SRI/USEPA-GHG-VR-02
September 1999

Environmental Technology Verification Report

A&A Environmental Seals, Inc.
Seal Assist System (SAS)
Phase I Report

Prepared by:

Southern Research Institute

Under a Cooperative Agreement With
EPA U.S. Environmental Protection Agency

ETV ETV ETV

EPA REVIEW NOTICE

This report has been peer and administratively reviewed by the U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

SRI/USEPA-GHG-VR-02
September 1999

Greenhouse Gas Technology Verification Center

A U.S. EPA Sponsored Environmental Technology Verification Organization

A&A Environmental Seals, Inc.
Seal Assist System

Phase I
Technology Verification Report

Prepared By:
Southern Research Institute
Greenhouse Gas Technology Verification Center
PO Box 13825
Research Triangle Park, NC 27709 USA

Under Cooperative Agreement CR 826311-01-0

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711 USA

EPA Project Officer: David A. Kirchgessner

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The Greenhouse Gas Technology Verification Center wishes to thank the staff and employees of Enron Gas Pipeline Group and its member company, Transwestern Pipeline Company, for their invaluable service in hosting this test. They provided the compressor station to test this technology, and gave technical support during the installation and shakedown of the technology. Key individuals who should be recognized include Richard Jolly, Jonny Hendricks, William Kendrick, James Peterson, Howard Begay, Calvin Largo, and Korey Kruse. Thanks are also extended to the Center's Oil and Natural Gas Industry Stakeholder Group for reviewing this report.

1.0 INTRODUCTION

1.1 BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) has created a program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the Environmental Technology Verification (ETV) program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. The ETV program is funded by the Congress in response to the belief that there are many viable environmental technologies which are not being used because of the lack of credible third-party performance testing. With performance data developed under this program, technology buyers and permitters in the United States and abroad will be better equipped to make informed decisions regarding environmental technology purchases.

The Greenhouse Gas Technology Verification Center (the Center) is one of 12 independent verification entities operating under the ETV program. The Center is managed by EPA's partner verification organization, Southern Research Institute (SRI). The Center provides a verification testing capability to GHG technology vendors, buyers, exporters, and others that have a need for independent performance data. This process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other data, and reporting findings. Performance evaluations are conducted according to externally reviewed test plans and established protocols for quality assurance.

The Center is guided by volunteer groups of Stakeholders. These Stakeholders offer advice on technology areas and specific technologies most appropriate for testing, help disseminate results, and review test plans and verification reports. The Center's Executive Stakeholder Group consists of national and international experts in the areas for verification.. It also includes industry trade organizations, environmental technology finance groups, and various government organizations. The Executive Group helps select technology areas that the Center should focus on. Oil and gas industry technology areas were targeted by the Executive Group as showing great promise for independent testing.

To pursue verification testing in the oil and gas areas, the Center has established an Oil and Gas Industry Stakeholder Group. The group consists of representatives from production, transmission, and storage sectors, technology manufacturers, and environmental regulatory groups. Individuals who are members of the Oil and Gas Industry Stakeholder Group have voiced support for the Center's mission, identified a need for independent third-party verification, prioritized specific technologies for testing, and identified verification test parameters that are most valuable to their industry. They also indicated that technologies which capture and utilize methane leaks from compressor rod seals used in the natural gas industry are of great interest to technology purchasers.

In the natural gas industry, interstate gas pipeline operators use large gas-fired engines to provide the mechanical energy needed to drive pipeline gas compressors. In the U.S., fugitive natural gas leaks from these compressors represent a major source of methane emissions, and a significant loss of economic and natural resources. To pursue verification testing on compressor seal technologies, the Center placed formal announcements in the Commerce Business Daily and industry trade journals, and invited vendors of commercial products to participate in independent testing. A&A Environmental Seals, Inc. (A&A) of La Marque, Texas, responded, offering the Seal Assist System (SAS) for testing at a natural gas compressor station. The SAS is designed to capture methane from leaking compressor rod seals, and route the captured gas into the compressor engine fuel line for use.

Installation of the SAS piping assembly was initiated on January 25, 1999, at a gas transmission station operated by Transwestern Pipeline Company - Enron Gas Pipeline Group in northeastern Arizona (Station 4). Following several weeks of shakedown and start-up activities, the performance verification test was initiated on March 10, 1999. Two phases of SAS technology evaluation were planned. Phase I focused on short-term technical performance evaluations and documentation of initial costs, while Phase II addressed longer-term technical performance and SAS economic payback potential. This report presents the results of the Phase I test, which occurred between March 10 and 31, 1999.

Details on Phase I and II verification test design, measurement test procedures, and Quality Assurance/Quality Control (QA/QC) procedures can be found in the report: *Test/QA Plan for A&A Environmental Seals' Seal Assist System (SAS), (SRI 1998)*. It can be downloaded from the Center's Web site at www.sri-rtp.com. The Test Plan contains a detailed rationale for the experimental design and lays out specific test and QA/QC procedures to be implemented. It has been reviewed by A&A, Transwestern Pipeline company, the Oil and Gas Industry Stakeholder Group, and the EPA Quality Assurance Team. It meets the requirements of the Center's Quality Management Plan (QMP), and conforms with ANSI's standard for environmental testing (E-4). Where deviations from the Test Plan occurred, detailed descriptions of why alternative procedures were used, and their effects on data quality objectives are noted in this Phase I report.

This section also introduces the SAS and describes the verification goals. Section 2 presents a background discussion of methane emission from natural gas compressors, description of the test site, and documentation of the as-built system installed at the test site. Section 3 presents Phase I test results, followed by an assessment of data quality in Section 4. Section 5 contains A&A comments on the test results and additional vendor supplied performance data on the SAS.

1.2 OVERVIEW OF THE SAS TECHNOLOGY

The SAS is a secondary containment device designed to prevent compressor rod packing leaks from escaping into the atmosphere. The SAS allows existing rod packing leaks to continue, but the leaking gas is contained within the secondary SAS containment gland. This allows the contained gas to be collected, recompressed, and routed into the compressor engine fuel line for use. Figure 1-1 presents the SAS flow diagram. It consists of four primary components: the Emission Containment Gland (ECG), the Jets, the Recycle stream, and an Eductor/Compressor system which pressurizes the collected gas to meet engine fuel requirements.

The ECG is a secondary seal that is attached to the exposed face of an existing rod packing located in the "doghouse" (see Figures 1-2 and 1-3). A doghouse is an access port which is located between the engine and the compressor. By removing this access port, site operators can perform routine maintenance on the rod packing and its seals. Each doghouse contains an oil drain and a vent pipe. Gas leaking from the ECG enters the doghouse area, and is vented out of the compressor building via the doghouse vent. Manual sampling was conducted at each doghouse vent to quantify the uncaptured gas. The ECG contains a 3-½ in. annulus area which is an arched channel of less than 360 degrees around the rod. The emission annulus prevents the rod emissions from entering the atmosphere, and maintains normal operating pressure that is slightly less than atmospheric. The annulus contains inlet (recycle line) and outlet channels which are connected to the jet manifold system (Mathis et al., 1998).

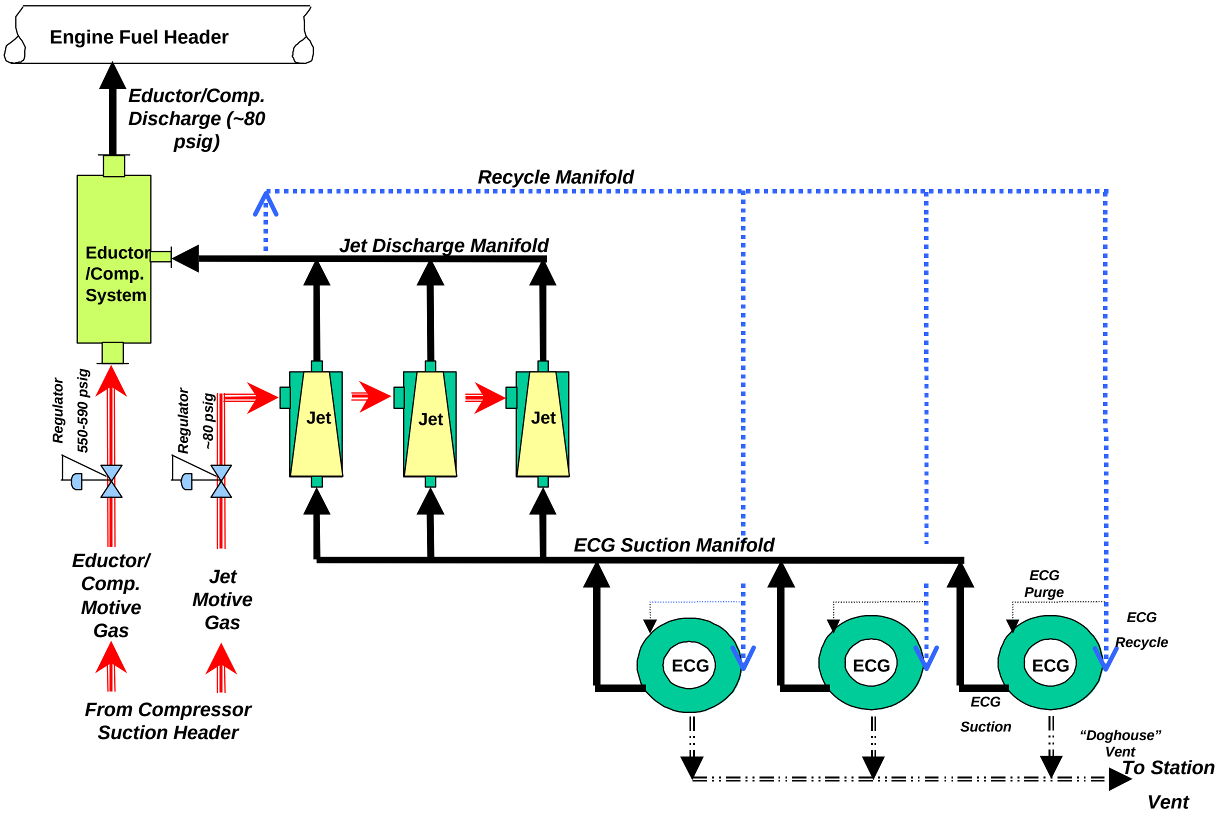


Figure 1-1. Simplified SAS flow diagram

The ECG also includes a floating face seal, called the tertiary seal. The tertiary seal prevents aspiration of air, that could result from negative pressures in the ECG, from entering the emission annulus. The tertiary seal is a u-cup lip seal riding in a carrier. The carrier has a carbon ring in contact with the rod which allows it to move with the rod and keep the tertiary seal aligned. The tertiary seal has a long life expectancy, provided negative pressure in the annulus area is maintained. Under a primary rod seal upset condition (i.e., partial or complete failure), the tertiary seal is designed to prevent gas leakage to the atmosphere by increasing face contact with its stationary element as pressure increases in the emission annulus. If this condition continues, the increased pressure causes the seals to wear quickly, requiring them to be replaced.

The gas isolated in the annulus is brought into the SAS piping assembly by a series of jets (see Figure 1-1). The jets contain a specially designed nozzle system which creates a partial vacuum between the inlet and outlet streams of the jet manifold assembly (see Figure 1-4). The partial differential vacuum is created by a motive gas stream, in this case natural gas at 80 psig, which creates a high, nearly sonic, velocity jet stream. The motive gas induces gas flow from the annulus area and transports the collected gas to the low-pressure side of the jets (i.e., ECG Suction stream). The mixture of the motive gas and fugitive emissions exits the Jet Discharge stream at slightly higher pressure (5 to 8 psig), causing a pressure differential across the jets (Tarrer and Stadig 1996).

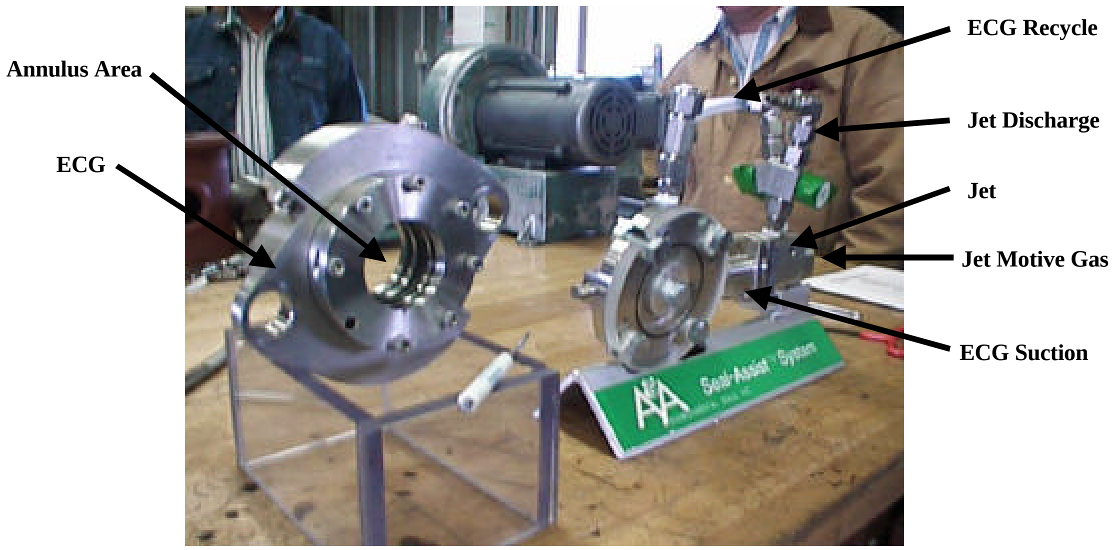


Figure 1-2. Illustration of the ECG and the jet manifold assembly

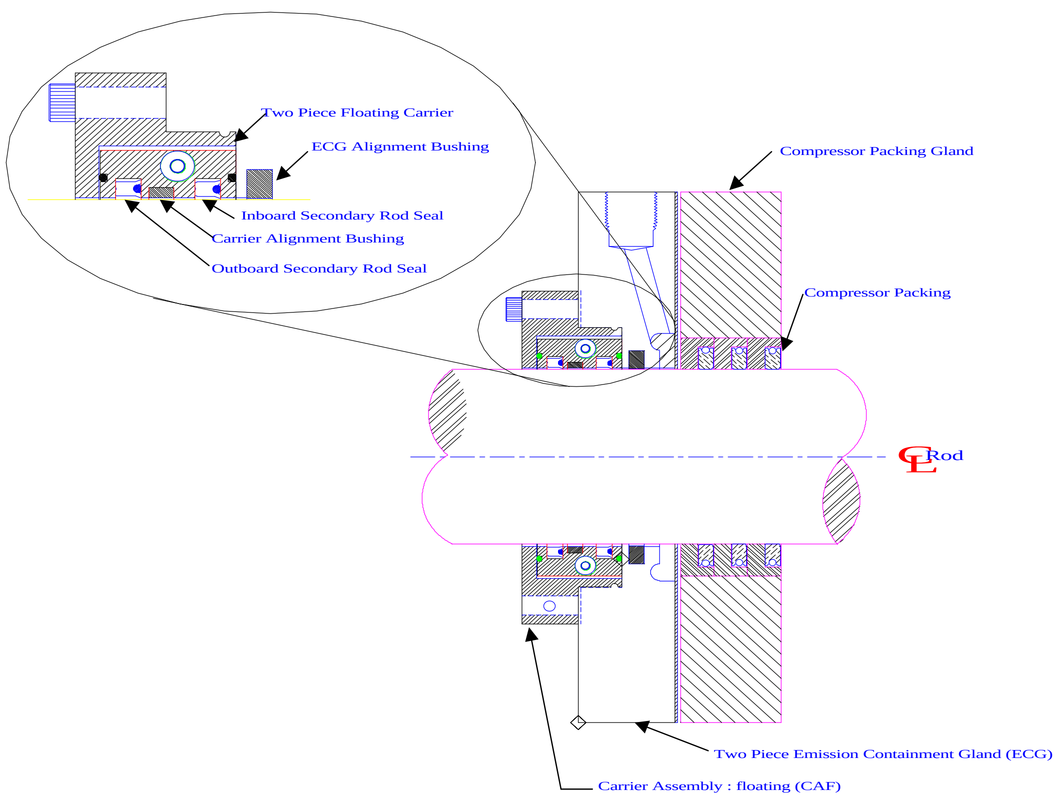


Figure 1-3. Cross-sectional view of compressor rod packing and the ECG

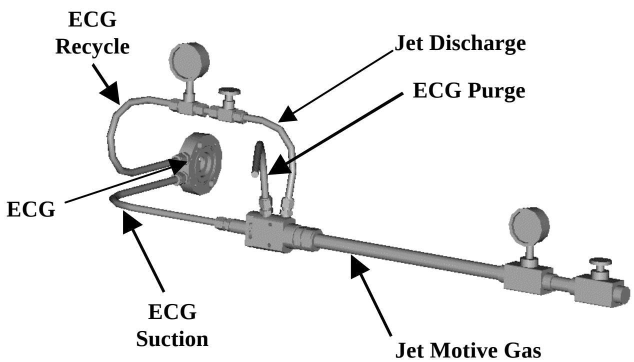


Figure 1-4. Schematic of the jet manifold assembly

A small portion of the Jet Discharge stream is recirculated to the ECG. The primary purpose of the recycle system is to provide sufficient fluid flow to move captured emissions (liquid, gas, or solids) from the annulus area to the Jet Discharge stream. A secondary benefit of the recycle system is the prevention of excess negative pressure in the gland. The recycle flow rate is controlled by a variable orifice located between the Jet Discharge and the inlet channel of the ECG. Near the ECG, a sidestream of the recycle stream is manually regulated to provide a continuous purge stream which prevents atmospheric air from entering the system. This purge stream ensures that a slight positive pressure is maintained with constantly supplied natural gas, preventing ambient air from entering the annulus area.

The gas exiting the Jet Discharge stream is pressurized and transported to the engine fuel header. To accomplish this, the SAS uses an Eductor/Compressor system. The Eductor/Compressor requires a motive gas flow of about 350 scfm natural gas at 550 psig to recompress the captured gas to meet the engine requirements (80 to 90 psig). The high-pressure motive gas for both the jets and the Eductor/Compressor is supplied by the site's high-pressure compressor suction line.

1.3 VERIFICATION GOALS

The specific verification goals and parameters associated with the Phase I and Phase II verification efforts are outlined below.

- Phase I SAS Evaluation:
  - Verify initial leak tightness
  - Verify initial gas recovery and use performance
  - Verify initial methane emission reduction
  - Document installation and shakedown requirements
  - Document capital and installation costs

- Phase II SAS Evaluation:
  - Verify long-term leak capture performance
  - Verify long-term gas recovery and use performance
  - Estimate annual methane emission reduction
  - Document long-term SAS operational requirements
  - Calculate SAS payback period

Phase I goals have been addressed through collection and analysis of direct gas measurements, the use of site operator interviews and logs, the collection and review of vendor supplied cost information, and the collection of installation contractor supplied data and perspectives. As shown in Table 1-1, the first three verification parameters enable short-term evaluations of the SAS's ability to capture leaks, the net gas recovered, and the net methane emissions reduced. The remaining two parameters document the Center's observations of the SAS installation and start-up activities, and the initial capital and installation costs for the as-built system. These costs are reviewed and modified to develop standard system costs, which account for materials likely to be supplied in future commercial applications.

TABLE 1-1. PHASE I VERFICIATION TEST MATRIX

SAS Verification Parameter	Description	Verification Approach	Measurement Method	Frequency/ Duration of Measurement
Verify initial leak tightness	Determine whether the SAS is leaking (i.e., emissions are entering the doghouse)	Check system for leaks; if leaks are detected, quantify the leak rates	Use a Flow Tube at doghouse vents and soap solution on system components	Initially soap test and pressure test the complete system; subsequently measure doghouse vents 3 times
Verify initial gas recovery and use performance	Quantify the volume of gas collected and injected into engine fuel header	Continuously monitor ECG suction lines, jet manifold motive gas and discharge lines	In-line mass flow meters	Continuous for 3 weeks
Verify initial methane emission reduction	Determine whether SAS perturbs uncontrolled emissions, and quantify net methane emission reduction	Manually measure uncontrolled emissions by disabling the SAS, and compare these rod leak rates with continuous gas measurements from above	Use a Flow Tube while the SAS is disabled, and use continuous mass flow meters while the SAS is operating	Measure 3 times with the Flow Tube and continuously measure with the flow meters for 3 weeks
Document installation and shakedown requirements	Ensure that installation/start-up procedures and any problems encountered are documented	Observe and document installation and start-up process at site	Visual inspection, installation contractor and site operator interviews, and logs	While installation, start-up, and shakedown are occurring
Document initial capital and installation costs	Ensure that all equipment, materials, and labor costs are documented	Obtain site-specific cost data from installation contractors, A&A, and others	Vendor invoices, contractor logs, and instrument invoices	N/A

A primary goal of Phase II testing is to determine the SAS payback period. As a practical matter, the Center cannot conduct direct testing for the extended, multi-year period that would be required to determine payback entirely through direct gas and other measurements. Therefore, several Phase II goals will be accomplished through a combination of medium-term (8 months) measurements and data extrapolation techniques. Extrapolation and other assumptions will be transparent in the final report, allowing readers to make alternate assumptions and assessments.

2.0 TECHNICAL BACKGROUND INFORMATION AND SITE DESCRIPTION

2.1 METHANE EMISSIONS FROM NATURAL GAS COMPRESSORS

In the oil and natural gas industry, gas compressors are used in many different sectors (e.g., production, processing, transmission, and storage) to transport natural gas. Gathering compressors are used in production fields to collect and transport natural gas from wells to processing plants where impurities (e.g., water, oil, and hydrogen sulfides) are removed. In the natural gas transmission sector, compressors are used to transport gas from processing plants to distribution centers. In the storage sector, compressors are used for injection of gas into and withdrawal of gas from storage systems.

A report published by the EPA Office of Research and Development and the Gas Research Institute (Hummel et al., 1996) suggests that substantial methane gas losses occur from compressors in the gas industry (specifically, from reciprocating, rather than centrifugal, compressors). In 1992, reciprocating systems emitted approximately 21 percent of the total emissions (314 $x10^9$ ft^3) from the natural gas industry, and centrifugal compressors emitted about 5 percent. Manufacturers of reciprocating compressors include Ariel, Clark, Cooper, Ingersoll-Rand, and Worthington. There are many different models and sizes, but their basic function is the same. As shown in Table 2-1, the population of reciprocating compressors is significantly larger than for centrifugal units.

TABLE 2-1. PERCENTAGE OF RECIPROCATING COMPRESSORS VS. CENTRIFUGAL COMPRESSORS (Hummel et al., 1996)

Sector	Reciprocating, %	Centrifugal, %
Processing	85	15
Transmission	91	9
Storage	91	9

Table 2-2 shows a breakdown of gas losses in the natural gas industry due to reciprocating compressors. The losses are shown as a percentage of the sector's total losses and as total loss by sector. The largest natural gas loss occurs in the transmission sector, accounting for over 37 $x10^9$ ft^3 of gas per year. These leaks occur from, in decreasing order, blow-down valves, rod seal packing cases, compressor isolation valves, and pressure relief valves.

TABLE 2-2. NATURAL GAS LOSSES BY SECTOR DUE TO RECIPROCATING COMPRESSORS (Hummel et al., 1996)

Sector	Percent of Total Sector Loss, %	Total Loss, $x10^9$ ft^3/yr.
Processing	68.5	16.7
Transmission	74.6	37.8
Storage	64.3	10.8

Data collected during the EPA/GRI fugitive emission study show that the average leak rate for all types of compressor seals is about 1.14 scfm (Hummel, et al., 1996). This average includes operating leak rates from both reciprocating and centrifugal compressors. The data in Table 2-2 do not fully consider a recent trend of replacing wet seal systems with dry seals. Wet seals have mated surfaces in contact with oil lubrication to help reduce leakage; while dry seals consist of such material as carbon-filled Teflon™, with rigid steel backs that are spring-loaded to ensure tight contact with the shaft. Rod seals are installed in series in the packing case, and create a barrier against the high-pressure compressed gas traveling down the shaft. The EPA Natural Gas STAR Partners report that recent trends toward the use of dry seals are the result of improved efficiency and reduced maintenance. The STAR Partners report that 50 percent of new seal replacements are currently the dry type.

2.2 SITE SELECTION AND DESCRIPTION

Because reciprocating compressors are most commonly used in the industry, and are the primary source of emissions from compressor operations, these types of compressors were targeted to identify a test site for SAS technology verification. Transwestern Pipeline Company – Enron Gas Pipeline Group expressed interest in becoming a host site for SAS technology verification because this technology provides an option for reducing gas losses at their compressor stations.

To select a host test site, Enron utilized its emissions survey data of natural gas leaks from compressor seals. A representative leak rate of approximately 1 to 4 scfm per rod was targeted to identify potential test sites. Of the sites identified, compressors which used dry seal systems were prioritized, and discussions with regional managers were held to identify a station where the site operators were willing to host the test.

The natural gas transmission compressor/engine selected for the SAS evaluation was Station 4, operated by Transwestern Pipeline Company – Enron Gas Pipeline Group. Station 4 is located near Klagatoh, Arizona, north of Interstate 40, off Exit 333. A photograph of the compressor/engine building, and a simplified floor plan are presented in Figure 2-1.

The Station operates three Clark gas-fired internal combustion engines (12 cylinders, 4500 hp) and moves 360 $x10^6$ ft^3 natural gas per day per engine. Each engine is equipped with three integral cylinder-type compressors operating in series. The rods and packing used at Station 4 have the same basic design and functionality as many reciprocating compressors used now and planned for use in the future. Each rod is 4-½ in. in diameter, which is on the upper end of the rod sizes used in the transmission sector (see Table 2-3). The rod packing system used at this station (dry seal system) is typical of many being built or retrofitted within the industry. Consistent with trends in the industry, wet seals were replaced with dry seals in December 1997. Specific data regarding the seals at Station 4 are given in Table 2-4, and include the age of the seals, the manufacturer, the number of seals in the packing case, and the initial leak rate measured during a pre-survey conducted by STAR Environmental, Inc.

TABLE 2-3. SECTOR SPECIFIC DISTRIBUTION OF COMPRESSORS AND ROD SEAL SIZES			
Sector	**No. of Compressors**	**No. of Seals**	**Rod Size, in.**
Processing	4,092	6 to 7	¾ to 2-½
Transmission	6,799	6 to 9	2 to 4-½
Storage	1,396	6 to 12	2 to 4-½

TABLE 2-4. STATION 4 – ENGINE 1 COMPRESSOR SEALS DESCRIPTION			
	Compressor 1	**Compressor 2**	**Compressor 3**
Installation Date	December 1997	December 1997	February 1999
Seal Manufacturer	MME	MME	MME
No. of Seals in Packing Case	9	9	9
Size of Each Rod, in.	4-½	4-½	4-½
Average Rod Leak Rate, scfm CH_4 – based on a single measurement conducted during a pre-test survey	0.30	1.58	5.70

Maintenance of the seals is generally not performed on a predefined schedule; rather, seals are replaced when maintenance on the rod is performed. The station uses rod temperature (measured at a clearance of about 0.01 in.) as the primary indicator of the need for rod or seal maintenance. The seals are expected to last several years, but can wear out quickly. Lifetime of the seals is a function of the type of service and routine maintenance performed by the operator, the state of the rod alignment with the engine, and impurities entrained in the gas that can damage the seals. When replacing the seals, the unit is usually down for 4 to 6 hours. It usually takes two people about 4 hours to replace the seals; however, if the seals are being replaced due to a rod failure, the process can take 6 hours or more. The approximate materials cost to replace only the seals is about $1,000.

2.3 THE AS-BUILT SAS AND MEASUREMENT SYSTEM AT STATION 4

The SAS was installed on all three compressor rods of Engine 1 (see Figure 1-1 for illustration). It includes three emission containment glands, three jet assemblies, an Eductor/Compressor motive gas system, miscellaneous safety equipment, system valves and regulators, and carbon/stainless steel tubing.

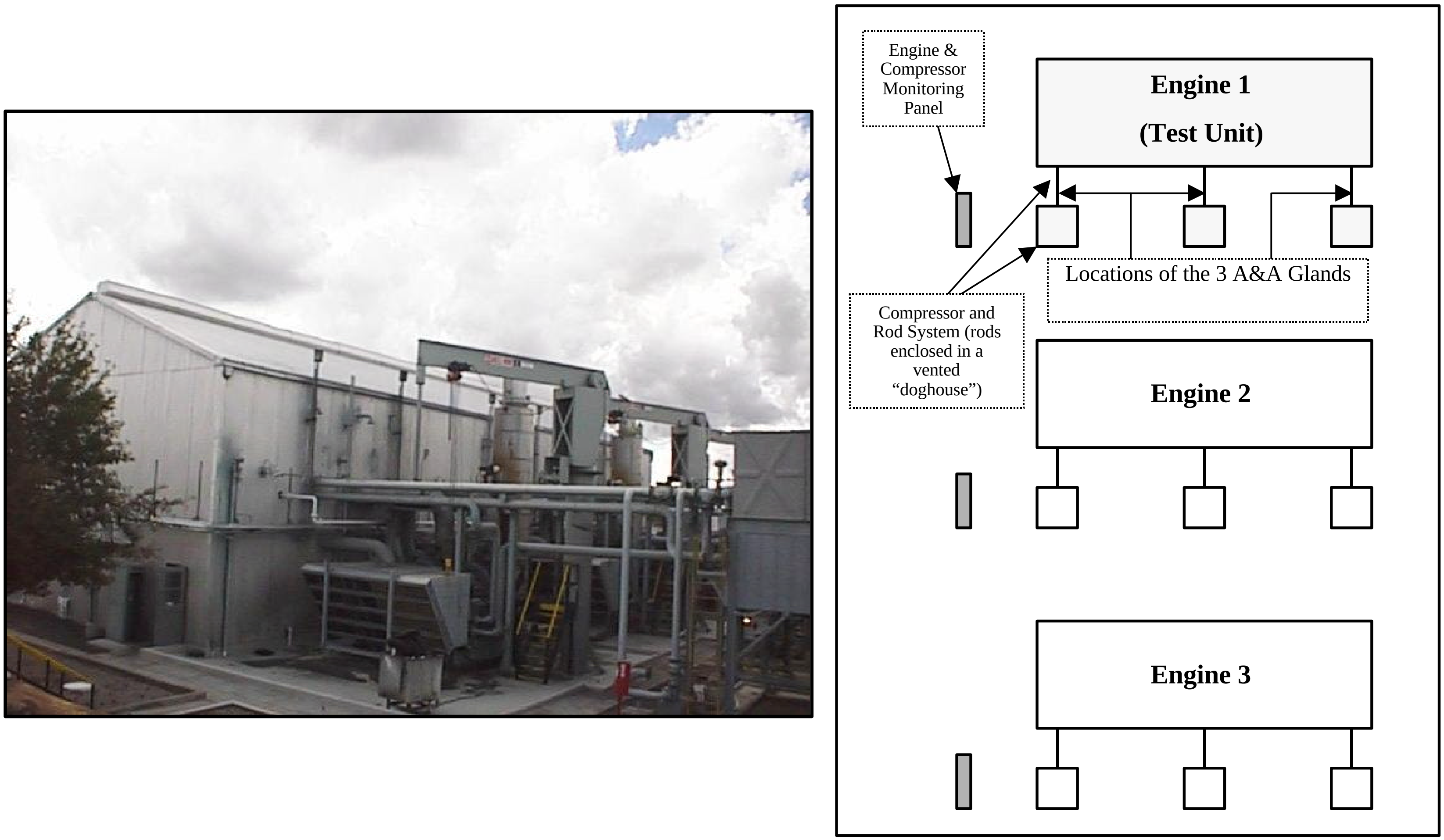
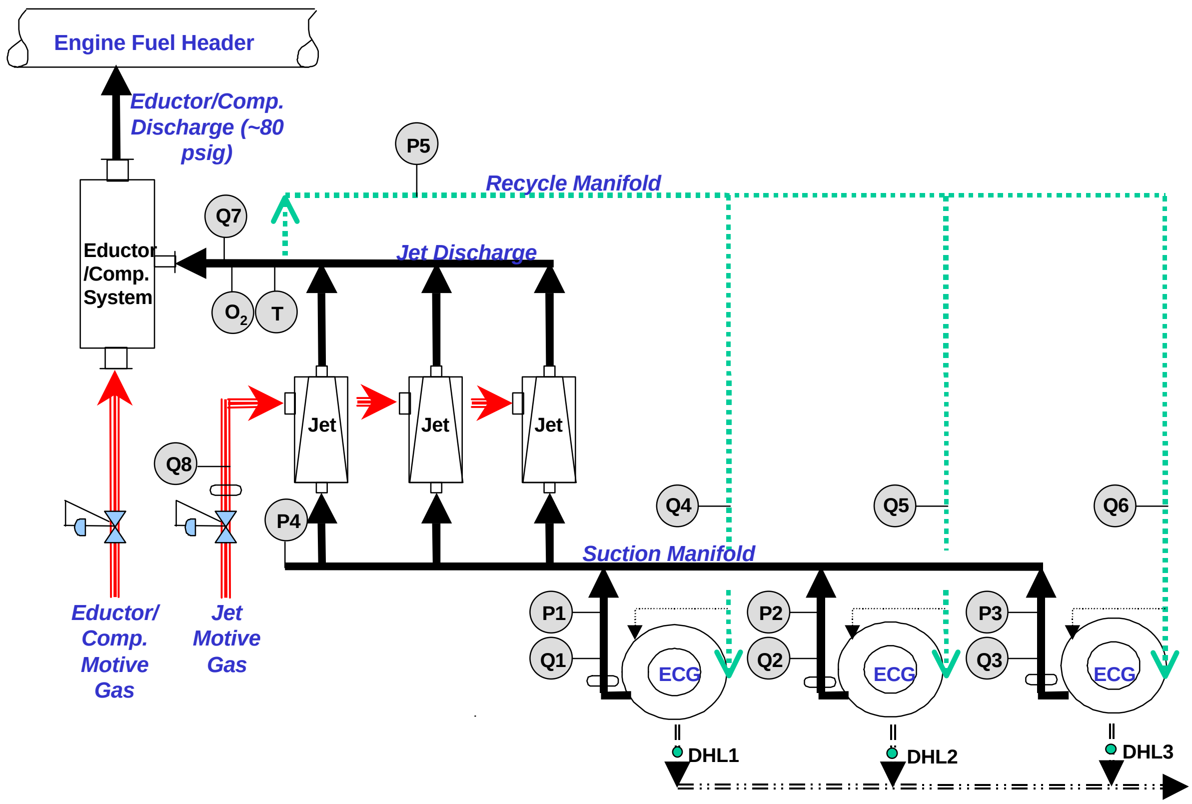


Figure 2-1. Photograph and floor plan for the host gas transmission line compressor station

Various measurement devices were also installed to conduct the verification test. This is depicted in Figure 2-2 and Table 2-5. Seven flow metering devices were used to continuously monitor the gas flows in the SAS piping. These consisted of three mass flow meters on each of the ECG suction lines (Q1, Q2, Q3) and ECG recycle lines (Q4, Q5, Q6). Gland-specific flow measurements were required to quantify rod-specific gas recovery performance and project economic payback under different rod emission profiles. A single flow meter was installed on both the jet discharge manifold (Q7) and the jet motive gas line (Q8). The net volume of gas captured by the SAS (for all three rods combined) is equivalent to the difference between the jet discharge flows and the jet motive flows (i.e., Q7 minus Q8).



Q1, Q2, Q3 = ECG suction line flow rates, scfm
Q4, Q5, Q6 = ECG recycle line flow rates, scfm
Q7 = Gas entering engine, scfm
Q8 = Jet motive gas, scfm

P1, P2, P3 = ECG suction line pressures, psig
P4 = ECG suction manifold pressure, psig
P5 = ECG recycle manifold pressure, psig

O_2 = Oxygen concentration, %
T = gas temperature, ºC
⬭ = approximate location of oil filters

DHL1, DHL2, DHL3 = Doghouse leak rate, manually measured with a Flow Tube, scfm

Figure 2-2. The as-built SAS and measurement system at Station 4

In addition to the flow measurement devices, five pressure monitoring devices were installed at strategic locations in the SAS piping. As shown in Figure 2-2, the ECG suction line pressures were monitored by three pressure sensors at each gland (P1, P2, P3). A single sensor was used to measure the ECG suction and ECG recycle manifold pressures, P4 and P5, respectively. An oxygen sensor, capable of measuring less than 0.1 percent and up to 25 ppm oxygen was installed in the jet discharge manifold for safety reasons. An automatic shutdown is triggered if the oxygen sensors detect more than 2 percent oxygen.

TABLE 2-5. SUMMARY OF SAS MEASUREMENT SYSTEM		
Item	**Description/Operating Range**	**Measurement Sensors**
ECG Suction	Connects the glands to the jets - ½ in. line at the glands enlarged to 1 in. line reaching the jets.	Gas Flows – Q1, Q2, Q3 Line Pressures - P1, P2, P3 Manifold Pressure - P4
ECG Recycle	Three ½ in. recycle lines split at jet discharge lines and feed into the ECGs.	Gas Flows – Q4, Q5, Q6 Manifold Pressure - P5
ECG Purge Loop	Three ½ in. lines split from the recycle lines into the glands.	Gas Flows – not measured Line Pressure – not measured
Jet Motive Gas	A 1 in. line from station compressor suction side that provides high-pressure motive gas to jets, 80 psig, 2.5 to 3.5 scfm gas per jet.	Gas Flows – Q8 Line Pressure – not measured
Jet Discharge	The jets exit into ½ in. lines which feed into a 1-½ in. manifold system. This stream connects the jets to the Eductor/Compressor, and contains the captured rod emissions, jet motive gas, and recycle gas.	Gas Flows – Q7 Line Pressure – not measured O_2 Meter Temperature – P6
Eductor/ Compressor Motive Gas	A 1 in. line from station compressor suction side that provides high-pressure motive gas to the Eductor/Compressor, 550 psig and approx. 352 scfm gas.	Gas Flows – not measured Line Pressure – not measured
Eductor/ Compressor Discharge	A 1 in. line leaving the Eductor/Compressor that injects the collected gas into a 2 in. engine fuel header, 5 to 80 psig, 35 scfm gas.	Gas Flows – not measured Line Pressure – not measured

Output signals from each monitoring device were converted into digital signals, and transmitted to the site control room via the control panel shown in Figure 2-1. These signals were stored in the on-site computer for routine remote downloading and on-line monitoring. This allowed both station operators and Center staff to collect, display, record, and assess all monitored SAS and engine variables in real time. A dedicated and password-protected computer in the Southern Research office in Research Triangle Park, NC, was used daily to automatically download the data. The signals downloaded were converted into units for reporting (such as flow rates in scfm and pressures in psig).

The ECG assemblies were installed on the test compressors during a scheduled shutdown on the week of November 22, 1998. Installation of the SAS piping and verification instruments was initiated on January 25, 1999, and was completed on January 30, 1999, by Transwestern-approved contractors. SAS start-up and shakedown activities occurred between February 2 and March 9. The SAS was verified as being operational on March 10, and the Phase I test evaluation was initiated.

During the initial start-up and shakedown activities, a significant quantity of oil/moisture was discovered accumulating in the system. Because the system was designed to operate under dry gas conditions, the measurement flow elements malfunctioned. Further investigation of the oil accumulation revealed that the ECGs were also affected. In order to avoid subsequent, similar problems, and to alleviate Transwestern's concerns about introducing oil into the engine fuel line, coalescing oil filters were added on all ECG suction lines and all locations where the flow sensors were affected (see Figure 2-2). Despite repeated efforts, the Center was unable to achieve detectable readings from the ECG suction flow meters (Q1, Q2, and Q3). Consequently, the SAS gas recovery performance evaluation was based on the total gas flow meters (i.e., Q7 and Q8). Further discussion of these activities and their effects on SAS performance are presented in Section 3.

To verify the first three performance factors, the Test Plan specified the use of a customized, High Volume Sampler (HVS). The HVS was specified to measure the gas which would be uncollected by the SAS, and emitted into the atmosphere through the doghouse vents. These manual measurements were to be conducted a minimum of three times during the Phase I test period while the SAS was operating and while the SAS was disabled. The resulting data were to be used in conjunction with the in-line flow sensor data to form conclusions on the first three verification goals.

The Center was unable to use the HVS because of potential patent conflicts. Consequently, deviation from the original testing approach was required, and a flow-measuring device (Flow Tube) was constructed to meet the manual testing goals of the verification test. The Flow Tube measures gas velocity of the doghouse vent in feet per minute. It consists of a 1 in. vane anemometer, manufactured by Omega, mounted on the inside walls of a PVC tube that is 30 in. long and 1 in. in diameter. Simultaneously with the velocity readings, the concentration of hydrocarbons present in the doghouse vent was quantified with a hydrocarbon analyzer. The velocity readings, given in feet per minute natural gas, are converted to volumetric flow rates (standard cubic feet per minute of natural gas) by using calibration curves developed with a known, standard flow measurement device. These readings are converted to methane flow rates by multiplying by the hydrocarbon levels measured in the doghouse vent and the fraction of methane present in the natural gas (based on compositional analysis data provided by Transwestern). Further discussion on the Flow Tube measurement procedures is provided in Appendix A.

The Flow Tube was fabricated in a relatively short time to avoid delays in SAS testing. It was employed on March 25 and 26 to quantify leaks from doghouse vents. Because of time constraints, laboratory calibration on the instrument was not performed prior to its use at Station 4, with the intention that the calibrations would be conducted immediately after field testing. Unfortunately, the highly sensitive vane anemometer in the Flow Tube was damaged in transit from the Station back to the Center's headquarters, and calibrations could not be performed. The Center installed a new anemometer, calibrated the Flow Tube with methane, and re-measured the doghouse emissions on April 27, 28, and 29, after the Phase I test was concluded.

To salvage the leak rate data collected in March, the calibration results of the new vane anemometer were used. This was based on the fact that all Omega vane anemometers are factory-calibrated and meet Omega's specifications. Therefore, it is likely that the performance of the damaged anemometer was similar to that of the replacement anemometer. The resulting data appear to be within the range observed in April measurements, and it is concluded that this approach may be valid. Further discussion on the Flow Tube calibration results, and their effects on data quality, are presented in Section 4.1 (Data Quality Assessment).

3.0 PHASE I TEST RESULTS

3.1 VERIFY INITIAL LEAK TIGHTNESS PERFORMANCE

According to A&A, each emission containment gland is designed to capture compressor rod seal leaks up to about 4 scfm gas, and the Eductor/Compressor design capacity is about 35 scfm gas (sum of captured emissions and motive gas). Two measurement approaches are used to verify initial leak tightness performance: (1) soap testing of the SAS piping system and its components (e.g., valves, fittings, and joints), and (2) measurement of uncaptured gas at each of the three doghouse vents with a Flow Tube. The first approach performs leak checks on the entire SAS piping system, and is intended to detect and correct fugitive leaks along the network of suction, discharge, and recycle lines. The second approach determines whether the SAS is fully capturing the leaking gas, and is not introducing uncaptured gas into the doghouse during normal operations. In this approach, measurements of fugitive emissions are conducted manually with the Flow Tube (i.e., velocity and the methane concentration in the gas stream are measured). The following two subsections summarize the leak tightness performance results of the SAS.

3.1.1 SAS Piping System Leak Checks

SAS component leak checks were conducted after piping and equipment were installed, and prior to initiating data collection. The SAS glands were installed on November 22, 1998, during a scheduled compressor shutdown. The installation for the SAS piping system began on January 25, 1999, and was completed on January 30, 1999. Leak checks were conducted on the suction, recycle, and purge lines of the ECG piping system, the high pressure motive gas lines which feed the jets and the Eductor/Compressor, the jet discharge lines, and the fuel header which routes the captured gas to the engine (see Figure 2-2). Leak testing was also performed on all key SAS equipment (i.e., ECG, jets, and Eductor/Compressor), measurement sensors (pressure, flow, temperature, and oxygen), manual/pneumatic valves, and miscellaneous equipment (fitting, joints, etc.). Table 3-1 describes the leak tests performed on the SAS assembly.

The SAS piping system was determined to be leak tight throughout Phase I. Leak testing of the SAS mechanical and piping assembly was completed on January 31, 1999. As shown in Table 3-1, corrective actions were taken during shakedown periods to tighten or replace all leaking components prior to Phase I testing, and the entire system was retested to ensure that all leaks were detected and repaired. On March 10, 1999, the valve on the station's main suction line (where jet motive gas and Eductor/Compressor motive gas are connected) failed, and was replaced immediately by Transwestern operators. The primary reason for this failure was over-tightening of the ball valve by installation contractors. Additional soap testing on the SAS was conducted on two separate occasions (during manual measurements conducted in March and April), and no further leaks were found.

TABLE 3-1. SUMMARY OF SAS COMPONENT LEAK TESTS

Date	Location of Leak Checks	Description of Leak Checks	Summary of Findings and Corrective Actions
1/30/99	Suction, recirculation, and purge lines of the ECG piping system	• These lines are exposed to a maximum pressure of 15 psig, and normally operate at much lower pressure (-2 to +5 psig). Initial leak checks using soap solution were conducted with the lines at 2 to 5 psig.	• No leaks were found
2/1/99 to 3/31/99		• On occasion, these lines have been broken/disassembled for system inspection, adjustment, and maintenance. On each occasion, leak testing with soap solution was conducted on all disturbed fittings.	• In general, few leaks were discovered. When leaks were found, all disturbed fittings were tightened or replaced to ensure integrity.
1/29/99	Jet and Eductor/ Compressor motive gas lines	• High pressure motive gas lines, which are rated at 1008 psig, and normally operate at 650 psig were pressure tested at 1650 psig (1.5 times the rated pressure). Industry accepted pressure testing procedures were followed for a period of 3 hours. • Pressure tests could be conducted only as far downstream as the pressure regulators for the Eductor/Compressor motive gas and the SAS jet motive gas because the pressure regulators could not withstand the 1650 psig test pressure without damage. All remaining fittings and equipment were tested with soap solution.	• No leaks were detected. (Complete documentation of this test, including data forms, strip charts, and certifications, is available.) • One leak was found downstream of the 80 psig regulator and repaired.
1/30/99	Jet discharge lines	• Soap testing was conducted on all piping and equipment	• No leaks were found
1/30/99	Fuel header line to engine	• Soap testing was conducted on all piping and equipment	• No leaks were found

3.1.2 Leaks in the Doghouse Vents During SAS Operation

The entire SAS was found to be leak tight, with the exception of the ECG, which vented emissions into the doghouse, and into the atmosphere via the doghouse vent. Table 3-2 presents the doghouse leak rates measured with the Flow Tube. In most cases, leaks were detected at all vents, ranging from 0 to 3.3 scfm CH_4 per rod. The total doghouse leak rate (sum of vented emissions from all three rods) ranged from 0 to 5.7 scfm CH_4.

The total doghouse leak rates (summarized in Table 3-2) and the total uncontrolled emissions from all rods are used to determine leak capture efficiency. It is calculated by: (1) taking the difference between the doghouse leak rate and the emissions from all three rods, and (2) dividing the resulting value by rod emissions.

TABLE 3-2. DOGHOUSE LEAK RATE MEASUREMENTS DATA (SAS OPERATING)

Date	Time	Rod #	Gas Velocity, fpm	Gas Temp., °F	Hydrocarbon Concentration, %	Doghouse Leak Rate, scfm CH_4
3/25/99[a]	10:04 - 10:10 a.m.	1	500	79	96	1.54
		2	285	79	96	0.86
		3	1050	79	96	3.28
	3:15 – 3:20 p.m.	1	0	-	-	0.00
		2	0	-	-	0.00
		3	200	86	96	0.59
3/26/99[a]	3:00 – 3:05 p.m.	1	0	-	-	0.00
		2	0	-	-	0.00
		3	85	104	96	0.23
	3:30 – 3:45 p.m. Oil filter elements removed from ECG suction lines	1	0	-	-	0.00
		2	0	-	-	0.00
		3	0	-	-	0.00
4/27/99	10:09 – 10:32 a.m.	1	614	89	97	1.92
		2	219	92	97	0.66
		3	317	91	97	0.97
	1:06 – 1:18 p.m.	1	614	93	97	1.92
		2	170	94	97	0.50
		3	256	91	97	0.78
	4:40 – 5:09 p.m.	1	825	89	95	2.55
		2	119	92	95	0.33
		3	559	92	95	1.71
4/28/99	9:25 – 9:37 a.m.	1	655	93	96	2.03
		2	244	92	96	0.73
		3	423	93	96	1.30
	10:27 – 10:35 a.m.	1	678	98	96	2.10
		2	236	94	96	0.70
		3	465	101	96	1.43
	12:27 – 12:35 p.m.	1	572	84	96	1.77
		2	55	84	96	0.13
		3	497	88	96	1.54
	1:26 – 1:41 p.m.	1	430	not measured	95	1.30
		2	0	-	-	0.00
		3	198	not measured	95	0.58
	2:31 – 2:47 p.m. Oil filter elements removed from ECG suction lines	1	120	91	96	0.34
		2	0	91	-	0.00
		3	120	91	96	0.34

[a] The Flow Tube could not be calibrated because of a damaged anemometer. Doghouse leak rate estimates for these days are based on calibration of a new anemometer that was field- and laboratory-calibrated.

The amount of gas uncollected by the SAS was measured manually with the Flow Tube at the doghouse vent. Table 3-3 summarizes the doghouse leak rates measured, and their corresponding leak capture efficiencies. Based on 12 measurement samples, the SAS leak capture efficiency ranged between 43 and 100 percent. The average leak capture efficiency was 70 percent.

TABLE 3-3. SAS LEAK TIGHTNESS PERFORMANCE

Date	Time	Flow Rates, scfm CH_4						Leak Capture Eff.[c], %	Pressures, psig	
		Total[a] Doghouse Leak Rate DHL	Gas Into Engine Q7	Jet Motive Gas Q8	Total Gas Recovered Q7-Q8	Total Recycle Q4+Q5+Q6	Total Rod Emission Rate[b] RE		ECG Suction Manifold P4	ECG Recycle Manifold P5
3/25	10:04-10:10 a.m.	5.68	13.70	9.41	4.29	6.51	9.97	43	3.43	5.13
	3:15 – 3:20 p.m.	0.59	18.30	9.83	8.46	2.84	9.05	93	-0.26	1.12
3/26	3:00 – 3:05 p.m.	0.22	19.41	9.88	9.54	1.29	9.76	98	-0.18	1.25
	3:30 – 3:45 p.m. Oil filter elements removed from ECG suction lines	0.00	17.72	9.78	7.94	2.81	7.94	100	-0.15	0.90
4/27	10:09–10:32 a.m.	3.55	13.35	8.28	5.07	3.08	8.62	59	3.23	4.09
	1:06 – 1:18 p.m.	3.20	12.86	8.67	4.19	3.05	7.39	57	2.35	3.29
	4:40 – 5:09 p.m.	4.59	12.51	8.96	3.55	3.41	8.14	44	1.37	2.12
4/28	9:25 – 9:37 a.m.	4.06	13.22	6.63	6.59	2.09	10.65	62	4.08	5.29
	10:27–10:35 a.m.	4.23	14.00	6.79	7.22	1.82	11.45	63	4.58	5.37
	12:27–12:35 p.m.	3.44	12.18	7.50	4.69	2.52	8.13	58	1.21	2.62
	1:26 – 1:41 p.m.	1.88	13.07	7.67	5.41	2.04	7.29	74	0.36	0.28
	2:31 – 2:47 p.m. Oil filter elements removed from ECG suction lines	0.68	15.75	7.63	8.13	0.79	8.81	92	-0.03	2.41
AVERAGE		2.68	14.67	8.42	6.26	2.69	8.93	70		

[a] Total represents sum of leak rates from all three doghouse vents
[b] Represents emissions from all three compressor rods, RE = (Q7-Q8) + DHL
[c] Leak Capture Efficiency (%) = (RE-DHL) / RE * 100 or (Q7-Q8) / RE * 100

Calculation of the SAS leak capture efficiency required estimates of uncontrolled emission rates prior to SAS being installed. Unfortunately, the Center was unable to obtain an accurate measurement of the rod emission rate prior to SAS being operational because of failures and unscheduled replacement of multiple rods after the SAS was installed. The only available uncontrolled rod emission rate data were collected by STAR Environmental, Inc. on October 22, 1998 (approximately 10 months after the seals on Rods 1 and 2 were replaced and 4 months before new seals were added on Rod 3). The total emission rate from Engine 1 (sum of all three rods) was estimated to be approximately 7.6 scfm CH_4. (See Appendix B for further details on this data set and the sampling methods employed). Since this measurement, the seals and packing case on Rod 3 have been replaced twice, and emissions from the remaining rods are likely to have increased because several months have transpired since the SAS operation was initiated. Unfortunately, a more current estimate of the rod leak rate is not available, and it is uncertain whether the 7.6 scfm CH_4 is a valid estimate of the rod emissions that the SAS was recovering.

An alternate method of estimating uncontrolled emissions from the three rods is applicable. This method relies on conducting a mass balance on the SAS, and employs all available measurements data:

specifically, the doghouse leak rate measurements (DHL); and the in-line flow sensor output (Q7 and Q8). As shown in Table 3-3, total methane emissions from all three rods, designated as RE, are equal to the sum of the gas recovered by the SAS (Q7 minus Q8) and the gas vented from the doghouse vents (DHL). Based on this approach, the total rod emission rate is estimated to range between 7.3 and 11.5 scfm CH_4, with an average value of about 8.9 scfm CH_4.

As shown in Table 3-3, the SAS leak capture efficiency appears to depend on operating pressures of the glands (i.e., ECG suction pressures). For example, the highest leak capture efficiency (>90 percent) was measured when the suction pressures were negative. The lowest efficiency of 43 percent was measured when both recycle gas flows and ECG suction pressures were among their highest values.

Figure 3-1 illustrates that the volume of gas leaking into the doghouse vent is a function of SAS suction pressures. The doghouse leak rate is most sensitive to pressure increases at lower pressures, and then tends to level off to a total leak rate of about 5 scfm CH_4 (sum of three doghouse vents) when the suction pressures are greater than 6 psig. This relationship is best described through a power function, as shown in Figure 3-1. Based on this trend, the lowest leak rate can be achieved when the suction pressure is slightly negative (leak capture efficiency > 90 percent). This pressure range was achieved for under 20 percent of the duration of the Phase I test (approximately 5 days). For the remaining 80 percent of the time, as shown in a time series plot of ECG suction pressures in Figure 3-2, the SAS was operating at significantly higher pressures (2 to 5 psig).

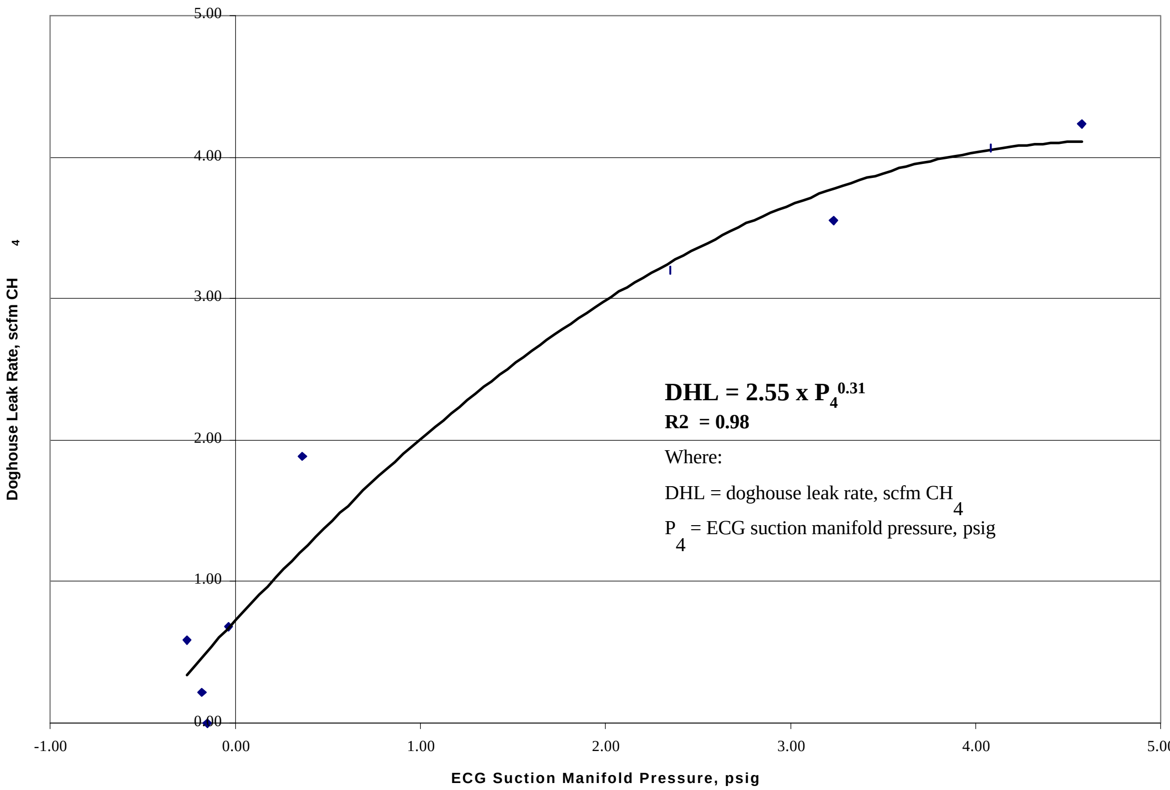


Figure 3-1. Leak rate versus ECG suction pressure

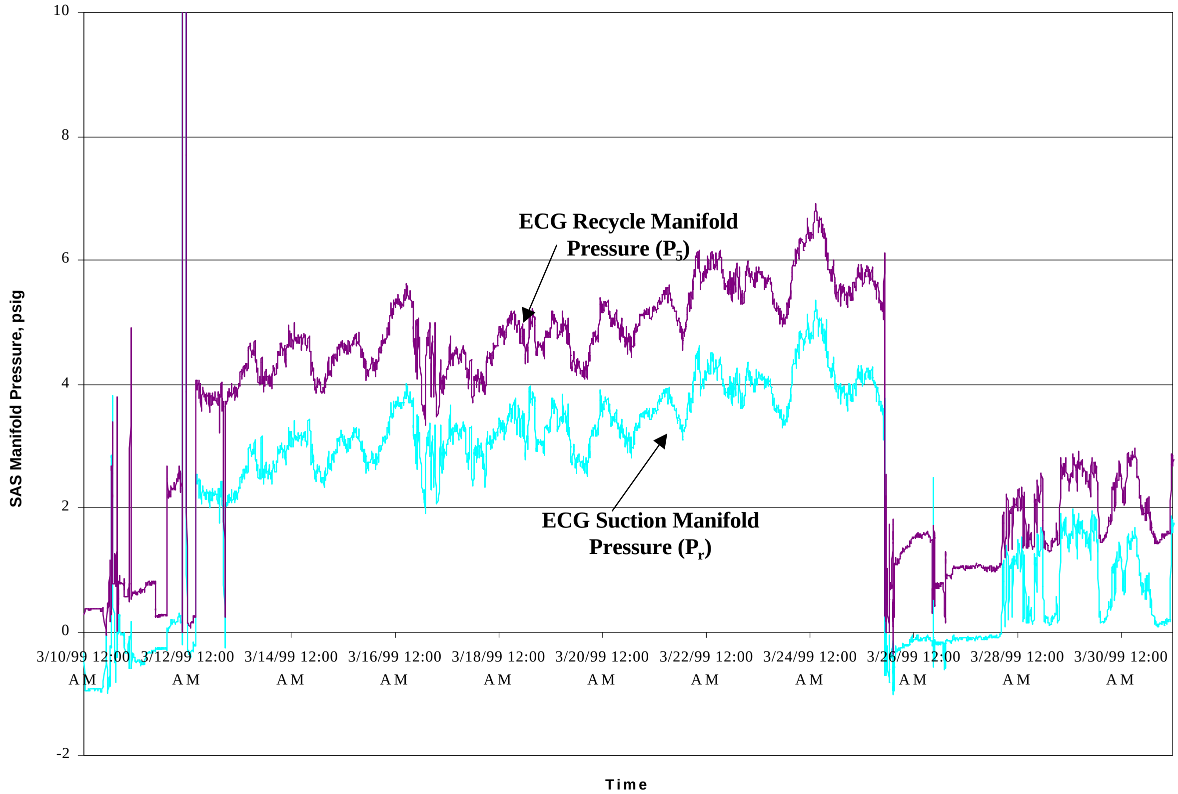


Figure 3-2. SAS manifold pressures versus time

3.1.2.1 Engine Fuel Header Pressure Effects on SAS Performance

The verification data collected during Phase I suggest that SAS performance is directly related to the operating pressures of the engine fuel header line. As shown in Figure 3-3, a linear relationship exists between the ECG suction pressures and the engine fuel header pressure. A small change in the fuel header pressures appears to cause a significant increase in the ECG suction pressures. For example, a 13 percent increase in fuel static pressure can increase SAS line pressures by a factor of 6.

The increases in fuel header static pressures appear to be the result of normal changes occurring at the station. These include: one or more engines being brought on/off the production line; and/or increases or decreases occurring in the engine speed and power ratings. To compensate for these changes and to maintain a constant pressure drop across the Eductor/Compressor, an operator must manually regulate the Eductor/Compressor motive gas pressure. Unfortunately, the Eductor/Compressor motive gas pressure can not be regulated higher than 590 psig. As a result, the Eductor/Compressor is unable to minimize the pressure differential between the Eductor/Compressor motive gas line and the Eductor/Compressor discharge line. This causes the Eductor/compressor to work harder and suck less gas contained in the jet discharge line, and because emission flows continue to be unchanged, pressure begins to build up in the SAS piping. Consequently, the ECGs begin to leak.

Based on these findings, it is clear that an automated or manual means of adjusting for changes in fuel header pressure and motive gas pressure is required to maintain steady state pressure conditions in the SAS. This could be accomplished by installing a pressure regulator in the fuel header that maintains constant static pressure, a pneumatically activated pressure regulator in the Eductor/Compressor motive gas line which adjusts to changes in fuel header static pressure, or a larger Eductor/Compressor which could accommodate larger pressure drops across the unit.

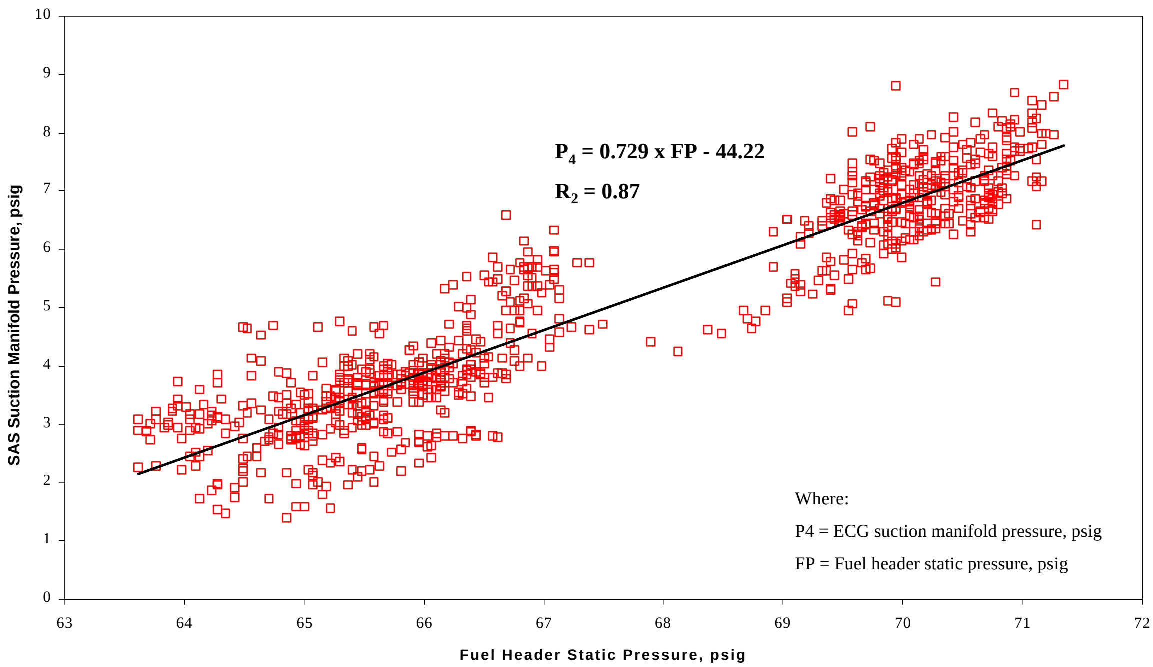


Figure 3-3. SAS suction pressures versus fuel header pressures

Conversations with Transwestern officials indicate that the first option could be implemented by station operators at a cost of about $3,000. An alternate to this modification is to automate the SAS/Eductor/Compressor to detect pressure changes in the fuel header line or the motive gas line, and make appropriate operating pressure changes as needed to maintain stable manifold pressure. This may require a process control system to be integrated into the SAS design. Finally, the Eductor/Compressor used in the verification test may be undersized, and a larger unit may be capable of meeting the engine fuel header requirements. Each of these options, including design changes to the tertiary seal, is being considered by A&A for future applications.

3.1.2.2 Tertiary Seal Effects on SAS Performance

The SAS performance is also affected by the inability of the tertiary seal to maintain a tight interface at the rod. This ultimately causes the gas to leak into the doghouse and reduce the gas collection capability of the SAS. Because the SAS had been operating at higher than its design pressures for most of the Phase I test, significant stress was placed on the seals because they are designed to function only as a backup system when positive suction pressures are encountered (i.e., significantly higher ECG suction pressures are maintained and/or a catastrophic failure of primary rod seals have occurred). Under these conditions, the seals are intended to prevent leaks for a relatively short period until repairs can be made.

A&A has confirmed that the tertiary seals on the first and third rods appear to be severely worn, and the fastening mechanism, used to bolt the seal to the rod, had been damaged from significant vibrations encountered at the compressor engines. Based on these findings, a design modification of the tertiary seal may be required. A&A is considering alternate seal designs and stronger bolting mechanisms for future SAS installations.

3.1.2.3 SAS Performance as a Function of Pressure Drop in Measurement Sensors and Oil Traps

It was suspected that a significant pressure drop across each of the five oil filters could occur, and this could affect SAS leak capture performance. Based on limited laboratory testing, the pressure drop at each oil filter is expected to be 0.35 psig, with 8 scfm gas. It was not feasible to remove the oil filters for the entire testing period because the oil present in the gas would cause all in-line flow sensors to malfunction and contaminate the engine fuel line, which violates Transwestern's fuel quality requirements. To address the effects of oil traps on SAS leak capture performance, all filters elements were temporarily removed on two occasions, and the doghouse leak rates were quantified. As shown in Tables 3-2 and 3-3, the leak capture efficiency was highest (92 and 100 percent) under this scenario. Both of these measurements were taken under relatively low ECG suction pressures. Based on earlier conclusions, it is clear that improved leak capture is primarily due to negative operating pressures, and removal of the oil filters is an additional means of optimizing performance.

It was also suspected that certain measurement sensors may be creating a pressure drop in the SAS piping which could negatively affect SAS performance. To reduce perturbations in SAS performance caused by the testing equipment, the Center attempted to identify and replace all sensors where a significant pressure drop could negatively affect SAS performance. Based on manufacturer specifications, it was concluded that the pressure drop across all pressure sensors and flow sensors in the SAS recycle lines is negligible. Flow sensors which monitor gas flows in the ECG suction lines are integral orifice types. These orifice meters, which are used on the ECG suction lines to measure varying gas flows by replacing the orifice plates, can introduce significant pressure drops in the SAS piping. The smallest orifice plates, which accurately measure 0 to 4 scfm gas, can cause the largest pressure drops. To minimize pressure drops in the ECG suction lines and to minimize disturbances to the SAS operation, a larger orifice plate (0.5 in.), capable of measuring 4 to 40 scfm, was installed. This option offers the least amount of pressure drop in the system (0.18 psig at 8 scfm gas). The total pressure drop caused by the measurement equipment is somewhat uncertain, but its contribution to SAS system pressure is estimated to be minimal (with the exception of the oil filters).

3.2 VERIFY INITIAL GAS RECOVERY AND USE PERFORMANCE

The amount of gas recovered by the SAS and routed to the engine for use is a critical parameter in determining gas savings and economic performance. Initial gas recovery performance is determined on the results of eight in-line gas flow measuring devices. Six of these devices measure the gas flow immediately upstream (ECG recycle lines) and downstream (ECG suction lines) from each of the three SAS glands shown in Figure 2-2. The remaining two meters, Q7 and Q8, measure the total gas recompressed by the Eductor/Compressor and the motive gas consumed by the jets, respectively. As previously stated, the three flow meters on the ECG suction lines (Q1, Q2, and Q3) were not functioning as a result of the oil contamination problem. For this reason, all conclusions made on the gas recovery performance are based on data recorded by Q7 and Q8.

Figure 3-4 illustrates the volume of gas recovered over the Phase I test period. The top chart illustrates all data collected, including initial days of operation when the engine was shut down. As shown in the chart, the gas recovered values are variable and appear to be sporadic when the engine is shut down for repair or maintenance (possibly because dramatic fluctuations in the SAS operating pressures were encountered). Once the engine is back on line, the system recovers relatively consistent gas volumes. For this reason, all time periods when the engine was down have been removed in the bottom chart shown in Figure 3-4. The gas recovery rate ranges between 3.7 and 11.6 scfm for the Phase I Test during engine operation. The average recovery rate is about 7.2 scfm gas.

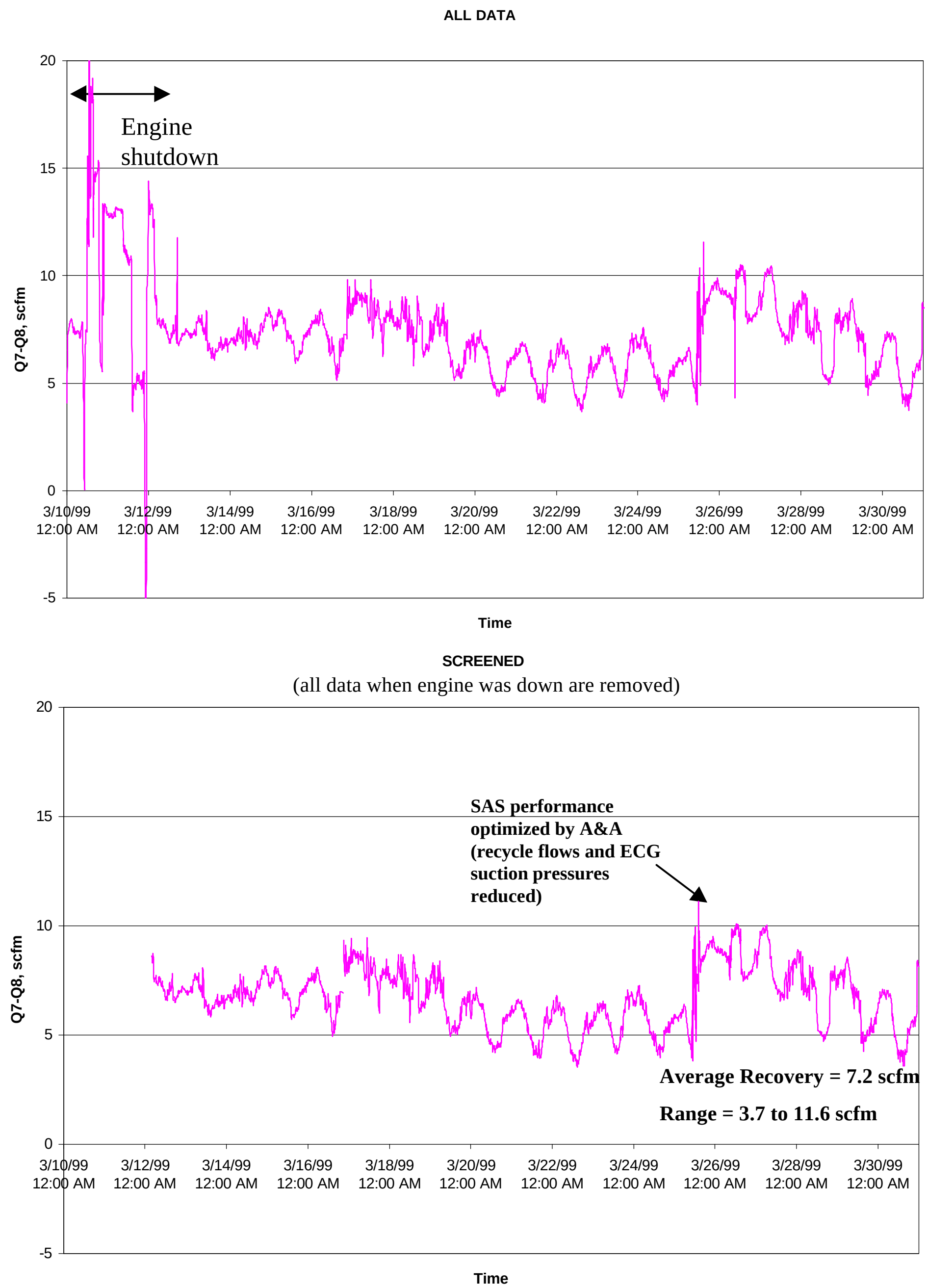


Figure 3-4. Gas recovery versus time (Phase I)

3.2.1 SAS Gas Recovery Rate As a Function of Suction Pressures

The SAS manifold pressures began to increase after Engine 1 was brought back on line on March 12. Based on manual measurements, it was clear that some gas was not collected by the SAS, and was emitted through the doghouse vents. Throughout this venting, the gas recovery rates varied significantly, from a low of 4.3 scfm when the doghouse leak rate was the highest, to 9.5 scfm when the doghouse leak rate was the lowest (see Table 3-3). Also evident from these spot measurements is that the greatest recovery (>8 scfm) was achieved while the ECG suction pressures were negative. These data clearly suggest that gland pressures affect SAS recovery rates.

Unfortunately, the doghouse leak rate was not measured continuously throughout the Phase I period. However, if an assumption is made that Figure 3-1 accurately represents the leak profile, then the doghouse leak rate can be estimated by using the equation shown on the figure. The total rod emission rate can be calculated as the sum of the total doghouse leak rate and the total gas recovered. Figure 3-5 shows the calculated doghouse leak rate and the total rod emissions over time.

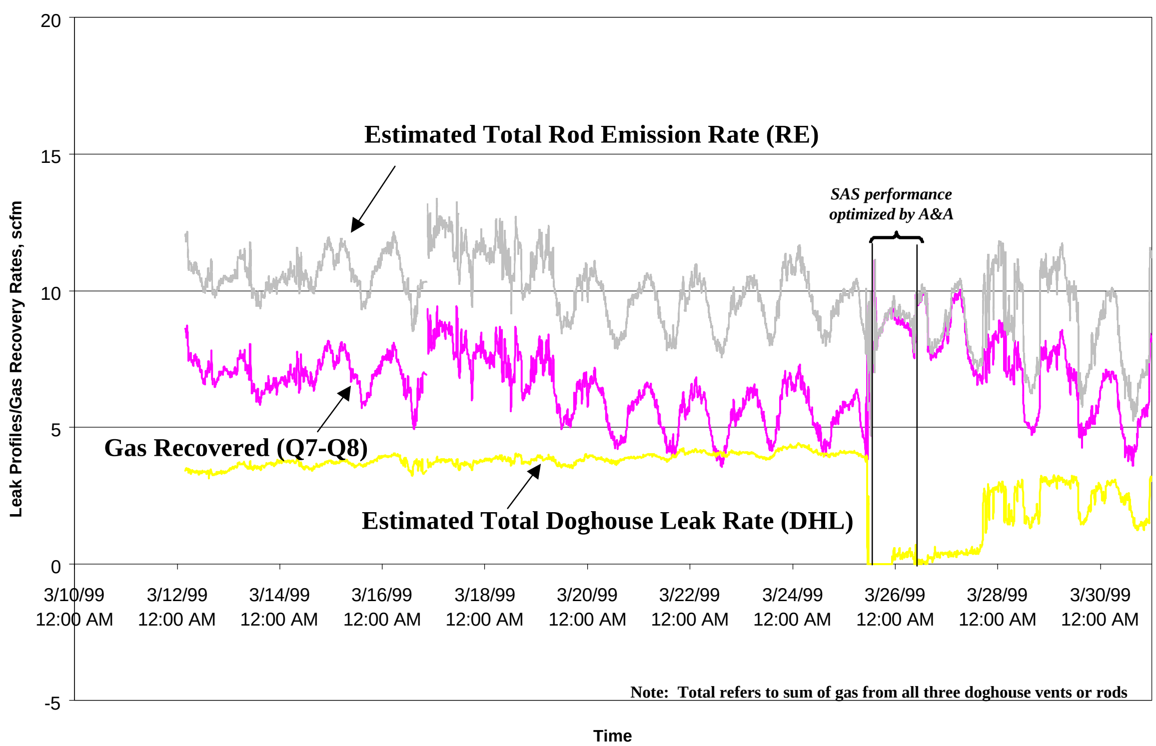


Figure 3-5. Time series leak profiles and gas recovery rates

The total doghouse leak rate for a significant portion of the Phase I test is estimated to be about 4.8 scfm. The leak rate drops to nearly 0 levels for a brief period while the suction pressures are negative. As shown in Figure 3-5, rod emissions and total gas recovery rates coincide during this brief period (3/25 through 3/27), suggesting that the SAS is fully capturing all emissions occurring at the rods. During this period, the total rod emission rate is estimated to range between 7.5 and 10.5 scfm gas. The average rod emission rate for the entire Phase I test is estimated to be 9.7 scfm gas. On average, the gas recovered by the SAS is about 72 percent of these emissions.

3.2.2 Diurnal Effects on Gas Recovery Rates

Within a single day, the calculated rod emission rate and the total gas recovery rate can vary significantly (see Figure 3-6). Typically, the gas recovered values recorded in the early morning hours can be 40 to 70 percent higher than the gas recovery rates recorded in late afternoon. These diurnal effects appear to be related to the temperature of the gas entering the compressor station.

As shown in Figure 3-6, the lowest gas temperatures are recorded at night when the ambient temperature is the coolest. As the air warms throughout the day, the gas temperatures in the high-pressure lines increase, and heat the inlet gas by about 1 to 2 percent. This rise and fall in the gas temperatures follow the peaks and valleys observed in the gas recovery rates and the rod leak rates (see Figure 3-6). It is speculated that cooler gas causes the rods to shrink, which in turn causes the rod emission rate to increase, as void space is created between the rods and seals and more gas is allowed to escape. As the rods expand at higher temperatures, the seals form a "tighter" fit, less gas is emitted, and the SAS gas recovery rate is reduced.

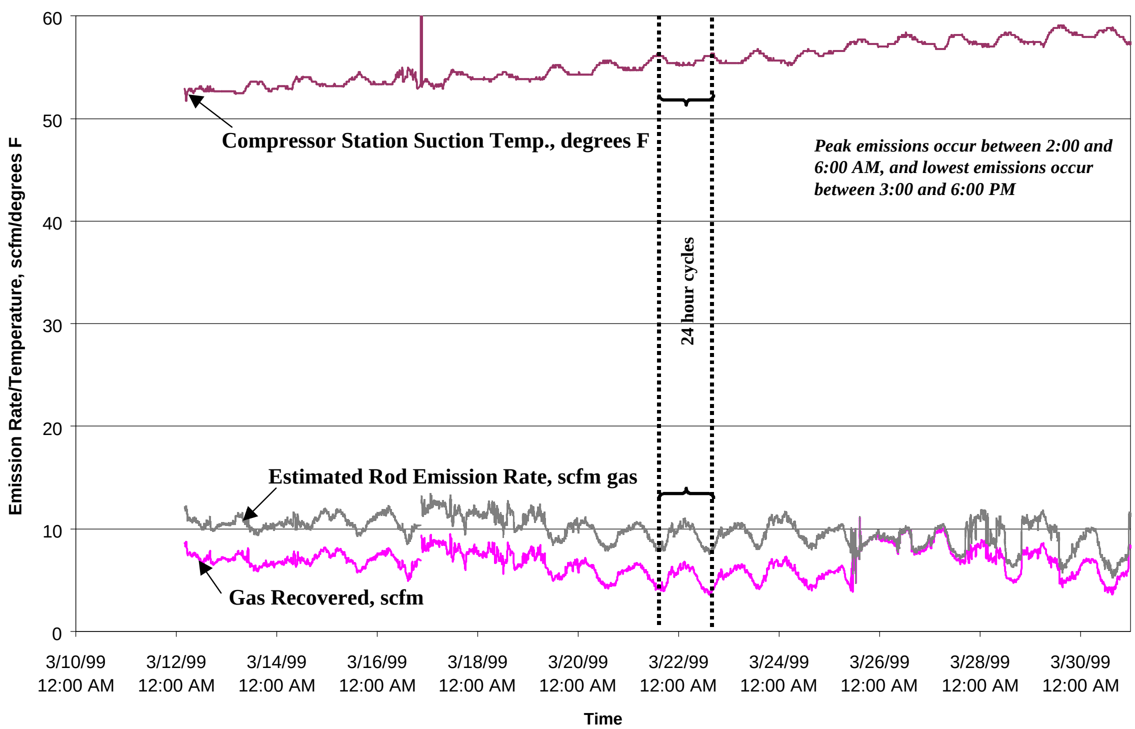


Figure 3-6. Diurnal trends in gas temperatures, rod leak rates, and gas recovery rates

3.3 VERIFY INITIAL METHANE EMISSION REDUCTION

A fundamental distinction must be made between the amount of gas recovered by the SAS (described in Section 3.2), and the atmospheric emissions reduced by the SAS (described in this section). If installation of the SAS does not alter rod seal leak rates, and if entrained air is not present within the SAS, then the methane emission reduction should equal the gas recovery reported in Section 3.2. On the other hand, if rod seal leak rates either increase or decrease as a result of SAS operation, or if significant air is present, then emission reduction and gas recovery values will differ. It is speculated that the low-pressure region established in the SAS annulus area can increase the net volume of gas entering the SAS from each rod. Under such conditions, the gas captured by SAS may be higher than the rod emissions that would be normally emitted if the SAS was not installed. Similarly, the SAS can decrease methane emissions because of the additional barrier present between the rod emissions, tertiary seal, and the primary seals, resulting in less gas to escape into the atmosphere.

Oxygen concentration was monitored in the jet manifold discharge to confirm that SAS does not introduce ambient air into the system. The oxygen sensor used in the test was capable of measuring 0.1 percent oxygen or less in order to provide adequate safety. As shown in Figure 3-7, oxygen levels appear to increase when the engine is shut down. This increase appears to be temporary as station operating conditions change. The oxygen levels quickly stabilize as the engine becomes fully operational. The increases in oxygen levels are likely to be an artifact of the measurements approach. That is, the oxygen sensor is pressure-fed off the SAS discharge header, and vents to the atmosphere. If the discharge header pressure reaches negative pressures as seen in Figure 3-2, ambient air will affect the sensor and cause high readings. For the remaining periods, with the exception of times when the SAS was being optimized or sensor function checks were performed, oxygen levels remained relatively stable near 0.01 percent. It is therefore concluded that the SAS does not entrain ambient air into the process.

To determine if the SAS significantly increases or decreases rod seal emission rates, rod emission rates were monitored manually prior to glands being installed and after the SAS operation was initiated (i.e., SAS was disabled, see Appendix A for measurement procedures). The emission rates were compared with the gas recovery rates described above. If the SAS does not affect leak rates, the measured values are expected to be the same.

A single set of measurements was collected to quantify the rod emission rate prior to the glands being installed. STAR Environmental, Inc. collected these data on October 22, 1998. As shown in Table 3-4, the uncontrolled total rod emission rate is estimated to be 7.6 scfm CH_4. This value is within the range of gas recovery rates measured in Phase I (see Table 3-5), suggesting that the SAS does not perturb uncontrolled rod emissions, and the methane emission reduction potential is equivalent to the volume of gas recovered.

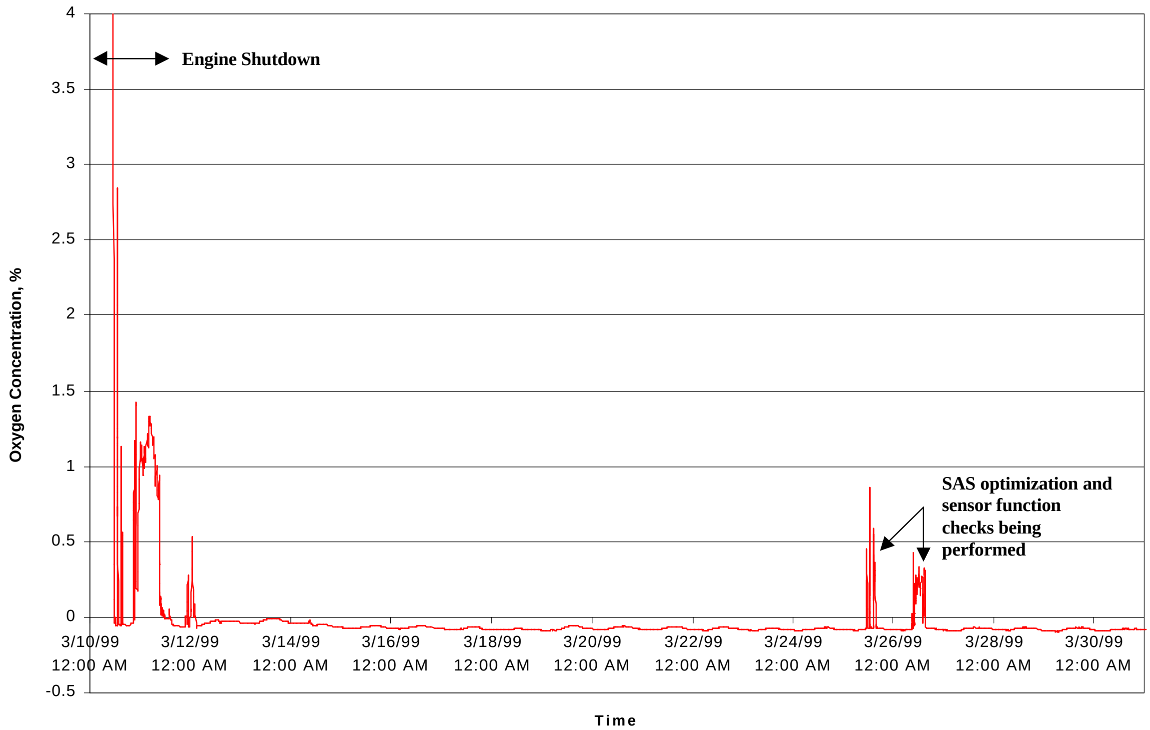


Figure 3-7. Oxygen levels versus time

TABLE 3-4. COMPARISON OF ROD LEAK RATES BEFORE AND AFTER SAS INSTALLATION

	Average Rod Emission Rate, scfm CH_4			Net, scfm CH_4
	Rod 1	Rod 2	Rod 3	
STAR data (prior to SAS installation)	0.30	1.58	5.70	7.58
SAS Operating[a]	-	-	-	7.39 to 10.65
SAS Isolated[a]	0.82	0.79	3.72	3.92 to 8.47

[a] See Tables 3-5 and 3-6

Unfortunately, this statement is not conclusive because the seals and packing case on Rod 3 have been replaced two times since the October measurement; and it is unclear whether the measured rod emission rate is truly what the SAS is recovering. During the Phase II evaluation, the Center will have the opportunity to measure the rod emissions without the glands. These results will be included in the Phase II verification report, and definitive statements on the methane emission reduction potential will be provided.

To determine if the SAS perturbs normal rod leak rates after the glands are installed, the ECG was first isolated by closing the jet discharge, ECG recycle, and ECG purge valves. The sampling port was then opened to expose the gland's annulus area to normal ambient conditions (conditions experienced when the gland is not present). The same Flow Tube used in doghouse leak rate measurements was used here. The measured leak rate was then compared with the in-line flow rates recorded by the mass flow meters prior to isolating the ECG. Table 3-5 summarizes the manual data collected while the SAS was isolated. The corresponding in-line flow data and doghouse leak rates immediately prior to isolating the SAS are summarized in Table 3-6.

On average, the rod leak rate measured while the SAS was operating was about 40 percent higher than the leak rate measured while the SAS was disabled. The reason for this is that the relatively small free area present in the ECG annulus restricts gas flows (provided the annulus is under pressure), ultimately inhibiting rod emission flow. That is, without suction, the glands cannot be evacuated because the rod leaks are not at sufficient pressure to push out of the annulus and into the borehole. With this reasoning, it is likely that the SAS operation does not perturb rod emissions. Rod emission rates will be compared directly immediately before and after gland installation in Phase II to verify this conclusion.

3.4 INSTALLATION AND SHAKEDOWN REQUIREMENTS

The SAS piping and auxiliary equipment were installed by a Transwestern approved contractor, with supervision and guidance provided by A&A technicians. Center personnel, available on-site throughout the installation and shakedown process, documented any modifications made or difficulties encountered.

A detailed installation, start-up, and operating manual for the SAS system has been prepared by A&A for use with the installed system, and is included in Appendix D as a reference. It includes procedures for initiating SAS gland start-up, obtaining design recirculation rate and pressure, initiating jet manifold operation, initiating the Eductor/Compressor, and verifying the functionality of the entire system by observing key monitoring sensors and data recording equipment. The following discussion does not focus on the step-by-step procedures, but rather highlights the Center's observations on the SAS installation, start-up, and shakedown requirements.

3.4.1 Center's Observations on the SAS Installation Process

SAS glands were installed by station operators on November 22, 1998, during a scheduled engine shutdown. The installation process required between 4 and 6 hours per rod to complete. Installation of the SAS piping began on January 25 and was completed on January 30. The actual fabrication, installation, and high-pressure testing occurred without any major problems. Based on contractor logs, the piping system fabricated at Station 4 and the installation of remaining SAS components (i.e., jets, Eductor/Compressor, valves, regulators, and miscellaneous equipment) required approximately 300 labor hours. A materials list of the installed components is provided in Appendix E.

TABLE 3-5. DOGHOUSE LEAK RATE MEASUREMENTS DATA (ECG ISOLATED)

Date	Time	Rod #	Gas Velocity, fpm	Gas Temp., °F	Hydrocarbon Concentration, %	Doghouse Leak Rate, scfm CH_4
3/25/99[a]	10:10 - 10:15 a.m.	1	325	79	96	0.99
		2	140	79	96	0.40
		3	872	79	96	2.72
	3:00 – 3:12 p.m.	1	308	100	96	0.93
		2	215	100	96	0.64
		3	795	86	96	2.48
3/26/99[a]	3:15 – 3:30 p.m.	1	510	87	96	1.57
		2	128	104	96	0.36
		3	941	104	96	2.94
4/27/99	1:45 – 2:31 p.m.	1	233	95	95	0.69
		2	558	95	95	1.71
		3	1950	140	95	6.07
	4:44 – 5:15 p.m.	1	196	100	95	0.57
		2	258	117	95	0.77
		3	935	154	95	2.89
4/28/99	9:43 – 10:03 a.m.	1	359	112	96	1.09
		2	242	124	96	0.72
		3	1841	143	96	5.79
	12:40 – 12:58 p.m.	1	261	112	96	0.78
		2	303	116	96	0.92
		3	1054	139	96	3.30
	3:07 – 3:40 p.m. Oil filter elements removed from ECG suction lines	1	128	not measured	96	0.36
		2	251	not measured	96	0.75
		3	902	not measured	96	2.81
4/29/99	8:30 – 8:53 a.m.	1	310	89	96	0.94
		2	278	121	96	0.84
		3	1414	148	96	4.44

[a] The Flow Tube could not be calibrated because of a damaged anemometer; therefore, doghouse leak rate estimates for these days are based on calibration of a new anemometer that was field- and laboratory-calibrated.

TABLE 3-6. SAS EFFECTS ON ROD LEAK RATES

Date	Time	SAS DISABLED, scfm CH_4	SAS OPERATING, scfm CH_4					% Difference Between Rod Emission Rates[b]
		Measured Rod Leak Rate	Total Doghouse Leak Rate DHL	Gas Into Engine Q7	Jet Motive Gas Q8	Total Gas Recovered Q7-Q8	Total Rod Emission Rate[a] RE	
3/25	10:10 – 10: 15 a.m.	4.11	5.68	13.70	9.41	4.29	9.97	41
	3:00 – 3:12 p.m.	4.05	0.59	18.30	9.83	8.46	9.05	45
3/26	3:15 – 3:30 p.m.	4.87	0.22	19.41	9.88	9.54	9.76	50
4/27	1:45 – 2:31 p.m.	8.47	3.20	12.86	8.67	4.19	7.39	115
	4:44 – 5:15 p.m.	4.23	4.59	12.51	8.96	3.55	8.14	52
4/28	9:43– 10:03 a.m.	7.60	4.06	13.22	6.63	6.59	10.65	71
	12:40–12:58 p.m.	5.00	3.44	12.18	7.50	4.69	8.13	62
	3:07 – 3:40 p.m.	3.92	0.68	15.75	7.63	8.13	8.81	45
4/29	8:30 – 8:53 a.m.	6.22	1.98	16.93	8.37	8.56	10.54	59
AVERAGE		5.39	2.50	14.87	8.52	6.35	8.85	60

[a] RE = (Q7-Q8) + DHL, see Figure 3-1

[b] % Difference = Rod Emission Rate When SAS Disabled / Rod Emission Rate When SAS Operating * 100

3.4.2 Center's Observations on the SAS Start-Up, Shakedown, and Operation Requirements

SAS start-up was initiated on February 2, 1999, after the Tariff period was concluded (all engines are required to be continuously operating). Within a few days, the system was shut down because a significant quantity of purge gas was venting into the doghouse, affecting SAS leak capture efficiency. New pressure regulators were installed to control the purge gas flows, and the system was brought back on line on February 5, 1999.

During the period from February 5 through 26, the SAS appeared to be operating. Throughout this time, daily SAS downloads indicated a problem in the measurement sensors. Upon investigation, it was concluded that oil accumulated in the SAS piping was causing the instruments to malfunction. Further investigation of the oil accumulation revealed that the ECGs were also affected (i.e., oil had coagulated onto the gland surface, inhibiting its ability to maintain negative operating pressure). The entire system was brought off-line for several weeks to systematically clean the glands, the jets, and the flow sensors. In order to prevent the sensors from malfunctioning in the future and to alleviate Transwestern's concerns about introducing oil into the engine fuel line, coalescing oil filters were added on all ECG suction lines and all locations where flow sensors were installed. Based on this observation, it is clear that a permanent and effective means of controlling engine oil is required, and A&A must offer a reasonable solution for future installations.

As discussed in Sections 3.1 through 3.3, the SAS operation appears to be unstable when engine operating conditions change. Specifically, the SAS begins to operate under pressure each time the fuel header pressure increases. This results in gas leaks into the doghouse through the tertiary SAS glands. Ultimately, the continued stress placed on the tertiary seals causes them to wear quickly, and the effectiveness of the SAS to recovery is reduced. Based on this observation, it is clear that a larger Eductor/Compressor, an automated means of achieving optimum SAS operating pressures, and a more effective tertiary seal design must be made available by A&A to ensure steady-state and reliable gas recovery performance. This may require design and installation of automated sensors to detect when significant pressure differential has occurred in the Eductor/Compressor, and provide a control mechanism to adjust the pressures as required.

3.5 INITIAL CAPITAL AND INSTALLATION COSTS

A key objective of the SAS verification test is to determine the technology payback period. To accomplish this, accurate documentation of the SAS capital costs and installation costs is required. The data presented in this section are based on costs submitted by the installation contractors, and discussions held with Transwestern and A&A personnel. Prior to the verification test, the contractors were instructed by the Center to determine and record all costs related only to the SAS assembly. The costs specific to the verification testing requirements (i.e., measurement sensors) were removed, and are not reported.

The as-built system, shown in Figure 1-1 and itemized in Appendix E, was used to develop a standard SAS process and instrumentation diagram for a typical SAS installation at a compressor station. A&A personnel and Transwestern management were interviewed to help develop a materials list and a cost estimate for the standard system. Figure 3-8 illustrates the resulting standard system diagram. It consists of basic SAS components, including: three ECG glands with jet assemblies, one Eductor/Compressor, various pressure and flow regulators, safety equipment, and miscellaneous piping equipment. A single oil coalescing filter, installed in the jet discharge manifold, is also included. For safety reasons, all instrumentation related to oxygen monitoring, including transmitters and electrical conduit to the station data acquisition, is included. Two flow metering devices are specified, each measuring the net gas flow into and out of the SAS. Finally, two in-line pressure sensors are specified to monitor ECG suction and recycle manifold pressures. A complete equipment list and an itemized cost table are summarized in Table 3-7. The total capital equipment cost for this standard system is estimated to be $30,933.

Table 3-8 summarizes the labor requirement for the standard SAS piping and instrumentation. It is estimated that the SAS mechanical components will require 297 hours to install, and the instruments will require approximately 203 hours. The total installation cost for the standard system is estimated to be $11,841.

The net initial capital and installation cost for the SAS is estimated to be $42,774. This includes the costs associated with electrical and instrumentation components ($12,822), some which can be offered as optional equipment by A&A.

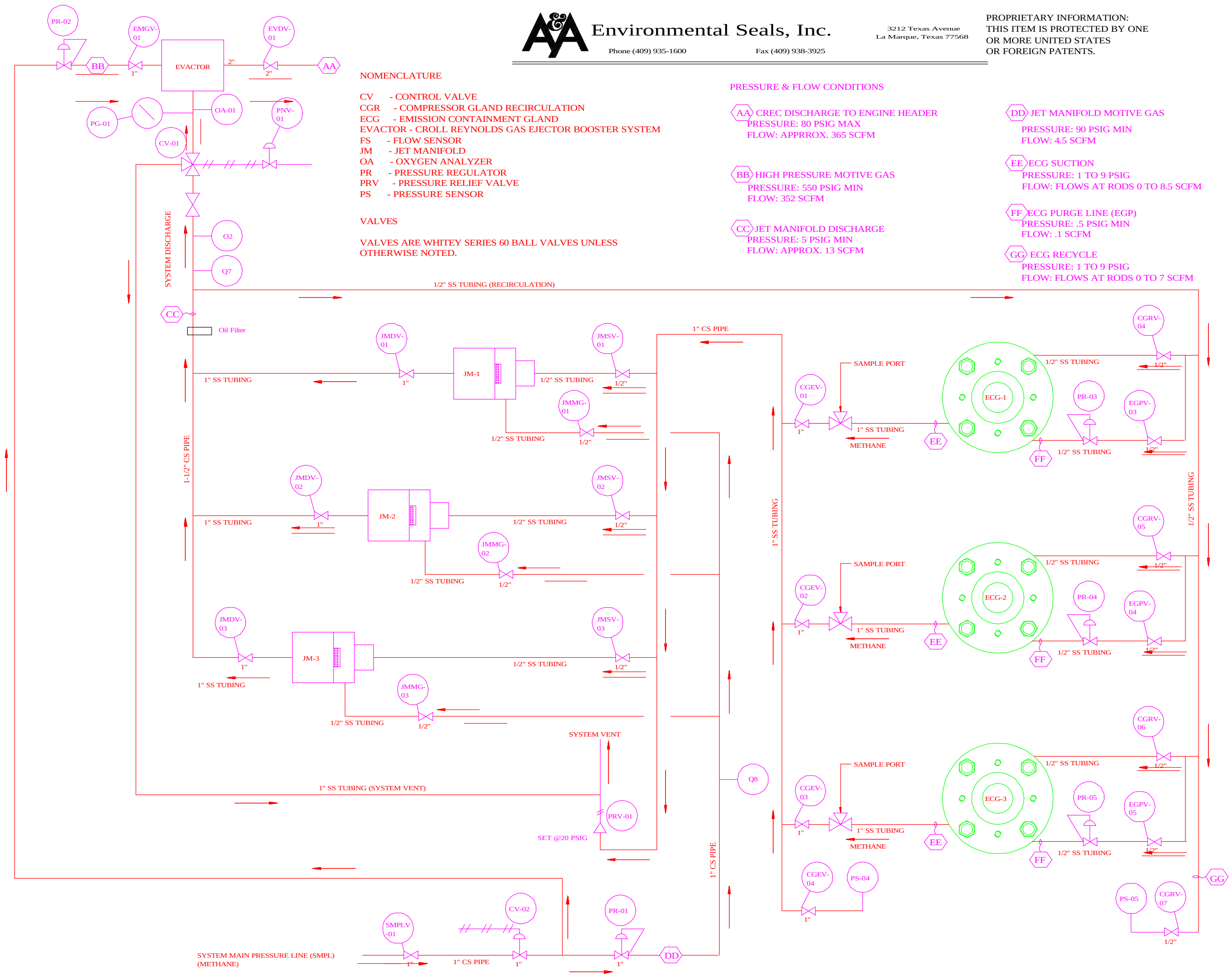


Figure 3-8. The standard SAS diagram

TABLE 3-7. INITIAL CAPITAL COSTS (STANDARD SYSTEM)

ITEM	AMOUNT, $
MECHANICAL AND PIPING	
Non-expendables [a]	2,918
Expendables	
(1) Eductor/Compressor	2,100
(3) Emission containment gland assemblies w/ jets	11,562
(1) Oil coalescing filter (1-in.)	150
(12) Flex-hoses (1/2-in.)	1,000
Miscellaneous hardware [b]	1,654
Carbon steel piping (1/2-in., 21 ft long)	54
Tubing 316 SS, (3/8-in., 80 ft long)	92
Tubing 316 SS, (1/2-in., 160 ft long)	250
(4) Ball valve (¼-in.)	94
(28) Ball valve (½-in.)	624
(2) Ball valve (¾-in.)	67
(2) Fisher 1-in. regulator (70-150 lb.)	381
(1) Fisher 1-in. regulator (275-500 lb.)	372
(1) Air-actuated ball valve (1-in.)	852
(1) Air-actuated 2-way ball valve (1/2-in.)	1,086
SUBTOTAL MATERIALS	*23,256*
ELECTRICAL AND INSTRUMENTATION [c]	
Non-expendables [a]	1,095
Expendables	
(2) UFM flow meters (Q7&Q8)	751
(1) Advanced Controls GPR-25 oxygen transmitter/probe	1,400
(1) Oxygen probe (for GPR-25)	150
(6) Input modules	564
(2) Rosemount 3051 pressure transmitters	2,314
Miscellaneous hardware [b, d]	1,403
SUBTOTAL MATERIALS	*7,677*
TOTAL CAPITAL COSTS	**$30,933**

[a] Examples of non-expendables are vehicle usage, equipment rental, and welding rig usage.
[b] Examples of miscellaneous hardware are fittings, couplings, wire strut, nuts, and bolts. A detailed listing of these items is provided in Appendix E.
[c] See Appendix E for more detail on the individual devices.
[d] This figure was calculated using a factor based on the cost of installing all the instruments in the as-built case (15) divided into the number of instruments in the standard case (6).

TABLE 3-8. INSTALLATION COSTS (STANDARD SYSTEM)			
Job Type	**Rate[a]**	**Hours**	**Total Cost**
MECHANICAL & PIPING			
Material handler	$18.00	2.00	$ 36
Laborer	$17.30	74.00	$ 1,280
Pipe fitter	$19.77	61.00	$ 1,206
Welder	$20.75	42.50	$ 882
Helper	$15.00	42.50	$ 637
Test Engineer	$23.00	13.50	$ 310
Supervisor	$38.44	61.00	$ 2,345
		SUBTOTAL LABOR	*$ 6,696*
ELECTRICAL & INSTRUMENTATION[b]			
Electrician	$24.81	99.00	$ 2,456
Instrument Tech	$28.45	72.00	$ 2,045
Helper	$19.50	29.00	$ 555
Supervisor	$29.50	3.00	$ 89
		SUBTOTAL LABOR	$ 5,145
		TOTAL LABOR COSTS	**$11,841**

[a] Rate averaged to include overtime rate
[b] This is based on six instruments being installed as opposed to fifteen for as-built case

4.0 QUALITY ASSURANCE AND PREVIEW TO PHASE II EVALUATION

4.1 DATA QUALITY ASSESSMENT

Data quality objectives are used to determine the values of key data quality indicators that must be achieved in order to draw conclusions on the measurement data with a desired level of confidence. In the Test Plan, the primary quantitative objective was to establish a payback period estimate with a maximum uncertainty of about 10 percent (±3 to 4 months). Inherent in this objective is documentation of the SAS's gas recovery and use performance.

Although establishing the payback period is not an objective under the Phase I test, the quality of measurements collected during this test period plays a significant role in the level of confidence of the payback estimates. To meet the maximum desirable error in the payback period estimate of 10 percent, the gas flow meters are required to be accurate within ±10 percent. During Phase I testing, mass flow meters, capable of providing accuracy within ±1 percent, were used. Table 4-1 presents a summary of all measurements employed in the test. Also listed in this table are the accuracy and precision goals, and indications as to whether these goals were met. The following discussion highlights the data quality achieved for key measurements and the verification factors.

4.1.1 Fugitive Leak Monitoring

Manual leak testing is required to determine the SAS leak capture and gas recovery performance. To meet the manual sampling requirements of the test, a flow measuring tube was developed and assembled by the Center. The Flow Tube consists of a vane anemometer housed in a flow straightening tube with an inside diameter of 1-in. and an overall length of approximately 30 in. An anemometer was placed in the tube (Omega Model HH-31A) to measure gas velocity in the range of 60 to 6,800 fpm with an instrument rated accuracy of ±1 percent of reading.

Measured gas velocities were converted to volumetric flow rates by calibrating the anemometer against a laminar flow element (LFE). The LFE was factory-calibrated with a rated accuracy of 0.08 percent of reading, and provides flow readings as a function of pressure drop (e.g., 1.6357 scfm gas is equivalent to 8.0 in. of H_2O). In order to simulate the flow properties of natural gas, calibrations were conducted using a cylinder of instrument grade methane (99.7 percent pure). Methane gas was introduced to the LFE and flow tube in series at a variety of flow rates, and pressure drop was recorded using a 0 to 10 in. incline oil manometer. Gas temperature, barometric pressure, and anemometer velocity readings were also recorded at each test point. After correcting for temperature, pressure, and gas viscosity, a calibration curve was developed for the anemometer with flow rate in standard cubic feet per minute of methane as a function of measured gas velocity.

Four calibration runs were conducted (two prior to the manual testing at Station 4 and two after the Phase I testing was completed). The calibration results are summarized in Appendix F. The accuracy of each run ranges from –2.5 to –2.9 percent, with an average value of –2.6 percent. The average value is assigned as the confidence level expected for readings conducted with the Flow Tube. Although this achieved accuracy and precision number is above the 1 percent goal, it is well below the 10 percent data quality objectives.

TABLE 4-1. SUMMARY OF QUALITY ASSURANCE GOALS AND TEST RESULTS

Measurement	Method	Operating Range	Instrument Precision/Accuracy		How Verified/ Determined	Effect on Data Quality Objectives
			Goal	Results- were goals met?		
Fugitive Leak Monitoring						
Gas Velocity	Vane Anemometer	60 to 6800 fpm	1% reading	no[a]	Multiple calibrations with a LFE resulted in a –2.6% accuracy and 1% precision	Does not meet QA goals, but the precision and accuracy are below the 10% data quality objectives
Methane Concentration	Thermal Conductivity	0 to 100%	2.0%	yes[b]	zero/span checks	Meets QA goals
SAS Gas Flows						
ECG Suction (Q1, Q2, Q3)	Mass Flow Meters – Integral Orifice	4 to 40 scfm	1% FS	cannot be determined[c]	Performance checks[d]	Does not meet QA goals, gland specific comparisons cannot be made with total flow rates
ECG Recycle (Q4, Q5, Q6)	Mass Flow Meters – Laminar	0 to 20 scfm	1% FS	yes	Performance checks	Meets QA goals
SAS Discharge (Q7)	Mass Flow Meters – Integral Orifice	0 to 50 scfm	1% FS	yes	Performance checks	Meets QA goals
Jet Motive Gas (Q8)	Mass Flow Meters – Laminar	0 to 20 scfm	1% FS	yes	Performance checks	Meets QA goals
Oxygen Concentration	Galvanic Fuel Cell	0 to 5%	0.5% FS	yes	Performance checks / single-point calibration	Meets QA goals
Methane Concentration	Transwestern GC Analysis	0 to 100%	0.02% FS	yes	Daily calibrations performed by Transwestern	Meets QA goals
SAS Pressures						
ECG Suction Lines (P1, P2, P3)	Transducer	-4 to +20 psig	0.5% FS	yes	Performance checks	Meets QA goals
ECG Suction Manifold (P4)	Transducer	-4 to +20 psig	0.5% FS	yes	Performance checks	Meets QA goals
ECG Recycle Manifold (P5)	Transducer	0 to 20 psig	0.5% FS	yes	Performance checks	Meets QA goals

[a] Based on four separate calibrations, the accuracy and precision of the velocity readings obtained with the vane anemometer ranged between –2.6% and 1.0%., respectively.

[b] Methane was calibrated according to manufacturer's specifications and using a certified gas mixture and calibration apparatus provided by the manufacturer (Part numbers MC-105 and PCA-001). Calibrations were repeated every 90 days.

[c] Severe contamination due to oil accumulation caused the meters to malfunction. Larger orifice meters were replaced, but actual flows are less than the specified range to achieve detectable levels.

[d] Performance checks as a means of verification implies that manufacturer's specifications for precision/accuracy were used, unless a check of sensor performance indicated a problem.

FS = Full Scale

As discussed in Section 3.1, the vane anemometer used for all leak rate measurements which were conducted prior to March 1999 was damaged, and calibrations could not be performed. The reliability of the data collected by the damaged instrument is uncertain, and accurate determination of the instrument's precision and accuracy cannot be made. However, conversations with Omega technicians have revealed that all HH-31A vane anemometers are factory-calibrated to meet manufacturer's specifications. Assuming that the damaged anemometer is likely to perform similar to other Omega anemometers, the calibration results of the new anemometer (discussed above) was applied. The leak rates calculated under this assumption are within the range observed with a properly calibrated anemometer. Thus, it was concluded that this approach provides reasonable means for salvaging earlier data.

4.1.2 SAS Gas Flows

As discussed earlier, the three ECG suction-side flow meters (Q1, Q2, and Q3) were not able to detect flows less than 4 scfm because larger orifice elements were inserted to minimize disturbances to the SAS operation. As a result, gas recovery from individual rods cannot be computed, leaving the total recovery, given by the difference between meters Q7 (SAS discharge total flow) and Q8 (SAS motive gas flow) as the sole measure of gas recovery. Because the redundancy in flow measurements envisioned in the Test Plan did not occur during Phase I, it is doubly important to ensure that QA goals for the Q7 and Q8 meters were met. To ensure that the accuracy and precision goals of 1 percent of full scale are met, the Plan called for following all manufacturer's startup checks, sensor function checks, and calibration checks. The following discussion describes the checks that were performed, and it can be concluded that the data quality goals for the flow meters were met.

- Q7 (Net Gas Flow Recompressed by the Eductor/Compressor)

Setup & Start-up Checks: In each flow sensor element, a transmitter calculates mass from differential pressure (DP) across an integral orifice element. To perform this calculation, the transmitter electronics must be programmed with information on the gas being metered and the operating conditions. This is accomplished using Rosemount's Engineering Assistant (EA) Software which is interfaced to the transmitter via a HART protocol serial modem. Specific setup parameters are described in detail in the EA on-line documentation. Setup was successfully performed on the meter. After setup was computed, the meter zero was checked by isolating the meter from the flow, equalizing the pressure across the DP sensors, and reading the difference pressure and flow with the EA software. In this condition, the flow output should read zero, and the DP measured should be zero. A small differential at zero can be corrected by offsetting the transmitter output, provided the differential is stable. The final check performed was to verify that the data acquisition system output agrees with the output obtained directly from the sensor via the EA software and the model. This check was successful for all meters.

Sensor Function Checks: Reasonableness checks were made during each field visit and frequently at all times as the data were collected and polled remotely. Q7 was also diagnosed to be functioning properly by a technician sent by the manufacturer. Q7 has not indicated a system problem via onboard diagnostics. Finally, Q7 has been manually zero-checked on several occasions, and has been operating according to manufacturer's specifications.

Calibration: Calibration certificates of testing traceable to NIST were obtained from the manufacturer. The calibration results were reviewed to confirm sensor temperature and DP.

- Q4, Q5, Q6 (ECG Recycle Flows), and Q8 (Jet Motive Gas Flow)

  Setup & Start-up Checks: These laminar flowmeters were factory configured to read 0 to 20 scfm methane over the 4 to 20 mA output. A sensor failure or off-scale reading is indicated with an over-range at +21 mA. During installation, all meters were checked to ensure that they were reading properly. After installation, Q8 indicated an over-range output, suggesting a malfunctioning meter. The meter was removed, examined, and found to be grossly contaminated with oil. The meter was disassembled and cleaned, following guidelines established by the manufacturer. The meter was then bench tested, and still gave an error reading. This meter was returned to the manufacturer for repair, and a new replacement meter was obtained from the manufacturer. The remaining meters were also contaminated with oil. All meters were cleaned, calibrated with the repaired flow meter, and their values were determined to be within instrument specifications. To avoid future contamination, a coalescing filter was installed in all lines where the meters were placed, and the site operators were instructed to periodically replace the filters. All meters provided response to flows as small as 3 percent of full scale.

  Sensor Function Checks: Reasonableness checks were made daily while reviewing the data to ensure that valid data were being obtained.

  Calibration: Manufacturer-supplied calibration certificates were obtained and reviewed for all flowmeters. In addition, each flowmeter was field-calibrated with a newly calibrated sensor.

4.1.3 Oxygen Concentration

Oxygen concentration was monitored in the SAS system discharge to confirm that the SAS does not introduce ambient air into the system. A sensor capable of measuring less than 0.1 percent oxygen was used to provide adequate safety. It is unlikely that this measured parameter will affect the quality of the payback period estimates because, if oxygen is detected in the system, the source of the leak will be quickly identified and repaired. Nevertheless, high quality and accurate reading is required to ensure high confidence in this critical safety check.

The oxygen sensor used was a galvanic fuel cell-a type of electrochemical cell with long life, high sensitivity, and fast response. The sampler draws a small sample from the SAS discharge manifold using system pressure. The reading is insensitive to changes in pressure. The response time is 90 percent of full scale in 9 seconds; however, the sensor will show a marked response to an increase in oxygen concentration almost immediately (within 1 to 2 seconds). The transmitter provides a 4 to 20 mA linear output from 0 to 5 percent oxygen.

The Test Plan called for performing manufacturer's startup checks, sensor function checks, and span checks to meet the QA goals. During initial setup, the oxygen sensor and transmitter were set up and checked against clean air for an upper span check. Some span adjustment was required. The sensor element wiring was found to be damaged on February 27 when it was removed for cleaning. It was replaced with a new element on March 1. The new element was also checked and adjusted against clean air. Routine quality control, which consists of daily checks for reasonableness, trends, spikes, or changes in operation that could indicate a system problem, was also performed. Finally, calibration certificates from the manufacturer were obtained and reviewed.

4.1.4 SAS Pressures

SAS system pressures were monitored continuously to provide an ongoing indication of overall system function. Pressure sensors P1 through P3 monitor the individual ECG suction pressures. P4 monitors the SAS suction manifold pressure. A pressure increase in P4 is likely to result in an increased leak rate from one or more ECGs. P4 is used to set an alarm level for gland pressure (initially set at +5 psig). This alarm does not require immediate action, but indicates a need to assess the source of the increased pressure, and possibly adjust the SAS jet flow and recirculation. P5 monitors the recycle manifold pressure and also indicates the SAS discharge pressure. P5 also indicates whether the SAS is producing sufficient operation pressure for the Eductor/Compressor.

All pressures were monitored using Rosemount model 3051 "smart" pressure transmitters which have a very high degree of stability over time (0.25 percent in 5 years). All pressure sensors transmit a 4 to 20 mA linear signal over the range with the accuracy given in Table 4-1. In the data acquisition system, the digital output for each pressure transmitter is arbitrarily scaled over a range of 0 to 100 with 12-bit resolution. To obtain the meter reading in engineering units, it is necessary only to scale the output to the full-scale range of the meter.

The pressure transmitters are designed to operate continuously and unattended. All manufacturer's start-up checks and sensor function checks were conducted. All transmitters were set to –5 to 20 psig over the 4 to 20 mA output range by the installation contractors. No error conditions were encountered. Routine quality control checks, which consist of daily reasonableness, trends, spikes, or other changes in operation that could indicate a system problem, were conducted. All pressure readings responded consistently in a reasonable manner to changes in system operation. It was concluded that the data quality indicator goals were met on all pressure readings.

4.1.5 Confidence Achieved In SAS Verification Factors

Through error propagation, the accuracy and precision obtained for each measurement (discussed above) can be used to determine uncertainty levels in the verification factors. Table 4-2 summarizes the uncertainty levels for key performance test variables.

TABLE 4-2. UNCERTAINTY BOUNDS OF SAS VERIFICATION FACTORS

Verification Factor	Uncertainty Bounds, %
Doghouse Leak Rate (DHL)	±5.5
Total Gas Recovered	±3.0
Total Rod Emission Rate (RE)	±5.5
Leak Capture Efficiency	±9.7

4.2 OVERVIEW OF PHASE II VERIFICATION TEST

The Phase II verification test will consist of a long-term (4- to 6-month) performance evaluation of the SAS technology. The goals of the test will be to:

- Verify long-term leak tightness performance,
- Verify long-term gas recovery and use performance,
- Estimate annual methane emission reduction,
- Document long-term SAS operational requirements, and
- Calculate the SAS payback period.

Several of these goals will be accomplished through a combination of measurement and data extrapolation techniques. The measurement and analytical procedures for verifying these parameters will be similar to the approach outlined in the Test Plan. One modification, described below, will be implemented in the test procedures. This modification integrates changes required in the sampling method to accommodate findings from the Phase I evaluation.

Rod emissions are expected to increase over time as seals wear normally or suffer damage. The Test Plan identified using gland-specific gas recovery measurements to quantify emission anomalies associated with individual rod seals. If one seal experiences an uncharacteristically large and rapid increase in emissions, it can be detected, quantified, and taken into account when assessing overall SAS system performance and payback. The purpose of this data set was to develop a gland-specific emission profile for the duration of the measurement period, and project the increase in emissions to calculate the SAS payback period. The Center will not be able to implement this approach because of the failures of the gland specific flow meters (i.e., Q1, Q2, Q3 on the ECG suction lines). Instead, the observed trends in total gas recovery rates (Q7 minus Q8) will be used to establish an emission profile for Engine 1, and the payback estimates will be based on this data set. This deviation from the Plan is not anticipated to affect the pre-set +/-10 percent data quality objective, but does reduce the Center's ability to characterize gland-specific trends and detect variability in emissions over time. The Center will routinely conduct manual measurements while the SAS is operating and while the SAS is disabled to determine if significant emission variability on a particular rod has occurred. This data set combined with the total gas recovery meters will enable an emission profile to be developed over time.

5.0 A&A COMMENTS

A&A Environmental Seals, Inc. (A&A) would like to thank all the people involved in this verification testing for participating in this Phase I test. We thank the same people in advance for their participation in the Phase II testing.

5.1 SUMMARY

Phase I verification testing has shown that, when the SAS is operating as designed (slightly negative pressure at the suction of the ECG), the system will capture all gaseous emissions from the primary packing system of a reciprocating compressor rod. The verification testing has also conclusively proven that “the SAS does not entrain ambient air into the process” when in operation.

The design, installation, and operation of future systems require accurate station operating parameters prior to selecting the system booster pressure system. In addition it must be assumed that the captured emissions will contain oil and other impurities which the system must be designed to accommodate.

While the basic SAS will be the same for diverse compressor stations, the installation, booster system, instrumentation, and operation of the system must be tailored to local conditions.

5.2 EDUCTOR/COMPRESSOR SYSTEM DESIGN

The Eductor/Compressor system was designed to boost clean, dry methane from a 2 psig suction pressure to a 90 psig discharge pressure. A line pressure drop of 5 psig was assumed to exist between the Eductor/Compressor and the engine fuel header. The Eductor/Compressor was designed to operate on a small range of pressure changes; therefore, an increase in the Eductor/Compressor discharge pressure will cause a corresponding increase in the Eductor/Compressor suction pressure.

The installed Eductor/Compressor’s suction pressure varies with the fuel header pressure. When the fuel header pressure increases, the suction pressure increases. This increase in suction pressure causes the SAS system to operate at an increased pressure resulting in a positive pressure within the ECG. This positive pressure in the ECG reduces the capture efficiency of the system.

It is our conclusion that the pressure drop between the Eductor/Compressor and the fuel line header is greater than 5 psig. Future systems must be designed to operate over a larger pressure drop range.

5.3 TERTIARY SEAL DESIGN

The installed tertiary seal utilizes two split lip seals and a split carbon throttle bushing which are captured by a stainless steel carrier which encircles the rod. The carrier, lip seals, and carbon bushing are split to allow installation on the compressor’s rod without having to remove the rod. The pieces, once placed around the shaft, are then fastened with two precision shoulder bolts. The shaft is 4.5 in. in diameter and is accessed through a small opening in the distance piece. Additional and longer fasteners will be included in future systems to make the installation of the parts easier.

5.4 SAS SYSTEM OPERATION

The SAS operates based on differential pressures, as do all sealing systems. The stuffing box has a higher pressure than the atmosphere, and gases, liquids, and powders will migrate across the face of the primary sealing device towards the atmosphere. The primary sealing surfaces require lubrication which is commonly provided by the process fluid resulting in low level emissions to the atmosphere.

The SAS is designed to capture and remove emissions by creating a pressure drop in the ECG's annulus area. This area of pressure drop, which encompasses the shaft, causes emissions entering the area to be "swept" out of the annulus area to the jet manifold. The SAS is designed to operate at a slight negative pressure at the suction side of the ECG and a slight positive pressure at the recycle side of the ECG. The differential pressure causes the recycle gas to sweep emissions out of the annulus.

The Phase I test results clearly show that, when the system is operating with a slightly negative pressure at the suction side of the ECG, 100 percent emission capture rates can and will be achieved. When the system operates at a positive pressure, the less than 100 percent emission capture rates were achieved. We believe this reduction in efficiency is a result of the split line in the ECG gland, operating the tertiary seals beyond the design pressure for extended periods of time, and damage to the tertiary seals during installation.

The system was never designed to operate continuously for more than a couple of weeks under positive pressures greater than 0.0 to 1.0 psig. The increased and varying operating pressures caused the tertiary seals to energize and wear, resulting in leakage under increased pressure. Additionally, examination of the tertiary seals shows mechanical damage which is assumed to have occurred during installation.

The ECG is split so that it can be installed without having to remove the compressor rod. The system is designed to operate at low positive pressures using close tolerance machining to seal the split line. When the units are installed, we recommend that a surface sealant, such as Hylomar™, be applied to the split line.

5.5 SYSTEM INSTALLATION COSTS

Each compressor station is unique. While the ECG and the Jet Manifold systems will be identical or very similar for all the compressor rods within a station and at different stations, the gas booster system, motive gas supply, engine fuel header, etc. will vary from station to station and company to company. The installation cost for this test was for one engine in the compressor station. The cost to install systems on multiple engines would not be a direct multiplier of the costs in this Phase I report. The costs per compressor, engine, and station will be less with more units and proper system planning.

The use of tubing whenever possible, a properly sized condensate trap for the station, one oxygen analyzer for multiple engines, one motive gas supply, and one regulator are just some of the items that will reduce the scaleup multiplier.

6.0 REFERENCES

Hummel, K.E., L.M. Campbell, and M.R. Harrison. 1996. *Methane Emissions from the Natural Gas Industry* – Volume 8 Equipment Leaks, Final Report, EPA-600/R-96-080h (NTIS PB97-142996). U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Research Triangle Park, NC, June 1996.

Mathis, A., J. Melancon, and F. Trackwell. 1998. *A New Method For Secondary Containment of Emissions From Primary Seals,* Proceedings of 15th International Pump Users Symposium, Turbomachinery Laboratory, Department of Mechanical Engineering, Texas A&M University, College Station, TX.

SRI 1998. *Test/QA Plan for A&A Environmental Seals' Seal Assist System (SAS),* SRI/USEPA-GHG-QAP-02, Greenhouse Gas Technology Verification Center, Southern Research Institute, Research Triangle Park, NC, December 18, 1998.

Tarrer, R., and W. Stadig. 1996. *Secondary Seal Captures and Recycles Emissions*, Chemical Processing, October 1996.

APPENDIX A

Flow Tube Measurement Procedures

Sampling Procedures

Configuration 1. SAS Fugitive Leak Rate Measurement
SAS Status: SAS Operating
Measurement location: Doghouse Vent

1. Follow manufacturer's procedures for the hydrocarbon analyzer (auto-zero away from the engine room).
2. Follow manufacturer's procedures for the flow tube (zero check and response to puff test).
3. Record the following information on the log sheet:

Engine ID	Date
Flow Tube ID	Ambient Temp
Flow Tube Calibration Date	Barometric Pressure

Time
Rod Number
Engine Operating Pressure

4. Disconnect doghouse vent union. Attach hydrocarbon analyzer.
5. Allow a minimum of 15 minutes to purge the doghouse area. Measure and record hydrocarbon concentration of the gas sampled.
6. If methane levels are not within explosive limits, proceed to next steps; or else wait until non-explosive levels are detected.

7. Remove hydrocarbon analyzer. Insert temperature probe into the doghouse vent.
8. Measure and record gas temperature.
9. Remove the temperature probe. Attach Flow Tube to open doghouse vent.

10. Switch anemometer display to show 16 sec average values.
11. Record 16 sec velocity readings until a minimum of 10 readings are recorded. Stop taking measurements until at least three continuous readings are within 5 fpm of each other.
12. Remove Flow Tube.
13. Use Flow Tube calibration data collected prior to the test to convert velocity readings to natural gas flow rates (scfm CH_4).

14. Insert the hydrocarbon analyzer.
15. Measure and record the final hydrocarbon concentrations.
16. Repeat above procedures for remaining doghouse vents.

Configuration 2. Rod Emission Measurement with SAS Disabled
SAS Status: ECG Isolated and Vented
Measurement location: Doghouse Vent and ECG Suction Bulkhead

1. Record time.
2. Isolate ECG by closing discharge valve, recycle valve, and purge valve.
3. Open ECG suction line (1/2 in. SS Flex Tube).
4. Disconnect doghouse vent pipe.

5. Allow ECG to vent through suction line while measuring leak rate at doghouse vent.
6. Follow steps 4 through 16, above.
7. Remove Flow Tube from doghouse vent, leave doghouse vent open, and attach the Flow Tube to ECG suction line.
8. Record time.
9. Follow steps 4 through 16, above.

10. Calculate total gas velocity at each gland (sum of readings at the doghouse vent and the ECG suction line). This provides an estimate of the rod emission rate without the SAS.
11. Use Flow Tube calibration data to convert velocity readings into methane flow rates (scfm CH_4).
12. Repeat Configuration 2 procedures for remaining doghouse vents.

SAS MANUAL SAMPLING LOG
SAS OPERATING
Date: _______
Engine No: ______

Pre-Test Checks

Date of methane sensor calibration: ____________ Barometric pressure: ___________

Date of Flow Tube calibration: ____________ Ambient temp.: ___________

Autozero methane analyzer: ____________ Synchronize clocks: ___________

Flow Tube zero response test: ____________ Operator(s): ___________

Configuration 1 – Doghouse Leak Rate Measurements Data

	Sampling Start Time	Sampling Finish Time	Gas Velocity (fpm)	Gas Temp (F)	CH_4 Concen (%)
Rod 1					
Rod 2					
Rod 3					

SAS MANUAL SAMPLING LOG
ECG ISOLATED
Date: _______
Engine No: ______

<u>Pre-Test Checks</u>

Date of methane sensor calibration: ____________ Barometric pressure: ___________

Date of Flow Tube calibration: ____________ Ambient temp.: ___________

Autozero methane analyzer: ____________ Synchronize clocks: ___________

Flow Tube zero response test: ____________ Operator(s): ___________

<u>Configuration 2 – Doghouse Leak Rate Data (ECG Suction Line Open)</u>

	Sampling Start Time	Sampling Finish Time	Gas Velocity (fpm)	Gas Temp (F)	CH_4 Concen (%)
Rod 1	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
Rod 2	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
Rod 3	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________
	________	________	________	________	________

<u>Configuration 2 – ECG Suction Line Data (Doghouse Vent Open)</u>

	Sampling Start Time	Sampling Finish Time	Gas Velocity (fpm)	Gas Temp (F)	CH_4 Concen (%)
Rod 1					
Rod 2					
Rod 3					

APPENDIX B

Pre-Test Doghouse Leak Rate Measurements

INITIAL QUANTIFICATION OF EMISSIONS FROM ENRON COMPRESSOR SEALS

Prepared for:

Southern Research Institute
P.O. Box 13825
Research Triangle Park, NC 27709-3825

Prepared by:

Michael Webb, P.E.
STAR Environmental
98 S. Sage Road
Pine Valley, UT 84781

November 4, 1998

INITIAL QUANTIFICATION OF EMISSIONS FROM TRANSWESTERN COMPRESSOR SEALS

Summary
On October 22nd and 23rd, 1998, STAR Environmental assisted Southern Research Institute in quantifying fugitive emissions from compressor seals at two gas compression stations in Arizona operated by Transwestern Pipeline Company – Enron Gas Pipeline Group. Individual seals from Station 4 were found to be leaking at rates ranging from 0.0 acfm to 7.6 acfm. Compressor seals at Station 2 were tested in groups of 6 and found to be leaking at rates ranging from 18 to 54 acfm per group.

Many of the leak rates exceeded the range of both the Indaco Hi Flow system and the STAR High Volume Collection System as currently configured and had to be measured using components of the two systems and equipment provided by Transwestern.

Description of Sites Monitored
Station 4 is located on the Navajo reservation in eastern Arizona at an elevation of approximately 7,000 feet. The station contains three compressors each of which has three cylinders. Station 2 is located west of Flagstaff, Arizona at an elevation of approximately 7,000 feet. The station contains three compressors each of which has six cylinders.

Description of Sampling Locations
Cylinder rods at both locations have access ports that allow visible inspection of the rods. When the port cover is removed, the section of rod between the high-pressure seals and the crankshaft can be seen. The access port is referred to as the "dog house". At these sites, the doghouses have vents and drains constructed of 3/4 inch pipe.

At Station 4, vents on all doghouses were opened simultaneously but sampled one at a time. At Station 2, each manifold that receives vent emissions from six doghouses was sampled by drawing air through the manifold in the opposite direction of normal vent flow.

Description of Sampling Equipment
Four methods were used by STAR to quantify emissions. In addition, Transwestern quantified emissions at Station 4 using the Indaco Hi Flow sampler. The four methods used by STAR were: 1) High Volume Collection System with Foxboro Model 108 OVA; 2) High Volume Collection System with Bascom-Turner Monitoring instrument; 3) Measurement of voluntary flow of emissions using anemometer; and, 4) Air-driven venturi and Bascom-Turner Monitoring instrument. Methods 1 through 3 were used at Station 4; Method 4 was used at Station 2.

Results

Station 4. Table 1 contains the results from Station 4. Unit 1 Rod 1 was measured at two different flow rates (range of 1.4:1) and gave the same emission rate (0.4 acfm). Rods 2 and 3 on Unit 1 were measured at one flow rate each and gave emission rates of 2.1 and 7.6 acfm, respectively.

Unit 2 Rod 1 was measured at five flow rates (range of 1.9:1) using two different methods and gave a fairly constant emission rate (about 3.2 acfm). Unit 2 Rod 2 was measured at four flow rates (range of 10:1) and gave approximately a constant emission rate of 0.1 acfm. Unit 2 Rod 3 was measured at five flow rates (range of 8:1) using two different methods and gave an emission rate of 1.0 acfm ±0.4 acfm.

Unit 3 Rod 1 was measured at four flow rates (range of 26:1) and gave a variable emission rate between 0.2 and 1.1 acfm. The emission rate appears to be a function of sampling rate. Unit 3 Rod 2 was measured at a single flow rate and gave and emission rate of nearly zero. Unit 3 Rod 3 was measured at two flow rates (range 2:1) using two different methods and gave an emission rate of 3.0 acfm ±0.4 acfm.

Station 2. Table 2 contains the results from Station 2. All vent manifolds were sampled at four rates (range of 3:1 or higher). Emission rates varied with sampling rate. The figure included on Table 2 shows the relationship of sampling rate to apparent emission rate for the three manifolds. There is no obvious explanation for this effect.

Conclusions

1. The maximum leak rate of a single compressor seal at Transwestern Stations 2 and 4 is 7.6 acfm or more.
2. The flow through the High Volume Collection System needs to be increased to 100 acfm at an inlet vacuum of -1 psig.
3. The reason for the apparent increase of emissions with increase sampling rate needs to be found.

Site #4 **Oct 22 98** Table 1

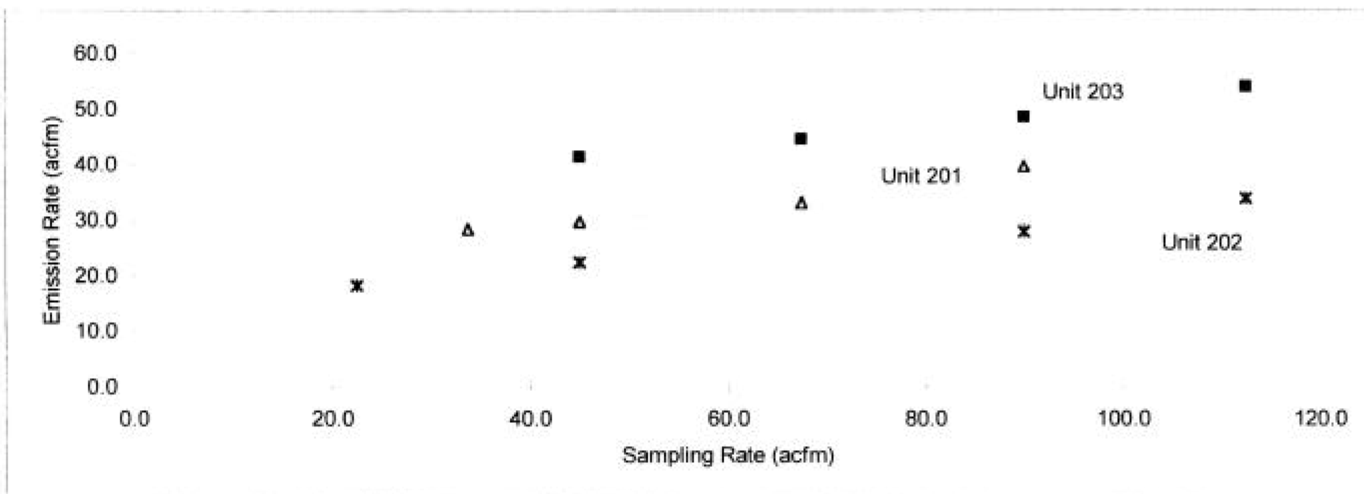
Pressure = 789.4 millibars **Compressor house temperature = 94F**

Unit	Rod	Sample Flow Rate (acfm)	THC %	THC Leak acfm	NOTES
1	1	5.7	7.5	0.4	Flow rate measured with HVCS; THC % measured with Foxboro OVA
1	1	4.2	10	0.4	Flow rate measured with HVCS; THC % measured with Foxboro OVA
1	2	2.1	100	2.1	**Flow rate measured with Dwyer anemometer, stream assumed to be pure THC.**
1	3	7.6	100	7.6	**Flow rate measured with Dwyer anemometer, stream assumed to be pure THC.**
2	1	5.7	61	3.5	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	1	4.1	79	3.2	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	1	3.3	93	3.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	1	3.1	100	3.1	**Flow rate measured with Dwyer anemometer, stream assumed to be pure THC.**
2	1	3.0	102	3.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	2	2.1	8	0.2	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	2	0.8	17	0.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	2	0.3	38	0.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	2	0.2	58	0.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	3	5.0	27	1.4	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	3	3.3	36	1.2	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	3	1.7	65	1.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	3	0.8	99	0.8	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
2	3	0.6	100	0.6	**Flow rate measured with Dwyer anemometer, stream assumed to be pure THC.**
3	1	5.3	21	1.1	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	1	0.6	56	0.3	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	1	0.3	90	0.3	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	1	0.3	91	0.3	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	1	0.3	92	0.3	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	1	0.3	94	0.3	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	1	0.2	85	0.2	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	2	0.3	0.2	0.0	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	3	6.0	55	3.3	Flow rate measured with HVCS; THC% measured with Bascom-Turner instrument.
3	3	2.6	100	2.6	**Flow rate measured with Dwyer anemometer, stream assumed to be pure THC.**

Site #2 **Oct 23 98** Table 2

Pressure = 783.3 millibars **Compressor house temperature = 89F**

Unit	Rod	Sample Flov Rate (acfm)	THC %	THC Leak acfm	NOTES
201	1-6	90.0	44	39.6	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
201	1-6	67.5	49	33.1	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
201	1-6	45.0	66	29.7	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
201	1-6	33.8	84	28.4	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
202	1-6	112.5	30	33.8	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
202	1-6	90.0	31	27.9	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
202	1-6	45.0	50	22.5	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
202	1-6	22.5	81	18.2	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
203	1-6	112.5	48	54.0	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
203	1-6	90.0	54	48.6	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
203	1-6	67.5	66	44.6	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.
203	1-6	45.0	92	41.4	Flow rate measured with Dwyer anemometer, THC% measured with Bascom-Turner instrument.



APPENDIX C

Phase I: Measurements Data Output
(Daily Averages)

Phase I: Measurements Data Output (Daily Averages)

Date	No. of Events	P1 (psig)	P2 (psig)	P3 (psig)	P4 (psig)	P5 (psig)	Q4 (scfm)	Q5 (scfm)	Q6 (scfm)	Q7 (scfm)	Q8(scfm)	Engine RPM	Engin
3/10/99	281	-0.03	-0.03	0.07	-0.05	0.74	1.43	0.73	0.16	23.45	10.17	35.96	48
3/11/99	260	0.39	0.41	0.39	0.39	1.29	2.71	1.85	0.20	17.76	7.91	284.47	388
3/12/99	97	1.75	1.76	1.74	1.74	3.13	3.50	2.32	0.83	16.42	7.91	299.38	410
3/13/99	96	2.75	2.77	2.74	2.74	4.32	4.29	2.79	1.17	15.37	8.32	291.15	408
3/14/99	99	2.91	2.92	2.90	2.90	4.40	4.18	2.64	0.96	15.70	8.36	296.44	420
3/15/99	96	3.06	3.07	3.05	3.05	4.61	4.03	2.63	0.80	15.47	8.18	299.54	425
3/16/99	94	3.16	3.18	3.16	3.15	4.67	3.79	2.64	0.90	15.71	8.41	295.81	418
3/17/99	99	3.03	3.06	3.03	3.03	4.30	3.45	2.17	0.55	16.79	8.41	296.54	418
3/18/99	97	3.36	3.36	3.35	3.34	4.82	3.49	2.52	0.59	15.63	8.08	297.41	415
3/19/99	101	3.18	3.19	3.18	3.17	4.66	3.48	2.48	0.97	15.37	8.67	298.09	409
3/20/99	96	3.39	3.40	3.39	3.38	4.99	3.82	2.72	1.19	14.73	8.92	298.68	414
3/21/99	109	3.71	3.72	3.70	3.70	5.31	3.88	2.78	1.21	14.66	9.16	299.19	412
3/22/99	101	4.06	4.07	4.06	4.05	5.74	3.95	2.79	1.21	14.10	8.71	298.93	411
3/23/99	106	4.03	4.03	4.02	4.01	5.63	3.80	2.69	1.06	14.64	8.70	297.98	413
3/24/99	97	4.33	4.33	4.32	4.31	5.92	3.84	2.75	1.20	14.45	8.71	297.78	409
3/25/99	218	0.76	0.70	0.70	0.68	2.03	2.09	1.34	0.81	17.86	9.99	298.68	409
3/26/99	273	-0.15	-0.16	-0.16	-0.17	0.91	0.79	1.04	-0.02	19.40	9.96	299.35	414
3/27/99	97	0.20	0.20	0.20	0.19	1.27	2.10	0.56	0.09	17.92	9.40	299.14	415
3/28/99	96	0.80	0.81	0.81	0.80	1.87	2.32	0.75	0.15	16.93	9.85	299.35	407
3/29/99	96	1.18	1.19	1.19	1.18	2.30	2.45	0.76	0.08	17.02	10.28	299.20	408
3/30/99	96	0.76	0.77	0.76	0.76	2.07	2.48	0.64	-0.02	15.90	10.00	299.30	414
3/31/99	52	1.48	1.48	1.49	1.48	2.73	2.34	1.98	6.07	16.79	9.12	247.34	347

APPENDIX D

SAS Start-up and Operating Manual

Start-up and Operating Specifications

For

A&A Environmental Seals, Inc.
STR Seal Assist System

At

Transwestern Pipeline Company
Compressor Station #4
Unit #1

Table of Contents

1.0 Description of System

Three (3) A&A Environmental Seals, Inc. ("A&A") CLR450987000S000 seal assemblies are installed on the three (3) compressor rods of Unit #1 at Station #4 operated by Transwestern Pipeline Company - Enron Gas Pipeline Group located near Klagatoh, Arizona.

The System requires 550 psig methane to operate the Croll-Reynolds C-R #22 gas OP EVACTOR (EVACTOR Motive Gas "EMG") and 90 psig methane to operate each A&A supplied Jet Manifold (Jet Manifold Motive Gas "JMMG"). Each SAS requires a seal assembly (emission control gland "ECG"), a Jet Manifold ("JM"), a JM discharge line (Jet Manifold Discharge "JMD"), a suction line (Compressor Gland Emissions "CGE"), a recirculation line from the JMD to the seal assembly, and a purge line from the JMD to the seal assembly (ECG Purge Line "EGP"). The EVACTOR will boost the JMD pressure to 80 psig (EVACTOR System Discharge "EVD") which then discharges into the compressor station's engine fuel line.

Operation and monitoring of the System requires pressure sensors ("PS"), flow sensors ("FS"), safety systems (oxygen analyzer "OA", temperature sensors "TS", & pressure relief valves "PRV"), sampling ports ("SP"), pressure regulators ("PR"), and control valves ("CV"). Isolation valves for the system are shown on PID03030402-003 where required. Digital signals from each monitoring device require interconnecting wiring between the device and Unit #1's Engine and Compressor Monitoring Panel.

2.0 Initial System Start-up

A. The following valves should be open and remain open until the proper sequence in the System start-up.
   1. One (1) 1-1/2 in. System Discharge (SD) valve (SDV-01).
   2. Four (4) ½-in. Compressor Gland Recirculation (CGR) valves (CGRV-04, 05,06, 07).
   3. One (1) 1-in. Compressor Gland Emissions (CGE) valves (CGEV-04).
   4. Three (3) ½-in. Jet Manifold Suction (JMS) valves (JMSV-01, 02, 03).
   5. One (1) 1-in. Jet Manifold Discharge valve (JMDV-01).

B. Close the three (3) Compressor Gland Emissions valves (CGE-01,02,03).

C. Close the two (2) Jet Manifold Discharge valves (JMDV-02, 03).

D. Close the one (1) pneumatic valve to PNV-01 which will isolate the SAS system and allow gas to continue to discharge to the System vent when the 1-1/2 in. three way valve CV-01 is pneumatically actuated.

E. Close the ½-in. Jet Manifold Motive Gas valves (JMMGV-01, 02, 03) so that each Jet Manifold is isolated.

F. Close the 1-in. EVACTOR Motive Gas valve (EMGV-01) feeding the C-R #22 EVACTOR.

G. Close the three (3) ½-in. Emission Gland Purge valves (EGPV-03, 04, 05).

H. Close all regulators:
   1. PR-01
   2. PR-02
   3. PR-03
   4. PR-04
   5. PR-05

I. Close all three (3) Jet Manifold control wheels (JMCW-01, 02, 03).

J. Open the 2 in. Booster System Discharge valve (BSDV-01) to the compressor station fuel line. Pressure Gage PG-01 should read fuel line pressure.

K. Obtain pressure readings from Pressure Sensors (PS-01, PS-02, PS-03, PS-04, PS-05, PS-06) and record on Data Sheet.

L. Manually open the System Main Pressure Line valve (SMPL-01).

M. Energize CV-01 and CV-02 pneumatic lines from Unit #1's Engine and Compressor Monitoring Panel.

N. CV-01 will open and load PR-01 & PR-02.

O. Proceed to start up the SAS (2.1) and Croll-Reynolds EVACTOR System (2.2).

2.1 A&A SAS Start-up Procedures

A. Gradually open Pressure Regulator PR-01 until the Jet Manifold Motive Gas pressure reads 90 psig.

B. Energize the purge lines by:
   1. Opening the ½-in. EGPV-03 valve and opening Pressure Regulator PR—03 until the purge pressure reads 1 psig.
   2. Opening the ½-in. EGPV-04 valve and opening Pressure Regulator PR—04 until the purge pressure reads 1 psig.
   3. Opening the ½-in. EGPV-05 valve and opening Pressure Regulator PR—05 until the purge pressure reads 1 psig.

C. Start up and set each Jet Manifold in sequence (JM-01, 02, 03) by:
   1. Fully opening the 1-in. Jet Manifold discharge valve (JMDV).
   2. Fully opening the ½-in. JMMGV valve.
   3. Gradually open the control wheel (JMCW) for the JM ¼ turn.
   4. Read and record the Pressure Sensor reading at PS-04.
   5. Gradually close the System Discharge valve SDV-01 until PS-06 is equal to 5 psig.
   6. Read Pressure Sensor PS-04.
   7. Balance the control wheel and the System Discharge valve until PS-04 is equal to 10 in. WC vacuum and PS-06 is equal to 5 psig.
   8. Isolate the Jet Manifold by first closing the ½-in. JMMGV valve.
   9. Close the Jet Manifold JMDV.
   10. Repeat for JM-02 & 03.

D. Place the Jet Manifold System in operation
   1. First open all three (3) 1-in. Jet manifold Discharge valves (JMDV-01, 02, 03).
   2. Open in sequence the three ½-in. Jet Manifold Motive Gas valves (JMMGV-01, 02, 03).
   3. Adjust the System Discharge valve until PS-06 is equal to 5 psig.
   4. In sequence open the three (3) closed Compressor Gland Emission valves (CGE-01, 02, 03) and close the three (3) Compressor Gland Recirculation valves (CGRV-01,02,03) for each compressor.
   5. Adjust the System Discharge valve until PS-06 is equal to 5 psig.
   6. Take and record the pressure reading for each Pressure Sensor (PS-01, 02, 03, 04, 05, 06). Pressure Sensors PS-01, PS-02, PS-03 & PS-04 should be negative (pulling vacuum) and Pressure Sensors PS-05 & PS-06 should read 5 psig. If Pressure Sensors PS-01, 02, 03 & 04 are not negative the compressor packing is leaking excessively and the Jet Manifold's capacity needs to be increased.
   7. Take and record the flow reading for each Flow Sensor (FS-01, 02, 03, 04, 05, 06, 07). At this time Flow Sensors FS-04, FS-05 & FS-06 should read zero. Flow Sensors FS-01, FS-02 & FS-03 should each read less than 5 SCFM and Flow Sensor FS-07 should read the sum of FS-01, FS-02 & FS-03 plus 1.5 to 3 SCFM.
   8. Gradually open one (1) Compressor Gland Recirculation valve (CGRV either 04 or 05 or 06) with the lowest flow reading (FS-01, FS-02 or FS-03) until the corresponding Recirculation Line Flow Sensor (FS-04, FS-05 or FS-06) detects flow.

9. Repeat Step 8 with the Compressor Gland Recirculation valve (CGRV-04, 05 or 06) with the next lowest flow reading (FS-01, FS-02 or FS-03) until the corresponding Recirculation Line Flow Sensor (FS-04, FS-05 or FS-06) detects flow.
10. Repeat Step 8 with the remaining Compressor Gland Recirculation valve (CGRV-04, 05 or 06).
11. Balance the system by continuing to gradually open in sequence the Compressor Gland Recirculation valves (CGRV-04, 05 & 06) until Pressure Sensors PS-01, PS-02, PS-03 and PS-04 are in the range of 5 to 10 in. WC, and Pressure Sensors PS-05 and PS-06 are equal to 5 psig.
12. Proceed to start up the Croll-Reynolds EVACTOR system.

2.2 Croll-Reynolds EVACTOR Start-up Procedure

The Croll-Reynolds model C-R #22 is a single stage gas operated EVACTOR exhauster gas jet ejector, with 2 in. 600# RFSO suction and discharge connections and a 0.75-in. RFSO motive gas inlet connection weighs approximately 50 lbs. The C-R #22 is designed to boost 81 lbs/hr (32.5 SCFM) of methane from 5 psig @ 608 F to 80 psig. The C-R #22 will require 768 lbs/hr (309 SCFM) of methane @ 550 psig and 608 F.

The EVACTOR is installed between the System Discharge Control Valve CV-01 (after the Oxygen Analyzer) and the EVACTOR Discharge valve EVDV-01. The EVACTOR system is placed in operation by:

A. Ensuring that the EVACTOR Discharge valve EVDV-01 is open and PG-01 has a reading of 80 psig or less.
B. Opening and adjusting the EVACTOR Motive Gas (EMG) Pressure Regulator PR-02 to 550 psig.
C. Fully opening the ¾-in. EVACTOR Motive Gas valve (EMG-01).
D. Reading Pressure Gage PG-01. The gage should read 5 psig or less.
E. Opening the pneumatic line to CV-01 by opening PNV-01.
F. Pressure Sensor PS-06 should read 5 psig.
G. The EVACTOR system is now in operation.

3.0 Trouble Shooting Guide

3.1 A&A SAS System

PROBLEM	POSSIBLE CAUSE	ACTION
No discharge pressure	Jet's control wheel is closed	Open control wheel until desired discharge pressure is obtained
	No motive gas	Open motive supply valve
Discharge pressure too high	Upset in control system or flare	Let upset settle out
	Jet is set too high	Close back on control wheel
	Discharge valve is closed	Open valve
	Discharge line plugage	Blow out discharge line
	Excessive leakage past primary sealing device	Repair primary seal
Loss of vacuum	Loss of motive gas	Check motive supply
	Increase in discharge pressure	Check high discharge pressure
	Jet is set too low	Jet control wheel needs to be opened some
	Primary seal leaking	Close back on recycle valve
	Primary seal blown	Repair seal
	Control wheel on jet opened too wide	Close control wheel until optimum vacuum is obtained
	Circulation lines plugged	Blow lines clear
External product leakage	Possible elastomer damage	Check elastomers
	Improper alignment of SAS	Check SAS alignment
	Loss of FSS or Lip seal purge	Check regulator and motive gas supply

3.2 Croll-Reynolds C-R #22 System

Problem	Possible Cause	Action
Low Motive Pressure	1. The motive gas line is restricted.	a. Ensure PR-02 is set to 550 psig. b. Ensure EMGV-01 is fully open. c. Ensure CV-02 is fully open. d. Ensure the System Main Pressure Line valve is open.
	2. All valves are open and problem persists.	a. Contact the Factory
High Back Pressure	Restriction in the discharge line.	Ensure EVDV-01 is fully open.
High Suction Pressure	1. System Discharge flow has exceeded the capacity of the EVACTOR.	a. Check Flow Sensor FS-07. If the flow exceeds 32.5 SCFM, one or more primary compressor packing sets have failed. b. Check Flow Sensors FS-01, FS-02, FS-03 and all Pressure Sensors (PS-01 to 06). c. If the combined flow readings from FS-01, FS-02, & FS-03 exceed 32.5 SCFM then open EGRV-01, 02 & 03 and close JMMGV-01, 02 & 03. d. Schedule the replacement/repair of the compressor packing.
	2. The Motive Nozzle is clogged.	a. Shut down the System by turning off CV-02 and venting the System through CV-01. b. A clogged motive nozzle is due to dirt or pipe scale. Remove and inspect the nozzle. Remove deposits with an air stream or fine emery cloth. c. Install the clean nozzle and restart the system.

APPENDIX E

Description of Installation Activities
for the As-Built and Measurement System

LABOR
Mechanical and Piping

Date	Occupation	Hours	Description of Activities
1/22/99	Material man	2.00	Take off materials from drawings and pick up materials in Farmington for Station 4.
	R. Labor	3.00	
1/25/99	Superintendent	9.00	Drive to Transwestern Station 4, unload and stage materials, walk-through job in compressor building.
	Pipe Fitter	9.00	
	R. Labor	9.00	
	Per diem	3.00	
1/26/99	Superintendent	10.00	Fabricate pipe supports and 1-in. fuel gas piping. Install brackets for 1-in. header piping.
	Pipe Fitter	10.00	
	R. Labor	10.00	
	Welder	10.00	
	Welder's Helper	10.00	
	Per diem	5.00	
1/27/99	Superintendent	10.00	Deliver materials from Farmington. Build spools for evactor unit.
	Pipe Fitter	10.00	
	R. Labor	10.00	
	Welder	10.00	
	Welder's Helper	10.00	
	Per diem	5.00	
1/28/99	Superintendent	10.00	Install header piping for 1-1/2 and 1-in. discharge lines, build 1-1/2 in. manifold and piping to evactor unit, build brackets for vent piping, pick up materials in Farmington for delivery to Station 4.
	Pipe Fitter	10.00	
	R. Labor	10.00	
	Welder	10.00	
	Welder's Helper	10.00	
	R. Labor	2.00	
	Per diem	5.00	
1/29/99	Superintendent	10.00	Install high-pressure gas line to evactor unit and test high-pressure piping. Install vent line to evactor unit. Build brackets for piping. Deliver materials to job site.
	Pipe Fitter	10.00	
	R. Labor	10.00	
	Welder	12.50	
	Welder's Helper	12.50	
	Test Engineer	13.50	
	R. Labor	8.00	
	Per diem	7.00	
1/30/99	Superintendent	12.00	Install 1-in. vent piping, build manifold for recirculation line. Install ½-in. tubing to compressor doghouses. Complete 1-in. piping.
	Pipe Fitter	12.00	
	R. Labor	12.00	
	Per diem	3.00	

LABOR
Electrical and Instrumentation

Date	Occupation	Hours	Description of Activities
1/22/99	E.S.	7.00	
1/25/99	Electrician	9.00	Drive to Transwestern Station 4, unload and stage materials, walk-through job in compressor building.
	Electrician	9.00	
	Electrician	9.00	
	Instrument Tech	9.00	
	Per diem	4.00	
1/26/99	Electrician	10.00	Install electrical header pipe 1-1/2 in.
	Electrician	10.00	
	Electrician	10.00	
	Instrument Tech	10.00	
	Per diem	4.00	
1/27/99	Electrician	10.00	Install 1-1/2 in. conduit to control boxes. Install drops to instruments. Deliver materials from Farmington.
	Electrician	10.00	
	Electrician	10.00	
	Instrument Tech	10.00	
	Superintendent	8.00	
	Per diem	5.00	
1/28/99	Electrician	10.00	Install electrical conduit to pressure sensors. Pick up materials in Farmington for delivery to Station 4.
	Electrician	10.00	
	Electrician	10.00	
	Instrument Tech	10.00	
	Per diem	4.00	
1/29/99	Electrician	10.00	Install ½-in. tubing to instruments and pressure sensors. Pull wire to electrical instruments and pressure sensors. Deliver materials to job site.
	Electrician	10.00	
	Electrician	10.00	
	Instrument Tech	10.00	
	Per diem	4.00	
1/30/99	Electrician	12.00	Install electrical conduit and sensors for system. Pull wire to sensors. All overtime rates.
	Electrician	12.00	
	Electrician	12.00	
	Instrument Tech	12.00	
	Per diem	4.00	
2/1/99	Instrument Tech	10.00	Pick up materials for job, travel, install conduit, make brackets for pipe, and run ½-in. tubing.
	Electrician	10.00	
	Instrument Tech	10.00	
	Electrician	10.00	
	Per diem	4.00	

2/2/99	Instrument Tech	10.00	Complete conduit, pull wire and terminate field devices and complete process and control tubing.
	Electrician	10.00	
	Instrument Tech	10.00	
	Electrician	10.00	
	Per diem	4.00	
2/3/99	Instrument Tech	10.00	Rearrange pressure transmitters. Check wiring terminations on all instruments.
	EJ	12.00	
	AP-3-4	10.00	
	AP-3-4	12.00	
	ES	5.00	
	Per diem	4.00	
2/4/99	Instrument Tech	12.00	
	AP-3-4	12.00	
	Per diem	2.00	
2/5/99	Instrument Tech	4.00	
2/8/99	Instrument Tech	5.00	
2/9/99	Instrument Tech	10.00	
2/10/99	Instrument Tech	12.00	Travel time, set up computer for calibration.
	AP-3-4	12.00	
	Per diem	2.00	
2/11/99	Instrument Tech	12.00	Re-tube purge system. Install tubing upstream of flow transmitters and calibrate Rosemount Transmitter #1. Try to put system in automatic Operation.
	AP-3-4	12.00	
	Per diem	2.00	
2/12/99	Instrument Tech	12.00	Re-tube purge system to original hook-up and complete calibration of Rosemount Transmitters Q2-Q3-Q7, and put SAS system back into automatic operation.
	AP-3-4	12.00	
	Per diem	2.00	

SAS SYSTEM MATERIALS COST
(AS BUILT)

Mechanical & Piping

ITEM	AMOUNT, $
Non-Expendables [a]	2,918
Expendables	
(1) Croll-Reynolds eductor	3,000
(3) Emission containment glands & jet assemblies	13,500
(1) Oil coalescing filter 1”	54
Miscellaneous hardware [b]	1,654
(12) SS flex hose ½” (supplied by A&A in 2 & 3 ft lengths)	1,000
Carbon steel piping 1.5” 21 ft.	54
Tubing 316 SS 80ft; 3/8X035	92
Tubing 316 SS 160ft; 1/2X035	250
(4) Ball valve ¼”	94
(28) Ball valve ½”	624
(2) Ball valve ¾”	67
(2) Fisher 1” regulator; 70-150lb range	381
(1) Fisher 1” regulator; 275-500lb range	372
SUBTOTAL MATERIALS	$24,060

ELECTRICAL & INSTRUMENTATION COSTS

ITEM	AMOUNT, $
Non-expendables [a]	4,108
Expendables	
(1) O_2 Probe	150
(1) Rosemount 244 temperature transmitter	381
(4) Rosemount 3095 multi-transmitters	14,141
(14) Analog input modules	1,316
(1) Digital input module	10
(5) Rosemount 3051 pressure trans.	5,785
(1) Advanced Controls GPR-25 oxygen transmitter	1,400
(4) UFM Model: OSF mass flow meters	3,004
Miscellaneous hardware [b]	5,260
SUBTOTAL MATERIALS	$35,555

[a] Non-expendables include such items as vehicle usage, equipment rental, and use of welding rig.
[b] Detailed breakdown of miscellaneous hardware may be found on pages E-7 through E-10. These items include fittings, couplings, conduit, wire, strut, nuts, and bolts.

SAS SYSTEM LABOR COST
(AS BUILT)

Mechanical & Piping

Job Type	Rate*	Hours	Total Cost
Material handler	$18.00	2	$ 36
Laborer	$17.30	74	$1,280
Pipe fitter	$19.77	61	$1,206
Welder	$20.75	42.5	$ 882
Helper	$15.00	42.5	$ 637
Test Engineer	$23.00	13.5	$ 310
Supervisor	$38.44	61	$2,345
SUBTOTAL LABOR			**$6,696**

(ELECTRICAL & INSTRUMENTATION)

Job Type	Rate*	Hours	Total Cost
Electrician	$24.81	247	$ 6,129
Instrument Tech	$28.45	178	$ 5,064
Helper	$19.50	70	$ 1,365
Supervisor	$29.50	8	$ 236
SUBTOTAL LABOR			**$12,794**

*** Rate averaged to include overtime**

Supplies

Mechanical & Piping:

Quantity	Description	Total Cost, $
4	Coupling straight1.5”	13.28
10	Nipple swage 1X1/4	42.10
2	Tee-SE 1.5X1/2	39.78
4	Valve-ball ¼	94.08
2	Nipple swage 1X3/4	6.72
6	Valve-ball 1/2	144.06
6	Tee-threaded ½”	14.58
6	Nipple swage 1X1/2”	20.16
6	Ell-45 degree ½”	11.04
6	Coupling straight ½”	3.84
10	Nipple-pipe 1X3	8.40
6	Ell-45 degree 1”	25.68
12	Nipple-pipe 1/2X1.5	5.04
20	Ell-90 degree 1”	64.00
12	Nipple pipe 1/2X4	8.52
20	Coupling straight 1”	26.40
1	Nipple swage 2X1.5	9.47
6	Thredolet	38.16
2	Flange-weldneck 2”	24.50
3	Gasket-flange 2”	6.93
2	Nipple swage 2X1	18.94
16	Stud alloy 5/8X4.5	10.56
1	Flange weldneck	18.75
4	Stud alloy 5/8X 3.5	2.36
2	Gasket flange ¾”	3.98
1	Nipple swage 1X3/4	4.37
21ft	1.5” pressure tubing	53.59
10	Bushing 3/4X1/2	6.50
10	Nipple pipe 1/2X12	20.80
12	Nipple pipe 1/4X2	8.52
6	Ell 90 degree ¼”	10.86
20	Ell 90 degree 1.5”	154.20
12	Nipple pipe 1/2X4	8.52
7	Tee threaded 1.5”	70.07
7	Nipple swage 1.5X1	40.81
3	Gauge 0-100 psi	109.62
12	Tee-SE 1X1X1/2	105.48
4	Union hex 1.5”	35.24
20 ft	Angle iron 2X2X1/4	15.89
10	Union hex 1”	45.80
10	Tee threaded	45.30
12	Nipple pipe 1Xclose	7.68
12	Nipple pipe 1/2X2	5.64
2	Tee threaded ¾”	6.92
2	Valve-ball	66.64

1	Plug hex head 1.5”	1.86
6	Plug hex head ½”	2.10
6	Plug hex head 1”	4.86
4	Coupling straight ¾”	3.48
4	U-bolt plated 2X5/16	2.92
10	Nipple pipe 1/2Xclose	4.00
2	Union hex ¾	7.00
10	Valve-ball ½	240.10
4	U-bolt plated 1.5X1/4	1.88
2 bottles	Compressed nitrogen	40.26
160ft	Tubing 316 SS 1/2X035	249.60
12	Ball valve 316 SS ½”	240.00
80ft	Tubing 316SS 3/8X035	92.00
2	Regulator 1” 70-150lb range	381.30
1	Regulator 1” 275-500lb range	372.00
Subtotal		$3,120.14
	15% contractor markup on above subtotal	$4,68.02
Total		**$3,588.16**

Supplies

Electrical and Instrumentation:

Quantity	Description	Total Cost. $
10	Nipple 3/4X6”	13.81
800ft	16/2 wire	208.00
150ft	#16 wire	72.00
60ft	1.5” conduit	72.53
60ft	1” conduit	45.94
40ft	½” conduit	17.14
1	Conduit seal 1.5” hub	29.11
1	Conduit seal 1” hub	16.33
1	Grounding hub 1”	5.15
1	Grounding hub 1.5”	7.69
30ft	Galvanized strut 1-5/8X1-5/8	31.79
20ft	B-T-B strut 1-5/8	59.83
20ft	Strut 1-5/8X13/16	18.98
20	Rigid conduit clamp 1.5”	21.33
20	Rigid conduit clamp 1”	15.50
10	Rigid conduit clamp ¾”	6.79
10	Rigid conduit clamp ½”	6.50
6	1.5” Tee conduit body	681.24
6	Conduit outlet box w/3” diameter cover & 1” hubs	194.58
6	Reducing bushing 1.5 to 1”	28.62
16	Reducing bushing ¾ to ½”	23.68
16	Reducing bushing 1 to ¾”	26.24
14	Fem/male union straight ½”	97.58
14	Explosion proof ell ½”	136.78
6	Explosion proof ell ¾”	71.58
6	Conduit outlet box w/ 3”diameter cover & ¾” hubs	176.94
6	Guax fitting ¾”	197.76
100	Hex head ¼-20X1	4.86
100	Hex head ¼-20 nuts	2.37
100	¼ flat cut washer	1.96
100	¼ med. split lock washer	1.54
100	¼-20X1.5 hex head cap screw	6.56
4	Fem/male union straight 1”	67.48
4	Fem/male union straight ¾”	39.56
1	Fem/male union straight 1.5”	33.53
6	Conduit body & cover ½”	185.28
10	Conduit nipple ½X6” rigid	11.82
5	Male connector 316 SS 3/8X1/4	24.38
5	Male ell 316 SS 3/8X1/4	41.93
2	Tube tee 316 SS 3/8	30.42
10	Tube tee 316 SS ½”	232.05
38	Male connector 316 SS ½”	314.93
20ft	Angle iron 1.5X1.5X3/6”	9.60
20	Tube union 316 SS ½”	240.50
2	Series gauge 1000lb	34.00

6	Male connector 316 SS ½	43.29
20ft	3/16X1 flat iron	5.00
50ft	Conduit ¾”	25.45
1	Rigid die head 1.5”	56.10
10	Rigid conduit clamp ¾”	6.79
3	Union tee	50.70
3	Dripwell/filter 0-120psi	87.00
2	Male connector	11.60
2	Male elbow	17.80
2	Conduit body 1.5”	227.08
2	Reducing bushing1.5 to 1”	9.54
10	3 hole flat corner plate	20.87
100	Spring nut 3/8”	68.70
5	Cord connector ½”	23.10
10ft	Galvanized strut	10.60
15	Conduit nipple ½”Xclosed	4.43
15	Conduit nipple ¾”Xclosed	5.72
8	Conduit nipple 1/2X1.5”	4.49
8	Conduit nipple	4.72
8	Conduit nipple	4.96
1	Conduit outlet box w/ 2” diameter cover & ¾” hubs	26.42
2	Conduit outlet box w/ 3” diameter cover & ¾” hubs	62.68
2	Conduit elbow explosion proof ½”	19.54
3	Conduit hub plug 1”	6.06
6	Ell 90 degree 1”	19.80
6	Bushing hex head 1X1/2	5.45
4	Bushing hex head 1/2X1/4	2.04
6	Union hex 1”	28.32
1	Type 50 dripwell/filter 0-120psi	29.00
3	Gen. Purpose equipment gauge 0-30	8.25
6	Male connector 316 SS 1/2X1/4	43.29
2	Male elbow 316 SS 1/2X1/4	23.92
Subtotal		$4,575.21
	15% contractor markup on above items	$ 686.28
TOTAL		**$5,261.49**

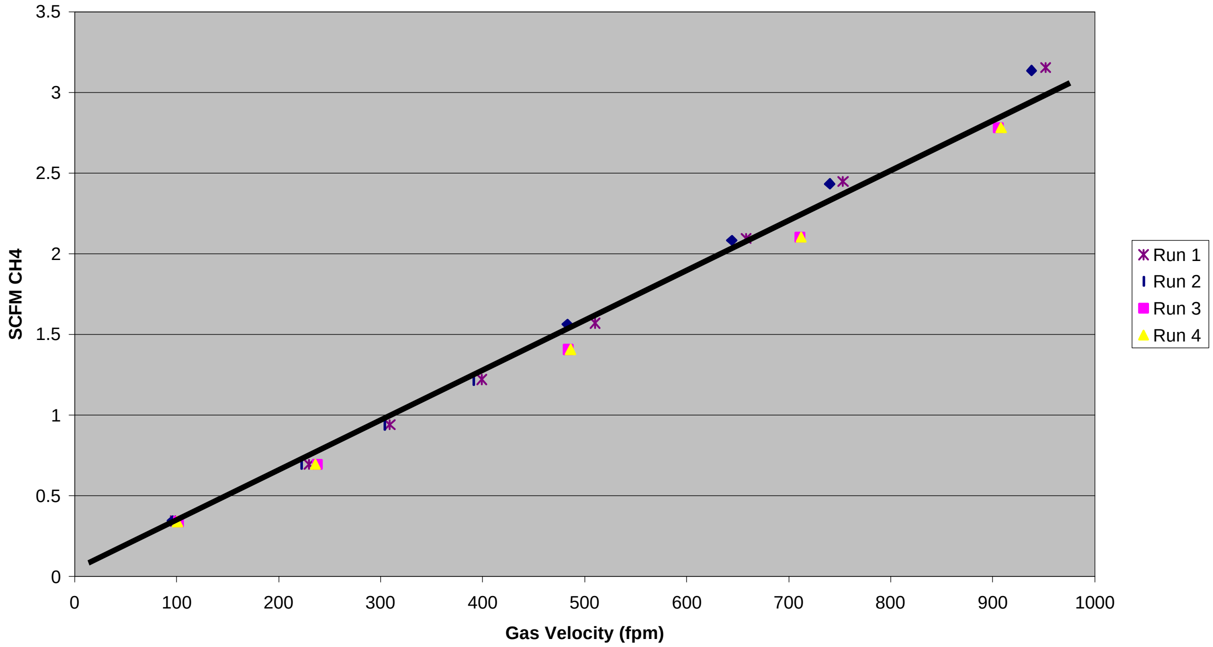
APPENDIX F

Flow Tube Calibration Results

Flow Tube Calibration

Runs 1 & 2: 4/20/99

Runs 3 & 4: 6/2/99



Flow Tube Calibration Results and Accuracy Calculations

Calibration Date	Run No.	Anemometer Velocity (fpm)	Actual Flow Rate Measured With LFE (scfm CH4)	Predicted Flow Rate Based on Linear Curve Fit* (scfm CH4)	Estimated Accuracy (+/-)
4/20/99	1	99	0.34	0.26	-23.9%
		230	0.70	0.69	-0.3%
		309	0.94	0.96	1.5%
		399	1.22	1.25	2.6%
		510	1.57	1.62	3.1%
		658	2.09	2.11	0.6%
		753	2.45	2.42	-1.1%
		952	3.15	3.08	-2.4%
				AVERAGE	-2.5%
4/20/99	2	96	0.35	0.27	-21.7%
		222	0.69	0.69	-1.0%
		304	0.94	0.96	2.2%
		391	1.22	1.25	2.5%
		483	1.56	1.55	-0.8%
		644	2.08	2.08	-0.1%
		740	2.43	2.40	-1.5%
		938	3.14	3.05	-2.7%
				AVERAGE	-2.9%
6/2/99	3	0.98	0.34	0.29	-13.7%
		2	0.69	0.70	1.0%
		4.05	1.41	1.44	2.3%
		6.05	2.10	2.12	0.9%
		8	2.78	2.70	-2.8%
				AVERAGE	-2.5%
6/2/99	4	0.98	0.34	0.29	-14.6%
		2	0.69	0.70	0.1%
		4.05	1.41	1.45	2.7%
		6.05	2.10	2.12	1.0%
		8	2.78	2.71	-2.4%
				AVERAGE	-2.6%

* Linear regression results:
Run 1 Predicted Flow Rate = 0.0033 * Gas Velocity -0.0644
Run 2 Predicted Flow Rate = 0.0033 * Gas Velocity -0.0451
Run 3 Predicted Flow Rate = 0.003 * Gas Velocity -0.0122
Run 4 Predicted Flow Rate = 0.003 * Gas Velocity -0.0061