TECHNOLOGY ASSESSMENT AND DECISION-AID UTILITY ANALYSIS IN FOSSIL FUEL-TO-FUEL CONVERSION

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PREFACE

In dealing with energy shortage problems around the world, energy utilization is closely related to technological development of fossil fuel-to-fuel conversion processes which provide alternatives to petroleum. Among the fossil fuel-to-fuel processes, several processes of making synthetic gas and oil from coal have been developed by several agencies. These processes are characterized by competitiveness and substitutability of diversified technologies in the same research and development area, and they have many deleterious effects on society, such as, resource exhaustion and environmental pollution. Thus alternative processes of technologies and their effects on human society should be examined and compared not only from the economic but from various social points of view as well. Thus, we propose the sociotechnique (SOTEC) concept for selecting the appropriate technology to the existing society.

To solve the Complex Problematique to which the SOTEC concept corresponds is a multicriteria problem. IIASA's System and Decision Sciences Area has recognized the neccessity of coping with the multicriteria problem. This study is going on at IIASA and at Kyoto as one of several cooperative studies. This paper can be seen as a preliminary and modest contribution in this direction. The results were presented at IFAC Symposium on Criteria for Selecting Appropriate Technologies under Different Cultural, Technical, and Social Conditions, May 21-23. 1979, Bari, Italy.

Technology Assessment and Decision Aid Utility Analysis in Fossil Fuel-to-Fuel Conversion

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I. INTRODUCTION

Recent research at MIT has pointed out that because utilization of natural gas in place of petroleum has been increasing, future energy demands will produce a serious shortage of natural gas itself if recent trends in natural gas use (e.g. 6% per year rate of increase in the U.S.) persist. On the other hand, new technologies for nuclear power and solar energy utilization have not yet been developed with acceptable levels of feasibility. In consequence, research and development of synthetic gas and oil produced by gasifying or liquefying coal has recently attracted increasing attention. The purpose of this paper, mainly based on the study by the MIT group (Hottel and Howard [1]), is to propose a methodology for selecting appropriate technologies for substitute-energy development under different resource and social conditions.

Methodology for technology assessment (T.A.) for choosing the most desirable processes among alternatives has not been well developed yet. Technology assessment is multiobjective.

The criteria of evaluation are noncommensurate and they are also often in conflict with each other. And the effects of alternative processes are still under uncertainty. Thus, we are concerned with establishing quantitatively the magnitudes of comprehensive profitability for choosing technological processes under these circumstances.

Technology assessment has two aspects. One is the necessity of examining technologies or processes not only technically but in the context of resource endowment, existing economic and social conditions and external (or environmental) effects. Thus, technology assessment is considered to be combined with location problems involved with technology choice.

In regional science, industrial-complex analysis has been devoted to identifying specific combinations of industrial activities for which one region is more favorable than another. (Isard, Schooler and Vietorisz [2]). Here the criterion of choice is exclusively locational advantages based on cost-revenue differentials as a result of resource endowment and economic development.

In contrast to industrial complex analysis, our method is based on the socio-technique complex (SOTEC) concept for technology assessment. In this concept, the economic advantage of spatial juxtaposition of substitute-energy processes with other industrial activities is not necessarily taken into consideration. Instead the stress is placed on the property of the object, an appropriate-technology development problem, as a complex problematique.

Another aspect of technology assessment is that development of expected technological processes is still under uncertainty. An empirical data base for evaluating alternative processes has not been well established yet, and conditions surrounding the technological development yield to unpredicted changes. Thus assessing preference for technology choice of alternative processes is a decision problem under uncertainty.

Decision analysis developed by Raiffa([3]), Schlaifer ([4]) and Platt([5][6]) presents a method for assessing the preference of the decision-maker for possible consequences of human actions, and for scaling his judgements concerning the chance of possible events. The utility concept is utilized for numerical presentation of his preference in a commensurated term. The expected-utility-maximization principle is used as the criterion for selecting alternative technological processes. The MANECON collection of computer programs for use on a time-sharing system is available to perform these evaluations. (Schlaifer [7])

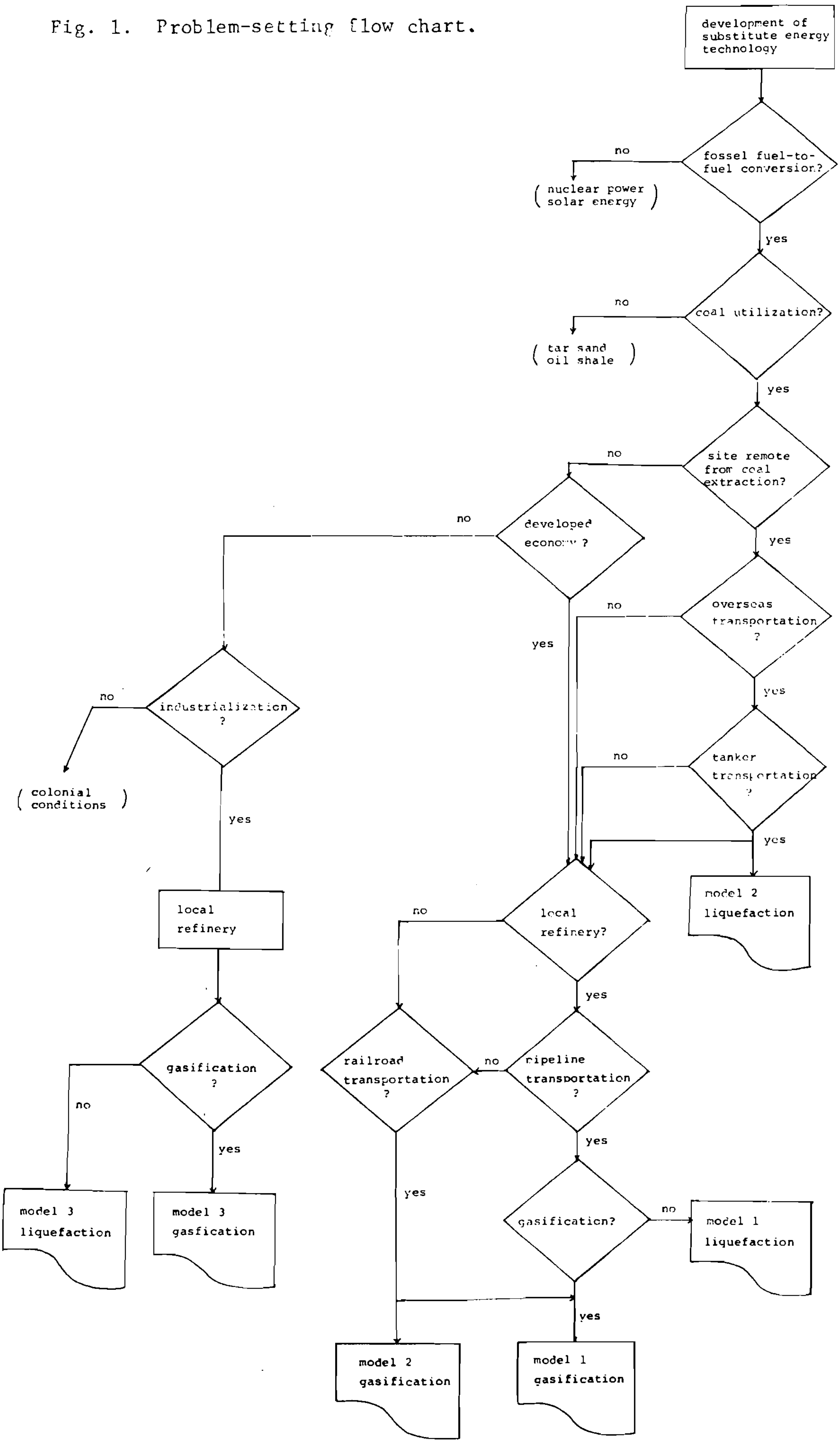
Considering these characteristics of technology assessment and referring to the above-mentioned methodologies, in this paper a modified decision-analysis device for selecting appropriate technologies under different economic and social conditions is applied to the MIT data.

II. PROBLEM SETTING AND METHODOLOGY

The fossil fuel-to-fuel conversion problem is combined with a complex of resource endowment, transportation facilities, industrial/societal conditions. The structure of the complex problematique is described sequentially in a decision-making flow-chart. In the terminal situation of the decision diagram, different types of the model can be discerned.(Fig.1) In model 1, the society has rich fossil fuel resources and has been highly industrialized. Thus this society has existing pipeline transportation facilities for liquefied natural gas. In model 2, the society has scarce natural resources and largely depends on overseas transportation from fossil fuel producing countries. On the other hand, this society has highly developed heavy-chemical industries and a great deal of substitute-energy demand; thus it is well-experienced in tanker transportation. In model 3, the society has plentiful coal resources but they have not been highly developed yet. However, if it does not desire to return to a colonial situation, industrialization must be the main object of economic policies. A typical society of model 1(M1) is the U.S.A.. Model 2(M2) is Japan and model 3(M3) is a society like South Africa or Australia which has large unknown possibilities for development.

In these models, decision-making is under uncertainty: even the resources-endowment conditions can be changed by unpredicted discovery of new mines. Marine transportation routes will not only be compelled to change for international political reasons but surface transportation may also suffer from deterioration of international relationships. Economic/societal conditions are greatly changed by political alteration. The uncertainties included in each model are taken into consideration as "risk" in assessing the preference of the model.

Fig. 1. Problem-setting flow chart.



A menu of alternative technological processes for gasification and liquefaction of coal is shown in Table 1. The characteristics of these processes are described in Table 2. The research and development of these alternative technologies in the future is also under uncertainty. Forecasting technological development includes many unpredictable factors. Such uncertain elements are considered in scaling the judgemental probabilities for each process.

The procedure for assessing the desirability of the alternative processes is as follows.

First, basic data for assessing each technological process is formed in quantitative terms. At this time the characteristics of the original data require some modifications of the device. One is that numerical information in comparable forms for the assessment is rarely obtainable from original data, and thus the subjective scale for non-quantified data must be utilized instead of the objective scale for quantified data. Another modification is that, because the data is composed of random variables, this property of the attribute of each process to be assessed is taken into account in calculating the expected utilities at a subsequent stage.

Second, a utility function of coal gasification and liquefaction for each model is assessed. The utility functions with decreasing positive risk aversion are fitted by the MANECON computer program SUMEXFIT in the following form. The MANECON program SUMEXFIT can also calculate parameters of the nonnormalized preference functions.

TABLE 1 Menu of Alternative Processes for Substitute-energy Technologies from Coal

label	Process	characteristics (energy supply, etc.)
Gasification		
A1	Hygas-electrothermal(IGT)	electrothermal & hydrogasifier
A2	Molten Carbonate(Kellogg)	molten carbonate gasifier
B1	Bigas (BCR)	oxygen and steam
B2	Synthane (Bureau of mines)	oxygen and steam
C1	Hygas-oxygen (IGT)	oxgen and steam hydrogasifier
C2	Steam-Iron (IGT)	air and steam hydrogasifier use of iron oxide
C3	Hydrogasification (Bureau of mines)	air hydrogasifier
D	CO_2 Acceptor(CSG)	hot air use of dolomite
Liquefaction		
A	Solvent refining of coal (SRC) (CSC)	hydrogen
B	Consol process (HRI)	hydrogen use of zinc chloride catalyst
C	H-coal (HRI)	hydrogen use of cobalt molybdate catalyst
D	COED	oxygen and steam hydrogen
E	Solvolysis (KKS)	use of asphlt as solvent

TABLE 2 Comparison of Alternative Gasification Processess

	coal size	temperature of gasfier	pressure	methane yield		
				A	B	C
A1	1/8inch	1300~1500F 1700~1800F 1800~1900F	1000~1500psi	0.33	1.69	0.83
A2	12mesh	1830F 1900F	420psia	0.098	0.50	0.29
B1	200mesh	1400~1700F 2700~2800F	750~1500psi	0.21	1.04	0.52
B2	200mesh	750F 1100~1470F 1750~1850F	600~1000psi	0.18	0.79	0.55
C1	1/8inch	1300~1500F	1000~1500psi	no data		
C2	1/8inch	1300~1500F	1000~1500psi	0.25	1.27	0.64
C3	50X100mesh	1650F	1000psi	0.50	2.90	0.95
D	1/4 to 1/8 inch (lignite)	1500F	140psia 300psia	0.16	0.90	0.46

source: Hottel and Howard, New Energy Technology

note: All based on feed of Illinois No. 6 coal, except CSG(Renner Cove Lignite), Molton Carbonate (Pittsburgh seam coal) and Bureau of Mines Hydrogasification (Pittsburg seam coal).
A=(Metane leaving gasifier)/(Carbon in solids feed stream to gasifier);
B=(Methane leaving gasifier)/(Methane-equivalent of hydrogen in coal);
C=(Methane leaving gasifier)/(Methane in final pipeline gas).

$$F(x) = -(e^{-ax} - 1) - c(e^{-bx} - 1) \qquad (1)$$

$$a > 0, \quad bc > 0$$

The normalized preference (utility) functions are obtained in the following form:

$$u(x) = \frac{F(x) - F(x_0)}{F(x_1) - F(x_0)} \qquad (2)$$

The local risk aversion function is

$$R(x) = \frac{-u''(x)}{u'(x)} = \frac{a^2 e^{-ax} + cb^2 e^{-bx}}{ae^{-ax} + cbe^{-bx}} \qquad (3)$$

The conditions $a > 0$ and $bc > 0$ guarantee that the risk aversion function is decreasing over $[-\infty, \infty]$. In addition, if b and c are positive, the risk-aversion function (3) is everywhere positive; if b and c are negative, the risk-aversion function is positive to the left of

$$x^* = \frac{1}{a - b} \log (-a^2/[b^2c]) \qquad (4)$$

are negative to the right of x^* where $R(x^*) = 0$. (Schlaifer [7]) Input data for depicting utility curves are derived by assessing certainty equivalents with 50-50 chance lottery techniques.

Third, a probability distribution $P(x)$ of the random variable x in each process is assessed with direct judgement. In fact the value x of the cumulative distribution function $P(x \leq \tilde{x})$ is assessed for several fractiles of the distribution. Using the MANECON program CDISPRI, continuous piecewise quadratic distributions are graphically printed in the form of the mass functions as well as cumulative functions. Characteristics of the distribution such as mean, standard deviation, and variance are also calculated.

Finally, expected value of utility for each process, $E[u(x)] = \int_0^1 p(x)\, u(x)\, dx$, is calculated with the MANECON program PREFEVAL. The numerical results for alternative processes are compared to each other within each model.

The MANECON program was interactively run under IBM CALL/370 with minor modifications. It was known that the computational works could be economically well done using this package.

III. DATA AND RESULTS

Data for items which characterize the coal gasification and liquefaction processes are shown in Table 3 and Table 4. The considerations for each process come from the MIT study above cited. Using these data along with ones in Table 1 and Table 2, the items for each process are examined altogether and are consolidated into one attribute for each process. Measures for the considerations summed up for each process are scaled with subjective judgement in the range of 0 to 10. The weighting for summing up the considerations is different according to the importance of each item for each process in each model.

TABLE 3 Data for Subjective Scale of Coal Gasification Processes

label	consideration	evaluation
A1	Highest noncatalytic methanation in gasifier of any process developed beyond bench-scale.	+ +
	Advanced pilot plants developed.	+
	Slurrying of fuel gives the reliable feed to high pressure system.	+
	Coal cost in price components is large(47.4%).	- (uncertainty)
	Coal preparation, hydrogasification and hydrogen costs requires large investment.	-
	Necessity of disposing of by-product char.	- (uncertainty)
	Electric energy need is economically questionable.	-
	Difficulties of pretreater temperature control.	- (uncertainty)
	Pretreating operation necessary to handle caking coal produces an extra gas stream and prevents making full use of the relatively high reactivity of fresh coal.	-
A2	Use of air instead of oxygen.	+
	Coal preparation costs less.	+
	Sodium carbonate has an advantageous catalytic effect on rate of solids gasification.	-
	Molten salt is very corrosive.	-
	Temperature of gasifier is too high for significant methanation.	-
	The lowest yield of methane.	-
	Energy loss for evolvement of carbon dioxide in conversion of bicarbonate to carbonate.	-
	Difficulties of process control.	-
	Sulfur and power production as by-products.	+ (uncertainty)
B1	Enough background of R & D (a result of a state-of-the art survey).	+
	Rapid gasification by entrained flow.	+
	Gasifier methanation is higher than other oxygen-blown processes.	+
	Temperature of reactor (cyclone gasification chamber) for steam-oxygen-char is much higher than in other processes with attendant higher thermal loss in slag.	-
	Lignite is available (low cost).	+
	Many unsolved or questionable technical aspects remain.	- (uncertainty)
B2	Direct use of caking coal(pretreatment cost is low).	+
	Concurrent flow at feed point minimizes loss of evolved hydrocarbons.	+
	Production of char stream as one of the final products.	- (uncertainty)
	Amount of catalytic methanation necessary is much higher than in hydrogasification processes.	-
	Many unsolved or questionable technical aspects remain.	-
	Coal cost is high (48.2%).	- (uncertainty)

label	consideration	evaluation
C1	Input of oxygen into a separate reactor requires considerably less oxygen than in class B processes which add it directly to the gasifier.	+
	Development in pilot plant stage.	+
	Efficiency of noncatalytic methanation (no data).	+
	Direct coupling of the hydrogen-carbon monoxide supply to the methanation process is absent, with attendant thermal loss.	-
	Costs of oxygen and hydrogen is a large component of the price.	-
	Yield of fuel by-products.	+
C2	Use of air, with attendant substantial reduction in equipment cost.	+
	High noncatalytic methanation in all the processes.	+
	Direct coupling of the hydrogen supply to the methanation process is absent, with attendant thermal loss.	-
	In pilot plant stage.	+
	Requirement of sulfur removal from effluent of a reducer of iron oxide.	-
	Continuous, high-pressure, large-scale hydrogen production process by stream-iron technique not well established.	- (uncertainty)
	Control problem for balanced operation of six fluidized beds (3 in gasifier, 3 in steam-iron).	- (uncertainty)
	Hydrogen cost high.	-
	Coal cost high (53.7%).	- (uncertainty)
C3	Use of air instead of oxygen.	+
	Substantial methanation within gasifier and relatively small amount of catalytic methanation (the highest noncatalytic methane yield).	+
	Requirement of sulfur removal from flue gas leaving air-blown fluidized bed combustor.	-
	Absence of direct coupling of the hydrogen-producing process to the methanation process (thermal loss).	-
	Relatively undeveloped state.	-
	Remaining unsolved technical aspects.	-
	Coal cost is less.	+
D	Use of air instead of oxygen.	+
	Efficient supply of reaction energy <u>in situ</u>.	+
	Use of lignite as material, with attendant minimal cost.	+
	Existence of temperature restriction in gasifier, with attendant restriction of usable coal materials.	-
	Regenerator outlet gas contains 3-4% CO and also SO_2.	-
	Noncatalytic methane yield is relatively low.	-
	Difficulty of system control.	- (uncertainty)

TABLE 4 Data for Subjective Scale of Coal Liquefaction Processes

label	consideration	evaluation
A	Use of coal tar as solvent with efficient dissolution capacity.	+
	Hydrogen recycling system requires less hydrogen.	+
	No catalytic treatment.	+
	Requirement of SO_2 treatment in effluent stock gas and ask disposal from residue furnace.	-
	Pilot plant stage of development.	+
	Sulfur as by-product.	- (uncertainty)
	Energe production from residue treatment process.	+
	Has solvent recovery plant.	+
	Storage of de-ashed desulfurized liquid stream by solidification for delayed coking (economically efficient).	+
B	Extract hydrogenation produces high cost.	-
	Has solvent recovery plant.	+
	Utilization of caking coal (low cost of coal material).	+
	Pilot plant stage of development.	+
C	Catalytic hydrogenation (high cost of hydrogen).	-
	Dependence on discounted cash flow (DCF) on grade of coal (high cost of coal material).	- (uncertainty)
	Possibility of high return on investment (DCF 18% for Illinois coal).	+ (uncertainty)
	Development in bench scale.	- (uncertainty)

label	consideration	evaluation
D	Staging of temperature by multistage fluidized-bed pyrolysis, which minimizes the loss of hydrocorbons that occur when cracking is too severe.	+
	Catalytic hydrotreating of oil (high cost of hydrogen).	-
	Utilization of char product as boiler fuel for power generation.	+
	Use of oxygen for reactor (high cost of oxygen).	-
	Minimization of gas products.	+
	High price of oil product.	-
	Possible utilization of the produced fuel gas and char as the process fuel for the operation.	+ (uncertainty)
	Pilot plant stage of development.	+
E	Use of asphalt as solvent (suitable for mass supply).	+
	Less efficient dissolution capacity of asphalt.	-
	Operation under air pressure (no requirement of hydrogen-use for elevating pressure).	+
	Low equipment cost.	+
	Ease of handling and safety of plant.	+
	High yield of liquid products (depending on the carbon content of coal).	+ (uncertainty)
	Advanced experiments performed in Japan.	+
	Requirement of sulfur removal.	-
	Use of nitrogen as inactive gas for reactor.	+ or - (model 3)

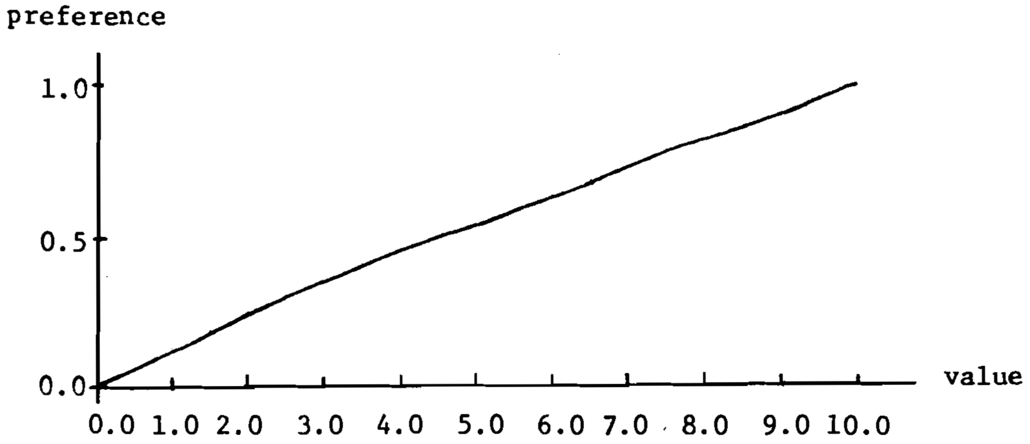
Based on the subjectively scaled attributes, utility functions are assessed. Parameters of the utility functions are shown in Table 5. The MANECON program PREFEVAL can evaluate and print out the values of the attributes and the corresponding preferences for them. Using these results, the utility functions for the oil-from-coal as well as gas-from-coal conversion processes in each model are graphically depicted in Fig. 2. The numerical values of the decreasing risk-aversion functions are also shown in the Figure.

The magnitudes of numerical values of the risk-aversion function R(x) are, in descending order, M3, M2 and M1 for the gasification process. In model 3, it is supposed that the decision-maker is most risk-averse in the first half of the whole range of the attributes and becomes rather risk-prone in the end. For the liquefaction process, the situation in model 3 is same. However, unlike in the gasification case, the decision-maker in model 2 is less risk-averse than in model 1. This is due to the relatively advanced stage of research and development for the liquefaction process in Japan.

TABLE 5 Parameters of Utility Functions

	A	B	C
GAS M1	0.72720	0.01016	127.9222
M2	0.40636	-0.02179	-6.29407
M3	0.34382	-0.27372	-0.01485
OIL M1	0.51448	0.09402	13.88968
M2	0.57441	0.03329	23.72738
M3	0.57615	-0.01800	-7.51167

GAS M1



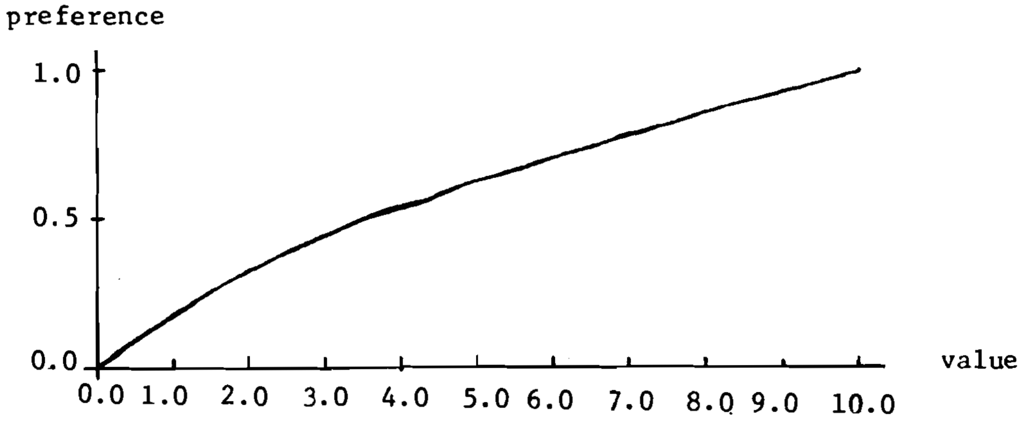
R(2.5)=0.07128

R(5.0)=0.02112

R(7.5)=0.01201

R(9.5)=0.01060

GAS M2



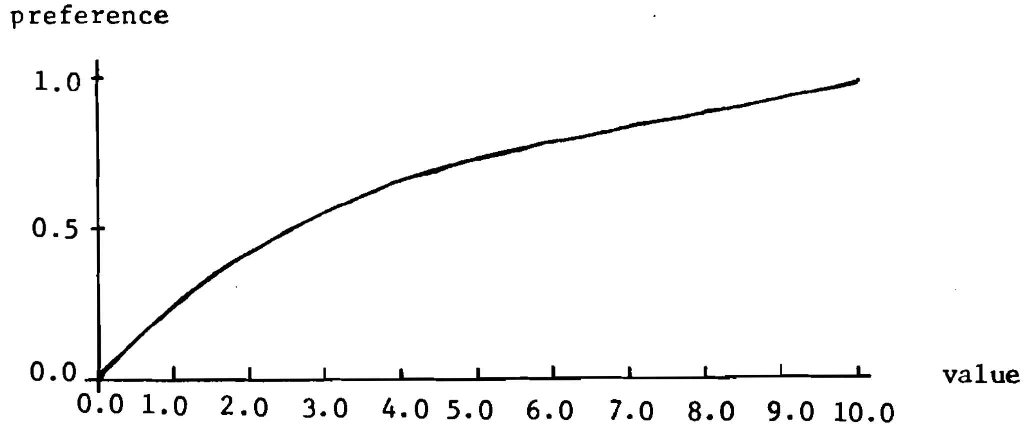
R(2.5)=0.19398

R(5.0)=0.08882

R(7.5)=0.02389

R(9.5)=-0.00112

GAS M3



R(2.5)=0.31143

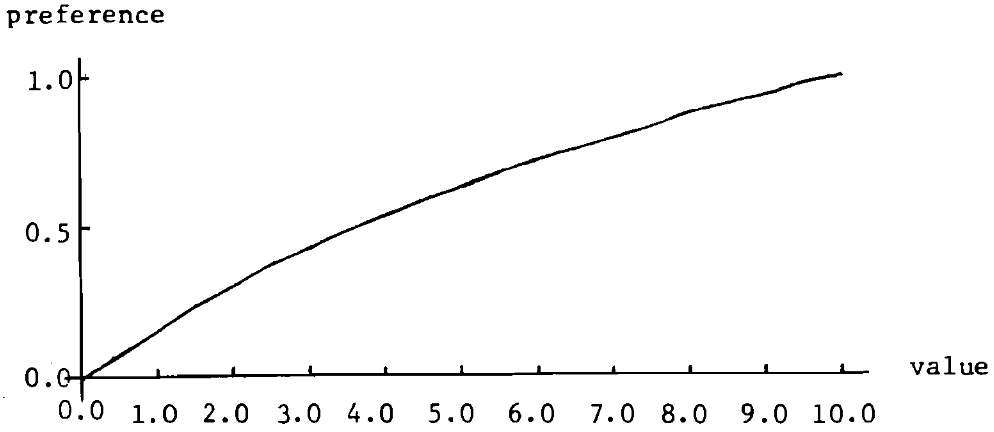
R(5.0)=0.21669

R(7.5)=0.00523

R(9.5)=-0.15436

Fig. 2. Utility functions and their values of risk averse functions.

OIL M1



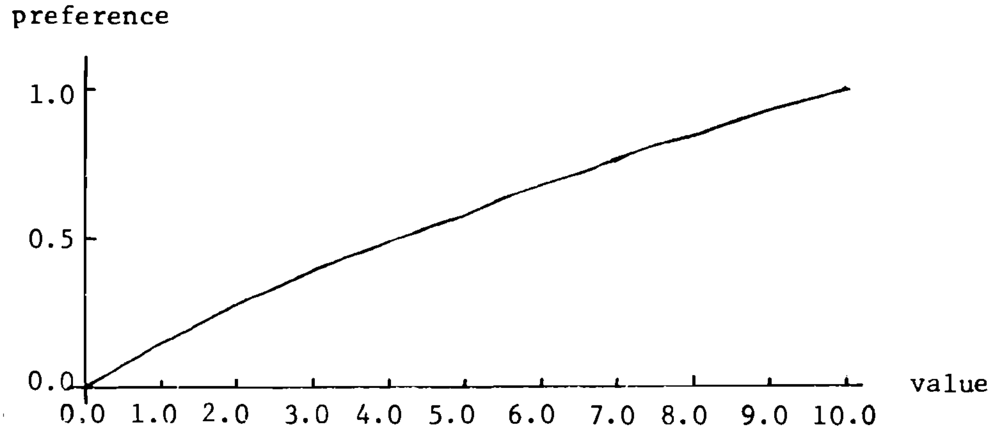
R(2.5)=0.14491

R(5.0)=0.11333

R(7.5)=0.10098

R(9.5)=0.09705

OIL M2



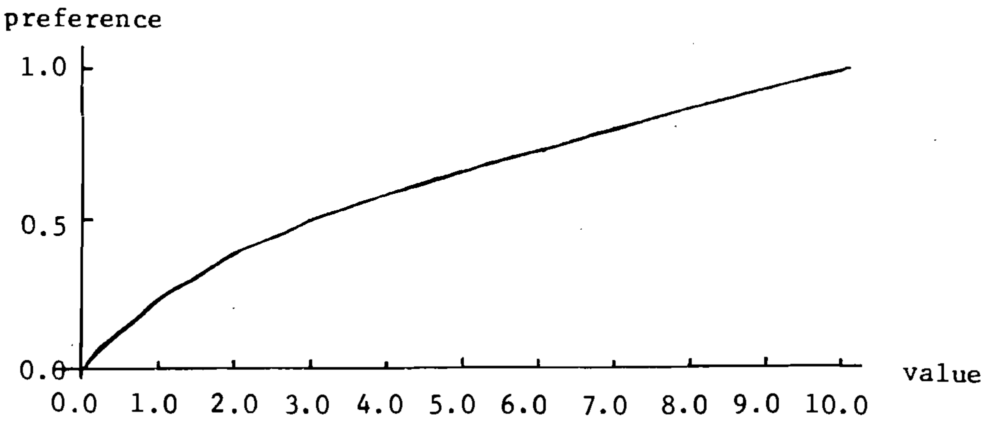
R(2.5)=0.11892

R(5.0)=0.05837

R(7.5)=0.04000

R(9.5)=0.03558

OIL M3



R(2.5)=0.27375

R(5.0)=0.08852

R(7.5)=0.01000

R(9.5)=-0.00918

Fig. 2. Utility functions and their values of risk averse functions.
(continued)

The attribute of each process is a random variable, and its probability distribution function is also assessed with subjective judgement. Characteristics of the distribution functions are also calculated and shown in Table 6. Examples of the probability distributions are graphically shown in Fig. 3.

As seen, among coal gasification processes in model 1, the mean of the probability distribution, or the mathematical expectation for the uncertain quantity of the attribute, is the highest for process C3. Processes C1 and A1 have secondary high values. In these processes, the degree of uncertainty expressed in the term of variance is relatively low. The process which has the highest degree of uncertainty is B2. This is mainly because of the unestablished status of the technology, uncertainty in predicting coal prices and the necessity of marketing char residuals. In model 2, the highest value of means is also in process C3 followed by process A1. The low magnitudes of means compared with those in model 1 reflect the delayed status of development of gasification processes in Japan. The numerical values of variance are generally high in model 2. This is because of the unpredictability of coal prices which obey external conditions. In model 3, the pattern of the mean value is almost the same as in other cases except that process D has a secondary high value. This is because of the efficiency of the energy supply system and utilizing air instead of oxygen, which are more suitable for less developed societies without well-established heavy-chemical industry complexes. In addition, use of lignite

TABLE 6

GASM1A1

```
MEAN      =      7.239
STD DEV   =      1.705
VARIANCE =       0.291E+01
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
 2282    2891     4790     6100     7500     8600      9309     9816     9941
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM1A2

```
MEAN      =      4.518
STD DEV   =      1.880
VARIANCE =       0.353E+01
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
  204     646     2040     3202     4500     5800      6903     9013     9688
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM1B1

```
MEAN      =      6.170
STD DEV   =      2.058
VARIANCE =       0.424E+01
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
  340    1074     3364     4800     6300     7800      8808     9649     9890
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM1B2

```
MEAN      =      5.591
STD DEV   =      2.183
VARIANCE =       0.477E+01
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
  242     765     2442     4000     5800     7300      8369     9491     9839
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM1C1

```
MEAN      =      7.282
STD DEV   =      1.574
VARIANCE =       0.248E+01
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
 2315    2995     5117     6300     7500     8500      9176     9755     9922
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM1C2

```
MEAN      =      6.568
STD DEV   =      1.797
VARIANCE =       0.323E+01
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
 1781    2389     4288     5300     6500     8000      9062     9773     9927
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM1C3

```
MEAN      =      7.712
STD DEV   =      0.411
VARIANCE =       0.169E+00
FRACTILES
 .001     .01      .1       .25      .5       .75       .9       .99     .999
 2780    3384     5268     6500     7800     8900      9560     9956     9996
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

TABLE 6 (continued)

GASM1D

```
MEAN       =      6.507
STD DEV    =      1.879
VARIANCE   =      0.353E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
 1312    1987    4097    5200    6500    8000    9062    9773    9927
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2A1

```
MEAN       =      6.332
STD DEV    =      1.781
VARIANCE   =      0.317E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
 2170    2537    3745    5000    6500    7750    8586    9553    9859
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2A2

```
MEAN       =      3.996
STD DEV    =      2.013
VARIANCE   =      0.405E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
  161     510    1607    2500    3700    5200    7000    9067    9705
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2B1

```
MEAN       =      4.967
STD DEV    =      2.317
VARIANCE   =      0.537E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
  165     522    1756    3202    5000    6800    8079    9401    9811
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2B2

```
MEAN       =      5.472
STD DEV    =      2.488
VARIANCE   =      0.619E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
  153     484    1768    3500    5800    7500    6643    9600    9874
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2C1

```
MEAN       =      6.080
STD DEV    =      1.657
VARIANCE   =      0.275E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
 1265    1837    3631    5000    6500    7250    7805    9279    9772
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2C2

```
MEAN       =      5.996
STD DEV    =      1.772
VARIANCE   =      0.314E+01
FRACTILES
 .001     .01     .1      .25     .5      .75     .9      .99     .999
 1218    1688    3182    4503    6000    7500    8546    9553    9859
     UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

TABLE 6 (continued)

GASM2C3

```
MEAN       =      7.041
STD DEV    =      1.781
VARIANCE   =      0.317E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 2253     2801     4516     5800     7200     8500     9314     9845     9950
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM2D

```
MEAN       =      6.086
STD DEV    =      2.090
VARIANCE   =      0.437E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 1178     1563     2905     4500     6500     7750     8586     9553     9859
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM3A1

```
MEAN       =      5.713
STD DEV    =      2.189
VARIANCE   =      0.479E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 1146     1460     2592     4000     5800     7500     8643     9600     9874
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM3A2

```
MEAN       =      3.387
STD DEV    =      1.719
VARIANCE   =      0.296E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
  132      418     1337     2201     3200     4200     5891     8326     9471
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM3B1

```
MEAN       =      3.796
STD DEV    =      2.048
VARIANCE   =      0.419E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
   92      290     1089     2200     3700     5200     6469     8874     9644
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM3B2

```
MEAN       =      4.539
STD DEV    =      2.054
VARIANCE   =      0.422E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
  202      639     2004     3000     4300     6000     7497     9210     9750
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM3C1

```
MEAN       =      5.896
STD DEV    =      1.797
VARIANCE   =      0.323E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
  361     1141     3582     4803     6000     7200     8123     9401     9811
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

TABLE 6 (continued)

GASM3C2

```
MEAN       =      5.867
STD DEV    =      1.595
VARIANCE   =      0.255E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
  392     1240     3916     5000     6000     6900     7680     9261     9766
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

GASM3C3

```
MEAN       =      6.553
STD DEV    =      2.051
VARIANCE   =      0.421E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 1678     2063     3405     5000     7000     8200     9011     9706     9907
        UQ VALUES JUST ABOVE ARE TO BE-MULTIPLIED BY 10E-3
```

GASM3D

```
MEAN       =      6.174
STD DEV    =      1.760
VARIANCE   =      0.310E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 1310     1980     4088     5000     6000     7500     8674     9617     9879
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM1A

```
MEAN       =      7.285
STD DEV    =      1.409
VARIANCE   =      0.199E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 2347     3096     5451     6500     7500     8300     8899     9650     9889
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM1B

```
MEAN       =      6.546
STD DEV    =      1.682
VARIANCE   =      0.283E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 1333     2053     4303     5500     6700     7800     8609     9560     9861
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM1C

```
MEAN       =      5.959
STD DEV    =      2.103
VARIANCE   =      0.442E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
  297      939     2952     4500     6200     7600     8584     9562     9862
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM1D

```
MEAN       =      5.820
STD DEV    =      1.841
VARIANCE   =      0.339E+01
FRACTILES
 .001     .01      .1       .25      .5       .75      .9       .99      .999
 1254     1802     3514     4500     5700     7200     8425     9524     9849
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

TABLE 6 (continued)

OILM1E

```
MEAN       =      6.877
STD DEV    =      1.715
VARIANCE  =      0.294E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
 2268     2848     4654     5800     7000     8200     9011     9706     9907
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM2A

```
MEAN       =      6.550
STD DEV    =      1.679
VARIANCE  =      0.282E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
 1355     2122     4546     5500     6500     7800     8823     9657     9892
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM2B

```
MEAN       =      5.818
STD DEV    =      1.968
VARIANCE  =      0.387E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
  312      986     3087     4500     6000     7300     8266     9450     9826
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM2C

```
MEAN       =      5.667
STD DEV    =      2.269
VARIANCE  =      0.515E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
  242      765     2442     4000     5800     7500     8643     9600     9874
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM2D

```
MEAN       =      5.428
STD DEV    =      2.226
VARIANCE  =      0.495E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
  231      729     2326     3802     5500     7200     8381     9504     9843
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM2E

```
MEAN       =      7.100
STD DEV    =      1.485
VARIANCE  =      0.220E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
 2312     2987     5097     6200     7300     8200     8862     9640     9887
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM3A

```
MEAN       =      6.617
STD DEV    =      2.128
VARIANCE  =      0.453E+01
FRACTILES
 .001      .01      .1       .25      .5       .75      .9       .99      .999
  355     1124     3522     5200     7000     8500     9145     9766     9925
      UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

TABLE 6 (continued)

OILM3B

```
  MEAN        =      5.466
  STD DEV     =      2.048
  VARIANCE    =      0.419E+01
  FRACTILES
   .001      .01      .1       .25      .5       .75      .9       .99      .999
    265      837     2631     4000     5500     7000     8103     9400     9810
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM3C

```
  MEAN        =      5.666
  STD DEV     =      2.533
  VARIANCE    =      0.642E+01
  FRACTILES
   .001      .01      .1       .25      .5       .75      .9       .99      .999
    189      599     2021     3700     5800     7800     9035     9812     9940
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM3D

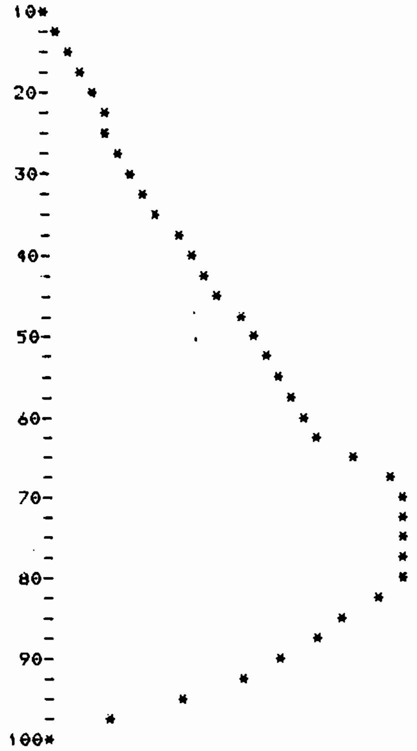
```
  MEAN        =      4.972
  STD DEV     =      2.481
  VARIANCE    =      0.615E+01
  FRACTILES
   .001      .01      .1       .25      .5       .75      .9       .99      .999
    129      408     1503     3000     5000     7000     8352     9510     9845
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

OILM3E

```
  MEAN        =      6.513
  STD DEV     =      1.905
  VARIANCE    =      0.363E+01
  FRACTILES
   .001      .01      .1       .25      .5       .75      .9       .99      .999
   1276     1873     3746     5200     6800     8000     8837     9642     9887
        UQ VALUES JUST ABOVE ARE TO BE MULTIPLIED BY 10E-3
```

```
OPTION?
?
4

VALUES ON UQ AXIS ARE TO BE MULTIPLIED BY 10E-1
```



```
OPTION?
?
5

VALUES ON UQ AXIS ARE TO BE MULTIPLIED BY 10E-1
```

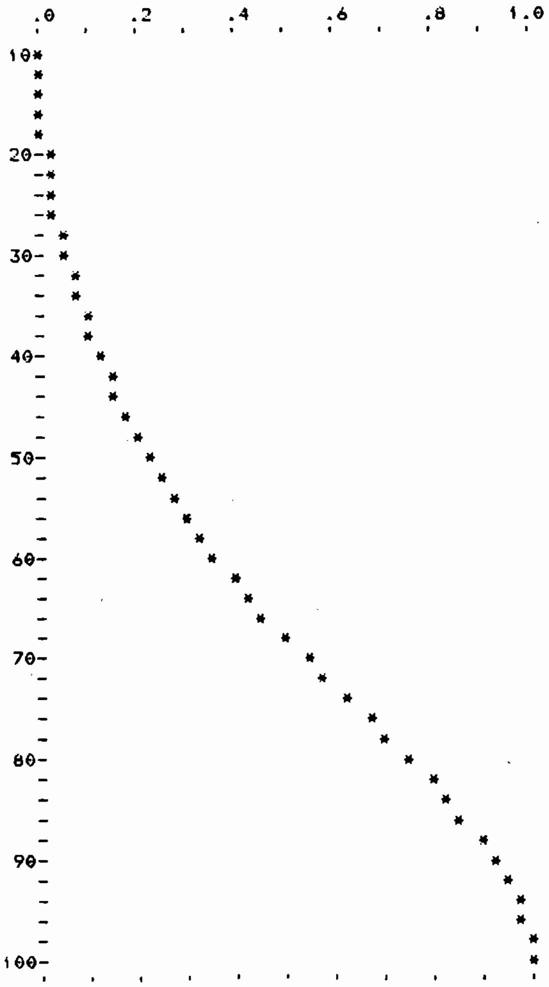


Fig. 3. Probability distributions of the attributes for selected oil-from-coal processes.

```
OPTION?
?
4

VALUES ON UQ AXIS ARE TO BE MULTIPLIED BY 10E-1
```

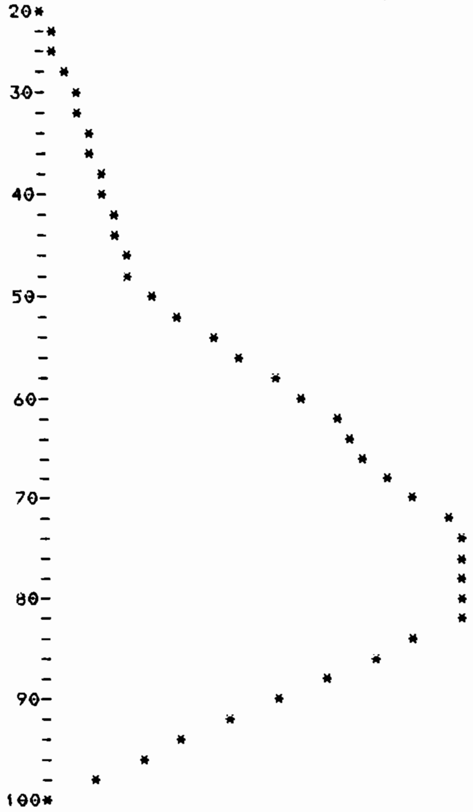
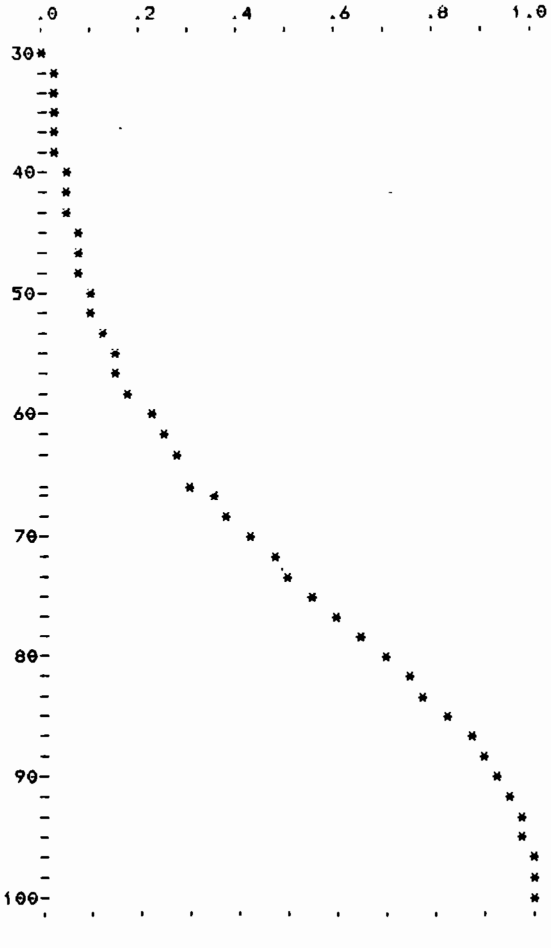


Fig. 3. Probability distributions of the attributes for selected oil-from coal processes. (continued)

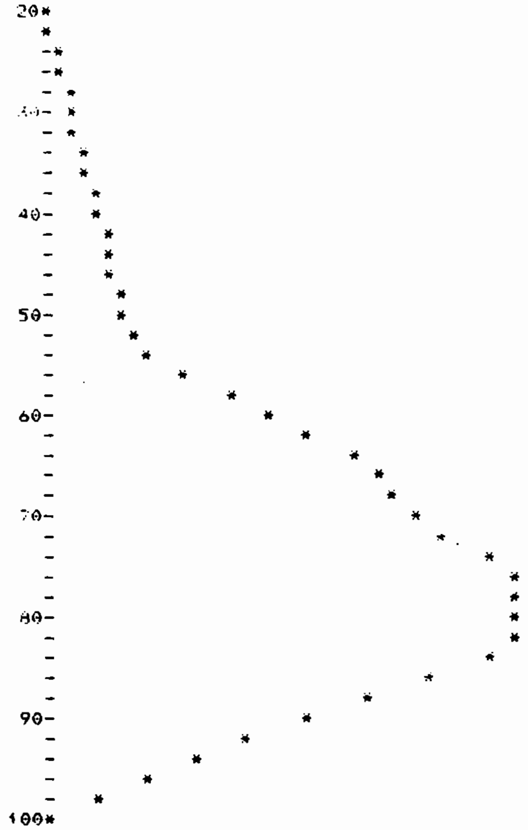
```
OPTION?
?
5

VALUES ON UQ AXIS ARE TO BE MULTIPLIED BY 10E-1
```



```
OPTION?
?
4

VALUES ON UQ AXIS ARE TO BE MULTIPLIED BY 10E-1
```



```
OPTION?
?
5

VALUES ON UQ AXIS ARE TO BE MULTIPLIED BY 10E-1
```

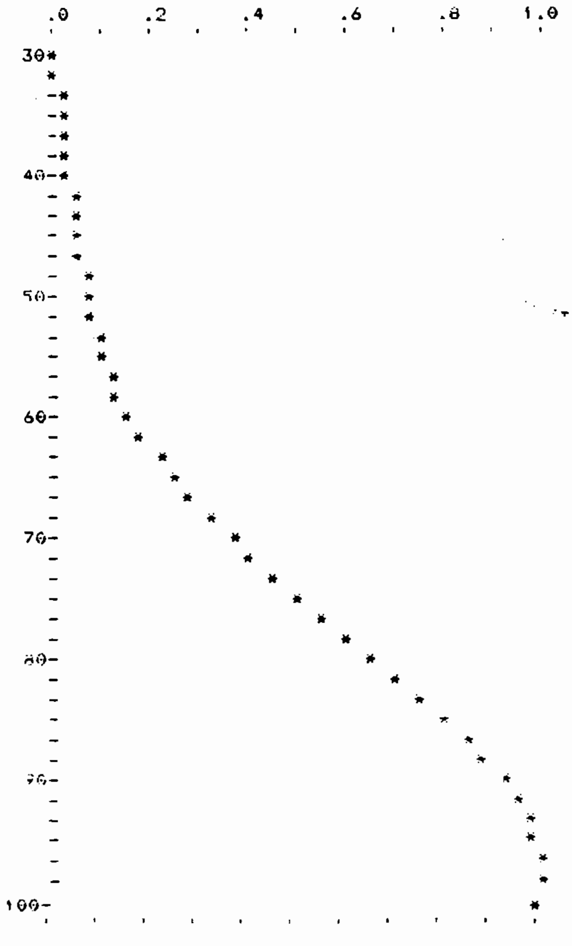


Fig. 3. Probability distributions of the attributes for selected oil-from-coal processes. (continued)

gives more leeway for locational choice. The degrees of uncertainty in model 3 are sometimes lower than in model 2: in these cases, locational advantages in coal-producing countries contribute to this situation.

For coal liquefaction processes, the mean value is the highest for process A in model 1, and for process E in model 2. The high values of variance in model 2 are caused by the same factors as in the gasification processes in that model. In model 3, process A has the highest mean value and process E is secondary. The variance for each process is often higher than in other models, and also higher than for gas-from-coal processes in that model. This means that, although there is a relatively good possibility for a liquid refinery with high profitability in coal-producing sites, the decision-making will come from consuming countries exclusively. Thus, uncertain quantities of the attribute of each process have a large variance.

The numerical values of the expected utility of the alternative processes are shown in Table 7, where we see that in model 1, process C3 has the highest value of the expected utility and processes C1 and A1 are secondary among the gasification processes. Process A has the highest value and process E is secondary among the liquefaction processes.

In model 2, the preferred processes of gasification are the same as in model 1. The high magnitude of the expected utility, except for more advanced processes in model 1, results from the fact that, research and development being generally less advanced in model 2, possible range for high profitability disperses

TABLE 7 Expected Utility of Alternative Processes

M1	Preference	M2	Preference	M3	Preference
GAS A1	0.7517	GAS A1	0.7303	GAS A1	0.7476
A2	0.4933	A2	0.5239	A2	0.5621
B1	0.6518	B1	0.5994	B1	0.5872
B2	0.5971	B2	0.6468	B2	0.6616
C1	0.7559	C1	0.7107	C1	0.7656
C2	0.6902	C2	0.6963	C2	0.7686
C3	0.7822	C3	0.7847	C3	0.8042
D	0.6842	D	0.7063	D	0.7880
OIL A	0.8237	A	0.7233	A	0.7678
B	0.7648	B	0.6566	B	0.6820
C	0.7095	C	0.6396	C	0.6911
D	0.7037	D	0.6161	D	0.6346
E	0.7913	E	0.7707	E	0.7642

with relatively high probabilities. This stems from the benefit of technology transfer to late-comers, or the "risk of developers." For liquefaction processes, the situation is in the opposite, and process E is most preferable.

In model 3, the situation is about the same as in model 2: however, process C3 is most preferable, process D is secondary, and processes C1 and C2 are third for gasification. For liquefaction, the order of preference is about the same as in model 1. The relatively low magnitude of numerical values of expected utility, compared with model 1, reflects the risk of expectation for high profitability due to plants being invited, and thus final decisions about them being made by consuming countries.

IV. SUMMARY AND CONCLUDING REMARKS

As assessment of alternative processes of technologies for substitute-energy from coal has been presented in terms of numerical expressions of preference. Our main device has been concerned with quantifying unquantified data in comparative terms. The variables are also uncertain quantities whose probability distributions can not be obtained from empirical/experimental mass observations. Thus subjective judgement has been used for assessing preferences and scaling probabilities of uncertain quantities of the attributes. As a result, the expected utility concept is used for final assessment.

The SOTEC concept has been used for structuring the problems and model classification has been performed according to this concept.

However, the results are still quite preliminary. As the MIT study points out, hasty conclusive assertions should be withheld because the money and time lost in going back to a complex process abandoned of an early stage are too great. Also, a data base for evaluation has not been well-established yet. Any process may have more advantage in large-scale operations than in laboratory research and pilot plant operations.

Also, the methodology for technology assessment has not been well developed yet. Although a modified version of decision analysis has been presented here, a device combining this method with multi-attribute utility analysis in a hierarchical system of decision making will be investigated, and development of a revised interactive computer program for this purpose is expected, In addition, impact assessment on residential and natural environments as well as on related industrial combinations in the region for locating fossil fuel-to-fuel conversion processes has not yet been performed in well-established quantified terms. Although we have to wait for such work until the arrangement of a suitable data-base is performed, methodological elaborations for technology assessment in terms of environmental control are expected in the near future.

The main directions of further research for technology assessment include greater utilization of the behaviorial scientific approach to preference theory. Computer-aided systems design will also be useful for efficiently calculating preference orders among alternative technologies in numerical terms. Interactive man-machine systems especially will contribute to evaluation procedures.

ACKNOWLEDGEMENT

The authors are indebted to Dr. Hitoo Kakiyama, Chief of the Chemistry Division of the National Industrial Research Institute, Kyushu, for providing valuable information on the Solvolysis liquefaction process. Mr. Kimio Ishimaru of the Research Center of Osaka Gas Company also provided a general state-of-art survey of fossil fuel-to-fuel conversion processes in Japan. Contributions made by Mr. Sumio Hasegawa were critical in assisting computer utilization and assessment work.

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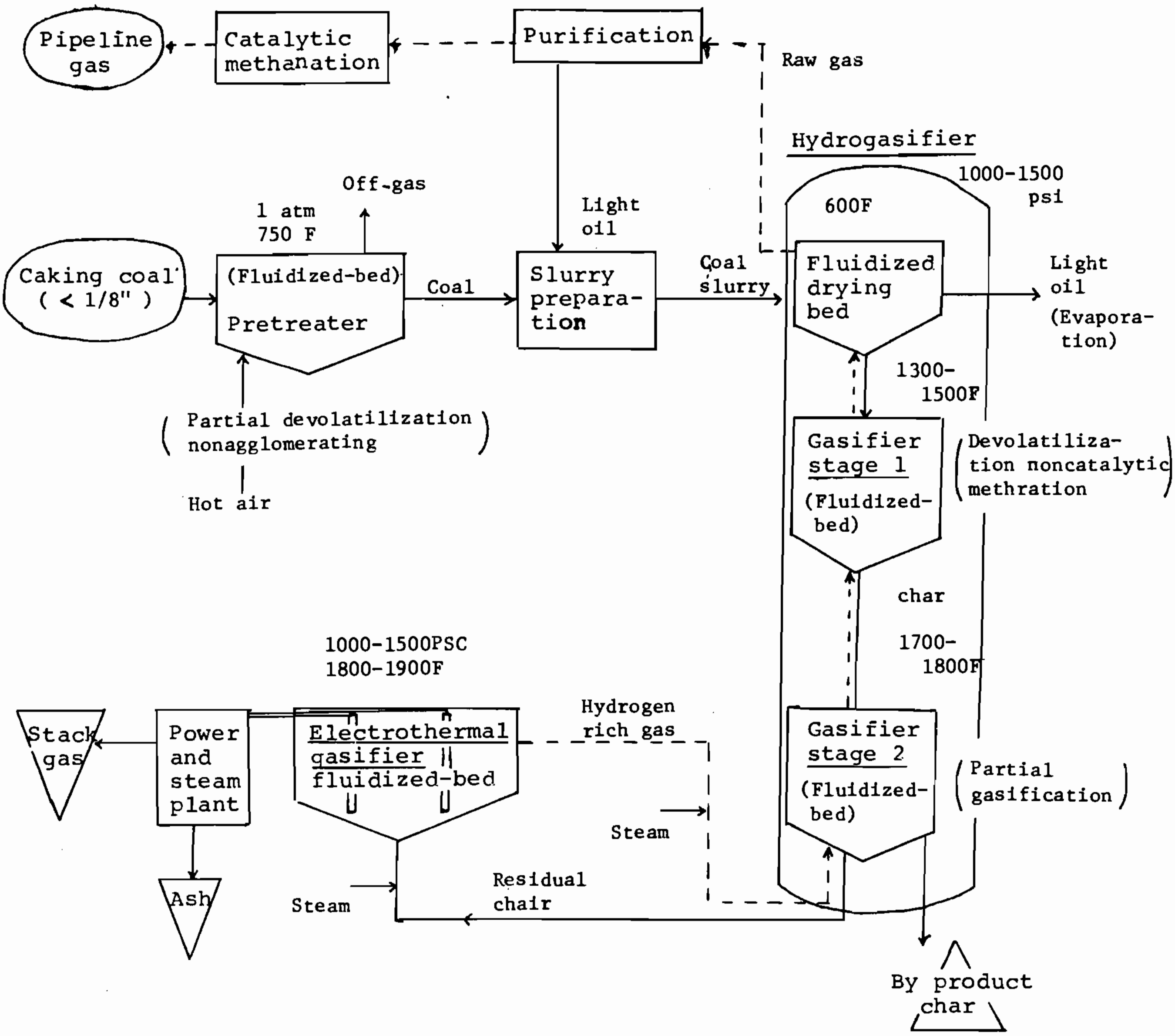
[5] Pratt, J.W. (1964). Risk aversion in the small and in the large. Econometrica, 32, 122-137.

[6] Pratt, J.W., H.Raiffa, and R.Schlaifer (1964). The foundations of decision under uncertainty: An elementary exposition, J. Am. Stat. Assoc., 59, 353-375.

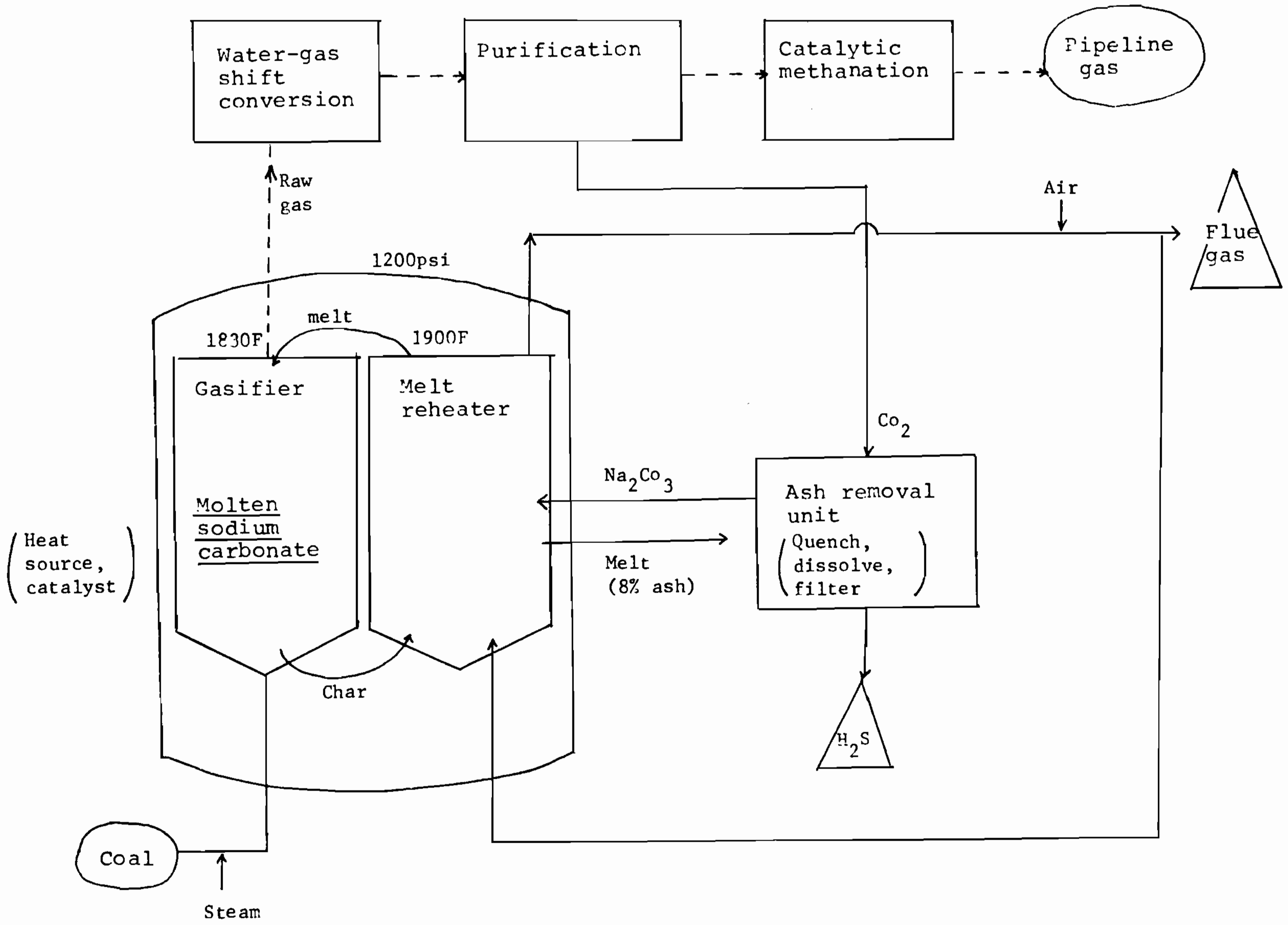
[7] Schlaifer, R. (1971). Computer Programs for Elementary Decision Analysis. Division of Research, Harvard Business School, Boston.

APPENDIX

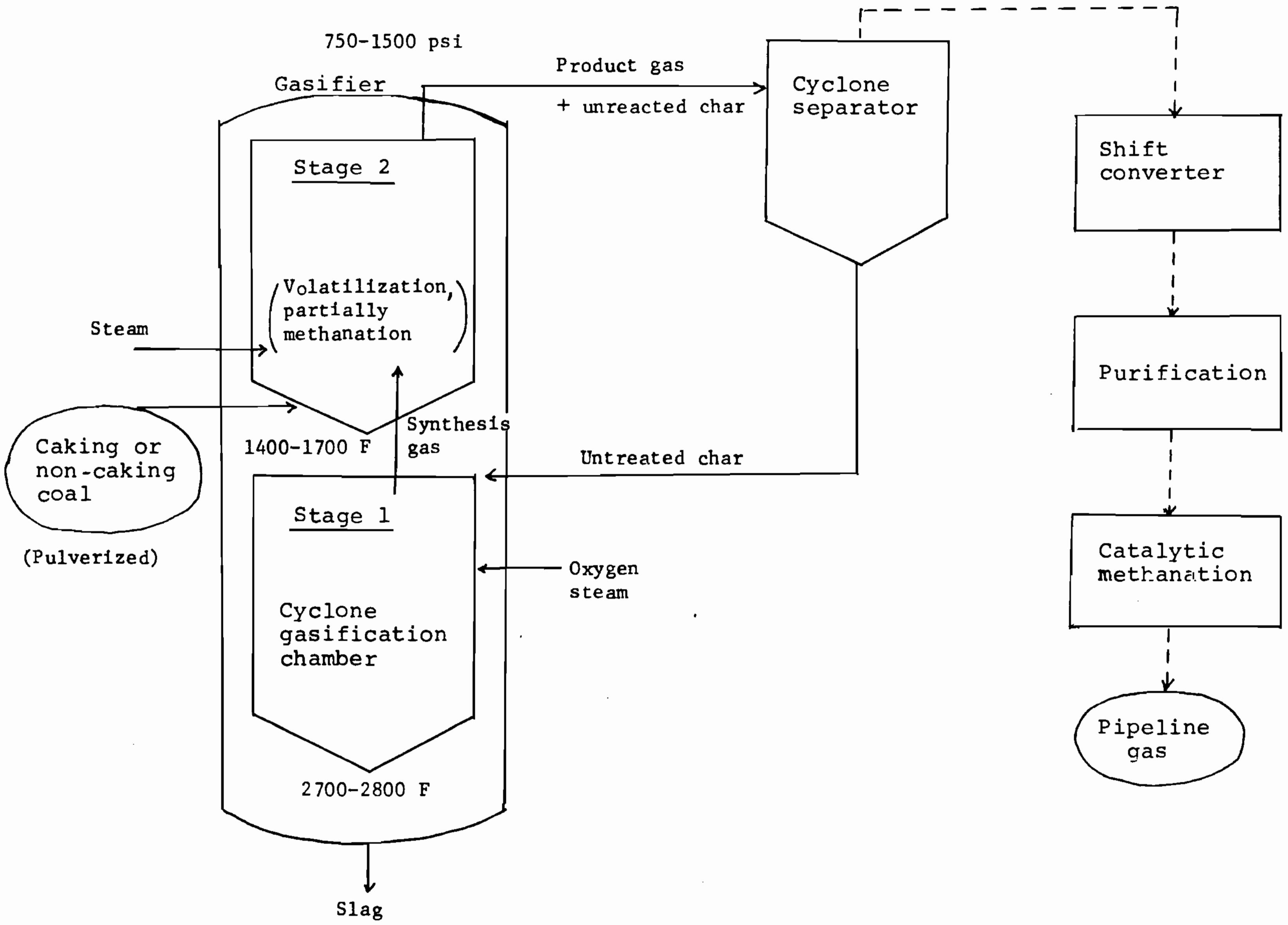
source: Hottel and Howard, New Energy Technology
(A1 to E)



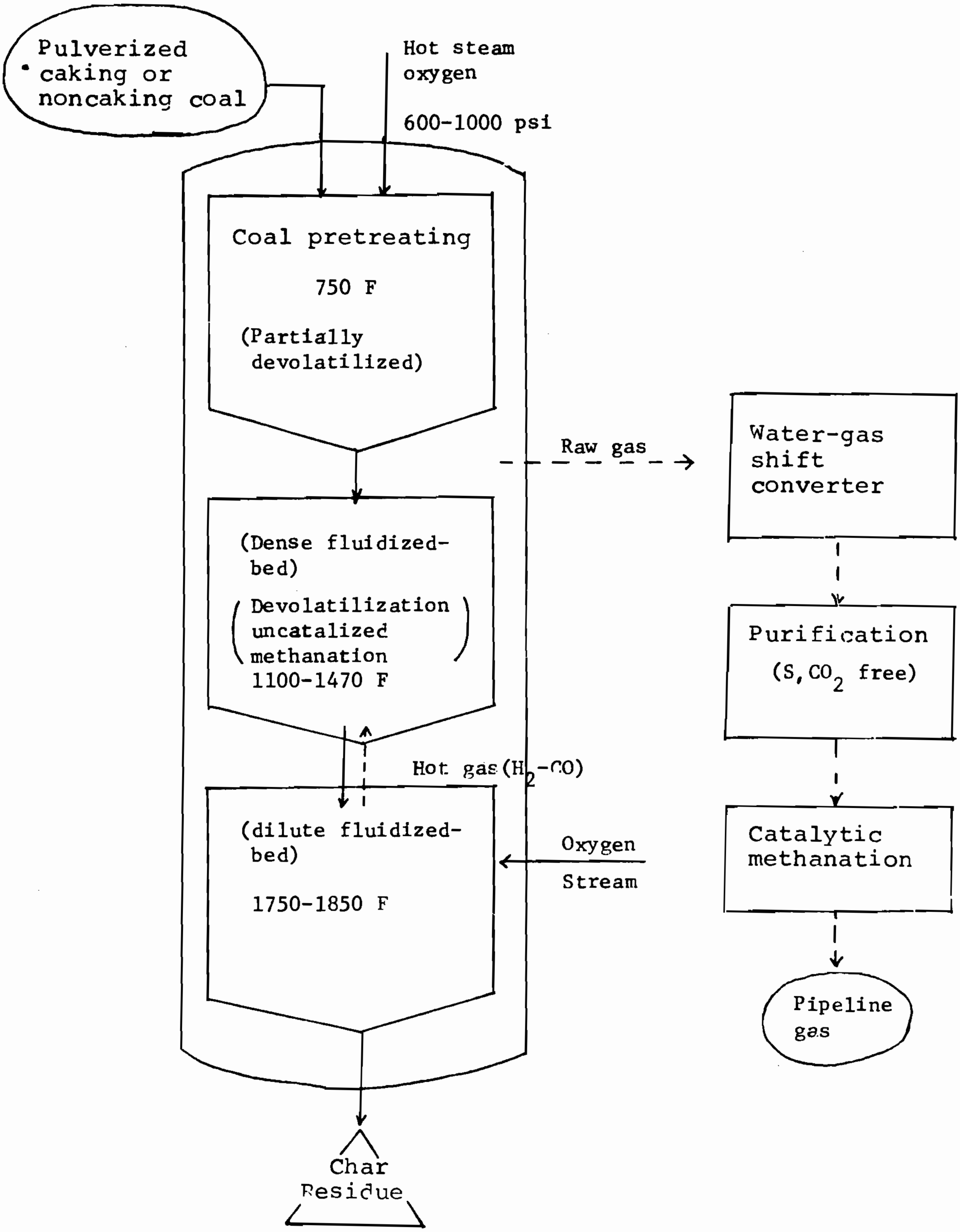
A1. Hygas-Electrothemal
(Institute of Gas Technology)



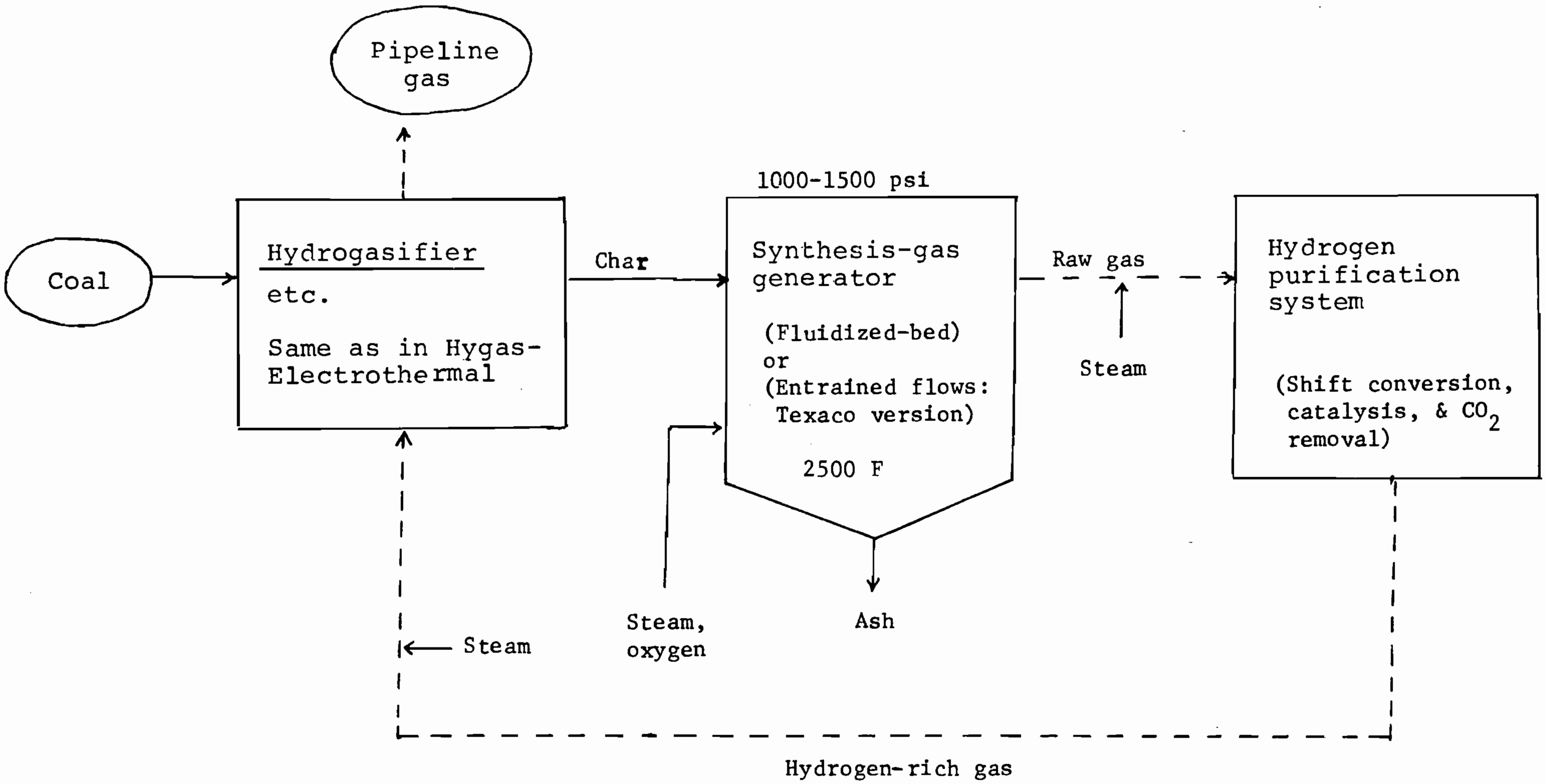
A2 Molten Carbonate (M.W.Kellogg Co.)



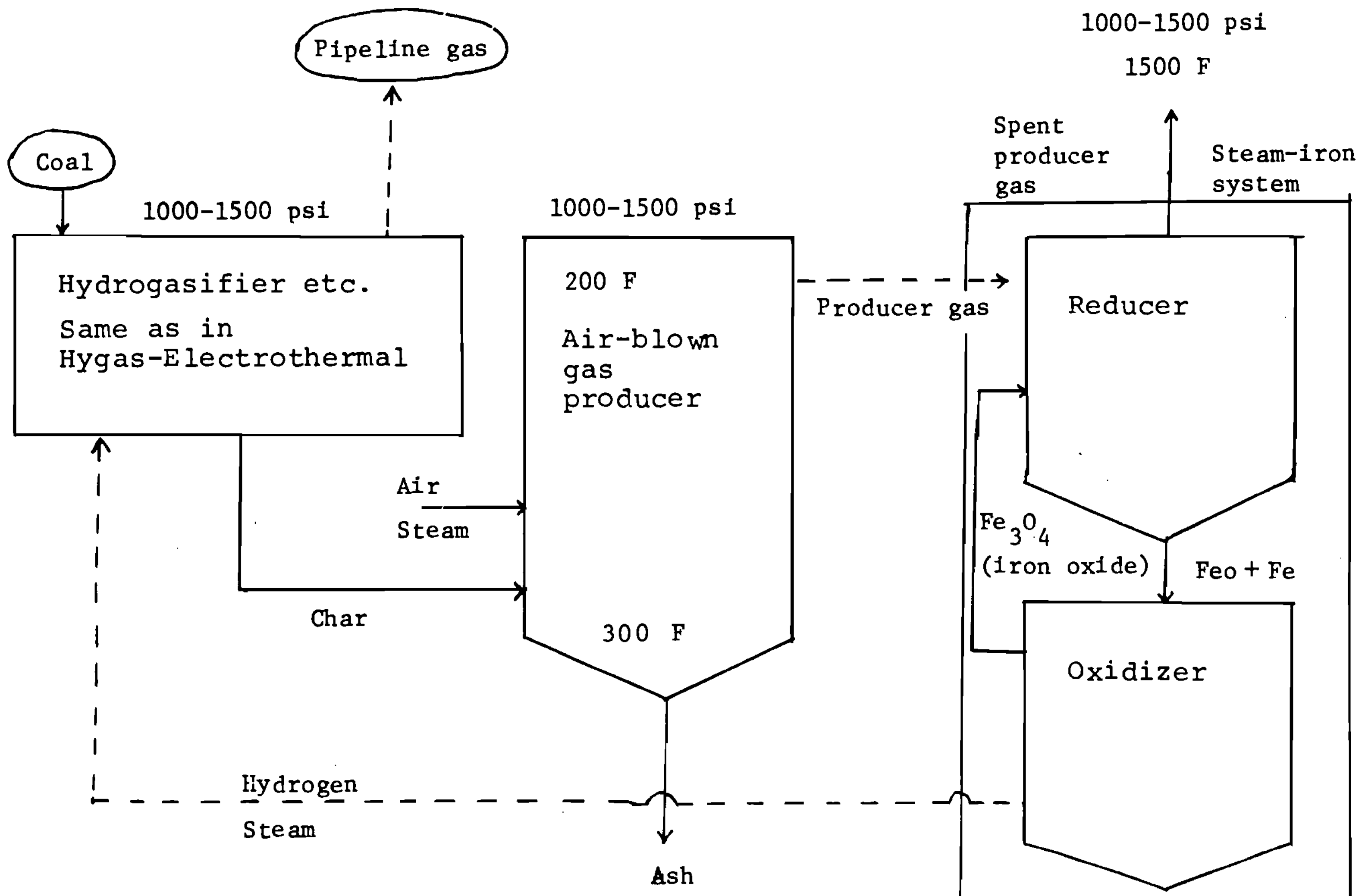
B1 Bigas (Bituminous Coal Research, Inc.)



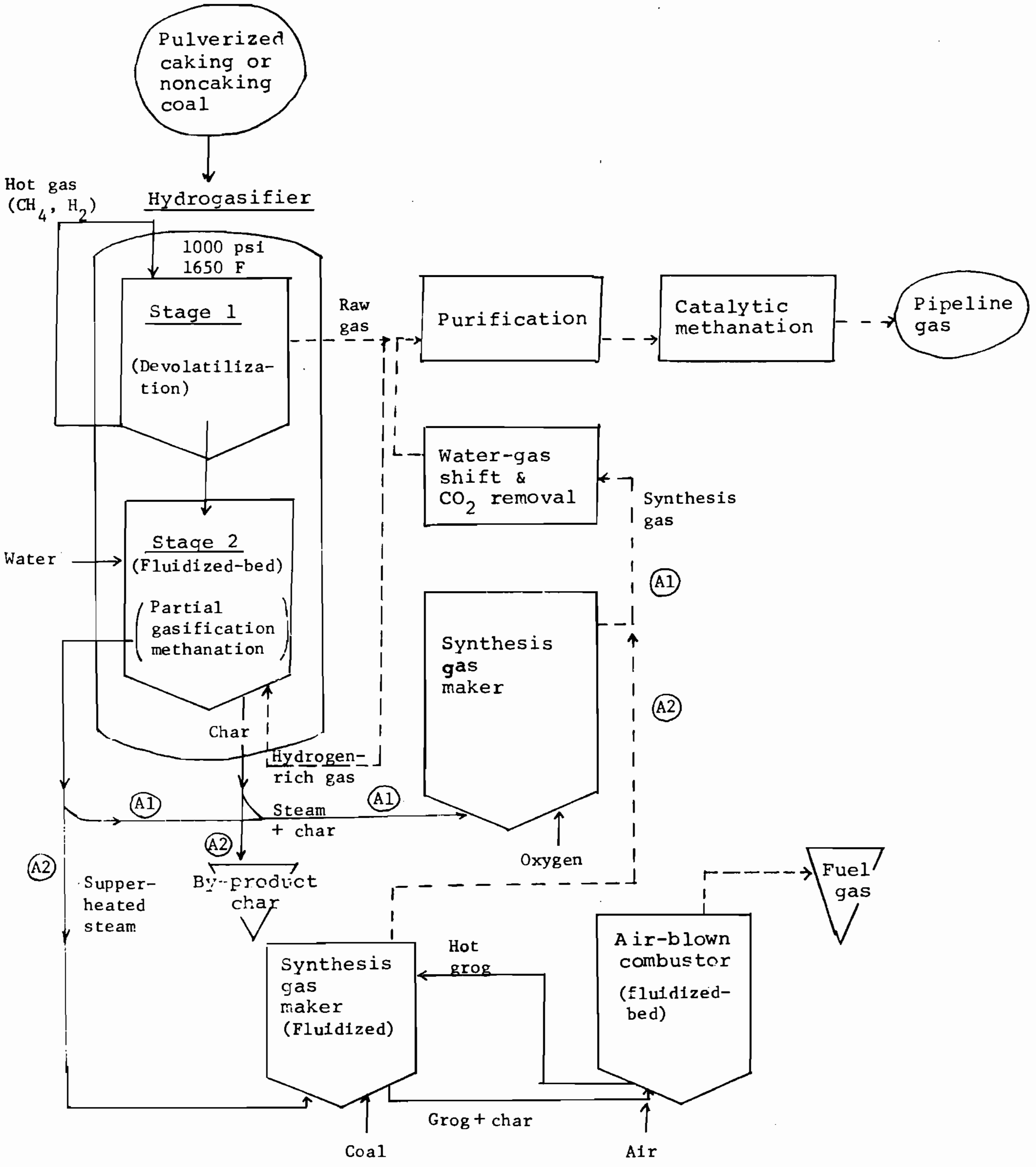
B2. Synthane (Bureau of Mines)



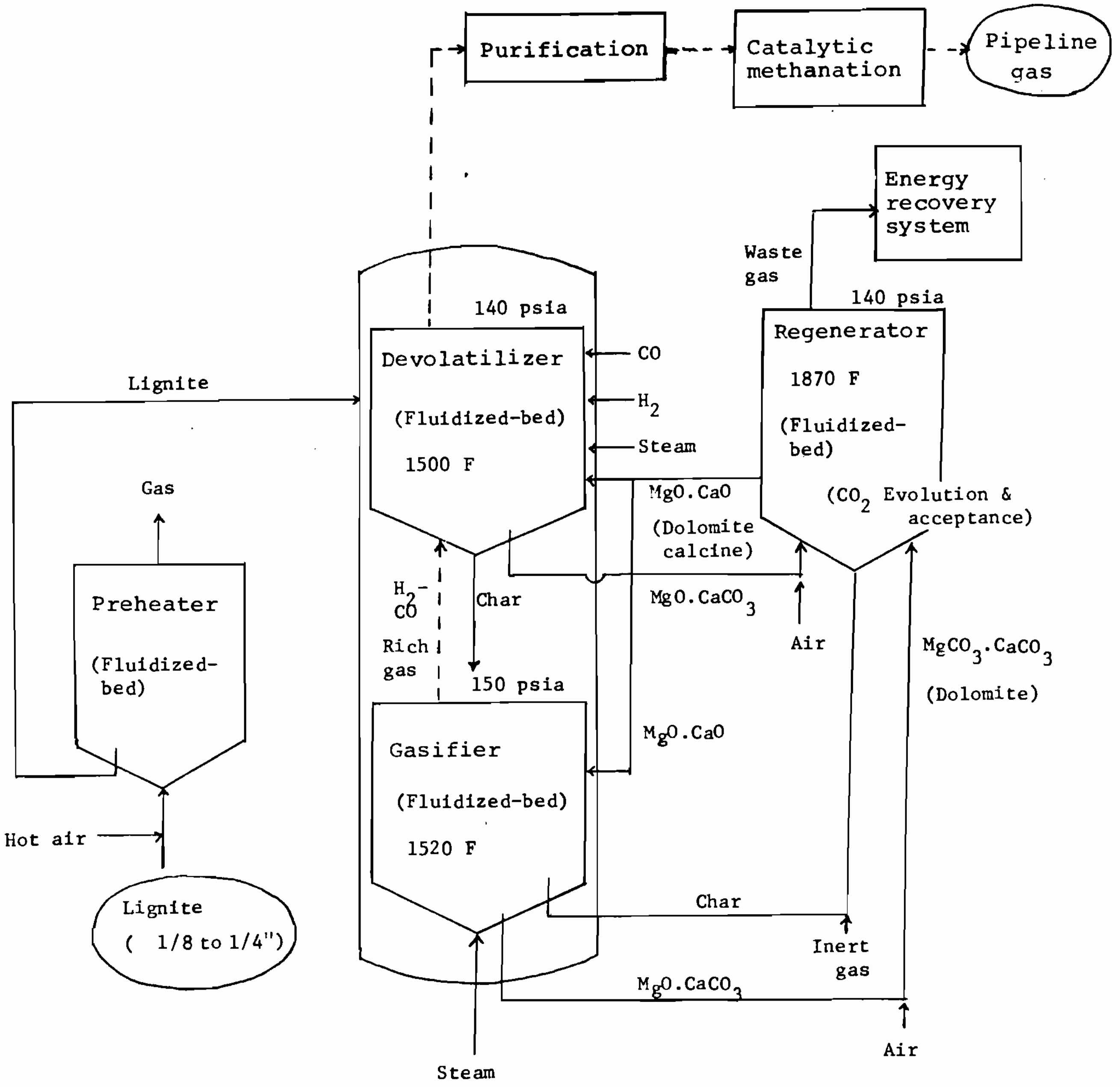
C1 Hygas-Oxygen (IGT)



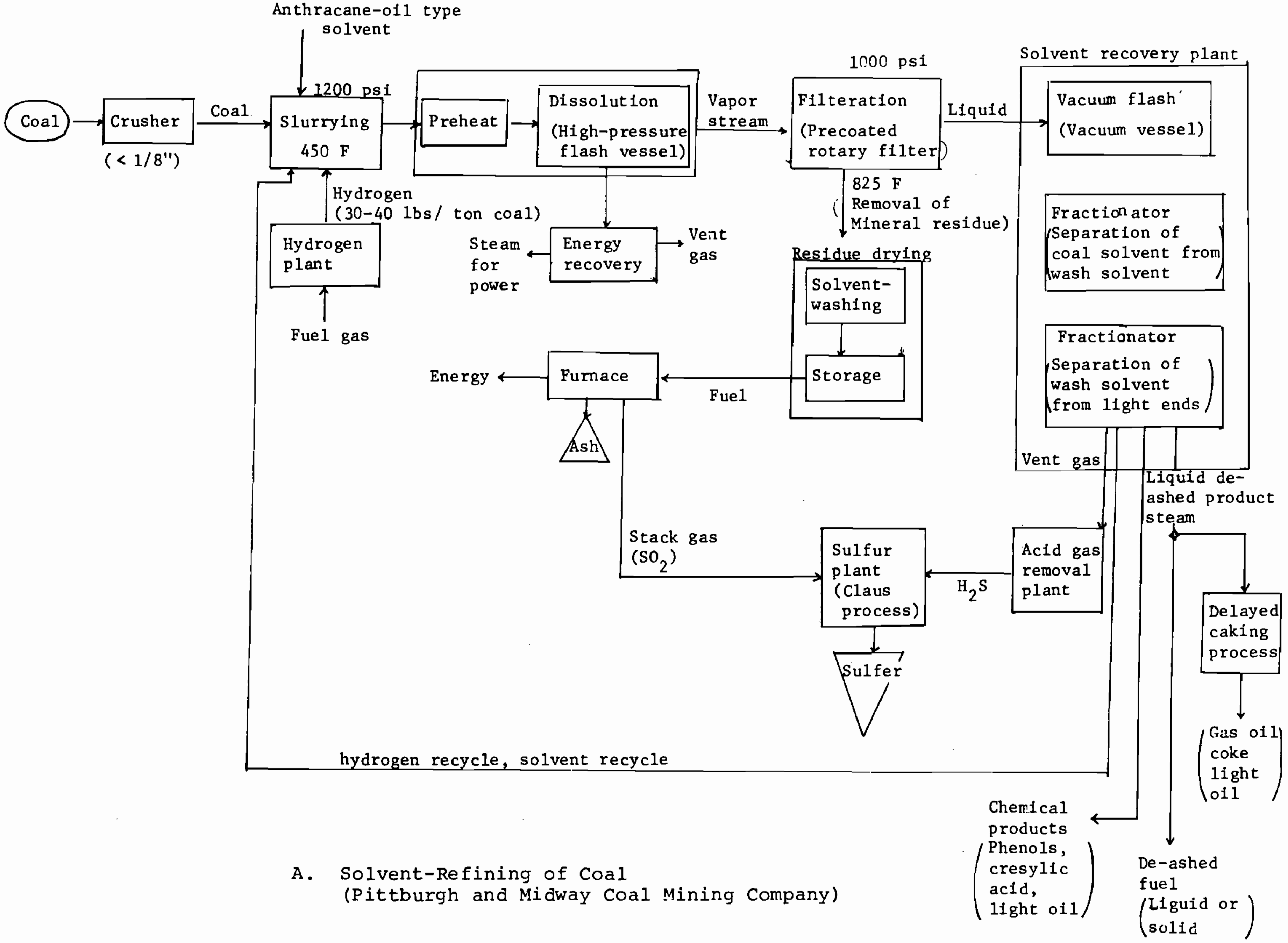
C2 Steam-Iron (IGF Fuel Gas Associates)



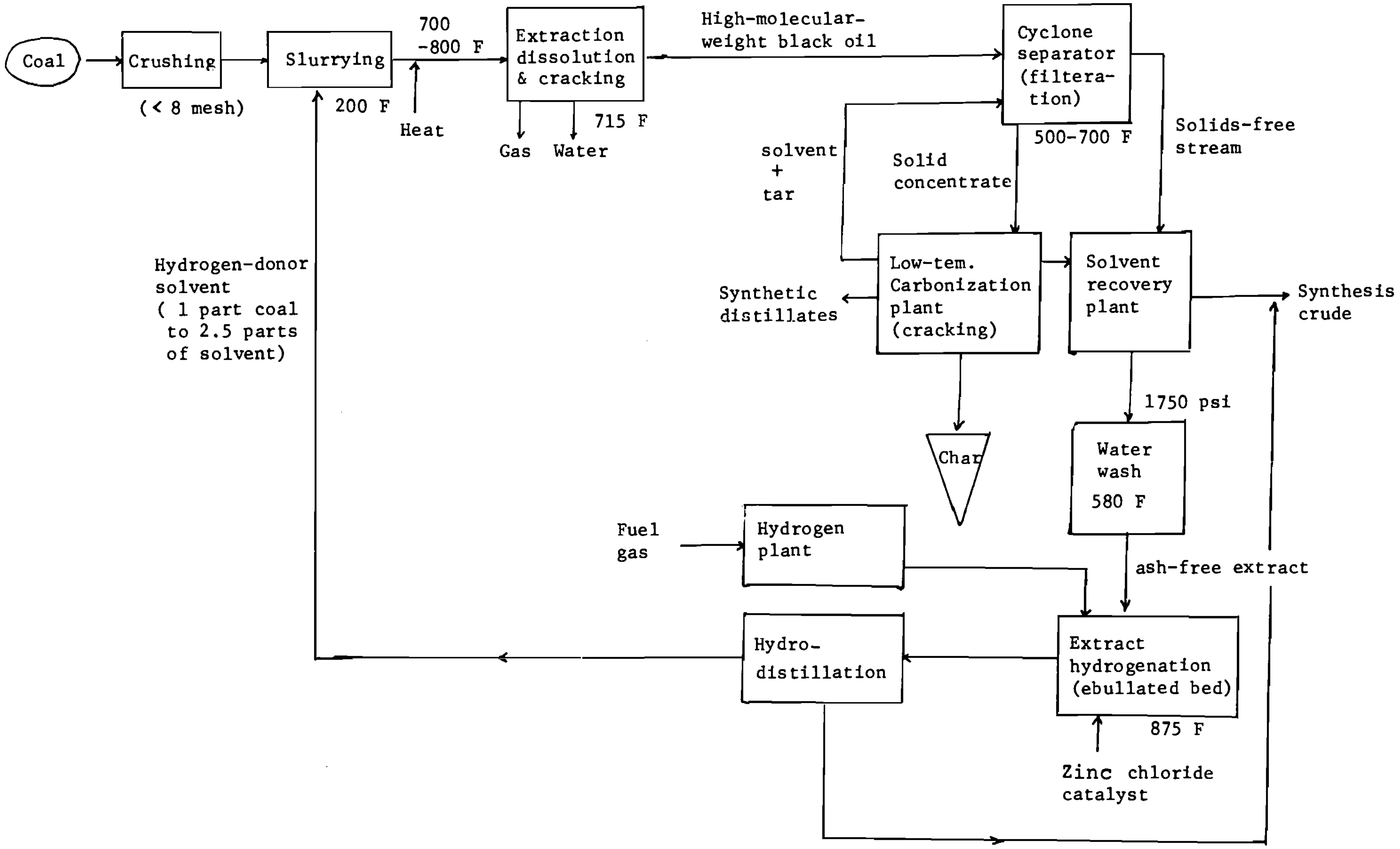
C3. Hydrogasification (Bureau of Mines)



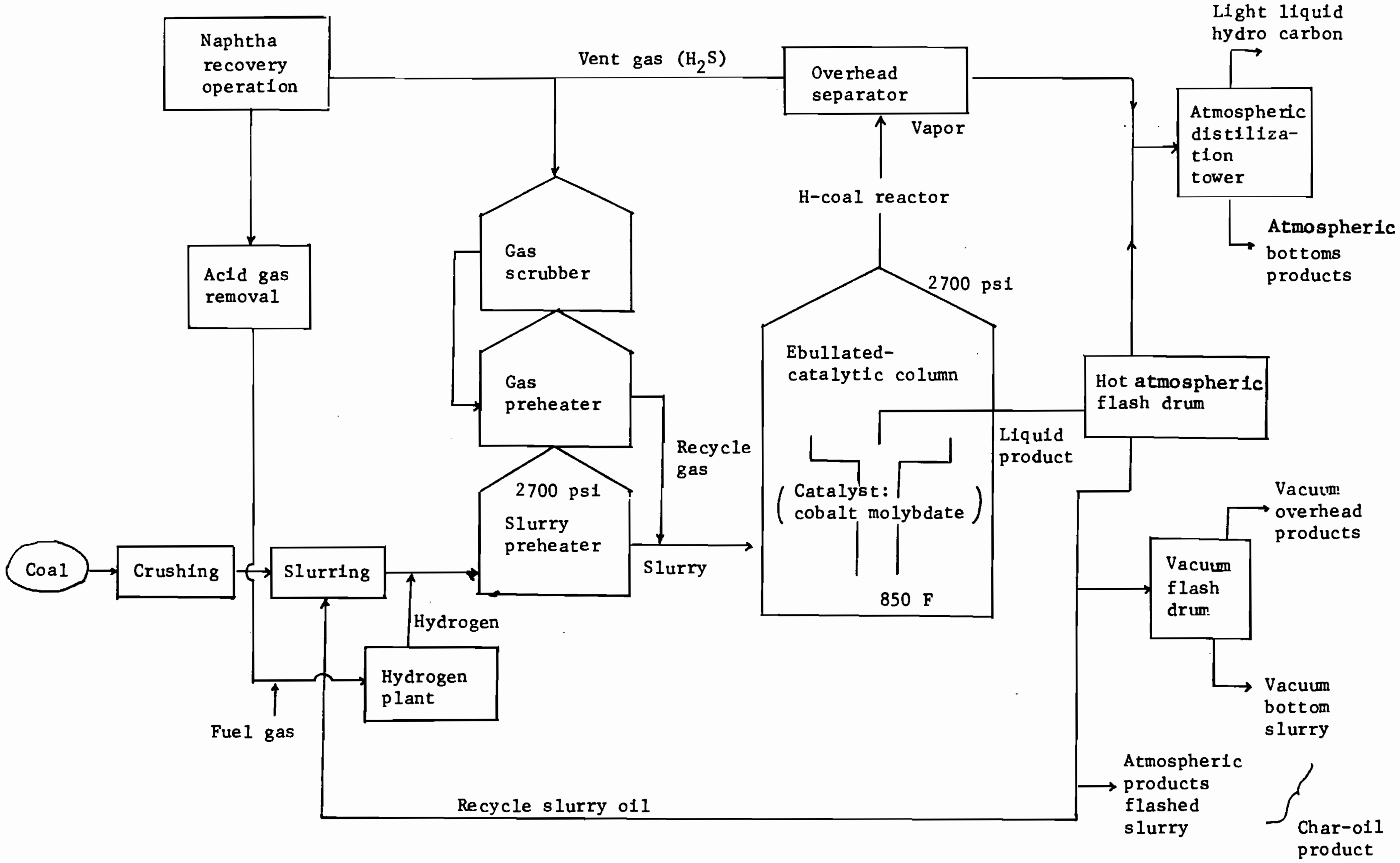
D1. CSG Process or CO_2-Accepter (Consolidation Coal CO.)



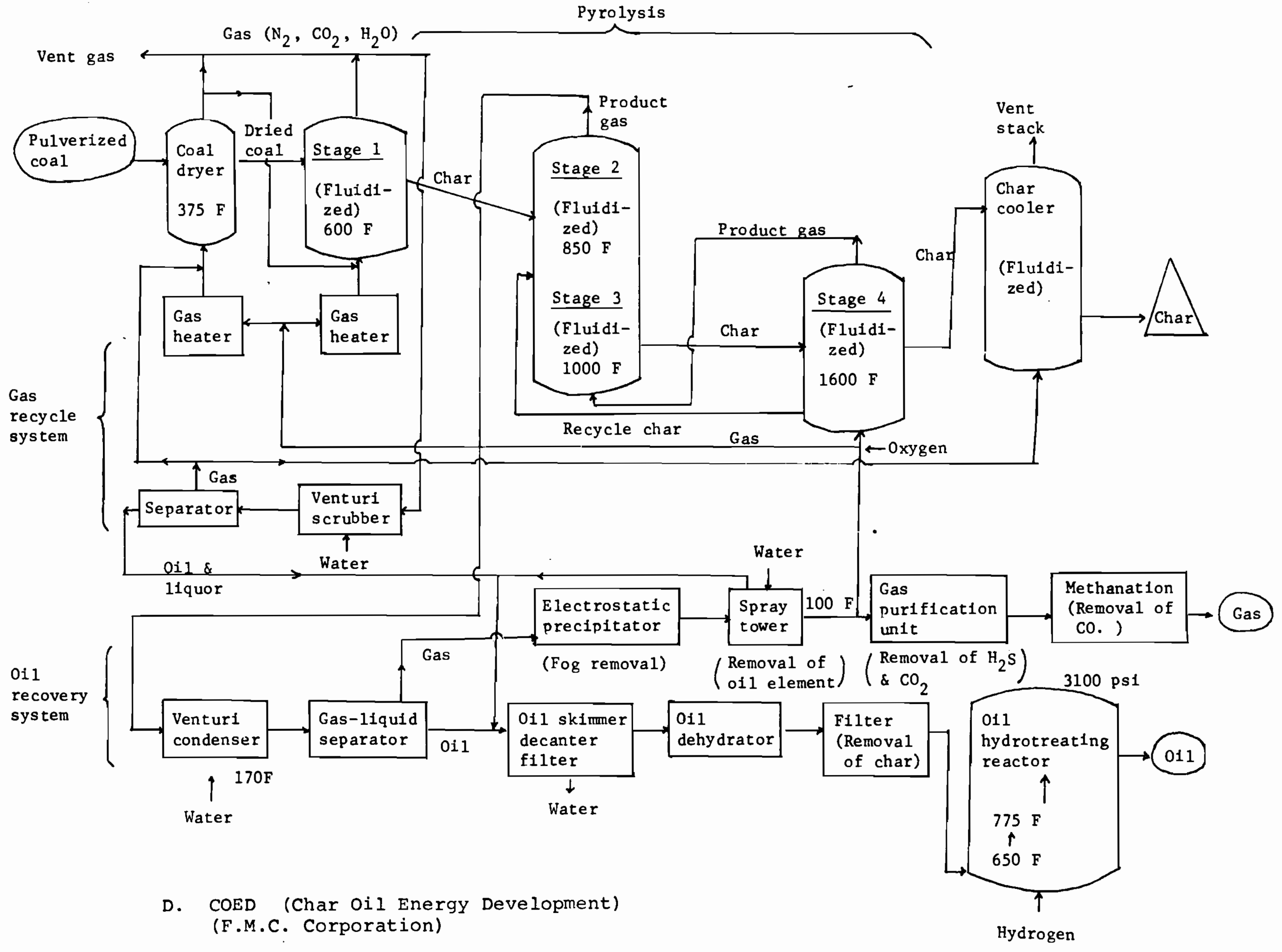
A. Solvent-Refining of Coal
(Pittburgh and Midway Coal Mining Company)



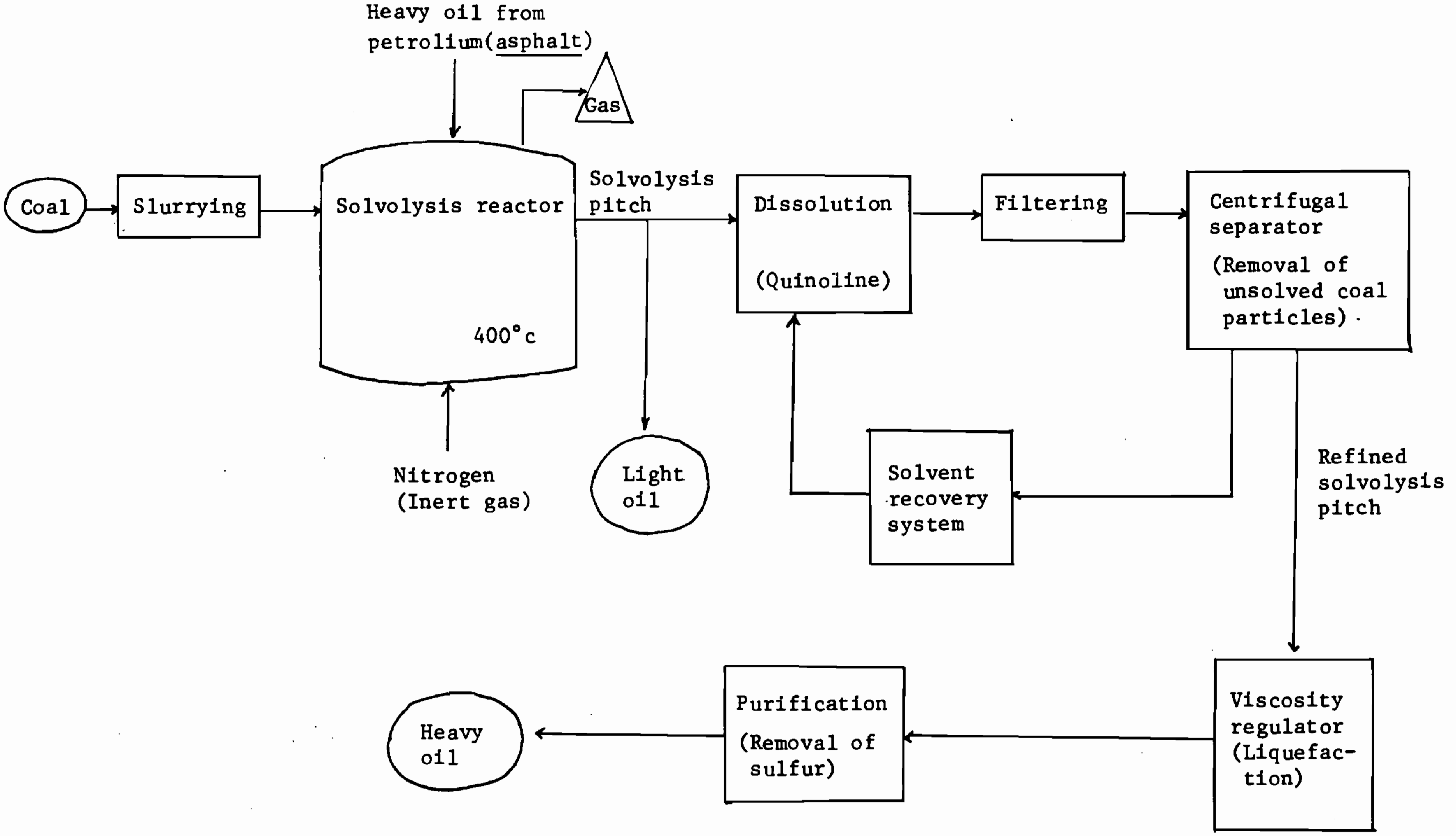
B. Consol Process (Consolidation Coal Company)



C. H-Coal (Hydrocarbon Research, Inc. HRI)



D. COED (Char Oil Energy Development)
(F.M.C. Corporation)



E. Solvolsis Liquefaction of Coal (National Industrial Research Institute, Japan)