EPA-650/2-74-021

March 1974

Environmental Protection Technology Series

EFFICIENCIES IN POWER GENERATION

Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

EPA-650/2-74-021

EFFICIENCIES IN POWER GENERATION

by

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Contract No. 68-02-1320
Task 7
ROAP No. 21ADE-29
Program Element No. 1AB013

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OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

March 1974

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TABLE OF CONTENTS

* Numbers in parentheses refer to topic numbers in Table 1, "Summary of Efficiencies".

LIST OF FIGURES

I. SUMMARY

Herein is assembled an introduction to some important aspects of the energy conservation problem with respect to pollution abatement and alternate fuel processing technology. Many of the topics have been researched and developed with energy conversion as the prime goal. Other studies have not addressed this subject but have been more concerned with the efficiency of pollution control.

From this investigation, we conclude that more exploration of the topics is needed, especially the fuel conversion processes. These appear to be poor choices for coal substitutes in electric energy production.

It is recommended that further investigations be conducted in the following areas:

1. Low and high Btu gasification of coal as a substitute for natural gas.
2. Coal cleaning for sulfur and ash removal.
3. Higher turbine inlet temperature.
4. Magnetohydrodynamics flue gas cleaning and insulator developments.
5. High-temperature gas-cooled nuclear reactor.
6. Topping and bottoming cycles. Materials for use in these cycles need to be developed.
7. Coal conversion to methanol fuels.

Certain areas show little promise in the near future as power generators. These are:

1. Fuel cells for utility use
2. Internal combustion engine

II. INTRODUCTION

An important consideration in the use of fuels for power generation has always been the efficiency of conversion. It enters directly into the economics of the process as a cost factor. Utility companies as compared to industrial users are notoriously conservative with a Btu of energy. This has mainly been due to the economic trade-offs made in design and ultimate use of the input energy. Rising fuel costs and environmental pressure have replenished interest in heat cycle and energy conversion techniques which make use of this input.

Since the early 1960's, energy consumption has risen faster than the GNP. Thermal efficiency of large fossil fuel electric generators has declined and nuclear energy seems to cost more each day. Any environmental control techniques have been crude and have generally required the addition of more power consuming equipment and cleaner fuels. All of these factors have contributed to the realization for many Americans that our energy resources are not inexhaustible. However, air quality criteria must not be relaxed. Thus, cleaner fuels and air pollution control techniques must continue to develop but in an overall conservation light (ecology, energy, economics).

This report is an introductory view of 23 ways of using or converting energy. The thermodynamic limiting, present and future (1990) efficiencies are compared in tabular form in Table 1. In all cases, the efficiency is concerned with energy input versus output. Thermodynamic limits are referenced to 70°F, 1 atm., unless otherwise stated. In some cases, practical limits are more meaningful and are used in lieu of a detailed thermodynamic analysis. This was done to expidite the study and provide the necessary overview of the topics. Limiting factors in thermodynamic or practically obtainable efficiencies are discussed in

Section IV. Through the use of the topic numbers, reference is made back to Table 1. The numbers in parentheses following the discussion heading in Section IV are these topic numbers.

Following the comparisons given, combinations of systems may be evaluated for overall efficiency. Here are five very general rules to apply when making comparisons.

1. When combining two energy convertors where the one uses the energy of the other as total input, the efficiencies (in terms of a fraction) are multiplicative.

2. When combining a system which operates in series with another energy extraction system, the overall efficiency is derived from the equation:

$$\eta_o = \eta_1 + (1-\eta_1)\,\eta_2$$

   where η_o = overall efficiency (in fraction form)
   where η_1, η_2 = system No. 1 and 2 efficiency (in fractions)

3. When fuels other than those for which the equipment was evaluated are substituted, losses or gains in efficiency may result from thermodynamic considerations. Comparison of these losses when applying a system will be necessary.

4. The form of the power output is important since any conversion will require energy.

5. Whenever combinations are made additional system components may be necessary to close the loop. With this in mind, the calculations will represent approximations to typical installations.

III. SUMMARY OF EFFICIENCIES

Table 1

EFFICIENCIES IN POWER GENERATION

Topic No.	Equipment	Efficiency (%) Present (1974)	Projected (1990)	Thermodynamic Limit	ΔG^b Btu/lb Fuel	ΔH^b Btu/lb Fuel
1a	Conventional Sub-critical Boiler	88	95	99	-12,400	-12,500
1b	Conventional Boiler Process (overall)	40	50	60	--	--
2	Conventional Boiler with Flue Gas Cleaning	36	48	60	--	--
3	Pressurized Fluid Bed Combustor	[a]88	90	99	--	--
4	Atmospheric Fluid Bed Combustor	[a]86	88	99	-12,400	-12,500
5a	Low Btu Gas Generator (Cold Cleaning)	75	86	96	-45,700	-47,500
5b	Low Btu Gas Generator (Hot Cleaning)	[a]80	92	98	-45,700	-46,500
6	High Btu Gas Generator	[a]65	75	77	-14,848	-19,194
7	Coal Liquifaction	[a]75	76	99+	-4,150	-4,150
8	Conversion of Coal to Methanol Fuels	[a]50	60	77	--	--
9	Coal Cleaning Plant	90	95	100	--	--
10	Chemical Coal Cleaning Systems	[a]91	95	100	--	--
11	Residual Oil Desulfurization	93	99	99	--	--
12	Chemically Active Fluid Bed	76	81	89	-3,890	-4,350
13	Steam Turbine	45	54	68	-780	-1,145
14	Gas Turbine	30	42	83	-8,700	-10,500
15	Combined Cycle (Gas and Steam)	42	59	95	--	--
16	Nuclear Steam Plants	33	43	72	--	-200 Mev
17	Feher Cycle	[a]18	42	82	--	--
18	Potassium Topping[c]	[a]16	20	45	--	--
19	Bottoming Cycle[c]	[a]12	14	50	--	--
20	Magnetohydrodynamics	[a]50	60	82	-12,400	-12,500
21a	Hydrogen Fuel Cell	[a]70	70	83	-51,030	-61,470
21b	Natural Gas Fuel Cell	50	55	93	-24,200	-26,100
21c	Methanol Fuel Cell	[a]48	48	96	9,444	- 9,769
21d	Hydrogen Fuel Cell from Converted Methanol	28	46	77	--	--
21e	Hydrogen Fuel Cell from Converted Coal	[a]45	52	60	--	--
22	Automotive (I-C Engine)	41	37	58	-12,000	-20,570
23	Diesel	48	48	66	-13,460	-20,395

a. These processes have yet to be applied to any commercial extent. The values given for present efficiencies are quasi-realistic.

b. ΔG and ΔH are for the best available mixture of the feed material or for elemental components (i.e., carbon, hydrogen) in the conversion process. Some values of ΔG and ΔH are not obtainable because of the complexity of the process; values for individual processes would be meaningless for comparison. These were eliminated.

c. When a topping or bottoming cycle is applied to a power cycle, the binary efficiency can be calculated as follows:

$$\eta_b = \eta_t + (1 \quad \eta_t)\,\eta_s$$

η_b = Binary efficiency (fraction)
η_t = Topping or bottoming efficiency (fraction)
η_s = Power cycle efficiency (fraction)

d. Thermodynamic limiting efficiencies are related to 70°F and 1 atm.

IV. DISCUSSION OF POWER SOURCES

Classifying equipment by a single efficiency number can be confusing and misleading. The power conversion and extraction systems referenced in Table 1, require definition and further discussion to minimize this. Generally, a range of efficiencies exists for each topic as opposed to the single stated value. Economic pressure can also favor a lower efficiency due to either low fuel cost or low capital requirements. These aspects are not discussed in any depth since the report purpose is to provide more of a scientific comparison. For comparison ease, the equipment topics are broken into six distinct categories:

Direct fuel use
Coal conversion
Fuel cleaning
Power producing machinery
Special energy conversions
Portable power sources

A. DIRECT USE OF FUELS

Coal, oil and gas are the convential fuels in common use today. The gas may be natural or man-made such as the coke-oven gases used by the British during World War II. With the exception of most natural gas, these fuels result in significant pollution when burned. However, there are two distinct concepts for utilizing these fuels while protecting the environment. These are:

1. Conventional boilers using flue gas cleaning
2. Pressurized and atmospheric fluid bed combustors

For reference, the conventional boiler without flue gas cleaning is discussed as a separate topic since this represents the majority of present day power generation.

1. Conventional Boiler

The state-of-the-art of conventional boilers is well advanced with economics dominating the energy conversion. The boiler is generally very efficient with most overall losses in efficiency on the steam side of the power production. These two topics are discussed separately, (1a) and (13) and as a combination (1b).

a. Boiler only (1a)

The conventional sub-critical boiler is represented by a common pulverized-coal steam boiler operating below the critical throttle pressure (3500 psia). Its efficiency is given in terms of its ability to convert coal to steam Btu's (see Figure 1).

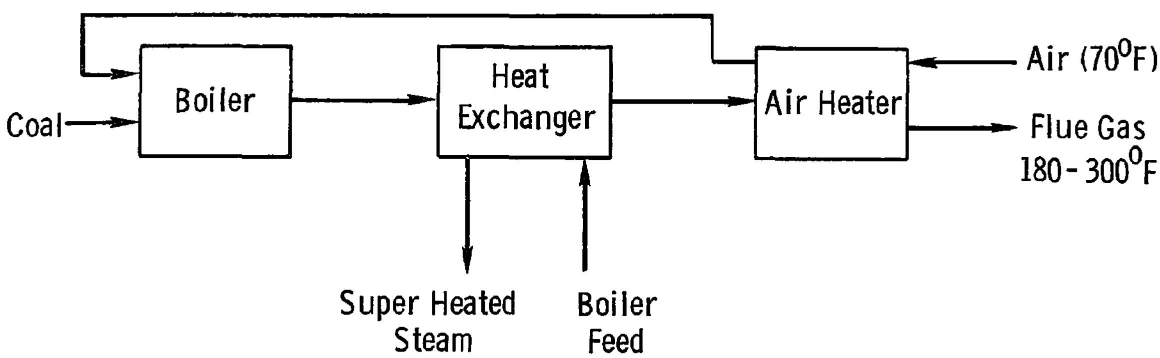

Figure 1 Conventional Boiler

Presently, boiler efficiencies range from 85-90%. The major losses are classified roughly as follows:

(1) Heating of excess air for combustion 2.0%
(2) Incomplete fuel combustion 2.0%

(3) Heating of moisture in coal and air 4.0%

(4) Dry gas losses (240°F) 4.0%

As the year 1990 approaches, improvements in the efficiencies will come with the use of physically or chemically cleaned coal. These will burn more completely, use less excess air, and have a lower moisture content. This should add about 6% to the present efficiency. Use of cleaner fuels should lower the final flue gas temperature, adding significantly to the efficiency. In 1990, the efficiency of conventional boilers is expected to be 90-96%, depending upon the coal quality. Losses would then be:

(1) Heating of excess air for combustion 1.0%

(2) Incomplete fuel combustion 1.0%

(3) Heating of moisture in coal and air 1.0%

(4) Final flue gas temperature 2.0%

The boiler process is well established and improvements are constantly being made. R&D programs are minimal; most improvements are made progressively as new full scale units are built and tested.

ΔG and ΔH in Table 1 are calculated based on a coal that is assumed to have 12,500 Btu/lb heating value and a hydrogen-to-carbon ratio of 0.9. If there were no losses, 99% of this value could be converted to steam energy. This is the limiting thermodynamic efficiency.

b. Overall process (1b)

Overall, a "conventional boiler process" would include the steam turbine and other components necessary to produce electricity. The present average operating efficiency of this type of process for the entire U.S. is 31%, but the most modern plants achieve 40%.[3] The Linden generating station of the New Jersey Public Service Electric and Gas Co. reportedly has achieved a 49% efficiency.[2] This was a record obtained using very low condensor temperatures and selling process steam.

A generator efficiency of 98% has been assumed in calculating the overall efficiency.

The conventional boiler process is shown in Figure 2. Figure 3 gives an overall heat balance.

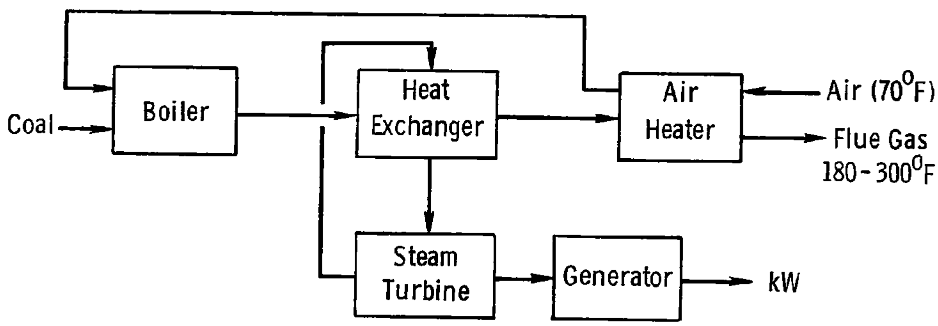

Figure 2. Overall Steam Boiler

The overall boiler process may be improved through the addition of topping and bottoming cycles. Advancement of materials technology to meet the severe steam conditions is needed.

Use of higher temperature boilers does not seem likely without oxygen enrichment. R&D efforts appear more worthwhile in other areas such as described in Section I (summary).

2. Conventional boiler with flue gas cleaning (2)

When flue gas cleaning is added to a boiler, the efficiency will go down. The removal of sulfur oxides and fly-ash consumes power which reduces the net power available. For particulate control, the reduction is 1-3% of the net power. For dry SO_x control systems the reduction is about 2% of the power input (thermal).[15]

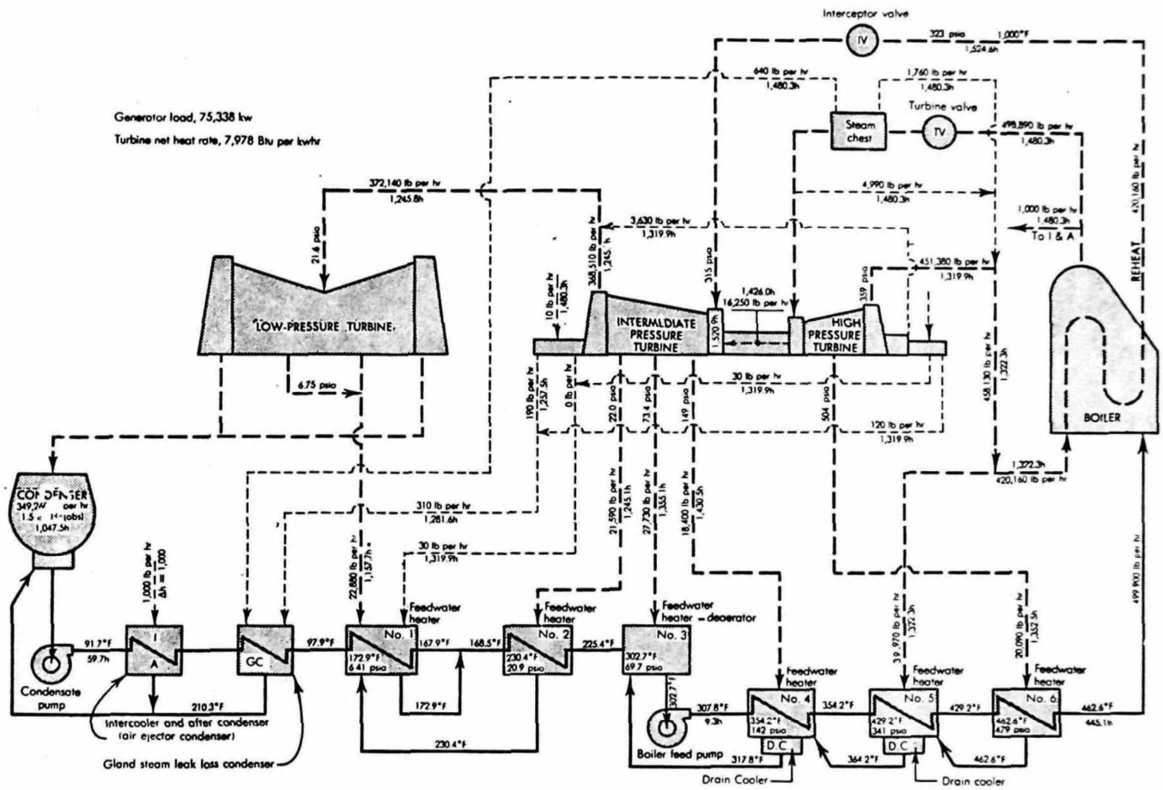

Figure 3. Conventional Steam Boiler
Overall Heat Balance
Capacity: 66 Megawatts

(courtesy, Steam Div., Westinghouse Electric Corp.)

A wet scrubbing system not including product recovery would use 3% of the net energy produced by the boiler.[10] Product recovery or reagent regeneration, such as in the Wellman-Lord or Molten Carbonate processes, can require 10% or more additional power. If steam reheat of the scrubber gases is involved, 1-2% of the heat available would be consumed.[4] Given a boiler with the following characteristics,

100 MW input (in the form of coal)
88 MW input to steam (88% boiler efficiency)
40 MW generator output

then the losses due to flue gas cleaning would be:

1.60 MW for wet scrubber (4% of net power)
1.32 MW for steam reheat (1.5% of steam input)
0.80 MW for particulate cleaning (2% of net power)

3.72 Total Losses

This reduces the overall efficiency to about 36%. The lower losses shown in Table 1 for 1990 result from expected improvements in scrubber design. The use of lower energy levels for cleaning will come with increased process confidence.

Summaries of on-going R&D in this area are plentiful; however, these do not directly address the efficiency problem. A major concern of the utilities is the power and cost required for pollution abatement. At best, sulfur oxide control systems will run $20-25/kW and cost over one mill/kW-hr to operate. This is exclusive of particulate control, which is also expected to increase power consumption.

3. <u>Pressurized fluid bed combustor (3)</u>

This type of combustor is shown in Figure 4. The fluid bed

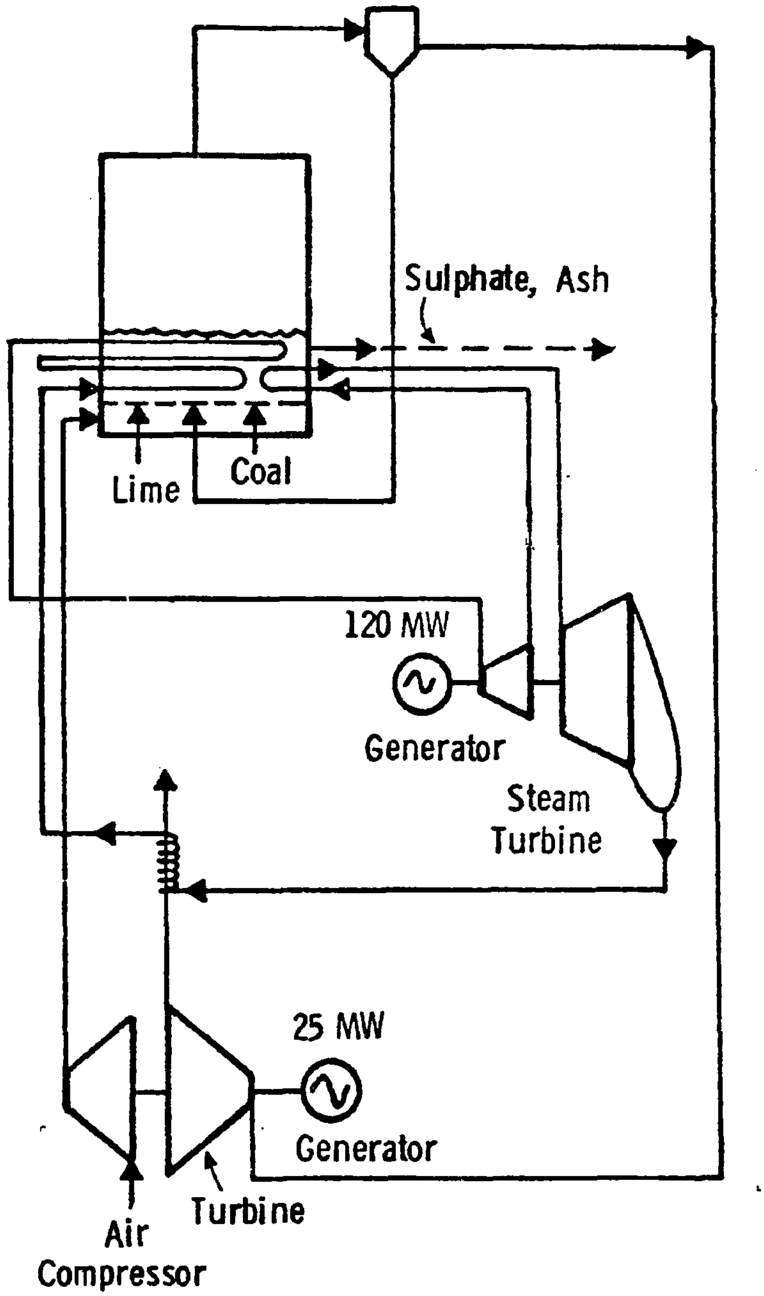

Figure 4. Pressurized Fluid Bed Boiler

(courtesy, Westinghouse Research Laboratories NTIS Publication PB211494)

is used to increase heat transfer and promote sulfur removal. Increased pressure results in lower losses to the combustion gas and moisture.

By raising the pressure, less excess air is needed at higher pressures. In fluidized bed combustors, the bed temperature must be near 1650°F. Raising the temperature will increase the combustion efficiency but bed life is seriously shortened. The major losses in efficiency are:[15]

(1)	Dry gas losses at 275°F	3.9%
(2)	Hydrogen and water in the coal	4.1%
(3)	Incomplete combustion	1.5%
(4)	Design factor and other losses	1.8%

The efficiency-limiting factors are basically the same as for the conventional boiler, with the added restriction of bed temperature. Although the boiler efficiency is reduced, the sulfur is removed from the gas stream. Present R&D activity by Pope, Evans & Robbins, Foster Wheeler, Oak Ridge National Laboratories, Westinghouse Research Laboratories, and the EPA Office of Air Programs is expected to yield pressurized fluid bed boilers by 1982.[14] Design factor losses should eventually be be reduced, raising the efficiency to about 90% in 1990.

4. <u>Atmospheric fluid bed combustor (4)</u>

Figure 5 shows the atmospheric fluid bed in a typical system configuration. Although it resembles a conventional steam boiler plant, the boiler size is reduced because of better heat transfer of the fluid bed. Losses are about the same as for a pressurized bed. Dry gas and moisture losses are increased due to the lower combustion temperatures. (in a pressurized bed, these are compensated for by the increased pressure.) Losses are:

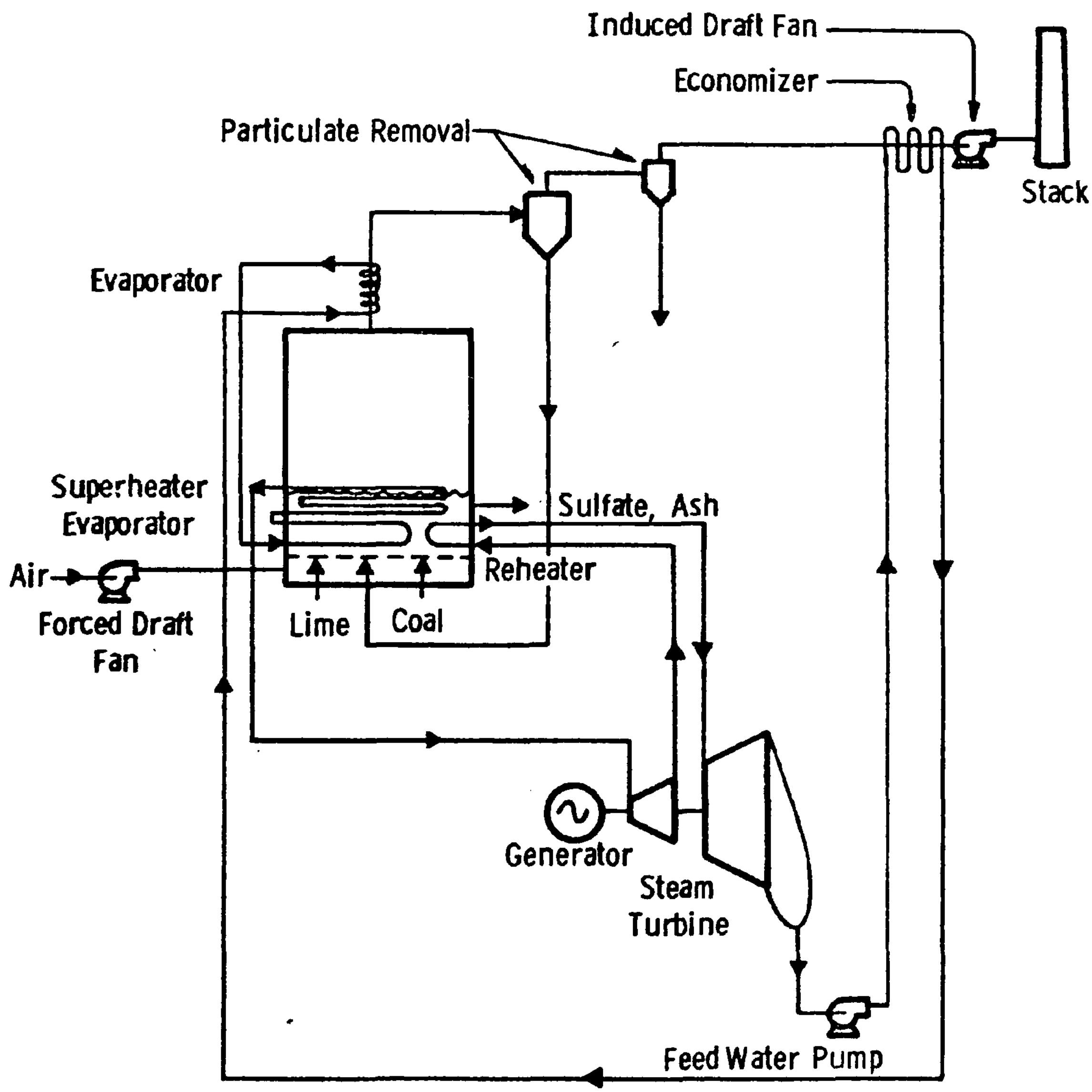

Figure 5. Atmospheric Fluidized Bed Boiler

(courtesy, Westinghouse Research Laboratories NTIS Publication PB 211494)

(1)	Dry gas losses (275°F)	4.3%
(2)	Hydrogen and moisture in coal	5.1%
(3)	Incomplete combustion	2.4%
(4)	Design factor and other losses	1.8%

As atmospheric fluid beds develop, design factor and combustion losses should go down, giving about 88% efficiency by 1990. Improvements are expected in the sulfur removal system and economic areas, but efficiency will be limited by the losses given as (1) and (2) above. The best route to improvement of the efficiency would be use of cleaner coal.

On-going R&D is conducted by the same organizations as for pressurized fluid bed combustors. Fluidized bed boiler concepts and design criteria are very closely related whether they are at atmospheric or elevated pressures. Hence, the research work in this area is not very different than that described in the previous section. The problems to overcome are very similar, regardless of the pressure.

B. COAL CONVERSION TO CLEANER FUEL

As an alternative to combustion of the coal, it may be processed to a cleaner fuel. Gas, oil and many other fluids may be produced from coal. Four coal conversion subjects are addressed in this section.

1. Low Btu gas generator (5a & 5b)

Coal converted to CO at 110°C, such as in the COGAS process (Figure 6) was evaluated in reference 6. Low Btu gas generators produce fuel with a heating value typically of 100-300 Btu/cu. ft. The majority of the gas is usually CO. Transformation of carbon to carbon monoxide can be very efficient. From thermodynamic considerations, 98% of the Btu content can be conserved. However, the efficiency is limited by more important factors than thermodynamics. These are:

(1)	Energy consumed in gas production	3%
(2)	Losses due to moisture and inerts in coal and ash	6%
(3)	Losses due to heat exchange and excess air	6%
(4)	Losses due to hydrogen enrichment necessary for the reaction	3%
(5)	Gas cleaning (not including thermodynamic loss of 2%)	3%

Most experts[7,8,9] agree that 80% efficiency is realistic for this process with a 5% penalty for cold cleaning. The Institute of Gas Technology is getting about 85% in their pilot process, but this is believed to be on a hot cleaning basis. A cold cleaning gas generator could be applied today at about 75% efficiency. Hot cleaning is expected in the mid 1980's along with process improvements to boost performance to about 92%.

The following is a list of on-going R&D efforts and commercially available units for low Btu gasification:

(1) Lurgi (moving bed)
(2) Wellman-Galusha (moving bed)
(3) General Electric (moving bed)
(4) Winkler (fluid bed)
(5) Synthane (fluid bed)
(6) CO Acceptor (fluid bed)
(7) Westinghouse (fluid bed)
(8) IGT (fluid bed)
(9) Battelle (fluid bed)
(10) Bi-Gas (entrainment)
(11) Combustion Engineering and Con Ed (entrainment)
(12) Pittsburgh & Midway Coal (entrainment)
(13) Koppers-Totzek

(14) Texaco (entrainment)

(15) ATGAS (molten iron)

(16) Kellogg (molten carbonate)

(17) Atomics International (molten carbonate)

Generally, higher temperatures and gas rates would improve each of these processes.

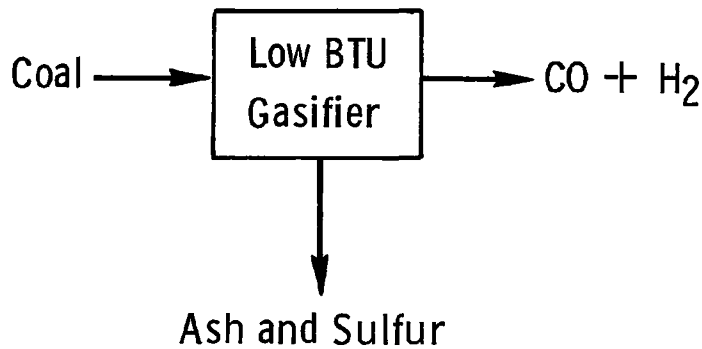

Figure 6. Low Btu Gas Generator

2. <u>High Btu gas generator (6)</u>

In high Btu gas generation, the ultimate product is usually a methane-grade gas similar to natural gas. It is suitable for use in pipelines and has a heating value typically of 900-1000 Btu/cu.ft. For definition purposes, a high Btu gas is defined as having more than 400 Btu/cu.ft. This is not rigid but includes all gasification which is not considered as low Btu.

Research into this process category is an on-going concern of many investigators. Commercially, the Lurgi and Koppers-Totzek processes are established in other countries. Some of the more common methods are the same as for low Btu gasification. The limitations are the same as with low Btu gas with additional energy consumed in the gas production and cleaning steps. The Synthane process is believed to offer efficiencies of about 75% when it is developed.[8] Analysis of a design study for producing 900 Btu/scf gas shows that 77% would be a limiting efficiency.[11]

Our personal contacts indicate that 65% could be achieved in the near future.[8,9] Although high Btu gasifiers are not used in this country, they are expected to be developed and in use by 1990.[14] At that time, efficiencies of 75% should be achievable.[8]

The prime limiting factor on efficiency is the amount of energy required to convert the carbon (coal) to a synthesis gas and ultimately to a methane-type product (see Figure 7). Because of this, production of pipeline quality (high Btu) gas will be discouraged compared to the low Btu gas for many years.

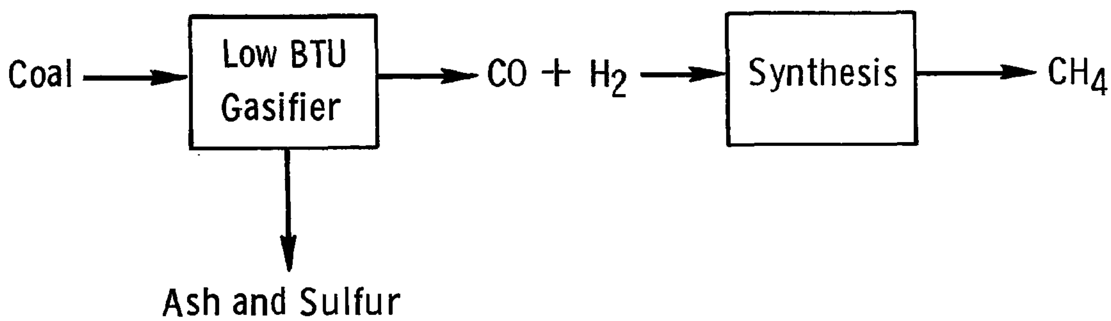

Figure 7. High Btu Gas Generator

3. Coal liquefaction (7)

Coal liquefaction is the process by which coal is transformed to a liquid hydrocarbon. The prime method is to treat the coal with hydrogen. This removes the sulfur as H_2S and gives a high H/C ratio liquid product as shown in Figure 8. Some liquefaction processes also produce light oils, gases, and even gasoline. One process was selected for evaluation (hydrodesulfurization of coal).[13] Depending upon the operating pressure, yields of 0.8 and 0.86 lb fuel oil/lb coal gave energy efficiencies of 97 and 99%, respectively. The other limiting factors that reduce the efficiency dramatically are specific to each process. Losses are expected to be about 20% of the available energy.[9]

Current R&D effort is based mainly in four processes. These are:

(1) FMC's COED process
(2) H-Coal process of Hydrocarbon Research
(3) Bureau of Mines Hydrodesulfurization
(4) Pittsburgh and Midway's Solvent-refined coal process

Areas with continued problems that could be improved by applying current technology are:

(1) High pressures
(2) Catalyst life
(3) High hydrogen consumption

When liquefaction becomes commercial in the mid 1980's,[14] it should be 75% efficient.[9]

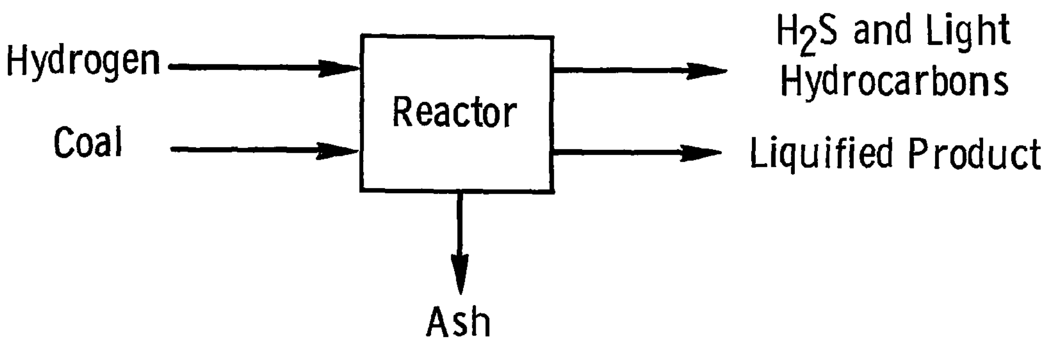

Figure 8. Coal Liquefaction

4. Conversion of coal to methanol and methanol fuels (8)

Another alternative in the liquefaction of coal is production of methanol from synthesis gas. Coal may be converted to a low Btu gas ($CO + H_2$) using Fisher-Tropsch (F-T) technology. The composition of this gas is perfect for methanol synthesis, as shown in Figure 9a. An important side reaction is the production of methane and water, which is emphasized in high Btu gas manufacture. Grade AAA methanol may be produced by this scheme but at a maximum efficiency of 35%.

Figure 9b describes another process of liquefaction of coal to produce "methyl fuel".[27] Here the catalyst is promoted to produce higher alcohols which give a higher available energy than methanol alone. It has been estimated by promoters of this process than 133 to 272 gallons of this fuel can be produced from a ton of coal.[28] This corresponds to a 34 to 69% energy efficiency. We find that about 77% of the energy could be available as a thermodynamic limit. Concensus values are reported in Table 1.[24,29]

Limiting factors which have not been quantified in prior studies on methanol fuels are as follows:

(1) Energy required to run gasifier and converters
(2) Energy input to Claus unit and strippers
(3) Losses of available energy as CO_2
(4) Energy required to produce reactants, steam or oxygen.

These factors may be significant and could reduce the operating efficiency from the maximum expected value. Estimates have been made which indicate efficiencies as low as 25 to 30% for methanol fuel production when these energy inputs are accounted for on a theoretical basis. Thus, a great deal of study is necessary in this field to determine the extent of these limitations in the production of methanol fuels from coal.

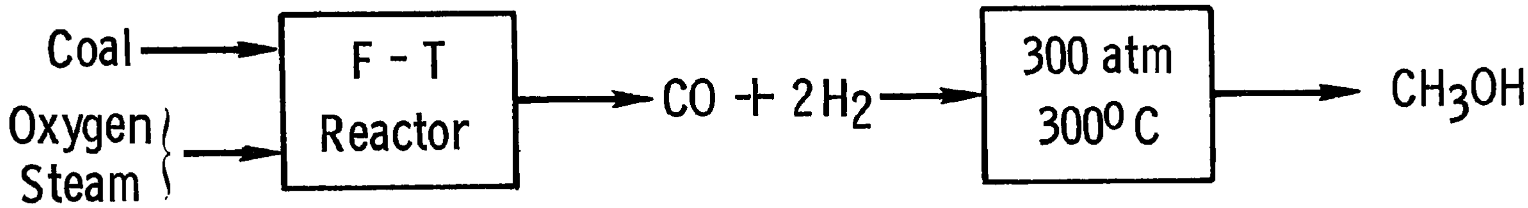

Figure 9a. Coal to Methanol

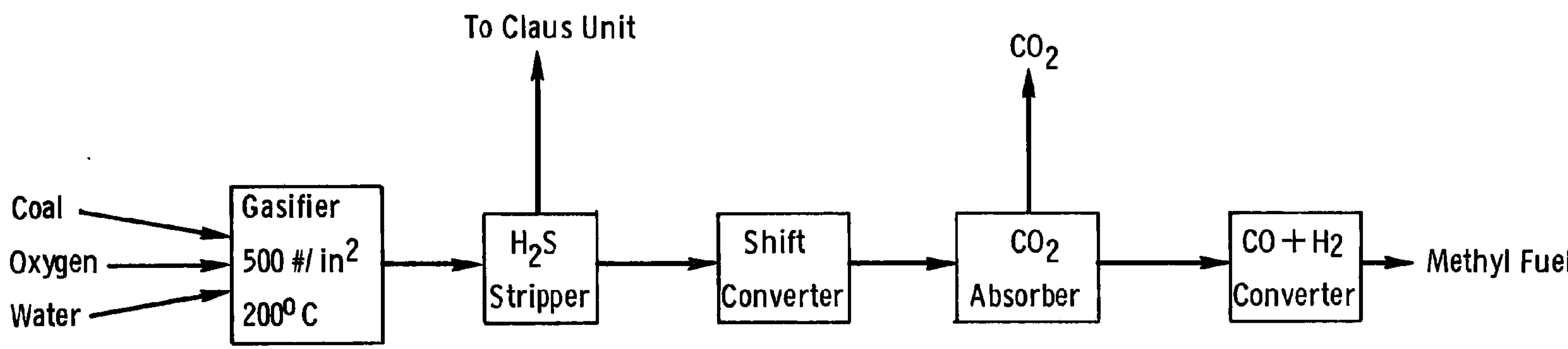

Figure 9b. Methyl Fuel Process

C. FUEL CLEANING METHODS

Certain fuels can be used directly to produce power in conventional equipment if the pollutants are removed prior to combustion. Examples are coal, residual oil and low Btu gas.

1. Coal cleaning plant (9)

Physical cleaning of the ash and separable pyrites from coal has been well established (Figure 10). Present efficiencies run from 60 to 95%[9] depending upon the type of coal, how it is mined, and the economic value of the products. If economics warrant, coal could be cleaned with little loss. There is no applicable thermodynamic limit.[9] Losses may be expected in:

(1) The heating value of the non-organic sulfur removed

(2) The coal physically bound to the pyrites that are removed

It is not reasonable to expect that physical coal cleaning efficiency will improve beyond 95%. No major R&D programs are under way, although electrostatic/electromagnetic methods are constantly being evaluated and improved.

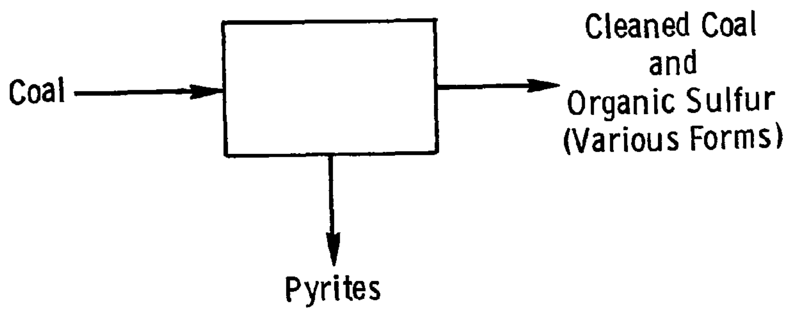

Figure 10. Physical Cleaning of Coal

2. Chemical coal cleaning systems (10)

In chemical coal cleaning a solvent is used to supplement physical coal cleaning of the pyritic sulfur. It is possible to remove virtually all of this sulfur and some of the organic sulfur this way (see Figure 11). In terms of energy, losses are confined to:

(1)	heat requirements	5%
(2)	sulfur combustion value	<1%
(3)	solvent losses (heat value)	<1%

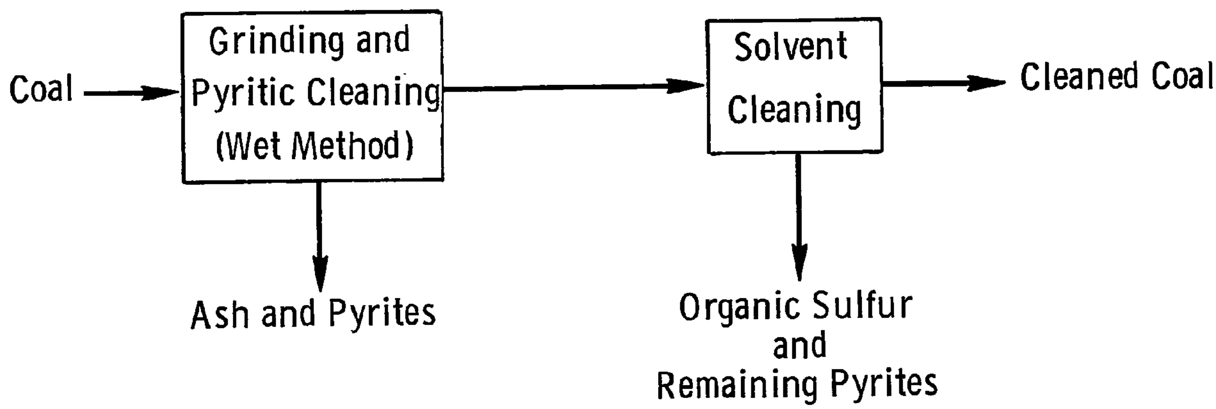

Figure 11. Chemical Coal Cleaning

For a physical yield of 94.2% with an increase of 5% in the heating value of the product, 93.9% of the energy is conserved. This analysis is based on bench scale work,[12] but shows that chemical coal cleaning has more than sulfur control value. In this cleaning, ash is also reduced by about 30%, which ultimately reduces losses in the boiler.

Chemical coal cleaning is expected to start at about 91% efficiency and by 1990 reach 95% or better. Areas of process improvement will be in leaching rates, economical production of finer coal sizes, and solvent removal from the product.

The R&D effort described in reference 12 best exemplifies some of the better efficiencies obtained thus far in chemical coal cleaning.

3. Residual oil desulfurization (11)

Crude oil has been treated catalytically for years to remove sulfur and improve quality. With the use of high sulfur Middle East crudes, this process has gained more prominence recently and may be applied to residual oils. Figure 12 is a schematic of a typical residual oil desulfurization unit. Between 92 and 94% of the potential energy is conserved, with 96% being the limit according to one source.[16] Data from the Gulf HDS process indicates that 99+% of the energy can be conserved when applied to a petroleum operation.[22] R&D efforts are concentrated on improving catalysts since the state-of-the-art with regard to energy conservation is well-established.

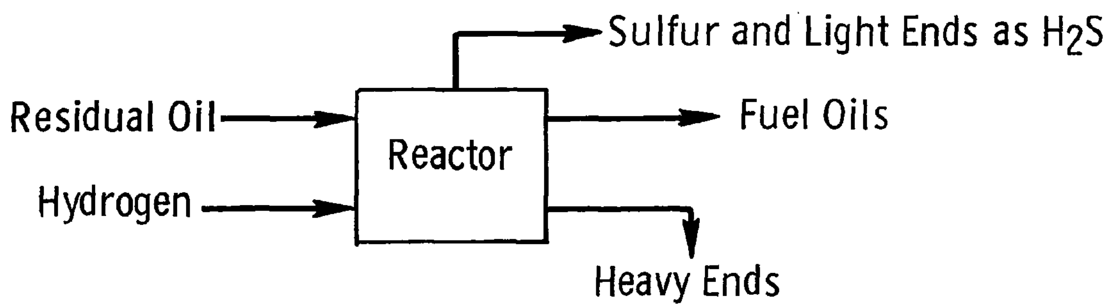

Figure 12. Residual Oil Desulfurization

4. Chemically active fluid bed (12)

A chemically active fluid bed combustor suffers heat losses from solid chemical addition, but offers an economical way to clean and burn low Btu gas. Losses are expected as follows:

(1) Chemical reaction and absorption 3%
(2) Unburned CO 2%
(3) Unaccounted for and radiation 1.5%
(4) Sensible heat (350°F flue gas) 6.5%

Process improvements should reduce some of these losses. Efficiencies as high as 86% should be achievable by 1990. Comparison to fluid bed operation indicates that the performance is quite similar. Thermodynamic performance is that envisioned for CO combustion (low-Btu gas). Figure 13 is a diagram of this process. One method of improving this process is proper selection of the gas composition, which could improve thermodynamic performance.

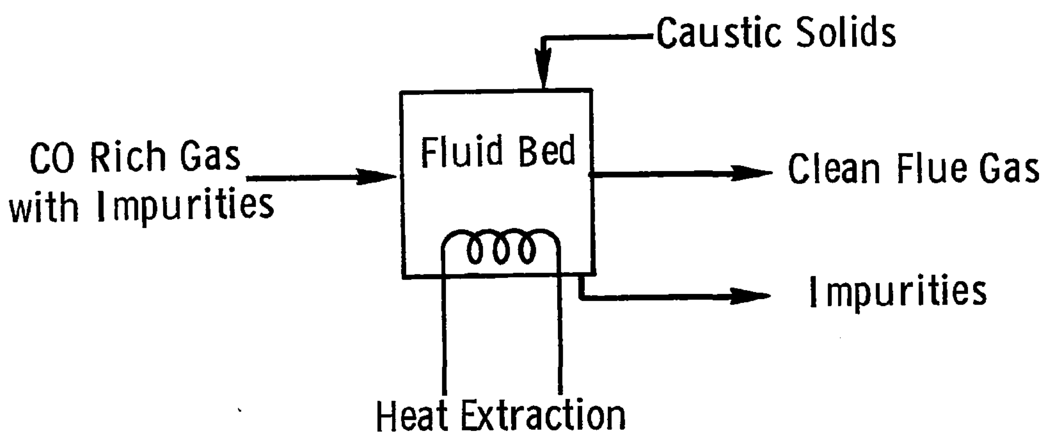

Figure 13. Chemically Active Fluid Bed

D. POWER PRODUCING MACHINERY

To extract electrical power from a hot gas conventionally requires a conversion of heat to rotating mechanical energy. Steam and gas turbines are the work horses of the power industry in this respect. They may also be combined to give better conversion efficiencies.

1. Steam turbine(13)

Presently, the better steam turbines operate at efficiencies of 45%. Unavoidable losses occur due to the cycle itself. These are:

(1) Condenser heat rejection - residual heat is lost to the sink when the steam is condensed.

(2) Turbogenerator losses - mechanical and electrical losses are inherent in design.

(3) Radiation losses - other than nonrecoverable heat dissipation.

While the efficiency of the steam turbine may be increased by using higher inlet pressures and temperatures, most boilers operate just over 1000°F for best overall plant economy[2] with boiler gas temperatures of 2000°F. ΔG and ΔH were selected for 1000°F and 1200 psia throttle steam pressure. A Carnot cycle limiting efficiency of 63% corresponds to these conditions but does not take into account the effect of reheat. An increase of 4 to 5% can result from this. Figure 14 schematically defines the section of a steam boiler defined as the steam turbine. Figure 3 gives a typical steam turbine heat balance with an efficiency of 42.7%.

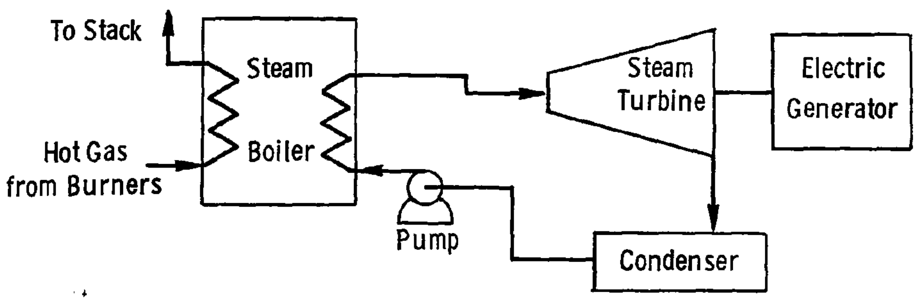

Figure 14. Steam Turbine

2. Gas turbine (14)

The gas turbine, shown in Figure 15, generally uses an intercooler and regenerator to improve the basic Brayton cycle. The thermodynamic efficiency of the Brayton cycle can be expressed as follows:

$$\varepsilon = 1 - (P_1/P_2)^{\frac{1-k}{k}}$$

where ε = efficiency
k = ratio of heat capacities (C_p/C_v)
P_1 = lower pressure
P_2 = upper pressure

Based upon present technology, gas inlet temperatures of 1800°F with an outlet of 1130°F gives an efficiency of 30%. A steady improvement in design is expected to give 42% by 1990. This is based upon 2600°F inlet and 1300°F outlet temperatures. The efficiency of a gas turbine is directly related to its inlet temperature and various techniques are available to increase this temperature. Research into the use of ceramics for gas turbines is widespread. Although applications may be difficult in large turbines, this is a viable means for increasing the operating temperature. Studies of metal creep and corrosion resistance could well uncover a material that would also withstand higher temperature. It is expected that inlet temperatures of 2600°F can be reached by 1982 with an aggressive R&D effort.[5] Another possible route to improvement is to increase the turbine pressure ratio at the higher temperatures. For a pressure ratio of 16, the limiting efficiency is 55%.

The gas turbine must be supplemented by another heat cycle to economically extract the energy. The thermodynamic limit on efficiency is 83% for a gasified coal product of about 400 Btu/cu. ft.

Realistically, the gas turbine output is about 1100°F.[5] Thus, it is usually combined with some other means of heat extraction (i.e., a steam boiler).

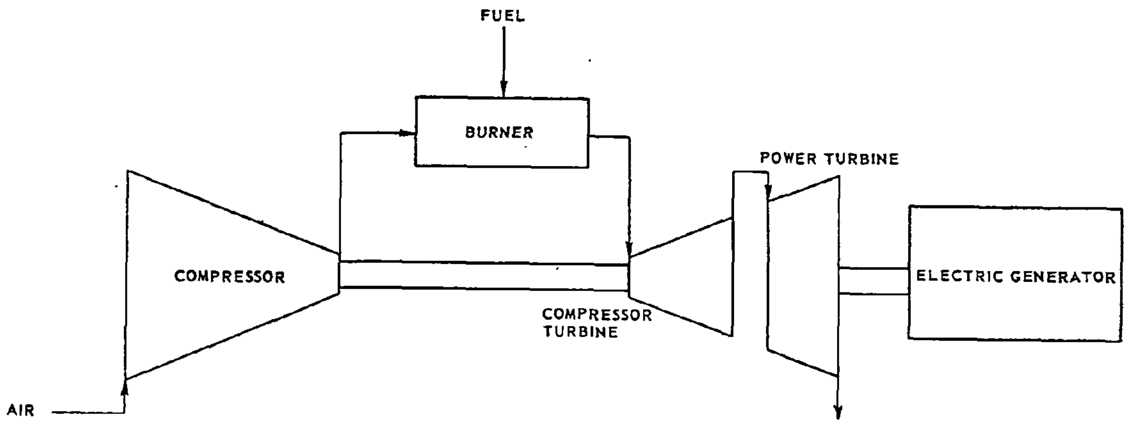

Figure 15. Gas Turbine

3. Combined cycle (15)

In the combined gas and steam turbine cycle an improvement in overall efficiency results from supplemental use of gas turbine energy (see Figure 16). This method is limited by the efficiencies of the steam and gas side. In addition to the basic limits of each component, these two systems are used in series to extract the available energy. Referring to Table 1, the gas turbine is capable of removing 30% (1974) of the energy. Since the corresponding turbine exit gas temperature would be 1130°F the steam cycle efficiency would be much lower. A steam-side efficiency of 17% would be expected, giving a combined cycle efficiency of 42%. As the inlet turbine temperature rises the exit temperature will also go up. This leads to higher steam efficiencies. Based upon a gas exit temperature of 1300°F, the steam efficiency is 30%.

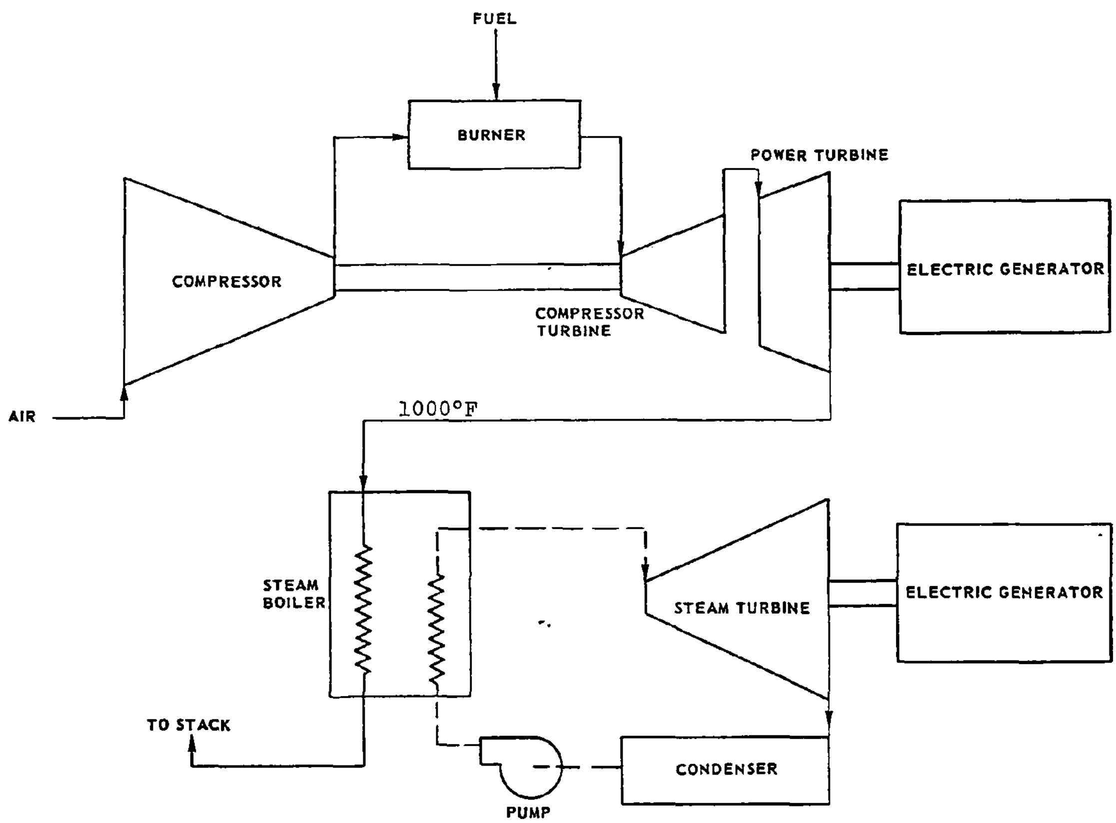

Figure 16. Combined Cycle System

E. SPECIAL ENERGY CONVERSION METHODS

In addition to the methods of producing power discussed in the previous sections, there are other alternatives. Further energy extraction from either the hot gases or heat rejection (condensor, etc.) can come from the use of topping or bottoming cycles. Electrical energy can be extracted directly from the hot gas with magnetohydrodynamics. Nuclear reactors are still another source of energy using special fuels. Most of these processes are viable alternatives in improving the efficiency of power generation.

1. Nuclear steam plants (16)

There are three basic types of nuclear steam plants. These are schematically shown in Figure 17. The pressurized and boiling water reactors are 32 to 33% efficient in the newest plants.[3] The high temperature gas-cooled reactors are about 39% efficient.

Efficiency is limited by:

(1) The upper sink temperature
(2) Lower condenser temperature
(3) Reactor safety considerations

The heat input to the steam cycle can be virtually 100% of that released by the reactor. Thus, the efficiency limitation would be on the steam side. R&D into improving and upgrading nuclear plants is a primary concern of the AEC. Most R&D effort has been placed on lowering reactor cost and improving safety. The closed loop nature of nuclear power provides high heat efficiency.

The use of steam in nuclear power plants will limit the attainable efficiency. Considerable R&D is being focused on other energy transfer media to lift this limitation.

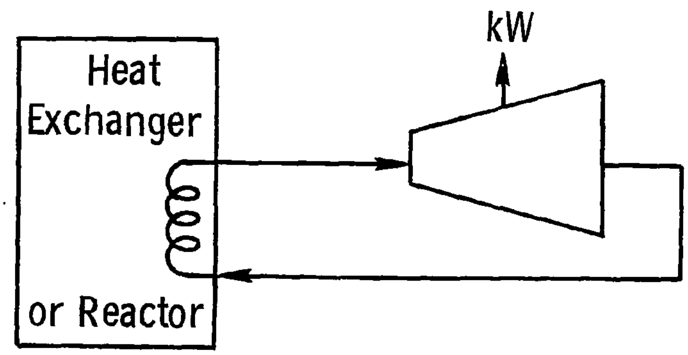

Figure 17. Nuclear Reactor

2. <u>Feher cycle (17)</u>

The Feher cycle is similar to the Brayton cycle except that it operates entirely in the supercritical pressure region. Working fluids such as carbon dioxide are used in a closed-loop cycle for energy extraction. Real gas effects are important in this range. At present this process has only been able to give about 18% efficiency.[6]

The thermodynamic limit would be the same as for the Brayton cycle. By keeping the pressure high, the turbine inlet temperature can be kept at lower, achievable temperatures. Figure 18 gives the overall system concept. Achievable efficiency is limited by turbine inlet temperatures only. No technological breakthrough is needed to achieve a working machine.[23] The Department of Defense is developing units for portable and special purpose applications. At turbine inlet temperatures of 1400°F, efficiencies of 42% are achievable.[23]

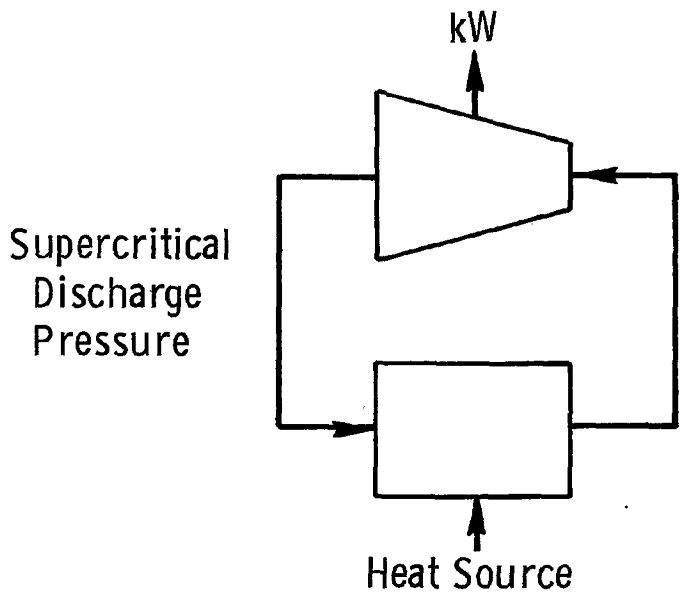

Figure 18. Feher Cycle

3. Potassium topping cycle (18)

Topping of a steam cycle is represented in Figure 19. Efficiency is limited by Carnot cycle limitations which come from high temperature material problems. At 2200°F, the thermodynamic limiting efficiency is about 45%. Materials for high temperature and corrosion free service are needed to extend the usefulness of topping. The turbine presently has an intrinsic design limit value of 1500°F on the blades.[5]

This gives an efficiency of 16%.[6] If inlet temperature could be raised to 1800°F, the efficiency would increase to 20%.[6] Potassium topping has gained attention due to improvements in liquid metal technology. At present, developments in corrosion resistance beyond 1600°F are necessary to extend use of this method.[6] Columbium addition to stainless steel is thought to offer protection up to 2200°F. With the present decline in aerospace activity, R&D in this technology has been curtailed and only minor programs remain.

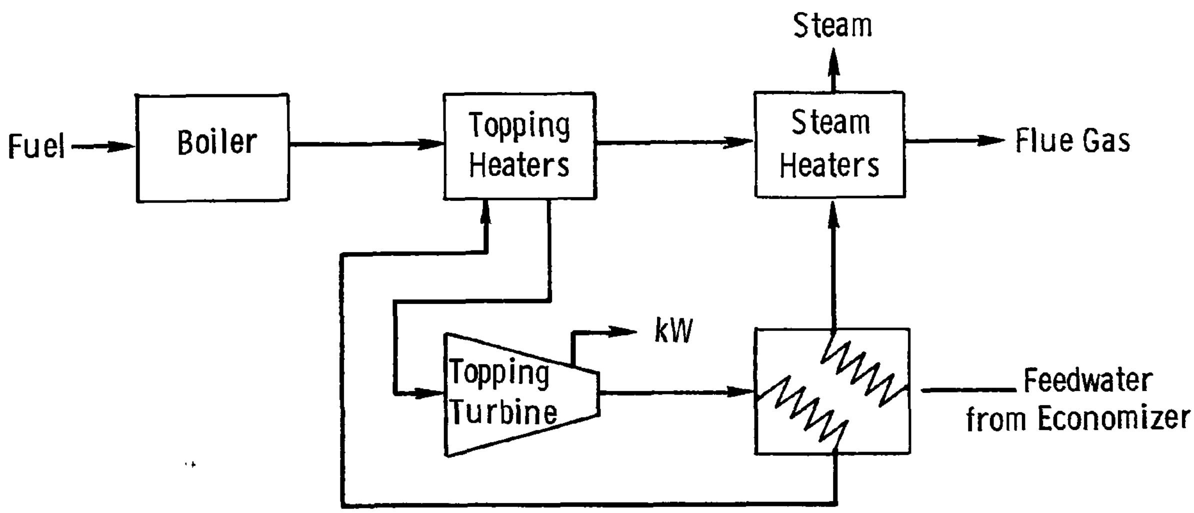

Figure 19. Topping Cycle Applied to Steam Boiler

4. Bottoming cycle (19)

The bottoming cycle is best approximated by a Rankine cycle, as shown in Figure 20. The limiting temperature available for the heat source would be 600°F, so efficiency is limited to 50%. Depending upon the fluid, the efficiency varies from 10 to 16%[6] for practical cases.

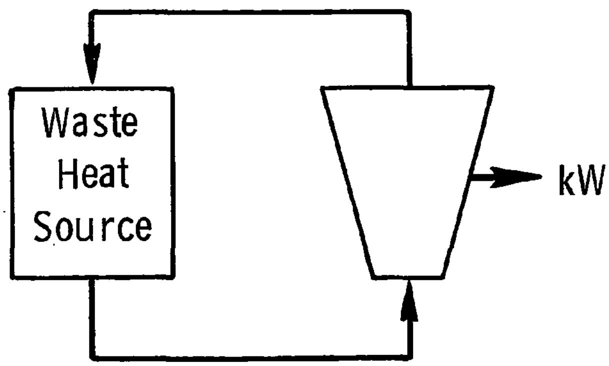

Figure 20. Bottoming Cycle

The limiting factors are:

(1) Heat source temperature
(2) Inlet turbine pressure
(3) "Wetting" characteristics of working fluid
(4) Critical temperature of working fluid

Further investigation of this cycle should uncover a better fluid. The technology of the cycle exists, but application has been unwarranted in the past by economics.

5. Magnetohydrodynamics (MHD) (20)

MHD may be used to produce dc electricity in a variety of ways. It is expected that commercially available units will first be used with steam power plants by 1980. In this case the steam cycle supplements the MHD channel output. An efficiency of 50% should be achieved with the MHD air turbine cycle shown in

Figure 21(b). For central station use, the dc output is believed to be better than ac output[3] and eliminates the necessity for power conversion. Major limitations in efficiency are:

(1) Preheat temperature of combustion air

(2) Magnetic field strength

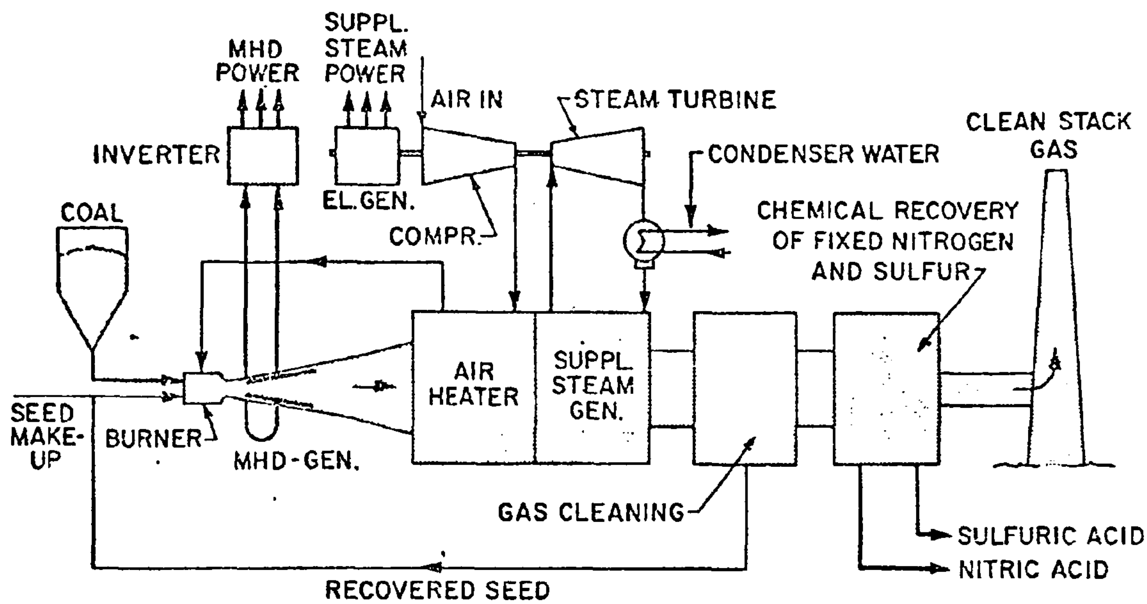

Figure 21(a). MHD Steam Cycle

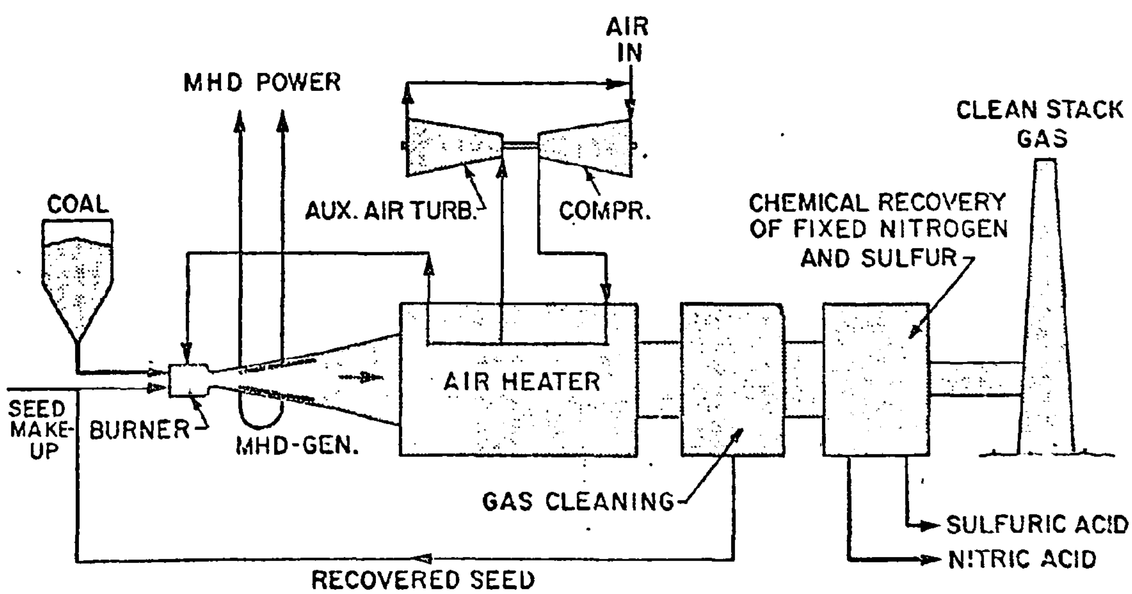

Figure 21(b). MHD Air Turbine Cycle

For a MHD station operating around 5 Teslas (1 Tesla = 10,000 gauss) with a preheat temperature of 3000°F, efficiencies of 60% may be achieved in a binary cycle such as Figure 21(a).

Typical losses from MHD are:[23]

(1)	Burner heat	2.5%
(2)	Dry gas at 300°F	8.5%
(3)	Expansion and contraction	4.0%
(4)	Other process	2.0%

Thermodynamically, a regenerative Brayton cycle would have a limiting efficiency of about 82%. However, the binary MHD cycle efficiency will be reduced because of the steam cycle; 65% is considered a practical limiting efficiency.[17] Use of Rankine cycles could make this achievable by the year 2000.

R&D by Avco has been continuing since the early 1950's. Major present-day efforts are primarily concerned with seed recovery, high temperature combustion, air pollutants, and superconducting magnets.

F. PORTABLE POWER SOURCES

Fuel cells and internal combustion and diesel engines are useful portable power souces for electricity or motive power. They are not as bulky as other power equipment and can provide power whenever needed. Although the efficiency may not compare to other sources, in many cases they represent the only feasible alternative for power production. Fuel cells are generally so efficient that the power industries interest is economic as well as conservation oriented.

1. Fuel cells (21)

Attempts have been made to use fuel cells for central power stations with little success. Although the efficiency is generally high, their cost is too high and durability too low for today's utility market. Since an individual fuel cell produces about one volt, the number of possible trouble points in a unit big enough to give reasonable outputs is staggering. A natural gas fuel cell has been successfully used for small homes and for portable power generation.[3] Hydrogen/oxygen cells are routinely used in space with effciencies as high as 90% (non-condensing) methanol has been widely investigated as a fuel cell by a variety of researchers.[20]

Limiting factors are all practical problems since under controlled conditions 80-99% of the thermodynamic energy can be recovered. Direct methanol fuel cells lose excessive fuel to carbonate formation and evaporation in most applications. Thus they have lower efficiencies than hydrogen cells even though the thermodynamic limit is higher. This is caused by oxidation at the anode and cathodic corrosion. This leads to low over-voltages and low current densities.

Several substance can be used to extract hydrogen for a fuel cell from water (see figure 22(a) and 22(b)). Examples are coal and methanol. They may also contain substantial amount of hydrogen which can be liberated. Methanol can be reformed according to the following endothermic reaction:

$$CH_3OH + H_2O \rightarrow 3H_2$$

Energy efficiency of this reaction has been demonstrated to be 36%.[25] Since economics do not favor this method of producing hydrogen, very little has been done with it since about 1950. An efficiency of 60% was used for 1990 and supposed economic

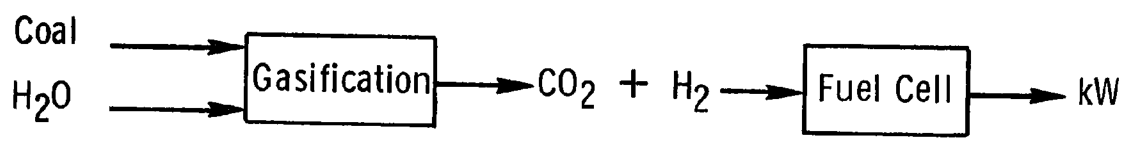

Figure 22(a) Hydrogen Fuel Cell Methanol

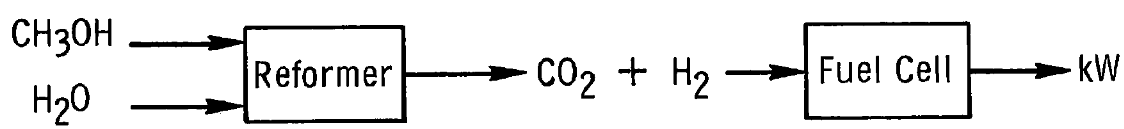

Figure 22(b) Hydrogen Fuel Cell Using Coal

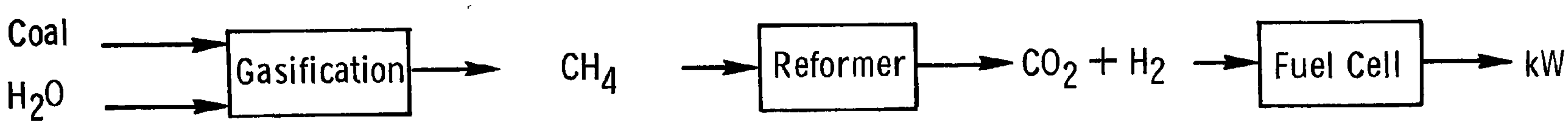

Figure 22(c) Pratt and Whitney Fuel Cell System interest in this path. Coal may also be used to produce hydrogen from water through a similar reaction:

$$C + 2H_2O \rightarrow CO_2 + 2H_2$$

This is a low Btu gasification process which operates at lower efficiency due to the greater amount of hydrogen produced. The limiting efficiency is 77.5% for the conversion. In both cases the hydrogen is used to produce electricity in the fuel cell. The reforming and fuel cell efficiencies are multiplicative.

Pratt & Whitney and a group of utilities have studied the technical feasibility of using fuel cells for peaking power but progress has been slow in overcoming mechanical failures.[3] When developed the Pratt & Whitney system is expected to be similar to that shown in Figure 22(c).[26] Westinghouse and the Office of Coal Research ran out of funds in developing a coal-energized fuel cell system in the early 1970's. Fuel cells may be applied to major power generation to a limited extent, but probably not until after 1990.

2. Automotive (22)

The internal combustion (I-C) engine is best approximated by the Otto cycle. The thermodynamic efficiency is a function of the compression ratio only. Reduction of this efficiency from thermodynamic is a function of the variable specific heats, dissociation, and heat loss. For a typical 9:1 compression ratio engine, (100% theoretical air) the efficiency is presently 41%.[1] When this same engine is used to drive a typical American-made automobile, (16 mpg), the efficiency drops to 8%,[23] but efficiencies as high as 28% have also been recorded. Major limiting factors are:

(1) Vehicle weight
(2) Air drag
(3) Idling losses
(4) Drive line drag and losses

Vehicle redesign with emphasis on loss factors (1) and (2) should improve the efficiency. These are expected to be counteracted by lower compression ratios and air usage necessary to meet emission control requirements. The I-C engine is not expected to survive beyond 1990.[21] It will probably be replaced with diesel or turbine engines, or electric motors.

3. Diesel (23)

Diesel engines operate at higher compression ratios and compress the combustion air prior to fuel injection. As in the Otto cycle (I-C engine) the efficiency can be obtained from the known compression ratio. A 15:1 ratio was selected for determinations in this study. The vehicle efficiency is much lower and the limiting factors are the same as for the automobile. No R&D programs aimed at improvement of this engine are known.

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA-650/2-74-021	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Efficiencies in Power Generation		5. REPORT DATE March 1974
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) T. R. Blackwood and W. H. Hedley		8. PERFORMING ORGANIZATION REPORT NO. MRC-DA-404
9. PERFORMING ORGANIZATION NAME AND ADDRESS Monsanto Research Corporation Dayton Laboratory 1515 Nicholas Road, Dayton, Ohio 45407		10. PROGRAM ELEMENT NO. 1AB013; ROAP 21ADE-29
		11. CONTRACT/GRANT NO. 68-02-1320 (Task 7)
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED Final, 11/73 - 2/74
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT The report introduces 23 different ways of using or converting energy. It provides a tabular comparison of the thermodynamic limiting present and future (1990) efficiencies. It includes a brief discussion of efficiency limiting factors, possible general routes for process improvement, and relevent on-going research and development. The report concludes that more study is required in several of the following (alphabetically listed) areas: atmospheric fluid-bed combustion, automotive, bottoming cycle, chemical coal cleaning systems, chemically active fluid-bed combustion, coal cleaning plants, coal liquefaction, combined cycle (gas and steam), conventional boilers, conventional boilers plus flue gas cleaning, conversion of coal to methanol, diesel, Feher cycle, fuel cells, gas turbines, high-Btu gas generation, low-Btu gas generation, magnetohydrodynamics, nuclear power plants, potassium topping cycle, pressurized fluid-bed combustion, residual oil desulfurization, and steam turbines.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Boilers	Air Pollution Control	13B
Power	Flue Gases	Combined Cycle	10A
Energy	Fluidized Bed		20M
Utilization	Processing		18E
Conversion	Nuclear Power Plants		10B
Thermodynamics	Gas Generators		18L
Liquefaction	Desulfurization		

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 47
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)