ROTARY-VALVE, FAST-CYCLE PRESSURE-SWING ADSORPTION TECHNOLOGY ALLOWS WEST COAST PLATFORM TO MEET TIGHT CALIFORNIA SPECIFICATIONS AND RECOVER STRANDED GAS

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ABSTRACT

Off-shore production/processing platforms often strand valuable associated and/or natural gas reserves due to severe space and weight/or limitations on the platform prohibiting the installation of gas processing and/or treatment facilities.

This paper will describe how one such oil producer, located in the Santa Barbara Channel, met the aforementioned challenges by first demonstrating the effectiveness of Fast-Cycle Pressure-Swing Adsorption through on-board, pilot plant studies, then in a full-scale production unit capable of processing up to 5.0 MMscfd. The Rotary-Valve, Fast-Cycle PSA, which encompasses a space on the platform no larger than 18 ft(L) X 8 ft(W) X 9 ft(H), takes the place of three traditional gas processing plants; an amine unit (to remove CO_2) a chiller (to remove C_3^+ compounds) and a glycol dehydration unit, resulting in a dramatic reduction in size and weight, thereby saving the platform millions of dollars in capital costs as well as eliminating any need to structurally change the platform.

In addition, the Rotary-Valve, Fast-Cycle PSA has successfully proven to be able to handle high levels of ethane, allowing the platform to meet and/or exceed stringent California Air Resource Board standards; ethane removal has previously been proven very difficult for other, older technologies, such as refrigeration.

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Introduction

Santa Barbara Channel Oil Production

The Santa Barbara Channel, located off the Central California coast (approximately 100 miles northwest of downtown Los Angeles), has had perhaps one of the longest histories of man’s involvement with petroleum-based products and industries.

Historically, local Indians tribes produced cakes made of asphaltum - or tar – from naturally-occurring oil seeps as torches, and other trade goods. Many items—including bowls, jewelry, knives, and canoes—were decorated with asphaltum inlaid with chips of abalone and other shells. Baskets and water bottles were waterproofed inside and out with asphaltum. Chumash Indians used refined asphaltum to build their plank canoes, a crowning achievement of Chumash technology.

These natural oil seeps were first recorded by Spanish explorer Juan Rodríguez Cabrillo on Oct. 16, 1542; and then by English explorer George Vancouver two-and-a-half centuries later.

Later, immigrants traveling across California in 1849 used oil from these natural seeps to grease their wagon wheels. By the 1850's and 60's some of the early settlers were mining oil from natural seeps to crudely refine in order to pave roads, burn in oil lamps, and as a lubricant for machinery. The oil was mined by digging pits and tunnels at seep sites, and, eventually, by drilling under natural seeps in search of underground oil reservoirs; most early discoveries of oil in California were found in this way. In 1896, the channel was home to the first offshore oil well, located off the cost of Summerland, California.

Platform Gail

Today, the oil from the channel is removed via twenty offshore platforms; one of the largest of these was constructed by Chevron Corporation in 1987 and is located in 739 feet of water. Called Platform Gail, the platform is now owned and operated by Venoco, Incorporated, (of Carpinteria, CA) and has produced over 40 MMbbls since production began in 1988. Platform Gail is located approximately ten miles off the California coast, is 160 by 250 feet, and consists of three main decks above the well bay. Generally speaking, the platform houses between thirty and fifty operating personnel and contains 36 well slots, 26 which are currently being used, producing 3,500 bpd of 18° API crude oil and approximately 2.0 MMscfd of associated gas from the Sockeye Field.

Platform Gail Operations

Original Design Operations

As shown in Figure 1, crude oil and associated gas are produced on the platform via gas lift, where high-pressure (2,000 psig) associated gas is injected through the well tubing-casing annulus, thereby aerating the fluid to reduce its density. The oil reservoir formation pressure is then able to lift the oil column and force the fluid out of the wellbore and up to the platform. There, a portion of the gas is then separated from the fluid and then re-compressed through the gas lift compressors, completing the gas lift cycle.

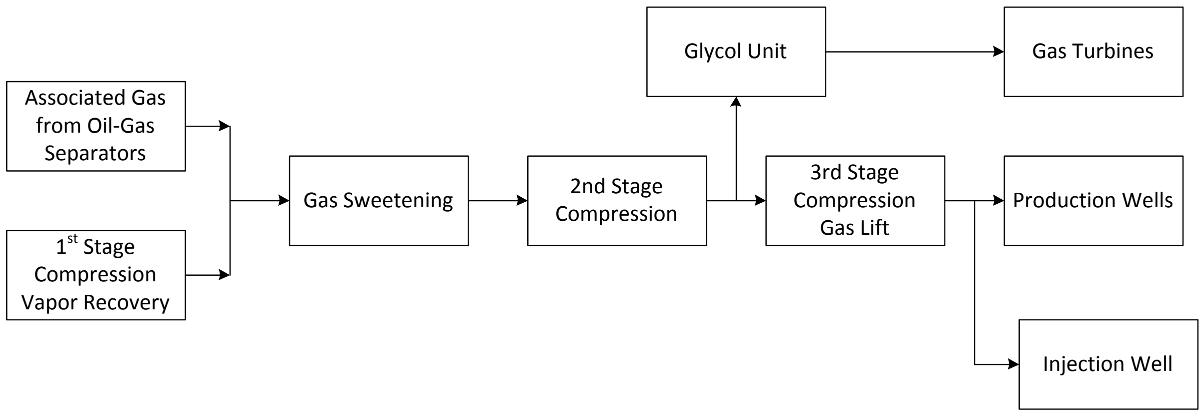


Figure 1. Original Platform Gail Gas Block Flow Diagram

The gas produced on Platform Gail is quite sour (containing approximately 4,000 ppm of H_2S), and is therefore sweetened through a liquid iron redox process (SulFerox®) before being compressed to levels where stress corrosion cracking would be a concern. Following compression to approximately 4,000 psig, a slip stream of the gas was separated from the gas lift stream, dehydrated using triethylene glycol, and used as fuel in three 3.1MW (each) Rolls Royce electrical-generating turbines. Approximately 1 MMcsfd of excess gas is disposed of through an injection well (as shown in the diagram), due to insufficient on-board processing equipment and the extreme on-shore permitting difficulties faced in California.

Stranded Gas

The associated gas produced on-board Platform Gail is quite sour, containing approximately 4,000 ppm of H_2S. The gas also contains levels of inert (primarily carbon dioxide) and heavy light hydrocarbon compounds that are significantly higher than allowed by State of California.

Specifications for natural gas are proposed in the state by the California Air Resource Board (CARB) and then established by the California Public Utility Commission; these specifications are shown in Table 1.

The stranded gas shown in Figure 1 could be sold if it met the tight California specifications. However, due to the relatively low volume of the gas, it was always thought that treatment would not be justified, regardless of how much Venoco desired to capture the value of the stranded gas and also reduce compressor load

Table 1. Platform Gail Produced Gas/CA Sales Gas Specification

Component	Platform Gail Produced Associated Gas (mol%)	California Sales Gas Specification (mol%)
Total Inerts (N_2, CO_2 and O_2)	15	4.0
Carbon Dioxide (CO_2)	13	3.0
Methane (CH_4)	64	88.0
Ethane (C_2H_6)	8	6.0
Propanes Plus ($C_3H_8^+$)	13	3.0
Butanes Plus ($C_4H_{10}^+$)	7	1.5
Water (H_2O)	Saturated	< 7 #/MMcf

As can be seen Table 1, not only was the associated gas produced by the platform high in CO_2, it also contained excessive levels of ethane, propane, butanes and water, all of which resulted in a low methane content. Since this gas did not meet California sales and/or pipeline standards, the gas was injected in a gas disposal well at an approximate 2.0 MMscfd rate, thereby stranding the gas which resulted in a loss of revenue of approximately $3.25MM/year (at $4/MMbtu).

Sales Gas Options

Potential Solutions

Several engineering and/or feasibility studies were undertaken in order to best determine the optimum method for treating the stranded gas; methods researched included:

- CO_2 removal via processes that use aqueous solutions of various alkanolamines
- Refrigeration to remove propane and heavier light hydrocarbons
- Lean oil absorption in order to remove ethane (using existing on-board equipment)
- Turbo expansion and molecular sieve
- Dehydration by triethlyene glycol and/or adsorption

Due to the many challenges of operating offshore various combinations of the above four listed technologies were investigated, both onshore and offshore - on Platform Gail as well as on neighboring, sister platforms. All of these methods were eventually discarded, as it was soon realized that while the optimum location for treating the stranded gas was aboard Platform Gail, there was insufficient room to do so; any projects that involved the creation of more space aboard the platform (that involved deck expansion) were prohibitively expensive.

After fruitlessly researching and investigating gas treating/processing methods for several years, gas treating technology caught up with Venoco's unique needs for multiple technology capabilities, in a small, reliable, easy-to-operate package – the Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption unit. This technology has been primarily used for gas separation downstream of methane reformation unit or in landfill gas/biogas upgrading; although the technology appeared to address all of Venoco needs, for CO_2, $C_2H_6^+$, and H_2O removal, it was still very uncertain as to whether it could be applied offshore to associated gas.

Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption

The Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption gas separation system, developed, designed and manufactured by Xebec, Incorporated (of Blainville, Quebec), is designed to separate gas mixtures by means of the Pressure Swing Adsorption (PSA) process. This process selectively adsorbs different gases by adsorbents when subjected to varying pressures. The gas mixture (Feed Gas) is made to flow vertically upwards through a tall column of adsorbent material at relatively high pressure. The adsorbed components of the mixture ('heavy' components) are retained by the adsorbent while the less easily adsorbed gases ('light' components such as methane) are released from the top of the column as purified (product) gas. Before the adsorbent material becomes saturated by the 'heavy' gas components, pressure is released from the bottom of the adsorbent column/bed. The lower pressure releases the heavy gases from the adsorbent as exhaust gases; the adsorbent bed is then re-pressurized and is ready to repeat the cycle.

To ensure a continuous supply of product gas, the PSA is equipped with six adsorbent beds which are cycled in a sequential manner through identical operating cycles. The system contains four slowly rotating, multi-port, selector valves, which are central to the operation of the unit. These four valves help to create a very efficient, rapid PSA cycle, and replace over two dozen high-maintenance, solenoid-type valves found in conventional systems; thereby allowing Xebec to utilize a more efficient, faster PSA cycle that translates into smaller equipment packages with reduced capital and installation costs.

Figure 2. Detailed Photographs of Heavies/Lights Xebec Rotary Valves

Two valves control the gas flows into the bottom end of the adsorbent beds and are called the "Heavies" Valve, while the other two valves control the flow at the top end of the beds and are conversely called the "Lights" Valve. These valves are driven by a gear motor and a variable frequency drive, in order to adjust valve speed, and therefore, bed cycle time.

Unit performance (i.e. product purity and flow) are controlled by bed cycle time, and therefore rotary-valve speed. For example, an increase in the valve speed will decrease the bed cycle time resulting in a more pure (less contaminant-laden) product stream. Although the product stream will increase in purity with increasing valve speed, the product volume will *decrease*, resulting in an *increase* in exhaust flow. Therefore, final gas product purity can be controlled by simply adjusting the rotary-valve speed and controlling contaminant removal and methane recovery, thereby making the unit very operator-friendly, and therefore, well suited for offshore operations.

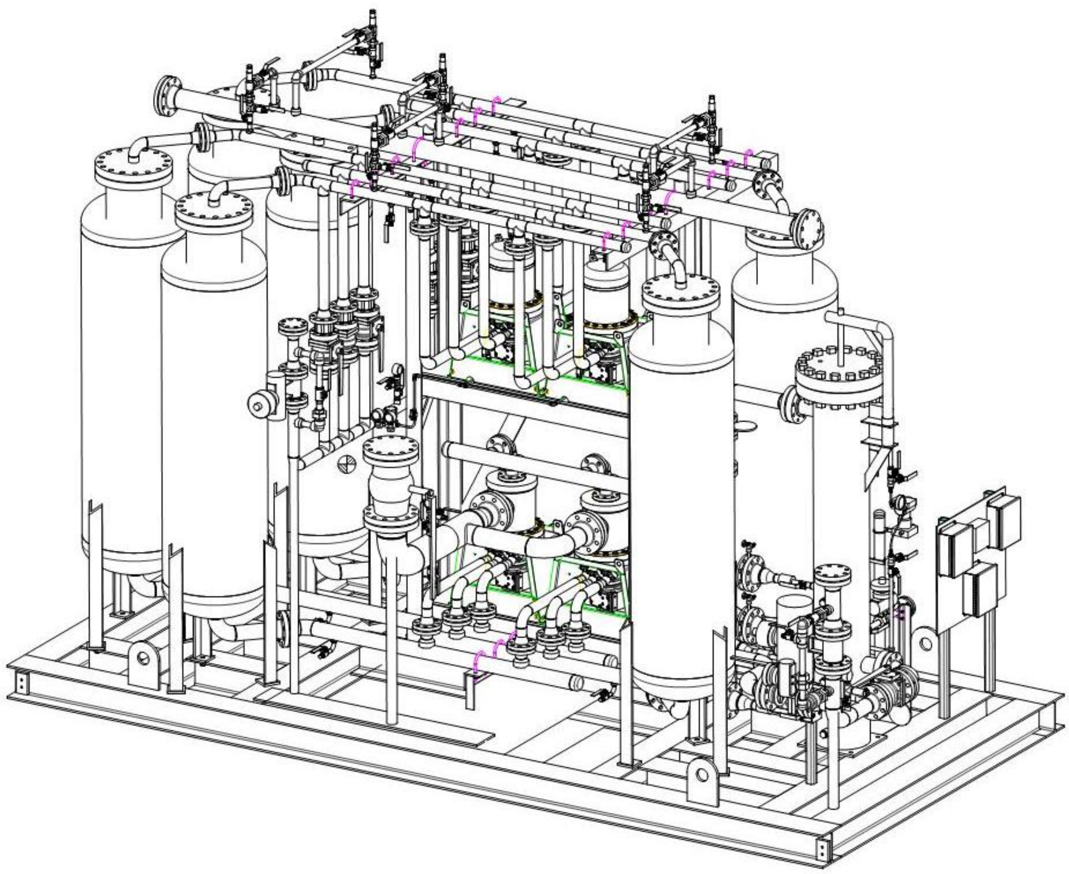


Figure 3. Detailed Drawing of Xebec Model M-3100 Used on Platform Gail

The use of the rotary valves, therefore, made the operation of the PSA more operator-friendly, by following the two basic rules outlined found on the following page.

1. If a higher methane purity is required, then the rotary valve speed is increased, which will result in a decreased volume of a more pure product stream, thereby increasing the exhaust gas stream flow rate

2. If a lower methane purity is required, then the rotary valve speed is decreased, which will result in an increased volume of a dilute product stream, resulting in a decrease in the exhaust gas stream volume

In addition, to being easy-to-operate, having much fewer moving parts than conventional Pressure-Swing Adsorption Units, the Rotary-Valve, Fast-Cycle PSA would cover a much smaller footprint (18 ft(L) X 8 ft(W) X 9 ft(H)) than conventional PSA (which probably would be several times larger than the Rotary-Valve, Fast-Cycle Unit) and/or the other technology applications that Venoco was investigating (which would have encompassed several decks).

Adsorbent Selection

The adsorbents used in the Xebec Rotary-Valve, Fast-Cycle M-3100 units are selected based on several criteria.

- Adsorption capacity for the target components
    - Affinity for CO_2, ethane, water, but not methane
- Selectivity between components competing for the same adsorption sites
    - For example, the preferential adsorption of H_2O over CO_2 has to be accounted for
- Regenerability
    - The adsorbent must release the adsorbed target components at a reasonable pressure rate of gas diffusion into the adsorbent bead
    - This affects the size of bead that is chosen and consequently the pressure drop across the bed
        - An insufficient diffusion rate requires smaller diameter beads that result in higher pressure drop and increased operating costs
- Chemical compatibility
    - Ensure that no chemical attack that would poison or destroy the adsorbent (such as liquid hydrocarbons causing physical breakdown of the adsorbent, resulting in loss of efficiency and backpressure)

After Xebec's laboratory/modeling of available adsorbents, non-silica, metal-based, solid adsorbents were selected in order to provide Venoco with the proper contaminant removal to meet the tight California sales gas specifications.

Testing

Demonstration Plant Study

Still remaining however, were questions about extended-term performance using associated gas in an offshore platform environment – especially considering the variability of feedstock quality; Venoco and Xebec therefore agreed to an on-site, pilot/demonstration test in order to resolve these unanswered questions.

The test was designed using a single, conventional, full-scale Model M-3100 Unit and was conducted in late April 2006. This test processed 1st Stage Outlet Gas at 145 psig as shown in Figure 4 on the following page; exhaust gas was vented back to the vacuum system at 5 psig.

The results of the demonstration plant were quite dramatic, as the PSA decreased the total inert levels in the produced gas from fifteen to less than four percent, reduced the ethane level eight to slightly more than two percent, and increased the methane concentration in the gas from sixty-seven to more than ninety-three percent. In addition, to the successful performance of the unit, off-shore operations personal were greatly impressed by the operability, the compactness, the very few moving parts, as well as the potential for additional revenue offered by the Xebec unit.

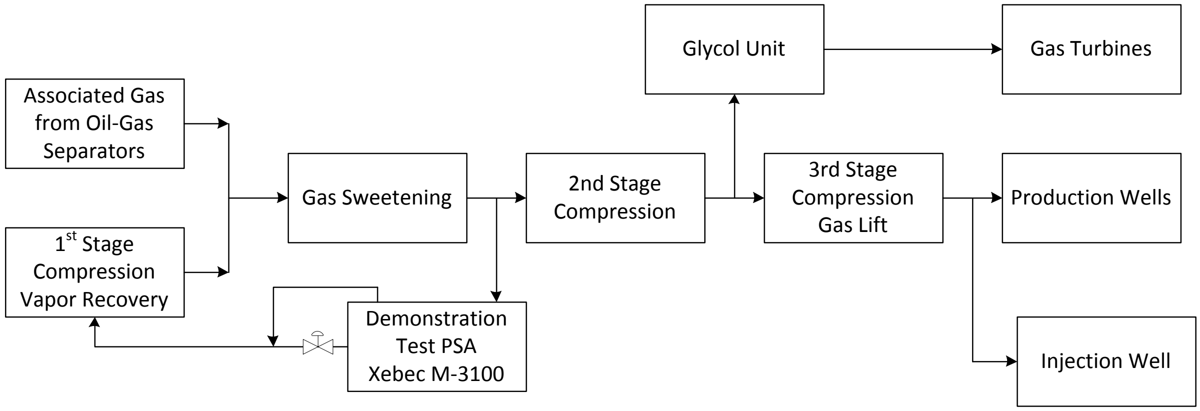


Figure 4. PSA Demonstration Test Block Flow Diagram

Due to the results listed in the above paragraph, which are detailed in Table 2 (below), and due to trouble-free way the PSA operated during the demonstration test, the evaluation of the Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit was deemed a success.

Table 2. Demonstration Test Results

Component	Platform Gail Produced Associated Gas (mol%)	Demonstration Test Product Gas (mol%)	California Sales Gas Specification (mol%)
Total Inerts (N_2, CO_2 and O_2)	15	3.70	4.0
Carbon Dioxide (CO_2)	13	2.03	3.0
Methane (CH_4)	64	93.64	88.0
Ethane (C_2H_6)	8	2.35	6.0
Propanes Plus ($C_3H_8^+$)	13	0.32	3.0
Butanes Plus ($C_4H_{10}^+$)	7	0.03	1.5
Water (H_2O)	Saturated	3 #/MMcf	< 7 #/MMcf

Based upon the success of the demonstration test results, it was decided to install a full-scale, M-3100 Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit in order to process excess production/lift gas to meet the sales gas specifications. The unit was sized to handle up to 5.0 MMscfd at approximately 300 psig.

Commercial Application

Re-Designed Platform Gas Treatment Operations

The new unit was placed downstream of the fuel gas dehydration unit, in order that the PSA exhaust stream would not contain any appreciable amounts of water, and therefore, affect turbine operation and/or performance. An existing rotary-screw compressor was used as a tail gas compressor for the new unit. Total weight added to the platform was 42 tons (after 32 tons of abandoned equipment was removed).

Figure 5 provides a basic sketch of how gas is currently processed aboard Platform Gail.

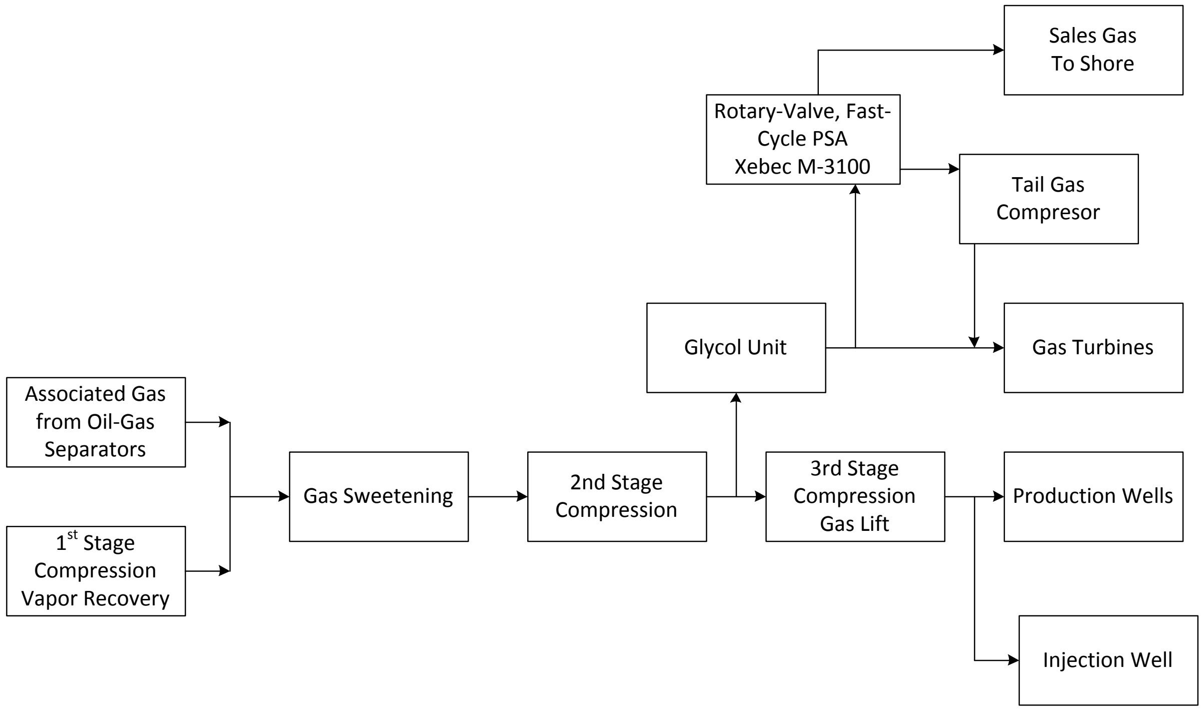


Figure 5. Current Platform Gail Gas Block Flow Diagram

As can be seen from the above sketch, excess production gas at 400 psig is dehydrated using triethylene glycol; it is then sent to the M-3100 Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit in order to produce sales quality gas prior to shipping the gas to shore. This design was selected because it offers Venoco several attractive features:

- Excess gas is no longer pressurized to 2,000 psig, thereby saving energy as well as compressor capacity
- Sales quality gas is now injected into the approximately 10-mile long pipeline to shore, negating the need for line pigging and subsequent need for line shutdown
- Dehydration of the gas prior to the PSA results in no water vapor being handled by the electrical-generating turbines, resulting in higher turbine efficiencies
- Processing the PSA Vent Gas through the turbine allows Venoco to benefit from:
  - Capture of the higher, light hydrocarbons in the feed gas (mostly C_2 through C_5)
  - Processing the high amounts of CO_2 (approximate 15 mol%) from the PSA helps to lower the flame temperature in the turbine, thereby negating any potential negative effects from ignition of the heavier hydrocarbons described above

The system as outlined in the drawing on the preceding page has been on-line since May; start-up was remarkably trouble-free, prompting one executive from Venoco to term it as "the easiest start-up in the history of the company."

In addition, due the small size of the unit (and the companion Tail Gas Compressor skid), transportation of the PSA from land to the platform was accomplished by the standard workboat. A larger skid and/or unit would have required a bigger boat to be used, thereby creating potential logistical issues and adding to installation costs (a breakdown of project costs are provided later in this paper).

Operation of the M-3100 Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit continues to be unproblematic; thus far slightly more than 2.5 MMscfd (average flow) of previously stranded gas has been recovered by Platform Gail since start-up on 05/10/10. Operations and maintenance personal continue to be extremely happy with the operability of the unit that was demonstrated during on-board testing.

Figure 6. Photograph of Entire Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit On-Board Platform Gail (note – above rotary valves)

PSA Performance

Performance of the M-3100 Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit closely resembles those results obtained during the on-board demonstration test, as shown in the table in Table 3.

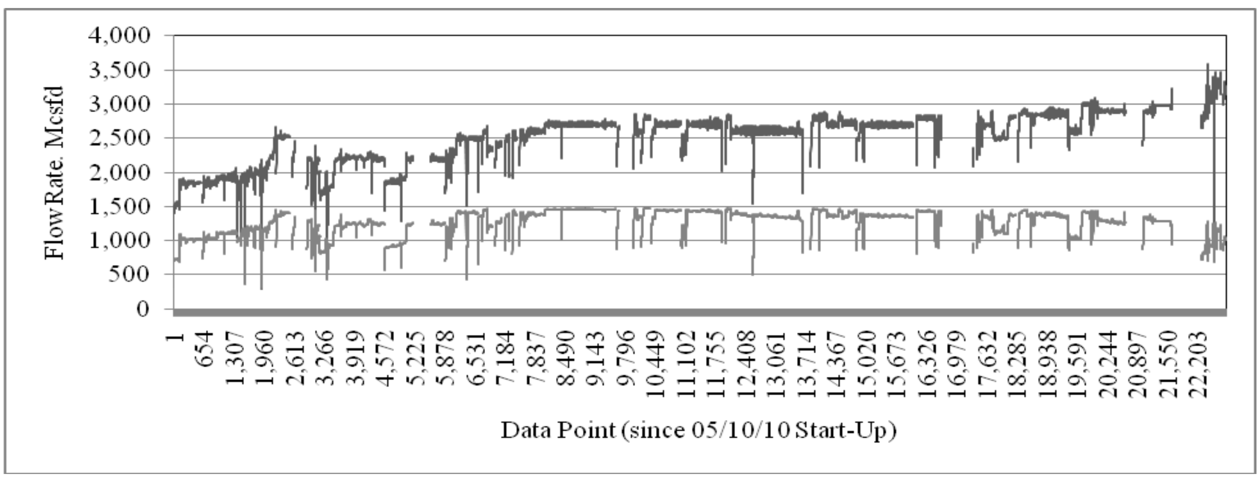
Once again, the unit has proven successful at absorption and reduction of ethane, by adsorbing slightly more than sixty-three percent of this compound from the associated gas, and exceeding the sales gas specification on this and all other components.

Table 3. Rotary-Valve, Fast-Cycle PSA Performance

Component	Platform Gail Produced Associated Gas (mol%)	Exhaust Gas from M-3100 PSA (mol%)	Sales Gas from M-3100 PSA (mol%)	California Sales Gas Specification (mol%)
Total Inerts ($N_2/CO_2/O_2$)	15	18	2.61	4.0
Carbon Dioxide (CO_2)	13	17	1.42	3.0
Methane (CH_4)	64	40	93.08	88.0
Ethane (C_2H_6)	8	10	2.95	6.0
Propanes Plus ($C_3H_8^+$)	13	32	1.36	3.0
Butanes Plus ($C_4H_{10}^+$)	7	22	0.57	1.5
Water (H_2O)	Saturated	-	< 7 #/MMcf	< 7 #/MMcf
Specific Gravity	0.8735	1.248	0.6043	-
GHV, dry (btu/scf)	1,153	1,709	1,033	-
GHV, wet (btu/scf)	1,134	1,679	1,015	-

PSA Inlet/Outlet Flow Rate

Using Venoco's data archive system, which records data every nine minutes, PSA flow rate data was tabulated and then plotted on the following page in Graph 1. As can be seen from the plotted data, the sales gas flow is slightly less than two-thirds of



Graph 1. PSA Inlet (upper) and Sales (lower) Flow Rates

the inlet flow; while this may seem like a low recovery for this type of a system, one must keep in mind that in this particular design, every molecule passed through the M-3100 Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit is recovered – either as sales gas (approximately 62 % recovery), or as turbine fuel.

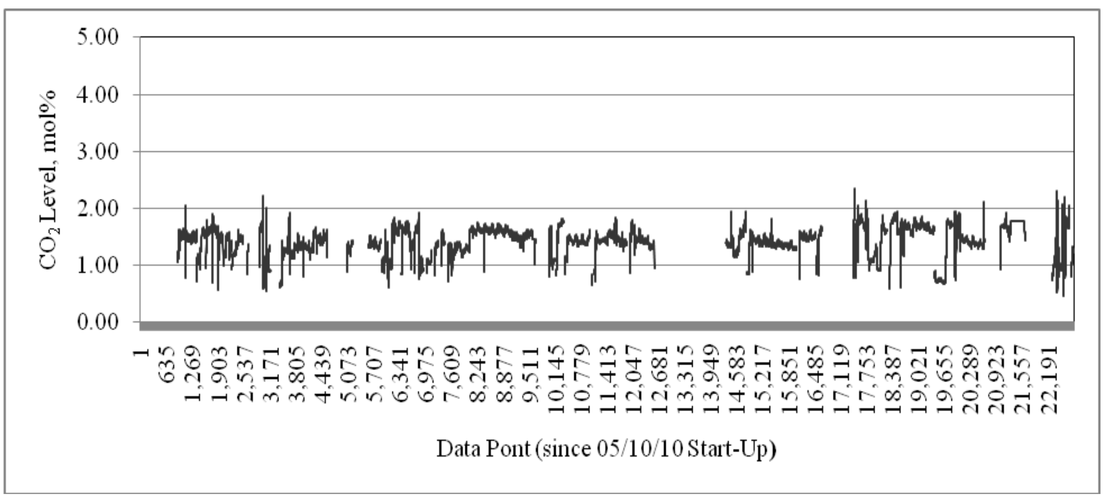
As also shown by the data, there were several (if not many) interruptions in the operation of the PSA. This was due to periods when one of the turbines was off-line and the platform needed to terminate operation of the Tail Gas Compressor in order to "shed load" to meet the electrical output of the two, remaining, on-line turbines. During these periods when one of the turbines is down, Venoco is currently investigating allowing the PSA exhaust gas to be temporarily vented to the Vapor Recovery System, thereby eliminating the need for PSA shutdown and improving program economics.

CO_2 Removal

Using the data archive system along with on-line gas chromatograph data, the CO_2 level in the sales gas was graphed and is provided on the following page. As can be seen by the data provided, the CO_2 level of the sales gas was consistently below the specification limit of 3.0 mole percent.

As stated earlier in this report, CO_2 removal and sales gas flow rate are both functions of rotary valve speed; as the speed of the rotary valve is increased the quality of the sales gas improves (i.e. the CO_2 level in the sales gas decreases), but the rate of the sales gas decreases. As shown by the two graphs, Venoco could slow down the rotary valve speed, allowing the CO_2 content of the gas to slightly increase, and also increase the flow rate of the sales gas, improving program economics.

These and other optimization steps are currently being planned for this project, and will be undertaken in the near future.



Graph 2. Sales Gas (PSA Outlet) CO_2 Level

Ethane Removal

Table 4 provides an overview of ethane removal results through the M-3100 unit; as can be seen, removal results vary between fifty and seventy percent. When CO2 removal is considered, ethane removal is actually between 57 and 79 percent. On the full-scale unit C_2H_6 removal is actually higher than in Xebec laboratory screening/modeling and in the demonstration tests.

Table 4. Ethane Removal through Rotary-Valve, Fast-Cycle PSA

	C_2 Inlet (mol%)	C_2 Outlet (mol%)
Laboratory Tests	7.5	3.25
Demonstration Test	8.0	2.35
Actual Unit	8.0	2.95

Turbine Emissions

Table 5. Turbine Exhaust NO_x Level

Turbine	*Turbine Exhaust NO_x Level (ppm)*	
	Five months prior to PSA Start-up	*Five months after PSA Start-up*
G-01	*0.61*	*0.50*
G-02	*1.85*	*0.57*
G-03	*1.12*	*0.94*

A potential concern of this project was the effect of the heavy light hydrocarbons upon turbine emissions; a meeting with Rolls-Royce was conducted, and subsequent modeling data indicated that the effect of the heavier gas stream would be negligible, more than likely, due to the increased CO_2 in this gas stream.

Project Economics
Cost break-down of the project was as follows:

Engineering	$180,000
PSA Skid	$770,000
Compressor Skid	$600,000
Demolition	$130,000
Structural Modification	$300,000
Installation	$750,000
Materials (pipes, electrical, etc)	$100,000
Total	$2,830,000

At current projections, project payback is approximately one and one-half years (at sales gas value of $4.00/MMbtu). Some of the optimization steps discussed in this report should shorten that time considerably – Venoco is very pleased with the success of this project and is currently investigating the feasibility of installing another unit on another platform (also located in the Santa Barbara Channel).

Optimization

Future Plans – Best Practices Learned from PXP-Adams Street (Downtown Los Angeles)
At an on-shore site, located in downtown Los Angeles, an M-3100 Xebec Rotary-Valve, Fast-Cycle Pressure-Swing Adsorption Unit has been successfully operating for

approximately two years. This particular application is primarily concerned with ethane removal as well as heavy light hydrocarbons, as carbon dioxide reduction is not a concern at this location.

At this location the speed of the rotary-valve is control by a gas chromatograph in order to control methane number, a requirement mandated by the purchaser of the gas; the sales specification is greater than 80 MN. The gas is currently controlled at 80.5 MN via the gas chromatograph, and the system is working well at this mostly unmanned site.

With the success of the above application, especially the automatic control of the rotary valve speed, effort should be made to implement the same type of control onboard Platform Gail.