

Conversion of Coal to Substitute Natural Gas (SNG)

- Steam-Oxygen Gasification
 - Catalytic Gasification
 - Hydrogasification
 - Underground Steam-Oxygen Gasification
 - Underground Hydrogasification (PCM)
-

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PROCESSES FOR CONVERSION OF COAL TO SUBSTITUTE NATURAL GAS (SNG)

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Because the increasing demand for natural gas (methane) in the United States and the limited domestic supply, foreign natural gas imports have grown and the cost has risen to a value between \$6 and \$9 / MSCF. Unconventional sources such as coal bedded methane (CBM) are increasing in supply importance. A singularly large indigenous energy resource in the United States is coal. It therefore becomes prudent to examine the technology and economics of processes for conversion of coal to substitute natural gas (SNG), which would open another source of supply for methane. Table 0 lists important reasons for converting U.S. coal to SNG.

There are at least 5 process methods for conversion of coal to SNG.

1. Steam-Oxygen Gasification
2. Catalytic Steam Gasification
3. Hydrogasification
4. Underground Steam-Oxygen Gasification
5. Underground Hydrogasification

1. Steam-Oxygen Gasification

Fig.1 shows a process flow sheet and Table 1 gives the process chemistry, mass balance and energy balance for the steam-oxygen gasification process. This process is demonstrated in the North Dakota Gasification Plant in Beulah, North Dakota, where approximately 20,000 T/D of lignite is converted to 120×10^6 SCF of methane (SNG). The calculated thermal efficiency based on data in the Table indicates a thermal efficiency of 61.9% for conversion of the heating value of lignite to the heating value of the methane produced. The capital investment for the

plant is high because of the need for an air liquefaction plant, a steam-oxygen coal gasifier, and a catalytic methanator.

It is estimated that the capital investment is of the order of \$6,250 / MSCF/D of methane produced, determined by updating the North Dakota plant investment. For estimating the production cost, the financial factors used previously (HCEI-11-04-2) are adopted here.

Production Cost based on \$12 / ton lignite = \$0.73 / MMBTU and Thermal Efficiency = 61.9% is calculated as follows:

Factor	Calculation	<u>\$/MSCF</u>
Lignite	= $0.73 / 0.619 =$	1.18
Fixed Charges	= $(0.20 \times 6250) / (0.8 \times 365) =$	4.28
O&M	= $0.15 \times 4.28 =$	0.64
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Production Cost		6.10

2. Catalytic Steam Gasification

FIG.2 shows a process flow sheet and table 2 gives the process chemistry and mass and energy balance for catalytic steam gasification of lignite. The process was originally developed by Exxon in the 1970s. The catalyst is potassium carbonate used in large quantities, amounting to about 20% by weight of the feedstock, which combines with the coal ash, and has to be separated and recovered from the alumina and silica in the ash. It is estimated that the energy requirement for the recovery process is equivalent to 0.05 moles CH₄ per mole of lignite. Catalytic gasification requires less energy input to the gasifier than steam-oxygen gasification and the methane is produced directly. There is no requirement for an oxygen plant and a methanator. The capital investment would, therefore, be about 75% of the investment in the steam-oxygen gasification plant, which results in a capital investment of \$4,688 / MSCF per day. The catalyst cost assumes that 1% of the weight of the coal carrying 20% catalyst is lost and has to be replaced at \$500 / ton of K₂CO₃.

Production Cost Based On \$12 per ton lignite = \$0.73 / MMBTU and thermal efficiency = 71.4%

<u>Factor</u>	<u>Calculation</u>	<u>\$/MSCF</u>
Lignite	= $0.73 / 0.714 =$	1.02
Fixed Charges	= $(0.20 \times 4688) / (0.8 \times 365) =$	3.21
O&M	= $0.15 \times 3.21 =$	0.48
Cost of Catalyst	=	0.41
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Production Cost		5.12

3. Hydrogasification

FIG. 3 shows the process flow sheet and Table 3 gives the mass balance and energy balance for the hydrogasification of lignite to produce substitute natural gas (SNG). The main feature of this process is that the hydrogasification is exothermic, which makes the process thermally energy efficient. The main problem is the necessity of making up for the deficiency of hydrogen by reforming part of the methane produced in the hydrogasifier.

The thermal efficiency of the process is 79.6%, which is 30% higher than the steam-oxygen gasification.

It is estimated that the capital investment for this plant is 75% of that of the steam-oxygen plant - \$4,688 / MSCF per day, about the same as the catalytic gasification process.

Production cost estimate is based on \$12 / ton lignite = \$0.73 / MMBTU:

<u>Factor</u>	<u>Calculation</u>	<u>\$/MSCF</u>
Lignite	= $0.73 / 0.796 =$	0.92
Fixed Charges	= $(0.20 \times 4688) / (0.8 \times 365) =$	3.21
O&M	= $0.15 \times 3.21 =$	0.48
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Production Cost		4.61

The estimated production cost is 25% lower than the steam-oxygen gasification plant and 10% lower than for the catalytic gasification plant.

4. Underground Steam-Oxygen Gasification of Coal (UCG)

This process is the same as the above-ground steam-oxygen gasification of coal with the exception that two boreholes are drilled into a coal seam: one is an injection borehole and the other is an extraction borehole. Fracturing the coal seam between the boreholes is accomplished by explosives or hydraulic pressure to provide a path for the steam and oxygen between the injection and extraction boreholes. The oxygen permits burning the coal, which creates the temperature and pressure and provides the energy for the steam to endothermically react with the coal in the seam. Oxygen instead of air avoids dilution of the gases with nitrogen.

The gasification reaction produces carbon monoxide and hydrogen synthesis gas. The sulfur and nitrogen in the coal are converted to H_2S and NH_3 , which are extracted with the synthesis gas. Above ground, the sulfur and nitrogen compounds and any entrained coal or ash particulates are removed using hot gas cleaning operations.

The hydrogen to carbon monoxide ratio in the extracted reaction gas is adjusted by water gas shift to provide a 3 to 1 ratio of hydrogen to carbon monoxide. This ratio is needed to convert the gas to methane in a catalytic methanator. The methane reaction is exothermic and the heat generates steam for the process. The water produced in the methanator is condensed to produce a concentrated substitute natural gas (SNG) product for pipelining.

The thermal efficiency for this process is 61.9%. FIG. 4 is a schematic of the underground steam-oxygen gasification of coal process.

By eliminating the mining of the coal, but including underground site preparation, it is estimated that the capital investment for steam-oxygen gasification is reduced to \$6095 / MSCF/D of methane. Continuous operation, gas storage and redundant equipment can provide a high capacity factor.

The production cost is calculated as follows:

<u>Factor</u>	<u>Calculation</u>	<u>\$ / MSCF</u>
Fixed Charges	= (0.20 x 6095) / 365 =	3.34
O&M	= 0.15 x 3.34 =	0.50
<hr/>		
Production Cost		3.84

5. Underground Hydrogasification of Coal (aka Pumped Carbon Mining, PCM)

The underground hydrogasification of coal for SNG production is similar to the above ground process with the exception that the hydrogasification takes place underground. This process is especially useful for unminable coal seams and where methane is produced from coal bedded methane (CBM) in these seams.

The coal seam is accessed by two vertical boreholes spaced a distance apart; one is the intended injection borehole and the other is the intended extraction borehole. A flow connection is then established between the boreholes. This can be accomplished by a number of means, one of which is by horizontal drilling between the holes.

The existing methane resource in the coal seam is removed through the extraction borehole using established coal bedded methane extraction procedures. In this process, the water in the seam is also removed and this is beneficial to the subsequent hydrogasification process.

The hydrogasification process then begins with the injection into the coal seam of heated and pressurized hydrogen. Under these conditions, the hydrogen exothermically reacts with the coal, producing methane and carbon monoxide. Some of the nitrogen and sulfur in the coal is converted to ammonia and hydrogen sulfide. An excess of hydrogen is used to convert the carbon to methane under equilibrium conditions (see HCEI 10-04-3).

The reaction gas flowing out of the extraction borehole is subjected to hot gas cleanup, which removes most of the unwanted contaminant gases and particulates and leaves a methane-rich stream containing hydrogen and carbon monoxide. The methane is separated from the other

gases by pressure swing adsorption (PSA) or cryogenically. Since there is insufficient hydrogen in the coal to combine with the carbon in the coal to form methane, the hydrogen must be produced by reacting part of the methane produced with water in a steam-reforming operation. The net methane produced results in a thermal efficiency of 79.6% for conversion of the energy in lignite to the energy in the methane.

When connecting the hydrogasification to coal bedded methane (CBM) operations, the underground site preparation cost is borne by the CBM operation and there is no oxygen or methanator investment. This reduces the capital investment to about \$4,571 / MSCF/D (HCEI-11-04-2).

The production cost is estimated as follows:

<u>Factor</u>	<u>Calculation</u>	<u>\$ / MSCF</u>
Fixed Charges	= (0.20 x 4571) / 365 =	2.50
O&M	= 0.15 x 2.50 =	0.38
<hr/>		
Production Cost		2.88

QUALITATIVE ANALYSIS OF PROCESSES FOR PRODUCTION OF SUBSTITUTE NATURAL GAS (SNG) FROM COAL RESOURCES

There are at least five processes for conversion of coal to substitute natural gas (SNG) as described previously. The following is a critical qualitative analysis of these processes.

1) Steam Oxygen Gasification of Coal

The steam-oxygen gasification of coal is a well-know process, which has been practiced since the 1940s. Various types of gasifiers have been developed employing steam and oxygen with coal feedstock. The following is a list of the drawbacks in using this process for conversion of coal to SNG:

1. The steam-oxygen reaction with coal to form synthesis gas (CO and H₂) is highly endothermic.
2. An oxygen plant is required.
3. A methanator is required.
4. The thermal efficiency is low, about 60%.
5. Capital investment is high.

2) Catalytic Gasification of Coal

Exxon developed this process during the 1970s, operating it in a pilot plant. A full scale production plant was never built because it was not competitive. The features of the process compared to steam-oxygen gasification are as follows:

1. The catalytic steam reaction is endothermic, but much less so than the steam-oxygen process.
2. There is no need for an oxygen plant.

3. There is a huge requirement for catalyst, amounting to as much as 20% of the coal feedstock. Recovery of catalyst, K_2CO_3 from coal ash is costly.
4. There is no requirement for a methanator.
5. The thermal efficiency is higher than steam-oxygen gasification, reaching into the 70%.
6. The capital investment is lower than for steam-oxygen gasification.

3) Hydrogasification of Coal

Hydrogasification of coal for production of methane (SNG) was pilot planted in Germany in the 1970's, but the process was never put into practice at full scale. The features of this process are as follows:

1. The hydrogasification of coal is exothermic, thus requiring no oxygen or steam addition.
2. There is no requirement for a methanator.
3. The process has a high thermal conversion efficiency reaching into the 80%.
4. It is necessary to convert part of the methane back to hydrogen by reforming with steam.
5. The capital investment is lower than for steam-oxygen gasification.
6. There is no requirement for a catalyst.

4) Underground Steam-Oxygen Coal Gasification (UCG)

There has been much research and development on underground coal gasification in the United States and Russia during the 1970s. The features of the process are as follows:

1. Coal mining and preparation for above ground processing is eliminated.
2. Steam-oxygen injection is required underground, which may have safety problems due to incomplete reaction and production of explosive gaseous mixtures in confined spaces.

3. Difficult to control problems with fissures and crossovers to keep inflow and outflow paths separated.
4. An oxygen plant and methanation reactor are required.
5. Thermal conversion efficiency is lower than hydrogasification.

5) Underground Coal Hydrogasification (Pumped Carbon Mining, PCM)

The underground hydrogasification of coal has been proposed in the 1980s, but was never tested. It has been recently proposed in conjunction with coal bedded methane extraction. The hydrogasification is beneficial in configuration with the extraction of methane from unminable coal deposits. The features of the process are as follows:

1. After the coal bedded methane is extracted, the hydrogasification of the remaining coal would increase the production of methane from the coal seam by a factor of 20 or more times that produced from the coal bedded methane recovery operation alone (HCEI-11-04-2).
2. There is no mining or handling of coal for above ground processing.
3. The additional hydrogen needed is produced by steam reforming part of the methane directly produced by hydrogasification.
4. No oxygen or methanator plants are needed, so that the capital investment is lower than steam-oxygen processing.
5. The cost of the preparation of the mine for underground hydrogasification is borne by the coal bedded methane operations.

It should be noted that underground catalytic gasification of coal as developed by Exxon is not feasible because of the large loss of catalyst underground even if it were possible to inject catalyst underground.

Table 4 gives a summary comparison of the various factors for conversion of coal to SNG. Underground hydrogasification of coal (PCM) for SNG appears to have the highest thermal efficiency and lowest production cost.

CO₂ Emissions

Increasing efficiency also has an impact on carbon dioxide emissions. All of these processes essentially emit concentrated carbon dioxide streams, which can be captured and sequestered. However, the higher the thermal efficiency, the lower the carbon dioxide volume and thus the lower sequestration requirements. Thus, the hydrogasification process at 79.6% thermal efficiency emits 46.5% less carbon dioxide than the steam-oxygen gasification process at a thermal efficiency of 61.9%.

PUMPED CARBON MINING (PCM) COST ESTIMATE Based On Large Central Plant Servicing A Number Of Coal Bedded Methane Wells

As noted in the cost estimate report, HCEI 11-04-2, it is possible to optimize the size of the hydrogen production plant so that it can supply hydrogen to a number of underground hydrogasification wells. The optimized hydrogen plant would collect the gas from a number of extraction boreholes of the wells and deliver hydrogen to the injection boreholes. Insulated piping to and from centralized processing would be utilized to deliver the high temperature and high pressure hydrogen and carbon monoxide to the wells and carry back the methane rich gas to the central processing plant. The central processing plant would contain the hot gas cleanup, heat exchangers, water gas shift and methane and carbon dioxide gas separation and pumping equipment as well as the steam reformer for the hydrogen production. The concept of a central processing plant is important because each well may have variable production. It would become expensive to locate all processing equipment at each such well especially for those wells that had relatively small production capacity.

A rough example of an optimized central processing plant is as follows:

A methane reforming plant producing 100,000 MSCF / D of hydrogen should cost today approximately \$100 million (HCEI-11-04-2). This amount of hydrogen can service the

following capacity of methane produced by the Pumped Carbon Mining or lignite gasification process following extraction of the coal bedded methane.

Methane Production	=	46,000 MSCF / D
Methane to Reformer	=	25,000 MSCF / D
Methane to Furnace	=	<u>9,000 MSCF / D</u>
 Total Well Methane Produced	=	 80,000 MSCF / D

If the amount of the total methane produced is 20 times more than the coal bedded methane (CBM), then the CBM production capacity would be 4,000 MSCF / D. If the average CBM capacity per well is only 200 MSCF / D (Ref. Mike Gatens, Oil & Gas , pp. 41-43, Dec. 13, 2004), then the central plant can handle gases from 20 wells, or if the CBM wells produce an average of 400 MSCF / D, then the central plant can process gas from 10 wells.

A rough capital and production cost estimate fro this capacity is as follows: The flow sheet of FIG. 5 is followed where only one water gas shift reactor is needed. The highest cost element is the methane reformer. The other equipment is roughly estimated relative to the reformer.

Capital Investment

<u>Unit</u>	<u>\$ Millions</u>
Hot Gas Cleanup	10
Heat Exchanger	10
Water Gas Shift (Included in the H ₂ plant cost)	---
Gas Separation (PSA or Cryo)	20
Circulator Pumping	10
Methane Reforming for H ₂	<u>100</u>
 <u>Total Capital Investment</u>	 <u>150</u>

Production Cost: (using same financial factors as in HCEI-11-04-2)

<u>Factor</u>	<u>Calculation</u>	<u>\$ / D</u>
The underground lignite well preparation		charged to CBM
Fixed Charge = $(0.2 \times 150 \times 10^6) / (365 \text{ D / yr})$	=	82,190
<u>Op. & Maint. = $0.15 \times 82,190$</u>	=	<u>12,330</u>
 Total Production Cost	=	 94,520

$$\text{Unit production Cost of Methane} = 94,520 / 46,000 = \underline{\underline{\$2.05 / MSCF}}$$

Thus, it is shown that by centralizing the processing and collecting the gas from a number of wells, the unit methane production cost can be reduced significantly, resulting in a high rate of return.

Table 0

Why Convert Coal to Substitute Natural Gas (SNG)?

1. Coal is Largest Indigenous Energy Resource in the United States.
2. Natural Gas is the Most Convenient and Cleanest Consumer Fuel For Heat, Power & Automotive Use.
3. Transportation and Distribution of Natural Gas by Pipeline is Widely Available and Economical.
4. Natural Gas Resource in the U.S. is Limited.
5. Natural Gas Demand is Increasing – Resulting in Reliance on Imports (Gas from Canada and LNG from Overseas).
6. Natural Gas has Significantly Increased in Cost.
7. Processes for Conversion of Coal to SNG are Increasing in Competitiveness.
8. Coal Bedded Methane (CBM) Production is increasing in Supply.

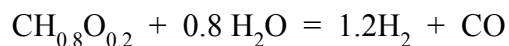
Table 1

Steam-Oxygen Coal Gasification for Production of Substitute Natural Gas (SNG)

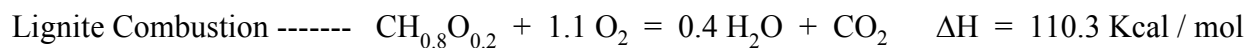
Unit Operations and Process Chemistry

Basis: Lignite Coal

1) Steam-Oxygen Gasification of Lignite



$\Delta H = +47.7$ Kcal/mol lignite – endothermic - 90% lignite conversion

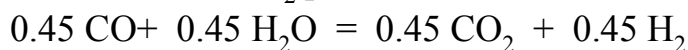


2) Oxygen Plant – using an Electricity Powered Cryogenic Process

$$\text{Energy} = 11.4 \text{ Kcal / g-mol lignite}$$

3) Hot Gas Cleanup – Remove Sulfur and Nitrogen Compounds

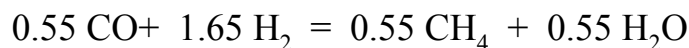
4) Water Gas Shift for H₂ production



$\Delta H = 0$ – energy neutral

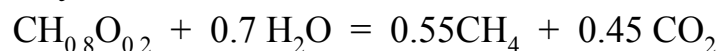
5) CO₂ Separation – Pressure Swing Adsorption - PSA

6) Methanation



$\Delta H = -33.0$ Kcal – exothermic for steam production

Overall Stoichiometry



$$\text{Thermal Efficiency} = \frac{0.55 \text{CH}_4 \times 0.9}{1.0 \text{CH}_{0.8} + 0.432 \text{CH}_{0.8}\text{O}_{0.2} + \text{O}_2 \text{ Plant Energy}} = 61.9\%$$

$$= \frac{0.55 \times 0.9 \times 212}{110.3 + 47.7 + 11.4} \times 100 = 61.9\%$$

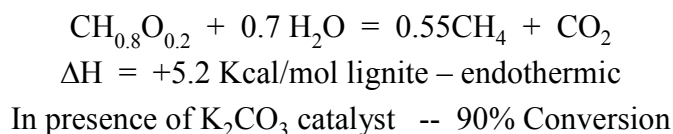
Table 2

Catalytic Steam Gasification of Coal for Production of Substitute Natural Gas (SNG)

Unit Operations and Process Chemistry

Basis – Lignite Coal

1) Catalytic Steam Gasification of Lignite



Catalyst Content is 20% of lignite feedstock by weight

2) Separation and Recovery of K_2CO_3 from ash containing silica and alumina

Takes 0.05 g-mol CH_4 of equivalent energy for process per g-mol lignite

3) Pressure Swing Adsorption or cryogenic separation of CH_4 and CO_2 from H_2 and CO

4) Recycling H_2 and CO and preheating in a methane-fired furnace takes 0.08 mols CH_4 / g-mol lignite

$$\text{Net CH}_4 \text{ produced} = 0.55 - 0.05 - 0.08 = 0.42 \text{ g-mol}$$

$$\text{Thermal Efficiency} = [(0.9 \times 0.42 \times 212) / 110.3] \times 100 = 72.7\%$$

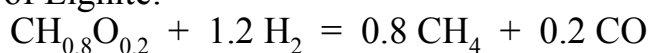
Table 3

Coal Hydrogasification for Production of Substitute Natural Gas (SNG)

Unit Operations and Process Chemistry

Basis – Lignite Coal

1) Hydrogasification of Lignite:



$\Delta H = -9.8$ Kcal/g-mol lignite – exothermic -- 90% Conversion

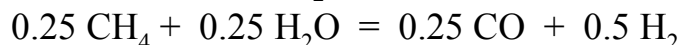
2) Hot Gas Cleanup. Remove Sulfur and Nitrogen Compounds.

3) Water Gas Shift : $0.2 \text{CO} + 0.2 \text{H}_2\text{O} = 0.2 \text{CO}_2 + 0.2 \text{H}_2$

$\Delta H = 0$ – energy neutral

4) Pressure Swing Adsorption or Cryogenic Separation of CH_4 and CO_2 from H_2 and CO

(5) Steam Reforming of Methane for H_2 Makeup Production

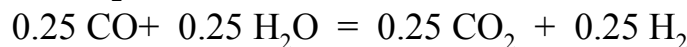


$\Delta H = 0 + 15.0$ Kcal - endothermic

(6) Methane Combustion: $\text{CH}_4 + 2 \text{O}_2 = \text{CO}_2 + 2 \text{H}_2\text{O}$

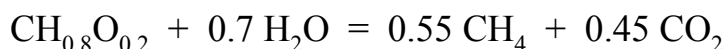
$\Delta H = 212$ Kcal / g-mol – at 80% eff. $\text{CH}_4 = 15 / (0.8 \times 212) = 0.09$ g-mol

(7) Water Gas Shift for H_2 production:



(8) CO_2 Separation – PSA

(9) Overall Stoichiometry:



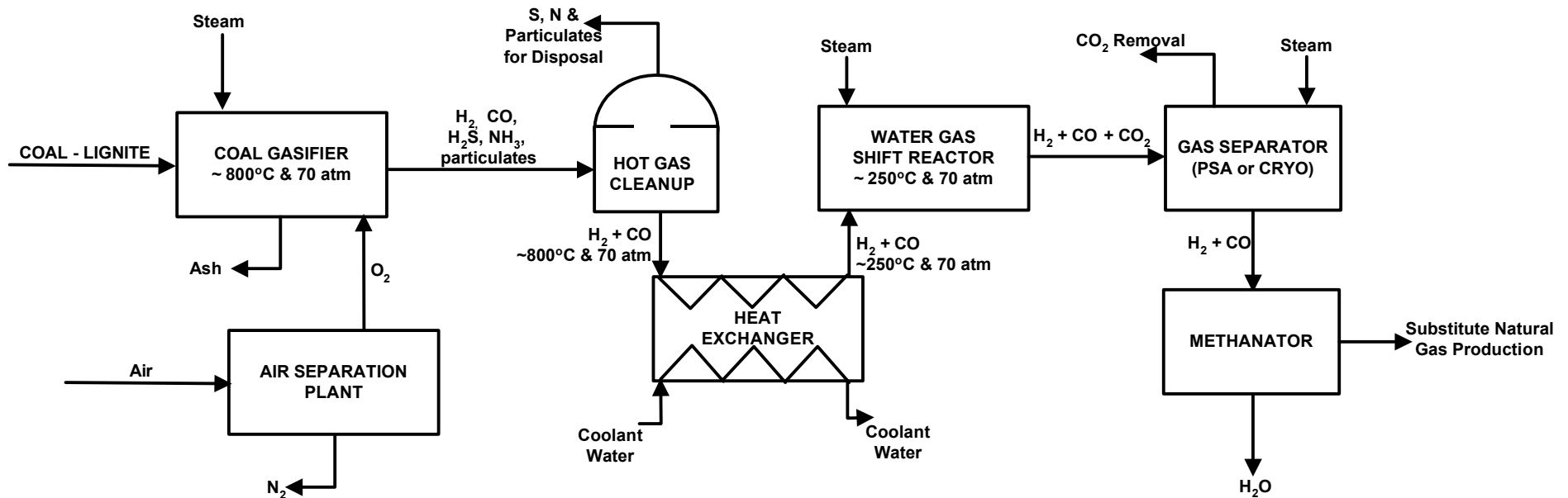
(10) Net CH_4 produced = $0.55 - 0.09 = 0.46$ g-mol

(11) Thermal Efficiency = $[(0.46 \times 212 \times 0.9) / 110.3] \times 100 = 79.6\%$

Table 4
Comparison of Processes for
Conversion of Coal to Substitute Natural Gas (SNG)

Item	Steam-Oxygen Gasification	Catalytic Steam Gasification	Hydrogasification	Underground Steam-Oxygen Gasification	Underground Hydrogasification Pumped Carbon Mining (PCM)
Coal Feedstock	Mined, Crushed, Transported	Mined, Crushed, Transported	Mined, Crushed, Transported	Underground Fracturing of Coal Seam	Following Coal Bedded Methane Extraction
Oxygen Plant	Yes	No	No	Yes	No
Methanator	Yes	No	No	Yes	No
Thermal Efficiency	61.9%	71.9%	79.6%	61.9%	79.6%
Catalyst Requirement	No	Yes	No	No	No
CO₂ Emission Lbs CO₂/MSCF	276	193	164	276	164
% Reduction CO₂	0	30.0	45.5	0	45.5
Capital Investment \$ per MSCF per day	6250	4688	4688	6095	4571
Production Cost \$ per MSCF	6.10	5.12	4.61	3.84	2.88

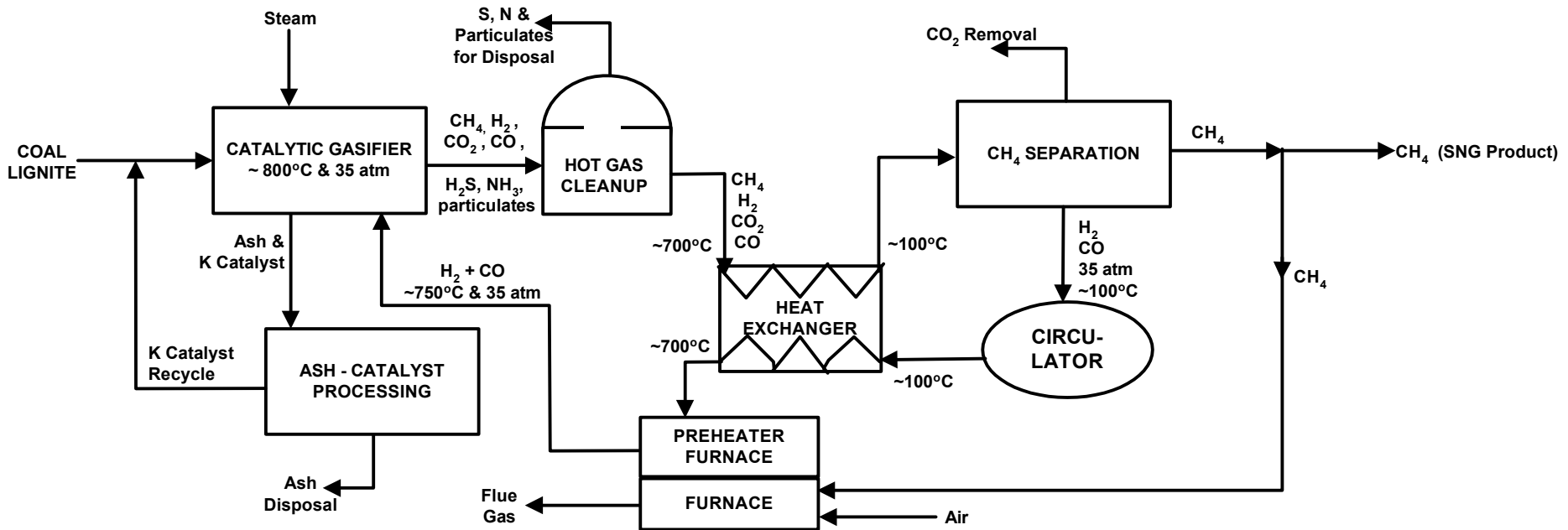
FIG. 1
STEAM-OXYGEN COAL GASIFICATION FOR
SUBSTITUTE NATURAL GAS (SNG) PRODUCTION



REACTION CHEMISTRY -Calculated Thermal Efficiency = 61.9%

- (1) Steam Gasification of Coal Lignite: $\text{CH}_{0.8}\text{O}_{0.2} + 0.8 \text{H}_2\text{O} = 1.2 \text{H}_2 + \text{CO}$ --- $\Delta H = + 47.7 \text{ Kcal / g-mol lignite}$ - endothermic
- (2) Lignite Combustion: $\text{CH}_{0.8}\text{O}_{0.2} + 1.1 \text{O}_2 = 0.4 \text{H}_2\text{O} + \text{CO}_2$ --- $\Delta H = - 110.3 \text{ Kcal / g-mol}$
- (3) Hot Gas Cleanup removes N, S & particulates
- (4) Water Gas Shift $0.45 \text{CO} + 0.45 \text{H}_2\text{O} = 0.45\text{CO}_2 + 0.45 \text{H}_2$
- (5) Gas Separator, e.g. Differential Pressure Swing Adsorption or Cryogenic Separation, takes out CO_2
- (6) Methanation: $0.55 \text{CO} + 1.65 \text{H}_2 = 0.55 \text{CH}_4 + 0.55 \text{H}_2\text{O}$ --- $\Delta H = - 33.0 \text{ Kcal}$ – exothermic for steam production
- (7) Overall Mass Balance: $\text{CH}_{0.8}\text{O}_{0.2} + 0.7 \text{H}_2\text{O} = 0.55 \text{CH}_4 + 0.45 \text{CO}_2$

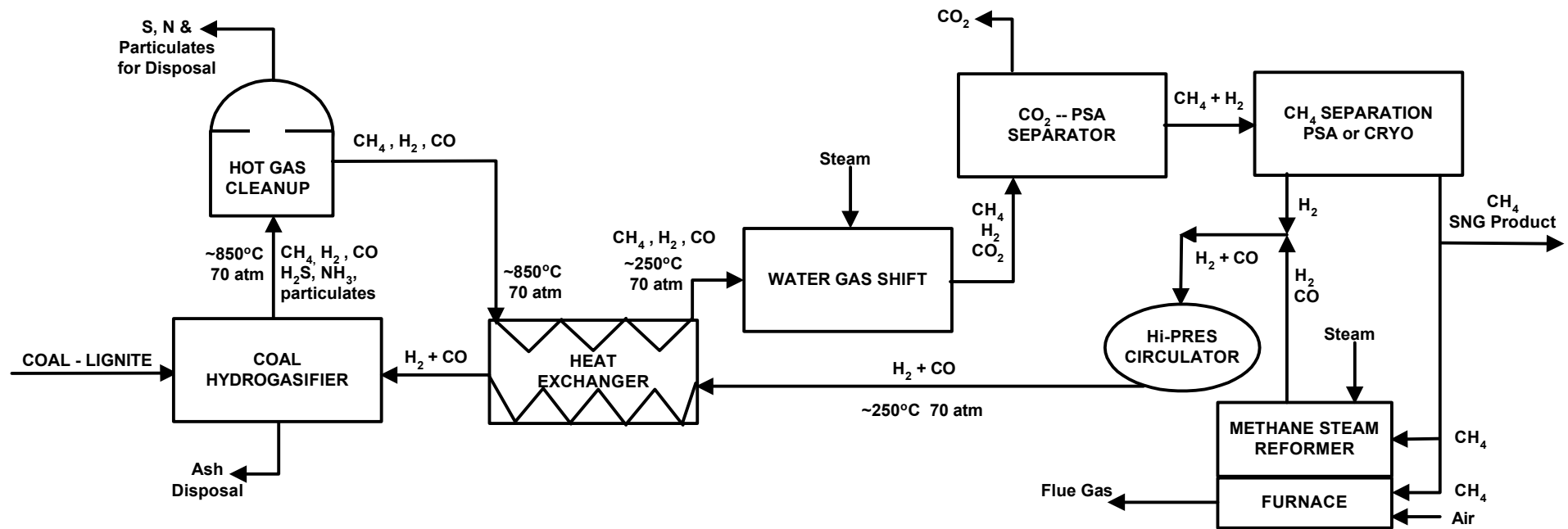
FIG. 2
CATALYTIC STEAM GASIFICATION FOR
SUBSTITUTE NATURAL GAS (SNG) PRODUCTION



REACTION CHEMISTRY - Calculated Thermal Efficiency = 72.7%

- (1) Catalytic Steam Gasification of Lignite: $\text{CH}_{0.8} \text{O}_{0.2} + 0.7 \text{H}_2\text{O} = 0.55 \text{CH}_4 + 0.45 \text{CO}_2$ --- $\Delta H = + 5.2 \text{ Kcal / g-mol lignite}$ - endothermic
- (2) Hot Gas Cleanup removes N, S & particulates
- (3) K_2CO_3 / SiO_2 ash separation
- (4) CH_4 Cryogenic Separation 0.05
- (5) CH_4 for Preheat - 0.08 g-mol

FIG. 3
LIGNITE COAL HYDROGASIFICATION FOR
SUBSTITUTE NATURAL GAS (SNG) PRODUCTION



REACTION CHEMISTRY - Calculated Thermal Efficiency for SNG Production = 79.6%

(1) Hydrogasification of Lignite: $\text{CH}_{0.8}\text{O}_{0.2} + 1.2 \text{H}_2 = 0.8 \text{CH}_4 + 0.2 \text{CO}$ --- $\Delta H = -9.8 \text{ Kcal / g-mol lignite}$ - exothermic.

(2) Hot Gas Cleanup Removes N, S & particulates

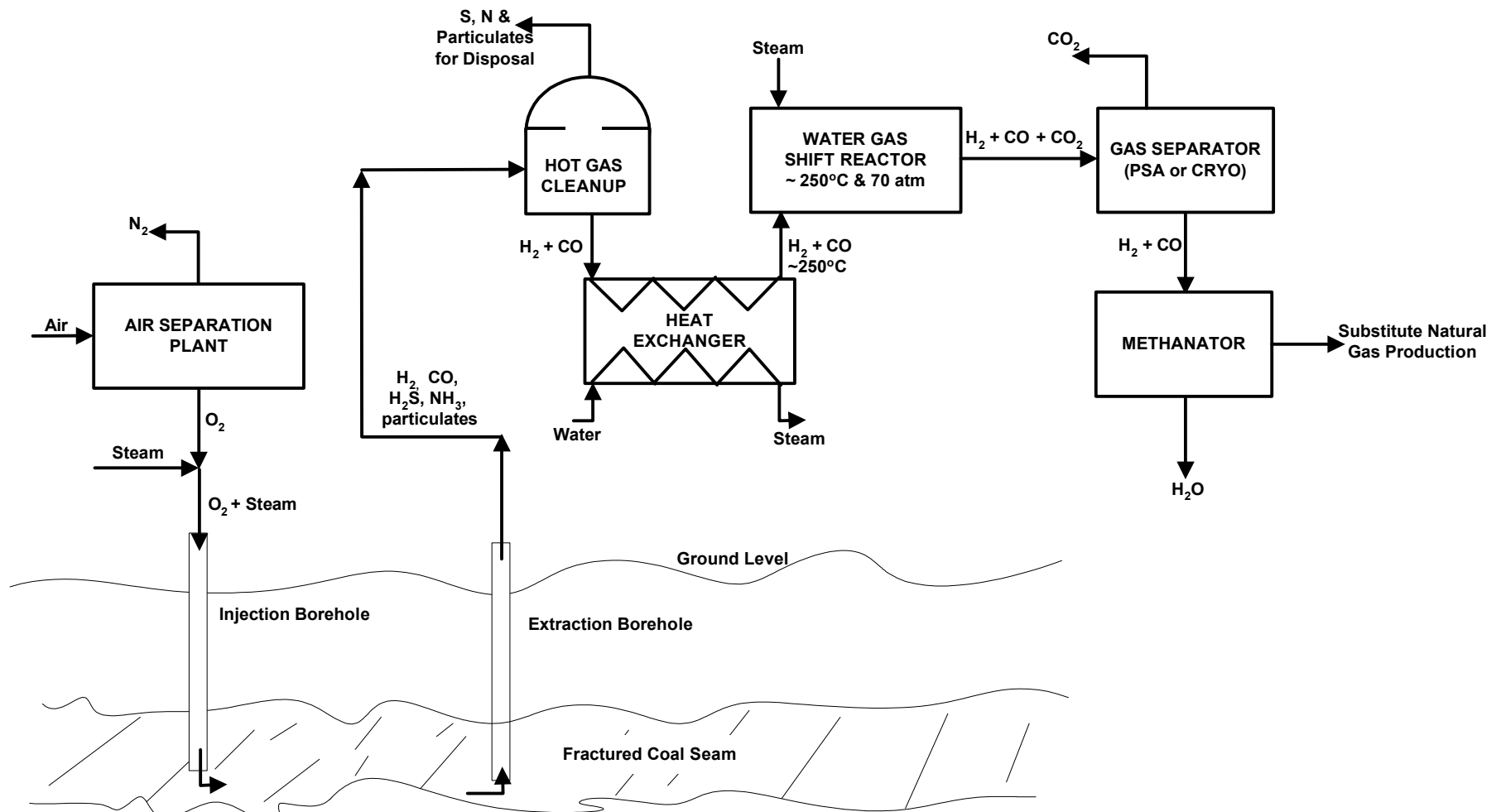
(3) Water Gas Shift: $0.25 \text{CO} + 0.25 \text{H}_2\text{O} = 0.25 \text{CO}_2 + 0.25 \text{H}_2$ --- $\Delta H = 0$ Neutral

(4) Steam Reforming of Methane: $0.25 \text{CH}_4 + 0.25 \text{H}_2\text{O} = 0.25 \text{CO} + 0.75 \text{H}_2$ $\Delta H = +15.0 \text{ Kcal}$ - endothermic

(5) Methane Combustion: $\text{CH}_4 + 2 \text{O}_2 = \text{CO}_2 + 2 \text{H}_2\text{O}$ --- $\Delta H = -212 \text{ Kcal / g-mol}$, requires only 0.09 g-mol CH_4

(6) Overall Stoichiometry: $\text{CH}_{0.8}\text{O}_{0.2} + 0.7 \text{H}_2\text{O} = 0.55 \text{CH}_4 + 0.45 \text{CO}_2$

FIG. 4
UNDERGROUND STEAM-OXYGEN COAL GASIFICATION FOR
SUBSTITUTE NATURAL GAS (SNG) PRODUCTION



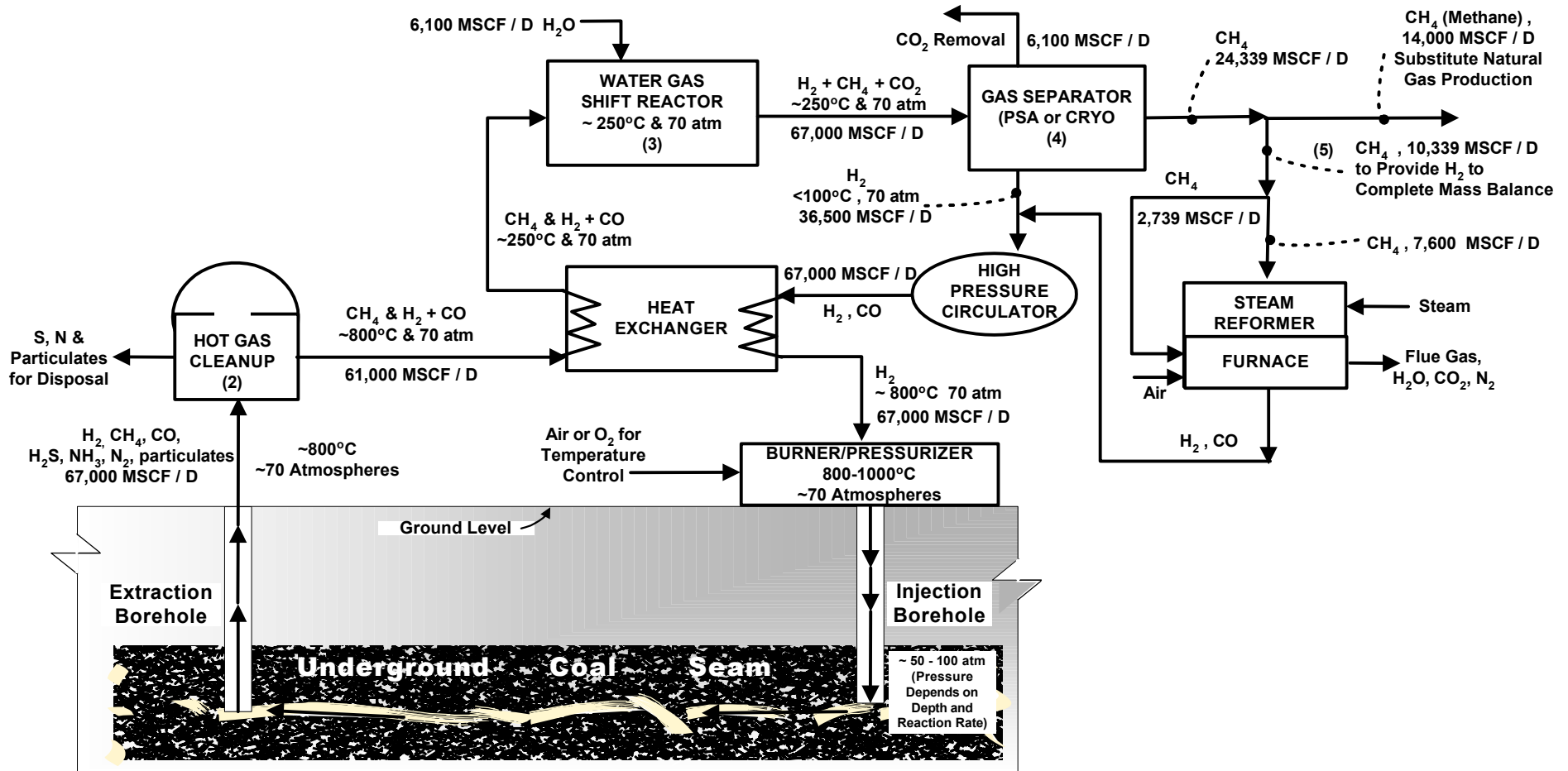
REACTION CHEMISTRY - Calculated Thermal Efficiency = 61.9%

- (1) Underground Lignite Gasification: $\text{CH}_{0.8} \text{O}_{0.2} + 0.8 \text{H}_2\text{O} = 1.2 \text{H}_2 + \text{CO}$ --- $\Delta H = + 47.7 \text{ Kcal / g-mol lignite}$ - endothermic
- (2) Combustion of Lignite: $\text{CH}_{0.8} \text{O}_{0.2} + 1.1 \text{O}_2 = 0.4 \text{H}_2\text{O} + \text{CO}_2$ --- Combustion = endothermic $\Delta H = - 110.3 \text{ Kcal / g-mol}$
- (3) Hot Gas Cleanup removes N, S & particulates
- (3) Water Gas Shift $0.45 \text{CO} + 0.45 \text{H}_2\text{O} = 0.45\text{CO}_2 + 0.45 \text{H}_2$ --- $\Delta H = 0$
- (4) Gas Separator, e.g. Differential Pressure Swing Adsorption or Cryogenic Separation, takes CO_2
- (5) Methanation: $0.55 \text{CO} + 1.65 \text{H}_2 = 0.55 \text{CH}_4 + 0.55 \text{H}_2\text{O}$ --- $\Delta H = 33.0 \text{ Kcal}$ – exothermic for steam production
- (6) Overall Mass Balance: $\text{CH}_{0.8} \text{O}_{0.2} + 0.7 \text{H}_2\text{O} = 0.55 \text{CH}_4 + 0.45 \text{CO}_2$

FIG 5. PUMPED CARBON MINING: SUBSTITUTE NATURAL GAS PRODUCTION

Underground Coal Hydrogasification With Above Processing

Process to Increase Initial Coal Bedded Methane Net Production Rate of 700 MSCF / D to 14,000 MSCF / D



REACTION CHEMISTRY - Calculated Thermal Efficiency = 79.6%

(1) Hydrogasification of Coal Lignite: $\text{CH}_{0.8}\text{O}_{0.2} + 1.2\text{H}_2 = 0.8\text{CH}_4 + 0.2\text{CO}$

1.2 H_2 excess is circulated to reach equilibrium CH_4 concentration (40%). Other gases formed are $\text{H}_2\text{O}, \text{CO}_2, \text{H}_2\text{S}, \text{NH}_3, \text{N}_2$

(2) Hot Gas Cleanup removes N, S & particulates

(3) Water Gas Shift $0.2\text{CO} + 0.2\text{H}_2\text{O} = 0.2\text{CO}_2 + 0.2\text{H}_2$

(4) Gas Separator, e.g. Differential Pressure Swing Adsorption or Cryogenic Separation, takes out all gases except hydrogen. PSA removes CO_2 with zeolite, CH_4 on carbon adsorbant.

(5) To complete balance, 1 mole H_2 must be added. It is obtained by steam reforming

0.25 mole CH_4 : $0.25\text{CH}_4 + 0.25\text{H}_2\text{O} = 0.25\text{CO} + 0.75\text{H}_2$

0.25 $\text{CO} + 0.25\text{H}_2\text{O} = 0.25\text{CO}_2 + 0.25\text{H}_2$; Furnace heat required: $0.09\text{CH}_4 + \text{Air} = 0.09\text{CO}_2 + 0.18\text{H}_2\text{O}$

Overall Mass Balance: $\text{CH}_{0.8}\text{O}_{0.2} + 0.7\text{H}_2\text{O} = 0.55\text{CH}_4 + 0.45\text{CO}_2$; Net CH_4 Production = $0.8 - 0.34 = 0.46\text{CH}_4$