

# **Upgrading Methane Using Ultra-Fast Thermal Swing Adsorption**

**Quarterly Report  
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## Abstract

The purpose of this project is to design and demonstrate an approach to upgrade low-BTU methane streams from coal mines to pipeline-quality natural gas. The objective of Phase I of the project was to assess the technical feasibility and cost of upgrading low-BTU methane streams using ultra-fast thermal swing adsorption (TSA) using Velocys' modular microchannel process technology. The objective of Phase II is to demonstrate the process at the bench scale.

The project is on schedule and on budget. A technical and economic feasibility assessment was completed in Task 3. The proposed Velocys technology appears feasible for the methane upgrading market. Evaluated categories include adsorbent selection, rapid-cycle valve selection, microchannel manufacturability assessment, and system design and cost.

The selected adsorbent, granular microporous carbon from either Barnaby-Sutcliffe or Calgon, experimentally demonstrated sufficient methane capacity under differential temperature at 100 pounds per square inch gauge. Several valve options were identified, including candidates that can operate millions of cycles between refurbishment. The microchannel adsorber and desorber designs were made using internal Velocys manufacturability standards, and the associated costs are acceptable as included with the complete nitrogen rejection unit (NRU) cost projection. A system design and cost estimate was completed for the NRU section of the methane upgrading system. As integrated into the complete system, the cost is in line with the market requirement.

The system has six main unit operations: feed compressor, dehydration unit, nitrogen rejection unit, deoxygenator, carbon dioxide scrubber, and a sales compressor. The NRU is the focus of the development program, and a bench-scale demonstration will be initiated in the next fiscal year. The Velocys NRU system targets producing methane with greater than 96% purity and at least 90% recovery for final commercial operation. A preliminary cost analysis of the methane upgrading system, including the Velocys NRU, suggests that costs below \$2.00 per million (MM) BTU methane may be achieved. The cost for a conventional methane upgrading system is well above \$2.30 per MM BTU, as benchmarked in an Environmental Protection Agency study.

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## Executive Summary

The purpose of this project (41905) is to design and demonstrate an approach to upgrade low-British thermal unit (Btu) methane streams from coal mines for subsequent deployment as pipeline-quality natural gas. This approach is based on applying Velocys' modular microchannel process technology to achieve ultra-fast thermal swing adsorption (TSA). The ultra-fast TSA project is a two-phased, 18-month effort. The objective of Phase I was to assess the technical and market feasibility of a Velocys TSA approach for upgrading low-BTU methane streams. The objective of Phase II is to demonstrate the process at the bench scale. The status of all tasks is listed below:

- Task 1.1: adsorbent ranking – *complete*
- Task 1.2: adsorbent testing – *complete*
- Task 2.1: process design – *complete*
- Task 2.2: component design – *complete*
- Task 3: cost and feasibility analysis – *complete*
- Task 4: proof-of-principle demonstration – *on-going*

Highlights of the third quarter effort are as follows

- The project is on budget and on schedule.
- The feasibility study is complete and is positive to move forward to Phase II
- Tasks for the fourth quarter milestones have been initiated.

Technical progress to date includes

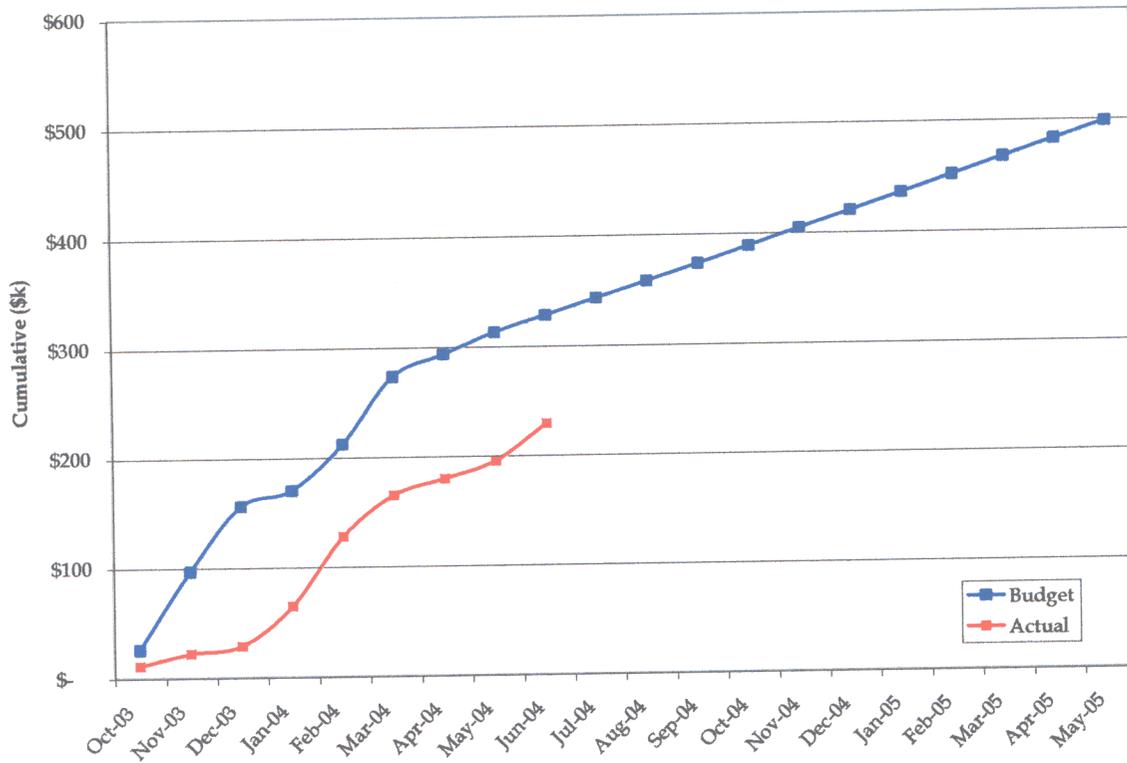
- Completed adsorbent selection for demonstration, a microporous carbon from either Calgon Corporation or Barnaby-Sutcliffe are sufficient
- Completed system design, including a cost and feasibility assessment
- Initiated design of a bench-scale demonstration device

For Task 3, the cost and feasibility assessment was broken into four main categories:

- Adsorbent selection
- Valve selection
- Microchannel component feasibility
- System cost

Progress is ongoing for the fourth-quarter milestones

- Complete the design and initiate fabrication of a bench-scale unit



While the program's progress remains on schedule, the actual cost slightly lags the original projection. The increased experimental testing associated with the bench-scale demonstration is, however, anticipated to require additional funds.

# Experimental

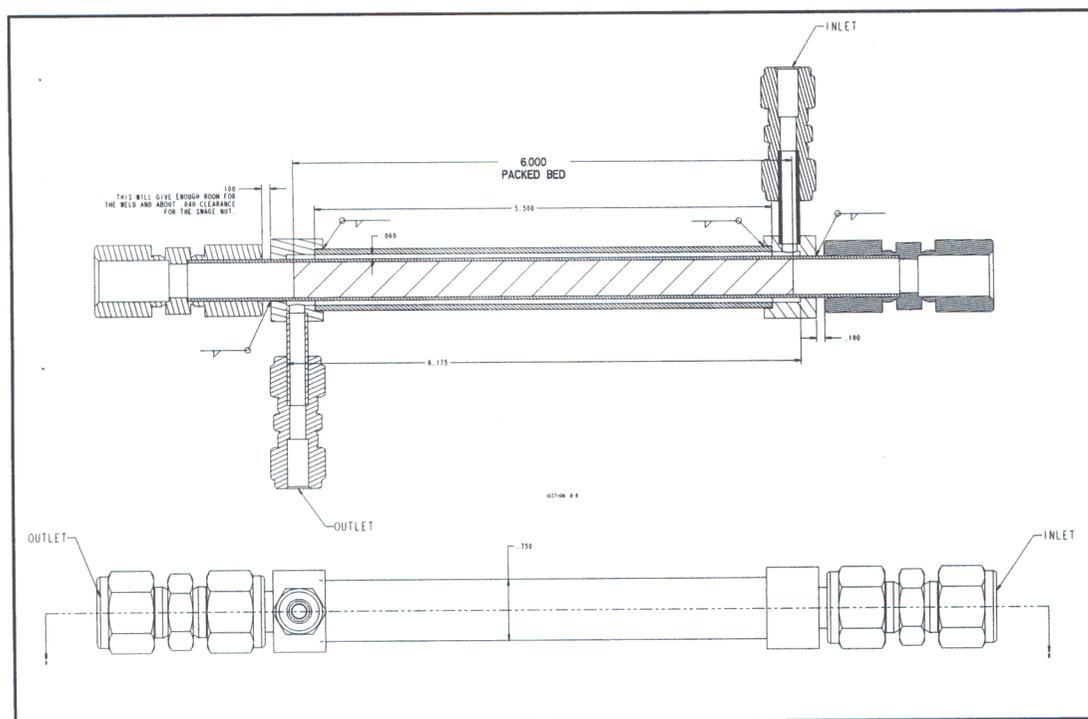
## Task 1.2 Adsorbent Validation

### Task Objective

The goal of the Adsorbent Validation task is to identify an adsorbent candidate suitable for initiating a conceptual system design and a subsequent bench-scale demonstration.

### Experimental Description

The testing system is designed to measure capacity as a function of temperature, pressure, and composition for different solid granulated forms of adsorbents. The system includes an adsorbent bed with heat exchanger to maintain isothermal operation during experiments (as shown in Figure 1). Figure 2 is a flow diagram of the adsorbent testing system.



**Fig. 1.** Adsorbent testing apparatus. Process gases flow downward through the (vertically mounted) adsorbent bed in the center tube, and heat exchange fluid flows co-currently in an outer annulus to maintain near isothermal operation.

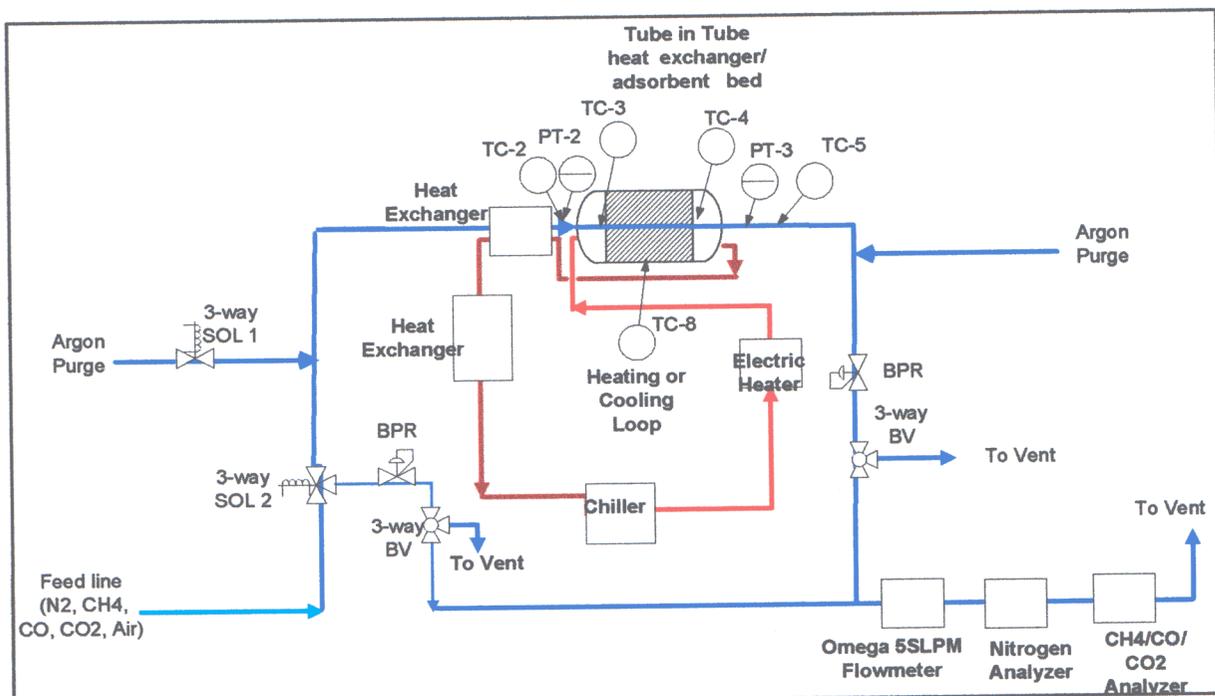


Fig. 2. Adsorbent testing system flow diagram

## **Task 2.1 Conceptual System Process Design**

### **Task Objective**

The goals of the Conceptual System Process Design Task are to define the critical unit operations (including order) which involve the following:

- Mass and energy balance of the required unit operations
- Capacity (duty) and performance assumptions of each identified unit operation
- Temperature, pressure, flow rate, and composition of each process stream
- Summary metrics of product recovery and thermal efficiency

### **System Design Basis**

To provide a basis for the system study, several variables were fixed and conventions adopted.

- The methane upgrading system was sized for 3 million standard cubic feet per day (MMSCFD) of sub-quality natural gas entering from a gob gas well or wells
- Composition of the gas from the well is 70% CH<sub>4</sub>, 4% O<sub>2</sub>, 22% N<sub>2</sub>, 4% CO<sub>2</sub>, and saturated with water at ambient conditions
- Composition required for the pipeline: 96% CH<sub>4</sub>, <4% N<sub>2</sub> or CO<sub>2</sub>, 10 ppm O<sub>2</sub>, and dry to -40°C at 600 psi
- Inlet temperature and pressure from the well: 20°C and 1 psig
- Outlet temperature and pressure to pipeline: <200°C and 600 psig

The results and implications are discussed in the Results and Discussion section.

## **Task 2.2 Conceptual Component Design**

### **Task Objective**

The goals of the Conceptual Component Design Task are to design a nitrogen rejection unit (NRU) system, which includes

- Overall size of the adsorber and desorber box
- Mass and energy balance of the components
- Capacity (duty) and performance of the components
- Temperature, pressure, flow rate, and composition of each process stream for the components

### **Component Design Basis**

To provide a basis for the component design, several variables were fixed and conventions adopted.

- The methane upgrading system was sized for 3 MMSCFD of sub-quality natural gas entering from a gob gas well or wells
- Composition of the gas for design purposes is 70% CH<sub>4</sub>, 30% N<sub>2</sub>
- Inlet pressure of the gas: 100 psig (after process compressors)
- Performance of the adsorbent and desorbent is assumed
- Pressure drop in the process gas in NRU is less than 10 psi

The results and implications are discussed in the Results and Discussion section.

## **Task 3 Cost and Feasibility Assessment**

### **Task Objective**

The goals of the Cost and Feasibility Assessment task are as follows

- Estimate capital and operating costs of an ultra-fast TSA NRU
- Assess the reduction of greenhouse gas emissions

### **Feasibility Study Variables**

To provide a basis for the system study, variables were fixed and conventions adopted for the following

- Adsorbent
- Valves
- Component
- System

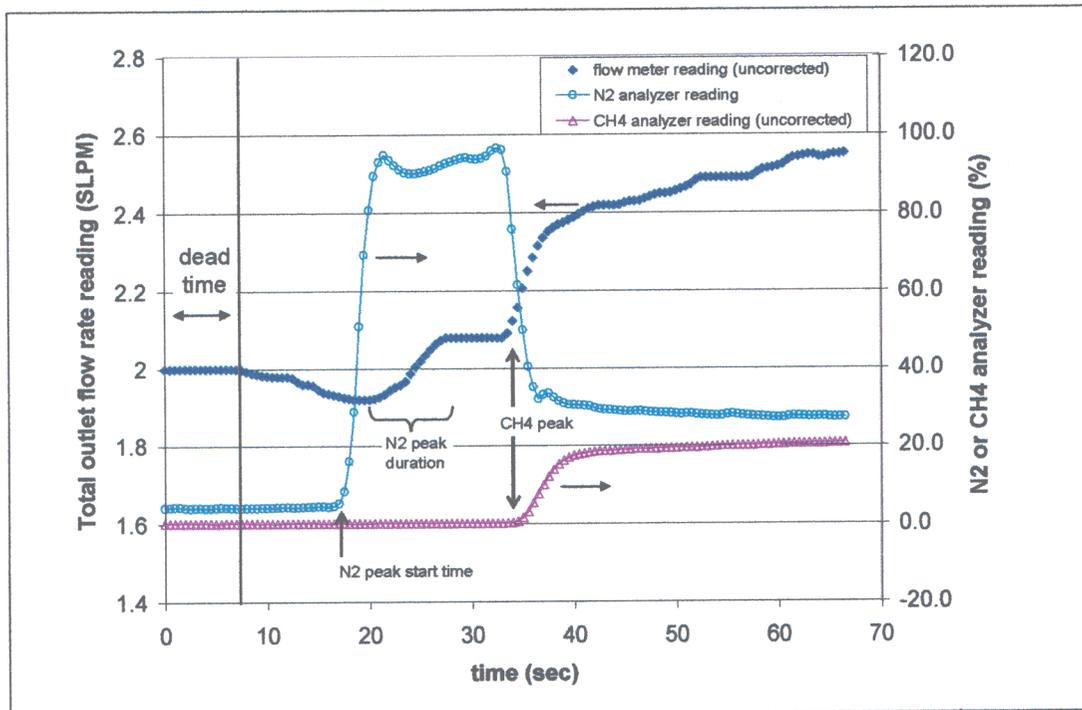
The basis for this study is the same used in conceptual component design, described above. The results and implications are discussed in the Results and Discussion section.

## Results and Discussion

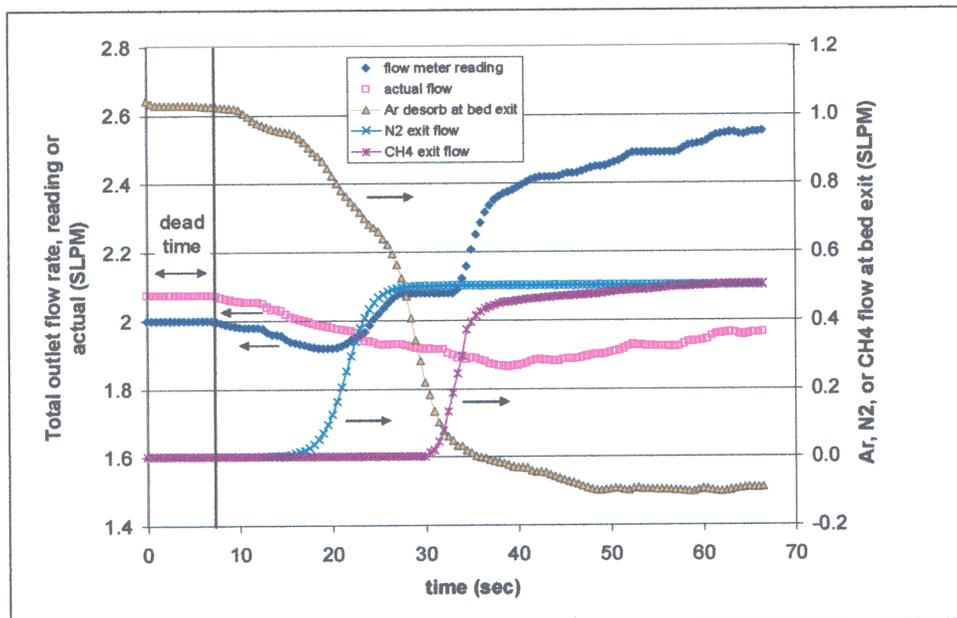
### Task 1.2 Adsorbent Validation

Typical analyzer and mass flow meter reading curves are shown in Figure 3. Figures 4 and 5 depict outlet flow curves produced from typical tests at 100 psig with mixtures of 50/50 and 90/10 (v/v) methane/nitrogen, respectively. The results of the adsorbent capacity screening tests are shown in Tables 1 through 5. Tables 1 and 2 summarize the measured *carbon* adsorbent capacities for the 2-psig and 100-psig tests, respectively. Table 3 shows the measured Calgon carbon adsorbent capacities for the 200-, 300-, and 400-psig tests. Tables 4 and 5 summarize the measured *zeolite* adsorbent capacities for the 2-psig and 100-psig tests, respectively. The zeolite adsorbents were obtained from Alpha Aesar and Grace-Davison. These capacities can then be used to determine differential capacities between any two temperature conditions for a given inlet composition and pressure. (The differential capacity for a given component is simply the difference between the two measured capacities for that component at the low and high temperature.)

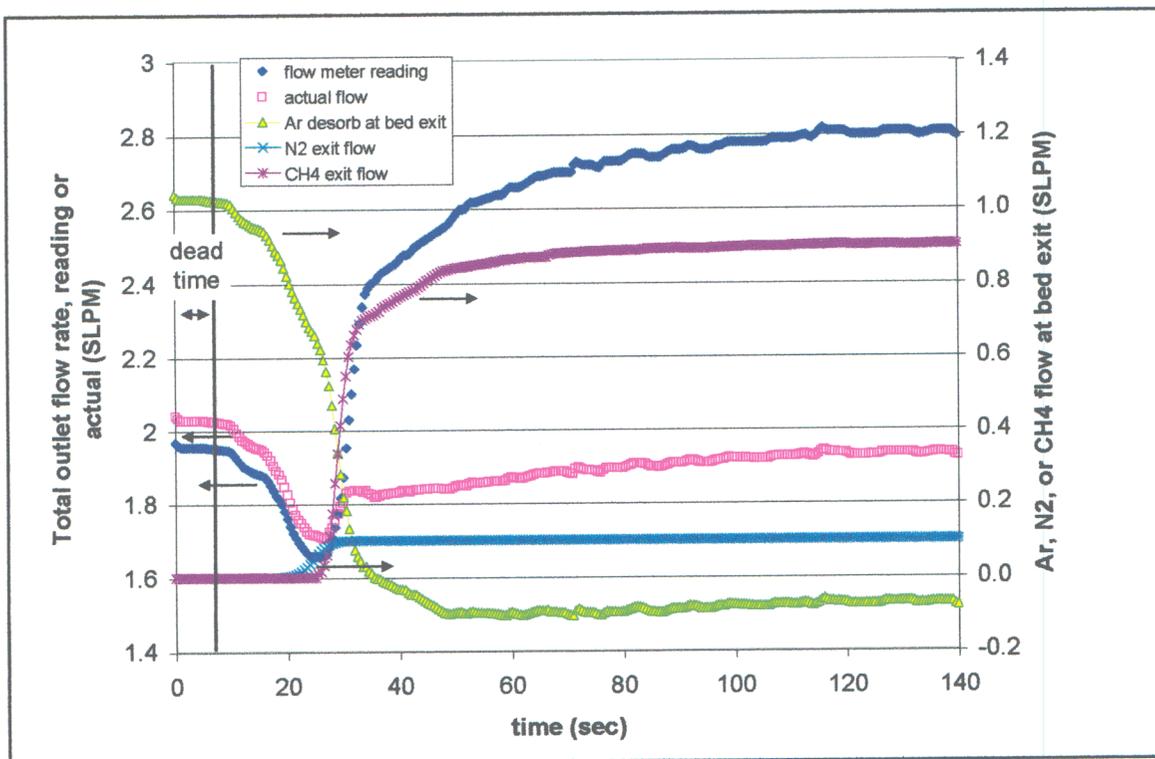
It is desirable to have a high differential capacity for methane and a low differential capacity for nitrogen over a given temperature range to effect separation by thermal swing adsorption. In general, the carbon adsorbents had much higher differential capacities than the zeolite adsorbents over the range of conditions tested. The 2-psig pressure capacities were always lower than the corresponding 100-psig capacities, so the best adsorbent for a 90/10 mixture over the interval of 40 to 60°C was identified from the data at 100 psig. The adsorbent from Calgon was further tested at 200, 300, and 400 psig. Surprisingly, performance at these higher pressures showed no significant increase in differential capacity as compared with the 100-psig performance.



**Fig. 3.** Outlet flow rate reading from mass flow meter (left axis) and nitrogen and methane analyzer readings (right axis, before calibration correction) for adsorption capacity tests on Calgon carbon adsorbent using an equimolar feed mixture at 60°C and 100 pounds per square inch gauge (psig). Dead time was 7 seconds.



**Fig. 4.** Outlet flow rate reading from mass flow meter and corrected total outlet flow (left axis) and argon, nitrogen, and methane flows at the adsorbent bed exit (right axis) for adsorption capacity tests on Calgon carbon adsorbent while feeding 0.5 standard liters per minute (SLPM) CH<sub>4</sub> and 0.5 SLPM N<sub>2</sub> at 60°C and 100 psig. Dead time was 7 seconds.



**Fig. 5.** Outlet flow rate reading from mass flow meter and corrected total outlet flow (left axis) and argon, nitrogen, and methane flows at the adsorbent bed exit (right axis) for adsorption capacity tests on Calgon carbon adsorbent while feeding 0.9 SLPM CH<sub>4</sub> and 0.1 SLPM N<sub>2</sub> at 60°C and 100 psig. Dead time was 7 seconds.

Carbon adsorbents, 2 psig			Barnaby-Sutcliffe		Calgon		PICA	
Temp (C)	CH <sub>4</sub> Flow (sccm)	N <sub>2</sub> Flow (sccm)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)
6	100	900	6.5	10.1	-	-	-	-
6	500	500	19.7	7.7	16.4	6.4	18.2	7.6
6	900	100	26.7	2.5	23.6	1.9	24.6	2.1
23	100	900	3.8	5.7	-	-	-	-
23	500	500	12.3	4.8	11.4	4.2	13.3	6.3
23	900	100	18.2	1.4	16.1	1.3	16.9	1.6
40	100	900	2.3	3.2	-	-	-	-
40	500	500	9.4	2.8	7.8	4.3	8.4	5.0
40	900	100	12.3	0.9	9.5	1.0	10.9	1.3
60	100	900	1.7	4.3	-	-	-	-
60	500	500	5.1	2.4	4.8	2.9	4.9	2.9
60	900	100	8.3	0.5	7.1	0.8	5.7	0.9

**Table 1.** Carbon adsorbent capacities measured over a range of temperature and feed mixture compositions at near ambient pressure

Carbon adsorbents, 100 psig			Barnaby-Sutcliffe		Calgon		PICA	
Temp (C)	CH <sub>4</sub> Flow (sccm)	N <sub>2</sub> Flow (sccm)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)
6	100	900	16.5	40.7	-	-	-	-
6	500	500	55.5	27.1	44.4	22.5	54.9	28.6
6	900	100	75.7	6.1	63.0	5.0	75.0	5.9
23	100	900	12.4	32.1	-	-	-	-
23	500	500	44.2	25.6	36.0	18.7	40.0	18.9
23	900	100	57.8	5.1	54.6	4.1	59.6	4.3
40	100	900	8.6	24.9	-	-	-	-
40	500	500	36.9	22.8	31.7	17.6	28.9	13.3
40	900	100	48.1	4.4	41.6	3.5	42.9	2.6
60	100	900	7.5	22.2	-	-	-	-
60	500	500	28.0	18.4	23.4	10.7	25.3	11.1
60	900	100	39.6	3.8	31.8	2.5	35.3	2.6

Table 2. Carbon adsorbent capacities measured at 100 psig

Calgon carbon, high P			200 psig		300 psig		400 psig	
Temp (C)	CH <sub>4</sub> Flow (sccm)	N <sub>2</sub> Flow (sccm)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)
6	500	500	52.1	29.8	66.5	40.0	76.1	45.1
6	900	100	66.2	6.3	91.4	8.5	112.7	10.2
23	500	500	41.8	23.8	51.2	34.2	65.5	39.5
23	900	100	63.1	5.4	81.3	7.5	95.2	8.4
40	500	500	35.3	22.0	43.2	26.7	50.5	31.7
40	900	100	51.5	4.6	70.2	6.3	87.5	8.3
60	500	500	33.2	18.4	39.4	25.8	54.6	32.9
60	900	100	45.4	3.8	63.3	5.3	84.6	7.4

Table 3. Measured Calgon carbon adsorbent capacities as a function of temperature and mixture composition for 200-, 300-, and 400-psig bed pressures

Zeolites, 2 psig			Z-10-02		Z-10-06		Alpha Aesar	
Temp (C)	CH <sub>4</sub> Flow (sccm)	N <sub>2</sub> Flow (sccm)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)
6	500	500	5.5	3.3	5.7	5.5	4.7	4.2
6	900	100	7.5	1.2	8.2	1.4	6.9	0.9
23	500	500			3.6	2.6	3.1	2.2
23	900	100			6.4	0.8	4.7	0.4
40	500	500	1.8	1.4	3.2	2.0	2.4	1.8
40	900	100	2.1	1.3	4.1	1.0	2.5	0.3
60	500	500			1.5	1.6	1.0	0.9
60	900	100			2.5	0.6	1.2	0.2

**Table 4.** Zeolite adsorbent capacities measured over a range of temperature and feed mixture compositions at near ambient pressure

Zeolites, 100 psig			Z-10-02		Z-10-06		Alpha Aesar	
Temp (C)	CH <sub>4</sub> Flow (sccm)	N <sub>2</sub> Flow (sccm)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)	CH <sub>4</sub> Capacity (mg/g)	N <sub>2</sub> Capacity (mg/g)
6	500	500	24.5	14.2	24.7	14.7	21.7	13.7
6	900	100	36.0	4.4	39.1	4.5	34.0	3.4
23	500	500			18.6	13.9	16.8	9.2
23	900	100			28.0	3.2	28.2	2.4
40	500	500	15.5	9.3	15.8	8.9	12.4	7.1
40	900	100	23.7	2.1	24.3	2.1	20.9	1.7
60	500	500			13.4	8.7	-	-
60	900	100			22.5	2.0	-	-

**Table 5.** Zeolite adsorbent capacities measured at 100 psig

## Task 2.1 Conceptual System Process Design

### Methane Upgrading System

The system study evaluated the complete process for upgrading coal-bed methane to pipeline quality. This process, as shown in Figure 6, consists of six steps: process compression, dehydration, nitrogen rejection, oxygen removal, carbon dioxide rejection, and sales compression.

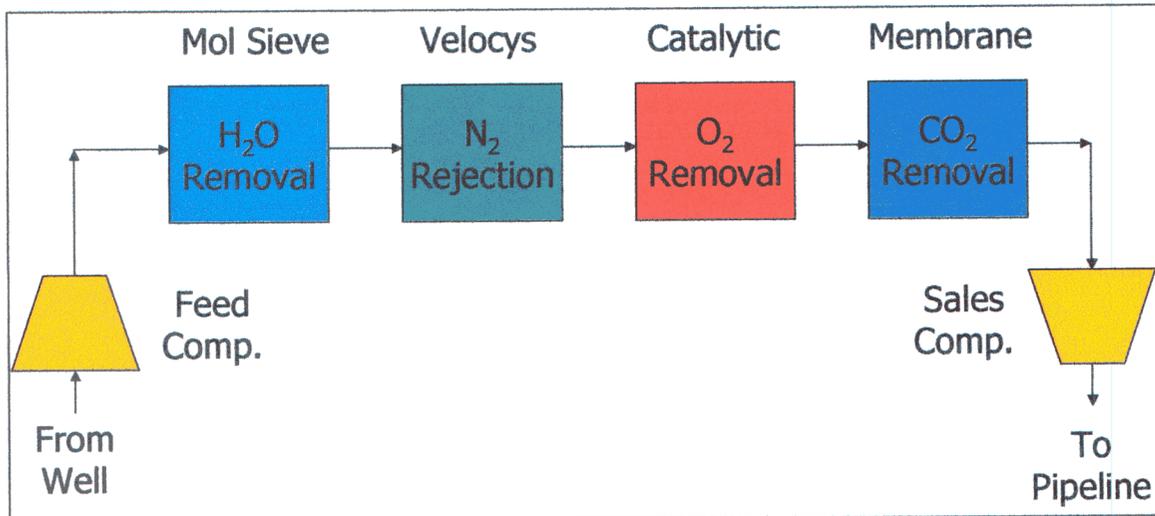


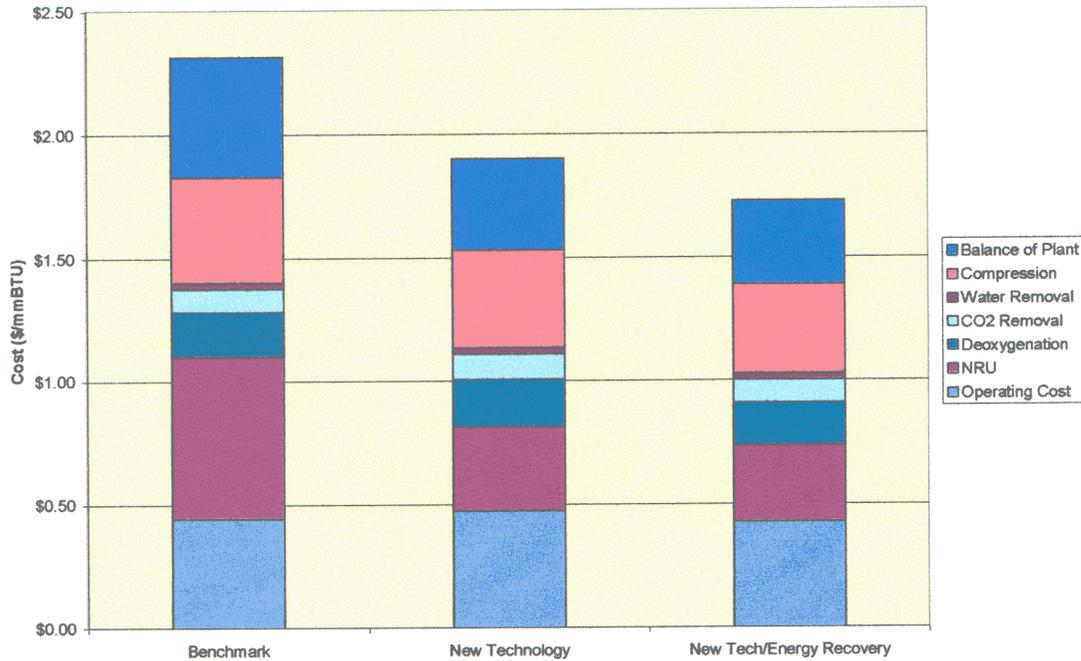
Fig. 6. Methane upgrading process system configuration

The complete process was modeled in detail using ChemCAD, a process simulation software package. The results are shown in Appendices I and II and project that the Velocys Technology NRU can achieve 90% recovery, the target recovery and system design point.

Background information for the technology and economics are from an EPA Coalbed Methane Outreach Program study titled, *Technical and Economic Assessment of Potential to Upgrade Gob Gas to Pipeline Quality*, and published in 1997.

### Preliminary Cost Comparison

Based upon the Velocys Technology NRU achieving the operational and cost targets, the resulting methane upgrading system should have a distinct cost advantage. The graph in Figure 7 shows the results of a preliminary system cost study and compares the results with a case from the EPA study (benchmark). Note that the costing data will be further refined later in the project, and estimates may change.



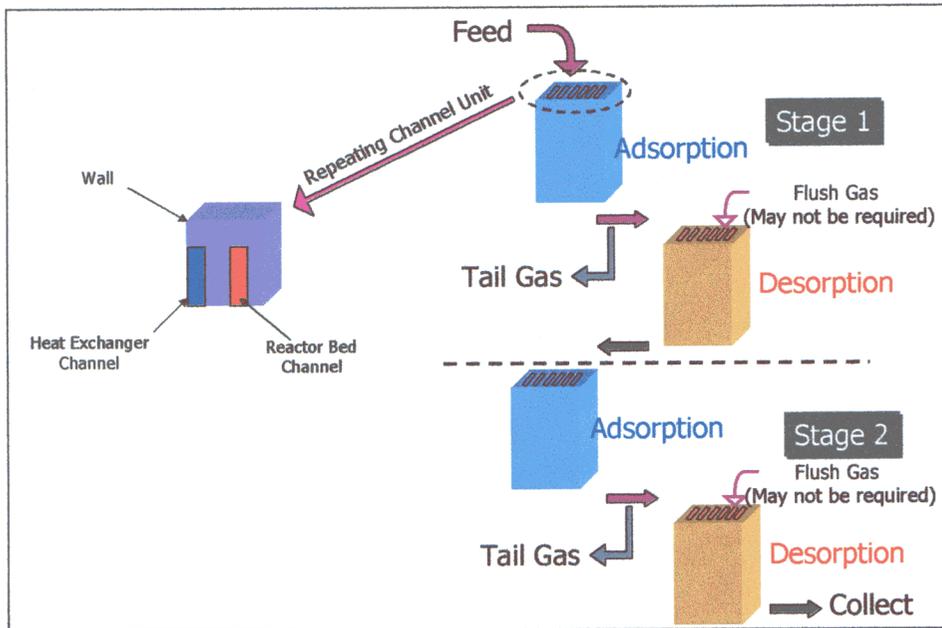
**Fig. 7.** Preliminary system cost comparison (3 MMSCFD basis)

### Nitrogen Rejection Unit

This section of the system study focused on the summary metrics of product recovery and thermal efficiency. To determine these key parameters, a mathematical model was developed to simulate a multi-stage NRU. A series of runs were performed on the model with the following objectives:

- To determine key parameters governing energy requirements for an NRU.
- To design system to deliver required energy to NRU.

Figure 8 shows the schematic of the model NRU system. The theoretical NRU has channels housing adsorbent material adjacent to heat exchange channels. The heat exchange channels are used to swing the bed temperature between the adsorbing and desorbing temperature state. The feed gas enters the low-temperature adsorbent section of the NRU to preferentially adsorb methane. A nitrogen-rich exhaust stream, labeled “tail gas,” is rejected out of the unit prior to breakthrough of the product methane. After the adsorber unit is filled to capacity with methane, the device is heated to desorb methane. To flush removed methane out of the box, a small quantity of “flush gas” may be flowed. The methane released from the desorption cycle may become the feed for the next stage or may be collected as product if sufficient purity is attained.



**Fig. 8.** NRU schematic

The inputs to the computational NRU model are

- Channel dimensions
- Adsorbent characteristics
- Inlet feed gas composition and outlet methane flow rate
- Adsorption/desorption temperature and cycle time
- Construction material of box

By varying the following inputs, two potential NRU design concepts were developed. The first, called “early entry,” requires more energy to swing the temperature of the adsorbent bed, but is expected to be a more straightforward development effort. The second, which uses an engineered form of the adsorbent material, is expected to have a longer development effort, but will result in improved methane recovery and reduced energy consumption. The specifics of each concept are presented in Table 6.

	Early Entry	Engineered Form
Material of Construction	Stainless Steel	Porous Carbon Engineered Form/Stainless Steel Composite
Adsorbent Form	Powdered	
Cycle Time	1 to 5 seconds	1 to 3 seconds
Energy Requirement	~1.65 megawatts (MW)	~400 kilowatts
Methane Recovery	>80%	>95%

**Table 6.** NRU process performance targets and anticipated performance

## Heating and Cooling System for NRU

Integral pieces of the NRU are the heating and cooling systems that permit the rapid temperature swings. A schematic of these systems is shown in Figure 9.

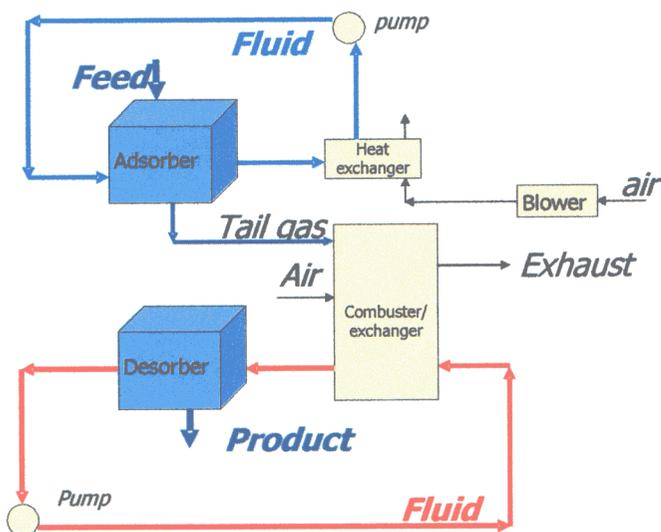


Fig. 9. NRU heating and cooling systems

The system is fueled by methane in the tail gas, which is combusted with air to provide heat to desorb the bed. An efficiency of 70% was assumed for heat transfer from combusted gas to the NRU. Achieving this energy efficiency may require the use of efficient microchannel heat exchangers. The heat from the combusted gases is transferred to a circulating fluid that flows through the NRU system to provide heat during the desorption cycle.

Other sources of heat, such as inter-stage and/or after-coolers on the compression equipment, also may be used to affect the thermal swing. If these other sources can be tapped, then a further reduction in the amount of tail gas methane required for the desorption cycle is possible.

For the adsorption cycle, heat is removed from the NRU system by a cooling circuit, as shown in Figure 9. A cooling fluid removes heat from the NRU system. In a closed-loop process, heat is rejected to ambient from the cooling fluid prior to returning into the adsorber unit.

## Task 2.2 Conceptual Component Design

The adsorber and the desorber units were designed for a total capacity of 3 MMSCFD of gas fed to the NRU system. Below are the assumptions used for designing the adsorber and desorber unit:

*Adsorbent characteristics for the selected granular carbon:*

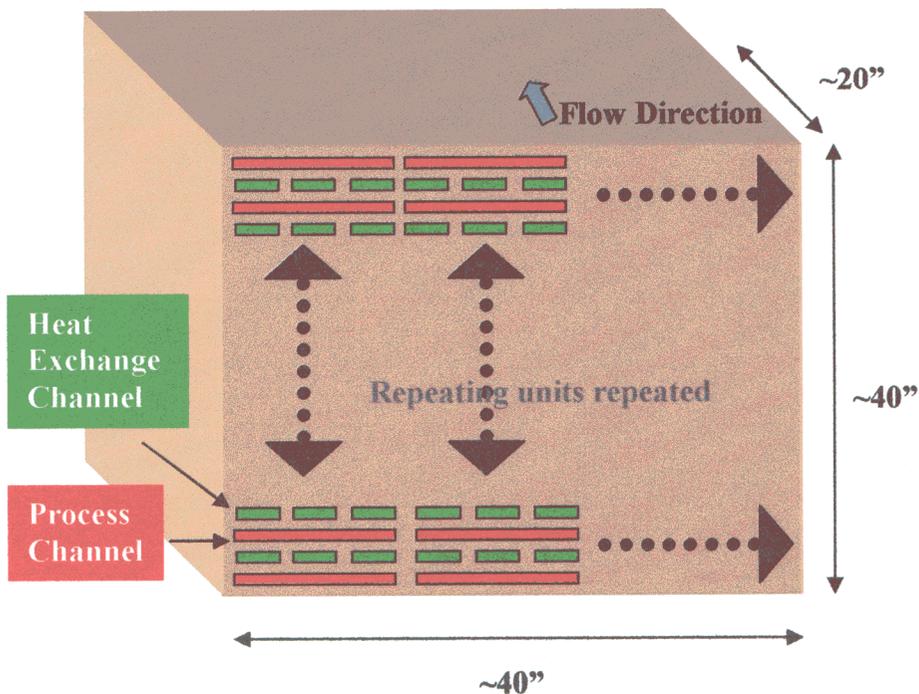
1. Differential capacity of  $\text{CH}_4 = 0.01$  gram (gm)/gm
2. Differential capacity of  $\text{N}_2 = 0.0003$  gm/gm
3. Particle size = 315 micrometers
4. Heat Capacity = 1,260 Joule/kilogram/ $^{\circ}\text{C}$

5. Bed Density = 540 kg/cubic meter
6. Void fraction = 0.4

*Feed gas design basis:*

1. Molar composition: 70% CH<sub>4</sub>, 30% N<sub>2</sub> at inlet
2. Adsorber temperature = 40°C
3. Desorber temperature = 60°C
4. Process pressure = 100 psig
5. The desorbed gas is removed from the channels by pressure differential

The adsorber and the desorber were designed to withstand a total absolute pressure of 150 psig and differential pressure of 70 psi. The material of construction is Stainless Steel 304L. Figure 10 shows a representative picture of the adsorber and desorber unit.



**Fig. 10.** Representative picture of adsorber/desorber unit, where the adsorption channels are the longer slots interleaved between heat exchange microchannels

The picture shown in Figure 10 is illustrative and is not to scale. The overall dimension of the unit is ~40" (width) x ~40" (height) x ~20" (flow length). The unit has parallel process and heat exchange channels. Both the process and heat exchange channels have a microchannel gap on the order of 1000 microns. The process channel contains an adsorbent bed to adsorb methane from the process gas. The heat exchange channels heats and cools on adjacent sides of the adsorbent channel to adsorb and desorb methane.

The design basis feed gas is a mixture of 70% methane and 30% nitrogen. The adsorber operating temperature is approximately 40°C, while the desorber operating temperature is approximately 60°C.

The design performance of the adsorber/desorber unit is

1. Purity of the product = 96%
2. Recovery of methane = 90%
3. Cycle time = 4 seconds
4. Number of stages required = 1
5. Energy required to swing the temperature of the unit = 1.65 megawatts (MW)

The energy requirement of the box to swing temperature is obtained by combustion of the tail gas (assuming 70% energy transfer efficiency).

Water is used as coolant for heat exchange channels to provide and remove heat from the box for desorption and adsorption, respectively. The total flow rate of water required is roughly 20 kg/second. A schematic of heating and cooling system is shown in Figure 9.

### Task 3 Cost and Feasibility Assessment

The capital cost estimate was based on the design derived in Task 2 of the project. The microchannel component of the ultra-fast TSA system was determined using in-house models in conjunction with Velocys expertise in the field. Accompanying equipment costs were based on information from vendors and factored estimates. Operating costs included the mineral value of the fuel consumed in the system, maintenance, and other personnel costs.

#### Potential Impact on Greenhouse Gas Abatement

The possible greenhouse gas (GHG) emission reduction was measured by installing an ultra-fast TSA NRU system using the global warming potential (GWP) methodology. This technique evaluates the relative atmospheric warming potential of a variety of greenhouse gases relative to the potential of carbon dioxide, the most abundant GHG. The time horizon used for these calculations was 100 years, which gives methane a GWP factor of 21.

The same basis used for the design and cost study was used to calculate the GWP advantage for a coal-mine methane project using the Velocys NRU. The results of these calculations are shown in Table 7 below. Assuming that 600 MMSCFD of gas upgrading facilities are built each year in the five years following the development program, which is projected to be complete by 2007, approximately 3 billion SCFD will be on-line in 2012. The resulting greenhouse gas abatement would be equivalent to decreasing carbon dioxide emissions by 148 million metric tons per year, or approximately 2% of the U.S. total.

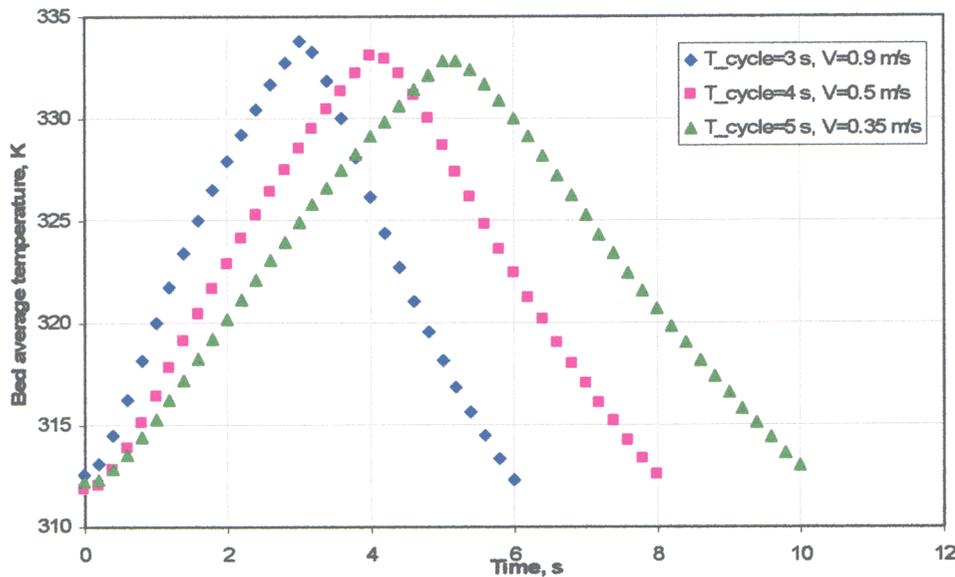
Scenario	Vented Gas	Gas Utilization
Inlet gas flow rate	3 MMSCFD	3 MMSCFD
CH <sub>4</sub> Released to Environment (kg/year)	1.42 x 10 <sup>7</sup>	0
CO <sub>2</sub> Released to Environment	2.24 x 10 <sup>6</sup>	6.55 x 10 <sup>6</sup>

(kg/year)		
Global Warming Potential (equivalent kg CO <sub>2</sub> /year)	3.01 x 10 <sup>8</sup>	6.55 x 10 <sup>6</sup>
Savings(equivalent kg CO <sub>2</sub> /yr and metric tons/year)		2.95 x 10 <sup>8</sup> (148,000)

**Table 7.** Greenhouse gas emission comparison

**Adsorbent Feasibility**

A dynamic numerical model was developed to study the impact of design variables on the time required to thermally swing the adsorbent unit. For the selected adsorbent and channel geometry, the predicted cyclic thermal profile in the adsorbent bed is shown as a function of the heating and cooling medium flow rate. The selected system cycle time of 4 seconds requires a water flow rate of 0.5 meters per second in adjacent microchannels.



**Fig. 11.** Average adsorbent bed temperature as a function of cycle time and heat exchange flowrate.

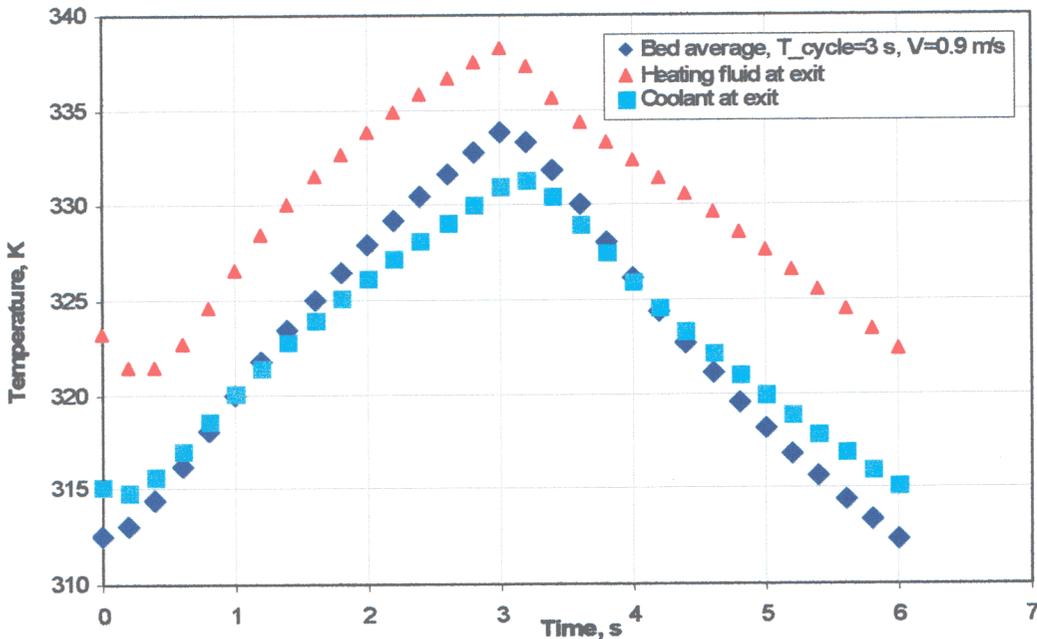


Fig. 12. Comparison of temperatures in bed and coolants for the case of three sec cycle

Measured capacity, as previously reported (10 milligram [mg]/gm methane and < 1 mg/gm N<sub>2</sub>), appears feasible for obtaining the projected process performance.

Adsorbent kinetics or time for equilibration within the granular carbon also appears feasible. The selected particle size is on average 315 microns in diameter. The time for gas-phase diffusion from the surface to the interior active sites is calculated to be on the order of 1 millisecond, while the gas spends more than a second in the adsorbent channel. The resulting time difference of two or three orders of magnitude suggests the adsorbate molecules should have sufficient time for equilibration within the adsorbent particle.

Diffusion time is estimated as the square of the longest diffusion distance divided by the diffusivity. The diffusivity for this mixture at temperature and pressure is estimated to be roughly 0.23 square centimeters per second using the Wilke equation. The longest transport distance is the particle radius, or 0.0158 centimeter. The resulting effective time for diffusion within a particle is estimated to be 1.1 milliseconds.

### Valve Selection

To optimize the benefits of the microchannel-based TSA NRU, it is desirable for the various process valves to fully stroke in milliseconds, every few seconds. An extensive effort was made to identify valves that 1) are capable of rapidly opening and closing, 2) have high number of cycles between failures, and 3) are inexpensive. Many styles of valves were examined and many potential vendors contacted. Table 8 contains a summary of pertinent data from a number of manufacturers. Unquestionably, the proposed application is a severe service for any valve, and this was validated by many manufacturers during the search.

Valve Type	Manufacturer	Actuator Type	Manufacturer	Cost	Stoke Time	Anticipated Life Cycle
Solenoid	Snap-Tite	Solenoid	Snap-Tite	3" - \$1,700	200-500 ms	20,000
Pinch	RF Valve	Solenoid	Unknown	Recommend 2" for Appl. 2" - \$1,275 4" - \$1,300 6" - \$1,600	< 1 sec	> 500,000
PVB	Fisher	Rack & Pinion	Bettis	4" - \$1,420 6" - \$1,828	~ 1 sec	Not Published
HPVB	DuZurik	Piston actuated Rack & Pinion	DuZurik	4" - \$2,500 6" - \$3,000	320 ms	>1,000,000 valve seat > 5,000,000 actuator Rep has experience with high-cycle apps.
Fuel Shut off in Gas Turbine	Whittaker Controls	Assume Solenoid	Unknown	2" \$9,000 in quantities > 100	100 ms (C) 200-330 (O)	Same as Woodward
GSOV- Spool	Woodward	Solenoid	Unknown	2" \$12,000	85 ms @ 600 psi (C) 300ms @ 100 psi (O)	20,000
Fuel - Spool	Woodward	Solenoid	Unknown	No Quote	90 ms (C) 1 sec (O)	Not published
Globe	Valtek	Linear	Valtek	6" \$10,000	300ms	>1,000,000
¼ Turn		Rotary	Schafer	No Quote	250 ms	2,000

Table 8. Summary of fast cycling valve data

High-performance butterfly valves (HPBVs) appear to be best suited for the application, based on a composite assessment of actuation speed, longevity, and cost. HPBVs are made by a host of manufacturers. Specific recommendations for optimizing the TSA NRU design were based on the DuZurik HPVB with its PowerRac® actuator. DuZurik has placed valves in severe cyclic applications and was able to provide more performance and life-cycle information for its HPBV and actuator than other vendors. There are valves that can cycle faster, but these are generally very expensive specialty valves and/or they are not made to cycle every few seconds.

The typical failure sequence for the HPBV is the seat, packing, and then actuator seals (rebuild). Except for tightening the packing gland, the valve must be removed from service for repair. None of these expected repairs is particularly expensive. The downtime associated with the repair is the more significant cost.

For the microchannel-based TSA NRU, a seat failure (minor leakage) should not be a major issue since a small leakage through the seat would have a small effect on unit performance. Secondary shutdown valves for emergency isolation on the feed and product streams may be required to operate the system safely. Assuming that tight shutoff cannot be guaranteed, seat seal life, relatively speaking, will be short. An actuator failure, on the other hand, could very easily force the system to shut down for maintenance. Consequently, the mean time between actuator failures becomes the basis for a preventative maintenance schedule. To minimize system downtime, valve seats and packing should be replaced during the actuator's planned maintenance schedule.

It is reasonable to assume that the actuators could be rebuilt on a biannual preventive maintenance schedule to ensure reliable operation. This is the recommended basis for design of the Velocys microchannel-based TSA NRU

### **Component Cost and Manufacturability**

For the NRU design concept, the manufacturing assessment indicates a cost to produce of between \$30,000 and \$55,000. These estimates assume the material of construction will be 304L stainless steel. Also assumed is a production capacity of 500 units per year, which would be sufficient to process approximately 600 MMSCFD.

At the production level of 500 units per year, much of the manufacturing is performed by subcontractors, and the associated costs included in the processing line item will be further reduced. As the production level increases, subcontract costs could be further reduced – thus reducing the overall the cost to produce the microchannel adsorber units.

In regard to manufacturability of the NRU design, the proposed design conforms to Velocys standards for feature size formation, tolerance allowances for subsystems and assembly, and metal joining requirements for either diffusion bonding or metal brazing. Loading and refurbishment of the granular adsorbent also conforms to Velocys standards for granular catalyst systems, and no further challenge is identified at this time.

### System Design and Cost Estimate

Two NRU sub-systems were evaluated: a stand-alone case and an integrated case that shares chilled water with the upstream dehydration sub-system and heating with an adjacent power cogeneration plant. Significant cost, energy, and environmental advantages may result from an integrated system.

A process flow diagram for the stand-alone NRU subsystem is presented in Appendix III and was the basis for the heat and mass balance calculations and cost estimating. The feed stream was compressed and dehydrated before entering the NRU subsystem. The NRU cycles between adsorbing and desorbing the methane (CH<sub>4</sub>). The process design and cost estimate treats the NRU sub-system as a continuous-flow, steady-state device although it cycles between adsorbing and desorbing two reactors/vessels.

Cooling fluid reduces the process temperature to 40°C during the adsorption cycle. Unrecovered CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub> and O<sub>2</sub> exit as rejected tail gas during this cycle. The valve sequence stops cooling fluid flow and feed to the first box and starts heating fluid flow for the desorption cycle to produce NRU product at 60°C. Table 9 lists the valve positions. For simplicity sake, the cooling and heating fluids were assumed to be water.

Stream	Valve #	Adsorber (Desorber) #1	Desorber (Adsorber) #2
Feed	1	Open	Closed
Product	2	Closed	Open
Tail Gas	3	Open	Closed
Cooling Fluid	4	Open	Closed
Heating Fluid	5	Closed	Open

**Table 9.** Valve positions

Surge tanks provide buffer capacity to stabilize flows during the valve cycling. NRU product proceeds to the O<sub>2</sub> and CO<sub>2</sub> removal sub-systems for further processing and purification.

Appendix IV contains the process flow diagram stream data for key streams within the stand-alone NRU. Methane recovery is 90% for the NRU. Other constituents, such as CO<sub>2</sub>, N<sub>2</sub> and O<sub>2</sub>, are separated at specific separation factors that require experimental validation. The tail gas is used as fuel to a conventional packaged boiler (hot water heater) for the heating fluid and heat recovery/integration with the overall system. The specific combustor design will establish the quantity of excess air that may be needed and the resulting combustion exhaust temperature.

Table 10 summarizes the equipment list, cost, and duty specifications for the stand-alone NRU sub-system. The costs of purchased equipment were estimated from quotes in project files for similar sizes and types of equipment. The sub-total, Purchased Equipment Cost, was used as the basis for a factored estimate of the shop-assembled sub-system that could be shipped to the site for field installation. The Shop Fabrication Cost Estimate subtotal may be compared to the NRU costs reported in the 1997 EPA report described under Experimental, Task 2.1.

<b>ID#</b>	<b>Description</b>	<b>Capacity</b>	<b>Size</b>	<b>Cost</b>
D-200	Hot Fluid Surge Drum	2000 gal	5-ft dia x 15 ft	11,500
Unit Op #10	Velocys TSA NRU			50,000
Unit Op #13	Velocys TSA NRU			50,000
Valve1, A&B	Feed Inlet to TSA			3600
Valve2, A&B	Product out of TSA			3600
Valve3, A&B	Tail Gas out of TSA			3600
Valve4, A&B	Cold Fluid out of TSA			4000
Valve5, A&B	Hot Fluid out of TSA			4000
P-101	Cold Fluid Pump	1190 gpm		7501
F-103	Cold Fluid Filter			5001
E-107	Cold Fluid Exchanger	5.5 MM Btu/hr		22,001
P-201	Hot Fluid Pump	1190 gpm		7501
F-203	Hot Fluid Filter			5001
E-204	Hot Fluid Heat Exchanger	5.5 MM Btu/hr		
F-301	Inlet Air Filter			
B-302	Combustion Air Blower			
E-303	Air Preheater	1.9 MM Btu/hr		20,001
Comb-310	Combustor			110,001
Subtotal (Purchased Equipment Cost)				330,937
<b>Shop Fabrication Cost Estimate (ex works)</b>				
Cost Element		Factor ( x PEC)		Cost, \$
Piping		50%		166,000
Instrumentation and Control		20%		67,000
Electrical		10%		34,000
Skid/Support/Assembly		25%		83,000
Insulation/Paint/Freight		10%		34,000
Engineering/Overhead		30%		100,000
Contingency/Profit		30%		100,000
<b>Total</b>		<b>275%</b>		<b>911,000</b>
Target				600,000
EPA Report (Cost range for Commercial NRU Subsystems)			1,030,000	1,390,000

**Table 10.** Stand-alone NRU equipment list and costs

After a 275% factor is applied to the raw equipment costs, the resulting NRU system cost is \$911,000, approximately 50% higher than the target of \$600,000. These cost factors, which include allowances for piping, instrumentation, engineering, and others, have been reviewed by out industry consultant, Joe D'Amico. He felt that, overall, the factors may be conservative, but are appropriate for this level of cost study.

Mr. D'Amico also provided guidance on ways to reduce the cost of the NRU. His suggestions centered around integrating the NRU with the other process equipment available at a gas upgrading project site. The result of these discussions was the integrated NRU sub-system shown in Appendix V. The feed stream was compressed and dehydrated before entering the NRU subsystem. NRU product continues to the O<sub>2</sub> and CO<sub>2</sub> removal subsystems, as in the stand-alone case.

In the integrated plant, the cooling fluid for the NRU adsorption cycle is from a chiller that supplies the dehydration subsystem. The cost for incremental capacity of chilled water is advantageous rather than buying two independent chillers. Operating the cooling fluid at 5°C (40°F) is also favorable for TSA performance.

Tail gas from the NRU has a heating value of approximately 230 Btu/SCF and may be mixed with feed gas (70% CH<sub>4</sub>, heating value of 700 Btu/SCF) as fuel to an engine-driven generator. On-site generation of electricity can be cost-effective with low-cost fuels as a site-specific evaluation. The estimated power requirement for a 3 MMSCFD gob gas upgrade system is estimated to be 1,200 horsepower to operate compressors, chillers, pumps, and auxiliary equipment. The exhaust from an engine-driven generator would heat water to 80°C (176°F) as the NRU heating fluid in exchanger E-204. This integration eliminates the combustor and associated equipment from the stand-alone case.

The NRU capital cost for the integrated case is lowered to \$584,000, slightly below the \$600,000 target. Coal mines are typically in remote locations with limited available electrical power. Many remote locations justify on-site power generation, especially with low-cost fuel, rather than paying for power distribution and the associated electrical operating costs. Carbon dioxide reduction credits may apply since this represents a more energy efficient and environmentally acceptable solution than venting the tail gas as is practiced for some NRU technologies.

Other advantages of the TSA sub-system include

- Less compressor power is required because the NRU product methane exits at essentially the same pressure as the NRU feed.
- Methane in the tail gas is used as fuel rather than vented to atmosphere.
- Flow is in one direction, which avoids the dynamic stability issues of reverse flow as practiced by some competing technologies.

## Conclusions

After testing all the selected adsorbents, the measured adsorption and differential capacities between 40 and 60°C were highest for microporous carbon. Both the Calgon AX-21 carbon and the Barnaby-Sutcliffe carbon gave similar performance at 100 psig. Surprisingly, the performance at 100 psig was better than either low pressure (2 psig) or higher pressure (>200 psig) for the Calgon carbon. An operating pressure of 100 psig was selected for further study

During this past quarter, the cost and feasibility analysis was completed. The results indicate the following:

1. The greenhouse gas abatement potential of this technology is significant, potentially reducing U.S. emissions by up to 2%
2. Heating and cooling cycles were modeled, which validated the design assumption of a 3-second cycle time
3. Appropriate valves to handle fast cycling have been identified
4. Cost targets for a “stand-alone” NRU are likely difficult to reach
5. However, integrating the NRU with the rest of the upgrading process system offers the opportunity to reduce the capital cost below the \$600,000 target

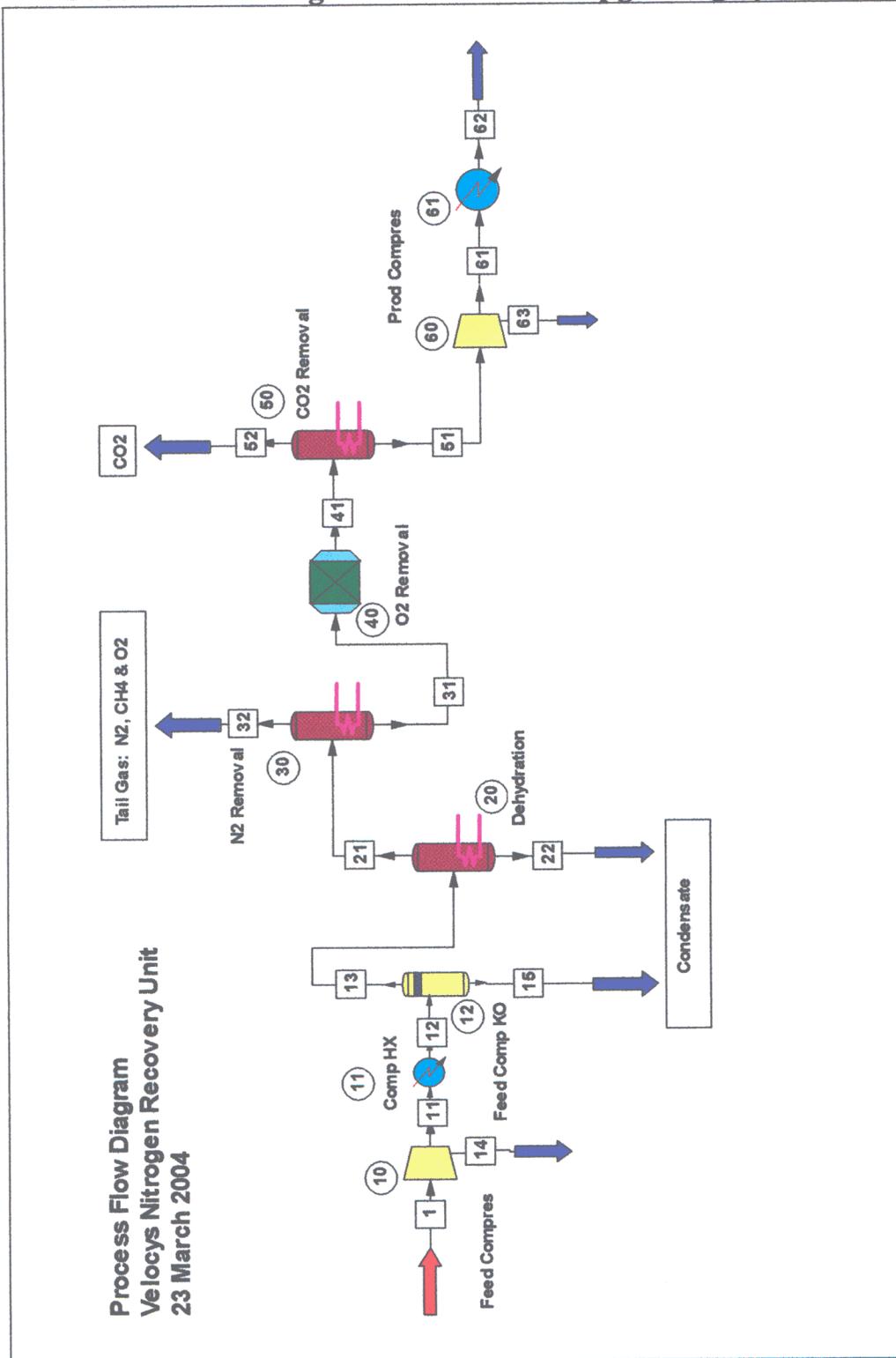
Plans for the fourth quarter of FY04 are as follows:

- Release the design of the bench-scale adsorber
- Initiate fabrication of bench-scale adsorber

## Acronyms, Initialisms, and Abbreviations

Btu	British thermal unit
GHG	greenhouse gas
gm	gram
GWP	global warming potential
HPBV	high-performance butterfly valve
kg	kilogram
mg	milligram
MMSCFD	million standard cubic feet per day
MW	megawatts
NRU	nitrogen rejection unit
psig	pound per square inch gauge
SLPM	standard liters per minute
TSA	thermal swing adsorption

## Appendix I Process Flow Diagram for Methane Upgrading System

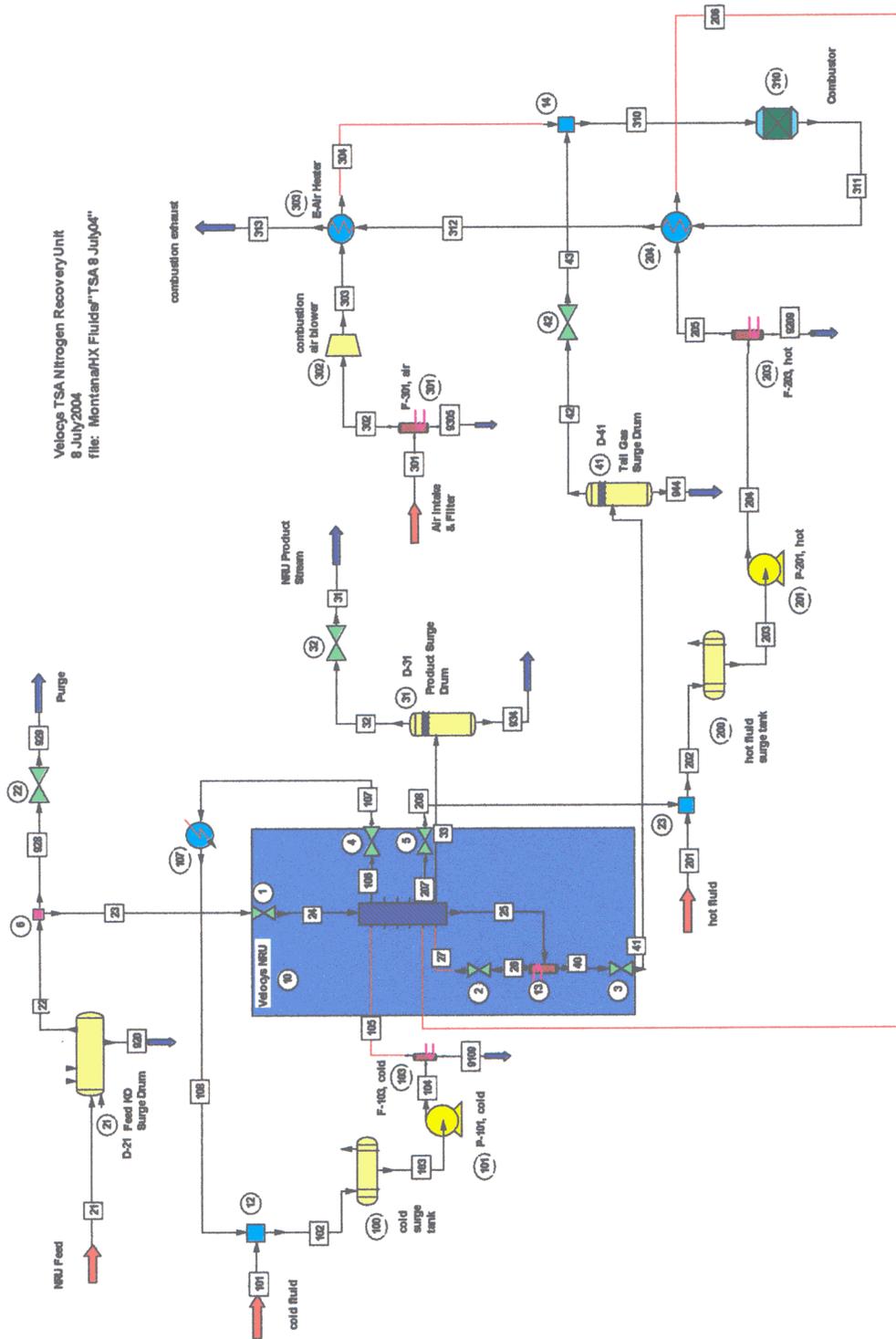


## Appendix II Adsorbent Stream Composition for Appendix I

ChemCAD/Montana/Metric PFD 3.0 feed, dated 23 March 2004

Stream No.	1	11	12	13	14	15	21	22	31	32	41	51	52	61	62	63
Name	Raw Gas Feed															
Molar flow kmol/h	158.5	158.5	158.5	157.7098	0	0.7903	155.5002	2.2095	103.9102	51.59	103.9099	99.4154	4.4944	99.4154	99.4154	0
Mass flow kg/h	3197.274	3197.274	3197.274	3183.038	0	14.2365	3143.233	39.8045	1798.11	1345.123	1798.111	1600.311	197.7998	1600.311	1600.311	0
Temp C	20	617.3591	48.8889	48.8889	0	48.8889	48.8889	48.8889	48.8889	48.8889	57.2449	57.2449	57.2449	238.526	45	0
Pres psia	1	125	123	123	0	123	123	123	113	113	113	113	113	620	618	0
Vapor mole fraction	1	1	0.995	1	0	0	1	0	1	1	1	1	1	1	1	0
Enth kW	-2988.2	-1782	-2958.4	-2896	0	-62.391	-2747.9	-174.44	-2528.7	-218.98	-2528.6	-2038.5	-490.09	-1831.6	-2065.3	0
Average mol wt	20.1721	20.1721	20.1721	20.1829	0	18.015	20.2137	18.015	17.3045	26.0733	17.3045	16.0972	44.01	16.0972	16.0972	0
Actual vol MMft3/day	47.4779	1.1572	0.4186	0.4186	0	0	0.4131	0	0.2996	0.1501	0.3077	0.2945	0.0131	0.0843	0.0496	0
Std liq liter/hr	7548.206	7548.206	7548.206	7533.968	0	14.2388	7494.157	39.8109	5548.272	1945.885	5547.422	5308.206	239.216	5308.206	5308.206	0
Std vap O C MMscfd	3.011	3.011	3.011	2.996	0	0.015	2.954	0.042	1.974	0.98	1.9739	1.8886	0.0854	1.8886	1.8886	0
Stream No.	1	11	12	13	14	15	21	22	31	32	41	51	52	61	62	63
Name	Raw Gas Feed															
Methane	110	110	110	110	0	0	110	0	99	11	98.9588	98.9588	0	98.9588	98.9588	0
Ethane	0	0	0	0	0	0	0	0	0	0	0.0007	0.0007	0	0.0007	0.0007	0
Propane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N-Butane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water	33	33	3	2.2097	0	0.7903	0.0002	2.2095	0.0002	0	0.0806	0.0806	0	0.0806	0.0806	0
Nitrogen	33	33	33	33	0	0	33	0	0.33	32.67	0.33	0.33	0	0.33	0.33	0
Oxygen	8	8	8	8	0	0	8	0	0.08	7.92	0	0	0	0	0	0
Carbon Dioxide	4.5	4.5	4.5	4.5	0	0	4.5	0	4.5	0	4.5398	0.0454	4.4944	0.0454	0.0454	0
Stream No.	1	11	12	13	14	15	21	22	31	32	41	51	52	61	62	63
Name	Raw Gas Feed															
Methane	69.4063	69.4063	69.4063	69.74838	0	0	70.73944	0	95.27455	21.32196	95.23521	99.54066	0	99.54066	99.54066	0
Ethane	0	0	0	0	0	0	0	0	0	0	0.00068	0.00069	0	0.00069	0.00069	0
Propane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N-Butane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water	1.892745	1.892745	1.892745	1.401144	0	100	0.000142	100	0.000213	0	0.077538	0.081043	0	0.081043	0.081043	0
Nitrogen	20.82019	20.82019	20.82019	20.92452	0	0	21.22183	0	0.317581	63.32623	0.317582	0.33194	0	0.33194	0.33194	0
Oxygen	5.047318	5.047318	5.047318	5.072609	0	0	5.144687	0	0.076989	15.35181	0	0	0	0	0	0
Carbon Dioxide	2.839117	2.839117	2.839117	2.853343	0	0	2.893886	0	4.330662	0	4.369004	0.045665	100	0.045665	0.045665	0

# Appendix III Process Flow Diagram for Stand-Alone Nitrogen Rejection Unit



## Appendix IV Stream Composition for Appendix III

Heat and Mass Balance Calculations for Selected Streams  
Selected information from TSA 8/July04

Stream No.	21	24	25	27	33	31	41	43	105	106	107	108
Name	NRU Feed	NRU Feed	Cooled Fe	Adsorbed F	Desorbed F	Product	Tail Gas	Tail Gas	Cooling Fil	Cold Fluid		
-- Overall --	0	0	0	0	0	0	0	0	0	0	0	0
Molar flow kmol/h	155.5	155.5	155.5	104.53	104.53	104.53	50.97	50.97	3600.8	3600.7	3600.7	3600.7
Mass flow kg/h	3143.23	3143.23	3143.23	1807.14	1807.14	1807.14	1336.1	1336.1	64868.43	64866.62	64866.62	64866.62
Temp C	48.9	48.88	40	38.97	60	58.98	38.98	38.55	30.02	51.39	51.39	30
Pres psia	123	122	113	112	111	110	112	28	30	28	20	19
Vapor mole fraction	1	1	1	1	1	1	1	1	0	0	0	0
Enth MMBut/h	-9.3762	-9.3762	-9.4211	-8.3248	-8.2507	-8.2507	-1.0967	-1.0967	-974.87	-969.34	-969.34	-974.85
Average mol wt	20.21	20.21	20.21	17.29	17.29	17.29	26.21	26.21	18.01	18.01	18.01	18.01
-- Vapor only --	0	0	0	0	0	0	0	0	0	0	0	0
Actual dens lb/ft3	0.4	0.4	0.38	0.32	0.3	0.3	0.49	0.12	0	0	0	0
Actual vol MMft3/day	0.41	0.42	0.44	0.3	0.32	0.32	0.15	0.58	0	0	0	0
Std vap 0 C MMscfd	2.95	2.95	2.95	1.99	1.99	1.99	0.97	0.97	0	0	0	0
Cp Btu/lbmol-F	8.45	8.45	8.38	8.82	9	9	7.48	7.4	0	0	0	0
Cp/Cv	1.33	1.33	1.33	1.32	1.3	1.3	1.38	1.37	0	0	0	0
Z factor	0.9928	0.9929	0.9924	0.9891	0.9917	0.9918	0.998	0.9994	0	0	0	0
Visc cP	0.01424	0.01423	0.01391	0.01207	0.01271	0.01271	0.01741	0.01734	0	0	0	0
Th cond Btu/hr-ft-F	0.02	0.02	0.0199	0.0206	0.0223	0.0223	0.0167	0.0164	0	0	0	0
Total kmol/h	155.5	155.5	155.5	104.53	104.53	104.53	50.97	50.97	3600.8	3600.7	3600.7	3600.7
Flowrates in kmol/h	0	0	0	0	0	0	0	0	0	0	0	0
Methane	110	110	110	99	99	99	11	11	0	0	0	0
Nitrogen	33	33	33	0.33	0.33	0.33	32.67	32.67	0	0	0	0
Carbon Dioxide	4.5	4.5	4.5	3.6	3.6	3.6	0.8	0.8	0	0	0	0
Oxygen	8	8	8	1.6	1.6	1.6	6.4	6.4	0	0	0	0
Water	0	0	0	0	0	0	0	0	3600.8	3600.7	3600.7	3600.7
Component mole fractions												
Methane	0.707	0.707	0.707	0.947	0.947	0.947	0.216	0.216	0	0	0	0
Nitrogen	0.212	0.212	0.212	0.003	0.003	0.003	0.641	0.641	0	0	0	0
Carbon Dioxide	0.029	0.029	0.029	0.034	0.034	0.034	0.018	0.018	0	0	0	0
Oxygen	0.061	0.051	0.051	0.015	0.015	0.015	0.126	0.126	0	0	0	0
Water	0	0	0	0	0	0	0	0	1	1	1	1
Total kg/h	3143.23	3143.23	3143.23	1807.14	1807.14	1807.14	1336.1	1336.1	64868.43	64866.62	64866.62	64866.62
Flowrates in kg/h	0	0	0	0	0	0	0	0	0	0	0	0
Methane	1764.73	1764.73	1764.73	1588.26	1588.26	1588.26	176.47	176.47	0	0	0	0
Nitrogen	924.46	924.46	924.46	9.24	9.24	9.24	915.22	915.22	0	0	0	0
Carbon Dioxide	198.04	198.04	198.04	158.44	158.44	158.44	39.61	39.61	0	0	0	0
Oxygen	255.99	255.99	255.99	51.2	51.2	51.2	204.79	204.79	0	0	0	0
Water	0	0	0	0	0	0	0	0	64868.43	64866.62	64866.62	64866.62

Heat and Mass Balance Calculations for Selected Streams  
 Selected information from TSA 8July04

Stream No.	205	206	207	208	304	311	312	313
Name	Inlet E-204 Heating Flt		0 Hot Fluid C	Preheated		0 Hot Exhaus	Exhaust	
-- Overall --	0	0	0	0	0	0	0	0
Molar flow kmol/h	3600.6	3600.6	3600.5	3600.5	300	350.97	350.97	350.97
Mass flow kg/h	64864.82	64864.82	64863.01	64863.01	8655.25	9991.34	9991.34	9991.34
Temp C	58.63	80.06	58.62	58.62	320.47	1020.35	538.58	370.47
Pres psia	30	29	28	20	29	23	22	21
Vapor mole fraction	0	0	0	0	1	1	1	1
Enth MMBtu/h	-967.45	-961.92	-967.43	-967.43	2.4946	1.3621	-4.1679	-5.9748
Average mol wt	18.01	18.01	18.01	18.01	28.85	28.47	28.47	28.47
-- Vapor only --	0	0	0	0	0	0	0	0
Actual dens lb/ft3	0	0	0	0	0.07	0.03	0.04	0.05
Actual vol MMft3/day	0	0	0	0	6.28	20.18	13.24	11
Std vap 0 C MMscfd	0	0	0	0	5.7	6.67	6.67	6.67
Cp Btu/lbmol-F	0	0	0	0	7.29	8.56	7.87	7.56
Cp/Cv	0	0	0	0	1.38	1.3	1.34	1.36
Z factor	0	0	0	0	1.0009	1.0004	1.0005	1.0006
Visc cP	0	0	0	0	0.03034	0.05028	0.03674	0.03121
Th cond Btu/hr-ft-F	0	0	0	0	0.0262	0.0503	0.0341	0.028
Total kmol/h	3600.6	3600.6	3600.5	3600.5	300	350.97	350.97	350.97
Flowrates in kmol/h	0	0	0	0	0	0	0	0
Methane	0	0	0	0	0	0	0	0
Nitrogen	0	0	0	0	237	269.67	269.67	269.67
Carbon Dioxide	0	0	0	0	0	11.9	11.9	11.9
Oxygen	0	0	0	0	63	47.4	47.4	47.4
Water	3600.6	3600.6	3600.5	3600.5	0	22	22	22
Component mole fractions								
Methane	0	0	0	0	0	0	0	0
Nitrogen	0	0	0	0	0.79	0.768	0.768	0.768
Carbon Dioxide	0	0	0	0	0	0.034	0.034	0.034
Oxygen	0	0	0	0	0.21	0.135	0.135	0.135
Water	1	1	1	1	0	0.063	0.063	0.063
Total kg/h	64864.82	64864.82	64863.01	64863.01	8655.25	9991.34	9991.34	9991.34
Flowrates in kg/h	0	0	0	0	0	0	0	0
Methane	0	0	0	0	0	0	0	0
Nitrogen	0	0	0	0	6639.32	7554.53	7554.53	7554.53
Carbon Dioxide	0	0	0	0	0	523.72	523.72	523.72
Oxygen	0	0	0	0	2015.94	1516.75	1516.75	1516.75
Water	64864.82	64864.82	64863.01	64863.01	0	396.34	396.34	396.34

# Appendix V Process Flow Diagram for Integrated Nitrogen Rejection Unit

Velocys TSA Nitrogen Recovery Unit  
 Integrated Case 28 July 2004  
 file: MontanaHX Fluids TSA Integrated case 23.Jul.04\*

