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POWERED STEAM-MHD CENTRAL POWER SYSTEMS
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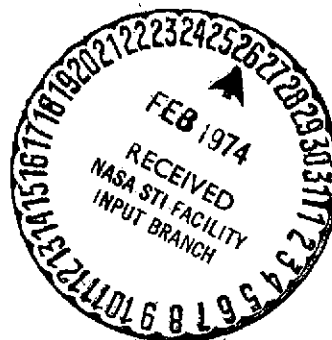
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Abstract

Estimates are made for both the performance and the power costs of H₂-O₂ combustion powered steam-MHD central power systems. Hydrogen gas is assumed to be transmitted by pipe from a remote coal gasifier into the city and converted to electricity in a steam MHD plant having an integral gaseous oxygen plant. These steam MHD systems appear to offer an attractive alternative to both in-city clean fueled conventional steam power plants and to remote coal fired power plants with underground electric transmission into the city.

INTRODUCTION

Central power stations with MHD generator topping cycles have the potential for very high efficiency. Because MHD generators have no moving parts and use volume rather than surface forces to extract power, they have the ability to operate at much higher temperatures than turbines. The combustion temperature and pressure usable in MHD generators are limited only by the maximum acceptable local heat transfer rate.

High-temperature high-efficiency MHD topped power plants can be constructed with negligible efflux pollution if oxygen is used in conjunction with a clean fuel. Use of oxygen, however, requires an oxygen plant. Hydrogen as a fuel tends to minimize the difficulties associated with using oxygen since hydrogen requires a minimum of oxygen per unit of heat release.

Combustion with pure oxygen requires larger MHD generator expansion ratios (inlet/exit pressure) to extract a given fraction of the enthalpy in the flow than combustion with air. However, if large expansion ratios can be achieved, higher fractions (over 45%) of the stream enthalpy can be extracted with reasonable power density in fuel-oxygen generators. This results from the expansion process being more nearly isothermal in generators using oxygen rather than air.

For cooled-wall combustors and generators the maximum allowable combustion pressure is limited by the allowable maximum local heat transfer rates. H₂-O₂ combustion at pressures up to 30 atm does not result in heat transfer rates that are excessive for water cooled combustors. For limited inlet pressures, very high expansion ratio generators require subatmospheric generator exit pressures. Steam MHD generators can be operated with less than 1/10 atm exit pressures since the steam can ultimately be condensed to water and pumped with little work to atmospheric pressure.

To assess the attractiveness of H₂-O₂ combustion powered steam MHD power plants, the projected cost of alternative fuels and the cost of transporting energy in various forms will first be examined. An attractive

thermodynamic cycle for steam MHD systems will then be discussed. Performance and advantages and disadvantages of four optional steam MHD systems will be considered. For each option a preliminary design of the required MHD channel was calculated.

Finally, the relative advantages and disadvantages of the steam MHD systems and various alternative systems will be compared. Included in this comparison are the power plant efficiency, capital cost, fuel cost, and fuel and power transmission cost. Environmental impact advantages of the H_2-O_2 combustion power systems will also be discussed.

Fuel Cost Projections

Fig. 1 shows estimated projections of the costs of various fuels in various years. All costs except the hydrogen costs have been taken from [1]. Hydrogen costs were calculated using the estimated gas and coal costs shown in conjunction with estimates of hydrogen production costs as a function of fuel cost from [2]. A 2500 ton/day H_2 plant was assumed. The gasifier assumed in [2] was based on the previous work of Hallett [3]. Fig. 1 indicates that by 1985 hydrogen could be an attractive, competitive coal-derived clean fuel. It may not, however, be as inexpensive as imported oil or gas and certainly will be more expensive than domestic coal.

Energy Transportation Costs

Fig. 2 shows estimates of the range of the cost of transporting energy in various forms. Cost in cents per million Btu's per hundred miles are shown as a function of distance for transporting various forms of energy by various techniques. Most of the data shown in fig. 2 are taken from [4]. The only exceptions are the underground transmission which were included from [5] and hydrogen transmission in gas pipelines which were taken from [6]. The range of costs shown for underground transmission includes estimates for superconducting and cryogenic lines as well as conventional transmission lines. Fig. 2 shows that electric power transmission is expensive for long distances, pipes are an excellent method of transmission for short and intermediate distances, and that the performance of carriers (trains, barges, and ships) becomes better with increasing distance because of the decreasing effect of loading and unloading costs. Transmission of gaseous hydrogen in pipelines is more costly than natural gas transmission. However, hydrogen transmission is still less expensive than cheaper coal-derived gaseous fuels such as producer gas or water gas (this results from their higher molecular weight and equal or lower energy content per cubic foot).

From fig. 2 it can be concluded that if hydrogen is to be produced from Western coal it may be more desirable to transport the coal by train to a hydrogen plant within a few hundred miles of the ultimate hydrogen consumption site. This would have the additional advantage that the water used in producing the hydrogen would not be required at the Western coal mine. In addition, hydrogen gasification plants initially located near Eastern or Midwestern surface mines would not become obsolete as their local coal supply is depleted.

Oxygen Costs

In estimating the gaseous oxygen costs for this study, costs have been subdivided into two categories; the first is the power required to run the gaseous oxygen plant and the second includes all other costs: operating, maintenance, and capital charges. Costs are based upon utilizing available air liquefaction technology. This breakdown of costs allows for a consistent way of charging for the power required to operate the oxygen plant.

Fig. 3 shows both the total cost and cost minus power cost for gaseous oxygen production as a function of plant size. The extrapolations shown have been made to estimate the costs for a 10^4 ton/day plant, the size required for a 2000 MW_T hydrogen power plant.

Fig. 4 shows that using present large air liquefaction plant technology, the power to produce oxygen for stoichiometric combustion at 30 atm as a fraction of the fuel higher heating value is respectively 10, 10, 13, and 14 percent for H₂, CO, CH₄, and typical coal. Thus, the efficiency of a H₂-O₂ power plant is 10 points lower than the gross efficiency based on electrical output to account for the power required for oxygen production.

STEAM MHD SYSTEM PERFORMANCE

The H₂-O₂ steam MHD generator can be easily integrated into cycles using steam turbines. Fig. 5 shows one such cycle. If the hydrogen and oxygen are preheated, the cycle efficiency is increased more by recycling water through the high pressure recuperative-boiler and turbine than by increasing the combustion temperature. The gross efficiency of the high MHD expansion ratio cycle is 70 percent (using the higher heating value) for a preheat temperature of 1500° K. Thus, this steam MHD cycle has the potential for obtaining a net efficiency of over 60 percent after subtraction of the power for oxygen production. Even without preheat the high expansion ratio steam MHD topped cycles offer the potential of over 50 percent efficiency.

Four options of the power plant shown in Fig. 5 are examined herein. In option 1, the H₂, O₂, and the steam diluent to the combustor are preheated to the steam bottoming plant temperature (839 K), and in the MHD generator the flow is expanded to a total pressure of 1 atm. In options 2, 3, and 4, 1500 K preheat is assumed and the expansion is to a total pressure of 1, 0.5, and 0.1 atm respectively. All options except option 4 use a low pressure turbine to expand the flow to a pressure of 1/10 atm before the steam is condensed. In all options the combustor is operated stoichiometric at 30 atm and 3468 K. To maintain this combustion temperature for the two different preheat temperatures the steam diluent flow is varied from 17 to 30 percent of the total MHD hydrogen and oxygen mass flow.

Although high and low pressure steam turbines are schematically shown as distinct components in Fig. 5, they would in fact be integral parts of the steam bottoming plant. The preheater in practice would be subdivided into low temperature and high temperature preheaters. The low temperature preheater would be an integral part of the bottoming plant boiler heater and would provide a temperature of 839 K. Separate sets of high temperature

refractory "pebble bed" type regenerators are required to preheat the O_2 and H_2 to 1500 K. The steam diluent can be effectively used as a regenerator purge at the end of each regenerator thermal cycle.

The MHD generator is assumed to be seeded with cesium hydroxide. The cesium seed in the MHD generator exhaust can conceptually be easily recovered as liquid cesium hydroxide which would start to condense to droplets at a temperature of approximately 600° K. Since the cesium seed will condense as cesium hydroxide independent of how it was injected, it is also desirable to inject it in this form, thereby simplifying the seed recovery and generator chemistry.

For each option an MHD channel was designed with an area variation so as to maintain a constant Mach number. This constraint automatically avoids choking of the flow and adverse pressure gradients. The generator seed fraction and Mach number are optimized to maximize the average generator power density. The generator performance is calculated assuming one dimensional flow and using a multispecies equilibrium chemistry program [7] to determine the species concentration and plasma conductivity. An ideal segmented Faraday generator is assumed, but power density is decreased inversely with the Hall parameter for values greater than one to account for experimental departures from ideal performance at high Hall parameters.

Various cycle parameters and conditions for the four steam MHD options are shown in Table I. Table I also contains, for comparison, similar parameters for the coal-air MHD system studies by Bergman et al. [8] with lowest power cost.

CAPITAL COST AND OPERATING COST FOR STEAM MHD SYSTEMS

Estimates of the cost of steam MHD systems are made in a manner consistent with previous cost estimates for coal-air MHD systems by Bergman et al. [8]. Analysis of their study indicates that MHD system cost can be well estimated from an assessment of the cost of the major MHD plant components, the steam plant cost, and the relative power outputs of the MHD and steam plants. The major cost MHD components are the MHD generator channel and magnet, the inverters required to convert the dc output to ac, and the high temperature preheater.

The resulting component costs and the capital cost for the four steam MHD plants are shown in Table I. MHD channel cost was estimated on the basis of wall area using a cost of \$13,000/M². The magnet cost was scaled on the basis of the total magnetic energy in the channel assuming \$0.025/J. These costs as well as the high temperature preheater cost are based on scaling the cost of the Bergman et al. [8]. For the clean fuel heated preheater their option 2 was scaled. It was based on previous studies by Heywood and Womach [9]. For this study the preheater structure cost was scaled by the ratio of the maximum pressures and the resulting total cost was scaled on the basis of the required heat transfer surface assuming turbulent heat transfer and equal fractional pressure drops.

As shown in Table I steam MHD options 1, 2, and 3 all yield low capital cost. Option 4, however, has significantly higher cost. The large cost

Increase in option 4 is primarily caused by the magnet cost associated with the lower average MHD power density operation. Only in option 4 does the high temperature preheater cost become significant because of the low pressure in the hot gas flow. In the other three options this cost is small compared to the coal-air MHD system because of the following: (1) clean gas heated heat exchangers are significantly less expensive than those heated by streams containing coal ash, (2) the steam MHD systems preheater heat flows are a much smaller fraction of the electric power, and (3) the steam MHD system preheaters operate with higher T than the coal-air MHD system.

Table I also shows the cost of power neglecting the fuel cost for the four steam MHD options. This is estimated on the basis of 7000 hr/yr plant operation with the annual power production cost being 25.6 percent of the power plant capital cost plus the oxygen plant production cost for other than electric power. The power costs minus fuel costs of the steam MHD options 2 and 3 (5.3 and 5.5 mills/kW-hr_e respectively) compare favorably with similar costs for either the coal-air MHD (8.0 mills/kW-hr_e) or conventional coal fired steam plants (6.7 mills/kW-hr_e with no SO_x removal, 8.7 ± .5 mills/kW-hr_e with SO_x removal).

COMPARISON OF POWER SYSTEMS

Table II shows representative average power cost for conventional steam plants using various fuels and for both coal-air MHD and steam MHD systems. In this table, energy and/or power transportation cost are neglected and only east/midwest surface mined coal is considered. Fuel costs are based on 1985 projections shown in Fig. 1.

Table II shows that the option 3 is the most attractive steam MHD system. This 55 percent efficient steam MHD system is also more attractive than all alternative clean fuel conventional steam power plants, particularly if they are fueled from domestic shale, coal, or crude.

Table II also shows that the direct coal fired power plants can produce power at the lowest average cost, the lowest cost system being a conventional coal fired steam plant with no SO_x removal. It is 0.9 mills/kW-hr_e below the coal-air MHD topped steam plant which would remove SO_x.

The power production cost will be only one major factor in determining future power plant choices; additional aspects of the cost of power in a city as well as the environmental impact of the power plant must be considered. In Fig. 6 the cost of power in a city is evaluated for various power plant concepts. The city is assumed to be either or both 100 miles from east or midwest surface coal mines or 1500 miles from western surface coal, syngas, syncrude (shale or coal), and domestic crude.

In-city power costs are calculated including energy/power transportation costs for in-city power plants using coal and clean fuels, for coal fired power plants 100 miles from the city with either overhead or underground electric transmission, and for western minehead coal fired power plants with overhead transmission. For the hydrogen fueled power plants the

hydrogen is assumed to be piped to the city from a gasifier located 100 miles outside the city.

Fig. 6 again shows that a 55 percent efficient steam MHD power plant has an attractive potential compared to domestic fueled clean fuel conventional steam power plants. This type plant is used in many cities in the United States. Oil and gas fired power plants account for approximately 25 percent of the U.S. electric power production.

Fig. 6 also shows that steam MHD power cost will be higher than in-city coal fired power cost but may have lower cost potential if the coal fired plant is required to be located 100 miles outside the city (the assumed gasifier location) and if electric power transmission into the city is required to be underground like the hydrogen transmission.

CONCLUDING REMARKS

H₂-O₂ combustion powered steam-MHD central power systems offer the potential of producing power without air pollution (except for the emission of CO₂ at a remote gasifier), the potential of low in-city thermal pollution power plants, the potential of lowering the cost of power from clean fuel power plants, and the potential of lowering the economic penalties associated with requiring coal consumption to be remote from cities and elimination of overhead electric power transmission. Steam MHD systems should, in addition, be the least difficult MHD technology to develop because of their clean fuel and relatively simple chemistry.

The steam MHD systems examined have not been fully optimized but should be representative of the general potential of such systems. The cost estimates, herein, for these systems are of course speculative in nature as are many other aspects of a comparison of future power plants including the prospects for satisfactory SO_x removal for conventional coal-steam plants, the feasibility of developing the difficult technology required for direct coal-air MHD systems, and future fuel and transmission costs.

The major potential disadvantage of the proposed steam MHD power plant system is not associated with the MHD plant but with the hydrogen gasifier. For this study the gasifier efficiency for conversion of coal Btu's to hydrogen upper heating value Btu's is only 54 percent. Thus, even though the MHD plant has a high 55 percent efficiency, the overall efficiency of converting coal to electricity is lower than in conventional steam plants. However, having noted this point, it should also be recognized that if significantly higher efficiency hydrogen gasifiers can be realized then large potential reductions in the estimated power costs could also be realized since these steam MHD power plants are low capital cost and high fuel systems. In a similar way improvements in oxygen plant technology could also lead to significant improvements in these proposed steam MHD systems.

Finally, a comment is in order regarding the major potential synergistic effects that could result from deployment of the proposed steam MHD plants. Deployment of hydrogen as a central power station fuel would unquestionably

act as a catalyst for the immediate deployment of numerous other aspects of a "hydrogen economy."

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TABLE I - MHD POWER PLANT CHARACTERISTICS AND COSTS

	H ₂ -O ₂ STEAM MHD				COAL-AIR MHD TOPPED STEAM
	OPTION 1	OPTION 2	OPTION 3	OPTION 4	
Combustion Chamber					
Temperature, K	3468	3468	3468	3468	2836
Pressure, Atm	30	30	30	30	8
Preheat Temp, K	839	1500	1500	1500	1473
MHD Generator					
Expansion Ratio	30	30	60	300	6.7
Max. Magnetic Field, T	6	6	6	6	6
Enthalpy Extraction, %	31	31	37	47	23
Av. Power Density, MW/M ³	76	76	40	8.4	18
MHD Power/Net Power	.74	.82	.89	1.04	.63
Steam Power/Net Power	.48	.38	.30	.12	.56
O ₂ Plant Power/Net Power	.21	.20	.18	.17	-
Compressor Power/Net Power	-	-	-	-	.19
High Temp Preheater					
Thermal Power/Net Power	0	.31	.27	.26	.52
NET EFFICIENCY, %	48	51	55	60	50
MAJOR MHD COMPONENTS, \$/kW _{MHD}					
MHD Channel	.53	.53	.63	2.1	1.5
MHD Magnet	4.74	4.74	8.96	50.8	14.7
Inverter	15	15	15	15	15.4
High Temp Preheater	0	.92	1.79	8.85	15.2
Compressor	-	-	-	-	10.3
Sum, \$/kW _{MHD}	20.3	21.4	26.4	76.8	57.1
CONSTRUCTION, \$/kW _e					
MHD Plant	26.8	31.2	42.3	144	63.9
Steam Plant	44.4	35.1	27.4	11.6	54.0
Total, \$/kW _e	71.2	66.2	69.7	156	118
Power Plant Cost, \$/kW _e	90.4	84.1	88.5	198	150
Capital Cost, \$/kW _e	128	119	125	280	214
Power Cost neglecting Fuel					
Cost, mills/kW-hr _e					
Power Plant	4.68	4.35	4.58	10.23	8.03
O ₂ Plant Other than Elec.	1.03	.98	.91	.83	-
Total	5.71	5.33	5.49	11.06	8.03

TABLE 11 - REPRESENTATIVE POWER COST
ENERGY/POWER TRANSPORTATION NEGLECTED

TYPE PLANT	EFFICIENCY %	AV. FUEL COST mills/kW-hr _e	AV. POWER COST mills/kW-hr _e
CONVENTIONAL STEAM			
East/Midwest Coal			
No SO _x Removal	40	2.2	8.9
With SO _x Removal	40	2.2	10.9
Oil			
Domestic Crude	40	8.9	15.5
Imported Crude	40	6.2	12.8
Syncrude - Shale	40	8.1	14.7
Syncrude - Coal	40	10.4	17.0
Gas			
Syngas - West Coal	40	8.7	15.4
Imported LNG	40	7.1	13.7
Hydrogen			
East/Midwest Coal	40	8.8	15.5
COAL-AIR MHD TOPPED STEAM			
East/Midwest Coal	50	1.8	9.8
H₂-O₂ STEAM MHD			
East/Midwest Coal			
Option 1	48	7.3	13.0
Option 2	51	6.9	12.2
Option 3	55	6.4	11.9
Option 4	60	5.9	16.9

PROJECTED FUEL COST
 YEAR INDICATED BOTTOM OF COLUMNS
 REF: SUMMARY REPORT NATIONAL PETROLEUM COUNCIL 1972

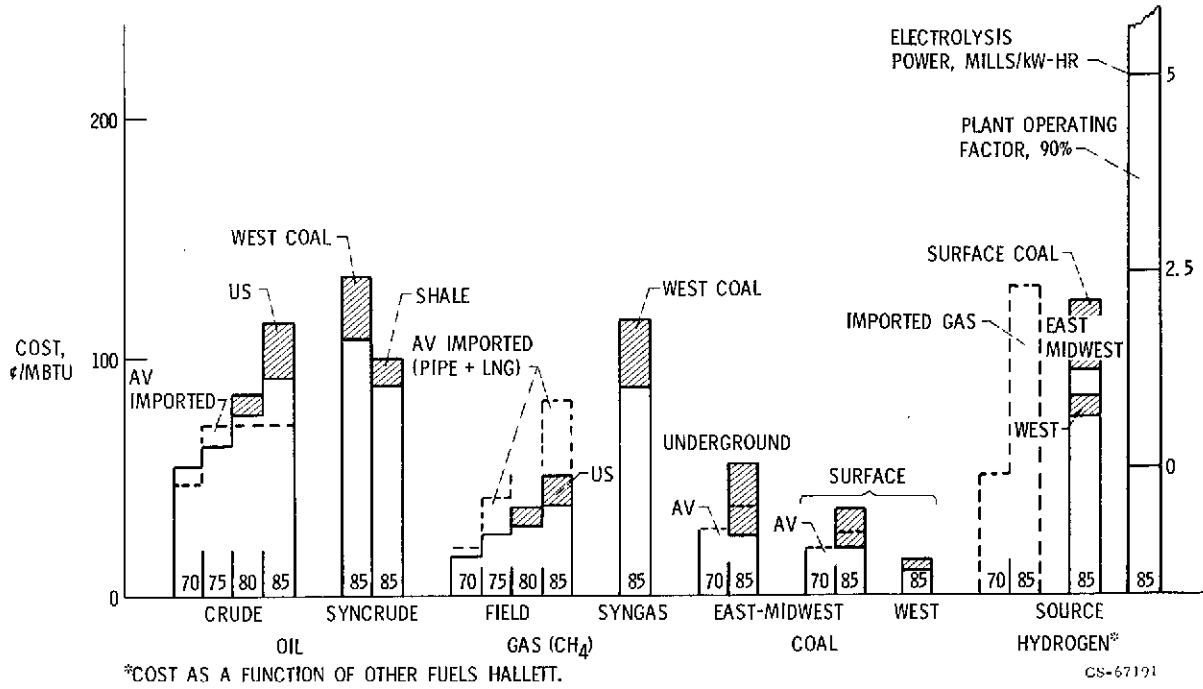


Figure 1.

ENERGY TRANSPORTATION COST

DISTANCE IN HUNDRED MILES INDICATED BOTTOM OF COLUMNS
 REF: HOTTEL & HOWARD EXCEPT AS NOTED

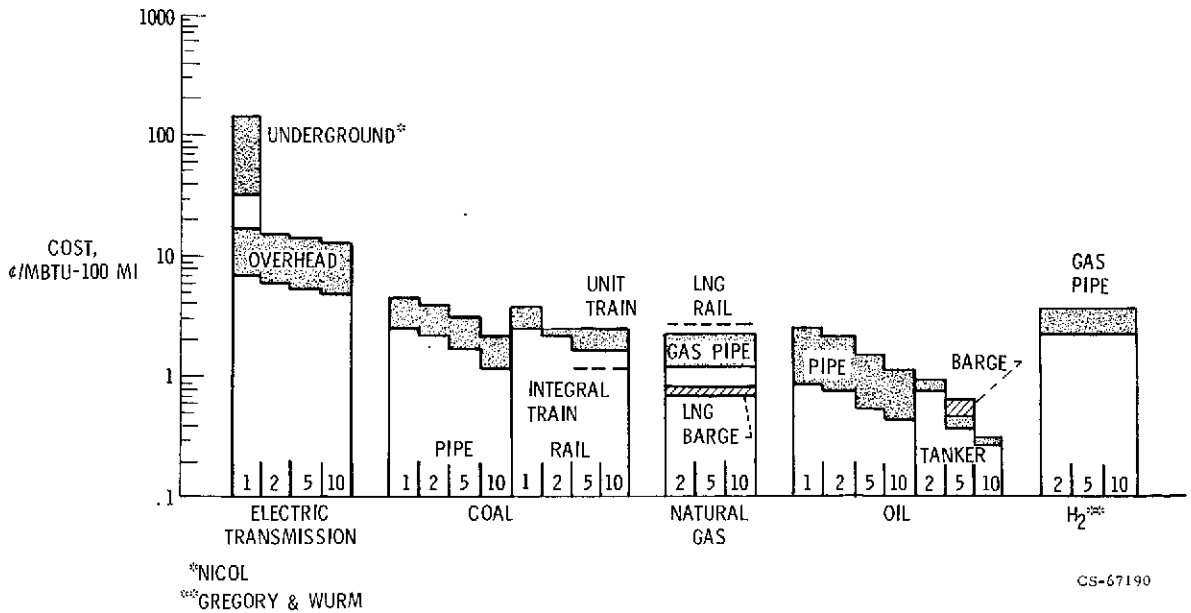


Figure 2.

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TOTAL COST AND COST OTHER THAN POWER TO PRODUCE HIGH PRESSURE GASEOUS OXYGEN

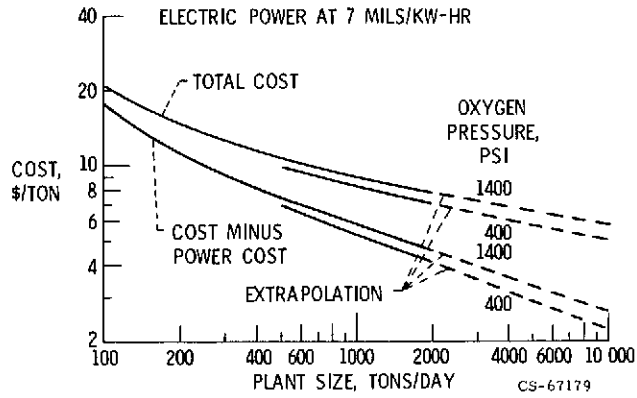


Figure 3.

POWER TO PRODUCE GASEOUS OXYGEN FROM AIR

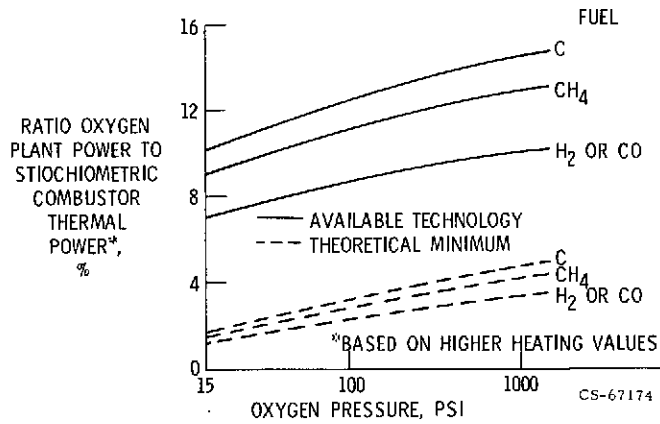


Figure 4.

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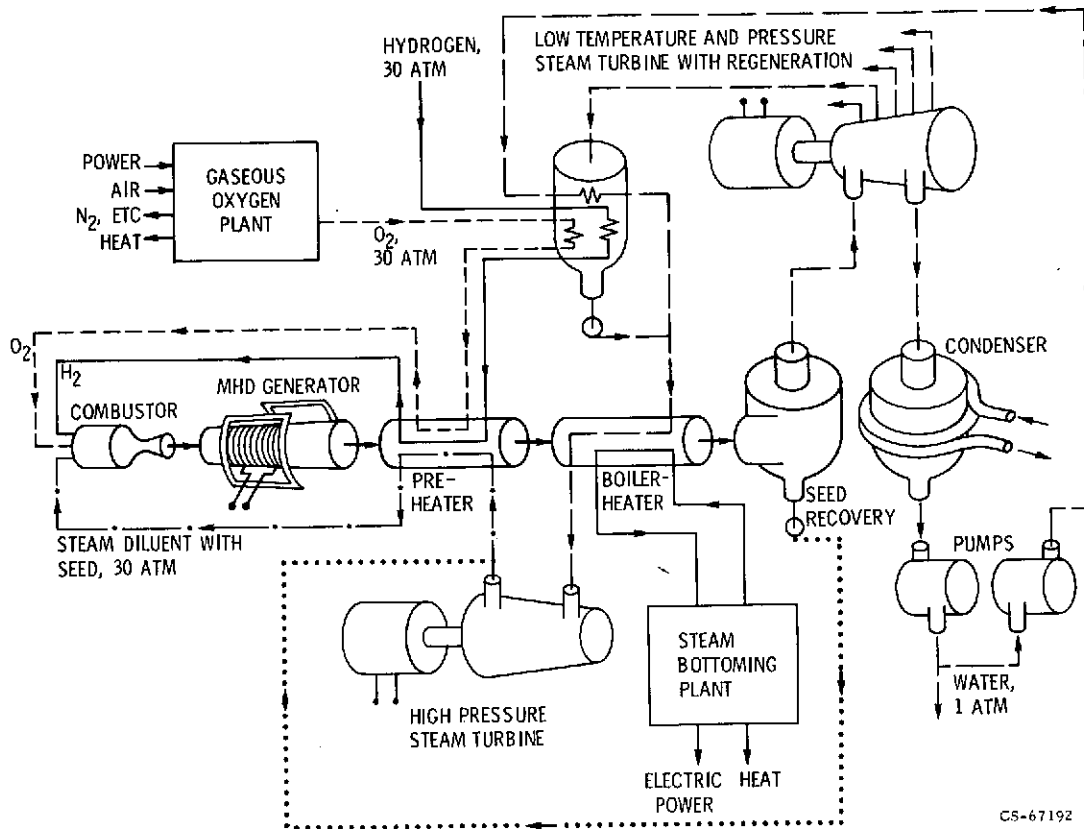


Figure 5. - H₂-O₂ Combustion steam MHD power plant.

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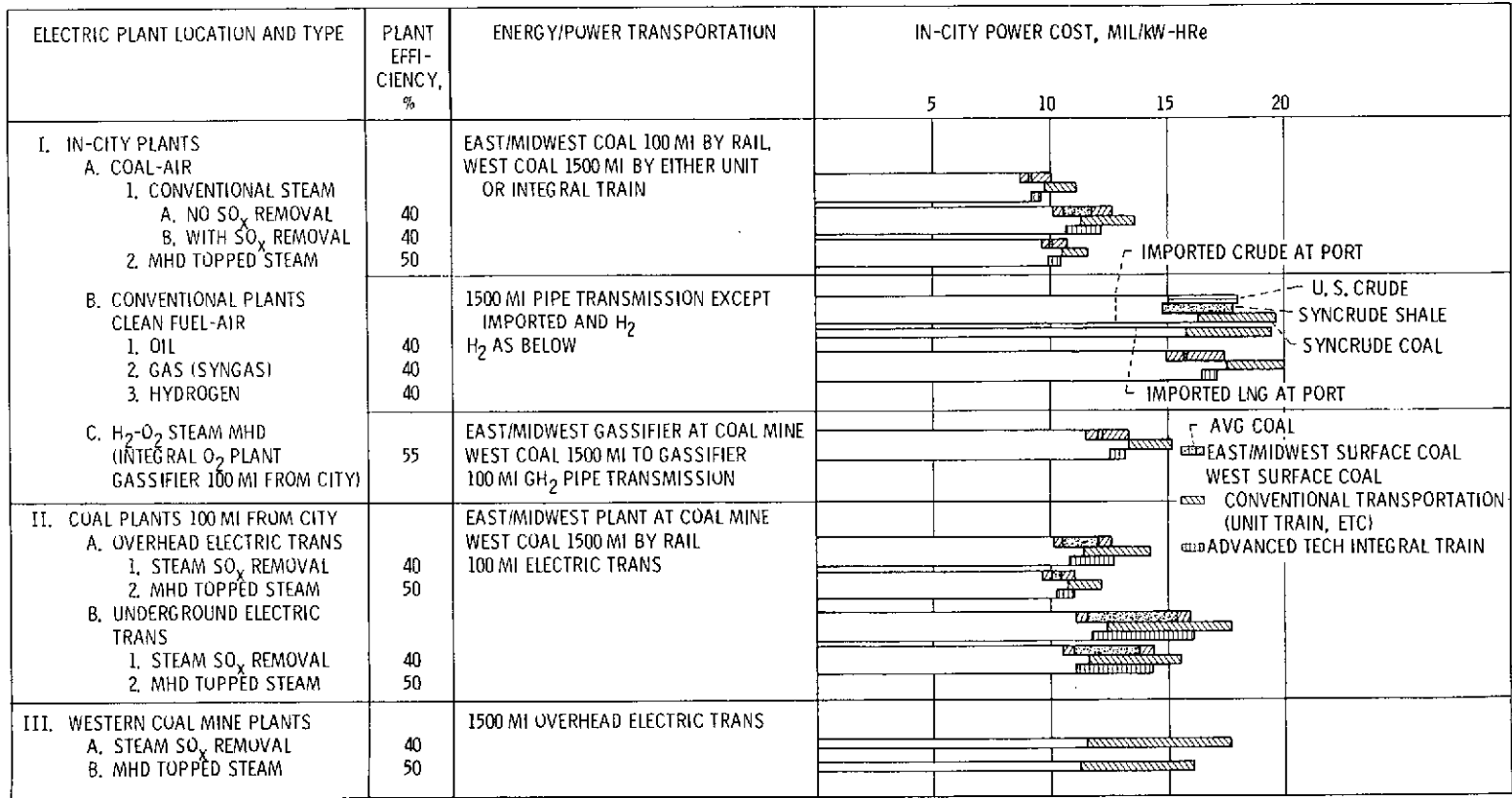


Figure 6. - Comparison of city power costs for various powerplant concepts.