

**PUMPED CARBON MINING (PCM)**  
**SUBSTITUTE NATURAL GAS (SNG) PRODUCTION**  
**Underground Coal Gasification with Above Ground Processing**

HCE, LLC

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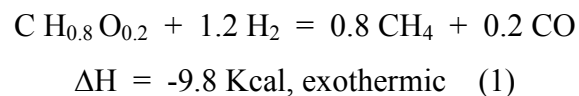
(Revision 1)

The process is useful after completion of a Coal Bedded Methane (CBM) extraction operation. It enables supplemental production of methane from a coal bed, approximately equivalent to an increase of methane production by as much as 20 times that obtained from the coal bedded methane production operation.

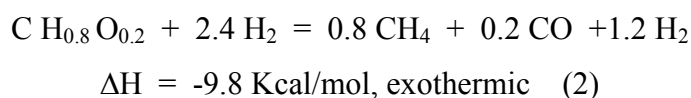
After extracting the free methane from the underground coal bed and dewatering the bed, heated hydrogen is circulated through the bed to heat it to reaction temperatures. The hydrogenation of the coal to form methane best takes place at elevated temperatures of the order of 800 – 900°C and elevated pressures of the order of 50 to 100 atmospheres. The specific pressure-temperature conditions depend on the type of coal in the bed and the reaction rate. These specific conditions are determined by laboratory experiments, above ground, with coal taken from the bed.

After the temperature-pressure process conditions are reached in the bed, hydrogenation begins and is self-sustained because it involves an exothermic hydrogenation reaction that releases thermal energy.

Based on one mole of an average lignite, the hydrogenation reaction is represented by the following stoichiometric chemical reaction:

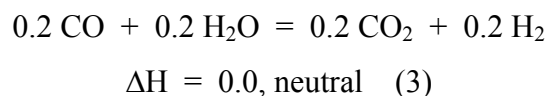


The hydrogenation reaction with the coal is equilibrium limited, so that in order to obtain maximum conversion of the carbon to methane, excess hydrogen must be circulated through the coal bed to maintain a high partial pressure of hydrogen throughout the bed. From equilibrium data<sup>(1)</sup> and a process demonstration unit (PDU)<sup>(2)</sup>, it is estimated that the equilibrium concentration of methane gas that can be obtained from coal in a high pressure, high temperature hydrogen stream is about 40%. This means that the excess hydrogen that must be added to the above reaction is about equal to the reacted hydrogen (1.2 moles H<sub>2</sub>). Thus, the hydrogasification reaction reads as follows:



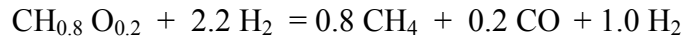
The exothermic heat released is -9.8 Kcal/mol. In addition to CH<sub>4</sub> and CO gas, small equilibrium amounts of CO<sub>2</sub> and H<sub>2</sub>O will be formed. Other contaminant gasses are H<sub>2</sub>S, NH<sub>3</sub> and N<sub>2</sub>. Small amounts of entrained ash particles are also expected in the effluent gas from the extraction borehole. The hot effluent gas is immediately sent to a hot gas cleanup, where the H<sub>2</sub>S, NH<sub>3</sub> and N<sub>2</sub> gas and ash particulates are removed. Standard processes are available for performing that hot gas cleanup.

The hot gas is then sent through a heat exchanger where the gas temperature is reduced to about 250°C. This lower temperature gas is then sent to a water gas shift reactor (WGS) where the following reaction occurs:



The WGS reaction is essentially thermally neutral. In the WGS, the carbon monoxide is reacted with water (steam) at about 250°C to form hydrogen and carbon dioxide. Hydrogen formed in this process allows the reduction of circulating excess hydrogen through the bed. Thus, only 1.0 mole of hydrogen, instead of 1.2 moles, is continually circulated through the system and the

amount of hydrogen entering the borehole per mole of coal reacted is 2.2, instead of 2.4:

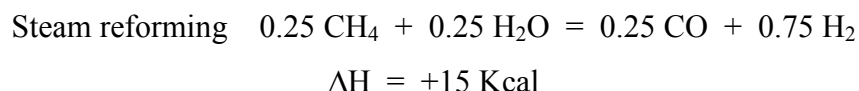


The gas emerging from the water gas shift contains 0.8 CH<sub>4</sub>, 0.2 CO<sub>2</sub> and 1.2 H<sub>2</sub>. In order to recirculate the hydrogen and produce Substituted Natural Gas, it is necessary to remove the CH<sub>4</sub> and CO<sub>2</sub> from the hydrogen stream. Several methods can be used: absorption/stripping in solvents, cryogenic separation, and pressure swing adsorption (PSA). The lowest cost gas separation process should be used to separate the CO<sub>2</sub> and CH<sub>4</sub> from the hydrogen.

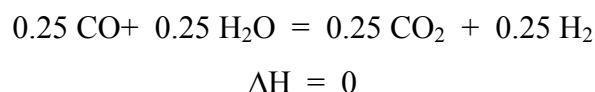
From industrial experience in hydrogen plants<sup>(3)</sup>, PSA has been used to separate carbon dioxide from water gas shift reactors using a zeolite (molecular sieve) adsorbant. To remove methane, activated carbon has been used. Two separate PSA units can be used. However, it should be possible to use a mixed adsorbant bed to adsorb both the carbon dioxide and the methane at the high pressure (70 atmospheres) and to intermittently differentially desorb at lower pressure (~10 atmospheres) and remove and produce carbon dioxide and methane separately. The hydrogen does not adsorb and passes through the absorption bed maintaining pressure at 70 atmospheres. The carbon dioxide is recovered pure, so it is ready for sequestration. The methane recovered is ready for pipeline distribution once it is adjusted to pipeline pressure.

The remaining hydrogen at low temperature from the PSA separation process is heat exchanged with hot cleaned gas to raise the temperature to 800°C. A gas-fired heater makes up for heat losses and assures the hydrogen will be brought to the hydrogen injection temperature of 800 - 1000°C. Oxygen or air injection into the hot hydrogen entering the injection borehole can be used to control the underground exothermic reaction by producing water, which results in an endothermic steam coal gasification reaction, preventing runaway hot spot reaction described in a previous paper.<sup>(5)</sup> The conversion efficiency of coal carbon to methane carbon Substitute Natural Gas product is as high as 90%.

To complete the mass balance, it will be necessary to add 1 mole of H<sub>2</sub> to the circulating hydrogen stream. This will be done by reforming 0.25 moles CH<sub>4</sub> by conventional steam reforming and water gas shift:



The steam reforming is endothermic, requiring 15 Kcal, which is supplied by combusting methane in the reformer furnace, which at 80% efficiency requires an additional 0.09 moles of CH<sub>4</sub>. The water gas shift completes the production of 1 mole H<sub>2</sub>. The reaction is thermally neutral



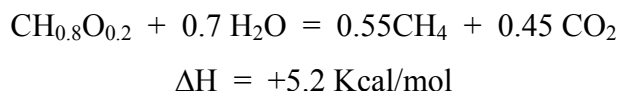
The CO<sub>2</sub> is removed by pressure swing adsorption (PSA). The total hydrogen production reaction is the sum of the two above:



The methane consumed in producing the 1 mole H<sub>2</sub> needed to complete the mass balance of the Fig. 1 flowsheet is the sum of 0.25 CH<sub>4</sub> + 0.09 CH<sub>4</sub> = 0.34 CH<sub>4</sub>

The net production of CH<sub>4</sub> from this process is then the methane produced (Reaction 1, above) minus the methane consumed 0.8 CH<sub>4</sub> - 0.34 CH<sub>4</sub> = 0.46 CH<sub>4</sub>

The overall mass balance equation for producing Substitute Natural Gas by Pumped Carbon Mining from lignite is then:



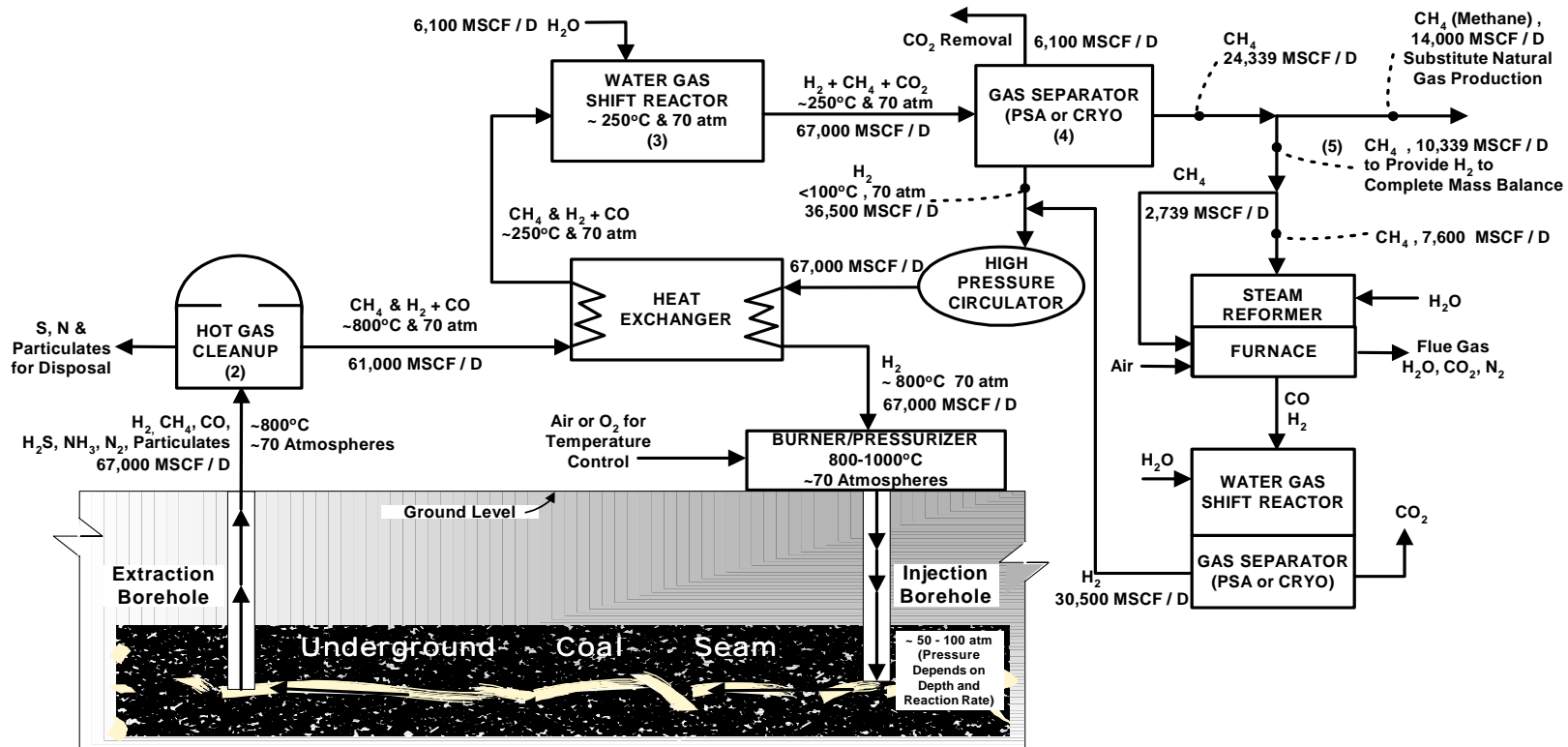
This endothermic energy is made up in the reformer. Subtracting the 0.09 CH<sub>4</sub> from the net CH<sub>4</sub> = 0.46 CH<sub>4</sub>. Thus, 46% of the carbon in the underground lignite is converted to SNG for sale. The thermal efficiency for conversion of the lignite to methane by this process is 80%, assuming 90% removal of the carbon by hydrogasification from underground. Thus, 41% of the carbon is extracted as methane. This compares favorably with above ground conventional steam gasification of coal, which is about 60% thermally efficient and requires an oxygen and steam supply.

The fraction of carbon extracted as methane from a dry, ash-free coal bed using a Coal Bedded Methane (CBM) process is about 2% of the total carbon in the coal bed. This estimate is based on Langmuir isotherm parameters at Langmuir pressure of 680 psia yielding 486 SCF/ton, which may be increased to 792 SCF/ton at 1100 psia in a coal seam at 4113 feet.<sup>(4)</sup> The Pumped Carbon process indicates a potential for extracting 41% of the carbon in the coal bed. This means that the Pumped Carbon Mining process holds the promise of producing an additional 20 times more methane than currently obtainable from a coal bedded methane operation alone.

### References

- (1) R.E. Baron, J.H. Porter and O.H. Hammond, "Chemical Equilibrium in Carbon, Hydrogen, Oxygen Systems," MIT Press, Cambridge, Mass. (1977).
- (2) S Lambertz, et al., "Recent Operational Results of the High Temperature Winkler (HTW) and Hydrogasification (HKV) Process," presented at Second EPRI Conference on Synthetic Fuels in San Francisco, Calif. (April 1985).
- (3) M. Steinberg and H.C. Cheng, "Modern and Prospective Technologies for Hydrogen Production from Fossil Fuels," Int. J. Hydrogen Energy 14, pp. 797-820 (1989).
- (4) D.H.S. Law, "Study for Enhanced Coalbed Methane Recovery Processes," SPE Alberta Research Council (ARC), Inc. et al., Report SPE 75669, Society of Petroleum Engineers, Inc. (2002).
- (5) HCEI-09-04 (September 2004)

**FIG. 1**  
**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**

- (1) Hydrogasification of Coal Lignite:  $CH_{0.8}O_{0.2} + 1.2H_2 = 0.8CH_4 + 0.2CO$   
 $1.2 H_2$  excess is circulated to reach equilibrium  $CH_4$  concentration (40%). Other gases formed are  $H_2O, CO_2, H_2S, NH_3, N_2$
- (2) Hot Gas Cleanup removes N, S & particulates
- (3) Water Gas Shift  $0.2CO + 0.2H_2O = 0.2CO_2 + 0.2 H_2$
- (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  
 $0.25 \text{ mole } CH_4: 0.25 CH_4 + 0.25 H_2O = 0.25 CO + 0.75 H_2$   
 $0.25 CO + 0.25 H_2O = 0.25 CO_2 + 0.25 H_2$ ; Furnace heat required:  $0.09 CH_4 + \text{Air} = 0.09 CO_2 + 0.18 H_2O$   
 Overall Mass Balance:  $CH_{0.8}O_{0.2} + 0.7 H_2O = 0.55 CH_4 + 0.45 CO_2$ ; Net  $CH_4$  Production =  $0.8 - 0.34 = 0.46 CH_4$