percent), an inability to utilize the energy in the diffuse radiation is a serious limitation of focus-collector systems.³⁵ It is now quite evident, even to some of the recent advocates of focused collectors, that even in Arizona there are too many days with thin cloud cover or haze for focused collectors to be attractive.³⁶

The second basic collector type is a "flat plate" collector consisting of a conduit containing a heat absorbing fluid that snakes around a "blackened" planar collecting surface. Again, the use of selective coatings and evacuation enhances the performance of the collector. A variation in this concept has recently been designed that behaves like a flat plate collector but has a configuration that is more easily evacuated.³⁶ The power generation steps would be essentially identical to those described above.

The intermittent nature of sunlight and the thermal time-lag inherent in the system of circulating fluid make it necessary to accompany the collectors and power generation facilities with an energy storage mechanism. Storage can either be in thermal form such as in the mixture of eutectic salts (which, like a bath of ice and water, maintains a constant temperature over a wide range of stored energy) or in chemical form, such as hydrogen, derived from electrical energy produced during peak periods.

It is extremely informative to estimate the quantities of materials required for installations following the basic concepts outlined above. All the estimates will be optimistic in the sense that any real installation will require more materials than derived from these simplified assumptions. Assuming a reasonable value of 30 percent for the efficiency of conversion of insolation to thermal energy, a thermal solar energy plant with 1 GW of electric output would require about 1.5×10^7 square meters of collector surface.* In any design, it will be essential to support the collector, and presumably the support could be made to form the collector's back surface. If this support material is a metal and is rather optimistically assumed to have an average thickness of 1 mm, then the volume of this substrate material required would be about 1.5×10^4 cubic meters. Presumably the collector would be covered with glass as a protective cover; consequently, about 1.5×10^7 square meters of glass would be required. (If the collector is not evacuated, a double-glazed glass cover would be advantageous to reduce convective losses of energy from the collector. This would double the glass requirement.) If the energy storage is accomplished in a salt mixture that is basically Na_2SO_4 (anhydrous sodium sulfate), then a 1-GW plant would require about 3.2×10^8 kg of this salt for each day of storage capacity. The selective coatings that are used to improve the performance of the collector generally include a refractory metal; molybdenum,⁸ hafnium,⁸ and gold⁸ have been mentioned. If these materials were used in a layer about 0.07 micrometers thick, about 1.1 cubic meters of the material would be required.

* New water cooled nuclear power reactors typically have a rated electrical output of about 1 GW; comparisons are made for 1 GW installations to facilitate comparisons.

The significance of these resource requirements can best be grasped by comparison with recent U.S. annual production figures as summarized in Table 1. Clearly, materials requirements are a significant consideration for contemplated solar energy developments, especially when it is realized that many installations of 1 GW output would be necessary. One of the most prominent advocates of a thermal collector solar energy installation speaks in terms of building ten plants of 1-GW capacity per year. Clearly, there will be environmental impacts associated with these resource demands, although they will not occur at the solar energy collection site itself.

It is also instructive to evaluate the quantity of energy that would be required to extract, refine, process, and fabricate a few of the key materials required in the plant. Recent work on the energy requirements for the production and consumption of automobiles has provided a detailed vertical analysis of the energy invested in several materials.³⁸ These are shown in Table 2 and form the basis for the last column of Table 1. The annual electrical energy output of a 1-GW plant running constantly at full capacity (possible only if adequate energy storage is provided) is 8.76 TWh. From this it can be seen that it would take about 0.36 years' operation to recover the energy invested on aluminum substrate material alone. Therefore, the expected productive lifetime of the installation becomes an important parameter, because the plant must reap more energy than is committed in the fabrication and operation of the installation.

As already indicated, a 1-GW thermal solar energy installation would require on the order of $1.5 \times 10^7 \text{ m}^2$ of collector surface. This is equivalent to a square nearly 4 kilometers on a side. An actual installation would be expected to require more land area, because the collector is unlikely to form a single continuous sheet and there are

Table 1

ESTIMATED MINIMUM MATERIALS REQUIREMENT FOR 1-GW
ELECTRICAL OUTPUT THERMAL SOLAR ENERGY PLANT*

	Quantity		U.S. Annual Production (year)	Requirements as Fraction of U.S. Annual Output (percent and year)	Energy Devoted to Materials Production for Solar Plant Twh (10^{12} Wh)
	Volume	Mass			
Alternative sub- strate materials					
Aluminum	$1.5 \times 10^4 \text{ m}^3$	$4 \times 10^7 \text{ kg}$	$3.6 \times 10^9 \text{ kg}$ (1970)	1 % (1970)	3.2
Steel	$1.5 \times 10^4 \text{ m}^3$	$1 \times 10^8 \text{ kg}$	$1.2 \times 10^{11} \text{ kg}$ (1970)	0.1 (1970)	1.7
Copper	$1.5 \times 10^4 \text{ m}^3$	$1.3 \times 10^8 \text{ kg}$	$1.4 \times 10^9 \text{ kg}$ (1970)	9 (1969)	5.3
Cover material					
Flat glass	$1.5 \times 10^7 \text{ m}^2$	depends on thickness	$2.7 \times 10^7 \text{ m}^2$ [†] (1970)	56 (1970)	--
Thermal storage for one day's output					
Na_2SO_4	$1.1 \times 10^5 \text{ m}^3$	$3 \times 10^8 \text{ kg}$	$6 \times 10^{11} \text{ kg}$ (1969)	0.05 (1969)	--
Thin film selective coating					
Hafnium	1 m^3	$1.5 \times 10^4 \text{ kg}$	$3.2 \times 10^4 \text{ kg}$ (1970)	46 (1970) [‡]	--

* Installed electrical generating capacity in 1970 in the United States was 340 GW.²⁹

[†] Plate or float glass between 1/8-in. and 1/4-in. thickness. A lower quality material such as sheet glass would probably be adequate.

[‡] Current production of hafnium is apparently demand-limited rather than resource-limited.³⁷

Table 2

ENERGY INVESTMENT IN FINISHED METAL
(Rolled)

Metal	Energy (kWh/kg)
Aluminum	80
Carbon steel	17
Copper	40

ancillary structures such as the generators and energy storage facilities. This raises a significant land-use question even in the arid land of the Southwest where this type of plant is most likely to be located. However, it is important to realize that much of the land in the Southwest is under direct control of the federal government and is used occasionally for various military tests that have rendered the land unsafe for public access, although probably safe enough for a solar energy plant. Additionally, other large tracts of land are controlled by native Americans; to them solar energy installations may represent a very attractive income-producing use of their land. It has been publicly noted that the "Four Corners" powerplant operated by Arizona Public Service Company already has under lease more land for the strip mining of coal to fire the plant than would be needed to construct a thermal solar energy installation of the same capacity.⁷

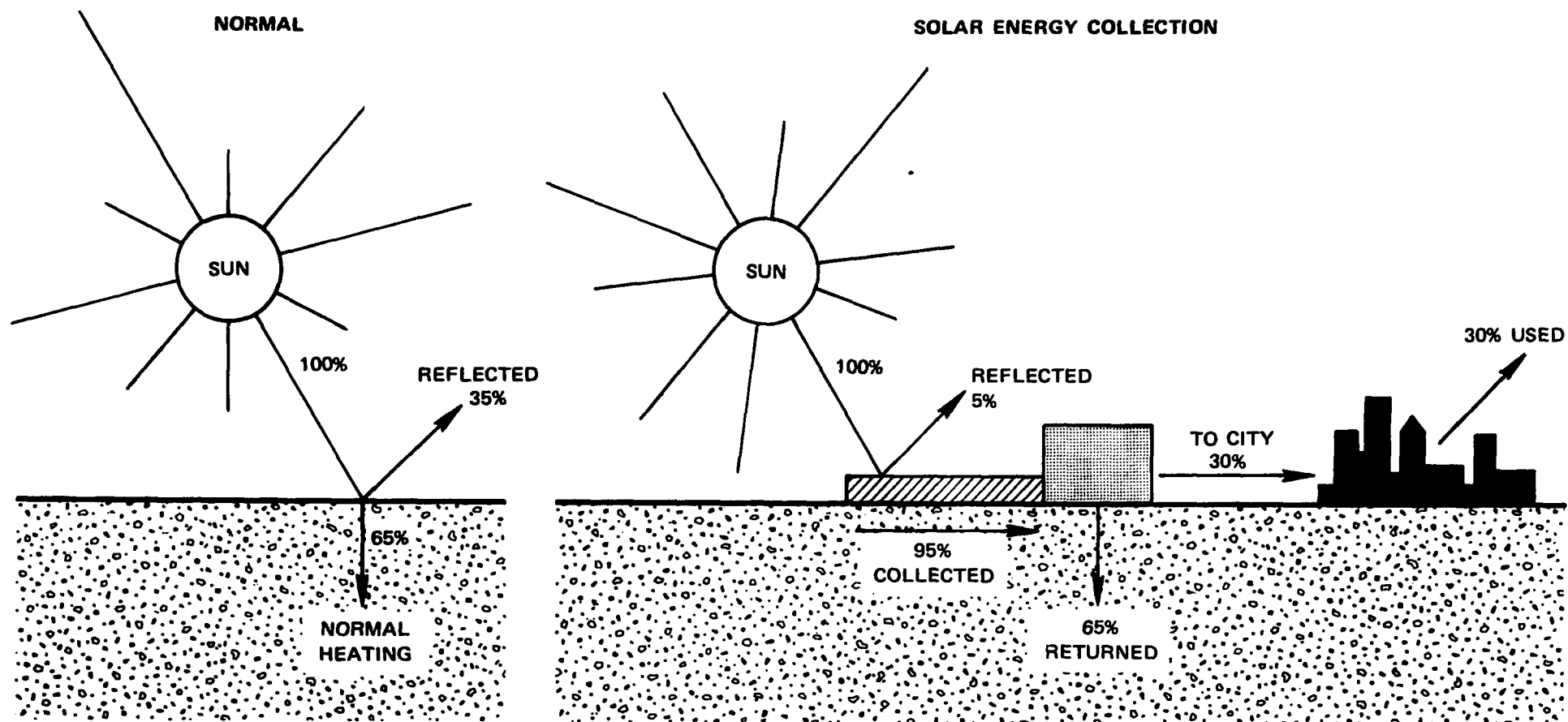
A significant environmental constraint on the deployment of large thermal solar energy installations in the Southwest is the acute shortage of water suitable for use as a cooling agent to recondense the working fluids of the boiler. The cooling water needed for each 1-GW electrical generator would be similar to that of a modern water cooled nuclear reactor of the same capacity, namely about 50 cubic meters per

second. Even if a nearly closed cycle cooling system using wet cooling towers were used, the amount of water needed to make up for evaporative losses is sufficiently large that cooling water will present an important issue in resource management in the Southwest.

The possibility of inadvertent climatic modification is one issue raised by large-scale energy collection. Figure 2 shows that collection of solar energy alters the flux of energy surrounding an installation. There has been considerable speculation, but no actual investigation, of the local climatic modification such collection would induce. Certainly some effects can be expected, since temperature gradients in the air are an important determinant of the winds and cloud cover. Since solar energy collection is sensitive to the degree of cloud cover or haze, investigation of this aspect will ultimately be necessary before an optimized plant design can be reached, because water vapor added by cooling towers or an alteration in cloud cover induced by the plant itself could degrade the plant's performance.

b. Thermal Installation for Local Heating and Cooling of Buildings

The most widely discussed concept for the heating and cooling of buildings concerns the use of flat-plate collectors essentially the same as those described above. However, rather than use the collected and stored thermal energy to generate electricity, the energy is used directly to heat the interior of the building and provide the hot water supply; with the use of an absorption refrigeration device, thermal energy also can be used to drive an air conditioner for cooling a building.⁶ Several designs, however, have used a combination of thermal collection and photovoltaic collection to raise the overall collector efficiency.^{4,39} In these systems, electrical and thermal energy are available, and the electricity



SA-2714-1

FIGURE 2 THERMAL ENERGY BALANCE (ADAPTED FROM REFERENCE 8)

can either be used for building appliances or to drive a heat pump* that adds to the heating and cooling ability of the solar energy collected in the thermal form.

To become a viable concept, residential thermal solar energy systems require storage facilities to provide useful energy into the evening, in the early morning, and on days with little insolation. Most studies have concluded that it is impractical to provide enough storage capacity to enable a building to rely completely on solar energy. It has been stated that about one-half day's store is the optimum amount. Consequently, systems of this type must be backed up with a nearly full-sized conventional heating and cooling system.

Although some redundancy can be removed by integrating the solar energy and conventional systems at the time the building is built, it is apparent that a solar energy system for the heating and cooling of buildings alters the resource demands created by building construction. The desirability of having a conventional system for back-up also has rendered it most likely that this application of solar energy will find use only in new buildings. The NSF/NASA solar energy study projects 10 percent market penetration in new construction by the following time periods:

* A heat pump is a device that essentially acts as a reversible refrigerator. When used to cool the interior of a building, it exhausts the extracted heat to the outdoors much as an air conditioner. However, when set to the impossible task of refrigerating the outdoors, it exhausts the extracted heat to the interior of a building, and thereby provides warmth to the occupants. In moderate climates, this last application can be useful even during the winter and usually delivers two or three units of heat energy to the building interior for each unit expended in operation. Thus these devices have an effective efficiency, or efficacy, of 200-300 percent.

- Water heating--in 1980
- Space heating--in 1985
- Space cooling--in 1985.

It is instructive to examine the implications of these projections on the demand for materials that would lead to off-site environmental impacts during their production.

In recent experience, approximately 1.5 million housing starts per year have been reported. If it is assumed that a 60-square meter thermal solar collector could provide about 75 percent of the heating and cooling requirements for a house, then in 1985 a national production of about 1.8×10^7 square meters of residential-type collector would be required. These collectors would probably consist of a glass cover surface and metal thermal backing and thermal exchange network probably of aluminum or copper. Table 3 shows materials requirements that can be contrasted with the annual production shown in Table 1. Once again, it is evident that applications of solar energy would create substantial demands for basic materials. It is important to note that the above estimates apply only to the collector portion of the system, and other materials would be required to provide the needed thermal storage capability.

Table 3

SELECTED MATERIALS REQUIREMENTS FOR
RESIDENTIAL SOLAR ENERGY SYSTEMS,
1985

Material	Amount
Double glazed flat glass	$3.6 \times 10^7 \text{ m}^2$
Backing and heat exchange material if copper	$7.2 \times 10^7 \text{ kg}$
if aluminum	$2.2 \times 10^7 \text{ kg}$

Some may argue that the introduction of residential solar energy collectors may result in offsetting reductions in materials demands elsewhere in the economy, such as a reduction in the average size of wire needed to supply electricity to a home. No doubt some of this offset will occur, but it is not a straightforward task to identify the sources or magnitudes of possible offsets in materials demands.

Thermal collectors for use on buildings provide a good example of indirect environmental impact. Air pollutant emissions factors have been compiled by the Environmental Protection Agency for the aluminum, copper and glass industries.⁴⁵ Even though it is too early to judge whether copper or aluminum will be the material used in commercial production of rooftop thermal solar energy collectors, it is instructive to itemize emissions of some relevant air pollutants for the materials listed in Table 3. This is done in Table 4 which also shows the emissions associated with roofing materials that the solar energy collectors might render unnecessary and the emissions from the same amount of domestic space heating achieved by the combustion of natural gas. For aluminum, the emissions factors given refer to the best available control technology for the most commonly used series of processes. Many installations do not achieve this degree of control today. It should be noted, moreover, that the technology of aluminum production may change dramatically in the future. The Aluminum Company of America has recently announced a new method of production that reportedly reduces the electricity required by about 30% and is based upon a chloride process rather than a fluoride process.⁴⁶ Consequently, the nature of the emissions and the control requirements and strategies are very likely to change in the next few decades (see Table 4).

The use of solar energy collectors on buildings, either thermal or photovoltaic, will lead to other environmental effects. One effect is related to the aesthetics of building design. It will be a challenge to architects and engineers to integrate solar energy collectors into the structure to make the buildings aesthetically pleasing (although it is natural to expect an evolution in the aesthetic tastes of the public). Another challenge will be the extent that solar energy collectors can be made to substitute for existing roofing or siding materials. Because of the constraints placed on architects by the availability of solar energy, enhanced consciousness of the ability to use fenestration and insolation to control the interior climate can be expected. In addition, land use in developing neighborhoods using solar energy will show increased attention to orientation and spacing of structures and thoroughfares to minimize energy needs and maximize solar energy capture. These aesthetic aspects of solar energy will play a significant role in its public acceptance.

Much as mineral rights have become an important aspect of land ownership, so sun rights may become an important determination of a homeowner's desire or ability to plant trees--especially those casting a shadow on a neighbor's collector. Ironically, in many parts of the country where trees play an important role in moderating the climate in residential areas, the evolution of solar energy utilization could lead to a relatively treeless cityscape--thereby enhancing the desire for artificial climate control.

It is now well known that cities and other conglomerations of human habitation create "heat islands," partly as a result of energy released by human activity but more by the texture and "roughness" of the cityscape itself. Although the effect of a large array of rooftop solar collectors on the urban heat island has not been investigated, it is apparent that some alteration would be expected. Since the urban heat

Table 4

AIR POLLUTANT EMISSIONS ASSOCIATED WITH MATERIALS PRODUCTION FOR THERMAL SOLAR ENERGY COLLECTORS FOR BUILDINGS, 1985
(Emissions factors given per unit final material product) Compiled from Reference 45

Material	Amount Required	Total Particulates		Fluorides				Sulfur Oxides		Carbon Monoxide		Hydrocarbons		Nitrogen Oxides	
		Emissions Factor	Total Emissions	Gaseous Emissions Factor	Total Emissions	Particulate Emissions Factor	Total Emissions	Emissions Factor	Total Emissions	Emissions Factor	Total Emissions	Emissions Factor	Total Emissions	Emissions Factor	Total Emissions
Glass (soda-lime)	3.2×10^8 kg	1.0×10^{-3} kg/kg	3.0×10^5 kg	$2F \times 10^{-3}$ kg/kg*				6F $\times 10^5$ kg*	--	--	--	--	--	--	--
Aluminum (best controls, most common process)†	2.2×10^7 kg	2.2×10^{-2} kg/kg‡	4.8×10^5 kg	2.7×10^{-4} kg/kg	5.9×10^3 kg	$>2.0 \times 10^{-4}$ kg/kg	$>4.5 \times 10^3$ kg	4.1×10^{-5} kg/kg§	9.1×10^2 kg	1.2×10^{-3} kg/kg§	2.6×10^4 kg	6.8×10^{-5} kg/kg§	1.5×10^3 kg	4.1×10^{-2} kg/kg§	9.1×10^5 kg
Copper (controlled)†	7.2×10^7 kg	8.1×10^{-4} kg/kg	5.8×10^4 kg	--	--	--	--	0.25 kg/kg	1.8×10^7 kg	--	--	--	--	--	--
Asphalt roofing	(Amount potentially saved) 1.8×10^7 m ²	4.9×10^{-4} kg/m ²	8.8×10^3 kg	--	--	--	--	--	--	6.6×10^{-4} kg/m ²	1.2×10^4 kg	1.1×10^{-3} kg/m ²	2.0×10^4 kg	--	--
Natural gas for domestic space conditioning	(Amount potentially saved) 5.1×10^8 m ³ /year	3.0×10^{-4} kg/m ³	1.5×10^5 kg/year	--	--	--	--	9.6×10^{-6} kg/m ³	4.9×10^3 kg/year	3.2×10^{-4} kg/m ³	1.6×10^5 kg/year	1.28×10^{-4} kg/m ³	6.5×10^4 kg/year	1.28×10^{-3} kg/m ³	6.5×10^5 kg/year

* Published information does not specify whether these emissions are gaseous or particulate. The variable F in the stated emissions stands for the weight percentage of fluoride input to the furnace. For example, if the fluoride input is 5% the total emissions would be 30×10^5 kg.

† Existing installations do not generally achieve this degree of control. However, these data refer to actual installations where controls have been evaluated.

‡ Includes pollutant emissions from a power plant burning natural gas to produce electricity for the electrolysis process.

§ Arising from the production of electric power (from natural gas) for the electrolysis process.

island is believed to influence the extent of urban cloud cover, precipitation, and even atmospheric mixing, an alteration of the urban heat island could conceivably affect urban air quality. This is expected to entail a series of subtle effects, and it is premature to predict its importance.

2. Photovoltaic Collection of Solar Energy

a. Large-Scale Centralized Terrestrial Collection

The most favorable location for large scale terrestrial collection using photovoltaic technologies is in the Southwest. In the area around Phoenix, Arizona, the integrated annual insolation is about 2 MWh/m^2 .¹⁸ If an installation is to deliver energy at a rate equivalent to a steady 1 GW, then solar cells operating with a 10 percent photovoltaic efficiency would require about 4.4×10^7 square meters of collector area (optimistically assuming a lossless energy storage technique). This is equivalent to a square about 6.6 kilometers on a side.*

Because of the lower efficiency of photovoltaic collection compared with thermal collection, a 1-GW photovoltaic installation would require about three times as much collector area. However, there are advantages of photovoltaic over thermal collection:

- Photovoltaic collection results directly in an electrical output whereas thermal collection requires an electrical generation stage.
- There is no need to pump a heat exchange fluid through the collector system because the energy is collected electrically.

* It is worth noting that units 2 and 3 of the San Onofre, California,⁵ nuclear power station, will each produce 1.1 GW, and occupy about 10⁵ square meters.

- There is no need to utilize double glazed glass enclosures or thin film selective coatings; however, the photo cells do require encapsulation for protection to prevent environmental degradation.
- Energy storage in the chemical form can be more efficiently accomplished by using peak hour electrical energy to electrolyze water to yield hydrogen for later combustion or electrical generation in a fuel cell.
- No cooling water is necessary, since there is no thermal generation of electricity that requires cooling a boiler working fluid.

The quantities of materials required are, again, quite large. A substrate would be needed to support the cells, and if this were metal 1-mm thick, then $4.4 \times 10^4 \text{ m}^3$ of metal would be required. This is nearly three times the quantity given in Table 1 for the thermal collection system. In addition, if silicon solar cells with a typical thickness of 0.25 mm (0.01 inch)⁴⁰ were used, the demand for high purity silicon would be $2.6 \times 10^7 \text{ kg}$. The electronics semiconductor industry and the manufacturers of silicon for solar cells used in spacecraft both consume material of this quality. However, production in 1970 was only about $5 \times 10^5 \text{ kg}$.⁴⁰ Thus an increase in production of about a factor of 50 would be needed to establish even a single 1-GW solar energy installation based on silicon solar cells. The estimated 1970 production of low purity metallurgical grade silicon was $6.6 \times 10^7 \text{ kg}$.⁴⁰ However, no shortage of silicon exists in the United States or the world, since it is one of the most abundant elements in the earth's crust; common sand is SiO_2 . Great quantities of silica sand are consumed annually for glass and refractory products.

A major drawback of silicon solar cells is the need to use slices of what is known as "single crystal," which means that the

material is a large, essentially "perfect" crystal. While it is easy to obtain small samples of perfect crystals for most materials, it is difficult to obtain large perfect crystals because they must be carefully drawn from a melt of material of very high purity. Because of the high melting point of silicon and the extreme chemical reactivity of molten silicon, maintenance of the purity required for making single crystals of silicon is difficult. The need to use single crystals in silicon solar cells contributes to the very high costs of these solar cells. Furthermore, the high degree of purity required necessitates the expenditure of considerable amounts of energy during the multiple refining steps of the material production.

To overcome the drawbacks of silicon solar cells, several other semiconductor materials have been found with promising photovoltaic properties. Among these are CdS and CuS, which do not require single crystals to construct an effective solar cell, although they do have a low efficiency. The most promising material, from an observed and theoretical efficiency point of view, is a solar cell composed of the semiconductor GaAs. These cells can be made by vacuum deposition of thin films in the manner now common in the fabrication of integrated circuit solid state electronics. In a typical GaAs solar cell, the layers of Ga and As are only about 10^{-6} meter thick.

The quantity of Ga required for the 1 GW solar energy installation under consideration is about 44 cubic meters or 2.6×10^5 kg. This greatly exceeds the 1968 production of Ga of about 300 kg and the 1968 world production of 1000 kg. It also is about a factor of 10 greater than the expected cumulative total of 2.7×10^4 kg that the U.S. Geological Survey predicts will be recoverable by the year 2000.³⁷ At the present, Ga production is limited by demand. Although solid state electronics are now using many semiconductors based on Ga compounds, the quantity of Ga consumed is actually quite small. Recovery of Ga is principally as a

very minor constituent from bauxite and zinc ores, and there is little prospect of finding ores rich enough to exploit solely for their Ga content.³⁷ However, Ga is recoverable from the fly ash that results from the combustion of coal.³⁷ Because of the shortage of Ga that could develop once a good GaAs solar cell is routinely producible, it can be expected that on retirement of these solar cells the Ga content would be recycled. Thus, one would not expect a widespread problem of Ga residuals entering the environment. The Geological Survey reports that the toxicity of Ga in vegetation has not been established.³⁷ There exist supplies of As much more than adequate to match the available Ga.

Since even a single 1 GW photovoltaic solar energy installation based on GaAs solar cells would exhaust resources of Ga, it must be concluded that a large scale photovoltaic system cannot depend on GaAs solar cells.

Degradation from environmental exposure is one of the persistent technical difficulties impeding the terrestrial use of photovoltaic solar cells. In normal use, exposure to the sunlight results in a temperature rise, which not only lowers the efficiency of the cells but also speeds internal diffusion processes which ultimately leads to the cell becoming ineffective. Unless a photovoltaic solar energy collector can be made to last long enough to recover all the energy invested in its production and maintenance, it would be folly to deploy such systems. At the present, no information is available to indicate the total energy inverted in the solar cells themselves, but it is straightforward to determine that, if the support substrate were made of Al, 1 mm thick, it would require about 1.1 years of operation merely to recover the energy invested in the aluminum substrate. Consequently for photovoltaic solar energy collection, the lifetime of the collector system is a very important parameter.

As in the case of large installations using thermal collection, alteration of the local climate is an important concern. The effects would tend to be somewhat different, since a photovoltaic system absorbs a smaller fraction of the incident solar energy, but as a compensation the collectors would be spread over a large area of land.

b. Satellite-Borne Solar Energy Collectors

Studies have shown that the SSPS of optimum size would deliver about 10 GW of power to the earth.^{27, 28} As noted previously, this would require placing 2.5×10^7 kgs of material into orbit and would require between 300 and 1000 flights of a second generation space shuttle. In addition, about 1.4×10^4 kg of propellant would be expended by the SSPS in altitude or orientation control. Like all solar energy projects, much of the environmental impact comes from the vast materials demands created.

For most solar energy systems, the environmental impact is limited to the terrestrial or lower atmosphere regimes. However, the many flights of the space shuttle required to deploy the SSPS will result in injection into the upper atmosphere of significant quantities of water vapor arising from the combustion of liquid hydrogen and liquid oxygen fuel. Therefore, this raises the same questions about potential alteration of the upper atmosphere as were raised by the operation of a fleet of supersonic transports. Scientific debate has not completely settled the question of the impact of water vapor injection into the stratosphere.

Proponents of the SSPS (notably Peter Glaser of Arthur D. Little, Inc.) have stated that the energy expended to construct the SSPS could be recovered by SSPS operation according to the following schedule:

<u>Materials</u>	<u>Months Operation</u>
• Propellants	6
• Solar cells	3
• Ground support equipment	3

This list is clearly incomplete and, moreover, fails to account for indirect energy inputs which could be expected to increase this payback time by about a factor of five. It has also been claimed that as the SSPS would not place undue demands on resource supplies including Ga. However, a single SSPS of dimensions usually cited²⁸ that used GaAs solar cells would appear to require about 10^5 kg of Ga; this quantity 4 times as large as the cumulative total the Geological Survey expects to have become available by the year 2000.

The solar energy collected by the SSPS would be sent to earth over a beam of microwave radiation at about 3.3 GHz.^{27,28} The cross section of this beam must be made large enough that the energy density in the microwave flux is below levels that could cause damage to the health of humans and other organisms. To achieve an acceptably low energy density at the edges of the beam,* the receiving antenna would need to be about 7 km in diameter and would intercept about 90 percent of the transmitted energy.^{27,28} The hazards to passengers flying through the beam in an aircraft are theoretically negligible, although experimental confirmation would be warranted; the hazards to birds flying through the beam are not known.²⁸

* The present U.S. standards based on human health impairment from thermal (heating) effects is 10 mW/cm^2 . However, the Russians believe that dangers of a nonthermal nature exist and have set their standard a factor of 1000 more stringent. Scientific debate has not clarified this discrepancy.⁴¹

Some climatic change could be induced by an SSPS for several reasons. The first, and probably the most important reason arises from the additional energy added to the heat load of the planet. Unlike terrestrial collection, which intercepts only radiation that would reach the earth anyhow, an SSPS intercepts and beams to earth radiation that would not otherwise have reached the surface of the earth. In this manner, an SSPS contributes to an alteration of the thermal radiation balance between the earth and outer space. The detailed effects that would result from an alteration of the heat balance are debatable, but it is generally held that climatic change would result.

An SSPS could also potentially affect the climate through the heating of the atmosphere by the microwave beam. However, the attenuation of the beam by the molecules constituting the atmosphere as well as by suspended matter (including rain) is sufficiently small that no problems are expected.²⁸ The energy loss rejected to the environment by the receiving antenna and electrical rectification circuits has been calculated to be less than 10 percent.²⁸ This percentage is far lower than the rejected heat from conventional or nuclear power generation (between 60 and 70 percent). It is believed that this amount of waste heat can be convected directly into the atmosphere,²⁸ and therefore no cooling water would be needed, thereby removing at least one important environmental constraint on the siting of a receiving antenna.

Even though terrestrial solar energy collection schemes do not require a continuous expanse of level land, details of the terrain pose even less of a constraint on the SSPS receiving antenna. It could be sited on otherwise derelict land such as unrestored strip mines.²⁸ Moreover, the receiving antenna can be sited near the ultimate energy consumption, such as the Northeast, thereby eliminating the cost and environmental disruption of electrical distribution.

c. Small-Scale Installations on Buildings

Because photovoltaic collectors capture a smaller percentage than thermal collectors, the surface area required for the photovoltaic systems is larger. In thermal systems, the collected energy would be used directly to heat or cool a building, but in a photovoltaic system, the electrical output would be required to drive an electrical resistance heater, a heat pump, or air conditioners. Moreover, with present battery technology it is awkward, as well as expensive, to provide much energy storage capability. Photovoltaic systems, however, do offer the advantage of having an electrical output that is more easily controlled and distributed throughout the structure. Therefore, this increases the likelihood that existing structures would be retrofitted to make use of solar energy.

The space program has had need for ensembles of solar cells arrayed on flexible sheets that could be transported into space in a small package and then unfurled. Industrialists believe that eventually solar cells can be fabricated and interconnected in a single process that would result in a thin, flexible, durable sheet of solar collector material that could be used as the "skin" of new or existing structures. If this were achieved at low enough cost, many orientation and spacing design constraints could be relaxed for buildings using solar energy. The building could simply be "papered" with solar cells (some of which would operate inefficiently because of poor orientation or exposure). Such a solar cell skin material would also make viable the collection of solar energy on buildings in northern climates.

As can be expected from the delicate nature of the solar energy resource, any photovoltaic system designed for buildings will require a substantial commitment of special materials resources.

The aesthetic and local climatic consequences of photovoltaic systems on buildings would be quite similar to thermal collection of solar energy on buildings as discussed above.

3. Thermal Energy from the Sea

Some preliminary conceptual designs for sea solar plants have been published.^{23,32} Warm surface waters at about 25°C are drawn past heat exchange surface where energy is transferred to a working fluid that vaporizes; the warm water is exhausted, slightly cooled to about 23°C. The vaporized working fluid drives a turbine to generate electricity and then the working fluid is reliquified as it passes another heat transfer surface that is cooled by water about 5°C that has been pumped up from the depths; the cooling water is warmed slightly and is exhausted at about 7°C. The thermodynamic efficiency of a turbine working between such a slight temperature difference is only a few percent at best. For this reason, the extraction of solar energy stored in the heat capacity of sea water requires a thermal exchange surface with a very large area.

From published discussions of conceptual designs,^{23,32} it is possible to estimate the materials requirements for a 1-GW plant. The heat transfer surfaces for the boiler and condenser need to have an area of about $1.4 \times 10^7 \text{ m}^2$. This surface area is essentially the same as that estimated for the 1-GW large scale thermal plant discussed earlier. Consequently, if the heat exchange surfaces can be made rather thin, say 1 mm, the materials requirements are nearly the same as the large scale terrestrial thermal plant. A highly efficient heat transfer surface made of an aluminum alloy has been mentioned as an appropriate choice.³²

Unlike the terrestrial collection of solar energy, the heat transfer surface need not be arrayed in a single large surface. Instead, it can consist of a network of parallel tubes or passages through which

the water can pass. Experience with structures in the marine environment has given clear evidence that it will prove very difficult to prevent the fouling of the relatively small heat transfer tubes by marine organisms.⁴³ It will be essential, however, to inhibit colonization of the small passages by organisms because their presence will both lower the efficiency of the heat transfer surfaces and will impede the flow of the water. The energy required to pump the vast quantities of water involved already pose a significant design constraint, even without accounting for these additional losses. Consequently it can be forecast with reasonable certainty that chemical inhibitors would be injected into the flowing water to suppress the unwanted growth of organisms within the heat transfer apparatus. Since the concept calls for a once-through passage of vast quantities of water, the amount of biological inhibitors released to the marine environment would be very large. It will require careful analyses by experienced marine biologists to ascertain whether the amount of inhibitor employed can be chosen to prevent colonization of the power plant on one hand, yet not harm the natural ecology downstream from the plant on the other hand. There is another source of contamination besides the inhibitor. The metallic surfaces of the passages and conduits may corrode and erode at about a rate of 0.025 mm (1 mil) per year. Besides imposing an engineering design constraint to ensure that the thin walls of the installation (1 mm or 40 mils) have an adequate lifetime, this erosion could become a non-trivial environmental contaminant.

To collect the water from the depths, a long, vertically suspended conduit is needed; designs routinely mention lengths of more than 600 meters, and the conduit would need to be about 38 meters in diameter for a 1-GW plant. Presumably this conduit can be designed to flex with the currents and need not be particularly thick. If the conduit is 1 cm in thickness, it would require about $5 \times 10^3 \text{ m}^3$ of material; if aluminum were used, the requirement would be about $1.4 \times 10^7 \text{ kg}$. This is

about 15 percent more aluminum than would be required for the heat transfer surfaces.

Since the entire plant would be submerged and parts would extend vertically for long distances under water, very considerable marine construction problems are implied. However, there has been experience with FLIP, a research oceanographic platform that is sailed into position like a ship and then partially flooded and thereby flipped on end to become a long, submerged vertical research platform. However, use of such a technique undoubtedly implies more structural integrity and therefore more materials.

Although a submerged structure poses considerable questions of construction technique, submersion eliminates some of the problems normally associated with boilers and turbines in conventional electric generation plants.³² In particular, conventional boilers are operated at high temperatures and experience a large pressure differential between the two sides of the boiler wall. As a result of the pressure differential, compounded by the weakening of most materials at elevated temperatures, the boiler walls need to be rather thick. For a submerged boiler, the depth of submersion can be selected so that the pressure of the sea water exactly matches the pressure of the vaporized working fluid.^{23,32} Moreover, the low temperature of the sea water driving the boiler very substantially reduces the thickness needed to provide the requisite structural integrity. The low temperature of the sea water also implies that a working fluid with a low boiling point, such as ammonia or propane, is needed. Some workers,⁴³ however, are wary of relying upon submersion to establish a pressure balance. They point out that prior to startup of the facility and in the event of a rupture, the pressure of the water might crush the closed system containing the heat transfer fluid, thereby resulting in a massive spill. Since ammonia (which is very toxic) is believed to be one of the most suitable heat transfer fluids for this technology,^{23,33,43} a spill could have a catastrophic effect upon marine life.

Clearly, a great deal of water must be moved past the heat exchange surfaces to extract sufficient energy to make the concept viable. In fact, it has been cited that about one-third of the gross power output must be consumed to drive the pumps.³² Other information, however, leads to a somewhat lower estimate: about one-eighth the power needs to be consumed to drive the pumps.²³ In any event, the movement of this much water requires some careful thought in engineering design to prevent the warm and cool effluents from mixing in such a way that an eddy current is established, drawing cool water to the warm water intake and thereby stagnating the very thermal differences required to run the plant. Proponents of this concept of tapping solar energy maintain that it will be possible to make use of natural currents to sweep away the water once it is used and to replenish both the warm and cool thermal reservoirs. Assuring this cleansing effect places a constraint on the choice of locations suitable for these plants.

Even though careful design may prevent thermal stagnation, the movement of these vast quantities of water will lead to a change in the ecology of the ocean. Whether this change is for the better or the worse will be partly a matter of plant design and human desires. It is well known that the richest fishing grounds are found in areas where there is a natural upwelling to the surface of nutrient-rich cool waters from the depths.⁴² A plant to extract solar energy stored in sea water will artificially create much the same effect by raising nutrient rich cool waters near the surface. This "plowing" of the ocean can be expected to increase the population size of living forms as well as alter the species composition of the population, since the ecological niche will have been altered by the change in temperature. Since this could be managed to lead to a larger harvest of marine life, this could be regarded as a beneficial side effect.

An important aspect of the solar sea power concept is the location of the plants. Many countries, especially the less developed ones, border warm tropical waters. However, the combination of water conditions necessary to operate a plant are seldom found very near the shore; many locations are more than 40 kilometers offshore. Countries in the Caribbean area are important exceptions. A suitable site has been identified about 6 km off the Florida coast (east of Miami) and about 2 km off Puerto Rico. The distant locations of these large plants from the nearest shores may raise important questions of international law regarding exploitation rights in international waters, environmental change, and the establishment of installations that could interfere with navigation.

The long distance from shore of most possible installations poses problems of delivering the energy generated to the point of applications. Underwater electric transmission lines have been considered, but some people working in the area feel that production of hydrogen at the plant site for later distribution for use as a fuel represents the most desirable solution to the problem of energy delivery. Production of hydrogen at the site clearly requires additional structures, perhaps on floating platforms. Hydrogen could be sent to shore by underwater pipelines or in liquid form in special tank ships. It is clear that either an underwater electrical transmission line or a hydrogen pipeline would result in some environmental disruption during construction.

One of the chief advantages of the use of solar energy stored in the sea lies in the continuous availability of the energy. There would be no important diurnal changes and only slight seasonal changes in the power output of the station. This uniformity of output effectively eliminates the need to store energy that is typical of terrestrial collection of insolation. This fact allows the plant output to be designed to closely match actual demand and thereby eliminate the need to commit materials resources for spare plant capacity that is used only occasionally.

4. Wind Power

The extraction of energy from the winds, although a very old technology, has fallen into such disfavor that few serious attempts have been made to evaluate its potential for energy production in light of modern aerodynamic concepts and lightweight, high strength materials. Winds are generally not continuous, although they are usually predictable and are remarkably regular in their occurrence. Consequently, like almost all other solar energy concepts, utilization of wind power requires an energy storage mechanism to buffer the timing discrepancy between supply and demand for energy. Since all wind power concepts envision the use of a turbine of various designs to extract the kinetic energy of the winds and convert it into rotational energy of a shaft, generation of electricity is the most obvious form of energy output. Once again, the awkwardness of storing energy in electrical form suggests that the electrolysis of water to obtain hydrogen or some other chemical form of energy storage would be appropriate.

Not all regions of the country have winds of sufficient regularity or strength to make wind power an attractive proposition--especially since idle time greatly increases the already high capital investment in wind power generators. A brief inventory of appropriate sites on U.S. soil or near the shoreline have indicated that in the year 2000 it might be possible to generate about 175 GW.⁶

Large-scale application of wind power will require very large-sized windmills. The recent NSF/NASA solar energy report⁶ suggests that a turbine about 60 meters in diameter would be required to generate 2MW. Thus 500 of these 60-meter turbines would have to be deployed to generate 1 GW of power--when the wind blows at the design level of the turbine.

Although too few conceptual designs of large windmills have been published to make estimates of materials needs for windmills a productive

exercise at this time, it is clear that, like all solar energy collection processes, the materials needs of the collection mechanisms are enormous. Thus, although wind power may itself be pollution free, substantial off-site pollution associated with the materials production would occur.

Wind power cannot be considered separately from climate or weather modification. For one reason, it is still unknown whether the erection of lines or clusters of windmills that extract from 10 to 20 percent of the kinetic energy from the area swept by the turbine would alter the local or regional climate. Just as a windbreak of trees offers sufficient impedance to the flow of wind to result in a local shift in air flow, and hence microclimate at the ground, so an array of windmills would probably offer sufficient impedance to somewhat deflect the winds. Another reason is that the deployment of windpower installations might be materially affected (either beneficially or detrimentally) by weather modification programs undertaken for other purposes. Enhancement of wind power potential might itself become a motive of weather modification projects.

5. Energy Plantations

Growing plants to be used as fuel for an electricity generating plant or as feedstock for a process such as fermentation that yields a chemical fuel can be appropriately termed an "energy plantation." This concept is being studied (at SRI among other places) to determine its feasibility. In the past, rather lavish claims based upon unrealistically optimistic assumptions of photosynthetic efficiency have been advanced about the effectiveness of this concept.²⁵

An energy plantation would borrow heavily from both modern intensive agricultural and forestry techniques. Plants would be selected to optimize the following variables:

- Photosynthetic efficiency through the growing cycle (including periods when the canopy of foliage is not closed).
- Amount of dry plant material produced per unit energy input into husbandry activities (e.g., cultivation, harvesting, irrigation).
- Resistance to disease and climatic variations.
- Convertibility of plant material into a usable form (such as by chipping).
- Ease of harvesting and handling.

Rather large areas are required for an energy plantation.

Sugar cane is one of the most suitable plants identified to date. With a typical 20-month growing period, about 650 square kilometers of sugar cane plantation would be required to sustain a 1-GW electric power plant. Therefore, it is clear that a highly efficient, highly mechanized operation is essential to the viability of the energy plantation concept.

Many environmental problems associated with an energy plantation transfer from experience with intensive agricultural production:

- Displacement of natural plant and animal populations.
- Erosion control.
- Irrigation practice including concern for induced chemical change in the soil.
- Pest control (plant and animal).
- Maintenance of fertility.
- Run-off polluting waterways (fertilizer, pesticides).
- Dust and erosion control during tilling and harvesting.
- Simplifications of ecosystems.
- Introduction of exotic species (and their potential for escape and infestation elsewhere).
- Major land and water development projects.

The problem of vegetable wastes typical of foodstuff agriculture would be avoided in an energy plantation because the crop would be completely utilized. However, after combustion or chemical processing, there would be an ash or sludge residual that would require disposal. Unlike coal ash, however, these residuals can be returned to the soil (in a controlled manner) without harm. This return of residuals to the soil is, in fact, desirable to lessen the need to add chemical fertilizers. Maintenance of the humus content of the soil could become a problem because no organic matter would be returned to the soil to decompose.

Compared with other solar energy collection techniques, an energy plantation requires relatively little commitment of physical materials. Instead, a significant commitment of land and water that might have major usefulness for foodstuff production is required. Although lands considered marginal for conventional agriculture might be selected, hilly terrain or low productivity of the soil compromise the energy efficiency of the system.

An aquatic plantation, either fresh or marine, may also prove feasible. Water hyacinth, for example, has attributes that are especially attractive for the rapid production of biomass. A land-based aquatic plantation would require the establishment of a large number of ponds to produce an adequate quantity of aquatic plant matter. These ponds, of course, would require continued surveillance to control incidental pest species--e.g., mosquitos. Although natural waterways could act not only as a growth substrate but also as a means for waterborne plants to deliver themselves to a downstream processing plant, it is not very likely that sufficient surface area could be made available for this purpose. One significant problem with water hyacinth and some algae species is that they spread easily and are difficult to control. Their reputations as "weeds" would probably lead to public resistance to their deliberate and large-scale cultivation and encouragement--especially if natural waterways were contemplated.

As in all energy processes, it is important to consider the energy balance to ensure that more energy is actually produced than is consumed in the various processes. Drying the crop turns out to be the major energy requirement in the energy plantation system. Sun drying appears to be the most efficient way to eliminate the water from the plant tissues preparatory to combustion or digestion. The cut plants can be crushed and rended during harvesting to open the plant tissues to accelerate drying. Left in the field for only a matter of days or weeks, nearly all the water can be eliminated from plants so conditioned. Should additional drying prove necessary, careful attention to design could make waste heat available from the energy conversion installation for final drying. Because field drying occupies land that could otherwise be supporting plant growth, this second form of solar energy utilization increases the amount of land needed for the plantation by about 10 percent.

Several ideas have been advanced to improve the photosynthetic efficiency of the plants cultivated:

- Use the warmed power plant cooling water to irrigate the plantation.
- Recycle the CO₂ from the combustion process by erecting canopy-like enclosures for the crop.

These measures must be evaluated in terms of the investment and operating energies required by the hardware of the irrigation system and the enclosing canopies to determine whether the measures result in an actual net increase in system effectiveness.

III SOLAR ENERGY: IMPLICATIONS AND RECOMMENDATIONS FOR EPA ACTION

Although it is not accurate to maintain that the use of solar energy is "pollution free," most of its environmental impacts would arise indirectly rather than directly. The prevailing theme of solar energy utilization is the deployment of collectors with a large surface area, and most of the environmental effects would result from the mobilization of sufficient natural resources to construct these collectors. Consequently, many of the environmental impacts of the use of solar energy can be classified as a continuation or intensification of the impacts resulting from present resource development activities. However, a few unique impacts such as certain land use questions, the evolution of sun rights, and the plowing of the sea, would result from the various solar energy systems already discussed.

The present status of solar energy utilization technology is summarized in Table 5 (adapted from Ref. 6). Thermal collection for use in buildings is currently receiving emphasis from the National Science Foundation, the agency of the federal government assigned to oversee solar energy research. Contracts to be awarded by NSF in late 1973 will lead to hardware that can be marketed in about 1978. The use of solar energy for biological conversion of organic matter to fuels, such as methane, may become a minor activity by 1985, although in that time frame this effort is expected to remain largely confined to solid waste conversion. No other class of solar energy technology is expected to be ready for meaningful deployment until the 1985-2000 time frame.⁶

Because of the present major uncertainties in the configuration of solar energy utilization technologies, it seems premature for EPA to initiate the development of technologies intended to control potential

Table 5

PRESENT STATUS OF SOLAR UTILIZATION TECHNIQUES

Application	Status					
	Research	Development	Systems Test	Pilot Plant Demonstration	Prototype Plant	Commercial Readiness
Thermal energy for buildings						
Water heating	X	X	X	X	X	X
Building heating	X	X	X			
Building cooling	X	X				
Combined system	X	X				
Renewable clean fuel sources						
Combustion of organic matter	X	X	X	X		
Bioconversion of organic materials to methane	X	X	X	X		
Pyrolysis of organic materials to gas, liquid, and solid fuels	X	X	X	X	X	
Chemical reduction of organic materials to oil	X	X	X			
Electric power generation						
Thermal conversion	X					
Photovoltaic						
Residential/commercial	X					
Ground central station	X					
Space central station	X					
Wind energy conversion	X	X	X			
Ocean thermal difference	X	X	X			

X indicates effort is underway but not necessarily complete. Source: NSF/NASA Solar Energy Panel⁶

adverse environmental impact. Indeed, because so much of the environmental impact of solar energy would be associated with the production of materials on a vast scale for collectors, most of this control function is already being accomplished by the present EPA air, water, solid waste, and land use programs that address the environmental problems associated with minerals recovery and materials production.

EPA is, however, in a favorable position to initiate a program to influence the course of development of solar energy technologies in directions that will minimize or avoid future environmental control activities. This program could begin modestly but increase in importance and effort as solar energy technologies become more clearly defined in terms of configurations, processes, and the materials employed. Either an office within EPA or a contractor could be assigned a continuing responsibility for interactive liaison with the solar energy research and development activities sponsored by government and industry. By keeping abreast of the state of the art and analyzing potential environmental impacts on the one hand, and by conveying to the technologists the environmental implications of the devices being developed on the other hand, a continuing and constructive cooperative dialogue could be established. In this manner EPA would be taking positive advantage of the available opportunity to anticipate and influence technology as it emerges, rather than become obligated to take remedial action to correct environmental insult.

A set of guideline objectives common to all solar utilization technologies might take the following form:

- Technologies should employ the minimum amount of materials possible, especially those whose production is known to have significant environmental impacts.

- Technologies should avoid use of materials for which there are few domestic resources, so that recovery of lean resources will not disrupt the environment and require large quantities of processing energy.
- Devices should be designed to facilitate their dismantling and recycling upon retirement.
- The materials employed should not be toxic, to avoid contamination of the environment during the erosion or weathering resulting from prolonged exposure.*
- Designs should be secure against the release of hazardous or toxic materials during a device failure or natural disaster event.
- Designs and concepts should take early cognizance of potential legal or institutional barriers, such as the emergence of the concept of "sun rights" analogous to mineral or water rights.

In addition to these general guideline objectives, EPA could impart its concern for potential environmental problems associated with specific technologies, such as

- Release of chemicals to suppress growth of marine organisms in ocean thermal difference installations.

* This category includes some subtle but significant concerns. For example, it has been reported that sheep grazing under overhead high-voltage electric transmission lines have been killed from copper poisoning. The soil directly under the wires contained concentrations of copper higher than those of nearby soil, although neither concentrations were high on an absolute scale. Since this enrichment of copper in the soil under the wires was not found in rural areas, it has been suggested that erosion of copper cables may result from the action of sulfur dioxide in the polluted air of urban areas.⁴⁴

- Special pesticide requirements of energy plantations.
- Climate modification induced by large terrestrial arrays of solar energy collectors.

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Appendix B

GEOHERMAL ENERGY

by

Evan E. Hughes

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I GEOTHERMAL ENERGY: STATE OF THE ART

A. Introduction

The production of electric power from energy contained in steam and hot water beneath the earth's surface is currently being accomplished. In fact, such production has been going on since 1904 in Italy and since 1960 in the United States. Therefore, this discussion of the environmental impacts of the production of energy from geothermal sources can be based in part on actual experience. The main reason for treating geothermal energy as a new energy technology is that any use of this resource on a scale at all comparable with that of this country's use of energy would indeed be new and could become visible as a new set of environmental impacts. This working paper examines the present use of geothermal energy and draws conclusions regarding the environmental impacts of the projected use of this resource to meet a significant fraction of future energy needs in the United States.

First we survey the present technology for converting geothermal energy into electrical energy. The experience with this technology forms the basis for our recognition of some environmental impacts and for our projections of changes in the nature and scale of geothermal energy use. We do not necessarily view the present state of the art as the technology that will actually be deployed to tap most of the geothermal energy resource, but it should provide a more accurate projection of future geothermal technology than projections we now have for other energy sources not currently in commercial operation.

B. Use of Natural Geothermal Steam

In a geothermal power plant, the steam used to drive the generators of electrical power is obtained from wells drilled into reservoirs of steam or hot water hundreds of meters below the earth's surface. The crucial contrast to a conventional fossil fuel power plant is the fact that the steam is obtained without the combustion of fuel to fire a boiler. This contrast provides the basis for the expectation that geothermal energy will alleviate the environmental problems so clearly associated with our usual steam-electric plants. No combustion means no emission of the familiar air pollutants: oxides of nitrogen, oxides of sulfur, carbon monoxide, unburned hydrocarbons, and particulates. This constitutes a significant environmental advantage.

The steam that is obtained from below the earth's surface is not identical to the steam obtained from the boiler of a fossil fuel plant. The differences between the steams necessitate differences in the turbine-generators used to convert the steam energy into electrical energy. The differences between the steams also give rise to additional contrasts between the environmental impacts of fossil fuel and geothermal power plants. These contrasts, occurring both before and after the boiler stage, do not accumulate to the environmental advantage of the geothermal plant. We now turn to an examination of these technical and environmental differences as they appear in state-of-the-art power plants of the two types.

1. Contrasts: Fossil Fuel Versus Geothermal

The turbine is the classical heat engine stage of a steam power plant. It receives energy in the form of the heat of the high temperature, high pressure steam and converts some of that heat into the mechanical energy of the rotating shaft common to both the turbine and the generator. The heat energy not converted into mechanical energy emerges from the

turbine as the heat of the low temperature, low pressure steam bound for the condenser unit of the power plant. The laws of thermodynamics limit the fraction of the input heat energy that can be converted into mechanical energy (work) to a value that depends on the temperatures of the steam at input and output. To maximize this ratio of work to input energy the input temperature must be as high as possible and the output temperature as low as possible. Modern fossil fuel plants obtain thermodynamic efficiencies of over 40 percent by superheating the steam that goes into the turbine from the boiler. But a geothermal steam plant must take the steam provided by the subsurface reservoir and such geothermal steam, although sometimes superheated, has never been found at temperatures comparable with those obtainable in boilers. The consequence of these physical facts is that a geothermal plant must take in and exhaust out considerably more heat than a fossil fuel plant producing the same amount of electrical energy.

Here are the figures for a quantitative comparison of the sort just described: A modern fossil fuel powered plant (Pacific Gas and Electric's new units numbered 7 and 8 at Moss Landing, California) has turbines accepting superheated steam at a temperature of 540°C and a pressure of 25 MPa and exhausting this steam to the condensers at 29°C and 4.1 kPa (1.2 inches of mercury). The theoretical efficiency of an ideal heat engine operating between these two temperatures is 63 percent. The actual operating experience at the plant is that 8.71 MJ of heat content of fuel produce 1 kWh of electricity. This implies an actual boiler and conversion efficiency of 41 percent, which also implies that, if the unit were scaled up to generate electrical power at the rate of 1.0 gigawatt (GW), then waste heat would be exhausted into the plant's environment at the rate of 5.2 TJ per hour (2.4 GW). These figures are to be compared with a recent (1971) addition to this country's geothermal generating capacity. The turbines of a modern geothermal plant (PG&E's

units 5 and 6 at The Geysers, California) accept the steam provided at a temperature of 180°C and a pressure of 0.784 MPa and exhaust this steam to the condensers at 52°C and 14 kPa (4" Hg). The theoretical efficiency of an ideal heat engine operating between these two temperatures is 28 percent. The actual operating experience at the plant is that 22.8 MJ of heat content of steam (8.2 kg of steam at the entering temperature and pressure) produce 1 kWh of electricity. This ratio of electricity to heat implies a conversion efficiency of 16 percent. It also implies that to generate electrical power at the rate of 1000 MW this type of geothermal plant would exhaust heat into the environment at the rate of 19.3 TJ per hour (5.2 GW). The numbers used in developing this comparison are summarized in Table 1.

The low thermal efficiency revealed by the figures just given is inherent in geothermal energy development. The input steam cannot be at a temperature higher than that provided by the natural reservoir. Increased efficiency obtained by lowering the temperature at the discharge end of the turbine is limited by the ambient temperature of the local environment. Because the heat energy in geothermal steam is supplied without fuel costs, geothermal plants are economically competitive with fossil fuel plants despite their lower thermal efficiency. Given that known geological steam reservoirs have temperatures in the range 200 to 350°C (400 to 650°F), marked improvement in thermal efficiency cannot be expected, and the relatively larger injection of heat into the plant's environment must be accepted as a necessary consequence of geothermal power production.

Increases in the economic efficiency of power plants are indicated by decreases in the cost of generating a given amount of electrical energy. Such increases in efficiency have been realized through the economics of scale in the case of fossil fuel and nuclear plants. The

Table 1

COMPARISON OF FOSSIL FUEL AND GEOTHERMAL POWER PLANTS

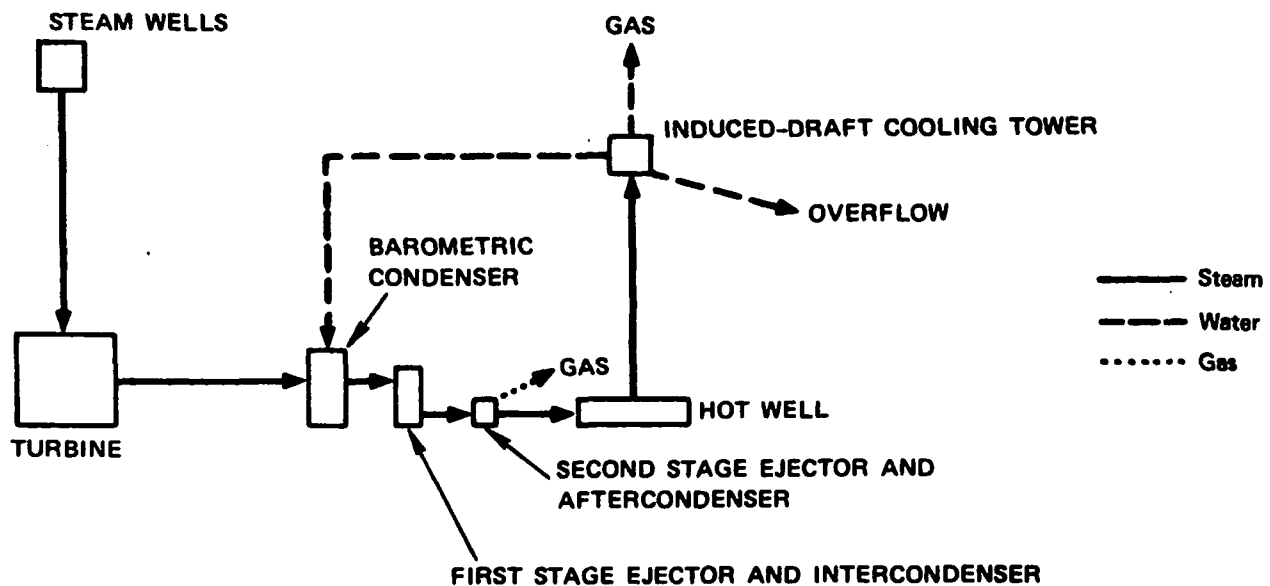
	Fossil Fuel Moss Landing Units 7 and 8	Geothermal The Geysers Units 5 and 6
Rated capacity of unit	750 MW	55 MW
Steam temperature entering turbine	540°C (1000°F)	180°C (355°F)
Steam pressure entering turbine	25 MPa (3675 psia)	784 kPa (114 psia)
Steam temperature leaving turbine	29°C (84°F)	52°C (126°F)
Steam pressure leaving turbine	4.1 kPa (1.2" Hg)	14 kPa (4.0" Hg)
Ideal thermal efficiency	63 percent	28 percent
Actual heat rate	8.7 MJ/kWh (8,296 Btu/kWh)	23 MJ/kWh (21,690 Btu/kWh)
Actual efficiency	41 percent	16 percent
Heat rejected at plant site per GW electric power	1.4 GW (5×10^9 Btu/hr)	5.2 GW (18×10^9 Btu/hr)

Source: SRI, 1973.

trend toward larger plants would have to be included in an assessment of the state of the art in the technology of such plants. In the geothermal case, however, the peculiarities of reliance on a natural source of steam enter the analysis and suggest that the limit on unit size is already within sight and is appreciably below the thousand megawatt sizes now common for new fossil fuel and nuclear generating plants. Generating units at The Geysers have been scaled up by successive factors of two since the early 1960s, but are now seen as leveling off not much above the 106-MW capacity of the unit scheduled to go on line in 1974.^{1*} In that particular case, the limit is said to be based on considerations of transportation of the unit over the access roads and of the length of steam supply lines. This latter consideration concerns an issue of importance to any geothermal plant, namely, the power generating capacity per unit of land area.

The geothermal power plant does away with the boiler required in fossil fuel and nuclear plants, but in its place it must substitute a network of wells and pipelines to tap and transport the energy contained in the geothermal steam. (A schematic diagram of the system used at The Geysers is shown in Figure 1.) In terms of environmental impact, it is more useful to view the steam gathering facilities as replacements for the mining, oil drilling, fuel processing, and other such facilities associated with fossil fuel or nuclear plants. However viewed, the particular kind of energy collection used in a geothermal plant determines many of the technological constraints and environmental impacts of this means of producing electrical energy. Unit size and waste heat production have already been named in this connection. Other consequences of using naturally occurring geothermal steam are discussed in succeeding sections.

* Numbered references are listed on page 210 at the end of Appendix B.



SOURCE: Kaufman, 1964. (Reference 2)

FIGURE 1 GEOTHERMAL POWER GENERATION—DRY STEAM WELLS, SINGLE CYCLE

2. Constraints on Plant Size

We have stressed the fact that the steam temperature is determined by the geophysical conditions of the natural reservoir, and to this extent it is beyond the control of the plant designer. However, the designer does have control over details of how the natural reservoir is to be tapped. Decisions must be made as to the size and spacing of the wells drilled into the reservoir. These decisions tend to be based on experience obtained in operating geothermal steam fields and power plants. An important design decision, related to the eventual decision on generating unit size already mentioned, concerns the spacing of the wells. To minimize the energy lost in transporting the steam to the turbine, the wells should be placed as close as possible to the power plant, and hence close to each other. But two other features call for a large separation of steam wells, namely, (1) the interference effect whereby the addition of a nearby well decreases the steam production rate of an existing well and (2) the depletion rate effect whereby the spacing of wells closer together causes

the total production rate to decline in a shorter length of time.³ Once the depletion characteristics of the field are known, this information combined with the desired lifetime for the generating plant determines the rate of production of steam that can be maintained for the lifetime of the plant from a given surface area of land. Because there is a limit to the distance the steam can be usefully transported over the surface, there is a limit to the land area that can be tapped for a single generating unit. There follows then a limit to the capacity of the generating unit.

Again, some numbers taken from the operating experience at The Geysers can illustrate the design considerations we have just discussed. The closest well spacing is about one well per five acres of land. To place wells much closer together would result in unacceptably large interference effects and short depletion time. Adopting 2 hectares (5 acres) per well for the spacing and combining it with the observed production rate per well of 68,000 kg/hr (150,000 lbs/hr) gives a figure of 34,000 kg of steam per hour per hectare at The Geysers. Given that experience dictates a limit of less than a mile for the distance over which steam can be economically transferred by pipe,⁴ we arrive at the expectation of obtaining about 9 million kg of steam per hour from the 250 hectares in the square mile of land one could tap for a single plant.

The quality of this steam and the efficiency of the generators are such that it requires about 900,000 kg of steam per hour (2×10^6 lbs/hr) to generate 100 MW of electrical power.⁵ This suggests that a plant of 1,000 MW could be powered by the steam within transportable distance of the plant. However, depletion considerations reduce this maximum plant size still by a considerable factor. Measurements of production rates of steam wells over the past six years at The Geysers⁶ show an average exponential decay with a five year half-life for wells spaced at two hectares. This implies that over the 20-year lifetime of a generating unit the production of wells at this spacing would fall to one-sixteenth

of their initial production rate, thus necessitating the drilling of 16 times the number of wells needed initially. Because land sufficient for drilling a large number of replacement wells must be set aside, the actual capacity of a generating unit supportable on a square mile of land is on the order of 100 MW rather than 1000 MW. Thus the peculiarities of the geothermal resource limit the possibilities for economies of scale in the building of the turbine-generator units.

Estimates of the land area needed to support a given geothermal generating capacity can be derived from the same specific facts used here to explain the relatively small unit sizes contemplated for geothermal electrical power generation. Because the subsequent discussions of environmental impact in this report make use of this estimate of the land area involved, the figures just presented are summarized in Table 2. Table 2 also shows that the larger spacings such as 8 or 18 hectares per well lead to substantially the same generating capacity per square mile because the decreased number of wells is compensated for by the increase in well lifetime. Thus, as one might expect, the power capacity per unit area is determined by the nature of the steam resource rather than by the way it is tapped.

3. Impurities in Natural Steam

The effects discussed so far are based on the energy content of natural geothermal steam. A number of other technical and environmental effects have their basis in the material content of naturally occurring geothermal steams. These steams vary in content from one geothermal deposit to another, but the natural deposits invariably contain impurities that would not be allowed in water for the boiler of a fossil fuel or

Table 2

LAND USE AND DEPLETION CONSIDERATIONS
FOR THREE POSSIBLE WELL SPACINGS

	2 hectares (5 acres) <u>per well</u>	8 hectares (20 acres) <u>per well</u>	18 hectares (45 acres) <u>per well</u>
Number of wells possible on one square kilometer	50	12	5
Time for production rate to drop by half	5 years	12 years	19 years
Number of wells to support 30 MW plant at initial production rate of 60,000 kg steam/hr per well	5	5	5
Number of wells needed per initial well to make up for depletion over 20-year period	16	3	2
Total number of wells drilled to support 30 MW plant for 20 years' operation	80	15	10
Area required to support 30 MW plant for 20 years of operation	1.6 sq km	1.2 sq km	1.8 sq km

Source: SRI, 1973.

nuclear plant. The presence of impurities has technical consequences for the construction and operation of a geothermal power plant and has environmental consequences for both the air and water media.

The technical complications that arise from the use of natural steam are the special steps needed to avoid impact damage and corrosion. Traps and separators to capture sand particles are built into the steam pipe system and the dust content of the steam is monitored to minimize damage caused by the impact of small particles on the turbine blades. At The Geysers, the operating time between overhauls of the turbines should soon be extended to about two years, a figure to be compared with the five to six year interval that is routine with PG&E's fossil fuel units.⁷ Molecular impurities present in the steam at The Geysers include a variety of metals and ions, as well as a variety of noncondensable gases. These constituents are detailed in Tables 3 and 4. The presence of these materials can adversely affect the operating equipment as well as the surrounding environment. This threat of corrosion is met by the use of special alloys and protective coatings in the construction of the power plant. Tests lasting for several years are being performed at The Geysers to determine which materials are most resistant to the particular corrosive influences present. Austenitic stainless steel, 13-percent chromium steel, and aluminum appear to have key roles in the construction of a geothermal power plant resistant to corrosion and impact erosion.¹⁰

Because a geothermal reservoir discharges gases other than steam when tapped, there is the potential for air pollution. The noncondensable gases found in the geothermal steam at The Geysers were listed in Table 3. The most abundant such impurity is carbon dioxide, which is not regarded as an air pollutant. (It can be argued that manmade CO₂ has the potential to affect global climate, but that is not a regional air pollution issue and, in any case, is not an adverse effect peculiar to geothermal power plants. In fact, the CO₂ emissions from a fossil fuel

Table 3

NONCONDENSABLE GASES IN THE
GEOTHERMAL STEAM AT THE GEYSERS

<u>Gas</u>	<u>Percent by weight</u>		
	<u>Low</u>	<u>High</u>	<u>Design</u>
Carbon dioxide	0.0884	1.90	0.79
Hydrogen sulfide	0.0005	0.160	0.05
Methane	0.0056	0.132	0.05
Ammonia	0.0056	0.106	0.07
Nitrogen	0.0016	0.064	0.03
Hydrogen	0.0018	0.019	0.01
Ethane	<u>0.0003</u>	<u>0.002</u>	<u>-</u>
TOTAL	0.120	2.19	1.00

Source: Finney, 1973 (Reference 1, Table 1).

Table 4

COMPOSITION OF GEOTHERMAL FLUIDS

Component	Parts per million by weight		
	The Geysers, California	Cerro Prieto, Mexico	Niland, California
Sodium	.12	5,610	53,000
Potassium	.10	1,040	16,500
Calcium	.20	321	27,800
Lithium	.002	14	210
Magnesium	.06	Negative	10
Strontium	.10	28	440
Barium	--	57	250
Rubidium	--	--	70
Cesium	--	--	20
Iron	--	--	2,000
Manganese	--	--	1,370
Lead	--	--	80
Zinc	--	--	500
Silver	--	Trace	--
Copper	--	Trace	--
Silicon dioxide	.50	--	400
Chlorine	20.00	9,694	155,000
Boron	.10	12	390
Fluorine	.10	Trace	--
Sulfur	7.10 (sulfate)	10	30
Total Dissolved Solids	28.38	17,000	259,000
Ammonium	236.0		
Bicarbonate	775.0		

Source: Rex, 1970 (Reference 8) and Koenig, 1970 (Reference 9).

plant are about 20 times those from an equivalent geothermal plant.)¹¹
The most critical air pollutant listed in Table 3 is hydrogen sulfide.

Since no emission controls are yet in use at The Geysers, the gases listed escape freely to the air. This emission occurs sporadically as a result of the venting of steam and continuously as a result of the release of steam from the turbine to the condenser and cooling tower. The environmental impact of such emissions is discussed later in this report. The amount of sulfur put into the air by a 1000-MW geothermal plant at The Geysers would be comparable with that emitted by a 1000-MW fossil fuel plant burning coal with a 1 percent sulfur content. The sulfur is emitted as H_2S from a geothermal plant and as SO_2 from a fossil fuel plant. PG&E is investigating the possibility of controlling H_2S emissions by the condensing of the sulfur as sulfate in the condenser. Apparently about 30 percent of the sulfur already goes out of the steam via this route.¹² Catalyzed precipitation of the sulfur is also under investigation.

The impurities in the steam that have their primary effect as dissolved matter in the condensate were listed in Table 4. In addition to the equipment corrosion problems posed by these materials in solution, a potential water pollution problem arises from the ejection of condensate into the local water supply. The high content of boron and ammonium in the condensate led to the decision not to continue disposal into local streams at The Geysers after unit number 4 was added in 1968. The alternative to ejecting the condensed steam and its contents into the water supply is the reinjection of this material into the subsurface geothermal reservoir. This has been successfully carried out at The Geysers for the past several years. The alternative of chemical treatment of the power plant's waste water was found to be prohibitively expensive.¹³

4. Other Consequences of Using Natural Steam

In addition to the effects on equipment, air, and water discussed so far, the reliance on a natural source of steam has other environmental effects that differ from those associated with other types of steam generating plants. Foremost among such effects are those arising from the exploration and drilling that necessarily accompany the tapping of a geothermal energy source. Exploration and drilling also accompany the production of energy from oil and gas. This means that both the technology and the environmental impact of these aspects of geothermal energy development are similar to the oil and gas case.

Two significant contrasts should be pointed out. First, in the geothermal case the exploration and drilling take place at the site of the generating plant. This fact implies the concentration of the impacts associated with fuel collection, fuel processing and transport, and electricity generation to a single site. It also implies the lack of the freedom to place the electrical generator close to the site of electricity consumption. The second contrast to oil and gas drilling operations is the particular noise problem associated with geothermal steam production. The inadvertent blowout of a geothermal steam well produces a loud noise as the steam rushes into the air. Some deliberate ventings of geothermal steam into the atmosphere must occur as a part of normal operations when a well is being put on line to feed its steam into a generating unit being started up. At The Geysers, although mufflers are installed to reduce such noises once a well is completed, a noise problem remains. Some noise is inevitable and cannot be muffled, as when the steam reservoir is first tapped during the drilling. It is also a fact that the noise is hard to muffle because of its intensity and the low frequency of its spectrum.

5. Hot Water Versus Vapor-Dominated Geothermal Systems

The description up to this point has been based on the one case where geothermal energy has been put to use in the United States, namely, The Geysers power plant in California. This particular geothermal reservoir is an example of the type that is most easily tapped for electric power generation. It is a vapor-dominated geothermal system as opposed to a hot water-dominated system. The present discussion of the state of the art of geothermal energy must go on now to include aspects peculiar to the hot-water systems. The inclusion of this material is made all the more necessary by the fact that most of the known geothermal energy resources of this country are systems dominated by hot water.

The distinction between hot water-dominated geothermal systems and vapor-dominated geothermal systems is made on the basis of which of the two relevant phases of water, the vapor or the liquid phase, is the continuous fluid that controls the pressure within the subsurface geothermal reservoir.¹⁴ The significant contrast as far as the production of electrical energy is concerned is that to tap the energy of a hot water-dominated system large quantities of liquid water containing dissolved minerals must be brought to the surface. The vapor required by the turbine-generator is obtained either by using the hot water to vaporize some other fluid, such as isobutane, which then becomes the working fluid for the turbine, or by allowing the hot water to turn into steam by virtue of its being subject to lower pressure than it experienced in the reservoir. This latter process, allowing the water to flash to steam, has the disadvantage of using only the fraction of the water that becomes steam as an energy input to the turbine. This fraction is only about 15 to 25 percent.⁹

6. Power Plants for Hot Water Resources

Flashed steam from hot water wells is being used to produce electricity in New Zealand and Mexico. The New Zealand geothermal power plant at Wairakei (160 MW) has not been an unqualified success. The first experimental plant was abandoned in 1964 after only a year of operation because of an insufficient steam supply from the wells.¹⁵ The plant was constructed again on a more centralized plan using extensive pipelines to bring the steam to a site where a river could be used for cooling water. Recent discoveries of natural gas in New Zealand have resulted in a decision to postpone the expansion of geothermal power which had been planned for this decade.

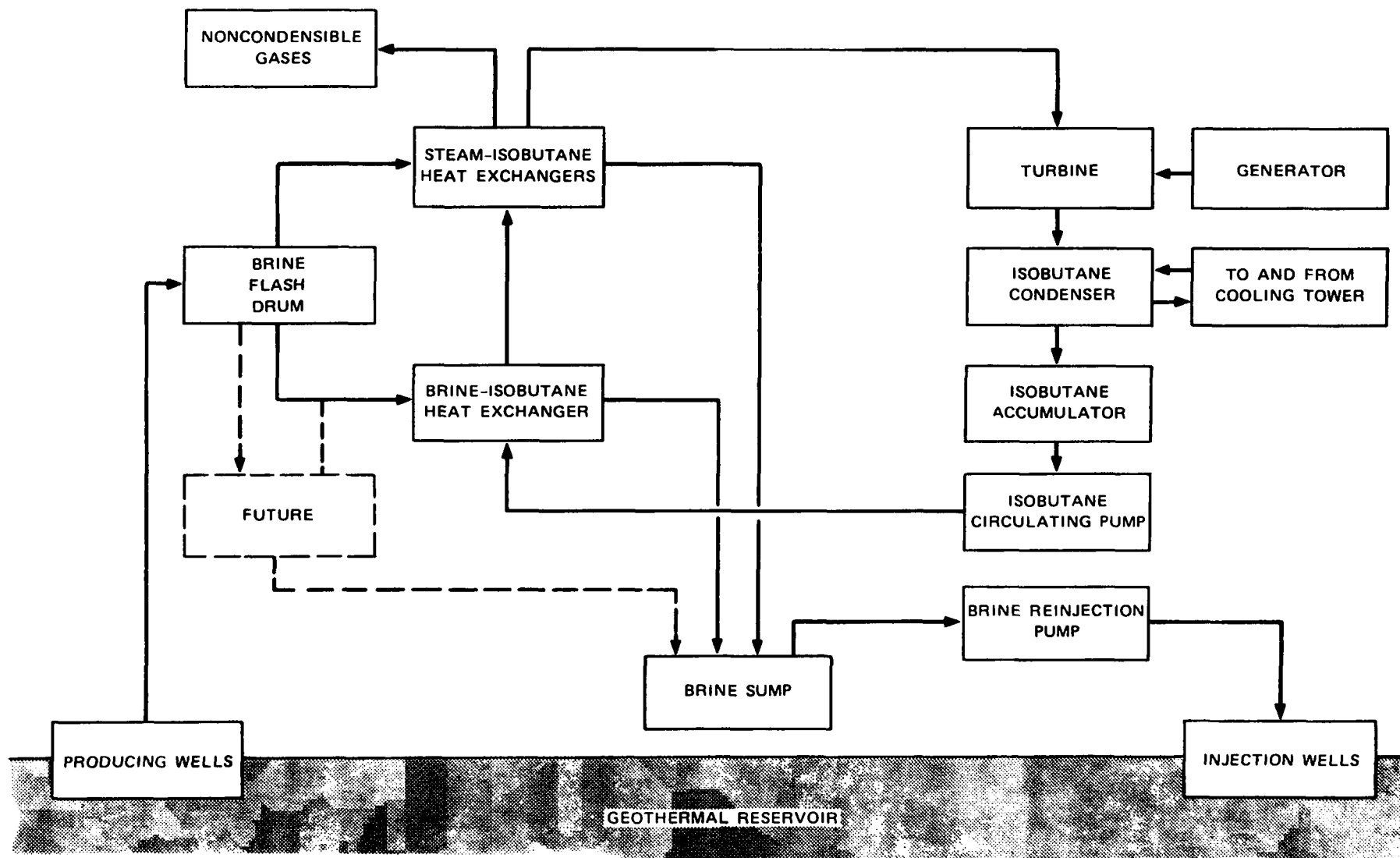
The experience with geothermal power from hot water wells in Mexico is more likely to be useful for applications envisioned for the United States. At Cerro Prieto, near the north end of the Gulf of California, a 75-MW geothermal power plant is just beginning operation. The reservoir is water at temperature somewhat over 300°C and of high salinity, about 15,000 parts per million. The Cerro Prieto plant is on the southern extremity of a geothermal field extending into the Imperial Valley of California, and warrants special attention because of the great similarity of the resource to significant geothermal resources in the United States. The conversion of steam to electricity will be comparable in efficiency and method with that at The Geysers. But because Cerro Prieto is a hot water field, the 9 kg of steam needed to produce 1 kWh of electricity will be accompanied to the surface by at least 30 kg of water of high salinity.^{16, 17} No attempt is being made at Cerro Prieto to reinject this waste brine into the geothermal reservoir, but plans for similar installations in California's Imperial Valley envision either reinjection or desalination of the brine.¹⁸

One method of estimating the economic costs or the environmental impacts of geothermal power from a hot water source such as the Imperial Valley is to assume similarity to the actual experience at The Geysers and then to add on the additional costs or impacts associated with the brine. This method has been used by Goldsmith.¹⁹ As experience accumulates at the Cerro Prieto plant, another basis for such estimates will be established.

As was mentioned above, reinjection is being carried out at The Geysers. Because the reinjection there is easier than it would be in a hot water field, two important contrasts should be noted. First, the amount of waste water brine to be disposed of is much greater in the case of a hot water system. At The Geysers, the condensed geothermal steam becomes the cooling fluid for the condenser by virtue of its passage through the evaporative process in the cooling tower. Since this evaporative cooling is accomplished by the evaporation of about 80 percent of the condensed steam, the amount of condensate remaining to be disposed of by reinjection is only 20 percent of the mass of steam brought to the surface in the first place. Given the additional fact that a typical hot water generating system produces at least 3 pounds of water for every pound of steam, it follows that about 15 times as much waste water is to be reinjected (or otherwise treated and disposed of) than is being reinjected for a comparable generating system at The Geysers. The second contrast in the reinjection processes derives from the lower pressure required for reinjection in the case of a vapor-dominated system like The Geysers. Because the steam pressure in a vapor-dominated reservoir is less than the hydrostatic pressure at the same depth,²⁰ the natural gravitational pressure of the column of water in the reinjection well is sufficient to force the waste water back into the reservoir. On the other hand, reinjection into a hot water reservoir may require pumping to increase the pressure above hydrostatic and, therefore, may require energy from the power plant. It is more like the reinjection practiced in many oil fields.

There is an alternative technology for the exploitation of hot-water-dominated geothermal energy resources, a technology that is further removed from our present base of experience in that it is not simply a system like The Geysers with provision for handling of hot water wastes added on. This alternative power generation scheme is referred to in various ways, the most common being combined cycle, binary cycle, or vapor-turbine cycle. The method entails bringing the hot water to the surface under enough pressure to keep it in the liquid phase, extracting its thermal energy by heat exchange to another fluid, expanding this working fluid through a turbine to power the electrical generator, and reinjecting the hot water, now somewhat cooled by the heat exchange, back into the geothermal reservoir. A schematic of a generating plant using this technology is shown in Figure 2. This schematic is for a 10-MW binary cycle power plant built as a test facility by San Diego Gas and Electric Company (SDGE) near Niland on the Buttes anomaly in the Imperial Valley. This particular example of a binary cycle plant includes the possibility of flashing some of the hot water (brine) to steam before the passage through the heat exchanges.

The design of an electrical generating system using a hot water geothermal source contains a number of trade-off decisions based on a knowledge of economic costs and environmental impacts, as well as of technical principles. Thus, the complications of the binary cycle must be weighed against those of sending steam flashed from saline water directly into the turbine and condenser. The benefits of getting input heat from water or steam at the highest possible temperature and pressure must be weighed against the costs in dollars and energy of using pumps rather than natural percolation action to get that heat to the surface. The air quality advantages of the binary cycle, which derive from keeping both the geothermal brine and the working fluid in closed cycles and away from exposure to the atmosphere, must be weighed against its added water



SOURCE: San Diego Gas and Electric Company Geothermal Test Facility.

FIGURE 2 GEOTHERMAL POWER GENERATION—HOT WATER WELLS, BINARY CYCLE

resource costs, which derive from not having condensed steam available for use as cooling water. Work has been done to establish systematic procedures for optimizing the performance of a binary cycle generating plant given the characteristics of a particular geothermal site.²¹ The combination of such engineering work and the operating experience beginning to emerge from small scale projects around the world will soon put the assessment of hot water sources on an empirical basis more like that for dry steam sources such as The Geysers.

The description so far has dealt with the tapping of naturally occurring geothermal reservoirs. These reservoirs consist of hot water or steam heated by thermal energy from within the earth and contained within some large, continuous volume under the earth's surface. These energy resources are tapped by using the naturally occurring water or steam to carry the heat to the surface via wells drilled for that purpose. Therefore, such natural reservoirs constitute hydrothermal-convection systems whether they are dry or wet in nature. In addition to the techniques discussed so far, there are ways to obtain geothermal energy without depending solely on natural occurrences of the combination of (1) a geothermal heat source, (2) a large volume capable of holding water or steam, and (3) the presence of water in the heated volume. Energy obtained by intervention designed to create this combination where it does not occur naturally is referred to as stimulated geothermal energy.

C. Use of Stimulated Geothermal Resources

Like the hydrothermal-convective systems we have been describing, geothermal energy systems that result from stimulation must rely on some natural mechanism to bring heat from the earth's interior, and, as in the case of hydrothermal-convective systems, the greater the rate of natural heat flow the greater the potential of the energy resource. Stimulation, then, does not entail the generation of the heat source but rather entails

the creation of one or both of the other two ingredients of the combination required for a geothermal reservoir, namely, the large, continuous volume and the water present in that volume. The large, continuous volume of a useful geothermal reservoir usually consists of the spaces within interconnected cracks in fractured crystalline rocks. This suggests that the creation of a geothermal reservoir can be stimulated by intervening to fracture rock that is near a strong heat source but is not sufficiently fractured to constitute the chamber needed to store and transport water or steam. Various means of fracturing the hot, dry rock have been suggested and some have been studied in detail. Hydrofracturing, high explosives, acid treatments, thermal fracturing, and nuclear explosives have all been mentioned in this context. Considerable analysis has been done on nuclear stimulation as a part of the AEC's Plowshare program.

Because the development of stimulated geothermal energy is appreciably behind that of hydrothermal convective and because extensive use of stimulated sources will have to follow the demonstrated success of significant exploitation of the natural hydroconvective sources, this report does not pursue the technology and environmental impact of stimulated geothermal energy. To the extent that the guarantee that geothermal energy can assume a major share of the production of electricity in the United States becomes a determining factor in the decisions of utilities to go ahead with use of this source at all, the possibilities for stimulating geothermal energy could become crucial because of the vast increase in potential sites that would accompany a stimulation capability. However, at the present time, utilities are going ahead with development of hydrothermal convective sources, and concentration on these environmental impacts is warranted for the near term. The tests of stimulation techniques should be carried out with environmental protection in mind, both in the physical execution and in the data collection stages. This appears to be the case.

D. Use of Geopressured and Magmatic Resources

Two other categories of geothermal energy exploitation are currently under discussion but are not yet in the testing stages. These are the use of geopressured resources and the use of magmatic resources. Geopressured reservoirs consist of hot water and methane gas stored in the interstices of porous, as opposed to fractured, rock in sedimentary basins. Such aquifers are detected by their abnormally high fluid pressures and can be tapped for energy in three ways: (1) the chemical energy of the contained methane gas, (2) the mechanical energy of the water released from its high pressure containment, and (3) the thermal energy (heat) of the water. The relatively low quality (i.e., low temperature) of the thermal energy in these reservoirs prevents their exploitation by the techniques now used for hydrothermal convective sources and, thus, puts their possible use further into the future.

The second category, magmatic geothermal reservoirs, consists of the locations where hot, molten rock from the earth's interior has penetrated close enough to the surface to become accessible via drilling. At present, neither the extent of such resources nor the technology for tapping them are clear. In short, geopressured and magmatic resources exist as potential sources of geothermal energy production but are so far behind hydrothermal convective resources in terms of their utilization that they lack priority for present environmental impact research.

II GEOTHERMAL ENERGY: ENVIRONMENTAL IMPACTS

A. Introduction

The description of geothermal energy technology presented in the first part of this working paper emphasized that the major environmental liabilities of geothermal energy are direct consequences of the fact that we must accept the hot water or steam as nature provides it. The major environmental advantages are consequences of the same fact, viewed in a different light, namely, the fact that nature has provided us with thermal energy capable of producing electricity without the necessity of combustion in a boiler or fission in the core of a nuclear reactor. Hence, we should focus on the properties of geothermal steam or water as providing the best introduction to some details of the environmental impact associated with the use of the most accessible geothermal energy resource, namely the hydrothermal convection system. Table 5 summarizes several properties of such geothermal reservoirs, selected from fields being studied or tapped throughout the world. A brief description of the contents of Table 5 can serve to introduce this discussion of environmental impacts of geothermal energy.

B. Survey of Properties and Impacts of Geothermal Resources

The temperatures in column 2 are low in comparison with the 500°C (or higher) temperatures of the steam generated in the boiler of a modern fossil fuel plant. The consequence of this was stressed by the comparison of PG&E's latest fossil fuel and geothermal generating units given in the first part of the paper. The low thermal efficiency which characterizes geothermal plants is the inevitable consequence of the

Table 5

CHARACTERISTICS OF SELECTED GEOTHERMAL FIELDS

(1) Field	(2) Reservoir temperature, °C	(3) Reservoir fluid	(4) Enthalpy, cal/g	(5) Average well depth, meters	(6) Fluid salinity, ppm	(7) Mass flow per well, kg/hr	(8) Non- condensable gases, %
Larderello, Italy	245	Steam	690	1,000	< 1,000	23,000	5
The Geysers, U.S.A.	245	Steam	670	2,500	< 1,000	70,000	1
Matsukawa, Japan	230	Mostly steam	550	1,100	< 1,000	50,000	< 1
Otake, Japan	200+	Water	~ 400	500	~ 4,000	100,000	< 1
Wairakei, New Zealand	270	Water	280	1,000	12,000	--	< 1
Broadlands, New Zealand	280	Water	400+	1,300	--	150,000	~ 6
Pauzhetsk, U.S.S.R.	200	Water	195	600	3,000	60,000	--
Cerro Prieto, Mexico	300+	Water	265	1,500	~ 15,000	230,000	~ 1
Niland, U.S.A.	300+	Brine	240	1,300	260,000	~ 200,000	< 1
Ahuachapán, El Salvador	230	Water	235	1,000	10,000	320,000	~ 1
Hveragerdi, Iceland	260	Water	220	800	~ 1,000	250,000	~ 1
Reykjanes, Iceland	280	Brine	275	1,750	~ 40,000	~ 400,000	~ 1
Namafjall, Iceland	280	Water	260	900	~ 4,000	400,000	6

Source: Koenig, 1973 (Reference 22).

Second Law of Thermodynamics given the temperature difference available when the steam in the reservoir is no hotter than 300°C. The temperature relevant to the calculation of the maximum possible thermal efficiency is the temperature of steam entering the turbine and this must be considerably lower than the reservoir temperature. A typical value for existing geothermal plants is 180°C for the entering steam. The corresponding value for the steam produced in the light water reactors now in use for nuclear power plants is about 300°C. In actual operation, efficiencies are typically 40 percent for a modern fossil fuel plant, 30 percent for a current nuclear plant, and 15 percent for a geothermal plant. These operating efficiencies correspond to the following rates of heat rejection into the environment at the plant site: fossil fuel, 5.4 MJ/kWh; nuclear, 8.4 MJ/kWh; and geothermal, 20.3 MJ/kWh.

When finally translated into environmental impact, the relatively low temperatures of the geothermal reservoirs imply that for every kilowatt-hour of electricity generated at a typical inland geothermal site about 6 kwh of heat will be put into the atmosphere in the form of water vapor emerging from an evaporative cooling structure. Most photographs of The Geysers show condensed steam rising into the air from a row of short, wide cylinders on the top of an induced-draft horizontal cooling tower. This is the visible form of the disposal of waste heat from a 106 MW generating plant.

The implications of column 2 of Table 5 for heat disposal are similar to the implications of columns 3 and 4 for fluid disposal. The specific enthalpy given in column 4 is a measure of the heat energy per unit mass of the geothermal fluid and, therefore, is directly related to the rate at which mass must be processed through the system to produce a particular amount of electric power. The Geysers' specific enthalpy of 670 cal/g (2.8 MJ/kg) is 1200 Btu/lb in old engineering units, which was the basis for

the 9 kg (20 lbs) of steam per kWh figure used in the first part of this paper. Even more important than the lower values of specific enthalpy characteristic of the reservoirs that are water rather than steam is the fact that most of the liquid is not flashed to vapor. Thus, the distinction in column 3 is crucial in considering the amount of matter that must be handled to produce the desired electrical energy. The next stage in the expansion of geothermal energy use will be the exploitation of hot-water-dominated reservoirs, and the typical operation will result in about three pounds of water for every pound of steam.

The next column in Table 5 gives some indication of how deep the wells must be to tap these hydrothermal convective reservoirs. The depth of the wells is a major factor in the cost of developing a geothermal field,^{23,24} although the relationship between costs of drilling and the final cost of the electricity is not yet established and used in the pricing of the electricity.²⁵ A typical 2 km (7000 ft) well at The Geysers now costs about \$400,000. In terms of environmental impacts, the figures on well depth in the table call attention to the fact that many impacts of geothermal energy production are similar to those of oil production. The depths indicated in column 5 are not atypical of the depths of oil wells, although the average oil well now drilled in the United States is probably more comparable with experience at The Geysers than with the lesser depths of the other fields included in Table 5. The early stages of development of a geothermal field produce environmental impacts quite similar to the exploration, road building, drilling, and testing stages of oil field development. One difference in drilling procedure is that air is used as the circulating fluid to remove drill cuttings once a geothermal drilling operation enters a steam bearing zone. This results in a so-called "controlled blow-out" which is noisy compared with oil drilling, where mud is the circulating

fluid. Muffling of the sound is helpful, but not completely effective. This noisy stage of the drilling is said to amount to only a few days out of the total drilling time.²⁶

The salinity of the steam or water obtained from the various geothermal fields is indicated in column 6 of the table. For comparison we note that the salinity of sea water at a typical mid-ocean point is 3.48 percent by weight.²⁷ This is the basis for the change in designation from "water" to "brine" in column 3 as the transition is made from 15,000 to 40,000 ppm salinity levels. The environmental implication of the salinity figures in Table 5 is that geothermal fluids cannot be discharged into fresh surface waters as a matter of course. In the first part of this paper it was pointed out that at The Geysers the unevaporated condensate (which constitutes 20 to 25 percent of the mass of the steam originally brought to the surface) is disposed of by reinjection into the geothermal reservoir rather than by discharge into Big Sulphur Creek. Yet, the much more saline geothermal waters at Cerro Prieto and Wairakei are discharged without treatment into surface waters. Local considerations account for the different practices, and it is a safe bet that the local considerations in the semi-arid regions of the western United States will call for either reinjection or treatment of the waters from geothermal systems.

Column 7 giving the rate of mass flow typical of single wells at the various geothermal sites illustrates again the point that much larger amounts of fluid must be handled at the surface when the geothermal resource is a hot-water-dominated system. Another point already made is that this mass ultimately will be removed from the plant site by evaporation, reinjection, or surface discharge (with treatment presumably preceding the discharge).

Two other aspects of the environmental impacts of geothermal energy follow from the mass flow rates. First, the mass flow rate can be combined with specific enthalpy in column 5 and the observed operating efficiency (ultimately limited by the reservoir temperature given in column 2) to obtain the electrical power producible by a single well. In the first part of the paper, this sort of calculation was combined with some facts of depletion experience to arrive at the estimate of 100 Mw per square mile for the land surface density of electric power production at The Geysers. Second, the high rate of removal of material accompanying appreciable generation of electricity from a geothermal field could cause local geophysical effects, namely, subsidence of the land surface or stimulation of earth tremors. Subsidence has long been observed in some oil fields, and has been treated by injection of water to replace oil removed from the reservoir. Earth tremors have been associated with the injection of liquid wastes into subsurface reservoirs in Colorado. Such experiences indicate the possibility of these geophysical impacts also arising from geothermal energy production practices, but whether they would occur and whether their occurrence would constitute an adverse environmental impact depend on properties of the particular site as well as on factors not adequately understood.

Column 8, the final column of Table 5, directs attention to the air pollution problem that can be associated with geothermal energy. Gases or volatiles come to the surface as a part of the geothermal fluid, and the fraction of this material that does not condense out to be handled as a liquid can escape into the air. To date, the escape of such gases has not been viewed as air pollution on a scale requiring control measures, but the need for control is likely to arise. This possibility is pointed out by the facts that the odor of hydrogen sulfide is detectable at The Geysers and that some corrosion of electrical

circuit elements at the power plants can be attributed to the concentration of this gas found in the atmosphere near the plants.²⁸ Control of hydrogen sulfide is under active investigation at The Geysers. The nature and quantity of the noncondensable gases in The Geysers' steam were presented in the first part of this paper as Table 3. Hydrogen sulfide's role as the most important of these prospective pollutants was indicated there. Ammonia probably ranks second.

C. Scaling Factors for Environmental Impacts

Those prepared to be critical of the alleged cleanliness of geothermal energy suspect that this new energy technology is simply enjoying the benefits of the invisibility that goes along with being small. The preliminary environmental analysis presented so far contains enough information to make some tests of this suspicion. What is required is knowledge of the nature of the environmental impacts and an estimate of how the sizes of the various impacts are related to the amount of electricity produced. That estimate is the scaling factor needed to project the impacts of use on a larger scale.

1. Scaling Factor for Land Use

For the impacts that are related more or less directly to the amount of land needed for the production of geothermal energy the required scaling factor has been estimated in Section I of this chapter. A factor of about 33 MW per sq km was derived by considering the production and depletion rates of wells spaced about 2 hectares apart at The Geysers. In the discussion that followed, it was pointed out that Table 2 presents figures indicating that a similar value is obtained by considering wells spaced with areas of 8 or 18 hectares per well. Therefore, for the scaling of land use impact we adopt the factor 33 MW per square kilometer.

As a rough indicator of accuracy, we submit that a factor smaller than 15 MW per sq km is very unlikely, as is a factor larger than 50 MW per square kilometer. The factor was obtained from a consideration of hydrothermal convective reservoirs and should be considered applicable only to this type of geothermal field.

2. Emission and Effluent Factors

Similar scaling factors can be obtained for estimating environmental impacts on air and water quality. Given information on the fractions of various potential pollutants in the geothermal fluids, information such as contained in Tables 3 and 4, and empirical rules for steam-to-electricity conversion, such as the 9 kg of steam per kWh rule applicable to The Geysers and Cerro Prieto, the appropriate emission factors (for air) or effluent factors (for water) are easily obtained. The results for the two most critical emissions to the air at The Geysers are factors of 4.5 kg per hour per megawatt (MW) for hydrogen sulfide and 6.3 kg per hour per MW for ammonia. To obtain the effluent factors for the Imperial Valley fields (Niland and Cerro Prieto), it is necessary to know the water-to-steam ratio for the flashing procedure used in the operation. Assuming 18 percent of the water flashes to steam¹⁷ (a 9-to-2 ratio) and using the 9 kg steam per kWh factor previously introduced, the figures in Table 4 lead to the following effluent factors for Cerro Prieto:

- Salinity--17,000 ppm and 40 kg/hr per kW give an effluent factor of 700 kg/hr per MW.
- Boron--12 ppm and 40 kg/hr per kW give an effluent factor of 0.5 kg/hr per MW.

For The Geysers some effluent factors so derived are:

- Salinity--28.4 ppm and 9 kg/hr per kW give an effluent factor of .25 kg/hr per MW.
- Boron--.10 ppm and 9 kg/hr per kW give an effluent factor of .001 kg/hr per MW.
- Ammonium--236 ppm (the rest goes to the air as gaseous ammonia) and 9 kg/hr per kW give an effluent factor of 2 kg/hr per MW.

These emission factors can be used, together with a knowledge of the air or water flow through the region of the geothermal field, to estimate the air or water quality that would result from uncontrolled emissions from a given level of electricity generation. When the resulting estimate of quality is compared with an air or water quality standard, we have an indication of the presence or absence of a significant environmental impact.

D. Environmental Impacts of Large-Scale Use of Geothermal Energy

Before applying this test of environmental impact to a few cases, it would be worthwhile to cite the actual experience at The Geysers. We have noted that hydrogen sulfide emissions at The Geysers has been sufficient to cause odor and some corrosion of electrical equipment. The experience with water pollution there is that Big Sulphur Creek, the channel for natural surface water flow at The Geysers, has an inadequate volume of flow at its low season to dilute the power plant condensate. Ammonia and boron were the primary water pollution concerns. As has been mentioned, the result of this concern was a decision to reinject the condensate into the geothermal reservoir.

To test the proposition that geothermal energy would not appear to be clean if it were used on a significant scale, we must adopt some quantitative definition of the term "significant scale." To do this

we will look at California's projected electrical energy consumption and see what happens if we assume that geothermal resources account for one-fourth of that projected growth. During the past year, SRI has developed projections of energy supply and demand in California. Here we will take some figures from that work for the period 1975 to 1985. The analysis by SRI projects the electric energy consumption in California to be 168 billion kWh during the year 1975 and 300 billion kWh during the year 1985. The increase in annual electrical consumption is then projected to be 132 billion kWh during that 10-year period. Defining geothermal energy use on a significant scale to be one quarter of this increase calls for an estimate of the environmental impact of building and operating enough geothermal generating capacity to produce 33 billion kWh of electricity during a year.

1. Land-Related Impacts

The land area needed to produce this electricity by geothermal means can be estimated as follows: Facilities capable of generating 3.8 million kW would produce 33 billion kWh of electricity if they operated all the time at full capacity for a year, i.e., operating with a 100 percent load factor. Since an 80 percent load factor is more likely for a geothermal plant supplying base line power, we will proceed on the assumption that 4,500 MW (4.5 million kW) of geothermal generating capacity would supply one-fourth of the increase in electricity consumption in California over the decade 1975 to 1985. The land area needed for this would be 135 sq km, according to the 33 MW per square kilometer land-use factor we have adopted. This area is 52 square miles or 33,300 acres. For comparison, it may be noted that power production at The Geysers now occupies about 30 sq km of a reservoir that is known to extend for about 50 sq km and probably extends to a

considerably larger area. The Imperial Valley covers over 3,000 square kilometers, with about half the land now devoted to agriculture. It appears that there is enough land for significant use of geothermal energy in California. However, because the land requirements of geothermal energy are appreciable and because the use of land as near as possible to the consumption of electricity is desirable, the possibilities for multiple use of geothermal lands should be investigated.

2. Impact on Air Quality

What would be the impacts on air and water from the generation of 33 billion kWh per year by geothermal plants with a total generating capacity of 4,500 MW located on over 100 sq km of California land? This question will be answered subject to the scaling factors already estimated and to assumptions concerning the volume of air and water available for dilution of the pollutants. For air, we will assume a box model of an air basin with wind and inversion height parameters characteristic of inland mountain and valley terrain.²⁹ For water, there are no characteristic parameters of flow that would be useful, because the variation from one geothermal site to another can be very large. However, to have some number for sensing the scale of the problem, the Colorado River will be used as a reference in what follows.

The box into which the hydrogen sulfide and ammonia are assumed to be emitted has a square base 10 km on a side (on the order of the 135 sq km) and is 0.3 km high. (A characteristic adverse inversion height is a few hundred meters.²⁹) Light winds, 5 km/hr, move air in one direction through the box for 14 hours a day, thus providing a volume of 0.3 km × 10 km × 70 km to contain a day's emissions from the power plants. These emissions from plants totaling 4,500 MW are at the rate of 20,000 kg/hr for hydrogen sulfide and 28,000 kg/hr for ammonia, giving a daily

total of 500,000 kg of hydrogen sulfide and 700,000 kg of ammonia. These totals diluted in the daily volume of 200 cubic km result in a pollutant concentration of $2500 \mu\text{g}/\text{m}^3$ for hydrogen sulfide and $3500 \mu\text{g}/\text{m}^3$ for ammonia. The California state standard to prevent odor from hydrogen sulfide is 0.03 ppm, which is $45 \mu\text{g}/\text{m}^3$, less than 2 percent of the concentration just estimated. The odor threshold for ammonia is 46.8 ppm,³⁰ which is about $35,000 \mu\text{g}/\text{m}^3$, a factor of 10 greater than the concentration just estimated. The conclusion is that in the case of hydrogen sulfide, at least, there is a potential air pollution problem from the production of geothermal energy on a significant scale.

3. Impact on Water Quality

We have used air pollutant emission factors based on experience at The Geysers. In turning now to water pollution considerations, we have effluent factors for both The Geysers and Cerro Prieto, and, as Table 4 indicates, we could obtain yet another set of effluent factors based on the geothermal brine at Niland. This further emphasizes the fact that water pollution considerations are likely to differ significantly from one site to another. Proceeding to make some gross estimate of the environmental impact from discharging geothermal waters into surface waters, we take the Colorado River to establish a sense of the amount of water available in the arid Southwest where hot water geothermal resources exist. The mean annual flow of water in the Colorado River is about $480 \text{ m}^3/\text{sec}$.³¹ Making the generous assumption that 10 percent of this water is available to dilute the Cerro Prieto type of geothermal waters from our envisioned 4,500-MW geothermal generating capacity, we find that a flow of 170 million liters per hour is available to handle the 2000 kg per hour effluent of boron and the 3 million kg per hour effluent of total dissolved solids. Including the 40 kilograms per hour

of geothermal water associated with each kilowatt of electricity, we have another 180 million liters per hour, making a total of about 350 million liters of water per hour. The resultant concentration of dissolved boron is then 2000 kg in 350 million liters, or 6 mg/l. For total dissolved solids (salinity), we have 3 million kg in 350 million liters or 8400 mg/l. The permissible concentration of these materials given in the 1968 Report of the Committee on Water Quality Criteria³² are 1.0 mg/l for boron and 500 mg/l for the total dissolved solids. Thus, it would take the whole (rather than one-tenth) of the Colorado flowing with pure water to provide enough dilution for the surface discharge of waters from geothermal power plants making a significant contribution to California's 1985 electrical energy production. This estimate tends to confirm the necessity of the plans being made for reinjection or treatment of the discharge from hot water geothermal wells.

III GEOTHERMAL ENERGY: IMPLICATIONS FOR EPA

Considerations of what is possible within the well established technologies of fossil fuel and nuclear power plants have entered into the setting of the particular environmental protection standards now applied to these plants. To the extent that what may be necessary for adequate environmental protection was compromised in favor of what appeared technically possible with fossil fuel and nuclear fission plants, it would be desirable to set higher standards for future technology. Thus, the apparent air quality advantages arising from the lack of combustion at a geothermal plant suggest that tighter atmospheric emission standards be set for geothermal plants.

EPA should be in a position to follow the development of geothermal energy technology and to use its knowledge of the state of the art, together with its standard-setting authority to stimulate the technology of minimum adverse environmental impact. It is important that the mechanisms designed to stimulate such technology do not create barriers and disincentives that prevent a technology with overall environmental advantages from capturing the market it deserves. The activities of EPA related to geothermal energy should be directed toward acquiring the knowledge needed to strike the right balance between constructive stimulation and unwarranted restrictions. In the matter of air quality, for instance, a policy is needed that ensures that the geothermal advantages, i.e., no emissions of oxides of nitrogen, reactive hydrocarbons, carbon monoxide, particulates, and radioactive fission products, can be realized at the same time that the unacceptable current emission level of hydrogen sulfide is brought under control. The most obvious

implication is a policy allowing a lenient hydrogen sulfide standard during the early development of geothermal energy technology while indicating that strict controls are envisioned for the technology that eventually operates on a significant scale.

In the case of hydrogen sulfide emissions, the implementation of such a policy requires that the preliminary estimate given in this paper for the potential impact of emissions be refined to obtain a clear idea of the degree of hydrogen sulfide control likely to be necessary for environmental protection. This estimate would be the basis for a goal to guide both EPA and geothermal energy producers as this method of generating electricity continues to develop. The preliminary estimate we have given suggests that something on the order of 98 percent control may be required, and implies the need for EPA to direct its attention to the hydrogen sulfide problem associated with geothermal energy. That the problem has intermedia aspects is indicated by some current ideas for control of hydrogen sulfide emission to the air by oxidizing the sulfur to sulfate in solution in the water or by precipitating it as a solid.

Although other federal agencies share the responsibility for supporting promising technological development while EPA alone has the primary responsibility for environmental protection, the Agency does have opportunities for encouraging technical advances deemed promising on environmental grounds. Thus, the results of a study of hydrogen sulfide emission control could be the basis for both the setting of emission goals and the provision of support for some specific technical experiments.

The findings presented in this working paper indicate that the development of the binary cycle turbogenerator could lead to geothermal plants free of air pollution by enabling the heat energy to be extracted

without exposing the geothermal fluid to the air. This particular technology appears worthy of support on other environmental grounds as well. It appears the most promising means for exploiting the energy contained in extremely saline geothermal brines like those found in the Imperial Valley. This binary cycle technology also provides a means for tapping low quality (i.e., low temperature), but potentially nonpolluting energy sources such as geopressured reservoirs or regions of high temperature gradients in the oceans.

Three other technologies emerge as candidates for further study and possible support as a result of the findings presented here: (1) methods for reinjection of geothermal brines, (2) processes for the treatment and reclamation of saline waters, and (3) condenser cooling systems. The need to study condenser cooling systems arises from two facts: (1) The hot-water-dominated geothermal fields of the western United States are areas where cooling water is not abundant. (2) Because these are hot water sources the use of geothermal waters for cooling will have more severe environmental consequences than are apparent from the experience with the vapor-dominated field at The Geysers. In particular, the possibility of using dry cooling towers, now estimated to cost about three times as much as their wet counterparts,³³ should be investigated.

Further environmental analysis of geothermal energy should stress the contrasts between the environmental impacts of geothermal energy production and those of its fossil fuel and nuclear alternatives. Such an emphasis would lay the groundwork for the day when EPA may wish to simultaneously weigh the advantages and disadvantages of a whole array of present and future energy technologies with an eye toward applying pressure for or against particular energy options for the United States. That day has not arrived. In the meantime, the comparative analysis is needed not only for the possible tightening of standards suggested above

but also for pointing out areas where geothermal energy has impacts more adverse than its alternatives. In these areas there is a need for EPA to apply pressure toward the incorporation of appropriate changes in the developing technology. The investigation leading to this paper has revealed some areas meriting this sort of attention from EPA. There is the possibility that the reinjection of geothermal brines may contaminate the ground water supply through leaks in the well casings. There is an array of intermedia problems associated with geothermal brines: the air pollution and lowered enthalpy of flashing to steam, versus the reinjection and cooling problems of liquid processing, versus the solid waste potentials of treatment. Specifically, the Bureau of Reclamation's plan for obtaining useful water from the geothermal brines in the Imperial Valley bears looking into, as does a study of the potentials for the recovery of materials from geothermal brines, contracted for by the Bureau of Mines. The land use problems arising from both the sizable area requirements and the specific nature of geothermal activities indicate that a study featuring a comparison with oil field experience and an assessment of the possibilities for multiple use of the land would be useful.

These implications for EPA are put forward on the basis of our perception of the role currently required of EPA in matters of new energy technology. According to this perception, the need now is to follow and to influence the emerging technologies so that necessary environmental protection measures are incorporated in their technical development and in the projections of costs. The influence is to be exerted by requiring certain standards of performance and by supporting particular lines of research and development.

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Appendix C
ENERGY FROM OIL SHALE

by
Robert G. Murray

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I INTRODUCTION

Oil shale is considered as a solid fuel because it contains organic matter (kerogen) that can be recovered by heating and converted into a crude shale oil, gas, and residue. Oil shale deposits occur in at least 30 states, but the largest domestic deposits are in the Green River formation underlying roughly 40,000 square kilometers (16,000 sq mi) in Colorado, Utah, and Wyoming (Figure 1).

The Green River formation is a series of lake sediments with minor river deposits. Although the Green River formation covers a broad area in Colorado, Wyoming, and Utah, the largest accumulation of organic material occurs in the Piceance Basin. The general stratigraphic relationships of sedimentary formations have been investigated by previous workers, and the thickness of several major units has been determined.

The most important rock units for purposes of this study are the oil shale formation itself and the material between the oil shale and the surface. The richest and thickest oil shale beds are contained in the Parachute Creek member of the Green River formation. This member is exposed in precipitous cliffs at the southern part of the basin. The Parachute Creek member, which ranges from about 150 to 500 meters thick, is subdivided into three zones. Richest oil shales occur near the base of the upper zone, in the Mahogany zone. The thickness of the Mahogany zone and its oil content are subject to considerable variations. Representative averages of oil recovery for thicknesses up to 30 meters of the Mahogany zone range from about 100 to 180 m³ per million kg (25 to 42 gallons per ton). A decrease in thickness and oil yield is indicated near the margins of the basin.

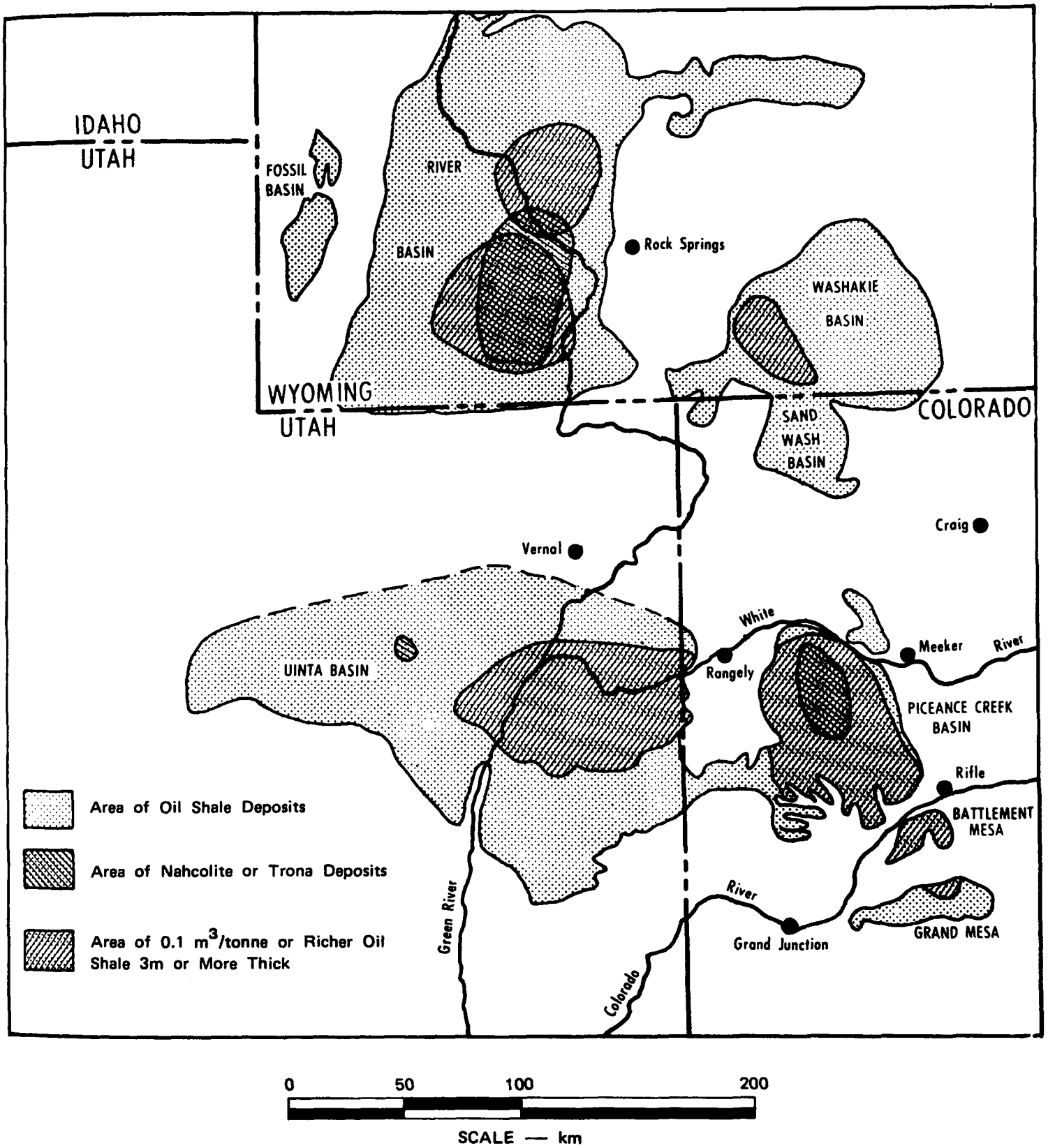


FIGURE 1 OIL SHALE AREAS IN COLORADO, UTAH, AND WYOMING

It is useful to classify shale reserves in terms of quality so that some perspective may be gained on the probable timing of commercial development.^{1*} Reserves of high-grade shale, defined as those deposits containing at least 0.15 m^3 oil per tonne shale (35 gal/ton) in beds at least 9 meters thick, are present that can yield $5.2 \times 10^9 \text{ m}^3$ (33 billion barrels) of oil. Reserves of intermediate grade of shale, at least 0.1 m^3 /tonne (25 gal/ton) and 9 meters thick, can yield $64 \times 10^9 \text{ m}^3$ (400 billion barrels) of oil. There are larger reserves of lower grade shale, but it is improbable that these will be recovered in this century.

Since approximately 30 percent of the high-grade shale exists in privately owned reserves, commercial development can be expected soon even if the federal leasing program should be delayed. The U.S. Department of the Interior plans to lease the shale reserves in each of the three states and has recently issued an environmental impact statement on this program. This leasing program will enhance the probability of commercial shale processing within the next five years.[†]

A production level of $8,000 \text{ m}^3$ (50,000 barrels) of oil per day is generally believed to be the smallest quantity that can be produced profitably at present oil prices. The tracts to be leased are about $20 \times 10^6 \text{ m}^2$ (5,000 acres) each, which will allow production of between 8,000 to $16,000 \text{ m}^3$ per day for a period of at least twenty years.

The quantity of oil recovered per unit area will depend upon the method of mining and retorting used, as well as on the shale assay and bed thickness. Demonstrated room and pillar mining has achieved shale

* Numbered references are listed on page 244 at the end of Appendix C.

† The final environmental statement was published in October 1973 and the first leases put up for bids in January 1974.

recovery on the order of 60 percent of the in-place reserves. Other methods of mining that recover a higher percentage of the reserves have been conceived, but as yet there is no demonstrated method for deeply buried shale.

The growth rate of a shale-processing industry depends upon technology and the availability of shale reserves, water, and capital. Technical success of mining retorting and disposal methods will reduce risks and provide the investment climate for a faster buildup of the industry. A low level of effluent emissions from all processing steps will allow the necessary social acceptability required for industrial growth. The ultimate limit on the size of the shale industry will be set by the availability of water in the shale region. This limit is probably in the range of 2.4×10^5 to 4.0×10^5 m³ (1.5 to 2.5 million barrels) per day with demonstrated methods of mining and retorting. It is reasonable to assume that methods of shale oil recovery will be developed that reduce this water requirement and will thus allow a higher limit on the ultimate size of the industry.

SUMMARY OF OIL SHALE RESOURCES

Piceance Basin, Colorado

1. Total estimated resources	$\sim 2 \times 10^{11}$ m ³ (~1,200 billion barrels)
2. Total resources in beds more than 9 m (30 feet) thick, averaging more than 0.125 m ³ /tonne (30 gallons per ton), Fischer Assays	$\sim 2 \times 10^{10}$ m ³ (~120 billion barrels)
3. Estimated recoverable reserves	$\sim 8 \times 10^9$ m ³ (50 billion barrels)

Source: National Petroleum Council, December 1972

II STATE OF THE ART OF OIL SHALE TECHNOLOGY

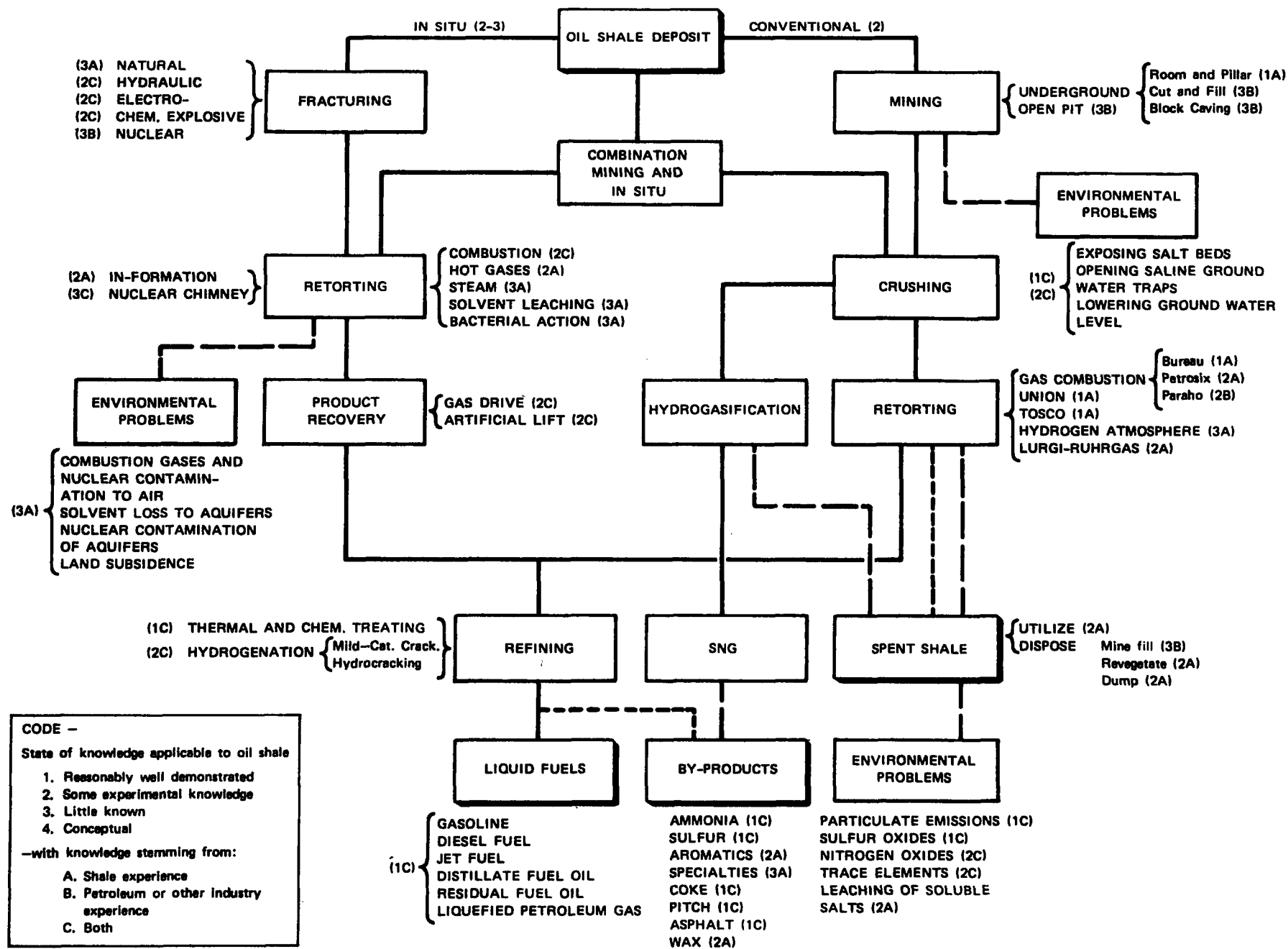
This section describes the present state of development of the processing steps required to recover liquid or gaseous products from oil shale. A graphic representation of the state of knowledge applicable to the various operations is presented in Figure 2.³ The probable direction and incentives of future research are also discussed.

A. Mining

Because most of the good oil shale occurs below an overburden of other rock or shale containing little or no oil, it will be necessary to use underground mining methods. There are a few areas where the shale lies close to the surface so that strip mining would be possible, but these are an exception to the general geology of the deposit. Surface mining has been used to supply small amounts of shale for tests. Room-and-pillar mining has been demonstrated at production rates equivalent to those reached in commercial practice from a single working face.

The generally accepted method of room-and-pillar mining is to create a room with a roof span of about 18 m (60 feet) leaving 25 percent of the shale in place as pillars. If the mined area is to be abandoned as soon as it has been mined out, the installation of roof bolts is usually unnecessary. Bolting is required in haulageways and rooms used for long periods of time. If a bench-and-header type of mining is used, it is possible to mine to a height of 18 m. Under these conditions very large mining and transporting equipment can be used underground.

If room-and-pillar mining is to be used in thick shale deposits, it would be necessary to develop more than one level and to leave a fairly



SOURCE: Based on original figure in H. Perry, "Prospects for Oil Shale Development," U.S. Department of Interior, 1968.

FIGURE 2 OIL SHALE UTILIZATION — PROCESSES, ENVIRONMENTAL EFFECTS, AND STATE OF KNOWLEDGE

thick layer of shale between levels. Under these conditions the total shale recovery could be as low as 40 percent.

Entry to a room-and-pillar mine may be by horizontal adit or by shaft. Early work was done on adit entry because this is the less expensive method. It will be necessary to use shaft entry on most of the high quality shale reserves.

Some research is being done on block caving, long wall retreat caving, and pillar retreat caving in an effort to reduce the quantity of good shale left in the mine. The objection to these caving methods is that the land surface is lowered, usually in an uneven manner, as the mining progresses. Subsidence may not be objectionable if the land is ultimately reclaimed and revegetated. One problem with caving schemes that result in subsidence is that some areas have aquifers above the high quality shale. Caving in these areas would destroy the integrity of the aquifer and could lead to serious problems of leaching soluble minerals from lower shale formations.

Research in the direction of reducing the quantity of explosives required for blasting or of nonblasting methods of rock busting would be desirable. Blasting creates both fine particulates and combustion products that must be vented from the mine.

B. Crushing

Retorts require shale to be of smaller particle size than that resulting from mining operations. The required size varies from a 5.1 cm (2-inch) maximum for the gas combustion retort to less than 1.3 cm (1/2 inch) for the Lurgi-Ruhrgas retort. The gas combustion retort cannot process shale finer than 0.95 cm (3/8 inch) and consequently these fines must be removed and either discarded or agglomerated. Two or three stages of crushing and screening are required to reduce run-of-the-mine shale to retorting size.

The primary environmental problems associated with crushing are the creation of dust and noise, but both problems can be controlled by current technology.

C. Transporting Shale

Mined shale must be transported to the crushing and screening plant, and crushed shale must be transported to the retort. Spent shale or shale ash must be transported to the disposal area. All methods of transport projected for oil shale have been used repeatedly in commercial mining operations so that no new problems are expected. The major problems are the creation of dust and noise.

D. Retorting

1. Classes of Retorts

Retorting processes have been grouped into four classes according to the method of heat transfer to the shale.⁴

Class I--Heat is transferred to the shale through a wall. The simplest form of this retort is a Fischer assay device for measuring the amount of oil that may be recovered from a sample of shale. The shale is placed in a closed container and heated by means of a fire outside of the retort. The retorted gas and liquids are uncontaminated by air and the sulfur compounds are in a reduced state, such as H_2S . Because the heat source is external to the retort, any fuel may be used. The emissions from the heat source will depend upon the fuel used. This type of retort is expensive in terms of capital and operating costs per unit of produced oil. It is not likely to be competitive with other types of retorts.

Class II--Heat is transferred to the shale from hot gases generated in the retort by the combustion of some of the carbon and hydrogen present in the shale. Examples are the gas combustion retort, the Union Oil Company retort and the Laramie simulated in-situ retort. A controlled

amount of air and recycle gas is introduced into the retort and mixture of product oil and low Btu gas is recovered. The advantages of this system are low capital and operating costs per unit of shale input. Disadvantages are low recovery of the total energy in the shale and the production of a large quantity of flue gas containing about 3 MJ/m^3 (80 Btu/SCF) energy content. For example a typical gas combustion retort plant producing $16,000 \text{ m}^3$ (100,000 barrels) per day of shale oil would also produce about 23 million cubic meters per day of low Btu gas. Sulfur contained in this gas would be on the order of 200 tonnes per day.

Class III--Heat is transferred to the shale by passing previously heated gases or liquids through the shale bed. Two examples are the Petrosix retort and the Union B retort. By recirculating high Btu product gas through the retort, the problems of the Class II retort are eliminated. The gas has much more value and sulfur compounds can be removed by amine scrubbing. However, the capital cost of the equipment required to heat the recirculating gas makes this a very expensive type of retort. Additional problems are caused by the tendency of the external gas heater to accumulate carbon deposits caused by oil mist in the gas. It is not likely that this class of retort will become commercial.

Class IV--Heat is transferred by the introduction of hot solids into the retorting bed. The two best known examples of this class are the TOSCO II retort in which heat is transferred by ceramic balls and the Lurgi-Ruhrgas retort in which heat is transferred by recirculating hot shale ash. The principal of retorting is to combine raw shale with enough hot recycle solids to produce retorting temperatures in the mixture. This class of retort is fairly expensive but does recover a high percent of the energy in the shale. The gas from the retort is high Btu and sulfur compounds are in the reduced state. Both TOSCO II and Lurgi-Ruhrgas retorts have the potential to become commercial.

In the TOSCO II retort the ceramic balls are heated in a separate furnace which may be fired with any acceptable fuel. The Lurgi-Ruhrgas retort employs a lift burner to burn the residual carbon from the educted shale so that no additional fuel is required to supply retorting heat. The Lurgi Company claims that very little SO_2 is found in the flue gas from the lift burner because it is absorbed on the fine shale particles.

This method of classifying retorts is useful to this study in that the waste products from the retort are quite different in the different classes. However, there is no known Class I retort under development, and it is unlikely that Class III retorts will be competitive with either Classes II or IV.

Class II retorts produce a large quantity of low heating value (3.7 MJ/m^3 or 100 Btu/SCF) gas as a byproduct, and most of the sulfur in this gas is in the form of SO_2 . The residual shale has had most of the organic carbon removed.

Class IV retorts produce gaseous products that are not diluted with air so that the gas has a high heating value and the sulfur is in the reduced state. The residual organic carbon may remain on the spent shale (TOSCO II) or it may be burned off in a subsequent process step (Lurgi-Ruhrgas). Generally, the residual shale is in the form of small particles.

All classes of retorts will require some emission control devices. General environmental problems will be the production of dust from shale handling, sulfur dioxide in stack gases from retorts and furnaces, nitrogen oxides in combustion products formed by burning crude shale oil, and sour water decanted from the product oil. Retorting shale produces a strong odor that is characteristic of organic nitrogen compounds and that may be carried several miles in a steady wind.

R&D in retorting processes is most likely to be directed toward increasing the mechanical reliability and reducing the capital and operating costs. The developers of retorting processes realize that they will be required to meet certain environmental regulations in order to operate. They are confident that when regulations are promulgated they will be consistent with those already set for similar processes in related industries, e.g., stack gas emissions from power plants, and that they have the ability to devise methods to meet the requirements.

Because most of the retort developers are negotiating process royalty plans or other financial arrangements with potential customers, they do not readily give out technical details of their processes.

2. SMG Producing Retort

The Institute of Gas Technology is developing a retort to produce high Btu gas directly from oil shale.⁵ Retorting heat is supplied in part by hot hydrogen containing gas and also by the exothermic heat of the methanation reaction in the retort. The retort operates at about 20,000 Pascal pressure (several hundred pounds per square inch) and is relatively expensive. However, it does recover more of the total organic material on the shale than the other types of retorts. The environmental problems are expected to be similar to the liquid-producing retorts.

3. In-Situ Retorting

In-situ methods for removing hydrocarbons from oil shale have a great many advantages, and much thought has been put into their development. Most in-situ concepts contemplate the use of heat to retort the oil shale without removing it from the ground. Research has recently been conducted into methods of extracting the hydrocarbons by solvent action or the use of bacteria.

The type of in-situ retort receiving most attention is one in which a chamber of solid shale filled with shale particles is created underground. The shale in this chamber is heated and the oil is educted, collected, and pumped to the surface.

Proposed heat sources include underground combustion, steam, hot gas, hot solvents, and combinations of these heat sources. Methods of providing a flow path for the retorting fluid include the use of wells, tunnels, natural porosity, a variety of fracturing techniques, and combinations of these methods.

Laboratory investigations on the use of thiobacillus, a sulfur oxidizing bacterium, to release kerogen from the mineral matter in shale are now in progress.⁶ The bacteria used do not require a hydrocarbon food but use sulfur and other nutrients from the shale. No assessment of the probability of technological or economic success can be made at this time.

To date, the field tests on in-situ methods of shale oil production have not indicated that a commercial venture would be economically successful. However, there are both economic and environmental incentives to develop in-situ oil recovery, and it is reasonable to expect much research toward this end. As would be expected in this early stage of in-situ development, most of the effort has been directed toward devising retort technology and very little work has been done on solving the environmental problems associated with any specific process.

The different methods of in-situ extraction will produce different impacts on the environment. The most prominent problems associated with the different in-situ processes are listed in Table 1.

It should be noted that in cases where the research is being conducted by private companies, very little information on the technical details is published. Information on simulated in-situ retorting is available from the Bureau of Mines at Laramie, Wyoming, based on experiments in a 150 ton capacity, above ground vessel. Laramie has also conducted experimental shale fracturing tests. This information is available to the public and could be used to derive quantitative estimates of combustion products. However, it is characteristic of in-situ

Table 1

POSSIBLE ENVIRONMENTAL PROBLEMS
FROM IN-SITU PRODUCTION OF SHALE OIL

<u>In-Situ Process</u>	<u>Environmental Problems</u>
Circulation of hot fluids	Loss of fluid to atmosphere Loss of fluid through fractures SO ₂ , NO _x , and particulates in flue gas Displacement of saline groundwater Odorous off-gases
Circulation of solutions or solvents	Loss of volatiles to atmosphere Loss of solution to adjacent areas Contamination of aquifers
Circulation of biologically active solutions	Loss of solution to adjacent areas Contamination of groundwater SO ₂ in off-gases Fine particulate matter from shale matrix carried to surface in circulating fluid
Underground combustion	SO ₂ , NO _x , and particulates in off-gas Odors in off-gas Loss of fluids to adjacent areas Contamination of aquifers
Nuclear chimney retorting	All problems common to underground combustion Blasting shockwaves detrimental to conventional mines and other installations Nuclear contamination of aquifers, air, and products.

processes that the location will determine the magnitude of many of the problems having to do with loss of fluids to adjacent areas.

Real data on the environmental problems of in-situ retorting will be expensive. Some large-scale tests in locations where the in-situ project is to be located will be required. Methods of monitoring fluid losses deep underground must be devised and be dependable over a range of geologic conditions.

E. Upgrading Crude Shale Oil

Shale oil produced in retorts or by most in-situ methods is not suitable for direct use. It is a heavy, viscous oil that contains about 0.7 wt % sulfur, about 1.8 wt % nitrogen, and oxygen compounds and usually has a pour point of about 27°C (80°F). Most plans for recovering oil from shale include a refining step to produce low sulfur fuel oil or a high quality synthetic crude oil. This refining unit is usually planned to be placed close to the retorts so that only a short distance of heated pipeline will be required.

Upgrading processing steps may include coking to remove asphaltenes and shale ash from the lighter fractions and hydrogenation to remove the sulfur, nitrogen, and oxygen compounds. Upgrading research may provide methods of eliminating the coking step to obtain higher yields of liquid products.

The environmental problems of upgrading are quite similar to those found in conventional petroleum refining. Possible contaminants are: H_2S , NH_3 , HCN, phenols, benzene, dissolved oil, SO_2 , and particulates. Likely by-products are elemental sulfur and liquid ammonia. Sulfur may have to be stockpiled or disposed of.

SNG may be made by direct hydrogasification in a retort, as previously noted, or by gasification of crude shale oil. The most economic path is still uncertain. Each method will present a different proportion of the effluent products found in the other upgrading processes.

The impact on the shale-producing area would be considerably reduced if an economic method of transporting crude shale oil can be developed that would allow upgrading units to be spread out among the several marketing areas. The result would be a reduction in water use and in population per unit of produced shale oil in the oil shale region.

F. Disposal of Waste Materials

From the standpoint of volume of waste materials, by far the largest will be shale residue. Other waste materials will be similar to those produced in coal gasification or liquification processes that are now being studied. It will be useful to divide waste materials into (1) shale-related wastes and (2) process-related wastes.

Shale-related wastes will be mostly mineral matter. Some of the components will be soluble, requiring great care and considerable expense to handle properly. Approximately 85 percent of all material mined for use in conventional retorts will be waste. Shale rock not subjected to retorting temperature remains insoluble except for included soluble salts that may be exposed to rock surfaces by size reduction. Once shale has been retorted, the organic binding is destroyed and the rock loses its strength and is easily crushed. Under these conditions soluble minerals may be exposed to the surface and easily leached out.

The amount of shale mining and retorting in the past was so small that no special precautions were taken to prevent runoff from spent shale dumps from entering natural water supplies. Methods for preventing shale wastes from contaminating water supplies have been devised. The most comprehensive include the placing of impermeable membranes under the shale dump, collection of all water entering the spent shale, evaporation of this water, and disposal of the precipitated salts.

Because future regulations will probably include rehabilitation of disposal areas so that they will support plant growth, soluble salts may have to be removed from the final surface and plant nutrients may have to be added. The initial revegetation effort is expected to require more water than that supplied by normal precipitation.

Some R&D work on spent shale disposal has been conducted by government agencies, educational research groups, and private companies. The reports are not entirely consistent. Reports of privately financed rehabilitation tests stress the fact that ground cover crops can be grown on shale dump areas. The work done at Colorado State University indicates that soluble salts are leached out of spent shale by a variety of mechanisms over a long period of time.^{7, 8} It may be concluded that much more work should be done in this area.

Process-related wastes will be quite similar in nature and magnitude to those generated by other hydrocarbon refining industries. Advances in disposal methods in coke processing, refineries, and coal gasification plants will be of use in shale oil plants. To a large extent the future shale processing industry will benefit from research in related process industries.

III ENVIRONMENTAL IMPLICATIONS OF OIL SHALE DEVELOPMENT

Environmental Aspects: Overview

Oil shale operations could cause significant environmental impacts. Large amounts of material would need to be handled. As the organic material represents only a small part of the total rock, the processed shale remains for disposal. The increase in bulk resulting from crushing and processing will prevent disposal by backfilling the shale mine, and surface disposal of at least one-third of the material will be required; actually, the amount of processed shale disposed of at the surface could be closer to two-thirds the total material processed. This processed shale will be finely divided, and will contain water soluble salts that could contaminate streams or ground water unless steps are taken to seal the disposal area for prevention of escape of deleterious materials. Revegetation of disposal areas is under study, and it remains to be determined whether encouraging experiments can be successfully extended to large-scale operations that would be necessary in connection with commercial oil shale development. A major environmental aspect is the possibility of encountering large volumes of saline water in mining operations. Management of this water would pose significant problems in mining operations, and could have adverse effects on ground water conditions in the area of the deposits.

The major environmental problems that will occur with the growth of an oil shale industry may be grouped into four categories: water use, land disturbance, air degradation, and aesthetic changes. The first three categories may be measured by physical methods; the aesthetic changes are not easily measured, are generally subjective, but nevertheless are real.

Oil shale is an energy source of national importance. The probability that oil shale will be developed is very high because the alternative to nonuse of shale leads to unattractive national consequences. The national problem with the production of shale oil, as with any other resource, is to ensure that true production, environmental, and social costs are reflected in the price of the product. In the case of oil shale the environmental and social costs will probably be lowest if the following parameters are minimized:

- Land disturbance
- Water use
- Population increase in area
- Construction activity
- Total SO₂ emitted to air
- Total dissolved solids discharged into river and ground waters.

The above items are "per unit of usable product." Resource recovery should be maximized.

A word of caution about the dangers of oversimplifying this complex subject is in order. It is not possible to predict with accuracy how the shale-processing industry will develop, what retorting or mining methods will be used, or how fast it will grow. The best that can be done at present is to indicate ranges of resource use under certain assumed conditions. The numbers derived will be no better than the underlying assumptions.

A. Water Use

It is generally believed that available water will limit the ultimate size of an oil shale industry. All good western shale is in the upper Colorado River drainage system, the only replenishable source of water. There is ground water in the shale area, some fresh and some containing

up to 60,000 ppm dissolved minerals. At present it is estimated that $2.2 \times 10^8 \text{ m}^3$ (180,000 acre feet) per year of Colorado River water could be made available for shale development. This quantity of river water, plus the use of ground water local to the mine sites, would allow an overall industry size ranging from 2.4×10^5 to $4 \times 10^5 \text{ m}^3$ (1.5 to 2.5 million barrels) per day of shale oil.

The water used per unit of net product will depend upon the type of mining, retorting, and upgrading used. In-situ methods are expected to require less water than conventional mining and retorting.

The largest single environmental problem will be the prevention of a salinity increase in the Colorado River water. Removal of $2.2 \times 10^8 \text{ m}^3$ (180,000 acre feet) per year of water from the upper rivers of the system is expected to increase the salinity at Hoover Dam by 6 to 10 milligrams per litre or about 1.4 percent.

It is generally conceded by those planning shale projects that no process water will be allowed to flow back into the river system. Plans usually include methods of using blowdown streams and other highly mineralized water to wet down spent shale and mining operations. So far these conceptual schemes have not been tested in a pilot program.

Water quality. Oil shale development could lead to impacts on water quality in the mining area, mainly from processed shale. Most present plans call for processed shale to be disposed of by transport as a slurry and depositing it in nearby canyons in engineered fills that take account of the characteristics of soil foundations and local geological factors. Although processed shale can be compacted to become virtually impermeable to rainfall so that there is no loss in strength in the mass of the deposit, snowfall eliminates the compaction in the top foot or so, and at least the top 2 feet of the deposit becomes permeable to water. This

enables soluble salts to be leached directly from the processed shale.

Moreover,

"... drying of the processed shale surface causes movement of water from the interior of the deposit to the surface by capillary action. On reaching the surface, the water evaporates leaving behind a white deposit that is clearly visible on the black surface. This deposit is dissolved during (subsequent) rainfall with the result that both concentration and composition of dissolved solids in the runoff water vary with time and depend on the amount of drying prior to the rain."*

Furthermore,

"... it would appear that compaction increases the concentration of dissolved solids in the runoff because compaction increases (density) and decreases (permeability). The rate at which the deposit (of soluble salts on the surface) is formed is clearly dependent on the rate at which capillary action can carry the very concentrated solution from the pores within the shale residue to the surface, because the material can be evaporated more rapidly than it can be transported to the surface by capillary action."

Use of slurry transport of processed shale to the disposal site will lead to entrapment of significant amounts of moisture in the disposal piles, no matter how well-engineered the fill may be. Clearly, this provides the mechanism for the capillary action and related surface concentration and dissolved solids at the surface of the deposit.

"... it would appear that maximum concentrations in the runoff will be found when compaction is greatest, slopes are steep, drying has been extensive, runoff has just begun, the shale residue has a low permeability, runoff water temperature is high, rainfall intensity is low, and length of overload flow is short."

* Ward, J. C., et al, "Water Pollution Potential of Spent Oil Shale Residues," EPA Report 14030, December 1971.

SUMMARY OF WATER POLLUTION POTENTIAL OF SPENT
OIL SHALE RESIDUES

1. Leaching tests show that there is a definite potential for high concentrations of Na^+ , Ca^{++} , Mg^{++} , and SO_4^{--} in the runoff from spent oil shale residues. However, with proper compaction, the piles become essentially impermeable to rainfall. On the other hand, snowfall eliminates the compaction in the top 20 to 40 cm and at least the top half meter of the residue becomes permeable to water.
2. Soluble salts are leached readily from spent shale columns.
3. Chemical concentrations of the effluent from spent shale columns may be predicted by using the relationships developed between soluble and exchangeable ions in soils which are in equilibrium with a water solution.
4. Sediment contained in runoff water from spent oil shale residue will be detrimental to water quality unless removed by settling.
5. Sediment in the runoff water from spent oil shale residue may be efficiently settled by the addition of small amounts of aluminum sulfate and/or by long periods of quiescent detention.
6. The chemical quality of surface runoff water from oil shale residue may be estimated by procedures developed within this report.
7. The dissolved solids concentration in snowmelt water is increased significantly by contact with oil shale residue, but not as much as in runoff from rainfall.
8. The chemical quality of surface runoff water from melting snow on oil shale residue may be estimated by procedures developed in this report.
9. The long contact period associated with snowmelt results in water percolation into a bed of oil shale residue and subsequent saturation.
10. Saturation eliminates compaction of oil shale residue.
11. Weathering of oil shale residue increases the tendency for percolation to occur.

12. Percolation caused by snowmelt may result in creep and slides.
13. Water which percolates through a bed of oil shale residue is very high in total dissolved solids.
14. Both the composition and concentration of dissolved solids in snowmelt runoff water from oil shale residue change with the cumulative volume of runoff.
15. Precipitation in the form of snow will not all appear as runoff.
16. The overland flow water quality model developed in this report is applicable to runoff from both rainfall and snowfall on oil shale residue.
17. Natural snow has a negligible dissolved solids concentration.
18. Compaction reduces the quality of runoff from rainfall and tends to be reduced by snowfall in at least the top few feet of depth.
19. The oil shale retorting residue need not be saturated for percolation from snowmelt to occur.

Sources:

Items 1 to 6: Ward, J. C., et al, "Water Pollution Potential of Spent Oil Shale Residues," EPA Report 14030, December 1971.

Items 7 to 19: Ward, J. C., and S. E. Reinecke, "Water Pollution Potential of Snowfall on Spent Oil Shale Residues," Colorado State University, June 1972.

To control the potential water pollution problem from processed shale, the following actions might be considered:

- Sealing the base of the shale disposal area by an impermeable layer so as to prevent losses of soluble materials by percolation downward through the deposits.
- Control of the amount of water used in shale deposit so as to minimize the rate of solution and transport of soluble salts to the surface of the deposit through capillary action.

- Protection of the surface of the deposit against weathering, erosion, and snowmelt effects by a layer of soil that, ideally, will be suitable for revegetation. The topsoil removed from the base of the disposal area might well be stockpiled and used for this purpose.

B. Land Disturbance

Although Figure 1 shows large areas of shale reserves underlying 41,000 square kilometers (16,000 square miles) of land, the area of interest in this century will be much smaller in extent. The area most likely to be developed in the next 25 years will be about 2,100 square kilometers (800 square miles) in Colorado in the Piceance Basin and up to 1,000 square kilometers (400 square miles) on the east side of the Uinta Basin, in Utah.

Land will be required for access roads and utility lines, mine and plant facilities, mine development spoil disposal, and shale residue disposal. The amount of land required will be dependent on the type of mining and disposal employed and will vary with geographic factors. Table 2 provides an estimate of the total land that will be altered as a result of producing 320,000 m³ (2,000,000 barrels) per day of oil for a 20-year period. This will range from 2 to 8 percent of the 3,000 square kilometers of good shale reserve land, depending on the mining and retorting process used.

C. Air Degradation

Industrialization of the western shale regions will result in a decline of the general air quality. The main sources of air pollutants will be vehicular emissions from mining, construction, and transporting equipment; dust from shale-handling operations; and gases from retorting and refining units. Minor sources of air degradation will be from the increased vehicular

Table 2

ESTIMATED LAND REQUIREMENT FOR 2 MILLION BARRELS PER DAY*
SHALE OIL PRODUCTION USING DIFFERENT PROCESSES
(20-Year Project Life)

Land Use	Square Kilometers of Land Disturbed		
	Surface Mine	Underground Mine	In-Situ Mine
Mine development	4	2	--
Overburden disposal	82	--	--
Temporary storage of lowgrade ore	12	--	--
Active well area	--	--	80
Surface facilities	16	16	8
Off sites	16	16	16
Shale residue disposal	<u>240</u>	<u>240</u>	<u>--</u>
Total disturbed area	370	274 [†] 114 [‡]	104
Maximum disturbed area during project life [§]	250	152 [†] 74 [‡]	64

* 320,000 m³ per day.

† Assumes above-ground disposal of shale residue.

‡ Assumes two-thirds of shale residue returned to mine.

§ Allowing 10 years for restoration of shale disposal sites (or well sites).

traffic and residential heating caused by an increase in population in the area and emissions from the mine-blasting procedures.

Conventional dust control technology is available to limit particulate emission from mine ventilation systems to 0.023 g/m³ (0.01 grain per cubic foot.) Crushing and screening operations can be held to a similar emission rate by properly designed enclosures and the use of wet scrubbing, bag filters, and dust suppression with water sprays. One problem that

has been observed in past retorting operations is that dust is carried off shale residue areas after the initial dust control water has evaporated. The problem is to achieve adequate dust control with minimum use of water.

Emissions from stack gases will be different for the different retorting processes. As previously discussed, the class of retort will determine whether the sulfur is in the oxidized or reduced form. Sulfur in the reduced form can be scrubbed from the retort gas using any of several methods, such as hot carbonate or amines. Oxidized sulfur in flue gas from the Union A or Lurgi-Ruhrgas retorts appears to be absorbed on the shale residue to a great extent. This point should be checked by pilot plant tests. SO_2 in the low heating value from gas combustion retorts may be more of a problem. The concentration of SO_2 will be fairly low, but the large quantity of gas produced could result in thousands of kilograms per day of SO_2 emissions. Presumably any stack gas scrubbing method developed for coal-fired power plants could be used on this low heating value gas.

Very little information is available on potential problems with NO_x in off-gases from shale oil retorts. Most retorting processes control the temperature of combustion in a range lower than that needed to fix nitrogen in the air. However, there is a high level of nitrogen in the shale oil that can increase NO_x emissions if the oil is burned in conventional steam-raising boilers.

Particulates in flue gases from retorts can be removed using existing electrostatic precipitators and wet scrubbers. Very little information is available on the existence of hazardous trace elements in shale ash.

The odor produced by retorting oil shale is distinctive and long lasting. On a subjective scale of odor preference, it is not so pleasant as an onion-dehydrating plant but much pleasanter than a kraft paper mill. There is no published work on the control or elimination of odors from shale retorting.

To control adverse air quality effects from oil shale development, it seems likely that the following methods would be practiced.

- Process design to reduce the concentrations of undesirable or harmful emissions as an integral part of the operation.
- Control of emissions to the extent necessary to remove compounds that remain in the released gases so as to comply with established standards of air quality.
- Control of particulates and dust resulting from the several stages of oil shale operations through a variety of collection and suppression methods that are appropriate to the individual stages.

D. Treatment of Processed Oil Shale and Reclamation of Mined Lands

Oil shale mining and processing removes only a small portion of the total rock (less than 1 percent by weight). It is not a simple task to dispose of the remainder. The acts of mining, crushing, and processing reduce the size of oil shale fragments and increase its volume by about one-third; even if the mine openings could be completely refilled, considerable amounts of processed oil shale would have to be disposed at the surface--closer to two-thirds of the total material handled. Processed shale will be finely divided (especially when mined by rapid excavation techniques) and will contain water soluble salts that could contaminate streams or ground water unless steps are taken to protect the disposal area. Control of erosion of disposal areas through revegetation also remains to be demonstrated, and species of plants and fertilizer/nutrient requirements to support vegetative growth on processed shale need to be determined.

One means of finding the solution to treatment of processed oil shale and reclamation of mined lands or disposal sites is to examine factors such as those briefly described above in connection with operations conducted or in progress at the vicinity of the Naval oil shale

reserves in Colorado. Previous work in that area produced quantities of oil shale for testing; the demonstration projects should provide a basis for conducting carefully structured experiments to examine the potential environmental effects of oil shale development through rapid excavation so as to determine prospective solutions to be incorporated into the design of excavation operations.

E. Aesthetic Impact of an Oil Shale Industry

The spectrum of changes caused by the development of a new industry ranges from those that are easily quantified, such as size of mine tailing area, to effects that are purely subjective, such as increased monotony of landscape. For convenience, all environmental changes that contain a high proportion of subjective evaluation are placed in the aesthetic category. This category includes changes in land use, plant growth, wildlife, recreational facilities, and cultural and scenic values.

The shale areas have a low population density, on the order of 1 person per square kilometer (three per square mile) less than half of whom live in towns. The population doubles during the few weeks of the deer-hunting season. Advanced planning of mine and process facility locations would allow the preservation of the few historic Indian culture ruins in the area. The quantity of shale residue accumulating in surface disposal areas will eventually create large plateau areas in a region that consists of rounded hills and deeply cut canyons.

Mining, transportation, and processing operations will produce noises similar to those now being experienced in other related industries. In addition to the usual human discomfort and loss of working efficiency, industrial noises will adversely affect the wildlife in the immediate area. For the most part, noise control methods developed for other industrial

and transportation equipment will be satisfactory for the shale industry. There may be instances where long conveyor systems used between processing units create enough noise to prevent normal wildlife migration paths from being used, even though there is no physical barrier.

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Appendix D
ENERGY FROM SOLID WASTES

by
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I INTRODUCTION--SOME FACTS ABOUT SOLID WASTE DISPOSAL

Steadily increasing quantities and concentrations of solid waste require processing. The quantity increases because of increasing population and because social and technological trends give rise to greater quantities of solid waste per capita. Concentrations of waste grow larger as metropolitan areas grow in population, as factories grow larger, and as agricultural and fuel processing operations become more intensive. Processing of these wastes is required primarily because great concentrations of waste give rise to increasingly undesirable effects. These range from the purely aesthetic ones of unsightliness and odor to the physical impairment of health, necessitating vector control and disease prevention. The general move of our society towards a clean environment demands a general cleanup of refuse of all kinds and under all conditions. Large concentrations of refuse, while posing special problems, also offer the best prospect for applying economic solutions to the disposal problem.

The simplest and most used method for waste processing is sanitary landfill. In proper applications of this method, control is maintained over hazardous materials, pollution of ground waters, disease vectors, and air pollution arising from open burning. However, control over all these factors is difficult to maintain indefinitely, and a proper site is not always available within a reasonable distance of the principal sources of the waste. The sanitary landfill method, moreover, is a large consumer of land, although the filled land can often be put to another use at a later date.

Not all data measuring the quantity of solid waste are consistent. For example, data from one 1968 survey indicates that U.S. per capita solid waste production was 2.41 kg (5.32 pounds) per day, with urban refuse at 2.59 kg (5.72 pounds) per day.^{1*} On the other hand, data from the 1968 National Survey of Community Solid Waste Practices shows average quantities of 3.59 and 3.71 kg (7.92 and 8.19 pounds) per day, respectively, for national and urban refuse.^{2*} The last figures include park and sewage treatment solids in the totals, but neither included agricultural and food industry wastes.

The quantities of all wastes to be handled in the future are expected to increase. The annual consumption of all materials involved in packaging has steadily increased in the last decade. More municipal sewage treatment plants will contribute to the load to be handled. Many agricultural operations are being modified and concentrated to the point that the wastes are a substantial nuisance, but available in concentrations that make possible economic recovery of energy values. Total agricultural wastes are estimated to be 22.5 kg (50 pounds) or more per capita per day.

With urban refuse amounting to approximately 3.6 kg (8 pounds) per day per capita, about 1.5×10^3 kg of refuse is generated annually per individual. When such refuse is compacted to approximately 450 kilograms per cubic meter (750 pounds per cubic yard) and 135 kilograms (300 pounds) of soil are used as cover there results an annual disposal requirement of 3.17 cubic meters (4.15 cubic yards) per capita. Fills often range from 3 to 30 meters in depth. With a 3 meter deep fill, about one square meter (10.6 square feet) of surface is required per person annually. An urban population of one million will require approximately 21 hectares (50 acres)

* References are listed at the end of this report.

† Data in the References expressed in English units have been converted to metric units and often rounded to reflect the precision of the original values.

filled to a depth of 15 meters (45.8 feet) each year.* One source sets a rule of thumb of 0.864 cubic meters (1.13 cubic yards) of landfill per person per year.³ This requirement is presumably based on generation rates of less than 4.5 kilograms (10 pounds) per capita per day.

The costs and bulk of landfill can be reduced by shredding, milling, crushing, pulverizing, or otherwise reducing the size of bulky refuse before it is compacted and covered. The treated refuse can be segregated into fractions having material value. Classification into ferrous (magnetic) metals, nonferrous metals, glass and ceramics, and paper components is possible. Simple separation of magnetic materials from mixed refuse is more common than any other separation scheme. The separated material value pays for the additional cost of the size reduction operation.

Incineration of wastes reduces their weight and volume substantially, 70 to 80 percent on a weight basis, and by a factor of 10 or more on a volume basis. Ordinary incineration normally requires additional fuel and is an energy consumer. Incineration is compatible with pretreatment operations such as size reduction and separation of valuable materials. Some recovery of valuable materials is possible after the incineration proper.

Incineration reduces problems with disease vector control, as it destroys putrescible material and most pathogenic organisms. It also destroys flammable materials and reduces the hazards of fire (and of the consequent air pollution). The absence of edible material (after incinerator treatment) reduces or eliminates the population of rodents and

* Ocean dumping is used by New York City and some other large communities. The wisdom and safety of this practice is debatable.

other scavengers at the refuse disposal area. This also improves vector control.

Incinerators have potential for detrimental effects. Combustion creates fly-ash that must be captured; and improper combustion conditions, frequently encountered when heterogeneous materials are burned, cause incomplete combustion and soot and smoke that might contain carcinogens. The heat of incineration will release volatile metals, acids and other substances that might also pollute the air. The incinerator must include equipment that will control such emissions within socially desirable and legally mandated limits.

Capital and operating costs of many incinerators are high. The average amortized cost of incinerator operation is probably in excess of \$7 per tonne of solid waste treated; and much higher costs have been reported (\$14 per tonne in Washington, D.C., and New Jersey; \$22 per tonne in New York City). This is a high price to pay for an inherently wasteful operation; landfill costs (exclusive of land) range from less than \$0.50 to less than \$3.50 per tonne of solid waste handled. As incineration implies, much of the usual solid waste is combustible, and heating values of the combustible fractions average around 4500-5500 kilogram calories per kilogram (18-22 MJ/kg or 8000-10,000 Btu/lb dry). The heating values of as-received (wet) refuse have a wide range from 1650 to 3300 kilogram calories per kilogram (7-14 MJ/kg or 3000 to 6000 Btu per pound). Usual values range from 2200 to 2800 kilogram calories per kilogram (9-11 MJ/kg or 4000 to 5000 Btu per pound).

This is a substantial heat value to waste through landfill or incineration at a time when fuels are in short supply. Additionally, with low sulfur coals currently priced at \$1.60 to \$2.40 per million kilogram calories (\$0.40 to \$0.60 per million Btu), delivered price, and projected costs of low sulfur oil at \$4.00 per million kilogram calories (\$1.00 per million Btu) in the mid 70s, a tonne of refuse

contains as much as \$10 in potential energy value. Properly used waste can help reduce our dependence on outside energy resources. At 25 percent overall efficiency for collection and conversion to energy a total waste load (including agricultural) of more than 27 kilograms (60 pounds) per day per capita would lead to an energy recovery equivalent to about 2 million barrels per day of oil, compared to a current total energy demand of about 35 million barrels of oil equivalent.⁵ The U.S. is now importing approximately twice that quantity. The economic value is likely to justify the investments necessary for energy conversion.

Energy recovery from refuse can be achieved from:

- (1) Incineration with heat recovery
- (2) Pyrolysis with heat recovery
- (3) Pyrolysis with energy product recovery^{*}
- (4) Hydrogasification with energy product recovery
- (5) Bacterial digestion with energy product recovery
- (6) Enzymatic digestion with energy product recovery.

It is the intent of this paper to describe briefly the basic technology and status of the six general methods of energy recovery listed above. Following this, the potential environmental impacts will be presented and recommendations for future Environmental Protection Agency action outlined.

^{*}The phrase "energy product" is used to mean a clean, readily combustible fuel.

II THE TECHNOLOGY AND STATUS OF ENERGY RECOVERY FROM WASTE^{*}

A. Energy Recovery Through Incineration

Incineration can be used to produce steam for space heating, process industry use, or for power generation. It can also be used to produce hot gases suitable for power generation in gas turbines. European installations to produce steam for power and heating have produced 1.1 to 1.6 kilograms of steam per kilogram of refuse burned, and 75 to 180 kilowatt hours of electricity per tonne of refuse burned.⁶ Installations in Montreal and Chicago are based upon European technology. The Montreal plant is designed to produce 45,350 kilograms (100,000 pounds) of steam at 260°C (500°F) and 16 kg per sq cm (1.5 MPa or 225 psia) pressure from 12.5 tonnes of refuse. The Chicago plant has a similar capacity.

Incineration in any such plant is a straightforward process. However, difficulties arise in the erosion and corrosion of furnace linings caused by the heterogeneous nature and variable composition of the fuel. Also, the flow of refuse through the system may be impeded by slagging and clinker formation. Particulate deposition on boiler tubes and heat exchange surfaces may reduce steam-raising efficiency. Slag characteristics can be controlled by controlling the temperatures in the combustion chamber, and excess airflow and auxiliary fuel can be used to this end.

^{*} Much of the material reported in this section is drawn from a series of studies performed by Stanford Research Institute for itself and for various industrial and governmental clients. This body of work will not be referenced further.

Refractory problems can be minimized through use of waterwall combustion chambers, or by use of a large air excess. The latter creates problems with particulate controls on the stack gas; the former seems to have operational difficulty.

Despite the apparent simplicity of the process, incinerators are not yet generally accepted for refuse recovery even when steam and electric power production is an adjunct. The matching of refuse disposal to steam demand is difficult because of seasonal variations in demand. Also, steam conditions do not permit efficient generation of electricity, so product values, and prices, are low. The potential for environmental pollution (to be discussed later) adds to the capital costs. It is not likely that direct incineration for steam production will be much used in the future.

Such problems as slagging, caused by variability of input and by the heterogeneous nature of refuse, can be controlled if the refuse is only a small part of the total feed to a furnace. Mixtures of refuse and coal are being fed to furnaces of the Meramec Power Station, Union Electric Co., St. Louis, Missouri, in an experimental program. Prepared waste (approximately 90 percent of input waste from which magnetic material has been removed) is fed with coal at an approximate rate of 1 kilogram of waste to 8 kilograms of coal. The combustion takes place in a chamber modified to accept dual feed (coal and refuse); steam is produced in a conventional boiler with reheat; and steam at the super-heater outlet will be at standard conditions of 98 kilograms per sq cm (9.6 MPa or 1400 pounds per square inch gage) and 510°C (950°F). The maximum continuous steam production is 420,000 kilograms (925,000 pounds) per hour. The reheat steam temperature is 490°C (925°F). This high quality steam has more value than that produced in refuse-only incineration. The experiments in progress will establish the technical and economic feasibility of this type of incineration operation. At an estimated future cost of

\$1.60 to \$2.40 per million kilogram calories (\$0.40 to \$0.60 per million Btu) for low sulfur coal, the additional capital requirement, amortization, maintenance, labor, and downtime costs must be less than \$4.90 to \$7.20 per tonne of refuse burned in order for the process to be economically viable. Note that these costs are comparable to those of the more economic direct incineration units. The process will be limited to regions where coal of the proper quality (sulfur content and slagging characteristics) is available.

Incineration to produce hot gases that drive a gas turbine has been tested on a pilot scale. The Combustion Power Company Inc., Menlo Park, California, has designed a plant that will handle 400 tonnes of refuse per day with a maximum capacity of 8000 kilowatt electric power. Combustion of prepared refuse (sized, and with ferrous metals removed) in a fluidized bed is followed by extensive cleanup of particulates from the hot combustion gases. The hot clean gases at approximately 810-820°C (1500°F) are fed to the turbine. The fluidized bed minimizes slagging and complete combustion at low temperatures and minimizes pollution from unburned hydrocarbons, oxides of nitrogen, and acid gases. Tests on a 100 tonne per day plant will be completed in 1974.

B. Direct Energy Recovery and Energy Materials Production--Pyrolysis

Pyrolysis, or thermal degradation, can be used to produce various gaseous or liquid products suitable for energy production or equivalent chemicals production, for use at a later date; or it can be used to generate steam for immediate use. The basic technology of refuse pyrolysis has been demonstrated in many fields. For example, Shell Oil and Texaco Development Companies offer partial oxidation-pyrolysis processes for manufacture of clean synthesis gas and/or hydrogen. Between 150 and 200 of these plants have been in commercial operation. Lurgi GmbH also licenses coal gasification processes based on combustion and pyrolysis.

In the United States, several pyrolysis processes have been investigated and some are now reaching demonstration stage under EPA grants. The steam-generating pyrolysis processes include Landgard, developed by Monsanto Chemical Co. A 1000 tonne per day demonstration plant to be used by the City of Baltimore is expected to produce the following products:

Steam	2.18×10^6 kilograms/day (4.8×10^6 lb/day)
Ferrous metal	70 tonnes/day
Aggregated glass	170 tonnes/day
Char	80 tonnes/day

The char has some residual heating value, but it will go to a landfill operation. Instead of low-pressure steam, the process can produce a low-heating value, 1000 kilogram calories per cubic meter (111 Btu per SCF) gas, at the rate of 1.3×10^6 kilogram calories (5.3×10^6 Btu) per tonne of refuse (about 4 MJ/m³ gas at the rate of 5.5 GJ/tonne).

In the process, presized refuse is fed to a rotary kiln that is heated partially by combustion of oil or gas feed. (See process diagram in Figure 1.) This extra fuel amounts to 10 to 12 percent of the input energy. The refuse is pyrolyzed, producing a gas and an inert mixture that is quenched and sorted to recover mineral values. The pyrolysis gas is burned with air to produce low pressure steam. The combustion gases are scrubbed and released to the atmosphere.

A similar process developed by Devco Management Inc., with engineering by Tellepsen Engineering Company, is in the pilot stage. A 120 tonne per day plant is reported to be operating in New York City. These processes, like the direct incineration ones, produce low-quality steam and also suffer the difficulties of load matching.

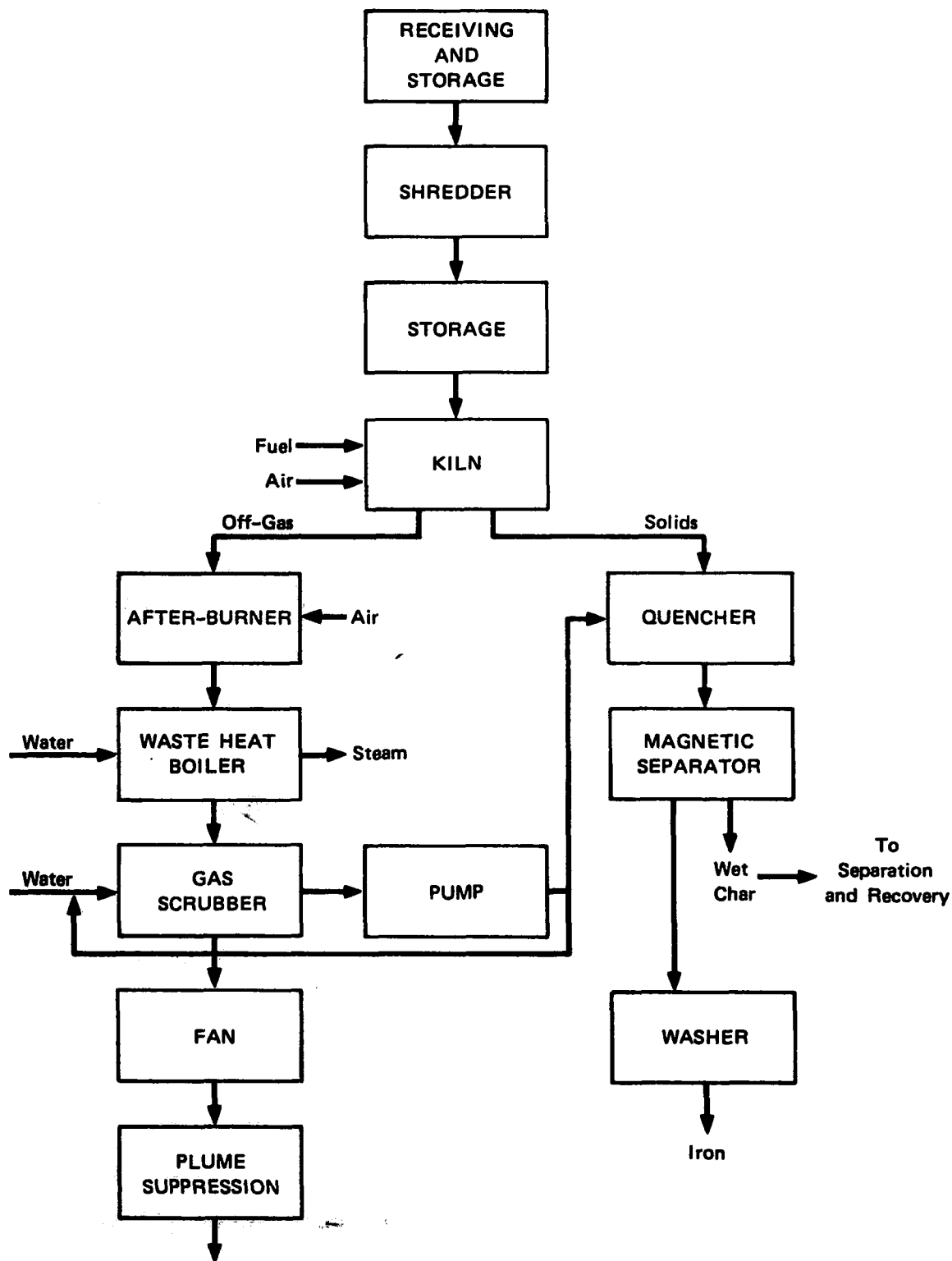


FIGURE 1 MONSANTO LANDGARD PROCESS BLOCK FLOW DIAGRAM

Another process designed to produce combustion gases for steam or power has been demonstrated by Torrax Systems Inc. in a 75 tonne per day pilot operation. This process, too, uses extra fuel to preheat input air to 1200°C (2200°F). The bulk, untreated refuse is fed to a tubular furnace where oil or gas is burned to produce pyrolysis heat. The high design temperatures of the vertical shaft gasifier produce fluid slags that drop to the bottom of the furnace. There the slag is continuously drawn off and quenched. The dry product, pyrolysis gas, has a heat content of about 1250 kcal/m³ (5.2 MJ/m³ or 140 Btu/SCF). The gas yield is about 1.5 million kcal (6.3 GJ or 6 million Btu) per tonne of refuse fuel, after allowance is made for the extra fuel used. This low-Btu gas can be burned to raise steam or drive a gas turbine. The slag can be sorted and valuable materials recovered.

Higher-heating value gases that can be economically transported short distances, used as synthesis gas, or converted into high-Btu substitute natural gas product, as well as used directly for steam and electric power production, can be produced by the Union Carbide oxygen converter process and the West Virginia University process, which uses a modification suggested by Stanford Research Institute. In the Union Carbide process, refuse, as collected, is charged directly to a vertical shaft furnace through lock hoppers as illustrated in the flow diagram (Figure 2). The refuse is pyrolyzed as it falls through hot combustion gases rising from the combustion zone where residual char and nonvolatile organics are burned in an oxygen atmosphere. The inorganic materials appear as a molten slag, which is drawn off and quenched. The produce gas has a heating value of approximately 2600 kcal per cubic meter (11 MJ/m³ or 300 Btu/SCF). It is cleaned of particulates and oil droplets in an electrostatic precipitator. The gases are scrubbed to remove HCl, H₂S, and organic acids. The salts from the scrubber are fed to the furnace and eliminated with the slag. Approximately 75 percent is recovered of the

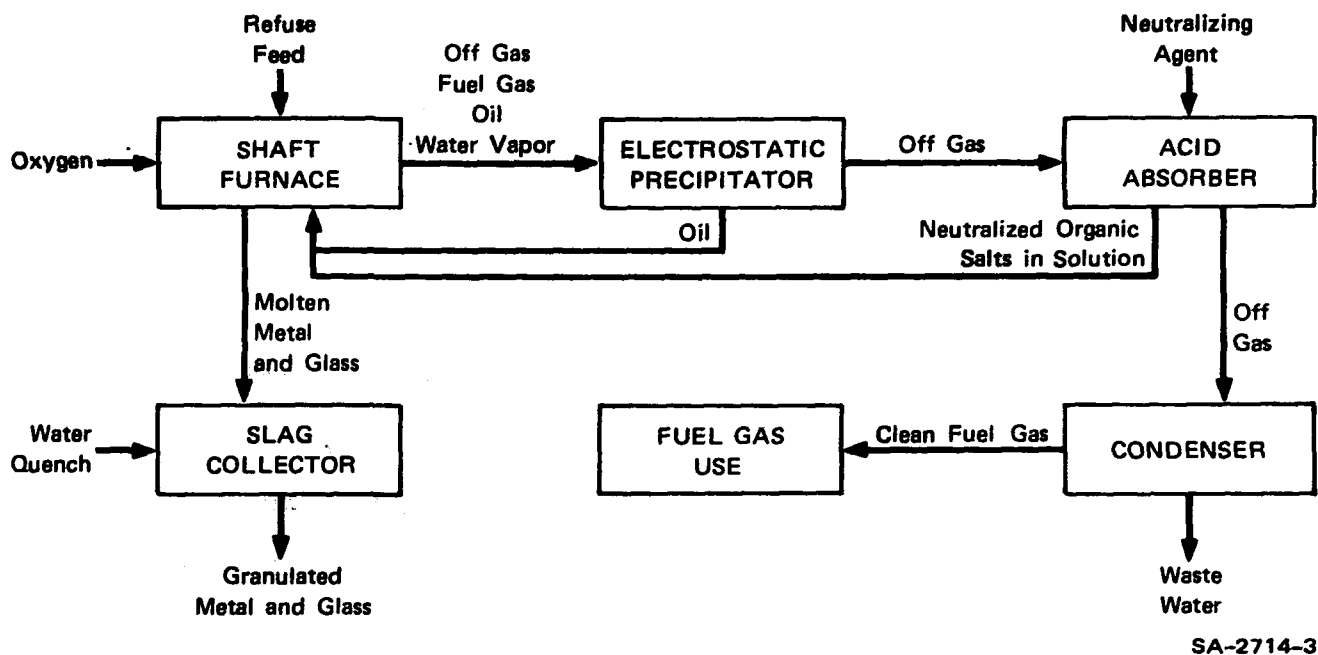


FIGURE 2 UNION CARBIDE OXYGEN REFUSE CONVERTER BLOCK FLOW DIAGRAM

heating value in the fuel. The product gas with the composition indicated in Table 1 could be chemically altered to produce methane, a substitute natural gas.

Table 1

COMPOSITION AND HEATING VALUE OF UNION CARBIDE
OXYGEN PROCESS PRODUCT GAS

Component	Refuse Product Gas (Percent)	Methanated (Percent)
CO	49	0.1
H ₂	29	7
CO ₂	15	3
CH ₄	4	78
C ₂ (hydrocarbons)	1	4
Inert	2	8
Gross heating value kilogram calories per cubic meter (MJ/m ³)	2570 (286) (11)	7900 (877) (32)

Data on process performance and pollutants will be available shortly, as the Company is constructing and will operate soon a 200 tonne per day pilot plant in Charleston, West Virginia.

A process similar to the Torrax and Union Carbide ones has been the subject of small-scale pilot plant investigations. Combustion with air provides the heat to a shaft furnace. Combustion in a lower zone is followed by pyrolysis in an atmosphere of combustion gas and steam. The temperatures are lower and the wastes are clinkered rather than slagged. The product gas contains more than 50 percent nitrogen, and the product gas has a low 1000 kilogram calories per cubic meter (4 MJ/m^3 or 110 Btu/SCF) energy content.

The West Virginia University, or Bailie process, illustrated in Figure 3, uses air instead of oxygen to burn and pyrolyze the refuse, but, through use of a two-chamber fluidized bed system suggested by Stanford Research Institute, produces a medium heat content gas, 3900 kcal per cubic meter (16 MJ/m^3 or 430 Btu/SCF). This gas is not diluted significantly with nitrogen from the air. Prepared refuse, size-reduced, classified, and dried, is fed to a pyrolysis reactor containing a fluidized bed of heated sand. Rapid pyrolysis follows. The product gas is first cleaned of char fines and oil and then of acid gases. The char and oil are transferred to a second chamber, a combustion reactor, where they are burned in air. This combustion heats a fluidized sand bed. The heated sand flows to the pyrolysis reactor, and cooled sand and bulk char return to the combustion reactor. Combustion gases are used to dry the incoming refuse. The process recovers over 75 percent of the heating value of the refuse, and minerals are recovered in the prepyrolysis, classification step. The product gas is useful as an energy source, a synthesis gas, and as a starting material for production of a high heating value fuel. Its estimated composition, given in Table 2, is similar to the raw Union Carbide pyrolysis gas but has a higher energy content.

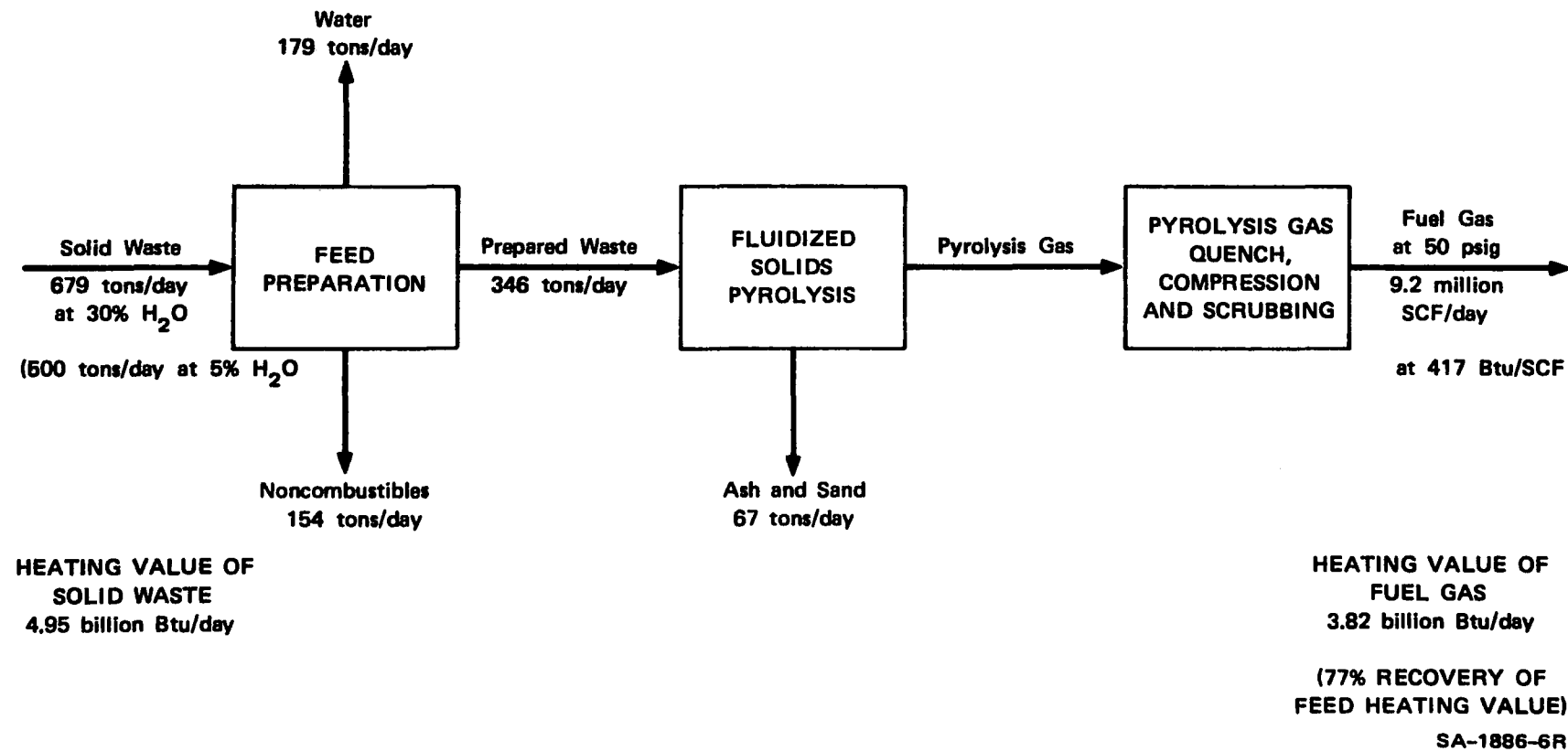


FIGURE 3 BLOCK FLOW DIAGRAM OF WEST VIRGINIA UNIVERSITY PROCESS

Table 2

COMPOSITION OF PRODUCT GAS--WEST VIRGINIA
UNIVERSITY PYROLYSIS PROCESS

Component	Composition (Percent)
CO	27.1
CO ₂	14.7
H ₂	41.7
CH ₄	7.7
C ₂ H ₆	7.8
C ₃ H ₈	1.0
Gross heating value kilogram calories per cubic meter	3900
(Btu per standard cubic foot)	(430)
(MJ per normal cubic meter)	(16)

This gas, too, could be methanated, if local conditions demanded. Conceptual plant designs for 500 and 1300 tonne per day plants have been prepared, but no development work is in progress.

Another process primarily designed for the production of storable and transportable liquid product is to be demonstrated in a 200 tonne per day plant at San Diego, California. The Garrett Research and Development Company process involves size reduction, classification, drying, secondary shredding, flash pyrolysis in a proprietary process, and product recovery. The low-temperature process being demonstrated at San Diego will produce oils more suitable for combustion than for refining. Yields of approximately 0.16 cubic meter (one barrel) of oil per tonne of refuse are expected. Higher temperatures in the pyrolysis unit could produce a gas with substantial heating value--6900 kcal/m³ (29 MJ/m³ or 770 Btu/SCF)--at yields estimated as 1.9×10^6 kilogram calories (8 GJ or 8.0 GJ or 7.6 million Btu) per tonne of refuse fed to the process.

A pyrolysis process which does handle sewage sludge mixed with urban solid wastes is under demonstration in the State of Delaware. This process, developed by Hercules, Inc., does not produce or consume an energy product. It will not be considered further. However, it is important to note that the other incineration and pyrolysis processes discussed above are not well adapted to handling the high water contents of animal manures and sewage sludges, while the Hercules process will.

The Union Carbide, Bailie, and Garrett processes create products with substantial heating value and chemicals content. They can be transported economically or converted to a transportable product. For these reasons, these processes may become more generally used than the other processes described in this section.

C. Energy Products Made by Other Processes

1. Hydrogasification

Another gas-producing process is under development by the Bureau of Mines. It uses technology similar to that developed by the Institute of Gas Technology for gasifying coal. Only limited, small-scale work has been done in batch equipment to define process conditions. Basically, hydrogen, or mixtures of carbon monoxide and steam, contact solid refuse under pressure^{*} to produce a product gas containing methane, carbon monoxide, hydrogen, carbon dioxide and water vapor. Heating values of 2900-5100 kcal/m³ (12-21 MJ/m³ or 330-570 Btu/SCF) and energy yields of $0.93-2.3 \times 10^6$ kilogram calories per tonne are projected. The gas could be readily converted to higher energy content by consecutive water shift and methanation reactions. However, the high pressures required will require inefficient batch operation or new developments in high-pressure feeding systems for heterogeneous materials.

* A typical experiment involved hydrogen at (550°C or 1022 °F) and 91 kilograms per square centimeter of pressure (8.9 MPa or 1300 psig).

2. Catalytic Gasification

Batch experiments at the University of Wyoming have shown that steam can react with solid refuse at moderate pressures, 2.1 to 18.3 kilograms per square centimeter (30 to 260 psig), and temperatures of 650 to 760°C (1200 to 1400°F), to produce a product that is half methane and half carbon dioxide. One pound of catalyst and relatively large quantities of potassium carbonate are required for each pound of waste.

The product gas can be easily treated to remove carbon dioxide leaving a high-heating value material, and for this reason the process is of interest. However, at this time the experiments have been on a very small scale, and the stability and longevity of the large quantities of catalyst required have not been established. The process is so far from demonstration that its true potential cannot be assessed and we will not consider it further in this report.

D. Digestion Processes

1. Anaerobic Digestion

Fermentation or digestion processes play a part in all naturally occurring waste disposal processes. They have been used to stabilize concentrated organic sludges or wastes in water. (Mixtures of sludge and urban refuse are used as starting material for the Hercules, Inc., process.) In the past, the generation of gas (methane) product has been incidental to the economic and sanitary disposal of unwanted organic wastes. The need for energy product and the advantages of large-scale processes now made possible by growth and concentration of urban refuse loads offer new incentive to develop and enhance gas recovery.

Aerobic and anaerobic environments have been used for digestion of solid wastes; however, only the latter process produces methane. The digestion process is usually conducted in an aqueous environment, so normal urban wastes are mixed with water or with watery wastes such as sewage sludge. Small particles speed the reaction, so the wastes must be pulverized as much as practicable. Mixing is required, if high processing rates are to be achieved.

Anaerobic digestion requires nitrates, nitrites, sulfates, carbon dioxide, or similar oxygenated compounds. These supply the oxygen needed for bacterial action. Typical reactions are

Organic matter + Nitrates + living cells \rightarrow

more living cells + N_2 + CO_2 + H_2O + NH_3

and

Organic matter + CO_2 + living cells \rightarrow

more living cells + CH_4 + H_2O + NH_3 + CH_3COOH .

The direct energy yield of anaerobic digestion is much smaller than for aerobic digestion. However the energy difference is stored chemically in the methane and other products. Not all organic material is biodegradable. The biodegradable material undergoes three steps.

- (1) Solubilization (or pulping). (This may or may not be assisted by bacteria.)
- (2) Acid forming in which the complex soluble material is reduced to simple organic acids.
- (3) Transformation of acids, primarily to methane and carbon dioxide.

In the continuous operations necessary for large-scale conversion, the three steps are occurring simultaneously. Temperature and pH control are important. The temperature range for the bacteria of interest lies between 5 and 65°C (40 and 150°F). Three different categories have peak metabolic rates within the indicated temperature ranges.

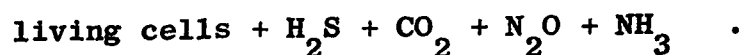
<u>Bacteria</u>	<u>Temperature (Degrees Centigrade)</u>
Psychrophilic	10-25
Mesophyllic	30-37
Thermophilic	55-60

Generally, the rate of bacterial action for a particular strain doubles for each 10°C increase in temperature. These bacteria are sensitive to poisons such as oxygen, chlorinated hydrocarbons, and heavy metals. While most anaerobic bacteria grow well over a wide range of acidity, the methane-forming bacteria are extremely sensitive, growing best in the pH range of 6.5 to 7.0.

In a system with all processes occurring simultaneously, and with the nutrient medium and poison species and concentration constantly changing as new materials are introduced, full control of bacterial growth is difficult to achieve. If the acid-forming bacteria grow too rapidly, the pH may drop below 6.5 or 6. The methane-forming bacteria will then cease to grow, and the process stops halfway. This "stuck," or sour, digester is full of organic acids that make disposal unpleasant and difficult.

Another reaction of environmental interest is the bacterial action of the particular bacteria known as desulfovibria.

Organic matter + sulfates + desulfovibria cells →



Since this reaction can occur in any anaerobic digester, the H_2S -containing effluent must be controlled or treated to prevent unpleasant odors.

A system arranged for methane production would perform the following operations:

- Size reduction.
- Segregation of heavy metals (and chlorinated hydrocarbon films, if possible).
- Slurrying of sewage solids and solid refuse (3 percent total solids).
- Digestion in heated tanks 60°C (140°F) with thermophilic bacteria. (Note that heat is required.)
- Gas collection and purification (removal of carbon dioxide, hydrogen sulfide, phosphene).
- Separation of undigested solids.
- Disposal (landfill) of inert solids.

Available experience indicates that gaseous fuel could be produced at the rate of 1.0×10^7 joule (10^4 Btu) per person per day from a mixture of sewage and urban solid wastes. Only 2 percent of the total will come from sewage sludge, although it is a necessary ingredient in the digestion process. Inert materials remaining after digestion may amount to as much as 50 percent of the volume of compacted dry refuse. Incineration of this undigested material to reduce its volume is possible, but the incineration will be difficult without additional drying steps

and there are problems such as the odor of gaseous by products. By contrast about 90 percent of animal wastes can be converted to gaseous form, and treatment of other agricultural wastes will leave from 10 to 50 percent solids for ultimate disposal.

No large-scale digestions that recover gaseous fuel from wastes are in operation in the United States; however, the art of sewage treatment that would form the basis of any gas production and recovery operation has been practiced for many years.

2. Enzymatic Digestion

Enzyme-based photosynthetic processes have been reported to produce hydrogen from water. These might be adapted to produce hydrogen from wastes, directly or indirectly. The technology is so little advanced that we are unable to offer any prognosis for the process or to predict its environmental impact. We will not discuss it further.

Landfill, and to a lesser extent, incineration, is the primary method for refuse disposal today. Future developments are expected to emphasize the importance of incineration with energy recovery, pyrolysis to produce energy products, and anaerobic digestion to produce methane. In fact, these latter two methods are expected to be the basis of most large-scale disposal facilities of the future. We will discuss the environmental effects of incineration, pyrolysis and anaerobic digestion in the following section.

III ENVIRONMENTAL IMPACTS OF SPECIFIC ENERGY-PRODUCING WASTE-DISPOSAL PROCESSES

A. Introduction

In assessing the potential effect of solid-waste recovery and its conversion to energy or energy materials, we will first consider the known or estimated effluents of typical energy-producing incineration, pyrolysis, and digestion processes. We will then make range estimates of the extent to which each general process will be adopted to establish total pollution impacts.

The literature dealing with energy-producing waste disposal processes is deficient in definitive data on quantity and quality of a given effluent from a given process. As a result, the following paragraphs will contain a few numbers that are based on quantitative data directly related to the process discussed and some that are based on inference from similar processes having quantitative data. Most will be inferred or assumed from qualitative estimates. Air pollution data from incinerator-type operations is directly available. Water pollution data for incinerators and all pollution data for other processes will be inferred with different degrees of extrapolation or interpolation.

Pollution data from disposal-only incineration processes can be applied directly to incineration processes that generate steam. Untreated stack gas from municipal refuse is reported to contain 15 kilograms of particulates per tonne of refuse (30 lbs/ton).⁷ This is typical of single chamber incinerators.⁸ This particulate effluent rate can be substantially reduced by systems to control particulates.⁹ (See Table 3.)

Table 3

COLLECTOR EFFICIENCIES FOR MUNICIPAL
INCINERATION PARTICULATE-CONTROL SYSTEMS

<u>Type</u>	<u>Efficiency (percent)</u>
Settling chamber	0-30
Settling chamber and water spray	30-60
Wetted baffles	60
Mechanical collector	30-80
Scrubber	80-95
Electrostatic precipitator	90-96
Fibric filter	97-99

At 90 percent removal, the particulate emissions reaching the atmosphere will be 1.5 kg/tonne (3 pounds per ton), and at 99 percent removal they will be 0.15 kg/tonne (0.3 pound per ton). Combustion of one tonne of refuse with 270 percent excess air will produce approximately 7,800 cubic meters (275,000 cubic feet) of gas at standard conditions.¹⁰ This gas has a CO₂ content of 6 percent. At 12 percent CO₂ (the standard basis for comparison), the concentration of particulates would be 0.366 and 0.0366 grams per cubic meter (0.16 and 0.016 grains per SCF) for 90 and 99 percent removal. A recovery of particulates of at least 95 percent is required, if the required upper limit for particulate pollution of 0.183 grams per cubic meter (0.08 grains per SCF) is to be met, under the assumed conditions.

Practical data from the Chicago steam-raising incinerator indicate that precipitator efficiencies of 96 to 97 percent were achieved and original particulate loads before the precipitator of about 10 kilograms

(22 pounds) of particulate per tonne of refuse burned were reduced to about 0.42 kilogram (0.93 pound) at the stack exit.¹¹ Direct incineration will also add approximately 0.4 kilogram (1 pound) sulfur dioxide and 1.3 kilograms (3 pounds) nitrogen oxides to the air per tonne of refuse burned.

The usual particulates will contain inorganic materials, including detectable amounts of free mercury and beryllium, lead and zinc.¹² (See Table 4.)

Table 4
CONCENTRATION OF SOME TRACE MATERIALS
IN INCINERATOR FLY ASH

	<u>Study 1 (amount)</u>	<u>Study 2 (percent)</u>
Be	Small or trace	0.001-0.01
Hg	Small or trace	
Pb	Small or trace	0.01-0.1
Zn	Small or trace	1-10

These heavy metals and others, such as cadmium and selenium, are potential health hazards whose overall effect is poorly known at present. Lead particulate inhalation may cause chronic intoxication; soluble lead components are cumulative poisons. Particulate beryllium produces pulmonary fibrosis. Cadmium oxide dust or fumes may cause pulmonary edema or hemorrhage. Zinc inhalation may lead to "metal fume fever" and damage to the respiratory tract.¹³ Total potentially hazardous inorganic effluent from a properly controlled stack is likely to be much lower than 0.05 kilogram per tonne (0.1 pound per ton) of refuse incinerated.

Handling of the collected incinerator fly ash also poses potential hazard to the refuse disposal worker.

While the ash is primarily inorganic in character, some organic material remains unburned. Chlorinated hydrocarbons and polynuclear hydrocarbons (resulting from pyrolysis as well as incomplete combustion) both pose potential health hazards. The former can cause damage to the central nervous system; the latter are known carcinogens. Quantities of these materials are low; total organic carbon in fly ash ranges from 10 to 20 percent, and the fraction of toxic or hazardous materials is much lower (although undetermined). Total potential hazardous organic material emitted from controlled stacks is certainly below 50 grams (0.1 pound) per tonne of urban solid waste burned.

Other volatile materials may escape combustion at low excess air values. These may cause problems with eye irritation and odor, but are not fundamentally hazardous. Formic, acetic, palmetic, stearic, and oleic acids; methyl and ethyl acetate and ethyl stearate; formaldehyde and acetaldehyde, hydrocarbons, and phenols have been found in incinerator stack gases. Potentially hazardous materials such as phosgene and hydrogen cyanide can be formed, but we expect these would be found in very low concentration. Hydrogen chloride can be an undesirable product when chlorinated hydrocarbons (such as those contained in plastic films) are burned. Proper incineration practice, including afterburning with additional fuel, should reduce all of these to unnoticeable or negligible levels.

The extent of use of quench water in incinerator practice is not recorded in the literature. In many instances air cooling is used. However, we will assume that all incineration for energy production utilizes water quench on the ash. We estimate 5 to 50 kilograms (10 to 100 pounds) of quench water will be discharged per tonne of refuse

treated. This material will have high pH (6 to 11.8) and contain suspended and dissolved solids in varying amounts [as much as 6 grams and 10 grams of solids per kilogram (0.006 and 0.01 pounds per pound) of water, respectively]. Secondary treatments incorporated in the solid waste disposal facility should provide adequate control.

The 180 to 225 kilograms (400 to 600 pounds) of residue after incineration of a tonne of refuse may have valuable materials extracted, but we will assume that all 225 kilograms is placed in landfill. This material is principally silicon, aluminum, calcium, and iron oxides. Leachates from it may percolate to ground waters, streams, and so forth. These leachates will have high hardness, but the composition and quantity are too dependent upon local conditions for any judgment of their ultimate environmental effect to be made without extensive field work and analysis. The environmental impact analysis for the individual location must define the potential effects.

Fluidized bed incineration will probably produce no more airborne particulates than will normal incineration if both facilities are properly managed. In fact, the Combustion Power Company process in which combustion gases are fed to a turbine to generate electricity requires extreme cleanliness. Particles and metal vapors can cause erosion and other problems with turbine blades; thus the process includes three stages of cyclone separation for particle removal.

Fluidized bed processes can usually be adjusted so as to absorb sulfur dioxide into the bed. The low combustion temperatures in the bed are expected to reduce nitrogen oxide formation. This better thermal contact should also reduce the quantities of unburned organic material, including chlorinated and polynuclear hydrocarbons.

Combustion (incineration) processes in which refuse makes up a small fraction of the total material fired will operate under the same

general conditions and produce the same general environmental effects as coal-fired boilers. The uncontrolled fly and bottom ash loads may be as much as 3 to 7 percent higher per pound of steam produced in the boiler when mixed refuse and coal is burned instead of coal only, but the emissions per tonne of refuse burned should be less than those listed above. The quantity of air required is expected to drop from 200 percent or more to 20 to 25 percent excess air. The reduced volume flow will cause less carryover to the cleanup system, and the more compact systems may be generally more efficient.

Pyrolysis processes such as Landgard, that produce steam as a principal product, will have air effluent problems similar to those of the combustion systems. Exit gas flows will lie between those found in normal incineration and those in combined burning with coal. Particulate loads will be no higher, and perhaps lower, than those from direct incineration processes. The secondary combustion of the pyrolysis gas will consume some of the hydrocarbons and other combustibles that escape from direct incineration. The gas burned in this step has a low calorific value, and thus flame temperatures will be lower than in incineration. Therefore, nitrogen oxide levels should be lower. Whether particulate, hydrocarbon, and nitrogen oxide emission levels are lower for pyrolysis for energy production plants than for incineration plants is probably more dependent upon individual differences in design and methods of operation than upon process fundamentals. Ash or slag characteristics, leaching of ash to ground water, and quench water discharge factors are expected to be about the same for incinerator and pyrolysis plants.

The emissions from pyrolysis processes directed to the production of energy product should be small. The product gases from each will be contained and can be scrubbed to remove acid gases and particulates. The entire gas output of the Torrax and Union Carbide processes will be so treated. The Bailie process produces separate streams of product

and combustion gas. The latter will be quite small in volume when compared to that from direct incineration processes. Only 10 to 15 percent of the combustibles will be directly burned. The burning, in a fluidized bed, should require little excess air, produce only small quantities of nitrogen oxides, and have low unburned hydrocarbon loads. Ash loads from several of these processes will approximate those from direct incineration. The fluidized beds of the Bailie process will produce about 50 percent more ash than the other processes. Thus, the landfill is larger and leachate loads may be slightly higher for it than from the other processes. Quench water discharge will be slightly larger, but treatment will reduce the effect to negligible proportions.

The proprietary nature of the Garrett process precludes direct comparison of expected effects; however, we expect it will produce stack gas, water, and solid waste effluents in amounts similar to those of the other energy product processes.

We cannot comment in detail on potential emissions from hydrogasification and catalytic methanation processes, as those are apparently far from demonstration, and serviceable data are lacking. However, it is likely that if developed, they will behave like the other energy-product-producing processes and have relatively low emission effect.

Anaerobic digestion, properly conducted, will collect product gases. The principle undesirable product, hydrogen sulfide, can be removed. However, removal of small quantities of hydrogen sulfide from carbon-dioxide-containing mixtures may prove to be difficult and uneconomical. More difficult to handle may be the problems encountered during off-specification operations. These will probably be caused by poisoning of the bacteria either by metals or acid. The "sour," partially treated mess is vile-smelling. Its disposal by landfill or incineration would not be well received by people for several miles downwind of a large plant.

Substantial quantities of organic material remain untouched by anaerobic digestion. The wastes could be further reduced in volume by incineration, if they can be dried sufficiently. If they are not so treated, the volume of waste placed in landfill could be as much as 50 percent of that from the original shredded and compacted waste.

B. Miscellaneous Effects

Several of the processes may require drying of the as-received solid waste on an occasional or regular basis. (As-received refuse may have from 20 to 50 percent water; 30 percent is very common.) This drying and the combustion of the refuse will release moisture to the environs of the plant. A 10,000 tonne per day plant will release 2500 to 4000 tonnes of moisture per day. Drying can produce noxious odors in the drying gas stream. Most of this can be removed by passing the exit gas through a high-temperature flame, one at 700 to 820°C (1300-1500°F). This requirement for an extra combustion step and necessity for extra fuel could reduce the economic attractiveness of the process that requires it.

Handling, size reduction, and classification activities create dusts, especially if the solid waste has been dried. The operator and designer must take potential dusting into account so as to minimize its effects. Vents or hoods over the equipment can lead the dusty air to a separate filter system or to the main stack. Total particulate discharge will not be measurably affected, and this impact can be credited to the general particulate discharge.

In any discussion of environmental effects, it should be noted that any waste-disposal process will require refuse collection, with the attendant noise and environmental effects of large truck transportation. At the collection station the noise of refuse transfer operations and the odors coming from untreated refuse in storage will create local

problems. Size reduction, which is essential for some processes and desirable for any materials recovery operation, is very noisy. Relatively small shredders capable of handling 5 tonnes per hour will produce noise levels of 80 to 85 decibels at 50 feet from the machine.¹⁴ This is equivalent to the noise arising from diesel trucks, compactors, and other equipment to be encountered at disposal sites. The noise impact will be restricted to a relatively small area in the immediate vicinity of the plant.

C. Specific Environmental Impacts of Solid Waste Disposal Plants

Most high solids (urban) wastes will be treated by energy-producing incineration or pyrolysis processes.* Fewer will be treated by direct incineration, with qualitatively similar environmental effects, and some by anaerobic digestion. If 75 percent of urban wastes are treated by some form of incineration or pyrolysis process, an urban population of 175 million in 1985 will produce from 50,000 to 250,000 tonnes of particulate contamination.[†] The lower figures are associated with pyrolysis plants producing energy product. In most cases these plants will use less combustion air and/or release smaller volumes of combustion products to the atmosphere. If the effluent gases are held to the same volumetric standard, then the total effluent from pyrolysis gases will be smaller. For comparison, we note that solid waste disposal (primarily direct incineration) now contributes 1.4 million tonnes of particulates annually to an atmospheric pollution that totals 25 million tonnes of particulates.¹⁵ The energy recovered from this urban waste could be as

* We include energy materials in this category.

[†] Assuming particulate emission for each plant meets the current national standard of 0.183 grams per cubic meter (0.08 gram per SCF).

much as 2.5 percent of the total anticipated energy demand in 1985, at the same time the particulate burden in the atmosphere will be reduced to below 1 percent of the current total.

The quantities of lead and zinc placed annually in the atmosphere can range from a few tonnes to perhaps a thousand tonnes. The current release of a comparable metal, cadmium, is estimated at 86,000 kilograms (190,000 pounds) through (uncontrolled) incineration.¹⁵ Rubber tire wear contributes 5150 kilograms (11,400 pounds), and superphosphate dispersal contributes 22,500 to 225,000 kilograms (50,000 to 500,000 pounds). (The superphosphate is not emitted directly into the atmosphere.)

Potential carcinogens and other hazardous organic materials may be discharged as particulates in tens to hundreds of tonne quantities. These quantity estimates are a reasonable maximum based on complete use of well-controlled, energy-producing incinerators, or production of energy products from pyrolysis.

We estimate that pyrolysis processes producing energy product will produce perhaps one-tenth to one-fifth as much particulate pollution as incineration processes. The larger factor has been used in the estimates of metals emission above. However, the exact ranges of quantities and concentrations to be expected from large economical plant operation need to be established by adequate experimentation at demonstration plants.

We now turn to the local effects of particulate emission. A 10,000 tonne per day solid-waste disposal-by-incineration plant serving some 2 million persons will discharge 15,000 kilograms (33,000 pounds) of particulates per day (assuming 90 percent control). Typical large cities with populations over one million have areas of 2500-5000 square kilometers. If we assume these particulates are discharged into a box with a base 60 kilometers square (3600 sq km) and a height of 0.3 kilometer, and that

the box is swept with light winds (5 kilometers per hour) for 14 hours a day, a volume of 1260 cubic kilometers is provided in which this effluent is dispersed. The concentration of particulate would then be 12 micrograms per cubic meter. Because the box model assumes quite unfavorable inversion conditions, the $12 \mu\text{g}/\text{m}^3$ concentration level would seldom be reached. For reference, we note that former urban air particulate concentrations of over 100 per $\mu\text{g}/\text{m}^3$ * are now being reduced by good air pollution control practices to meet secondary standards of $60 \mu\text{g}/\text{m}^3$.

Correlation between air quality and emission rate is dependent upon the stack height and stack gas velocity of the individual plant and the daily and annual weather conditions at the site. Thus the influence on local and regional air quality of a single solid-waste disposal process must be established on an individual basis. Regional air quality as a function of regional emission varies, too, as a function of meteorology. However, some selected metropolitan regions, e.g., Chicago, New Jersey, New York, Connecticut, Los Angeles, and the San Francisco Bay Area, have estimated median annual air qualities of 0.065, 0.14, 0.16, and $0.38 \mu\text{g}/\text{m}^3$ particulates per daily tonne of particulate emission.¹⁷ Air qualities (pollution) of 0.10, 0.22, 0.30, and $0.58 \mu\text{g}/\text{m}^3$ per tonne will be exceeded 20 percent of the time in these same cities.

Using these data, we deduce that the 10,000 tonne per day plant discharging 15 tonnes of particulate effluent would have median pollution effect over the entire area of roughly 1 to $6 \mu\text{g}$ particulate per cubic meter. The pyrolysis plant producing energy product would contribute $1 \mu\text{g}/\text{m}^3$ or less of particulate to the air burden. These data lead us to conclude that the urban areas would have ultimate particulate loads

* See Figure 1, Estimated Emissions of Air Pollutants by Weights, Nationwide, 1970, Preliminary Data, EPA. This is taken in turn by Mitre Corp. Report MTR 6013.

from energy producing waste disposal amounting to 1 to 10 percent of the established secondary air quality standards. While improved stack dispersal and further improvement in collection efficiency may be required under special circumstances, the concentrations of heavy metals introduced to the atmosphere (as particulate ash) from a 10,000 tonne per day plant are expected to fall well below values commonly encountered in urban atmospheres.

The quantities of sulfur and nitrogen oxides emitted also will be relatively small in all processes. Direct energy production processes (without fluidized bed combustion), e.g., Landgard, will emit sulfur dioxide (SO_2) in weight quantities equivalent to particulate emissions. Nitrogen oxide emissions will be about three times larger. If these processes were used to dispose all urban wastes, they would add 200,000 to 250,000 tonnes and 600,000 to 750,000 tonnes, respectively, to the national air pollution load. Currently, national sulfur oxides (SO_x) emissions are estimated to be 34 and nitrogen oxides (NO_x) emissions, 23 million tonnes.¹⁸ Fluidized bed combustion will reduce expected emissions from waste disposal by substantial amounts. The same general prediction can be made regarding energy product processes which utilize pyrolysis. Thus, as simple uncontrolled incineration is replaced by fluidized bed incineration and energy product recovery pyrolysis, the effluent loads [(particulate, SO_2 and nitrogen dioxide (NO_2))] from waste disposal will be reduced from 250,000 and 750,000 tonnes to perhaps 50,000 and 150,000 tonnes. The air concentrations will be similarly reduced. Relative or comparison data on the various emissions are shown in Table 5.

Table 5 compares the quantities of each effluent emitted by other waste-disposal processes to the quantity of effluent emitted by the incineration for energy process. Particulates are assumed to be limited to 0.183 gram per cubic meter (0.08 grains per SCF) of stack gas emitted.

Table 5

ESTIMATED ENVIRONMENTAL IMPACT OF SOLID-WASTE DISPOSAL METHODS
FOR URBAN WASTES, RELATIVE TO ORDINARY INCINERATION

	<u>Particulates</u>	<u>SO_x</u>	<u>NO_x</u>	<u>H₂S</u>	<u>Organics</u>	<u>Solids, Leachates</u>
Incineration for energy	1	1	1	nil	1	1
Pyrolysis for energy	< 1	< 1	< 1	nil	1	1
Pyrolysis with energy product	1/10-1/3	<< 1	<< 1	nil	<< 1	1
Anaerobic digestion	nil	nil	nil	possible trace	unknown	1-3

* Special disposal problems from stuck or sour digester.

Incineration processes will release small quantities of unburned hydrocarbons and partial combustion products. We are unable to estimate either the quantities emitted from incinerators or the effects to be expected from exposure of humans, animals or plants to these small concentrations of such materials. It can be pointed out that incineration and combustion in stationary sources are not now judged to be significant contributors to total hydrocarbon emissions.¹⁹ Furthermore, man-made emissions of partial combustion products, principally carbon monoxide, are now attributable almost entirely to vehicles and petroleum refineries.

Established limits for exposure deal with occupational exposures of 8-hour days and 40-hour weeks or a total exposure of 2000 hours per year. The effects of and limits for continual exposure have not been determined. If we apply the practice for limiting exposure to radioactive materials for nonoccupational (general population) groups to one-third that set as a limit for occupational exposure to the case of airborne chemicals, then clinical exposure limits are generally above $100 \mu\text{g}/\text{m}^3$. We do not expect concentrations of any single chemical in particulate form to be above $10 \mu\text{g}/\text{m}^3$ in the undiluted stack gas.

It must be noted that fourteen potentially carcinogenic chemicals are on a "prohibited" list, shown below in Table 6. These, or mixtures of these down to 1 percent carcinogen, are to be handled as toxic materials, and exposure to them poses a grave danger to employees.²⁰ By regulation, occupational exposure is controlled, to eliminate all contact (including inhalation) with these chemicals.

Even fewer data are available on effluent from scale anaerobic digestion. We expect particulate quantities to be low, and hydrogen sulfide emissions to be controllable. Incineration and pyrolysis effluents such as SO_2 and NO_2 will not be present in quantity. As the process will be applied primarily to agricultural and food processing wastes, which

Table 6

POTENTIALLY CARCINOGENIC CHEMICALS

Compound No.	Chemicals	Chemical Abstracts Registry No.
1	2-Acetylaminofluorene	53963
2	4-Aminodiphenyl	92671
3	Benzidine (and its salts)	92875
4	3,3'-Dichlorobenzidine (and its salts)	91941
5	4-Dimethylaminoazobenzene	60117
6	alpha-Naphthylamine	134327
7	beta-Naphthylamine	91598
8	4-Nitrobiphenyl	92933
9	N-Nitrosodimethylamine	62759
10	beta-Propiolactone	57578
11	bis-Chloromethyl ether	542881
12	Methyl Chloromethyl ether	107302
13	4,4'-Methylene(bis)-2- chloroaniline	101144
14	Ethyleneimine	151564

are digested almost completely, solid residues will not be an important consideration. However, when it is applied to urban wastes, the solid waste problem could be appreciable.

D. Some Research Needs and Opportunities

It is apparent from the discussion above that definitive knowledge of the kinds and quantities of materials generated by and released from energy-producing solid waste disposal processes is lacking. Mercury and other heavy metals, chlorinated hydrocarbons, and polynuclear (carcinogenic) materials are among those for which information would be especially significant. Operation of demonstration plants of newly

developed processes offer opportunities for generating this information. Demonstration plant operation offers opportunities for correlating the character of plant input to effluents and establishing the feasibility and effectiveness of waste segregation on environmental control. The demonstration plant operations should also develop ways to minimize all pollution effects, such as direct water wastes, leachates, and so on.

More measurements on effluents from existing incinerators would also be helpful in establishing baseline information. Volatile organic species and their concentrations are a potential concern. Our ability to detect or measure quantitatively will be tested in many instances.

Basic information on the mechanisms by which leaching transports metals, acid, alkali, and other contaminants from landfill to streams and water supplies should be established. Testing of the effects of existing ash-dominated landfill on the surroundings is needed.

The relative contribution of solid waste disposal processes to the overall environmental result can only be established after data of these kinds is gathered. It is apparent that several otherwise desirable processes will be discharging very small quantities of potentially harmful inorganic and organic materials into the atmosphere, and perhaps into ground waters. Final evaluation of the processes must depend on the development of sound information on the hazard (if any) from these materials at the very low concentrations expected. From these data on hazard and effluent concentration, one could establish possible needs for further effluent control, and direct the development of control methods. One could also evaluate the needs for control in terms of the relative hazard from solid waste disposal and other processes.

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Appendix E
UNDERGROUND COAL GASIFICATION

by
Albert J. Moll

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I INTRODUCTION

Underground (in-situ) coal gasification is a concept whereby fuel gas is made from underground coal deposits by reaction with oxygen and steam. The product gas may be in the form of substitute natural gas (SNG), or a low heating value gas (low Btu gas) that may be burned at the site to generate electricity. Gasification with oxygen is necessary to make SNG, while air may be used to make low heating value gas. Underground coal gasification is distinct from surface coal gasification. In surface coal gasification the coal is first mined and then gasified in process vessels on the surface. Underground gasification serves to replace the combined functions of mining and surface gasification--as well as coal crushing, coal storage, and ash disposal. Once formed, the raw gas must be reacted and purified much like the raw gas made by surface gasification.

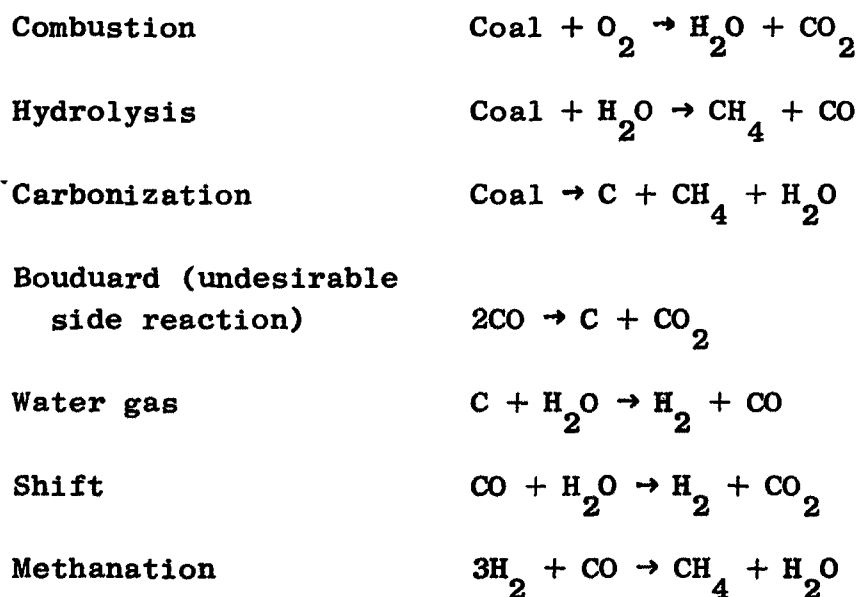
There are at least two commercial processes for surface coal gasification, Lurgi and Koppers-Totzek, and several other processes are being developed in the United States. At the present time, underground coal gasification is largely undeveloped in spite of decades of research in the United States, Britain, the USSR, and other countries. There are two active governmental development programs underway in the United States on underground coal gasification. One program is being carried out by the Bureau of Mines and the other by the Atomic Energy Commission. However, formidable technical problems must be overcome before underground gasification can be commercialized.

II STATE OF THE ART OF UNDERGROUND COAL GASIFICATION

A. Past Development Work

1. Mechanisms and Methods of Operation

The following reactions take place simultaneously during coal gasification:



In underground coal gasification, the most important of these reactions are combustion, carbonization, and water gas. Combustion provides the heat for carbonization and the water gas reaction. If there is poor gas contact with the coal, or poor permeability through the coal, little of the carbon product of the carbonization reaction is gasified by the water gas reaction. Thus, if carbonization predominates, there is low air (or oxygen) acceptance and a low yield of gas from the coal. The desired type of operation occurs when gasification follows carbonization. This type of operation is marked by high air acceptance and high gas yield.

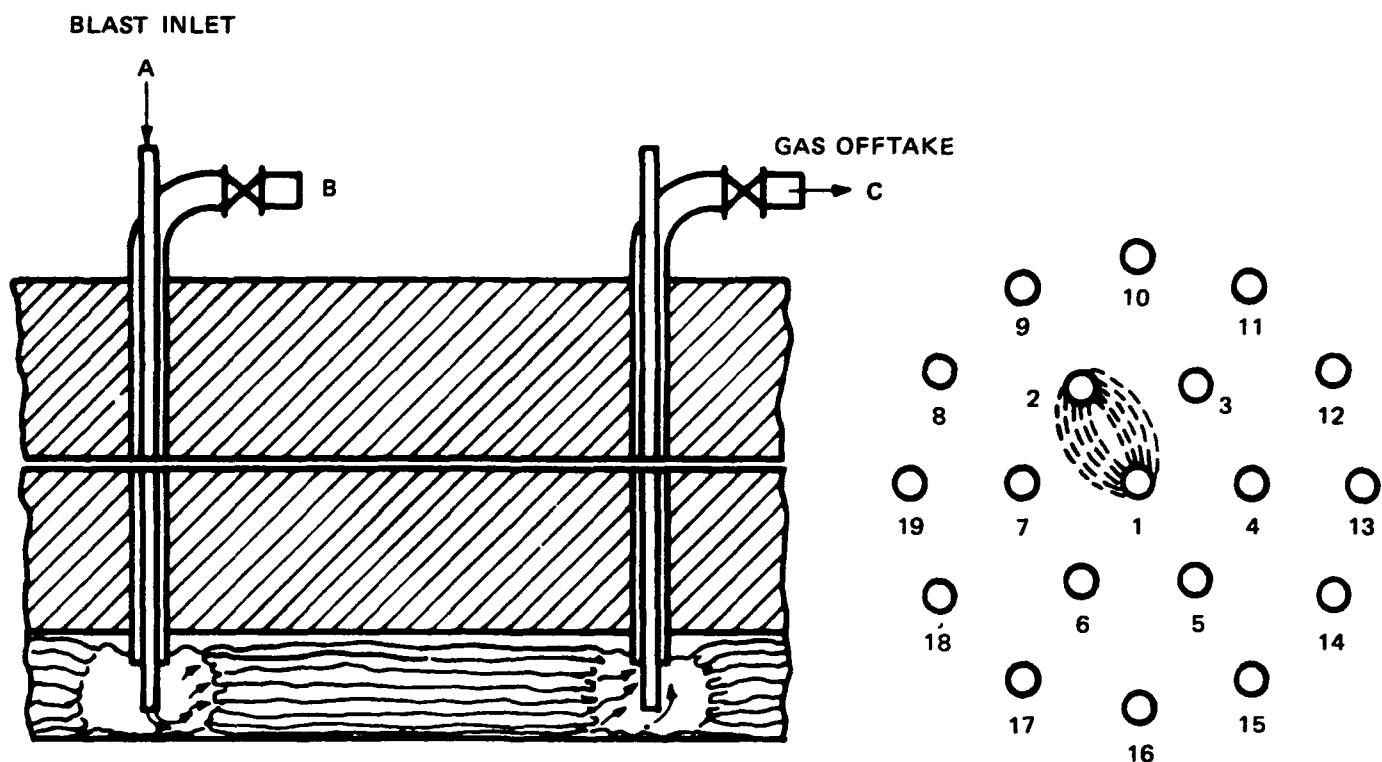
Previous studies, including both shaft and shaftless methods of underground coal gasification, are extensively reviewed in a report prepared for the Bureau of Mines.* The shaft methods require underground mines to prepare the coal for gasification. Most of the work in the USSR and England was devoted to shaft methods; however, there is no current interest in shaft methods because most of the effort spent mining coal would still be required.

With shaftless methods, no underground labor is used, and all access to the coal is through boreholes drilled from the surface into the coal seam. The approach used in the shaftless methods has been to inject air into an inlet borehole, ignite the coal, and attempt to produce gas from one or more outlet boreholes. The most simple shaftless method is the percolation method shown in Figure 1. Usually some means must be used to make the coal bed more permeable; methods of achieving permeability that have been tried or suggested include electrolinking, pneumatic fracturing, hydraulic fracturing, and explosives.

2. Electrolinking

The process of electrolinking, the electrocarbonization of coal, was first tried in the United States in 1947 in the laboratory of the University of Missouri. Field tests were undertaken subsequently under a cooperative contract between the University of Missouri and the Sinclair Coal Company of Kansas City. In 1951 at Gorgas, Alabama, the Bureau of Mines (in cooperation with the Alabama Power Company) further investigated the electrolinking-carbonization of coal underground. In England (about 1952) study and investigation were also directed to the

* References are listed at the end of this appendix.



(a) SECTION THROUGH BOREHOLES

(b) PLAN OF BOREHOLES

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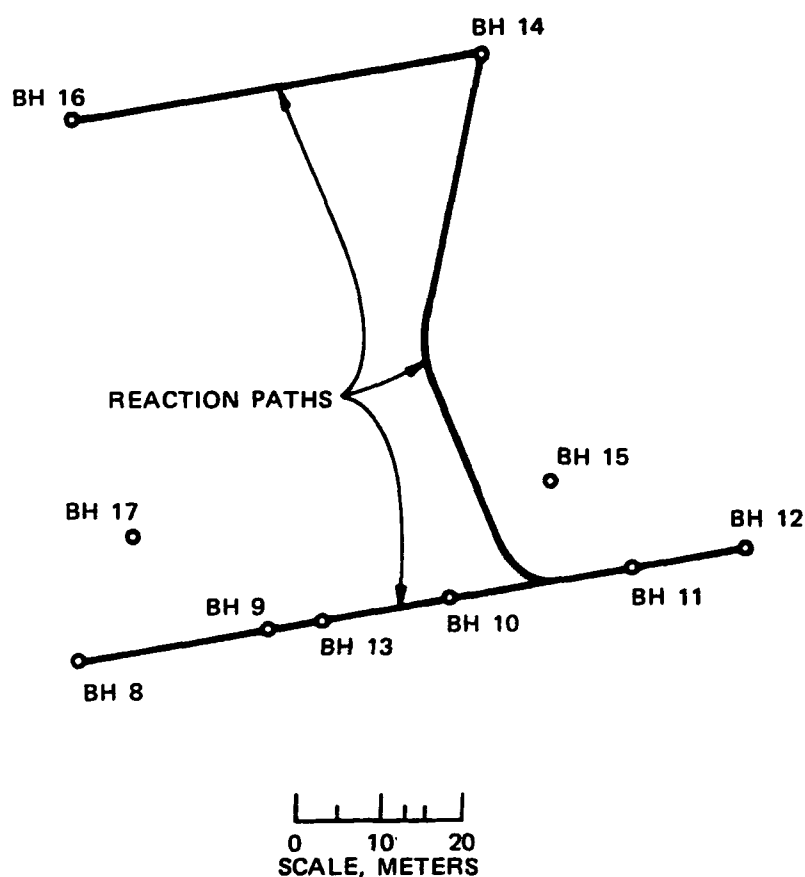
SOURCE: Bureau of Mines.

FIGURE 1 IN-SITU COAL GASIFICATION BY THE PERCOLATION METHOD

application of a technique to underground gasification processes. In the Russian work, which began prior to World War II, electrolinking-carbonization was successfully applied in large installations.

In the process of electrolinking, electrodes are installed within the coal bed at a given spacing. Passing an electric current between the electrodes carbonizes the coal by resistance heating to form a path of increased permeability; gasification can then proceed along this path. The Bureau of Mines performed experiments with an electrode spacing of approximately 45 meters with some success.

Figure 2 shows a pattern of electrolinked carbonization paths among a number of boreholes and illustrates one difficulty, viz., the lack of control when using this technique. The path of the current between two electrodes may be markedly affected by coal bed changes resulting from prior experimental work on the undisturbed coal seam. Therefore, the resultant unpredictability of electrolinking in the establishment of single gasification paths appears to offer a major difficulty. But, if multiple paths are to be established simultaneously, which is possible in a commercial application of area gasification, the precise path between two individual electrodes may be inconsequential.



SOURCE: Bureau of Mines.

SA-2714-5

FIGURE 2 PLAN VIEW OF REACTION PATHS INITIATED BY ELECTROLINKING AT GORGAS

Estimates made during the tests indicated that about 80 percent of the electrical energy had passed through the coal bed during the electrolinking phase, and this proportion rose to about 97 percent toward the end of the electrolinking-carbonization phase. Whether or not electrolinking-carbonization should have proceeded further to prepare a bed of greater permeability for the gasification operations was not well established. The results of British and Russian work were similar to those reported above.

3. Hydraulic Linking

The process of hydraulic linking involves injecting fluids under high pressure into a previously undisturbed coal seam to cause fracturing and consequently an increase in permeability. Hydraulic fracturing techniques have been used in oil field work for many years, and the method has been tried in the United States and Russia in connection with underground coal gasification.

In the United States, several tests were carried out at Gorgas by the Bureau of Mines. In the second and final test in 1957, the coal bed was fractured by injecting fluids at a rate of 750 to 2300 liters per minute at 63 to 70 kilograms per square centimeter (900 to 1000 psi) pressure. A total of 5000 kilograms (11,000 pounds) of sand were suspended in 128,100 liters (33,580 gallons) of water containing a gelling agent for stabilization. The fluid fractured the coal, and the sand served as a propping agent to hold the cracks and crevices open after release of the pressure; fracturing continued for about three hours. The injection took place in a centrally located drill hole. In these tests, there were 50- to 100-fold increases in permeability at the injection borehole, and air acceptance to other boreholes was increased about fivefold. Such effects should last at least several years. Subsequently, the hydraulically fractured areas were successfully gasified.

The Bureau of Mines has also done considerable work with incorporating liquid explosives in the fluids, and this technique shows some promise for further increasing the permeability in coal seams. For example, it may be possible to electrolink or to fracture hydraulically, then fill the fractures with liquid explosives, and explode them to produce larger volumes of fractured structures.

4. Pneumatic Fracturing

Work has been conducted in the United States and England on the use of high-pressure air to fracture coal formations pneumatically. Generally, it is possible to achieve initial success this way, but upon release of the pressure the new fractures tend to close, eliminating the temporarily increased permeability. This closing tendency also occurs in hydraulic fracturing if there is no sand to prop the fractures open after the pressure is released.

5. Gasification

After permeability is attained, gasification of the coal proceeds along the seam in essentially a horizontal direction. The small scale gasification tests made by the Bureau of Mines in the 1950s at Gorgas, Alabama, were carried out in a relatively thin (about 1 meter) seam of coal. Although a considerable amount of data was obtained, the results of the tests were discouraging: the energy content of the gas formed was low and variable, oxygen usage was high, and coal recovery was poor. There were several reasons for the relatively poor performance. One reason for poor performance was that poor gas contact with the burning face allowed oxygen bypassing; another reason was that the burning front tended to be unstable with preferential reaction of the coal along the top of the seam. The Gorgas tests were ended in 1958 with these problems still unsolved.

B. Current Program of the Bureau of Mines:
Gasification in Horizontal Direction

As indicated above, the approach of the Bureau of Mines in the past has involved gasification in a horizontal direction after one of a variety of methods has been used to achieve permeability. Their current underground coal gasification program applies the same approach, although the emphasis is on thick-seamed western coal.

A review of previous work¹ included a recommendation that the Bureau of Mines reactivate the underground gasification program on a limited scale. A modest two-phase program was suggested; neither phase included gasification experiments in the field.

The Bureau of Mines appears to have decided to forego the studies recommended in favor of field gasification tests. Their present program is aimed at establishing feasibility and showing that the problems encountered in previous programs can be solved. If the current program is successful, the Bureau would like to launch a more ambitious series of field tests to develop a commercial scale gasification process.

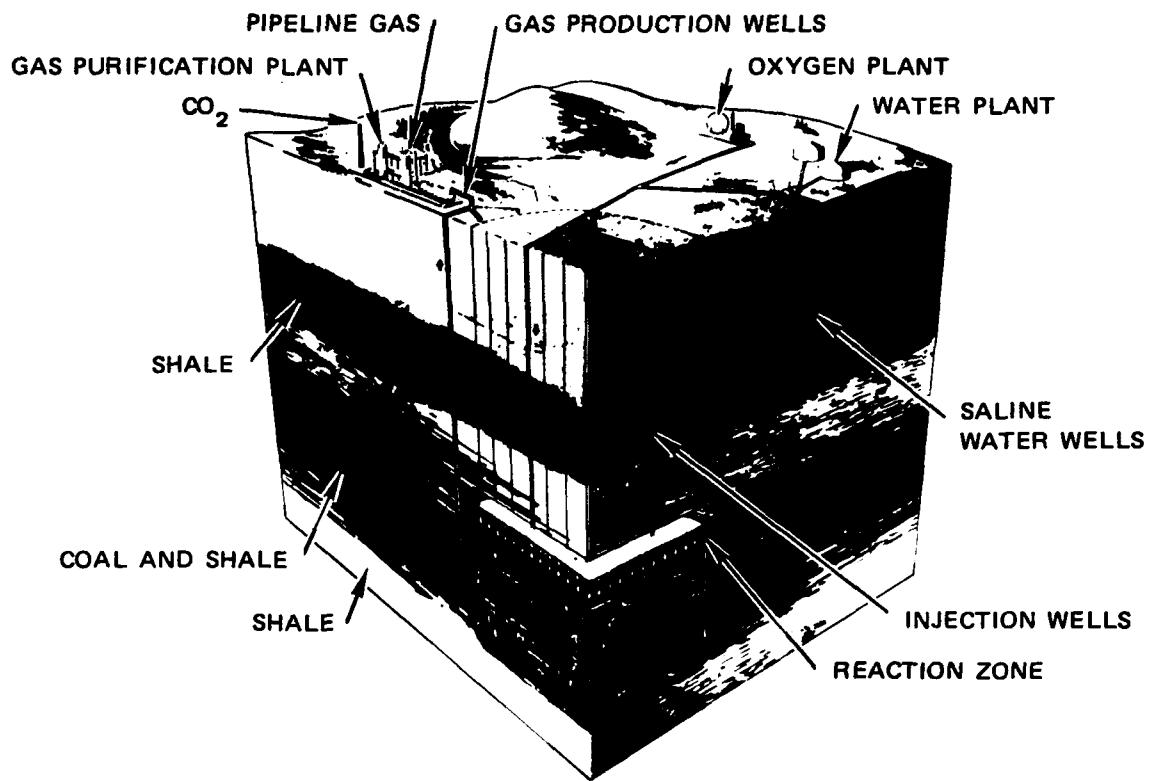
In fiscal 1973, about \$600,000 was spent making underground gasification tests on a site near Hanna, Wyoming. The coal seam used is 9 meters (29 feet) thick with a 120 meter (400 foot) overburden and dips at a 7 degree angle. Initial air acceptance tests gave unacceptably low rates by the percolation method. A hydrofracturing operation in March 1973 gave a fivefold increase in air utilization rates, however, the primary reaction occurring was still carbonization. In June 1973, after new drilling took place to take advantage of the hydrofracturing, air acceptance suddenly increased dramatically with a simultaneous violent blowout at a production hole. This obviously marked the establishment of a gasification path along one of the hydraulic fractures. The product gas was high in carbon monoxide indicating that gasification,

as well as carbonization was occurring. It has not yet been determined if the product gas rate and quality are such that the test will be considered successful. Preliminary reports indicate that the test results are encouraging for air blown gasification to make low heating value gas for on-site power generation, however, some oxygen-blown tests are also planned.

C. Current Program of the Atomic Energy Commission and Lawrence Livermore:
Explosive Fracturing with Downward Gasification

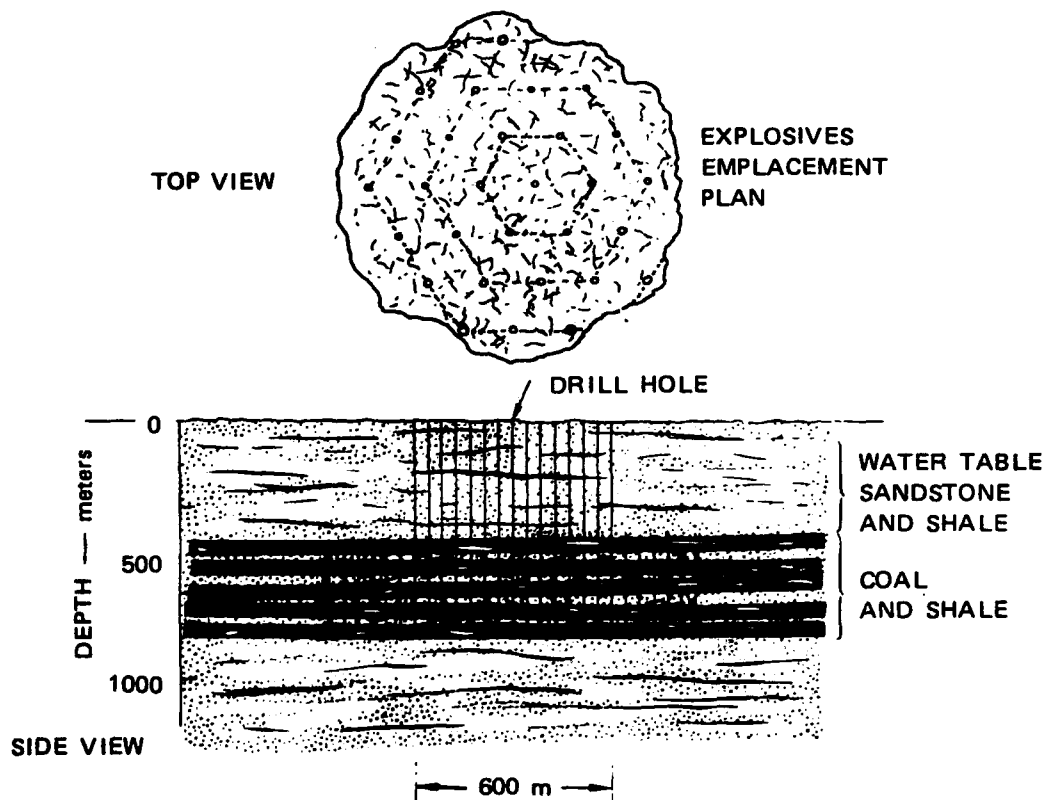
Lawrence Livermore Laboratory issued Atomic Energy Commission (AEC) sponsored reports in 1972 and 1973 outlining a new underground coal gasification process.^{2,3} The process is based on using underground explosives to fracture deep coal beds followed by gasification in the downward direction; about \$200,000 was spent on this work in fiscal 1973. At the present time, the Livermore process is merely conceptual, since only a limited amount of laboratory work has been performed.

Figure 3 illustrates the Livermore process in operation. The coal seam is first fractured by simultaneous detonation of a pattern of chemical explosive charges (Figure 4). Next, injection and production wells are drilled as shown in Figure 3. The coal at the top of the fractured zone is ignited; oxygen and brackish water are then injected into the top of the fractured coal bed through injection wells to maintain gasification. The product gas is removed from the bottom of the coal bed through directionally drilled production wells. Gasification in the downward direction in this manner is believed to be inherently stable because rapid reacting hot spots are slowed by the bouyancy of the hot gases. The production gas is treated in surface facilities to make pipeline specification gas, as shown in the block flow diagram (Figure 5). When the coal in one fractured zone has all been gasified, a new explosive pattern (Figure 4) must be detonated. Presumably, a certain amount of coal must be left ungasified between fractured zones.



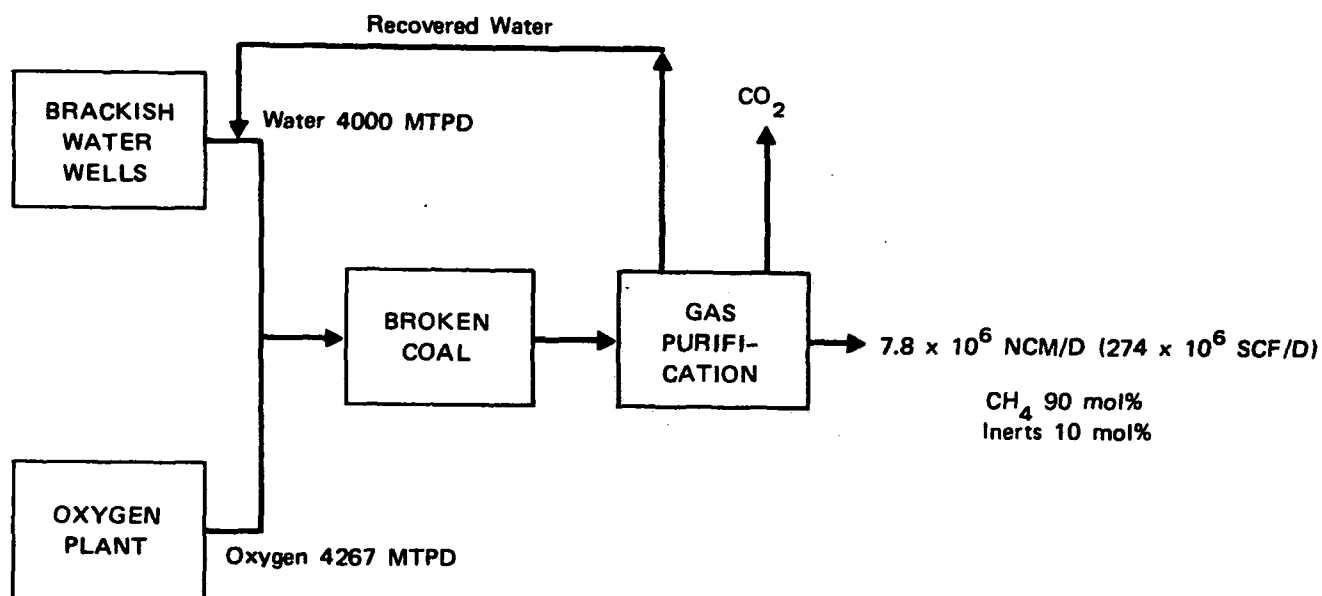
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FIGURE 3 LIVERMORE UNDERGROUND COAL GASIFICATION CONCEPT



TA-6990-58R

FIGURE 4 PROPOSED ARRANGEMENT OF EXPLOSIVES



TA-6990-59R

FIGURE 5 COAL GASIFICATION BY THE LIVERMORE UNDERGROUND METHOD-BLOCK FLOW DIAGRAM

The production gas is predicted to be primarily a mixture of methane and carbon dioxide,² with a negligible concentration of carbon monoxide and hydrogen sulfide. Achieving a high methane yield underground would be important economically, not only in eliminating surface methanation facilities but also in minimizing consumption of expensive oxygen. Also, underground removal of sulfur compounds would avoid surface facilities for sulfur removal and recovery. The high methane content in this concept results from gasification reactions followed by the methanation reaction, rather than from the carbonization reaction. Methanation is the key reaction in achieving high methane content under ground. At high temperatures (above about 800°C), methanation is limited by equilibrium. At lower temperatures, methanation proceeds slowly without the presence of highly active nickel catalysts. Livermore personnel believe that methanation will go nearly to completion because of the high pressure and the long gas residence times (about an hour in the high temperature zone) combined with catalytic action of the ash and shale. The

limited number of small scale laboratory experiments performed are said to support this belief.

An important objection to the feasibility of underground methanation is the virtual impossibility of maintaining close temperature control of the underground reactions. The Livermore report assumes that the temperature may be controlled by controlling the rate of water injection. However, the water and the oxygen cannot be intimately mixed. Furthermore, it is possible that above a certain level of water injection the gasification reactions will be extinguished. Consequently, a substantial amount of underground methanation must be regarded as unlikely.

It is also claimed that enough sulfur will be removed from the gas underground by the chemical constituents of the shale such that additional sulfur removal facilities on the surface will be unnecessary. This assumption also appears to be overly optimistic. Assuming that the coal gasified contains 1 weight percent sulfur, the carbon dioxide-rich gas purged from the acid gas removal section would contain over 11,000 ppm sulfur dioxide after incineration. This sulfur dioxide level is about 40 times the emission levels likely to be allowed for new facilities. Therefore, at least 97 percent removal of underground sulfur would be required to avoid surface sulfur removal facilities. Such a high underground sulfur removal is regarded as unlikely.

Livermore personnel have laid out an ambitious development program for the process. They propose a nine year period on laboratory, bench scale, and modeling programs followed by site selection and large scale prototype operation. The funding for such a program has not yet been approved.

D. Evaluation of the Current Programs

Problems common to the Bureau of Mines and the AEC-Livermore concepts include the following:

- Possible extreme variations in gasification characteristics from site to site.
- Variable product gas composition with time.
- Roof collapse with resulting decrease in permeability and surface subsidence.
- Possible plugging and reduced permeability because of the presence of slag or tars.

The problem of site-related variations is common to most mineral extraction methods. The problem is more serious in underground gasification since there are chemical and thermal aspects--as well as the mechanical aspects--of the extractive process that are affected by the configuration of the resource. Consequently, a steeply pitched coal seam may have a gasification rate and gas yield that differs from those encountered with a flat coal seam. Site-to-site variations with the AEC-Livermore concept is expected to be greater than with the Bureau of Mines method because of the additional effect of interlaying rock layers on the effectiveness of the underground explosives.

Time variation in product gas composition would probably be in the form of a decline in heating value of the gas because of partial gas combustion by unconsumed oxygen that has by-passed the coal. This problem is especially severe when gasifying in the horizontal direction as proposed by the Bureau of Mines. The tendency for preferential reaction at the top of the coal seam results in a cavity there through which oxygen can by-pass the coal and burn some of the product gas. A possible solution is to continuously fill the cavity with material that would fuse and expand to prevent oxygen by-passing. A large development program would be needed to develop the required methods and materials. The problem is

less likely to occur with the AEC-Livermore concept because of the probable stability of the downward reaction front. However, some less serious problems of temporary decreases in crude gas composition may be encountered with the AEC-Livermore concept when the reaction front crosses barren rock zones.

Roof collapse could affect gasification severely in some cases; but, in most cases it is not believed to seriously reduce permeability. Furthermore, roof collapse is not likely to help significantly in reducing oxygen bypassing. Another possible problem, surface subsidence--considered to be unavoidable--is discussed separately in the discussion of environmental effects in Section III of this appendix.

Plugging of the pores and cracks in the formation could reduce permeability of the formation and slow the gas production rate. Little is known concerning whether or not such plugging would actually occur, especially when gasifying western coals. Plugging by tars would occur downstream of the reaction front during the cooling of the crude product gas, and plugging by slag upstream of the reaction zone would be a potential problem, especially with the Livermore concept if the temperature of the reaction zone gets out of control. Only extensive field testing would determine if plugging is an important problem area.

There are two special potential problems specifically involving the AEC-Livermore concept:

- Oxygen loss by ground water intrusion
- Ignition loss in crossing barren shale zones.

The problem of oxygen loss is potentially severe because of doubling of oxygen usage would add at least 19¢/GJ (20¢ per million Btu) to the SNG cost. Moreover, if excessive ground water intruded into the reaction zone, loss of ignition could occur. The mechanism for potential oxygen loss and ground water intrusion is as follows: As the reaction proceeds

a cavity is formed above the reaction zone, which will eventually lead to collapse of the rock roof. If there is an overlying aquifer, the ground water would flow downward displacing the oxygen and causing the oxygen to flow upward into the space formerly occupied by the ground water. It is not known how near the aquifer would need to be to the reaction zone to cause this undesirable effect; it would depend upon the permeability of the collapsed rock. This problem could potentially limit the choice of attractive underground gasification sites severely.

The problem of loss of ignition as the reaction front crosses barren rock partings is also mainly site related. However, it is not known how thick the partings need to be to cause loss of ignition. The maximum parting thickness may range from one to one hundred meters, based on the present inadequate estimates. Livermore personnel believe that many of these so-called barren rock zones may contain enough coal inclusions to maintain ignition.

Considering these problems and the undeveloped state of the technology, underground gasification must be regarded as a potentially attractive--but very risky--long term prospect for gasifying otherwise uneconomical coal deposits. However, even after an extensive development program, large scale underground gasification may not prove to be feasible.

III ENVIRONMENTAL EFFECTS OF UNDERGROUND COAL GASIFICATION

A. Comparison with Surface Gasification: Effects upon Land Surface

The environmental effects of underground coal gasification would be quite different from those resulting from mining and surface gasification. Underground coal gasification, if it is developed commercially, would probably be used to gasify coal which is not presently strippable and for which even deep mining technology is not well understood. Therefore, a comparison of environmental effects with strip mining and surface gasification is a study of the alternate use of two different resources, as well as two different technologies. Plans for surface gasification facilities are underway in several locations in the western United States. In all areas the coal to be gasified will be strip-mined, resulting in massive problems of land reclamation.⁴ The arid climate of the region complicates reclamation efforts by retarding revegetation.

The effect of underground gasification upon the surface is in the form of mild subsidence, which leaves surface soil and vegetation intact. Moreover, less land space is required for surface facilities because space is not needed for coal storage, coal preparation, gasification, and ash disposal facilities. Of course, the ash residue from underground gasification stays underground.

Surface subsidence probably precludes the use of underground gasification under sites where permanent structures exist. In addition, it may

limit future building on these sites. The amount of surface subsidence to be expected is not well understood, but it is known that it will vary with the seam thickness of the coal gasified, the depth of the coal, and the nature of the rock strata overlaying the coal. For deep underground gasification, surface subsidence is expected to be a small fraction of the seam-thickness. A study of potential surface subsidence effects will be a requirement of any program for commercializing underground gasification.

B. Direct Water and Air Pollution

Some aspects of underground coal gasification are potential causes of environmental concern. Potential problems of ground water pollution and leakage of toxic carbon monoxide containing gas are not well defined. Toxic gas leakage is regarded as extremely unlikely for deep coal deposits if there are no nearby outcrops of the coal seams. There is little evidence regarding potential ground water pollution resulting from completed underground gasification projects; a possible analogy is the water pollution resulting from abandoned deep mines. The Livermore concept of using explosives to prepare coal for underground gasifications avoids--or minimizes--direct water and air pollution effects by gasifying only deep coal more than 150 meters (500 feet) below the surface.

C. Resource Recovery and Earth Tremors

The technology of underground coal gasification may be used only on otherwise unrecoverable coal. It should be noted that the Livermore method would involve repeated patterns of explosives (for example, Figure 4). It is probable that unfractured "walls" would need to be left between successive fractured zones. Therefore, the coal in the interstices between fractured zones may not be recoverable.

The Livermore concept could interfere with mining of other minerals at the same site more than would conventional strip or deep mining. This issue of resource recoverability must be decided on a site-by-site basis.

In addition, there is a small possibility of earth tremors--as has been feared--as a result of underground nuclear explosions; however, there is little evidence concerning this possibility.

D. Summary of Environmental Effects

Overall, it is clear that underground gasification would have less severe effects on the environment than a combination of strip mining and surface gasification. Typical resource requirements and effluent amounts are compared in Table 1.

The usefulness of the analysis of environmental effects depends upon the successful development of a commercial process for underground gasification. At the present time, success is not assured and companies interested in coal gasification are concentrating on surface gasification plants. Only large scale demonstration of underground gasification will change the situation.

Table 1

EFFECTS OF UNDERGROUND COAL GASIFICATION COMPARED WITH
STRIP MINING PLUS SURFACE GASIFICATION

	Underground Coal Gasification	Strip Mining Plus Surface Gasification
Land area for plant facilities, square meters	81,000	490,000
Stripped land per year, square meters	0	1,000,000
Total land subjected to subsidence per year, square meters	510,000	0
Water required, cubic meters per year	11,000,000	11,000,000
Sulfur recovered, kg per day (needs to be disposed of if it cannot be sold)	180,000	180,000
Ash to be disposed, kg per day	0	1,800,000

Basis: One plant producing 7 million normal cubic meters (250 million standard cubic feet) of SNG per day; coal containing one percent sulfur and 10 percent ash; 50 percent recovery of coal for Scheme A with a seam thickness of 15.2 meters (50 feet); 50 percent recovery of coal stripped for Scheme B with a seam thickness of 7.6 meters (25 feet).

IV IMPLICATIONS FOR THE ENVIRONMENTAL PROTECTION AGENCY

Underground coal gasification need not be a subject of near term concern on the part of the EPA, because of the undeveloped state of the technology. However, there are potential environmental advantages of underground gasification over surface gasification of stripped western coal. These advantages will be minimized if techniques for reclamation of stripped arid land are improved and if such reclamation is required by law.

At present it would be premature for EPA to commit substantial resources to either the prevention of undesirable environmental effects of underground coal gasification or to the development of this technology as an environmentally attractive alternative to coal mining followed by surface gasification. Reasons for this conclusion include the following:

- Other federal agencies are supporting the development of underground coal gasification.
- There is great risk that large-scale underground coal gasification is not technically feasible
- The potential environmental advantages of underground gasification are not compelling.
- Undesirable environmental effects (discussed herein) which are particular to underground gasification are possible.

Instead, SRI recommends that the EPA expend a small effort in following the progress of the development programs sponsored by the Bureau of Mines and the AEC. If at a future date both technical feasibility and environmental superiority of underground coal gasification is demonstrated, the EPA should at that time support commercialization. A somewhat more immediate role of EPA may be to monitor any large-scale underground gasification tests for undesirable environmental effects, such as those discussed herein.

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Appendix F

HYDROGEN AS AN ENERGY CARRIER

by

Edward M. Dickson

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I INTRODUCTION

It is becoming increasingly apparent that during the years remaining in this century hydrogen will emerge as an important additional component of diversity in the energy economy.^{1-3*} An energy economy completely dependent on hydrogen used as a fuel, however, is unlikely ever to occur.

Hydrogen is not a basic energy resource because it is not found in molecular form in nature. Consequently, energy must be supplied from some other basic energy resource to generate hydrogen from water or other hydrogen-containing chemical compounds. As seen in this light, hydrogen obviously cannot "solve" the developing problem of a basic energy shortage. Rather, hydrogen can become important only as an "energy carrier" used to store and transmit energy in chemical form. The potential for use of hydrogen is particularly large in the transportation area because the traditional fuels (oil and gas) are becoming increasingly precious.

In addition to its use as a fuel, consumption of hydrogen will gain in importance in chemical processing. At the present time the two major uses of hydrogen are: The production of ammonia, a chemical that is very important to the agriculture industry; and as a vital reactant in petrochemical reforming.³ Currently, this hydrogen is produced by the chemical decomposition of methane (CH_4) and by the so-called steam reforming of water with fossil fuels providing the necessary heat input.¹ Clearly, as these sources of fuel become increasingly costly with the depletion of resources, production of hydrogen by these means will become less and less attractive. Hydrogen is also currently used to chemically reduce some mineral uses.

*References are listed on page 324 at the end of this appendix.

By far the largest potential use of hydrogen in the near future will occur in the gasification of coal. Because coal contains approximately one hydrogen atom for each carbon atom, the hydrogen deficit must be made up to manufacture CH_4 from coal. Many coal gasification plans call for the combustion of some of the coal resource to provide heat for steam reforming of water to gain the necessary extra hydrogen. Obviously, the lifetime of any given coal resource could be extended if an independent source of hydrogen were available.

Hydrogen is frequently mentioned as a prime possibility for storage and delivery of energy collected by various solar energy technologies. Indeed, many of these technologies may not become operational without a parallel development of hydrogen storage, distribution, and utilization technology.

II STATE OF THE ART OF HYDROGEN TECHNOLOGY

A. Production

Hydrogen can be produced by electrolysis of either water or a hydrogen halide without consuming fossil fuel resources.² Because water is an abundant resource, it is the most favored feedstock. Electrolysis requires a source of electricity, but other energy technologies such as geothermal, solar, nuclear fission reactors, or possibly a nuclear fusion reactor can supply this. Obviously, the net efficiency of hydrogen production is dependent on the independent energy efficiencies of electric generation and electrolysis. In the past, water electrolysis has been used only in special situations, and energy efficiency has been a less important design consideration than cost and reliability. Currently available electrolysis units operate at efficiencies of about 65 percent, but areas of research have been identified that offer the possibility of increasing this figure to perhaps 90 percent.³ Such an improvement in electrolysis efficiency is an essential prelude to combining hydrogen generation with low efficiency electric generation such as solar or geothermal.

Research is underway to develop closed cycle thermochemical processes that could side-step electrical generation and use directly the high temperature heat that a gas-cooled nuclear reactor could provide.^{4,5} None of these cycles has been demonstrated to complete satisfaction and probably a decade or more of R&D effort is needed before commercial realization. This approach to hydrogen production is likely to have important environmental consequences because of the very reactive chemicals and very high temperatures that are anticipated. Indeed, the conditions of operation are so severe that many materials problems are

foreseen for containment vessels.⁵ In addition, no cycle of chemical reactions is ever truly closed. One need only recall how ostensibly closed systems engaged in chlor-alkali production resulted in release of large amounts of mercury into the environment,⁶ because a need always exists to periodically cleanse the system of accumulated contaminants--some of which arise from erosion of containment vessels.

B. Storage and Distribution

The vast quantities of hydrogen that may require storage could hardly be managed in gaseous form, especially since large high pressure vessels are extremely costly and the dangers of rupture are great. The liquid state, at about 20°K, has been considered a more practical form for storage.

Experience in the U.S. space program has demonstrated that trained personnel in suitable environments can handle liquid hydrogen (used as rocket fuel) in vast quantities.⁷ Consequently, cryogenic storage is considered to be feasible in many of the potential applications of hydrogen. At the present time liquid hydrogen is routinely shipped by railroad tank car and in large trucks over the public highways.⁸ Cryogenic technology is well-developed, and advances relevant to liquid hydrogen containment and handling are being made constantly.

Numerous metals and alloys form metal hydrides.⁹ Some of these hydrides actually exhibit a packing density of hydrogen atoms that exceeds that found in liquid hydrogen.⁹ Research has demonstrated that a suitably packaged powder or metal sponge can serve as a convenient and rather safe form of hydrogen storage. Research in the metal hydride field is continuing in an attempt to make large-scale storage of hydrogen via metal hydrides fully practical.

Pipelines have been used for many years in Germany for the long distance movement of hydrogen.^{5,10} Chemical and petroleum process industries in the United States also have experience in hydrogen pipelines.¹⁰ In certain circumstances, the transmission of energy could be accomplished more economically today by a hydrogen pipeline than by electric transmission line.^{2,11} Moreover, operations of natural gas pipelines have shown that by varying the pipeline pressure the pipeline system itself can serve as a reservoir for vast quantities of gas.

C. Use

Experiments, some sponsored by EPA, have shown that an internal combustion engine can be easily modified to run on hydrogen.^{12,13} Because no hydrocarbons are in the fuel, there are no carbon monoxide (CO) or hydrocarbon (HC) emissions (aside from a trivial amount arising from the lubricating oils). Moreover, nitrogen oxide (NO_x) emissions are lower when the engine is run on hydrogen than on gasoline.¹² This strongly suggests that automobiles designed to operate on hydrogen fuel would greatly alleviate urban air pollution. Before a hydrogen-fueled automobile could become a practical reality, however, numerous difficulties associated with fuel distribution and on-board storage require solution.

Conceptual design studies have determined that jet aircraft could be run easily on hydrogen.^{14,15} Indeed, because of its higher energy density (on a weight basis), hydrogen offers the potential for reoptimizing the design of aircraft. It is now clear that the gross take-off weight could be reduced without impairing the payload or range.¹⁵ Again, however, logistical difficulties suggest that a transition to hydrogen-fueled aircraft may be slow to occur.

Fuel cell technology is the inverse of electrolysis technology in many respects.¹⁶ A fuel cell combines hydrogen and oxygen to generate

an electric current with water and heat being the only effluents. Most fuel cells run on hydrogen and oxygen; those that consume other fuels first chemically "reform" the input fuel into hydrogen and waste by-products before actual consumption in the fuel cell.¹⁷ Most applications of fuel cells have been in the space program, federal support of fuel cell R&D has waned in recent years. Most contemporary fuel cell effort is done by industry and is proprietary. Pratt and Whitney Aircraft Corporation, considered the leader in the field, is developing fuel cell technology for electric utilities, and Public Service Gas and Electric of New Jersey has placed orders for the technology. Much of the basic electrochemistry research is applicable to both electrolysis and fuel cells.

Electric utilities currently envision three major applications of hydrogen in their operations:

- Electric generation by fuel cells in small installations that are quiet, nearly pollution free, and lack major requirements for cooling water, and can be located near the final demand in urban areas.¹⁸
- Underground pipeline transmission of energy from remote nuclear power stations to urban areas along heavily developed corridors that make deployment of additional overhead electric transmission difficult because of land use and aesthetic constraints.^{11,18}
- The use of hydrogen as a chemical means to store large amounts of energy to buffer mismatches in energy supply and demand.¹⁸ This application stems from a recognition that pumped hydrostorage is not well-suited for many geographical locations.¹⁹

Various combinations of these three applications are obviously conceptually attractive. A few energy utilities are now taking these possibilities very seriously.

D. Safety

In any discussion of hydrogen use, the question of safety arises. The public has seemingly concluded that hydrogen is unsafe--apparently solely on the basis of the publicity that is constantly renewed about the destruction of the Hindenburg in 1937 with the loss of 36 lives.²⁰ Many people who have considered the safety of hydrogen in comparison to existing fuels believe that the fear of hydrogen is overdrawn.^{3,11,20} Hydrogen is undeniably dangerous, but so are gasoline and methane, yet the public treats these two fuels with nonchalance in spite of regular and often spectacular accidents.²¹

A special hazard derives from the embrittlement of some metals immediately upon exposure to a high-purity hydrogen environment.²² This phenomenon is most pronounced around room temperature and high strength steels are especially affected.²² As a result of the greatly decreased flexibility of the metal, the design of devices intended to convey, store, or use hydrogen must reflect knowledge of embrittlement to avoid unexpected component failure and the consequent safety hazards this creates. Some knowledgeable people feel, however, that with proper attention to design, embrittlement will affect the economics more severely than the safety of hydrogen usage.

The physical properties of hydrogen make it less hazardous than conventional fuels in some situations but more hazardous in others. A blanket dismissal of hydrogen use on the basis of unsophisticated consideration of its safety is unwarranted.

III ENVIRONMENTAL IMPACTS OF HYDROGEN USE

Hydrogen consumed as a fuel will certainly result in less noxious emissions of the common air pollutants at the point of combustion. Against this, however, the knowledge must be weighed that at some other location, where the hydrogen is generated, environmental impacts may exist such as thermal pollution from a nuclear reactor generating electricity for electrolysis, radioactive wastes from the nuclear fuel cycle, and similar effects associated with all the candidate prime mover energy technologies. Moreover, because the generation of hydrogen adds another step in the chain of energy distribution from basic resource to final demand, it will inevitably reduce the net energy efficiency of the system and thus release more energy into the environment as waste heat. Improvements in hydrogen generation technology, however, may greatly lessen this effect.

The extension of some of these current hydrogen technologies to a large scale may create environmental problems of its own. For example, present water electrolysis cells use an asbestos membrane to separate the hydrogen and oxygen coproducts.²³ Since the oxygen may often be merely released to the atmosphere as a nominally harmless effluent rather than be retained for use, small asbestos particles can be released to the air. It is now fairly well-established that small asbestos particles are a dangerous carcinogen, and EPA has formulated air quality standards specifically covering asbestos.^{24,25} In the small electrolysis installations currently in operation, the oxygen is filtered to remove these asbestos particles. While such treatment is probably quite adequate to maintain an acceptable level of asbestos particles in small plants,

expansion of the process to the very large scale envisioned would most likely result in an unacceptable airborne concentration of these particles.

Another air quality implication arises from the possible use of powdered metal hydrides for hydrogen storage. One of the most likely candidates is an alloy of magnesium and nickel.⁹ Evidence is mounting that uptake of small amounts of many nickel compounds can be responsible for dysfunction in humans and many other biological systems.²⁶

Some resource availability limitations arise in the use of hydrogen. For example, to provide the storage sufficient to power an automobile conforming to typical American standards would require about 200 kg of a magnesium-based metal hydride.²⁷ To supply 100 million automobiles (about the current number) would therefore require about 2.0×10^{10} kg of magnesium and this is about 200 times the 1971 U.S. magnesium metal production of about 10^8 kg.²⁸ Currently available electrolysis technology uses nickel catalysts. It is far from clear whether electrolysis technology could continue to be dependent on nickel since this metal is in short supply (almost all the U.S. consumption is imported) and is vital to the steel industry for production of quality steels.²⁸

IV IMPLICATIONS FOR EPA

At first glance, it may seem that the subject of hydrogen could be neglected by EPA for a decade or so. Such neglect would almost certainly prove unwise because the emergence of hydrogen in the U.S. energy economy is made all the more likely by the other transitions in energy technology and usage patterns that are believed to be necessary. In many respects, hydrogen is the common denominator of many of the emerging new energy technologies. It is the most obvious chemical means of energy storage and is the chemical element most needed to facilitate synthesis or processing of other fuel. Thus, although hydrogen may never come into the hands of the general public, it will, nevertheless, play a key role behind the scenes of the energy economy.

Stanford Research Institute is currently engaged in a Technology Assessment of a Hydrogen Energy Economy under National Science Foundation sponsorship. The exploration of the societal and environmental impacts now being performed as part of that study can be expected to provide useful input into EPA planning activities. After information from the technology assessment is received, EPA could profitably establish a modest program to follow the development of hydrogen technologies and seek to influence its development in a manner that has environmental benefits. The program should be analogous to that outlined in Appendix A of this report.

In the interim, EPA could beneficially sponsor research in the following areas.

- Further quantification of the emissions characteristics of engines (both internal and external combustion) operated on hydrogen.

- . Environmental side effects of fuel cell technology.
- . Environmental pollutants associated with water electrolysis technology.
- . Effluents and emissions that might be associated with thermochemical decomposition of water by the use of high temperature heat from nuclear reactors.

This research would ensure that the potential environmental benefits of hydrogen used as a fuel are not overlooked.

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BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-600/2-74-002	2.	3. Recipient's Accession No.
4. Title and Subtitle Control of Environmental Impacts from Advanced Energy Sources		5. Report Date March 1974	
		6.	
7. Author(s) Evan E. Hughes, Edward M. Dickson, Richard A. Schmidt		8. Performing Organization Rept. No. Project 2714	
9. Performing Organization Name and Address Stanford Research Institute, Menlo Park, California 94025		10. Project/Task/Work Unit No.	
		11. Contract/Grant No. 68-01-0483	
12. Sponsoring Organization Name and Address Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., 20460		13. Type of Report & Period Covered Final	
		14.	
15. Supplementary Notes			
16. Abstracts The technology and environmental effects associated with production of energy from new or advanced sources are reviewed. These include solar, geothermal, oil shale, solid wastes, underground coal gasification, and hydrogen energy sources. Projections to the year 2000 of levels of energy production from the first four of these sources are presented. Environmental impacts on air and water quality, and land use are derived per unit of energy. Levels of pollutant emissions and other environmental effects of the development of these advanced energysources are projected. Impacts likely to require control measures are identified. Subjects for research and development directed toward control of environmental impacts are recommended. These recommendations are incorporated into a research and development plan. Approximate priority assignments derived from consideration of the timing of development and the importance and degree of definition of the identified environmental effects are given.			
17. Key Words and Document Analysis. 17a. Descriptors environmental impacts energy technology air pollutants solar energy geothermal energy oil shale solid wastes in-situ coal gasification hydrogen 17b. Identifiers/Open-Ended Terms			
17c. COSATI Field/Group			
18. Availability Statement Unlimited		19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 326
		20. Security Class (This Page) UNCLASSIFIED	22. Price