ECONOMICS OF THE KOPPERS K-T GASIFICATION PROCESS FOR SYNTHETIC GAS AND CHEMICAL MANUFACTURE

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INTRODUCTION

The commercially proven Koppers K-T gasification process is employed for the gasification of coal and other carbonaceous fuels to produce a carbon monoxide and hydrogen rich gas. The process involves the entrainment reaction of the fuel with oxygen and steam at high temperature.

Since 1952 a total of 39 gasifiers have been installed at 13 locations in the Eastern Hemisphere. An additional plant at Talcher, India, is scheduled for start-up sometime during 1978. Almost exclusively the plants have been utilized for the production of ammonia from coal. However, the latest commissioned plant in Modderfontein, South Africa, produces 65 metric tons per day of methanol as well as 1000 metric tons per day of anhydrous ammonia.

Inherent features of the K-T process result in the production of a gas which is extremely well suited for chemical synthesis applications. These favorable characteristics of the gas include:

- Tars, phenols, and other condensible hydrocarbons are totally absent from the raw gas. Aside from the obvious environmental advantages of this feature, problems are avoided with gas purification and with catalytic processing of the gas.

- The gas typically contains 85-90 volume percent (dry basis) carbon monoxide plus hydrogen. The third principal constituent is carbon dioxide which, of course, is recoverable or otherwise does not interfere in chemical processing. Sulfur in the fuel is converted predominantly to hydrogen sulfide and carbonyl sulfide, both of which are readily recoverable from the gas. Inert compounds, such as nitrogen and argon, are typically present at only 1 volume percent (dry basis).

- Negligible methane is produced, thus avoiding the need for employing costly steam reforming in applications such as hydrogen or ammonia production.

- The gas can alternatively or simultaneously be employed as an excellent industrial fuel gas, thereby adding to versatility in operation.

- Unlike natural gas, hydrogen to carbon monoxide ratios of 1:1 or lower are readily obtainable without the need for external utilization of excess hydrogen or importation or carbon dioxide. This feature can make the K-T process more practically suited than natural gas for growing applications in oxo-synthesis, methanol production, or Fischer-Tropsch technology.

An additional major advantage to the process is its ability to handle a variety of feedstocks, including all ranks of coal, char and petroleum coke. In addition, liquid feedstocks, such as heavy residuals or tars, can be processed. This advantage is important in contracting for an economical fuel supply or in switching to alternate fuels during the life of the plant. Presently designed units can process a maximum of 850 tons per day of solid carbonaceous fuel.

PROCESS DESCRIPTION

For the sake of brevity and due to the fact that many people are now reasonably familiar with the basic features of the K-T process very little discussion herein is made on the process description. Further information and performance data can be found in other Koppers publications.

The gasifier employs the low pressure partial oxidation of pulverized coal in suspension with oxygen and steam. Reaction temperature ranges from 3500°F at the burners to 2700°F at the gasifier outlet. The gasifier is a steam-jacketed, refractory lined carbon steel vessel. A four-headed gasifier employs four burner assemblies situated 90° apart, while a two-headed gasifier employs a pair of burner assemblies located 180° apart. Characteristically, the gas produced contains 50-55% carbon monoxide and 30-35% hydrogen, both on a dry basis. Carbon dioxide, sulfur compounds (H_2S and COS), and nitrogen principally make up the balance.

Heat is recovered from the gas leaving the gasifier by means of a waste heat boiler where up to 1500 psig saturated steam is generated. Gas from the waste heat boiler is scrubbed of particulates and is then compressed as necessary for the intended application. Sulfur compounds are removed from the gas and ultimately converted to sulfur by a variety of means which are selected based on gas application.

GENERAL ECONOMIC CONSIDERATIONS FOR COAL GASIFICATION

While it is not the intent of this paper to compare the K-T process to competitive coal gasification processes, it is safe to conclude that all applications of coal gasification will be more expensive than presently available sources of oil and natural gas. Paradoxically, however, there is growing evidence that the cost of coal gasification is similar, if not less, than the cost of developing some new sources of natural gas. The high cost of new natural gas today tends to be disguised by the lower cost of old gas production. This situation is gradually shifting with the advent of the fuel cost adjustment and of course the situation will be dramatically changed with inevitable gas deregulation. However, with gas from coal there are presently few well-defined institutional mechanisms for equitably distributing the cost. Consequently there is reluctance from private sectors to invest in coal gasification.

Synthesis gas is presently produced by reforming natural gas or by partial oxidation of oil. It is strictly a matter of time before the supply situation or governmental policy will restrict or prohibit such use of natural gas. Earlier emphasis on coal gasification was directed toward SNG, or high methane content gas. However, it often is illogical to produce SNG whenever industrial users are still reforming or burning natural gas. Thus, the production of CO-H_2 rich gas for industrial use is being favored as a more efficient and economical approach to coal gasification. In addition to the many synthesis gas applications, this gas has excellent properties as an industrial fuel.

Table 1 compares the investment of a fully integrated Koppers K-T plant producing intermediate btu fuel gas with investment required for several projects involving production of natural gas, SNG, and electricity. The K-T fuel gas plant would deliver 140 billion btus per day of 300 btu per cubic foot gas (intermediate Btu gas) at elevated pressure to a number of industrial users.

Although the actual costs of some of the new natural gas or SNG projects can be debated, the intent of presenting the table is merely to indicate that the costs of new sources of gas are much higher than in the past. Furthermore it is apparent that production of intermediate btu gas should be regarded as an equally viable venture. All of the efforts by the gas industry to increase production are important, and there are many areas such as residential markets, where methane is difficult to replace. Industrial fuel or synthesis gas production will ease the burden of supply. Presently industrial usage accounts for over 60% of natural gas consumption.

TABLE 1

Example of Capital Requirements for Gas Production

	Production Billion Btu/Day	Investment $MM 1977	1977 Investment $/Annual MM Btu
Current Embedded Investment in Gas Industry	58,900 (21.5 TCF/yr.)	52,000 1/	2.40
SNG from Liquids	60 (60 MM SCF/Day)	56.7 1/	2.85
LNG Imports (includes foreign investment)	1,000 (365 BCF/Yr.)	4,150 1/	11.35
Alaska Natural Gas Pipeline	2,400 (2.4 BCF/Day)	10,000 2/	11.40
SNG from Coal	250 (250 MM SCF/Day)	1,370 1/	16.60
Heat from Electricity (Nuclear Power)	---	($1,250/kw)	41.80
Intermediate Btu (300 btu/scf) Fuel Gas from Fully Integrated Koppers K-T plant	140	390	8.45

Table 2 presents examples of projected prices of intermediate btu gas with costs of existing natural gas and projected costs of new sources of natural gas. Again, cost of intermediate btu gas from coal compares favorably with the projected prices of new gas.

TABLE 2

Example of Gas Prices

	$/MM Btu (HHV), 1978
Present Natural Gas (Industrial)	2.00 - 2.50 3/
LNG (Existing Massachusetts Terminal)	2.37 4/
LNG (Current Applications for Import)	3.00 - 4.50 4/
Gas from Alaska Natural Gas Pipeline	3.65 - 5.35 5/
SNG from Coal	4.10 - 7.10 6/
Heat from electricity @ 2¢/kw - hr	5.85
@ 4.5¢/kw - hr	13.15
Intermediate Btu Fuel Gas from Fully Integrated Koppers K-T Plant (60% debt financing)	
- with coal @ $15/ton (64¢/MM Btu)	3.35
- with coal @ $30/ton ($1.28/MM Btu)	4.50

In cases where gas is employed for synthesis applications it is important to recognize that natural gas or SNG must be first reformed, which is not a cost requirement for the intermediate btu gas. In the case of a fully integrated, free-standing ammonia plant, about 15% more natural gas (HHV basis) is required than intermediate btu gas, as shown in Table 3.

TABLE 3

Btu Requirement Per Ton of Ammonia

Basis: Gas supplied to ammonia plant battery limits at 500 psig.

(MM Btu/Ton NH_3)	Natural Gas	Intermediate Btu Gas
Synthesis Gas Required *	18.5	23.6
Fuel Requirements:		
Reforming	9.7	---
Utility Support	10.1	8.8
Tail Gas Credit	-1.8	-1.3
Net Fuel Required	18.0	7.5
Total Gas Required	36.5	31.1

* Based on 97% reforming of methane; 94.5% conversion of H_2 to NH_3.

Table 4 shows that for a fully integrated methanol plant over 20% more natural gas is required than intermediate btu gas. Table 4 is based on 95% reforming of methane and does not employ CO_2 addition from an external source. Conversion of CO and CO_2 is 95% within the synthesis loop.

TABLE 4

Btu Requirement Per Ton of Methanol

Basis: Gas supplied to methanol plant battery limits at 500 psig.

(MM Btu/Ton Methanol)	Natural Gas	Intermediate Btu Gas
Synthesis Gas Required	26.0	24.9
Fuel Requirements:		
Reforming	13.3	0.0
Utility Support	0.0	0.8
Tail Gas Credit	-9.9	-1.9
Net Fuel Required	3.4	-1.1
Total Feedstock Required	29.4	23.8

An important, yet often overlooked, advantage of coal gasification is that the mining of coal can be performed with relatively stable capital productivity. This means that once a mine is opened a relatively uniform output of coal can be maintained over the economic life, particularly in view of the fact that coal deposits are well identified. On the other hand, oil and natural gas production is usually characterized by declining capital productivity. For instance, as well head pressure begins to fall, output declines until a point is reached where additional investment is required for secondary or tertiary recovery methods. Thus, capital cost per unit of output tends to increase significantly during the economic life of oil and gas production. This is a major reason why the cost of coal mining is expected to be less subject to price escalation than with natural gas production, particularly in cases where the mine is captively associated with the gasification plant. Of course, coal mining is more labor intensive, although this is less of a case with newer mines or strip mines. The effects of inflation are briefly discussed later in this paper.

FUEL CHARACTERISTICS OF K-T GAS

The K-T gas has excellent fuel characteristics, and is well suited for industrial applications as a so-called "intermediate" btu gas. A more detailed discussion of gas combustion properties can be found in other Koppers' papers. However, the most basic fuel characteristics are herein presented.

In comparison to natural gas, the nominal 300 btu/scf heating value of K-T gas necessitates an increased volumetric usage of fuel for a given heat duty. However, the air required for combustion of K-T gas is substantially reduced. As a consequence, the weight of combustion products is comparable to that produced upon combustion of the more conventional fuels. Table 5 compares overall firing characteristics of a furnace at typical levels of excess air for coal, fuel oil, natural gas, and K-T gas. For this example the K-T gas is humid and supplied at low pressure. Schemes are available for drying the gas if desired.

TABLE 5

Overall Furnace Performance

	Coal WT. %		No. 6 Fuel Oil WT. %		Natural Gas VOL. %		K-T Gas VOL. %
C	70.5	C	87.8	CH_4	83.0	CO	50.7
H	5.0	H	11.0	C_2H_6	16.0	CO_2	7.8
N	1.3	N	0.2	CO_2	0.5	H_2	34.5
S	2.5	S	0.5	N_2	0.5	N_2+Ar	1.2
O	7.5	O	0.5			H_2S+COS	0.1
Ash	10.1	Ash	Nil		100.0	H_2O	5.7
H_2O	3.1	H_2O	Nil				
							100.0
	100.0		100.0				

Gross Heating Value, Btu/Lb	12,809	18,500	---	---
Btu/Scf	---	---	1,128	277
Typical % Excess Air Used	15	5	10	15
Lb. Air Used/MM Gross Btu (60°F wet bulb)	867	793	792	653
Lb. Combustion Gas/MM Gross Btu	937	847	835	840

In retrofitting an alternate fuel to an existing furnace or boiler, the permissible draft loss is ordinarily a limiting consideration. Since K-T gas yields a favorable amount of combustion gas per unit of heat input there are minimal restrictions in retrofitting existing equipment. In addition, use of K-T gas results in a unit efficiency comparable, and often better, than that of more conventional fuels.

The K-T gas offers these additional fuel advantages to the chemical process industry:

- Equilibrium adiabatic flame temperature of the K-T gas with ambient temperature air is approximately 3750°F, compared to typically 3550°F for natural gas. This is important in high temperature processes, such as those involving radiant tube burners.

- The gas can be completely desulfurized and is free of ash constituents or alkali metals. This advantage is particularly important in certain chemical process applications such as firing of Dowtherm boilers, where oil often cannot be used due to its ash, sulfur, or vanadium content.

- The wide flammability limits of the gas promote good combustion efficiency and permit safe control of combustion temperature by use of a relatively high amount of excess air. The wide flammability limits permit reduced nitrogen oxide emissions by means of staged combustor firing.

- The versatile K-T fuel gas can be used as a fuel or as a synthesis gas, without the necessity of a reforming operation.

Within most industries, a reliable fuel supply is important. The K-T process has a proven history of reliability. Gasifier outages, such as those which occur during annual plant turn around, can be compensated by use of spare gasifier capacity or by the temporary use of alternate fuels. If natural gas is used as a back-up fuel, systems can be designed whereby air-ballasted natural gas is automatically used without necessitating burner alterations.

ECONOMICS FOR FUEL GAS OR SYNTHESIS GAS PRODUCTION

It is difficult to generalize the economics of producing synthesis gas from coal since costs are greatly influenced by a number of variables which are specific to each application. These variables include site selection, plant size, availability of off-site facilities, and cost of coal. In addition, specific financing variables such as capital structure, rate of return, and interest rates affect gas cost.

As an example of synthesis gas costs, a case is presented for a large plant which produces gas at 170 psig for delivery to industrial customers within a 100 mile radius. The plant consists of fifteen four-headed gasifiers, including one spare, to produce a net output of 140 billion btus per day (HHV) of gas with a gross heating value of 300 Btu/scf. Raw material for the plant consists of 9700 tons per day of 2" x 0" bituminous coal, with 5.7 wt. % moisture content and gross heating value of 11,810 Btu/lb. Gas is desulfurized and dried to a -18°F dew point before entering the distribution system. The plant satisfies its own utility requirements, except for 94 megawatts of imported electricity, by combustion of a portion of gas within an auxiliary boiler. The plant is a "grass-roots" plant and all general facilities and coal handling facilities are included.

Plant investment (mid 1978) would be about $410 MM, while total capital requirements would amount to about $510 MM. The total capital includes the plant investment plus interest during construction, start-up costs, and working capital (60 day cash supply).

Figure 1 is based on this plant and shows the effect of coal cost on gas cost for a debt to equity ratio of 60/40 and a 12 percent discounted cash flow rate of return. The cash flow method of analysis is representative of private investor financing. Figure 2 illustrates the effect of capital structure, or fraction of debt, on gas cost for a coal cost of $22.50/ton (95¢ per MM Btu). Project life is 20 years, with a 10 year (sum of years digits) depreciation schedule. Federal income taxes are taken as 48%. Debt is retired over the 20 year life of the project by a series of annual payments.

APPLICATIONS OF K-T GAS FOR CHEMICAL SYNTHESIS

Generally, there are three categories of chemical synthesis applications of the gas, either for captive or merchant markets. These are:

- Hydrogen Production
- $CO-H_2$ Based Synthesis
- CO Production

Hydrogen Production

The major present commercial use of hydrogen is in captive markets, that is, those areas where the hydrogen is used integrally with the process. Principally this market relates to ammonia production or petroleum refining applications, such as hydrodesulfurization or hydrocracking. Ammonia is, of course, the base material for such important chemicals as caprolactam, acrylonitrile, urea (and resins thereof), nitric acid, and fertilizers.

An important growing captive use for hydrogen will be in the area of coal liquefaction. In typical liquefaction processes hydrogen is generated by gasifying char or residue which is recovered in the processes. In 1975 the K-T process was successfully used to gasify FMC-COED char during tests in Spain. With residue type feedstock the K-T process is well suited for accommodating the high ash content characteristic of such residues.

$CO-H_2$ Based Synthesis

This application is based on direct synthesis of chemicals from the $CO-H_2$ gas. This use is of particular interest to the chemical industry due to the wide range of valuable products which can be made. It is particularly encouraging to observe the progress which is being made in $CO-H_2$ synthesis technology, especially in regard to catalyst improvements which permit improved yields and reduced synthesis pressures.

The modern schemes of synthesis generally require, stoiciometrically, at least a 1:1 ratio of H_2 to CO, as for example in various oxo-synthesis processes. Higher ratios are required in other applications, such as in methanol of Fischer-Tropsch synthesis, where a 2:1 ratio of H_2 to CO is required. Since K-T gas from coal has initially a H_2:CO ratio of typically 0.6, it is straightforward to obtain increased ratios by merely shifting a portion of the gas. On the other hand, reformed natural gas has a 3.0:1 to 4.0:1 ratio of hydrogen to carbon oxides. Thus, to comply stoiciometrically with certain synthesis applications it is necessary with natural gas based $CO-H_2$ to remove or otherwise utilize as fuel the excess hydrogen in tail gas. Conversely, CO to CO_2 could be added somewhere in the process schemes. Hence at times the practicality, cost, or energy involved in synthesis based on natural gas can be restrictive.

Methanol from coal is being considered for use as a direct fuel. Methanol has the advantage of being easily stored. Present economics do not justify the use of methanol as a fuel unless coal is inexpensive. With coal at $10 per ton, methanol by the K-T process would cost 35-55¢ per gallon depending on plant financing and other factors. Methanol also has traditional important chemical applications, such as, in the production of formaldehyde, methyl methacrylate, acetic acid, and isoprene rubber. Mobil Oil Corporation is developing a process for production of gasoline from methanol. Additional technology is under development for production of olefins, such as propylene, from methanol. These olefins can be used in oxo-synthesis. Oxo-synthesis is the process whereby aldehydes and other oxygenated compounds are produced by catalytic reactions of CO and H_2 with olefins. Products include paints, laquers, butyraldehyde, detergents, solvents, and plasticizers. Recent developments in oxo-synthesis technology by Union Carbide, Davy Power Gas and Johnson Matthey have led to practical use of low pressure technology and improved catalyst selectivity for at least one application (butyraldehyde).

CO Production

For carbon monoxide production the K-T gas is well suited due to its high CO content. Pure CO can be produced from the gas either cryogenically or by selective absorption methods such as the Cosorb process developed by Tenneco Chemicals, Inc. Recent developments in CO recovery technology are expected to greatly increase markets for CO. A major market for CO lies in direct ore reduction. Chemical synthesis applications include phosgene, toluene diisocyanate, and synthetic acids. Developments are aimed at extending CO use to production of terephthalic acid and p-cresol, and to use it as a co-monomer in thermoplastics.

ECONOMICS FOR ANHYDROUS AMMONIA PRODUCTION

An example of costs for anhydrous ammonia is given for a 2000 ton per day plant. The plant is completely integrated and includes coal receiving facilities and all general facilities, except raw water treatment. Four 4-headed gasifiers are used and no spare gasification capacity is provided. A total of 2845 tons per day of as-received bituminous coal is required for gasification. Additional coal is used for firing an auxiliary boiler to meet all plant utility requirements, except for the importation of about 17.5 megawatts of electricity. Coal is the same as that used in the economics of synthesis gas discussed previously. Flue gas from the auxiliary boiler is treated (Wellman-Lord Process) with recovered SO_2 sent to the Claus plant, along with H_2S from the gasification portion of the plant. Plant investment (mid 1978) is approximately $250 MM, while total capital is about $310 MM.

Figure 3 illustrates the effect of coal cost on ammonia selling price. Bases are representative for private financing and include:

- 12% Return on equity
- 9% Interest on debt
- 60/40 Debt to equity ratio
- 10 Year depreciation (sum of years digits)
- 20 Year debt retirement (annual payments)
- 48% Federal income tax.

Figure 4 shows the effect of capital structure, i.e., the extent of debt financing on ammonia price. All coal conversion processes are capital intensive, and it will probably be necessary to adopt non-conventional methods of financing to make coal derived products more competitive with those from oil and natural gas. Many of the recent discussions concerning synfuel projects have, therefore, touched upon concepts such as government loan guarantees, leveraged-leasing arrangements, tax free bonds, and even 100% government ownership as a means of reducing the financial burden of synfuel energy cost.

ECONOMICS OF HYDROGEN PRODUCTION

The economics of hydrogen are briefly discussed here since a more thorough discussion appears in a recent Koppers Company presentation.[7/] Table 6 presents a summary of hydrogen cost whenever bituminous coal cost is $20 per ton (81¢ per million btu).

TABLE 6

Cost of Producing 100 MMSCFD of Hydrogen

	Battery Limits Plant	Fully Integrated Plant
Plant Investment, $MM	185.0	288.0
Total Capital, $MM	229.0	352.5
Selling Price,		
¢/MSCF	1.79	2.27
$/Million Btu (HHV)	5.50	7.00

Bases for cost estimation include 75% debt at 9% interest rate and 25% equity at 12% discounted cash flow rate of return over the 20 year project life.

Hydrogen produced is 97.4 vol. % purity and is available at 500 psig. The principal impurities consist of methane, nitrogen, and argon. Residual carbon monoxide is about 5 ppmv, while molecular sieves are employed to control total carbon dioxide and water content at about 3 ppmv. Technology exists for producing 99.9 + vol. % hydrogen, however, the cost of so doing would be higher than those shown above.

Again, as is characteristic of a capital intensive project the extent of debt financing has an important effect. For instance, when producing hydrogen within a battery limits plant, costs would rise sharply from $5.50/million Btu (see Table 6) to $7.45/million Btu whenever 25% equity financing is replaced by 100% equity financing at 12% discounted cash flow rate of return.

EFFECTS OF INFLATION

In today's inflation dominated economy any cost analysis is incomplete unless the projection of future energy prices is considered. Long term predictions of energy cost are difficult to make, however, it is certain that costs will continue to climb. It is likely in fact that energy costs will be a major contributor to inflationary forces, and hence it would not be surprising if the rate of price escalation of conventional fuels becomes higher than the general inflation rate.

There are a number of reasons why it is expected that costs for alternate fuels will escalate more rapidly than costs from a coal gasification plant, particularly in cases where the coal mine is captively associated with the gasification plant. These reasons include:

- Oil and gas production is characterized by declining capital productivity, whereas the mining of coal is much less subject to such declines.
- Present price regulations on oil and gas production are expected to eventually be eliminated or diminished to a point where oil or gas prices are more representative of true market forces. Inherently, the convenience of conventional fuels should command a much higher free market price than coal.
- Projects involving new oil and gas production are very costly, and some of these projects could in fact be more expensive than the coal gasification options.
- Price of coal is less directly influenced by foreign pricing.

Figure 5 illustrates how the cost of fuel gas or synthesis gas might compare to cost of No. 2 fuel oil over the 20 year plant life, whenever inflation or price escalation occurs at an average rate of 8 percent per year. The 1978 price of the oil was taken as 37.2¢/gal. ($2.65/MM Btu), which is the reported wholesale price of this commodity according to U.S. Department of Labor recent statistics. Price of coal was taken at $22.50 per ton (95¢ per million Btu). The fuel gas plant depicted in Figure 5 is the same large plant (140 billion Btu per day) for which economics were presented earlier in this paper.

Once the gasification plant is built the capital associated charges are not escalated. In determining future cost of gas from the K-T plant it was assumed that all operating costs are subjected to inflation, except for coal, where it was assumed that only about 60% of the coal cost is subject to inflation. This 60% value appears to be representative of non-capital associated costs (such as labor) which are involved in coal mining. Naturally if coal were purchased on the open market, rather than by long-term contract, the full cost of coal would demand escalation.

As Figure 5 illustrates, a point is reached (in this case at about nine years) where the cost of fuel oil exceeds the price of K-T gas. More thorough analysis involving different inflation rates has usually indicated that the average cost of K-T gas or the present worth cost of K-T gas turns out to be lower than the cost of alternate fuels over the 20 year period. This more detailed analysis is beyond the scope of this paper. As previously mentioned this type of long term analysis is difficult and the intent of presenting Figure 5 is merely to show relative effects of price escalation which are difficult to generalize, yet important to consider. The implication is that strictly from a cost standpoint there can be sound financial basis for present investment in a gasification plant.

FIGURE 1

EFFECT OF COAL COST ON GAS COST

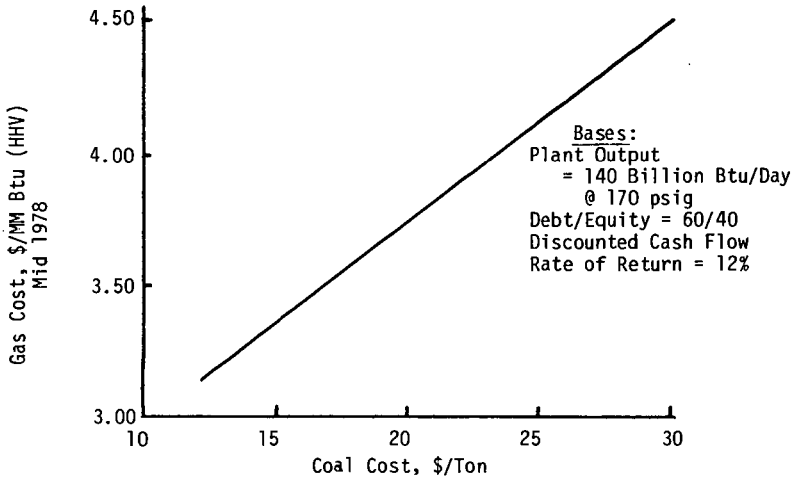


FIGURE 2

EFFECT OF CAPITAL STRUCTURE ON GAS COST

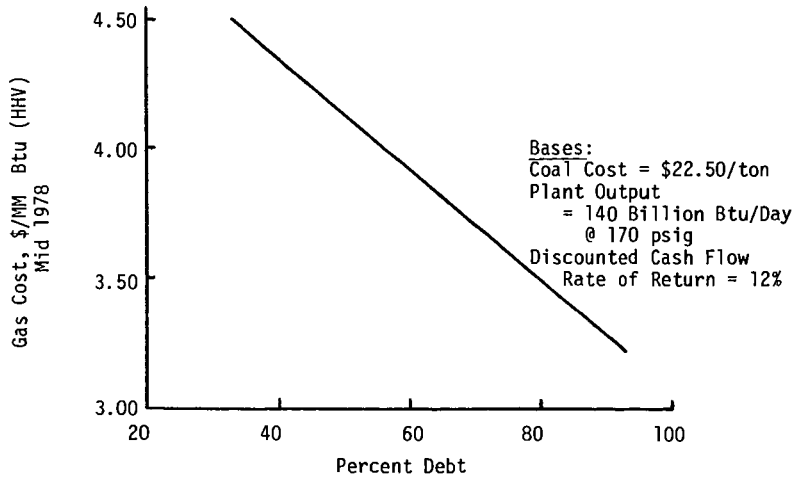


FIGURE 3

EFFECT OF COAL COST
ON AMMONIA COST

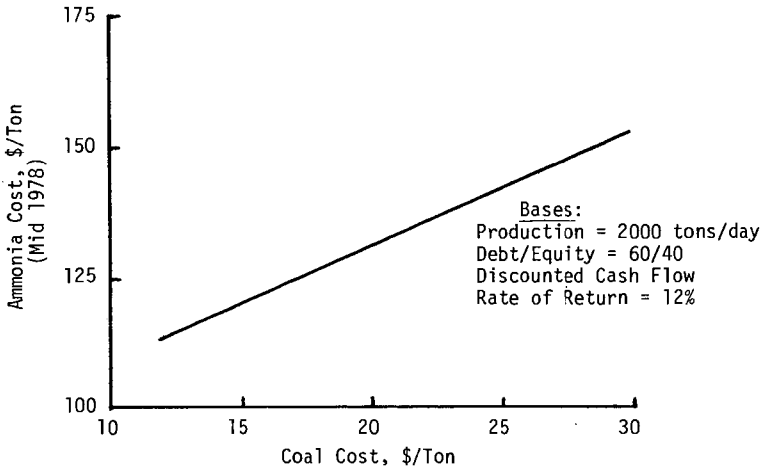


FIGURE 4

EFFECT OF CAPITAL
STRUCTURE ON AMMONIA COST

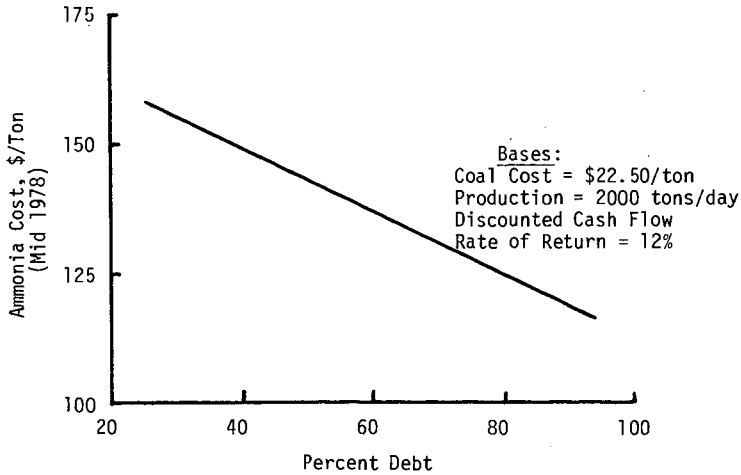
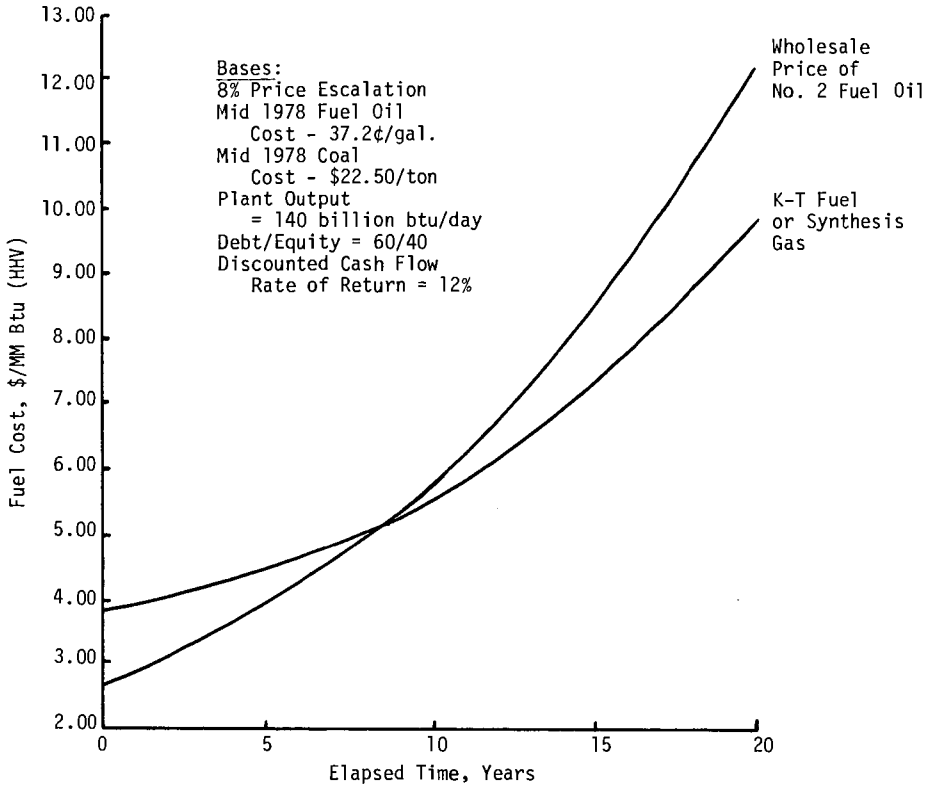


FIGURE 5

EFFECT OF PRICE ESCALATION
ON FUTURE FUEL COSTS



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