

AN ECONOMIC EVALUATION OF CARBON MOLECULAR SIEVE MEMBRANES IN LANDFILL GAS APPLICATIONS

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ABSTRACT

Carbon molecular sieve membranes have shown promise for the separation of carbon dioxide from methane. A potential application of these membranes is the removal of carbon dioxide from poor quality landfill gas in order to make it suitable for use as an engine fuel or to upgrade it to pipeline quality natural gas. The membranes are of particular interest because, based on preliminary tests, they offer increased permeance, selectivity, and stability over their predecessors. The improved stability over other types of membranes is obtained due to the inert materials used in production. This paper discusses the performance and economics of carbon molecular sieve membranes in landfill gas energy recovery applications.

INTRODUCTION

Landfill gas-to-energy projects can offer significant environmental, economic, and energy benefits (LMOP, 1996). Recently developed carbon molecular sieve membranes (CMSM) show promise for landfill gas (LFG) processing applications in that they enhance the BTU value of the landfill gas, enabling additional landfills to facilitate gas-to-energy projects. Such projects may otherwise be economically prohibitive. Shallow landfills, landfills located in arid environments, or landfills sites that extract landfill gas at a rate higher than it is generated in order to protect the surrounding environment are excellent candidates for this technology. Excessive air infiltration into a landfill may dilute the extracted landfill gas to a level that is no longer suitable as a fuel. Removing the CO₂ from the landfill gas will restore the methane quality to an acceptable level for use. It is estimated that this process could benefit 5 to 15 percent of all landfills by enhancing the quality of the collected LFG. This paper evaluates the use of CMSM in two applications. The first application utilizes spark-ignited engine generators to produce electricity and the second is purifying landfill gas to pipeline quality methane. It is anticipated that the development of these membranes will make it possible to convert LFG to high BTU gas more economically. The focus of this paper is on smaller landfills, i.e., 1 to 5 million tons of municipal solid waste (MSW) in place, since there are more landfills in this size range that have not yet been developed.

The work presented is a collaborative effort between Media & Process Technology, Inc.

(M&PT), the University of Southern California (USC), and GC Environmental, Inc. (GCE). In this effort a new type of supported CMSM is being developed using M&PT's porous ceramic tubes as the support for creating the selective carbon molecular sieve layer. In the following sections the membrane development stages are first briefly presented and then a performance evaluation of CMSM, based on treating and upgrading LFG, is discussed. Finally, the application and economics of CMSM in LFG service is evaluated.

Membrane Development

During the initial development stage of supported CMSM, US Filter mesoporous tubular substrates were used as the support to study the feasibility of such membranes on a laboratory scale. Polyetherimide (PEI) was used as the polymeric precursor for creating the selective carbon molecular sieve layer. To prepare supported CMSM, the support substrate (7mm ID, 10 mm OD), was dip-coated in PEI solution with proper concentration followed by drying in air and carbonization in an Ar atmosphere using a predefined temperature profile. The coating-carbonization cycle was repeated as required to obtain the desirable separation properties. **Figure 1** illustrates the ideal permeance and separation factor versus number of carbon layers for CO₂ and CH₄. The separation factor in **Figure 1** is calculated from the single gas permeance data obtained after each carbonization stage. The actual separation factor, as reported elsewhere (Sedigh et al., 1999), for an equimolar binary mixture of CO₂-CH₄ is roughly twice that of the ideal separation factor. The permeance and separation factors used in the performance evaluation of the membranes, presented in the following sections, are based on average values obtained from membranes prepared in the laboratory operating at similar temperature and feed composition conditions.

APPLICATIONS

Internal Combustion Engine Power Generation

Power project economics dictate that minimal gas processing be performed. LFG from the interior of a landfill may not require CO₂ removal to be a viable fuel. In this case the value added would be to utilize perimeter gas or poor quality interior gas, that may otherwise be flared, by treating it to the point that it is an acceptable fuel. In arid climates, LFG collected even from the interior part of a landfill may not be suitable for use in an engine. The value added in this case is to treat the entire gas stream to a level that is acceptable to the engines.

Upgrade Landfill Gas to Pipeline Quality

Upgrading the LFG for injection into a natural gas (NG) pipeline is the second application. With the use of the CMSM, this application may be economical even for smaller landfills (i.e., 1 to 5 million tons of MSW). One advantage of cleaning LFG to pipeline quality is that no modifications will be required to the end users' natural gas-fired equipment. This application requires relatively extensive treatment of landfill gas to remove CO₂ and impurities. Additionally, when gas is injected into a NG pipeline, there are strict specifications that can impose additional quality control and compression requirements. However, this may be an attractive option for some landfill owners, since it is possible to sell all high BTU LFG that is produced [LMOP, 1996].

Landfill Gas Generation and Collection Efficiency

The quantity of CH₄ gas produced in a landfill was estimated using a commonly utilized approximate formula [LMOP, 1996]. It should be noted, however that the quantity of methane generated per lb. of municipal solid waste (MSW) can vary greatly from landfill to landfill and over time. The quantity of 0.05 cf/lb. used in the calculations falls approximately midway in the range of CH₄ generated per lb. of MSW and is based on a LFG containing 50% CH₄. Dry landfills typically produce less CH₄ gas and wet landfills more than this approximation. The methane generation and collection rates are shown in **Table 1**.

	1	5
Waste in Place (million tons)	1	5
Methane Gas per Pound Refuse per Year (cf/lb./yr.)	0.05	0.05
Annual Methane Gas Generation (mmcf/yr.)	100	500
Methane Gas Generation (scfh)	11,400	57,100
LFG Flow at 57% methane and 70% collection efficiency (scfh) (High BTU Gas Application)	14,000	70,100
LFG Flow at 35% methane and 80% collection efficiency (scfh) (Power Generation Application)	26,100	130,500

The quality of LFG being collected for the internal combustion (IC) engine application is assumed to be 35% CH₄, 35% CO₂, and 30% N₂ and O₂ mixture. The quality of LFG being collected for upgrading to pipeline quality is 57% CH₄, 42% CO₂, and 1% N₂ and O₂ mixture. The difference in the LFG flow for the two applications is due to the amount of air pulled into the landfill during gas collection, and the collection system efficiency. LFG collection systems are not 100 % efficient, so the collection efficiency must be taken into account before the LFG flow can be calculated and the treatment system sized. Newer collection systems operated for energy recovery can be assumed to have a 75 to 85 % collection efficiency [LMOP, 1996]. This analysis assumes a collection efficiency of 80% for the IC engine application. LFG used for the high BTU application must have little air infiltration, so a lower collection efficiency must be used. A 70% efficiency for the upgrading to pipeline quality application is used in this analysis. The daily LFG flows are calculated by multiplying the CH₄ generation rate by the collection efficiency, and dividing the result by the concentration of CH₄ gas for each application.

Carbon Molecular Sieve Membrane Performance

In order for LFG to be used it must be of a suitable quality for the selected application. One of the largest hindrances to using LFG from landfill sites is gas dilution by air. To enhance the BTU value of LFG, CO₂ can be removed. For the internal combustion (IC) engine application, the feed and reject pressures are assumed to be 40 psig and the permeate pressure 0 psig. The quality of the LFG entering the membrane, as previously stated, is 35% CH₄, 35% CO₂, and 30% O₂ and N₂. The processed gas quality is assumed to be 50% CH₄, 10% CO₂, and 40% N₂ and O₂. The CH₄ yield of the process is 83.9%. The selectivity assumed for CO₂ over CH₄ is 10. The same selectivity is assumed for CO₂ over O₂ and N₂. The permeance of the CO₂ through the membrane is assumed to be 1.47 m³/m²/hr/bar. This application does not require high carbon dioxide removal, so a lower selectivity was used in this application to increase the permeance and reduce membrane costs. **Table 2** shows the results of the membrane performance calculations.

For upgrading LFG to pipeline quality gas, the feed and reject pressures are assumed to be 120 psig and the permeate pressure 0 psig. The quality of the LFG entering the membrane is 57% CH₄, 42% CO₂, and 1% O₂ and N₂. The processed gas quality is assumed to be 96% CH₄, 2% CO₂, and 2% N₂ and O₂. The CH₄ yield is 82.5%. The selectivity assumed for CO₂ over CH₄ is 30. The same selectivity is assumed for CO₂ over O₂ and N₂. The permeance of the CO₂ at this selectivity is 0.59 m³/m²/hr/bar. A high separation factor was used to reduce methane losses through the membrane and due to the high methane concentration required in the product gas. Membrane performance calculation results are shown in **Table 2**.

Table 2: Membrane Simulation Results for the Internal Combustion Engine and High BTU Gas Applications

	IC Engine		High BTU	
	1 MM Ton	5MM Ton	1MM Ton	5MM Ton
Feed Pressure (psig)	40	40	120	120
Reject Pressure (psig)	40	40	120	120
Permeat Pressure (psig)	0	0	0	0
Feed, X CO ₂	0.35	0.35	0.57	0.57
Feed, X CH ₄	0.35	0.35	0.42	0.42
Feed, X N ₂ , O ₂	0.3	0.3	0.01	0.01
Reject, X CO ₂	0.1	0.1	0.02	0.02
Reject, X CH ₄	0.5	0.5	0.96	0.96
Reject, X N ₂ , O ₂	0.4	0.4	0.02	0.02
Permeat, X CO ₂	0.72	0.72	0.88	0.88
Permeat, X CH ₄	0.15	0.15	0.117	0.117
Permeat, X N ₂ , O ₂	0.13	0.13	0.003	0.003
Overall Yield (%)	59.9	59.9	36.1	36.1
CH ₄ Yield (%)	83.9	83.9	82.5	82.5
Area (m ²)	270	1350	280	1420
Selectivity	10	10	30	30
Permeance, CO ₂ , (m ³ /m ² /hr/bar)	1.47	1.47	0.588	0.588
BTUs Out (mmBTU/hr) (1)	6.96 LHV	34.8 LHV	6.66 HHV	33.3 HHV
Gross kW Output-Engine at 12,500 (BTU LHV/kWh)	556	2782	-	-
Net kW Output (kW)	484	2421	-	-
Net BTUs Produced (mmBTU/day)	-	-	160	800
Annual Capacity Factor	0.9	0.9	0.9	0.9
Net Energy Sold (kWh/yr.)	3,816,000	19,085,000	-	-
Net Energy Sold (mmBTU HHV/yr)	-	-	52,500	262,500

(1) BTUs are reported as lower heating value for IC engines and higher heating value for pipeline quality gas applications.

ECONOMIC ANALYSIS OF APPLICATIONS

Since many landfills are now required to implement gas collection systems and flares, the costs of these systems are not included in the analyses. Only the treatment systems and equipment required to generate electricity (via an IC engine) and compress the gas to pipeline standards will be evaluated. To simplify the analysis in this paper, it is assumed that all collected LFG is processed by the membranes.

Internal Combustion Engine Power Generation

To determine the revenues from the sale of electricity generated by the IC engine, the power potential must first be evaluated. This is the installed power generation capacity that the gas flow can support. To do this the following formula is used [LMOP, 1996].

$$\text{kW} = \text{Landfill Gas Flow (cfh)} \times \text{Energy Content (BTU/cf) LHV} \times \text{l/Heat Rate (kWh/BTU)}$$

The net power generated is the gross power generated minus the parasitic loads from compressors and other auxiliary equipment. Parasitic loads are estimated at 13% for the IC engine application. The annual capacity factor is the share of hours in a year the equipment is producing electricity at its rated capacity. Typical values for LFG projects range between 80% and 95% and are based upon generator outage rates (4% to 10% of annual hours), LFG availability, and plant design [LMOP, 1996]. An annual capacity factor of 90% was assumed in this analysis. The annual

electricity generated is calculated by multiplying the operational hours in a year by the capacity of the electricity generation equipment. **Table 2** shows the net kWhs generated from landfills with 1 and 5 million tons of MSW. LFG power projects selling electricity to the utilities are currently receiving only 3 to 4 cents/kWh [EPA, 1993]. When power is sold directly to a retail customer, higher power rates can be obtained.

The capital requirement for a LFG power project includes the costs of the major equipment (e.g., IC engine) as well as the costs associated with the auxiliary equipment, construction, emissions controls, interconnections, gas compression and treatment, engineering, and "soft costs." Soft costs include up-front owner's costs (e.g., development staff, legal, permitting, insurance, property tax), escalation during construction, interest during construction, and owner's contingency, all of which are incurred prior to and during the construction process [LMOP, 1996]. Total capital costs for engine generators using automobile engines and induction generators are approximately \$380/kW [EPRI, 1986] escalating the costs at 3% per year. The estimated capital cost of the CMSM is \$242/kW. This estimation assumes membrane cost of \$500/m². Gas processing, compression, clean-up and waste gas disposal costs are estimated to be \$250/kWh for a 1 million ton landfill, and \$100/kWh for the 5 million ton landfill.

To obtain a levelized capital cost (LCC) in cents/kWh units, the annual cost calculated as described above must be divided by the expected operating hours per year as follows [LMOP, 1996]:

$$\text{LCC} = \text{Installed Cost} \times \text{Capital Charge Rate} / (\text{Capital Factor} \times \text{Hours per Year}) \times (100 \text{ cents}/\$)$$

Where we have assumed LCC = levelized capital cost (cents/kWh), installed cost = capital requirement (\$/kW), CCR = capital charge rate, CF = annual average capacity factor, hours per year = 8,760. The levelized capital costs are shown in **Table 3**. The cost of electricity generated for the 1 and 5 million ton landfills are 3.30 and 3.05 cents/kWh.

Table 3: Cost of Electricity Generated by Internal Combustion Engine		
	Internal Combustion Engines	Internal Combustion Engines
	1	5
Waste in Place (million tons)	1	5
Installed Capital Costs (\$/kW)	630	480
Membrane Capital Costs (\$/kW)	242	242
Capital Charge Rate	0.136	0.136
Annual Capacity Factor (%)	90	90
Levelized Capital Costs (cents/kWh)	1.50	1.25
O&M Expenses (cents/kWh)	1.80	1.80
Cost of Electricity Generated (cents/kWh)	3.30	3.05

Upgrade to Pipeline Quality Gas

Upgrading gas to pipeline quality can be relatively expensive, because of the substantial processing requirements to remove CO₂ and other constituents from raw LFG. This option was previously viable only at larger landfills (i.e., more than 4 million cfd), where significant economies of scale could be achieved. To determine the revenues from the sale of pipeline quality gas, the BTUs available for sale must be evaluated. This has been done for the 1 and 5 million ton example landfills, **Table 2**. The annual BTUs produced are approximately 52,500 and 262,500 mmBTU HHV/yr.

The treatment system is similar to the one for the IC engines except for the higher gas

pressure and additional gas clean-up to remove chlorinated hydrocarbons and water. **Figure 3** shows a block diagram of this process and **Table 4** lists the components of the treatment system and their estimated costs. The components fall into six main categories, which are civil, mechanical, electrical, engineering, construction, and contingency.

Table 4: Treatment System Component Cost Estimates				
Category	Equipment/ Part	Function	Cost Estimate (\$)	
Waste in Place (million tons)			1	5
Civil Construction	Grading, Foundations, Drainage		30,000	40,000
Mechanical	Compressor	Compresses LFG to 120 psig	65,000	125,000
	Scrubber	Water Removal	15,000	25,000
	Contaminant removal and dehydration	Removes chlorinated hydrocarbons and water	100,000	200,000
	Waste gas incinerator	Burns waste gas from membranes and removes contaminants	75,000	115,000
	Fin/Fan Cooler	Removes heat	25,000	30,000
	Coalescing Filter Separator	Removes oil from LFG	10,000	20,000
	Membrane	Removes CO ₂ from LFG	142,000	709,000
	Liquid Handling System	Handles condensate from system	20,000	30,000
Electrical	Controls		50,000	65,000
Engineering		System design	100,000	150,000
Construction		Build system	150,000	200,000
Contingency	20 %	Uncertainty and soft costs	156,400	341,800
Total (PW)			938,400	2,050,800

O&M expenses for LFG treatment systems vary depending on the system components, sizing, design, and percentage of on-time. The O&M expenses for the 1 and 5 million ton landfills are estimated to be \$142,000/yr. and \$314,000/yr. respectively. These costs include the cost of power to compress the gas at 6 cents/kW.

In order to amortize the initial capital costs of a treatment system for upgrading LFG to pipeline quality gas, the initial capital costs have been analyzed as installment loans, and annual payments based on 5 % and 8 % annual interest rates have been calculated, **Table 5**. The annual annuity payment for a present worth principal is given in the following expression:

$$AP = PW * ((I * ((1+I)^n))/(((1+I)^n)-1))$$

Where AP is the annual annuity payment (\$), PW is the present worth of the loan or the installed capital costs (\$), I is the interest rate per annual payment, and n is the number of annual payments (assume a 10 year payback).

Based on the costs of generating the pipeline quality gas, it is apparent that the projects will be economically feasible if the price of such gas is greater than \$4.89/mmBTU and \$4.58/mmBTU at annual interest rates of 8 and 5 % for the 1 million ton landfill, and \$2.15/mmBTU and \$2.01/mmBTU at annual interest rates of 8 and 5 % for the 5 million ton landfill. The economy of scale is clearly demonstrated by these examples. If the price of pipeline quality gas is less than the cost, then additional sources of revenue or alternative customers should be investigated. Tax credits and/or incentives may be available for upgrading landfill gas to pipeline quality gas projects.

Waste in Place (million tons)	1		5	
Installed Capital Costs (\$)	938,400	938,400	2,050,800	2,050,800
Annual Interest Rate	0.08	0.05	0.08	0.05
Number of Annual Payments	10	10	10	10
Annual Annuity Payment (\$)	139,850	121,500	305,600	265,600
Annual O&M Expenses (\$)	142,000	142,000	314,000	314,000
Value of Pipeline Gas Generated (\$/yr)	281,850	263,500	619,600	579,600
Annual Energy Content (mmBTU/yr)	57,600	57,600	288,000	288,000
Cost of Pipeline Gas Generated (\$/mmBTU)	4.89	4.58	2.15	2.01

Note: Costs do not include pipeline distribution costs.

Conclusion

The carbon molecular sieve membrane shows significant promise as a future technology to remove carbon dioxide from landfill gas. Advantages this membrane will offer over other technologies include excellent separation factor while maintaining good permeance, high stability in hot, damp, or corrosive environments, and low cost. Due to the development of this membrane, it may be possible to utilize landfill gas from sites that are not currently considered for development because of poor quality gas. This technology may also open additional opportunities to upgrade LFG to pipeline quality gas.

Future work needed to prove the long term effectiveness of the membranes is a field test using landfill gas. This work is scheduled for the year 2000 at a landfill in Southern California. Additional membrane development work will also be performed in year 2000 to optimize membrane production and reproducibility.

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References

Landfill Methane Outreach Program (LMOP), Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook, U.S. Environmental Protection Agency, September 1996.

Berenyi, E.B., and Gould, R.N. 1994-95 Methane Recover from Landfill Yearbook. Governmental Advisory Associates, Inc. 1994, New York, NY.

Very small (approximately 500kW low-cost gas-fired power plants. Electric Power Research Institute [EPRI]. AP-4837, November 1986.

Sedigh M. G., Xu L., Tsotsis T. T., Sahimi M., Transport and Morphological Characteristics of Polyetherimide-based Carbon Molecular Sieve Membranes, *Ind. Eng. Chem. Res.* 1999, 38, 3367.

Figure 1: Effect of number of carbon layers on permeance and separation factor for single gases.

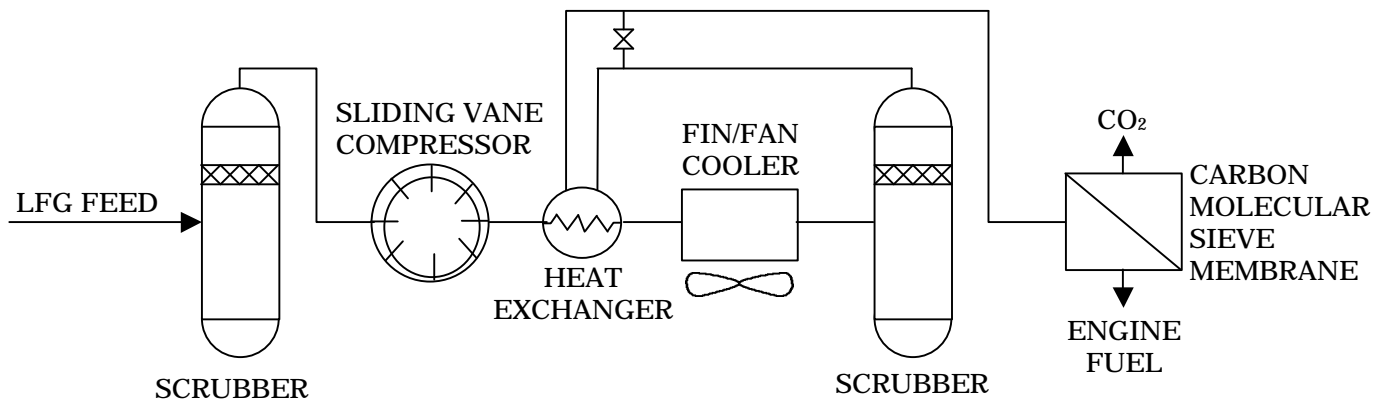
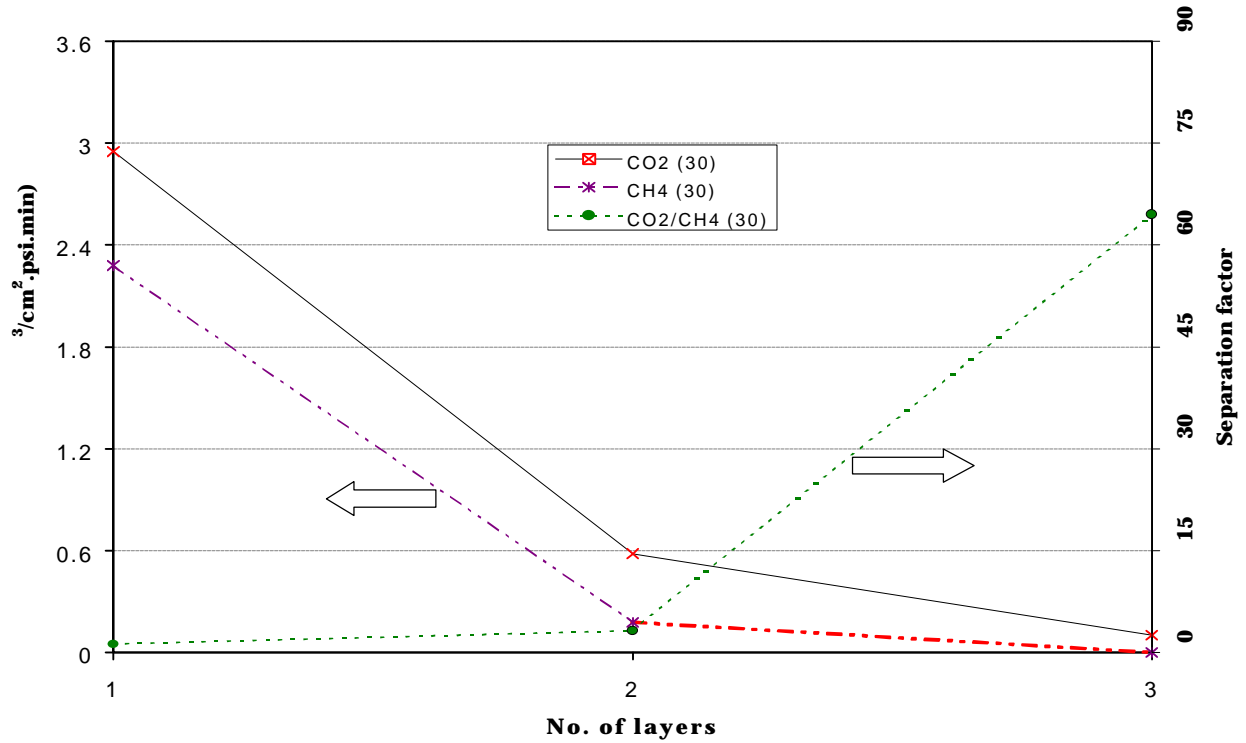


FIGURE 2: INTERNAL COMBUSTION ENGINE TREATMENT PROCESS

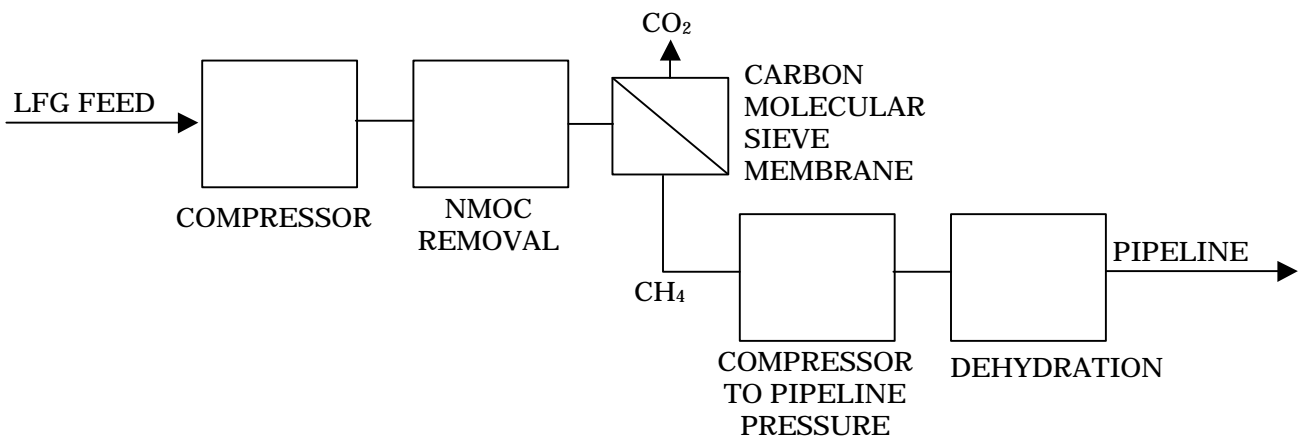


FIGURE 3: HIGH BTU TREATMENT PROCESS