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**NATURAL GAS CLEANUP: EVALUATION OF A MOLECULAR SIEVE CARBON AS
A PRESSURE SWING ADSORBENT FOR THE SEPARATION OF
METHANE/NITROGEN MIXTURES**

Topical Report

**By
R. William Grimes**

June 1994

Work Performed Under Contract No. FC21-86MC11076

**For
U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
Western Research Institute
Laramie, Wyoming**

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Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
Western Research Institute
365 North 9th Street
Laramie, Wyoming 82071**

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SUMMARY

This report describes the results of a preliminary evaluation to determine the technical feasibility of using a molecular sieve carbon manufactured by the Takeda Chemical Company of Japan in a pressure swing adsorption cycle for upgrading natural gas (methane) contaminated with nitrogen. Adsorption tests were conducted using this adsorbent in two, four, and five-step adsorption cycles. Separation performance was evaluated in terms of product purity, product recovery, and sorbent productivity for all tests.

The tests were conducted in a small, single-column adsorption apparatus that held 120 grams of the adsorbent. Test variables included adsorption pressure, pressurization rate, purge rate and volume, feed rate, and flow direction in the steps from which the product was collected. Sorbent regeneration was accomplished by purging the column with the feed gas mixture for all but one test series where a pure methane purge was used.

The ratio between the volumes of the pressurization gas and the purge gas streams was found to be an important factor in determining separation performance. Flow rates in the various cycle steps had no significant effect. Countercurrent flow in the blow-down and purge steps improved separation performance. Separation performance appears to improve with increasing adsorption pressure, but because there are a number of interrelated variables that are also effected by pressure, further testing will be needed to verify this.

The work demonstrates that a molecular sieve carbon can be used to separate a mixture of methane and nitrogen when used in a pressure swing cycle with regeneration by purge. Further work is needed to increase product purity and product recovery.

BACKGROUND

About one-half of the natural gas produced in the United States is low quality natural gas (LQNG) contaminated by other gases or water to the extent that it cannot be used without processing. Technologies for dehydration of LQNG are used extensively, but application of available technologies for the separation of other contaminants, particularly nitrogen, from natural gas has been limited because of economic considerations (U.S. Department of Energy 1992).

In the past decade, an increasing number of gas separation problems have been solved economically by the use of pressure swing adsorption (PSA) systems. PSA systems make use of various microporous solids that preferentially adsorb certain components from a gas mixture, thereby separating it into adsorbed and nonadsorbed fractions. The solid adsorbent has an increased capacity for the sorbate at elevated pressure; therefore, a cycle based upon adsorption at higher pressure followed by desorption as the pressure is reduced can be used to separate a gas mixture into its component streams.

The characteristics of the adsorbent, particularly with respect to the ease with which desorption takes place, determine the economics of a pressure swing separation process. In order to separate a binary gas mixture, an adsorbent must adsorb one component of the mixture more strongly than the other; however, the more strongly a component is adsorbed, the more difficult it is to desorb and the greater the energy requirement for sorbent regeneration. Thus, selection of the correct adsorbent is the key to adsorption-based gas separation processes (Kumar and Van Sloun 1989). Because of the relatively low value of the natural gas product, adsorbent selection is especially critical in an effort to develop an economically viable PSA cleanup process.

Early in 1990 Williams Technologies, Inc. (WTI) initiated a project with Minteco PSA in an effort to develop an economically viable PSA system capable of minimizing the nitrogen contaminant in a natural gas stream such that the methane would be saleable. The guidelines listed below were established for the process:

Feed Gas Volume	From 1000 to 20,000 mcf/day
Process Feed Pressure	From 50 to 100 psig
Manifold Pressure	From 3 psig to 25 psig
Feed Gas Analysis	Nitrogen <30%
	Methane >70%
Processed Gas Analysis	Methane >95%
Waste Stream	Methane <5%
Sale Gas Pressure	From 800 to 1000 psig
Process Cost	<\$0.90/MMBtu

The Minteco effort focused on finding an adsorbent that could separate N_2/CH_4 mixtures and be regenerated without the use of vacuum or heating. A number of natural and synthetic zeolites and active carbon adsorbents were tried using several different pressure swing cycles. Minteco reported that all the adsorbents tested required vacuum regeneration to maintain acceptable productivity. In the Conclusions and Recommendations section of their report which summarizes laboratory results for work conducted between June 1990 and January 1991, Minteco stated that "the material known in the industry as Molecular Sieve Carbon (MSC) warrants investigation" (Minteco PSA 1991). Dr. Charles Benham, a PSA consultant retained by WTI, concurred with this recommendation.

To continue the effort to develop an economically viable PSA system to remove a nitrogen contaminant from a natural gas stream, WTI transferred its PSA test apparatus to WRI. In the spring of 1993 WRI undertook a series of laboratory experiments to evaluate the feasibility of using a MSC adsorbent in a pressure swing cycle to separate a mixture of nitrogen and methane. The work was jointly sponsored by DOE and Williams Technologies, Inc. through the DOE Jointly Sponsored Research Program.

Based upon the recommendations contained in the Minteco report (Minteco PSA 1991) which was made available to WRI at the beginning of the work and Dr. Benham, a review of pertinent literature on PSA (White and Barkley 1989; Yang 1987; Sircar and Kumar 1986; Cheremisinoff and Ellerbusch 1978), and a survey of the limited number of commercially available molecular sieve carbons, a 5 Å molecular sieve carbon manufactured by the Takeda Chemical Company of Japan was selected for evaluation.

Two basic separation mechanisms (differential diffusion and equilibrium adsorption) can be exploited in PSA systems using molecular sieve carbon adsorbents. The separation mechanism is determined by the shape and size of the adsorbent pore structure. Differential diffusion processes are based upon kinetically-controlled gas diffusion through constricted pore openings. In equilibrium adsorption processes separation results from selective adsorption of gas molecules based upon differences in van der Waals forces.

The 5 Å pore size of the Takeda MSC used in these tests is sufficient to provide rapid diffusion of both nitrogen and methane. Therefore, this separation is based upon equilibrium adsorption in which the methane component is more strongly adsorbed than the nitrogen component.

The small (2.54-cm i.d.) column used in the tests represents a trade off of process efficiency in favor of experimental simplicity. However, it is realized that in the small column, the flow of gas tends to

increase near the vessel wall because a change in the packing order of the adsorbent results in a higher interstitial void fraction and a lower pressure drop. The resultant uneven flow distribution across the bed reduces the effectiveness of the separation process with the adsorbent near the walls becoming saturated faster than the adsorbent in the column center. The useful adsorbent volume is thus effectively reduced. A detailed analysis of the wall effect can be found in Design of Pressure Swing Adsorption Systems by White and Barkley (1989).

OBJECTIVES

The objectives of this project were: (1) to assemble and calibrate the PSA test apparatus supplied by WTI and (2) to test the Takeda MSC in a simulated PSA cycle at various pressures, temperatures, and flow rates.

RESEARCH STRATEGY

The performance of the Takeda MSC in this pressure swing separation was measured in terms of three interrelated parameters: (1) product purity, (2) product recovery, and (3) sorbent productivity. The product purity was calculated as the volume averaged concentration of methane in the effluent from the cycle steps from which the product stream was collected. Product recovery was calculated as the methane volume in the product stream divided by the methane volume in the influent gas stream. Sorbent productivity was expressed as the volume of methane per unit amount of adsorbent per cycle.

Adsorption tests using the Takeda MSC were conducted in a single-column adsorption apparatus supplied by WTI. The experimental work involved systematically changing adsorption cycle parameters and observing the effect upon performance in the separation of a mixture of 70% methane and 30% nitrogen. The raw data provided the volume and composition of effluent collected incrementally from the various cycle steps. Successive tests used the best conditions established in previous tests as a starting point, therefore, a steady increase in purity, recovery, and sorbent productivity was observed as the testing progressed.

The process guidelines established by Minteco required a product purity of 95% with a product recovery of 95%. Sorbent productivity was not established as such by Minteco. Because the size (and hence, the capital cost) of the adsorption system is inversely proportional to the sorbent productivity, this term was interpreted qualitatively. For cycles with similar purity and recovery, process performance was considered to be better for the cycle with higher sorbent productivity.

To maintain a continuity between the data collected by WRI and that collected by Minteco PSA, adsorption testing was begun with a simple two-step adsorption cycle described in the Minteco reports supplied by WTI, and progressed to a five-step cycle commonly used in multiple-column bulk separation systems. The adsorption cycle parameters investigated as test variables included: adsorption pressure, purge rate and purge volume, purge with pure methane, pressurization rate, feed rate, and flow direction in the blow-down and purge steps.

EXPERIMENTAL PROCEDURE

Pressure Swing Apparatus

The PSA apparatus used in the testing was constructed by Minteco, disassembled, and shipped to WRI. The apparatus consisted of an influent gas supply and measurement system, adsorption column, and effluent gas collection and measurement system. Because the apparatus was constructed by others, each piece was thoroughly evaluated as the apparatus was reassembled. The calibration of the pressure transducer and gauges was checked using a dead weight gauge calibrator. Inlet gas volume measurements were checked by water displacement using the effluent gas collection cylinders.

When the PSA apparatus was assembled, three-way valves were added at each end of the column to accommodate the flow reversal in tests using countercurrent blow-down and purge steps. An effluent collection system with six individually selectable gas receivers was added to provide integrated samples from the various cycle steps. Figure 1 is a schematic of the adsorption apparatus as it was assembled for use in these tests.

Pressurization gas, feed gas, and purge gas were supplied and measured separately by the influent gas system shown on the left side of Figure 1. Pressurization gas volume was calculated from the pressure change registered on gauge 1 (Figure 1) and the known volume of the pressurization gas cylinder. Ball valve 1, BV_1 , and flow control valve 1, FVC_1 , (Figure 1) provide on/off and rate control, respectively, for the pressurization gas stream. Feed gas volume was calculated by multiplying the flow rate, as measured and controlled by the mass flow controller, by the time that the three-way solenoid valve, SV_1 , (Figure 1) was open to the adsorption column, as measured by the elapsed time meter. Purge gas was measured and controlled in the same manner as the pressurization gas. BV_2 and FCV_2 (Figure 1) control purge gas flow.

A Porter model number 201SSVC, 0.1 scfm, was used for mass flow control. Gauge 1 (Figure 1) was a Wallace & Teirnan model 62B-2A-0300 graduated to 300 psig in 0.5 psi divisions. Gauge 2 (Figure 1) was a Marshalltown 0-30 psig Bourdon tube gauge. Whitey stainless steel gas sample cylinders were used for the pressurization gas and purge gas cylinders.

Figure 1. Schematic of PSA Apparatus

The adsorption column, shown in the center of Figure 1, consisted of a 40.6-cm length of 2.54-cm schedule 40 stainless steel pipe with machined Teflon end caps and O-ring seals. Gauges 3 and 4 (Figure 1) were U.S. Gauge 0-100 psig Bourdon tube gauges. The 0-100 psig pressure transducer, PT₁, (Figure 1) was made by Beckman Instruments, Inc.

The effluent system, shown on the right side in Figure 1, consisted of a back-pressure regulator with two controllable by-passes, a 16-loop gas sampler made by Valco Instruments, Inc., and six gas receiver tubes. Effluent gas volume was measured by water displacement in the six receiver tubes. Solenoid valves, SV₂ through SV₇ (Figure 1), were activated sequentially to direct effluent gas to the desired collector. BV₃ and FCV₃ by-pass the back-pressure regulator and provide on/off and rate control for the depressurization and blow-down steps. BV₄ is opened during the purge step.

Gas Analysis

The effluent gas composition was determined using a Hewlett Packard 5840A gas chromatograph equipped with a thermal conductivity detector and a 3.175-mm x 6.1-m column packed with Chromosorb 102. Helium carrier gas flow was 25 mL/min. From each of the gas receivers, a 0.50 mL sample was withdrawn and injected directly onto the column of the gas chromatograph by means of a gas-tight syringe. Detector response factors were calculated using the feed gas mixture as a calibration standard. A normalization method, where the area percent data are corrected using the appropriate detector response factors for the calibrated peaks and then normalized to 100%, was used to measure the concentration of nitrogen and methane in each sample.

Adsorbent

The Takeda 5 Å MSC used in the testing was supplied by TIGG Corporation. The adsorbent particles are hard cylindrical pellets approximately 0.4 cm in diameter and 0.6 cm in length. The bulk density of this MSC when packed in the 2.54-cm (i.d.) column was 0.58 g/mL. The adsorption column held 120.0 grams of MSC. The MSC was degassed by heating to 121°C (250°F) under vacuum for 1 hour. After degassing, the adsorbent was saturated with methane at 0 psig (11.3 psia) before the first test series was begun. The adsorbent remained in the column with no further treatment through the entire test program.

The Two-Step Adsorption Cycle

For the tests using the two-step cycle, SERIES 1, the column was pressurized with a mixture of 70% CH₄ and 30% N₂. A constant flow rate of 1.16 L/min was set with the mass flow controller. The back-pressure regulator was set to a pressure above the test pressure and remained closed throughout the tests. BV₃ was opened and FCV₃ (Figure 1) was

partially opened to provide a small leak rate from the end of the column opposite the feed during the pressurization step.

In a typical test, SV_1 (Figure 1) was opened to the column until a predetermined pressure was reached. As the column was pressurized, a small flow of gas (set by FCV_3) from the end opposite the feed was collected in one of the gas receivers. When the desired pressure was reached, SV_1 was closed to the column, and the column was allowed to depressurize from the feed end (3-WV₂ reversed) with the effluent being collected in the remaining gas receivers. Table 1 shows the valve operation sequence for a typical two-step cycle.

Table 1. Two-Step Cycle Valve Operation Sequence

Step	SV_1	BV_1	BV_2	3-WV ₁	3-WV ₂	BV_3	BV_4
1	open	close	close	forward	forward	open	close
2	close	close	close	forward	reverse	open	close

Adsorption pressures of 20, 30, and 50 psig were used in the two-step tests. Cocurrent and countercurrent depressurization were tried as well as several rates of flow from the end of the column opposite the feed during pressurization.

The Four-Step and Five-Step Adsorption Cycles

The bulk of the testing was conducted using four-step and five-step pressure swing cycles. The five-step cycle consisted of: (1) pressurization, (2) feed at pressure, (3) depressurization, (4) blow-down, and (5) purge. The four-step cycle consists of: (1) pressurization, (2) depressurization, (3) blow-down, and (4) purge. In the four-step cycle, step 2 (the feed at pressure step) was eliminated. Thus, the four-step cycle is essentially a five-step cycle with a very low (0) feed/pressurization ratio. For tests using the four-step cycle, the back-pressure regulator was set to a pressure above the test pressure and remained closed throughout the tests. Table 2 shows the valve operation sequence for a typical four-step cycle with cocurrent blow-down and purge.

The first tests using the four-step cycle, SERIES 2, were conducted to determine the effect of changing purge rate and volume and to establish values for these parameters to be used in subsequent tests. Purge gas to pressurization gas volume ratios ranging from 11% to 38% and purge gas flow rates ranging from 59 mL/min to 326 mL/min were used. In all tests the column was purged with the feed gas mixture (70% CH₄, 30% N₂).

Table 2. Four-Step Cycle Valve Operation Sequence

Step	SV ₁	BV ₁	BV ₂	3-WV ₁	3-WV ₂	BV ₃	BV ₄
1	close	open	close	forward	forward	close	close
2	close	close	close	forward	forward	open	close
3	close	close	close	forward	forward	open	close
4	close	close	open	forward	forward	close	open

A test in which the effluent from the purge step was sampled at 30 second intervals was conducted to establish purge volume for subsequent tests. The point where the methane concentration in the purge step effluent began to decline was chosen as the end of the purge step for subsequent tests.

A series of tests, SERIES 3, was conducted to determine the effect of purging the column with 100% methane. For these tests the purge gas cylinder was filled with pure methane. In all other tests the column was purged with the 70% CH₄, 30% N₂ feed mixture.

The four-step cycle was used to evaluate the effect of changing flow rate in the pressurization step, SERIES 4. Using the valve operation sequence shown in Table 2 and various adjustments of FCV₁ (Figure 1), pressurization gas flow rates of 132.3, 13.92, 4.89, and 1.86 L/min were evaluated in a cycle using 50 psig adsorption pressure and purge with the feed gas mixture.

Countercurrent flow in the blow-down and purge steps was evaluated using the four-step cycle. These tests used the valve operation sequence shown in Table 2 except that 3-WV₁ and 3-WV₂ were reversed in the blow-down and purge steps.

The effect of delaying the depressurization step was investigated in a test series, SERIES 5, using the four-step cycle. In this test series, the column was held at 50 psig for 0, 20, 30, and 60 seconds before beginning the depressurization step.

Adsorption pressures of 30, 38, 50, and 59 psig were evaluated in tests using the four-step cycle, SERIES 6. These tests used the valve operation sequence shown in Table 2 except that 3-WV₁ and 3-WV₂ were reversed in the blow-down and purge steps to provide for countercurrent flow in these steps.

Table 3 shows the valve operation sequence for tests using the five-step cycle. For these tests the back-pressure regulator was set at the desired adsorption pressure and FCV₁ was adjusted to provide the desired pressurization rate. BV₁ was opened until gas began to flow through the

back-pressure regulator, at that point BV_1 was closed and SV_1 was opened to begin the feed step. Effluent from the feed step was collected in the first gas receiver. All the tests with the five-step cycle used countercurrent flow in the blow-down and purge steps.

Table 3. Five-Step Cycle Valve Operation Sequence

Step	SV_1	BV_1	BV_2	3-WV ₁	3-WV ₂	BV_3	BV_4
1	close	open	close	forward	forward	close	close
2	open	close	close	forward	forward	close	close
3	close	close	close	forward	forward	open	close
4	close	close	close	reverse	reverse	open	close
5	close	close	open	reverse	reverse	close	open

Feed gas flow rates of 1.74, 1.16, and 0.58 L/min were evaluated using the five-step cycle with 50 psig adsorption pressure, SERIES 7. Figure 2 shows the column pressure through a typical five-step cycle with 50 psig adsorption pressure, 2.25-minute pressurization step, and 1 minute of feed at pressure.

Figure 2. Column Pressure Through Five-Step Cycle

A series of tests, SERIES 8, was conducted to evaluate the effect of increasing adsorption pressure in the five-step cycle. The test series used adsorption pressures of 20, 30, 50, and 60 psig, 1 minute of feed at 1.16 L/min, countercurrent blow-down, and countercurrent purge with the feed gas mixture.

For the final test series, SERIES 9, the blow-down step was begun at lower pressure (6 psig vs. 10 psig) and the purge volume was increased. Effluent from the blow-down step and the first 63.6% of the effluent from the purge step was collected as product with the remainder of the effluent gas going to the waste stream. The adsorption pressure was 60 psig.

RESULTS

Preliminary Testing

The cylinders used to measure the effluent gas were calibrated such that the volumes could be measured to ± 5.4 mL per cylinder. In a test using all six gas collection cylinders, the total effluent volume could be measured to within ± 32.4 mL. The volume of gas handled in a typical cycle was about 3000 mL; thus, total effluent volume was measured within $\pm 1.1\%$.

In six consecutive tests where the adsorption column was by-passed and the influent gas measuring system was connected directly to the effluent gas measuring cylinders, the gas volumes measured independently by the two systems all agreed within $\pm 2.42\%$.

The Two-Step Cycle

Seven tests were conducted using the two-step cycle, SERIES 1. The best separation performance in these tests was attained with a cycle where the adsorption pressure was 20 psig, and 62% of the pressurization gas stream was allowed to escape from the column outlet as the column was pressurized. For this test, product purity was 79.96%, product recovery was 18.30%, and sorbent productivity was 3.79 mL/g/cycle.

The Four-Step and Five-Step Cycles

Initial tests using the four-step cycle, SERIES 2, were conducted to establish the purge rate and volume to be used in subsequent tests. Table 4 lists the separation performance determined for the four-step cycles with increasing purge/pressurization gas volume ratios. All the tests used 50 psig adsorption pressure and cocurrent purge with the feed gas mixture.

Table 4. Separation Performance with Increasing Purge Volume, SERIES 2

Purge Volume/ Pressure Volume, %	Product Purity, %	Product Recovery, %	Sorbent Productivity, mL/G/cycle
11	76.58	38.97	6.00
13	77.87	35.42	5.62
20	80.79	46.19	7.82
24	84.70	47.49	8.45
38	80.42	44.27	8.55

In Figure 3 the methane concentration in the purge effluent is plotted against time as the purge step progresses. The purge gas flow was stopped after 5.5 minutes but the evolving gas was sampled for an additional 2 minutes. After about 2.5 minutes of purge gas flow, the methane concentration in the effluent began to decrease. At this point 627 mL of purge gas had been introduced to the column. This volume corresponded to a purge/pressurization ratio of 0.26. Based on these results, a ratio of approximately 0.25 was used in most of the subsequent tests.

Figure 3. Methane Concentration in Purge Effluent

Purge gas flow rates ranging from 59 mL/min to 326 mL/min were tried with no significant effect on separation performance. Product purity, product recovery, and sorbent productivity increased with countercurrent flow in the blow-down and purge steps. With countercurrent blow-down and purge, product purity was 85.69%, product recovery was 49.26%, and sorbent productivity was 8.72 mL/g/cycle.

Countercurrent purging of the column with 100% methane instead of the feed gas mixture, SERIES 3, resulted in a slight increase in product purity (86.60 vs. 85.69%). This increase was more than offset by decreased recovery (39.30 vs. 49.26%) and decreased sorbent productivity (7.42 vs. 8.72 mL/g/cycle).

Pressurization gas flow rates of 132.3, 13.92, 4.89, and 1.86 L/min were evaluated using the four-step cycle with an adsorption pressure of 50 psig, SERIES 4. Separation performance was not effected by the pressurization flow rate except at the highest rate where purity, recovery, and productivity all declined. Separation performance was not effected by delays of 0, 20, 30, and 60 seconds between the pressurization and depressurization steps, SERIES 5.

Table 5 lists the results of four tests using the four-step cycle with increasing adsorption pressure, SERIES 6. In all four tests, the column was purged with 590.8 mL of the feed gas mixture (70% CH₄, 30% N₂).

Table 5. Four-Step Cycle Separation Performance at Various Adsorption Pressures, SERIES 6

Adsorption Pressure, psig	Product Purity, %	Product Recovery, %	Sorbent Productivity, mL/G/cycle
30	80.69	55.58	7.46
38	82.35	48.72	7.46
50	85.39	49.26	8.72
59	85.69	45.85	8.81

The first test series using the five-step adsorption cycle, SERIES 7, compared separation performance with feed rates of 1.74 L/min, 1.16 L/min, and 0.58 L/min at 50 psig adsorption pressure. Feed rate changes had no significant effect on separation performance. The average separation performance for these tests was: purity 85.9%, recovery 56.7%, and sorbent productivity 14.5 mL/g/cycle. With the five-step cycle, product recovery and sorbent productivity increased significantly when compared to the four-step cycle.

A series of tests, SERIES 8, was conducted using the five-step cycle, adsorption pressures of 20, 30, 50, and 60 psig, 1 minute of feed at 1.16 L/min, and purge with the feed gas mixture. In this test series, product purity increased from 82.5% at 20 psig to 88.4% at 60 psig. Product recovery was 52.6% at 20 psig and 51.3% at 60 psig. Sorbent productivity increased from 10.1 mL/g/cycle to 14.7 mL/g/cycle as the adsorption pressure was increased from 20 to 60 psig. Table 6 shows the separation performance for these tests.

For the final test series, SERIES 9, the blow-down step was begun at lower pressure (6 psig vs. 10 psig) and the purge volume was increased. The blow-down effluent and the first 63.6% of the effluent from the purge step was collected as product with the remainder of the effluent gas going to the waste stream. With an adsorption pressure of 60 psig this test gave a product purity of 91.6%, a recovery of 37.1% and a sorbent productivity of 11.1 mL/g/cycle.

Table 6. Five-Step Cycle Separation Performance with Increasing Adsorption Pressure, SERIES 8

Adsorption Pressure, psig	Product Purity, %	Product Recovery, %	Sorbent Productivity, mL/G/cycle
20	82.49	52.64	10.15
30	83.22	61.47	13.85
50	86.07	57.66	14.84
60	88.44	51.32	14.66

Table 7 lists the inlet and outlet gas volumes and material balance closures as measured for the various test series. Material balances were within the $\pm 2.46\%$ accuracy of the gas measuring system for most of the four-step and five-step cycles.

Because more time than originally anticipated was required to define the purge step, adsorption tests at a higher temperature were not conducted.

CONCLUSIONS

The test results show that a pressure swing adsorption (PSA) system using this molecular sieve carbon adsorbent and a feed gas containing 30% nitrogen contamination can provide a significant methane enrichment of the product stream without the use of a vacuum regeneration step. The saturated adsorbent was successfully regenerated by purging with the

feed gas mixture. Flow rate in the feed and pressure changing steps was not an important factor in separation performance. Separation performance seemed to improve with increasing adsorption pressure through the range tested, but because of the limited nature of this study and the interrelation of process variables, further study will be required before a positive conclusion can be reached.

Table 7. Material Balances for the Various Test Series

SERIES	Test	Std. Vol. In, cm ³	Std. Vol. Out, cm ³	Closure, %
1	1	2563.00	2517.73	98.23
1	2	3572.66	3553.72	99.47
1	3	2582.42	2440.21	94.49
1	4	3009.58	1058.05	35.16
1	5	2737.00	2576.11	94.12
1	6	1592.17	1743.47	109.50
1	7	1860.06	2280.75	122.62
2	1	2659.22	2548.24	95.83
2	2	2739.49	2631.49	96.06
2	3	2920.96	2955.18	101.17
2	4	3072.04	3081.19	100.30
2	5	3332.76	3388.46	101.67
3	1	3030.17	2830.24	93.40
3	2	3015.31	2908.57	96.46
3	3	2998.76	3029.15	101.01
4	1	2796.35	2772.20	99.14
4	2	2911.51	2993.95	102.83
4	3	3037.15	3060.25	100.76
4	4	3072.04	3081.19	100.30
5	1	2977.82	3012.55	101.17
5	2	2976.35	2772.20	99.14
5	3	3037.15	3104.86	102.23
5	4	3037.15	3066.02	100.95
6	1	2318.25	2290.18	98.79
6	2	2642.80	2547.78	96.40
6	3	3054.60	3070.77	100.53
6	4	3316.33	3292.67	99.29
7	1	4404.43	4475.44	101.61
7	2	4360.20	4420.09	101.37
7	3	4441.92	4464.48	100.51
8	1	3329.86	3325.56	99.87
8	2	3889.01	3860.09	99.26
8	3	4441.92	4464.48	100.51
8	4	4931.87	4946.55	100.30
9	1	5194.05	5257.38	101.22
9	2	5152.18	5179.25	100.53

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DISCLAIMER

Mention of specific brand names or models of equipment is for information only and does not imply endorsement of any particular brand.

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