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September 2000

Environmental Technology Verification Report

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

Prepared by:

Southern Research Institute

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

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Greenhouse Gas Technology Verification Center

A U.S. EPA Sponsored Environmental Technology Verification Organization

A&A Environmental Seals, Inc.
Seal Assist System

Phase II
Technology Verification Report

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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 William Kendrick, Richard Jolly, Jonny Hendricks, James Peterson, Howard Begay, Calvin Largo, and Korey Kruse.

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 independent 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 that 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 organizations 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 who 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 guidance on specific technologies most appropriate for testing, help disseminate results, and review test plans and verification reports. The Center's stakeholder groups consist of national and international experts in the technology areas selected for verification. They also include industry trade organizations, environmental technology finance groups, and various government organizations. Based on stakeholder input, oil and gas industry technology areas have been targeted for verification by the Center.

To pursue verification testing in oil and gas technology areas, the Center established an Oil and Gas Industry Stakeholder Group. The group consists of representatives from the production, transmission, and storage sectors, technology manufacturers, industry consultants and service providers, 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 technology performance parameters of most interest to their industry. In a recent meeting, they indicated that technologies that 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, transmission 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 rod 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 startup, the Phase I performance verification test was initiated on March 10, 1999. The Phase I verification occurred between March 10 and 31, 1999, and verified short-term gas recovery performance and SAS cost. The Phase II performance verification, which is the subject of this report, addresses longer-term gas recovery and emission reduction performance, and estimates the economic payback potential of the SAS. Phase II verification testing began at the conclusion of Phase I and concluded on March 16, 2000.

Details on the verification test design, measurement 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 has been reviewed by A&A, Transwestern Pipeline Company, selected members of the Oil and Gas Industry Stakeholder Group, and the EPA Quality Assurance Team. The reader should be advised that deviations from the original Test/QA Plan occurred due to unexpected site operations, SAS operational characteristics, and other factors. Descriptions of alternative procedures and instruments used in the Phase I study are described in the Phase I Verification Report, while changes implemented later are described in this Phase II Verification Report. The Phase I report: *Environmental Technology Verification Report, A&A Environmental Seals, Inc. Seal Assist System (SAS) Phase I Report*, can also be obtained from the web site identified above (SRI 1999).

The remainder of Section 1 introduces the SAS, describes the Phase I and II verification goals, and presents an overview of the Phase I findings. Section 2 presents a background discussion on methane emission from natural gas compressors, a description of the test site, and documentation on the as-built system installed at the test site. Section 3 presents Phase II test results, followed by an assessment of data quality in Section 4.

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 is intended to allow existing rod packing leaks to continue while containing the leaking gas within the SAS emission containment gland or ECG. 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 ECGs used on each compressor rod (3), the jets, the recycle stream, and the eductor/compressor. Figures 1-2 and 1-3 provide additional detail on SAS components.

The ECG is a secondary seal that is attached to the exposed face of an existing rod packing case. The ECG is located within the "doghouse" located between the engine and compressor. The doghouse is an industry term for the enclosed space (or distance piece) within the compressor between the engine and the compressor piston. The doghouse provides access for routine maintenance of rod packing, and ensures that leaking gas from the packing case or ECG is contained and vented into the atmosphere. Each doghouse contains an oil drain and a vent pipe. At the test engine/compressor, doghouse vent pipes are connected by a common header that vents all leaking gas to the atmosphere from a roof vent.

The ECG contains an annulus area or channel that provides space for rod emissions from the packing case to flow into. The annulus contains an inlet (recycle line) and an outlet allowing gas to flow out of the ECG annulus and into the SAS piping. A suction is provided on the annulus area to facilitate flow using a specially designed jet manifold system (Mathis et al., 1998).

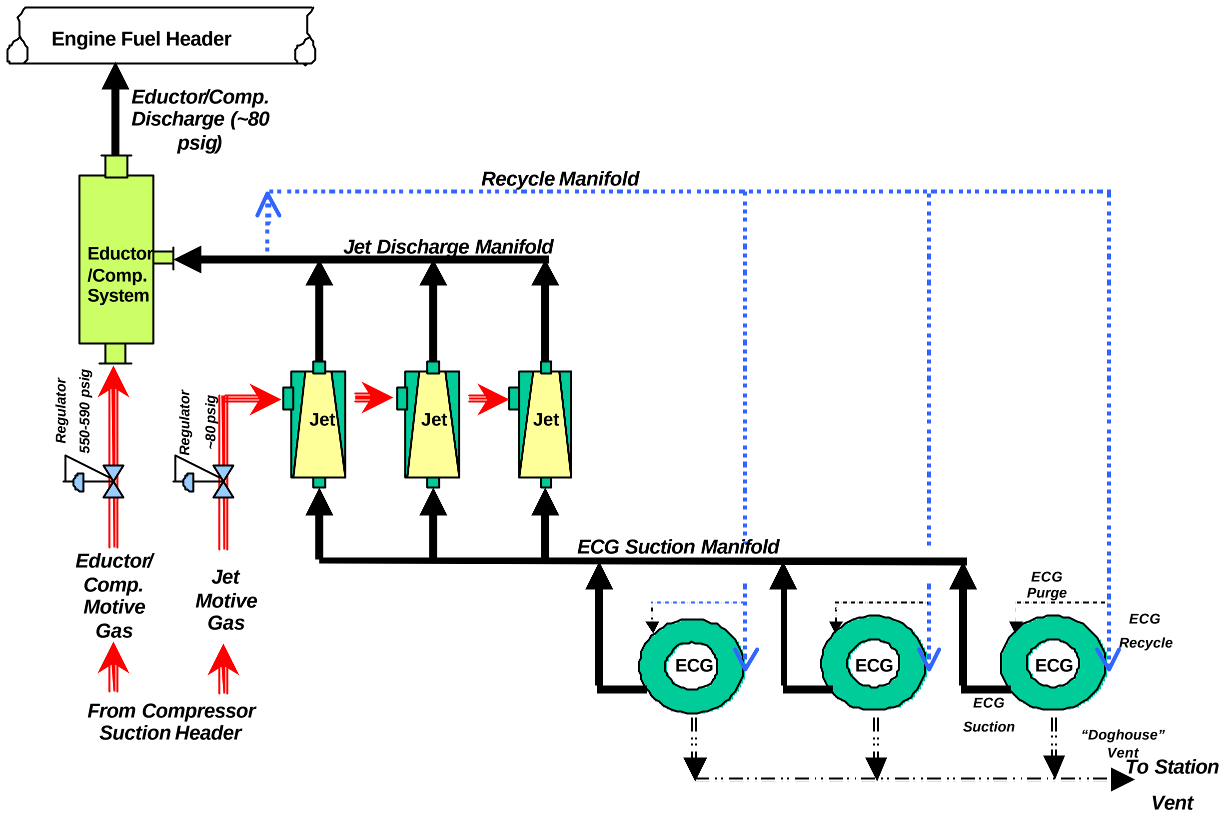

Figure 1-1. Simplified SAS flow diagram

The ECG includes a floating face seal, called the tertiary seal. The tertiary seal is intended to prevent aspiration of air into the SAS piping and engine fuel line that could result from the slightly negative pressure in the annulus. The tertiary seal is a u-cup lip seal riding in a carrier. The carrier also has a carbon ring in contact with the rod that allows it to move with the rod and keep in alignment. According to the vendor, the tertiary seal has a long life expectancy, provided negative pressure is maintained in the annulus area. If rod seal failure results in high packing case leak rates, the tertiary seal is designed to prevent gas leakage into the atmosphere by increasing face contact with its stationary element as pressure increases in the annulus. If this condition continues, the increased pressure causes the seals to wear quickly, requiring their replacement. In such cases, the vendor recommends increasing suction on the ECG by optimizing the flow from the jets described below, and by balancing the recycle flows.

Gas isolated in the annulus is brought into the SAS piping assembly by suction induced from a series of jets shown in Figure 1-1. The jets contain a specially designed nozzle that creates a partial vacuum between the inlet and outlet streams of the jet manifold assembly (see Figure 1-4). This partial vacuum is created by an 80 psig motive natural gas stream provided by the station, which creates a near sonic velocity stream within the jet. The jets induce gas flow from the annulus area and transport the collected gas to the low-pressure side of the jets via the ECG suction manifold. A mixture of motive gas and rod packing emissions exit the jet discharge at slightly higher pressure (Tarrer and Stadig 1996). A variable orifice located between the Jet Discharge and the inlet channel of the ECG controls the recycle flow rate.

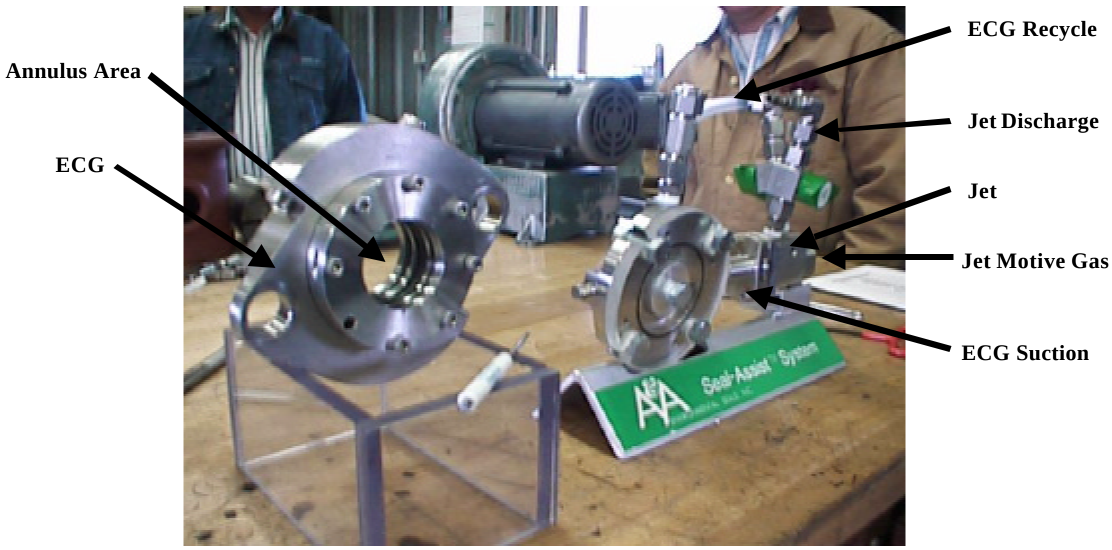

Figure 1-2. Illustration of the ECG and the jet manifold assembly

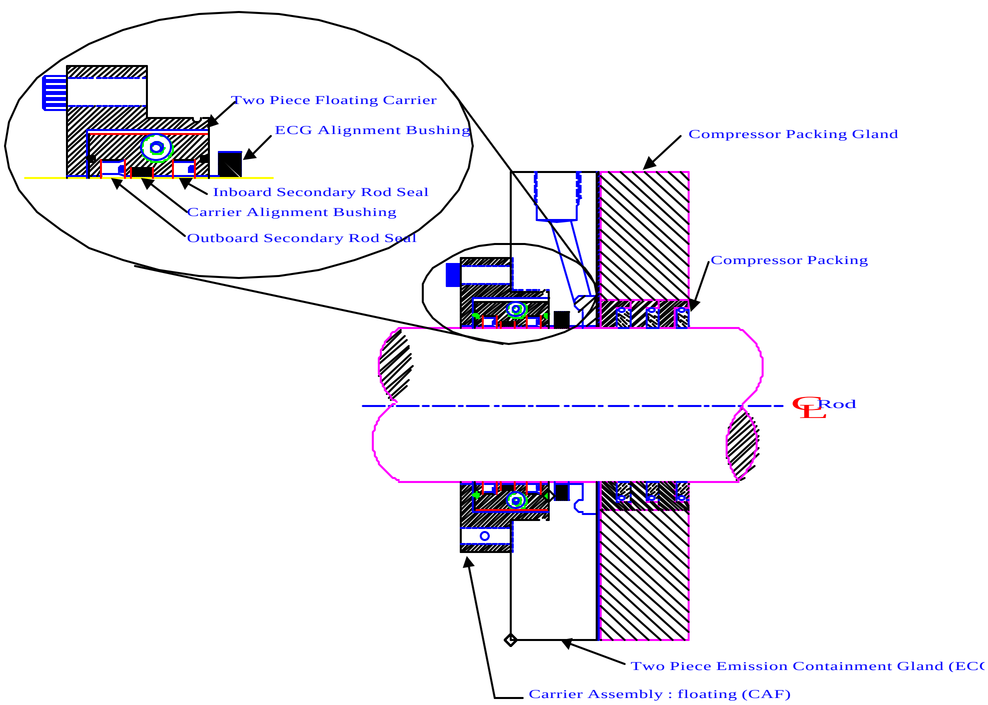

Figure 1-3. Cross-sectional view of compressor rod packing and the ECG

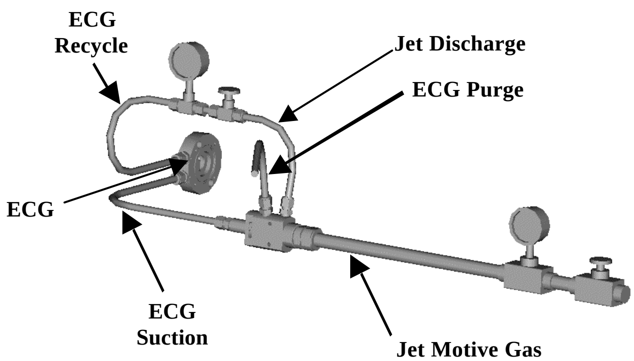

Figure 1-4. Schematic of the jet manifold assembly

A small portion of the jet discharge stream is recirculated to the ECG. The recycle system helps reduce large negative annulus pressures that could occur when rod packing emissions flowing into the annulus are low. This is intended to mitigate the dangerous situation where air inside the doghouse is pulled into the system through a leaking tertiary seal. Recycle flows can be controlled to a limited extent with ball valves installed in each recycle line.

The gas exiting the jet 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 from the station of about 350 scfm natural gas at 550 psig to compress the captured gas to an engine fuel line pressure of about 80 to 90 psig. High-pressure motive gas needed to operate both the jets and the eductor/compressor is supplied by the site's high-pressure compressor suction line.

1.3 PHASE 1 RESULTS AND PHASE II VERIFICATION GOALS

1.3.1 Phase I

Verification goals in the Phase I testing were to: verify SAS leak tightness, gas recovery, and methane emission reduction performance, document SAS installation and operating requirements, and calculate SAS capital and installation costs. Testing, analysis, and QA methods planned for the Phase I verification are described in the report *Test/QA Plan for A&A Environmental Seals' Seal Assist System (SAS), (SRI 1998).* The Phase I verification results are presented below and were obtained based on direct measurements, host site and field testing logs, cost data submitted by installation contractors and the vendor, visual inspection, and interviews with site operators and installers. The Verification Report titled *Environmental Technology Verification Report, A&A Environmental Seals, Inc. Seal Assist System (SAS) Phase I Report*, presents complete Phase I verification strategies and results, and identifies any changes made in testing methods made for the Phase I evaluation (SRI 1999).

- SAS Leak Tightness: The SAS assembly was found to be leak tight with the exception of the ECGs. Based on 12 individual measurements, a total leak rate of 0 ± 0.6 to 5.7 ±5.4 scfm methane (CH_4)

was measured (total from all three ECGs). The lowest leak rates occurred when the SAS was operating at design pressures (at or below 0 psig in the ECG suction header). Over the 3-week evaluation period, the SAS operated within design pressures for less than 20 percent of the time.

- Gas Recovery Potential: The SAS collected from 3.7 to 11.6 scfm gas, and injected it into the engine fuel line. The average collection rate for the Phase I test was 7.2 ± 0.22 scfm gas, which equates to an average leak capture efficiency of 70 ± 10 percent. (Leak capture efficiencies ranged from 43 to 100 percent.)

- Methane Emission Reduction Potential: It was speculated that the negative ECG suction pressure could increase rod packing emissions. With this, the volume of gas recovered would be different than that emitted to the atmosphere if the SAS was not installed. The Center was unable to conclusively determine if the SAS perturbs rod emission rates, and, due to the unscheduled failure and replacement of two rods after the SAS was installed, reliable uncontrolled emission estimates could not be determined in time for Phase I reporting. It was decided that data from the Phase II testing would be used to quantify methane emission reduction potential.

- Labor Requirements: The fabrication, installation, and pressure testing of the SAS required approximately 300 labor hours. An additional 200 labor hours were required to install electrical components and instrumentation.

- Capital and Installation Cost: The capital cost, including mechanical equipment, piping, and electrical and instrumentation components, was $30,933. Based on contractor logs, the net labor cost for SAS installation was $11,841. The total installed cost was $42,774. This includes electrical and instrumentation the host site requested ($12,822), and which the vendor considers optional.

- Optimum Performance: The maximum gas recovery rate and highest leak capture efficiency was achieved when the SAS operated at ECG suction header pressures that were negative. The SAS was unable to maintain design operational pressures when routine fluctuations in engine load caused the fuel header pressures to increase. This increased SAS pressures, which in turn caused the tertiary seal to leak as the ECG became pressurized. The pressure swings were stabilized at the beginning of Phase II by adding a pressure regulator on the engine fuel line.

1.3.2 Phase II

As outlined in the Phase I Verification Report, the parameters listed below were planned for verification in Phase II using measurements and other data collected at the host site.

- Long- term leak tightness and gas recovery potential
- Annual methane emission reduction
- Long-term SAS operational requirements
- SAS payback period

The testing and analysis methods used in Phase I were planned for use in Phase II. However, information obtained since the completion of Phase I make it clear that alternate procedures are needed, and as a result, new procedures have been adopted and are explained in this report. For example, in Phase I the rod packing emissions were calculated using in-line flow meters installed in the SAS piping, and these values were key in determining gas recovery potential. It is now known that SAS process anomalies occur that result in an overestimate of rod packing emissions using the in-line meters. In addition, it is now known that the host site frequently operated in an unusual manner (10 packing case replacements and

8 rod breakages over the period of about 12 months), and that these operating conditions significantly impacted SAS performance. Given this, the in-line data collected represent SAS performance under unusual compressor operation, requiring modification in the methods to facilitate the estimation of more representative SAS performance results.

Considering the problems outlined above, the approach for quantifying several verification parameters was revised to provide more valid SAS performance results. Figure 1-5 shows the verification parameters quantified in Phase II and the key measured values and other data used in their determination. Strategies used to verify each parameter are described in Section 3, and testing methods are outlined in the appendices to this report. Manual measurements collected during stable engine/compressor operations are used to quantify emission reduction and gas recovery performance in lieu of the continuous measurements originally planned. In addition, the methods for calculating emission reduction and gas recovery were simplified to reduce ambiguities that existed in the original approach, and to correct inaccuracies as well (i.e., use of the calculated rod packing emissions was eliminated). Continuous measurements are still used to assess SAS performance under upset and more extreme conditions, but on a semi-quantitative basis only (thus the dotted line in Figure 1-5).

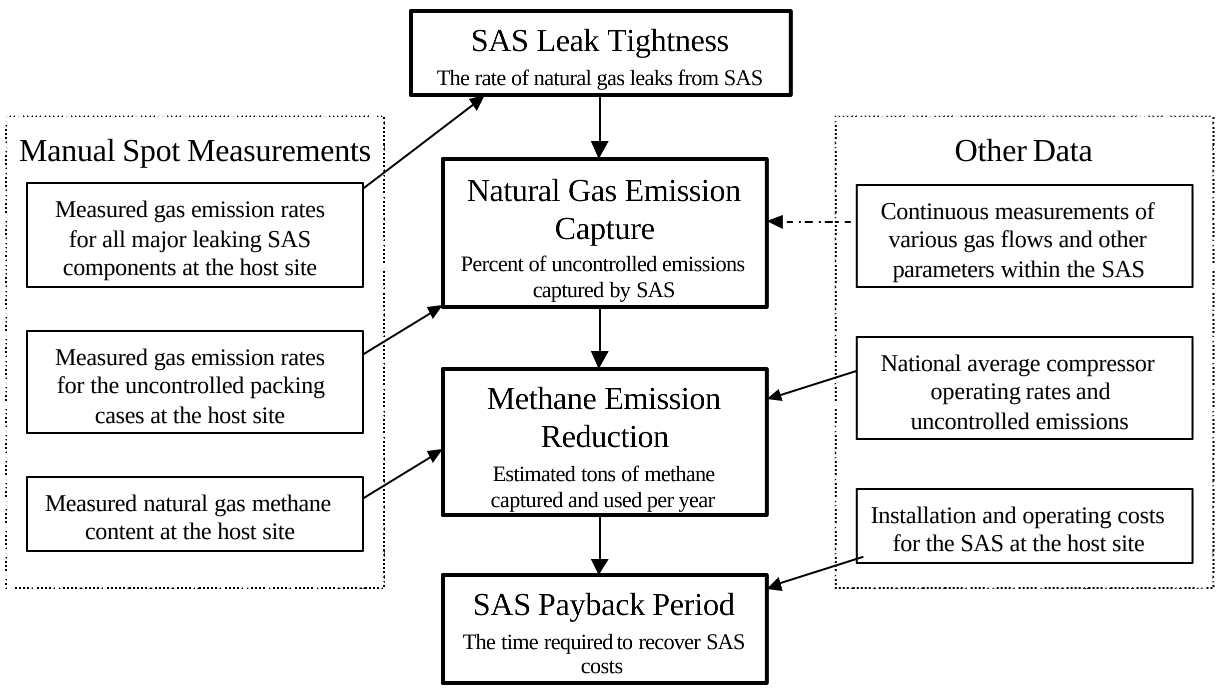

Figure 1-5. Phase II verification parameters and data sources

A primary goal of the Phase II testing is to determine the SAS payback period. As a practical matter, the Center cannot conduct direct testing for the extended period required to determine payback entirely through direct measurements, so original verification plans called for the extrapolation of medium-term continuous measurements (8 months) conducted at the host site. Given the operational problems encountered at the site, this wasn't feasible. Instead, SAS payback is estimated for an "average" compressor system with operating parameters based on national data sets compiled by industry trade organizations and the USEPA using the gas recovery rates measured during this verification.

2.0 BACKGROUND INFORMATION AND SITE DESCRIPTION

2.1 METHANE EMISSIONS FROM NATURAL GAS COMPRESSORS

In the natural gas industry, gas compressors are used in the production, processing, transmission, and storage sectors of the industry. 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 transmission sector, compressors are used to transport gas from processing plants to distribution centers. In the storage sector, compressors are used to inject and withdraw 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 natural gas industry (specifically, from reciprocating, rather than centrifugal, compressors). In 1992, reciprocating compressors 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 according to the EPA/GRI study. 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 largest natural gas loss occurs in the transmission sector, accounting for about 38 x10^9 ft^3 of gas per year. These losses or leaks occur from, in decreasing order, blowdown valves, rod seal packing cases, compressor isolation valves, and pressure relief valves. Leaking rod seal packing cases, a primary subject of this verification, contain rod seals that are arranged in series to create multiple barriers against high-pressure gas trying to escape down the rod into the atmosphere.

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

The data in Table 2-2 do not fully consider a recent trend of replacing wet rod seal systems with dry seals. Wet rod 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. 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 the dry type.

Based on the EPA/GRI study, an industry average rod leak rate of about 0.98 scfm of natural gas per rod is estimated for reciprocating compressors. A study conducted by the Pipeline Research Committee (PRC) reported an average leak rate of 1.86 scfm per rod (GRI 1997). Based on the same PRC study, the highest rod leak rate reported was 35 scfm, and based on three quarterly measurements conducted on this rod, an average leak rate of 19.5 scfm was reported.

2.2 SITE SELECTION, DESCRIPTION, AND OPERATIONAL OVERVIEW

Because reciprocating compressors are commonly used in the gas transmission sector, and are a primary source of emissions from compressor operations, they were used in the SAS technology verification. Transwestern Pipeline Company – Enron Gas Pipeline Group expressed interest in providing a host site for the SAS verification because of the systems potential to reduce emissions and product losses. To select a host test site, Enron utilized its emissions survey data of natural gas leaks from compressor seals to select a representative compressor station. Compressor stations with the following characteristics were sought: (1) rod leak rates of approximately 1 to 4 scfm per rod, (2) dry rod seal systems in use, and (3) site operators interested in actively participating in the SAS technology verification.

The natural gas transmission compressor/engine selected for the SAS evaluation is located near the New Mexico and Arizona border. A photograph of the engine/compressor 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 about 360 $x10^6$ ft^3 natural gas per day per engine. Each engine is equipped with three reciprocating compressors operating in parallel, which is close to the national average of 3.3 compressors estimated in the PRC study. The rods and packing used at the station have the same basic design and functionality as many reciprocating compressors. Each rod is 4-½ inches 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 is a dry seal system 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. Data regarding the seals used are given in Table 2-4, including the initial age of the seals, the manufacturer, the number of seals in the packing case, and the initial leak rate measured during a pretest survey.

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. Host Site Compressor Seal 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 pretest survey	0.30	1.58	5.70

The seals are generally not maintained on a predefined schedule; rather, seals are replaced when maintenance on the rod is performed or high leak rates are indicated. The station uses rod temperature (measured at a clearance of about 0.01 in.) as a primary indicator of the need for rod or seal maintenance. Visual inspection for signs of high leak rates is also used. The seals used are expected to last for several years, but surprisingly, they were found to wear out quickly. Over the 12 month verification period, the engine/compressor system experienced 10 rod seal replacements. Most seal replacements occurred on rod 3, as did most of the eight rod failures and replacements that occurred over the same period. This failure rate is not representative of average site operation, where failures occur on scales of years not months. Given this, its not surprising that rod seal leak rates were often variable and unrepresentative (i.e., emission rates of from 0 to over 100 scfm per rod were measured). The highest site measurement exceeds the highest industry value cited in the Pipeline Research Committee study by a factor of about 3. More detailed information on the operational characteristics of the test engine/compressor system are presented in Section 3.

The lifetime of rod seals is generally a function of the type of service and routine maintenance performed by the operator, the state of the rod alignment with the engine, and the impurities entrained in the gas that can damage the seals. Causes for the failures experienced on the test unit are not known. The engine/compressor unit selected for the test, along with others at the site, has excellent dependability with normal operating time in excess of 90 percent. Unfortunately the unit being tested, as well as the other units at the station, indicated significantly greater wear and breakdowns during the test than normally experienced. Investigations since the test have indicated that a section of line feeding the suction side of the station was cleaned about the time the test was started. This station, being the first station downstream of the cleaning, experienced higher than normal particulate levels in the gas. This condition during the test would be expected to reduce seal and rod life well below normal limits.

2.3 DESCRIPTION OF THE SAS AND MONITORING SYSTEM INSTALLED

The SAS was installed on all three compressor rods of Engine 1 (see Figure 2-1 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.

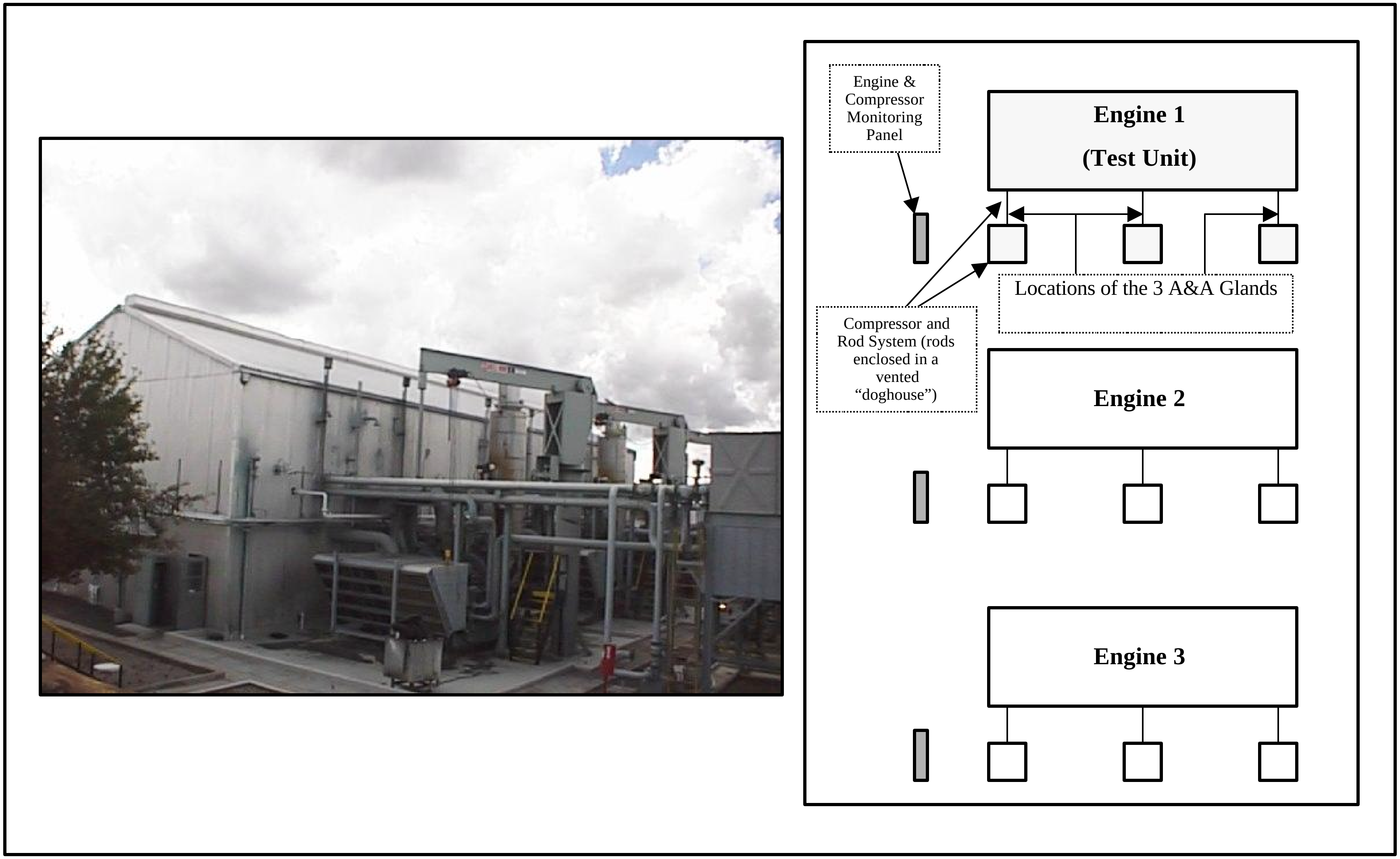

Figure 2-1. Photograph and floor plan for the host gas transmission line compressor station

Various measurement devices were also installed to conduct the verification test. These are depicted in Figure 2-2 and listed in 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, and Q3) and the ECG recycle lines (Q4, Q5, and Q6). Gland-specific flow measurements were planned to help quantify rod-specific gas recovery performance and economic payback, but excessive oil buildup within the SAS and ECG suction line meters required their removal early in the study (i.e., Q1, Q2, and Q3 were not used). Installation of a filtration system might have reduced the excess oil buildup, although the vendor indicated that such a system might create enough pressure drop in the lines to affect SAS performance. Flow meters were installed on the jet discharge manifold (Q7) and the jet motive gas line (Q8). The net volume of gas captured by the SAS is estimated by taking the difference between these two meters (i.e., Q7 minus Q8).

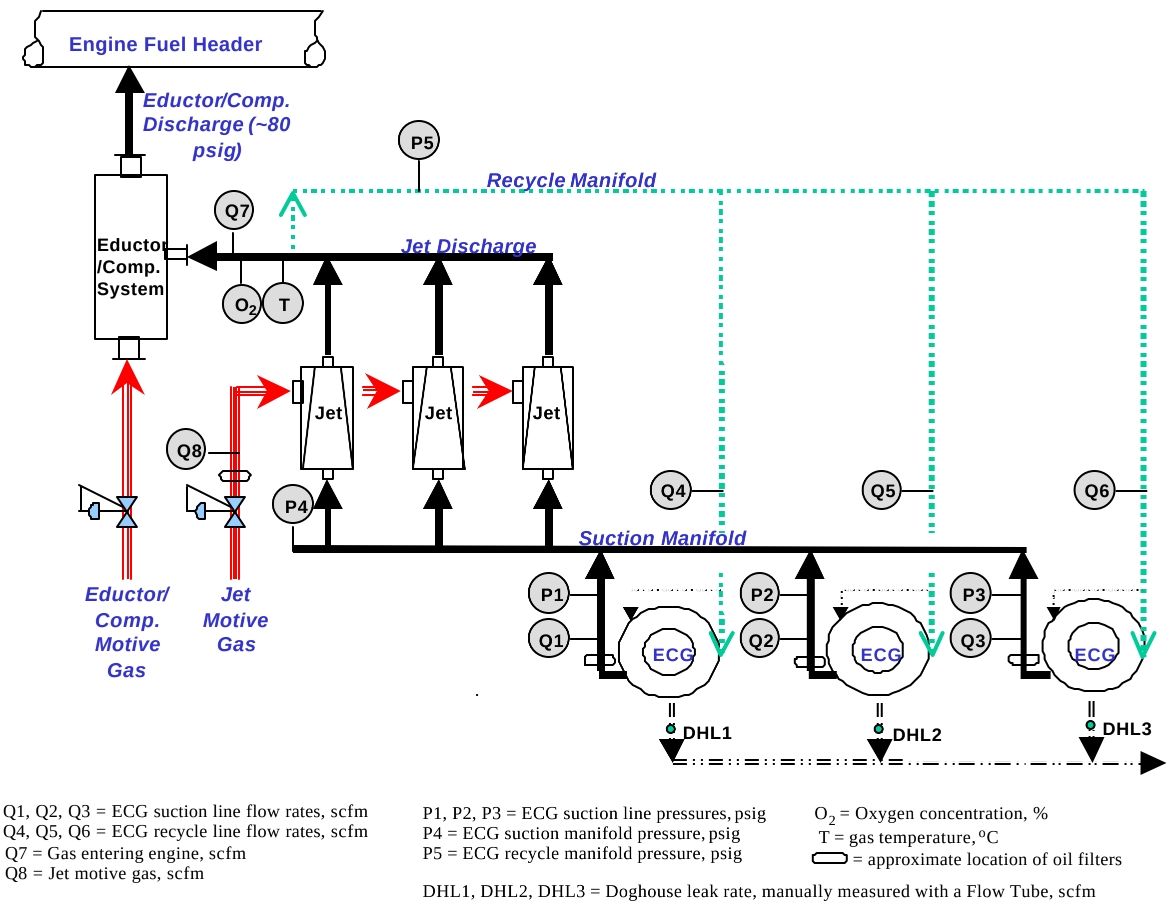

Figure 2-2. The as-built SAS and measurement system at the host site

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, three pressure sensors at each gland (P1, P2, and P3) monitored ECG suction line pressures. A single sensor is generally used to measure the ECG suction header pressure (P4) because it generally agrees well with the gland-specific measurements. A single pressure sensor is used to monitor ECG recycle manifold pressures (P5). Finally, an oxygen sensor, capable of measuring less than 0.1 percent oxygen was installed in the jet discharge manifold for safety reasons (i.e., to monitor for the presence of air in the event SAS pulls air into the fuel line system). 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	Measurement Sensors[a]
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 that 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	Gas Flows – Q7 Line Pressure – not measured O_2 Meter Temperature – T
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

[a.] See Figure 2-2 for locations of devices cited here.

Output signals from each monitoring device were converted into digital signals, and transmitted to the site control room. 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 computer at the Southern Research office in Research Triangle Park, NC, was used daily to automatically download the data. A spreadsheet prepared by the Center converted the raw signals into values such as flow and pressure. To verify rod packing emissions and leak rates, a manual flow-measuring device (the Flow Tube) was used. This device is described in more detail in Appendix A.

The ECGs were installed on the test compressors during a scheduled shutdown 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 startup and shakedown activities occurred between February 2 and March 9, 1999. The SAS was verified as being operational on March 10, 1999 and the Phase I test evaluation was initiated. A Phase I Verification Report was published in September 1999. A major finding from the Phase I verification was that the test engine's fuel header pressure varied significantly from day to day, causing SAS system pressures to fluctuate and emission capture performance to deteriorate. Slight fuel header pressure fluctuations are a normal occurrence in engine operations. The station operators and the SAS vendor installed a fuel header pressure regulator to help stabilize SAS performance prior to Phase II testing. In addition, longer retaining bolts were installed on the ECGs in response to engine vibration and in an effort to reduce seal wear caused by vibration that may have contributed to leakage from the tertiary seals.

Phase II verification testing re-started in July 1999, after the completion of about 3 months of host site-sponsored maintenance on the test engine's foundation and other systems. Phase II testing was concluded on March 16, 2000. Additional information on SAS installation and shakedown activities and costs can be found in the Phase I Verification Report (SRI 1999).

3.0 PHASE II TEST RESULTS

3.1 HOST SITE AND SAS OPERATIONAL SUMMARY

3.1.1 Compressor/Engine System

The host test site is a natural gas transmission station located near the border of New Mexico and Arizona. The Station operates three Clark gas-fired internal combustion engines (12 cylinders, 4500 hp), and each is equipped with three reciprocating compressors operating in series. Each compressor rod is 4-½ inches in diameter, and each uses a retrofit dry seal system that was installed in December 1997, about 1 year before the SAS installation.

The engine/compressor unit selected for the test, along with others at the site, has excellent dependability with normal operating time in excess of 90 percent. Unfortunately the unit being tested, as well as the other units at the station, indicated significantly greater wear and more breakdowns during the test than normally experienced. Investigations since the test have indicated that a section of line feeding the suction side of the station was cleaned about the time the test was started. This station, being the first station downstream of the cleaning, experienced higher than normal particulate levels in the gas. This condition during the test would be expected to reduce seal and rod life well below normal limits.

The Phase I and II test periods lasted from March 10, 1999 through March 16, 2000. Compared to the operational problems on the other two engine/compressor systems operated at the station, the test unit experienced greater operational and maintenance problems throughout the period. These problems resulted in significant engine/compressor down time, subsequent data loss, and more importantly, extreme operating conditions for SAS to respond to. As expected, SAS generally responded poorly to these adverse conditions, and in some cases, SAS was taken off line due to the level of rod packing emissions encountered.

The fluctuations in fuel header pressure observed during Phase I were caused by engine shutdowns and startups (three engines are serviced by this header), and these fluctuations caused the SAS discharge pressures to increase. Installation of the regulator did stabilize the test engine fuel pressure during Phase II and it appears that this also stabilized SAS discharge pressures. However, the engine and compressor operational problems that were encountered throughout most of Phase II limited our continuous data set and precluded the Center from making conclusive statements concerning the effectiveness of the regulator on SAS performance. It does appear that, for limited periods during February 2000, the SAS discharge pressures remained stable after engine shutdown and startup sequences when fuel header pressures were constant.

The longer ECG mounting bolts were installed in response to excess engine vibration and to ultimately decrease ECG seal wear and leakage. However, because the Center did not monitor engine vibration during this test and because of the high rod packing leaks encountered during Phase II, the Center couldn't evaluate the effectiveness of the longer bolts.

Operational problems at the test unit were extreme enough to consider the test engine/compressor system as operating in an unrepresentative state throughout much of the SAS verification period. The following is a chronological summary of operational problems encountered including compressor rod failures (rod breakage), compressor rod packing case replacements, and other maintenance activities.

1. The test engine and SAS were shut down on March 31, 1999 to replace rod 3 and its packing. The SAS was restarted on April 1, 1999.

2. The test engine was shut down from April 29 to July 19, 1999 to install new grouting and foundation systems to address potential rod alignment concerns. New rods and packing were also installed on all three compressors.

3. On July 24, 1999, rod 3 broke, and both the rod and packing case were replaced. SAS was returned to operation on July 25.

4. On August 14, 1999 the test engine was shut down to replace the packing on rods 2 and 3. The SAS was restarted on August 24.

5. On November 11, 1999 the test engine was shut down after breaking rod 3. Station operators replaced the packing on rods 2 and 3, and the SAS was restarted on November 16. Station operators also installed a rod lubrication system on the other units at the station, and notified the Center of their intention to do the same on the test engine after completion of the SAS test.

6. On February 18, 2000 the test engine was shut down to replace rod 3 and its packing. The SAS was restarted on March 16, 2000. The verification was terminated at that time.

As can be seen from the events above, significant problems occurred in the compressor systems that directly affected SAS operation and performance. These operational problems are reflected in the high uncontrolled rod packing emissions measured. The list below summarizes the natural gas emission rates measured over the course of this verification.

- Rod 1: Average value--0.96 scfm; Range--0 to 3.42 scfm
- Rod 2: Average value--2.28 scfm; Range--0.43 to 6.28 scfm
- Rod 3: Average value--15.06 scfm Range--2.25 to 102.94 scfm

Average emission rates for rods 2 and 3 are above national average values reported in studies of emissions from the natural gas industry, and the range reported for rod 3 exceeds any values reported. Specifically, based on the EPA/GRI study, an industry average rod leak rate of about 0.98 scfm of natural gas per rod is estimated, while the Pipeline Research Committee reports an average of 1.86 scfm per rod (GRI 1997). The same PRC study reported that the highest rod leak rate found was 35 scfm; a factor of about 3 below the highest value recorded at the host test site. The PRC study also reported that, based on three quarterly measurements conducted for this rod, the average leak rate was 19.5 scfm. This is close to the average value determined for rod 3 at the host site, suggesting the host site unit is in a class with the highest emitting compressor unit reported for the natural gas industry.

Figure 3-1 is a timeline that covers the entire Phase I and II verification period. The figure shows the operational events listed above, identifies when SAS performance optimization efforts were conducted, and plots an important indicator of SAS performance, the pressures exiting the ECGs (ECG suction header pressure). Important maintenance downtime periods are also shown.

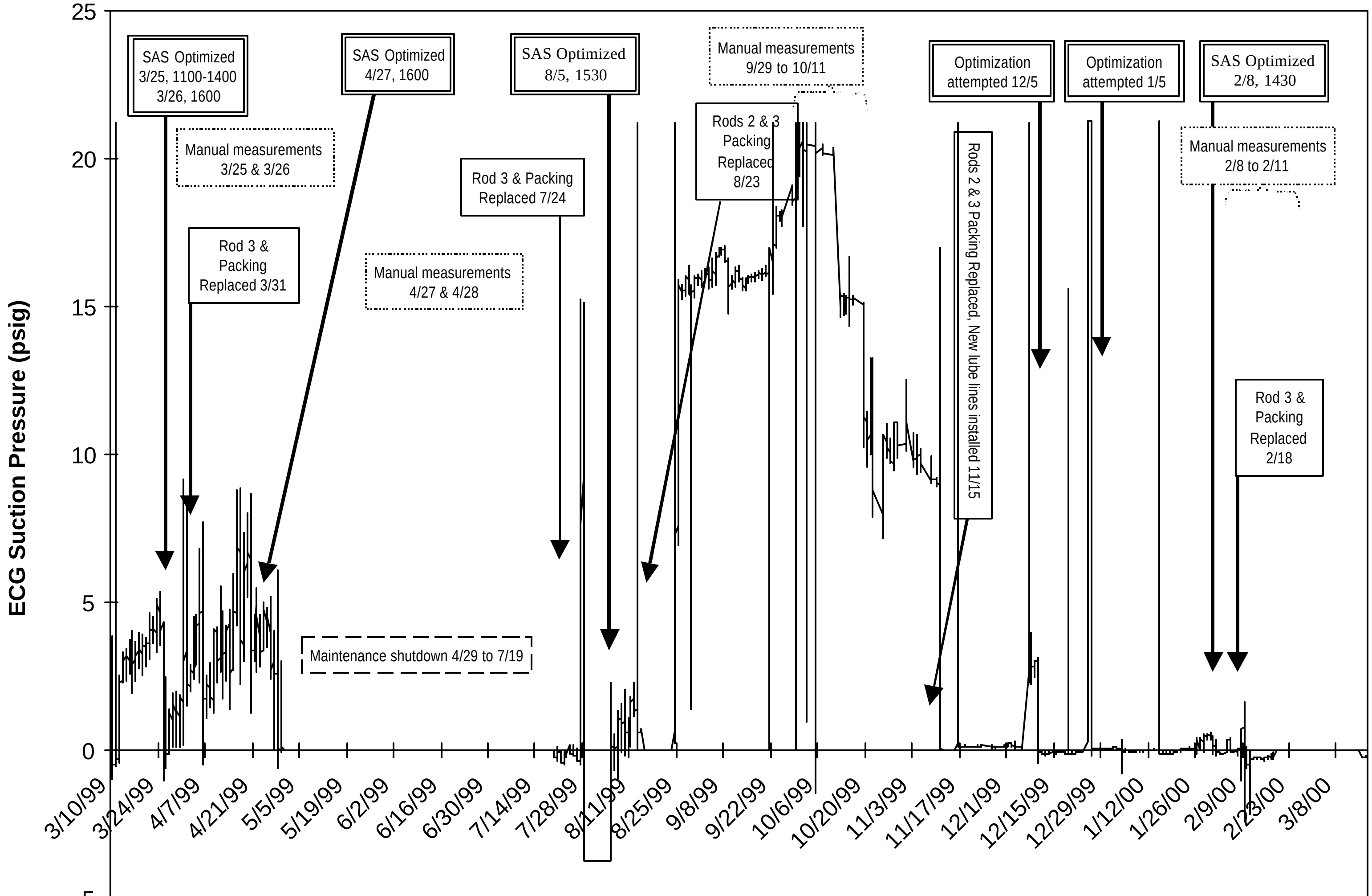

Figure 3-1. Phase I and II Timeline

3.1.2 SAS

An important operational requirement for the SAS is to maintain a slightly negative pressure on the suction side of the ECGs. With this, emissions can flow from the gland into the SAS collection system, avoiding high pressures that can build up and cause leaking and damage of the ECGs tertiary seals. The ECG suction header pressure measured throughout the test is plotted in Figure 3-1. As the figure shows, the pressure was rarely negative, indicating the SAS was operating outside its design operation for most of the testing period. This occurred in large part as a result of the large and rapidly changing leak rates associated with rods 2 and 3. These leak rates overwhelmed the SAS with gas flows well in excess of SAS design flows. This in turn pressurized the glands and caused the ECG tertiary seals to experience accelerated seal wear and leakage.

It is clear that SAS is unable to respond effectively and compensate for the high and rapidly changing rod emission rates encountered. Even under moderate changes in rod packing emissions, significant operator input is required to adjust SAS flows to optimize performance through jet manifold and recycle feed adjustments and to maintain negative pressure on the ECGs. The ball valves used offer limited control of SAS flows inhibiting SAS optimization.

Because the SAS operated at higher than design pressures for most of the test, significant stress was placed on the tertiary seals. They are designed to function only as a backup system when positive suction pressures are encountered, and under these conditions, the seals are intended to prevent leaks for short periods of time until repairs can be made or SAS optimization occurs. At the conclusion of Phase 1, the vendor confirmed the tertiary seals were severely worn, and the fastening mechanism used to bolt the seal to the rod had been damaged from the significant vibrations encountered at the test engine. A design modification to the tertiary seal was not made prior to Phase II, but the vendor used a stronger bolting mechanism to prevent further damage to the tertiary seal carrier.

Close examination of the SAS pressures in Figure 3-1 reveals that, on a few occasions, slightly negative ECG suction pressure was achieved and maintained. This generally corresponded to times when SAS optimization was conducted and achieved, and soon after rod seal failure and replacement occurred. Given the generally unrepresentative operation experienced at the host site, these periods correspond to the most normal or representative system operation experienced during the verification test period. As such, data during these periods were used to quantify SAS performance for the Phase II verification. Given that these events often occurred at the same time as the manual emission measurement campaigns, the manual measurement data play a significant role in determining SAS performance under normal operating conditions. Continuous data collected with mass flow meters and other in-line devices are used to qualify SAS performance under more extreme conditions.

3.2 SAS LEAK TIGHTNESS PERFORMANCE

SAS leak tightness is defined as the ability of the SAS to contain all of the gas passing through the system, including compressor rod leaks and motive gas introduced into the system by the jets. The sources of leaks include SAS piping connections, valves, fittings, jet and eductor systems, and the tertiary seal on the ECGs. Manual measurements and visual inspection procedures were used to located and measure leaks when they occurred, and these procedures were generally conducted during the manual sampling campaigns illustrated in Figure 3-1.

SAS leak tightness results are organized into two categories:

- Piping and component leaks: leaks to the atmosphere from SAS system components such as fittings, valves, and pipe connections. Soap screening was used to locate leaks from these components, and when located, the USEPA tent and bag procedure was used to quantify the leak (Protocol for Equipment Leak Emissions Estimates, Hausle, 1993). During SAS shakedown, a 3-hour pressure test was conducted to identify and repair leaks.

- Tertiary ECG seal leaks: leaks from the ECGs are the most significant SAS leak source. When leaks occur, they escape from a flexible lip seal located at the back of the ECG (Figure 3-2), then vent into the doghouse for quantification by the Flow Tube. Flow Tube measurement and calibration procedures are described in Appendix A. Flow Tube performance data are presented in Section 4.

3.2.1 Piping and Component Leaks During SAS Operation

Potential leaks throughout the system were initially examined by pressure testing the entire system at shakedown. 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). The other lines were tested at a maximum pressure of 15 psig, even though they normally operate at much lower pressure (-2 to +5 psig). All pressure tests continued for a period of 3 hours. During routine manual sampling events, leaks were identified using soap solution while system pressures remained in the 2 to 5 psig range. Leaks were rarely found and, when they were, were generally repaired.

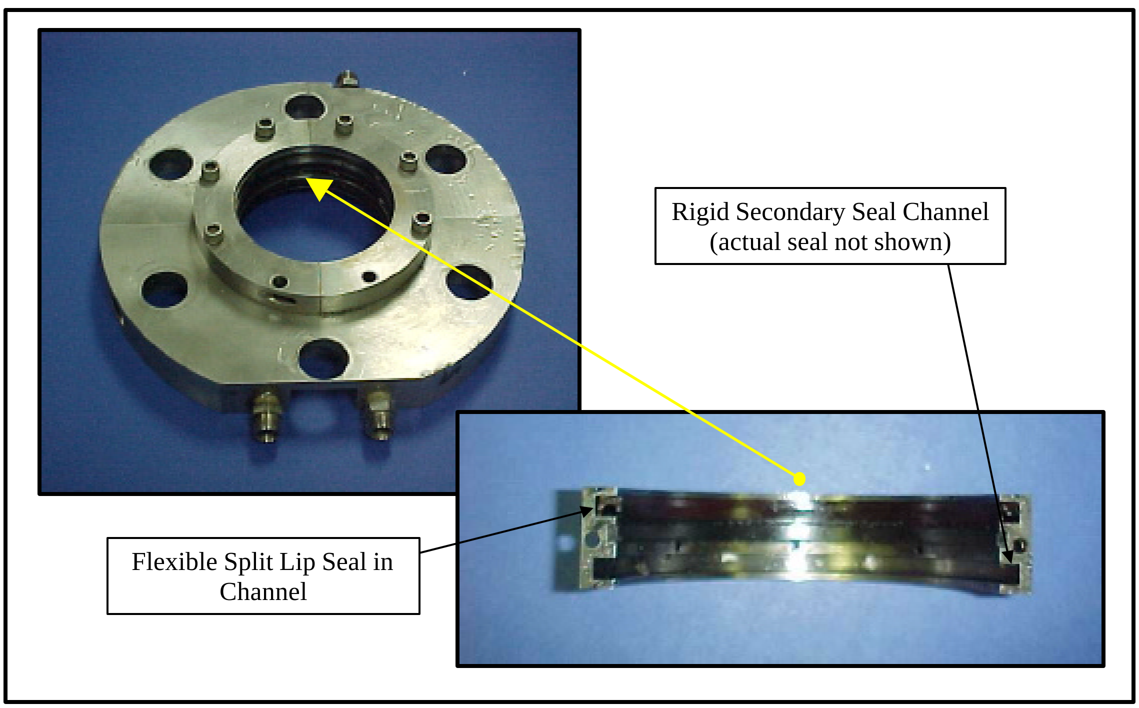

Figure 3-2. ECG and the tertiary seal system (photos taken after Phase II was completed)

Table 3-1 summarizes the leak testing procedures and results for piping and components. As the results show, few leaks were found over the Phase I and II periods, and few leak quantifications occurred. The one quantification conducted suggests that two leaks were located at the end of the Phase II period, and that together, these leaks represent an insignificant fraction of the total flow passing through the SAS. Compared to leaks from the ECGs discussed in the next section, these two leaks were insignificant: less than 0.01percent of the average leak rate associated with the ECGs over the testing period.

Table 3-1. Piping and Component Leak Test Results

Leak Checks and Methods	Date Checks Conducted	Summary of Findings and Corrective Actions
Sources; the suction, recirculation, and purge lines of the ECG piping system Methods: initial pressure test at startup followed by leak checks using soap solution	1/30/99 2/1/99 to 3/31/99 10/3/99 2/7/00	No leaks were found during the initial pressure test. Few leaks were discovered and, when they were, fittings were tightened or replaced. No leaks were found. No leaks were found.
Sources: jet and eductor/compressor motive gas lines Methods: initial pressure test at startup followed by leak checks using soap solution	1/29/99 2/7/00	No leaks were detected during the 3-hour initial pressure test. (Complete documentation of this test, including data forms, strip charts, and certifications, is available.) No leaks were found.
Sources: jets, jet fittings, valves, and discharge lines Methods: initial pressure test at startup followed by leak checks using soap solution	1/30/99 10/3/99 2/7/00	One leak was found in the pressure test downstream of the 80 psig regulator and repaired. No leaks were found. Two leaks were found: One on the jet 1 motive gas valve and another on the jet 3 motive gas valve. The larger of the two, the jet 1 valve, was quantified at 0.0005 scfm (or 0.003 percent of total SAS flow). Both leaks were repaired.
Fuel Header Line to Engine	1/30/99	No leaks were found.

3.2.2 ECG Tertiary Seal Leaks During SAS Operation

When ECG leaks occur, they are liberated into the doghouse that vents through a header system and into the atmosphere. Continuous monitors were not installed on the doghouse vents because significant ECG leakage was not anticipated. As such, manual Flow Tube measurements were used to quantify leaks from the ECG tertiary seals. Flow Tube measurements were collected as indicated in Figure 3-1 (see manual measurements) and Flow Tube performance and procedures are described in Appendix A and Section 4.

Table 3-2 summarizes the ECG leak rates measured over the Phase I and II periods. The table presents the velocity measured as the tertiary seal leak passed through the Flow Tube. The natural gas flow rate determined from this velocity is also presented, along with the hydrocarbon concentration measured in the leaking gas stream. In some cases, the Flow Tube indicated a gas velocity of 0 and, in keeping with Flow Tube operating procedures, a flow rate equal to half of the lower detection limit is used in most cases (in most cases, some flow was observed). In a few cases, negative Flow Tube velocities occurred, indicating that gas inside the doghouse vent system can be pulled past the tertiary seal and into the SAS system. This negative flow likely occurred because the ECG suction pressure was negative, the rod packing emissions were low, and the tertiary seal lacks sufficient integrity to eliminate flow into or out of the ECG.

Based on the results presented in Table 3-2, average ECG leak rates were determined. Simply averaging all the values, with the exception of the negative values, yields the following average leak rates (with standard error with a 95 percent confidence interval):

- ECG on Rod 1: Average leak rate of 1.18 scfm natural gas (± 0.46 scfm)
- ECG on Rod 2: Average leak rate of 0.90 scfm natural gas (± 0.60 scfm)
- ECG on Rod 3: Average leak rate of 1.05 scfm natural gas (± 0.49 scfm)
- Average of the sums of the leak rates from all three ECGs: 2.65 scfm natural gas

The average leak rate of 1.05 scfm reported for the ECG on Rod 3 does not include extreme leaks measured during rod seal failure because there were no time-matched uncontrolled rod packing emissions and these large leaks were not representative of normal system operation. Leak rates for all ECGs ranged from 0.07 to 3.45 scfm, and were determined over a relatively wide range of rod packing emission rates: 0.43 to 6.28 scfm of natural gas.

Table 3-2. Measured Leaks From the ECG Tertiary Seals During SAS Operation

		3/25/99		3/26/99		4/27/99			4/28/99					9/29/99	2/9/00	2/10/00	2/11/00
	Sampling Time	1004-1010	1515-1520	1500-1505	1530-1545	1009-1032	1306-1318	1640-1709	925-937	1027-1035	1227-1235	1326-1341	1431-1447	910-1005	1025-1126	833-904	1428-1500
Rod 1	Gas velocity in Flow Tube (fpm)	500	0	0	0	614	614	825	655	678	572	430	120	440	203	256	265
	Leak rate (scfm natural gas)	1.36	0.08	0.08	0.08	1.68	1.68	2.25	1.79	1.85	1.56	1.17	0.33	1.38	-0.84[a]	-1.05[a]	-1.09[a]
	Hydrocarbon Concentration of the gas (%)	96	96	96	96	97	97	95	96	96	96	95	96	94	0	0	0
Rod 2	Gas velocity in Flow Tube (fpm)	285	0	0	0	219	170	119	244	236	55	0	0	453	749	1164	1131
	Leak rate (scfm natural gas)	0.78	0.08	0.08	0.08	0.60	0.46	0.32	0.67	0.64	0.15	0.08	0.08	1.42	2.22	3.45	3.35
	Hydrocarbon Concentration of the gas (%)	96	96	96	96	97	97	95	96	96	96	98	96	94	98	98	98
Rod 3	Gas velocity in Flow Tube (fpm)	1050	200	85	0	317	256	559	423	465	497	198	120	706	b	b	b
	Leak rate (scfm natural gas)	2.87	0.55	0.23	0.08	0.86	0.70	1.53	1.15	1.27	1.36	0.54	0.33	2.23	na	na	na
	Hydrocarbon Concentration of the gas (%)	96	96	96	96	97	97	95	96	96	96	95	96	94	na	na	na
Other Data	Total SAS leak rate (scfm gas)	5.01	0.71	0.39	0.24	3.14	2.84	4.10	3.61	3.76	3.07	1.79	0.73	5.03	1.38	2.40	2.26
	SAS Optimization Occur?	no	yes	yes	yes	no	yes	yes	yes	yes	Yes	yes	yes	no	yes	yes	yes
	Optimization Achieve design pressure?	na	yes	yes	yes	na	no	no	no	no	no	yes	yes	na	yes	yes	yes
	ECG Suction pressure (psig)	3.24	-0.57	-0.18	-0.14	3.17	2.30	1.25	3.95	4.57	1.19	0.16	-0.008	18.33	-0.73	-0.57	-0.48

a. Gas flowing back into the SAS system past the tertiary seal.
b. Rod 3 was isolated from the SAS due to excessive emission rates and to allow the system to be optimized and operate under normal conditions
na Not applicable.

Table 3-2 also presents the average ECG suction pressure occurring during each test, whether SAS optimization occurred prior to conducting the test, and whether the optimization was successful at reducing ECG suction pressures. As Figure 3-3 indicates, ECG leak rates tend to be lowest when ECG suction pressures are very low or negative. However, the figure also shows that this is not always the case; moderately high leak rates occur even when SAS operates near design ECG suction pressure. The reasons for this are unclear, but could be related to excessive seal wear, which allows some leaking to occur at any pressure.

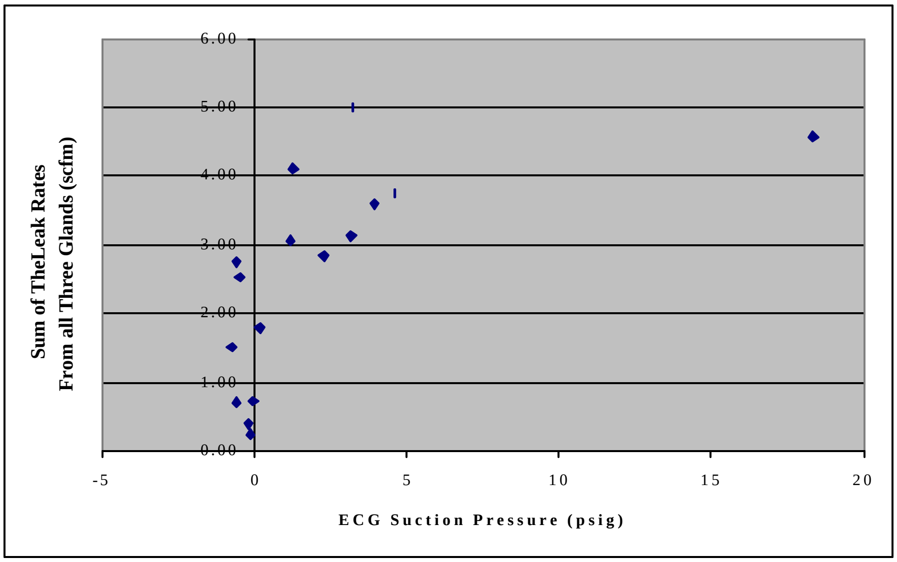

Figure 3-3. Impact of suction pressure on ECG leak rate

3.3 NATURAL GAS EMISSION CAPTURE PERFORMANCE

3.3.1 Choice of Continuous or Manual Measurements

Both manual and continuous measurements could be used to determine natural emission reductions for the SAS. At the conclusion of the Phase I study, it was speculated that the low-pressure region in the ECG annulus area could potentially increase the volume of gas leaking from the rod seal (i.e., ECG suction could actually pull additional gas from the packing case during SAS operation). Under such conditions, the amount of natural gas captured by SAS and measured with the continuous flow meters would be higher than actual rod emissions. In Phase I, this concern complicated the determination of natural gas emission reductions using continuous monitors, since the emissions captured could be overstated. It is now known that ECG suction can pull methane from the doghouse vent system into the SAS piping (see negative leak rates in Table 3-2 for rod 1), so speculation continues that this could also occur with rod seals or other components exposed to low ECG pressure. In addition, concern exists that SAS components exposed to pressures higher than internal SAS pressure could experience gas leakage into the system. For example, a SAS pressure relief valve (PRV), which is normally exposed to a vent-side pressure higher than that which exists within the SAS, could leak gas into the SAS if the PRV seal is fractured or improperly installed.

To assess these issues, gas flow rates measured during SAS operation (continuous meters) were compared with flow rates measured manually while the SAS was disabled (Flow Tube). Higher flows during SAS operation suggest that additional gas, other than that associated with the uncontrolled rod seals, is entering the system during operation. For the comparison, rod packing emissions were estimated using the in-line meters and ECG leak rates measured simultaneously with the Flow Tube. These estimated rod packing emissions were compared to values measured directly with the Flow Tube after disabling the SAS. Although not time-matched, the estimated and measured rod packing emissions were determined for periods that were within 30 minutes or less of each other. Figure 3-4 shows how estimated rod packing emissions were determined, which flow meters were used, and what mass balance assumptions were made. Figure 3-5 presents the results of the comparison.

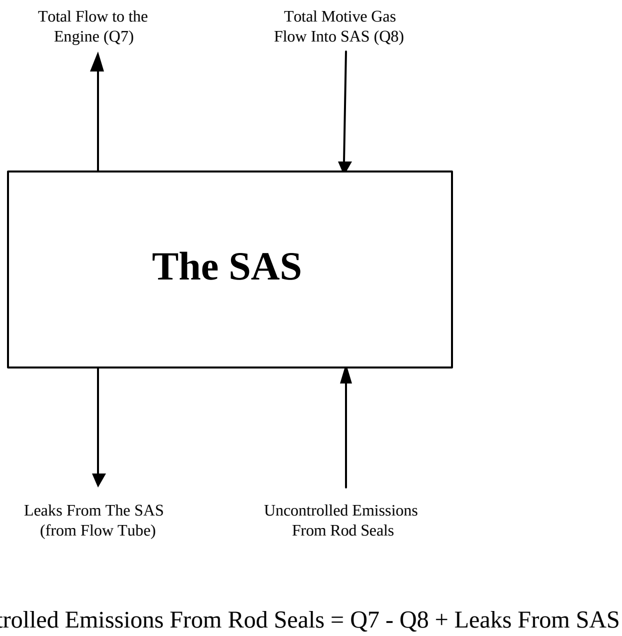

Figure 3-4. Determination of estimated rod packing emission rates

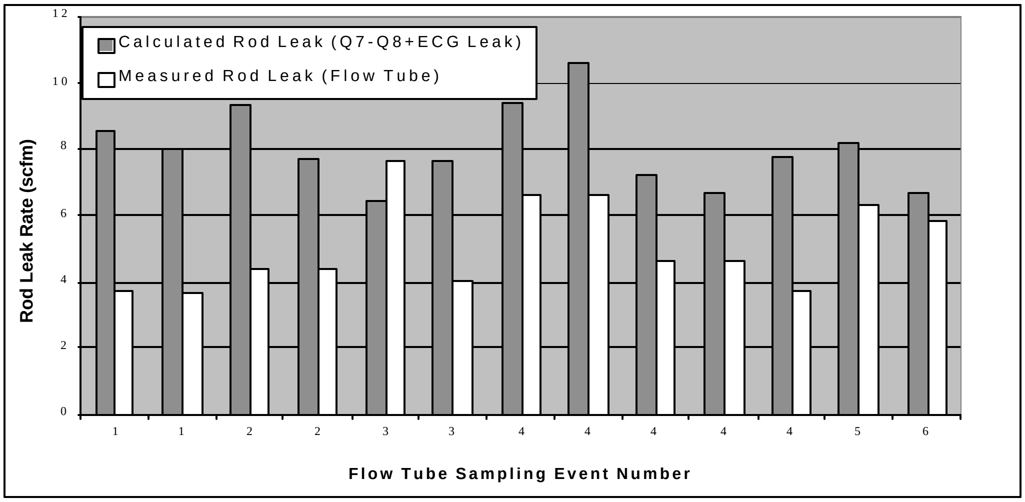

Figure 3-5. Comparison of rod leak rate determinations

Figure 3-5 shows that, with one exception, the "calculated" rod packing emissions are higher than actual rod packing emissions measured with the Flow Tube. This suggests that, in addition to the rod packing emissions, additional gas entered the SAS during operation. Efforts to identify the specific sources of this additional gas were unsuccessful. As mentioned previously, increased rod packing emissions may occur due to the negative pressures present in the ECG annulus area and, in at least one case, these negative ECG pressures pulled gas into the SAS from the doghouse header system.

Given that the flow monitors may not represent true emission reductions, and given that much of the continuous measurement data collected represent an engine/compressor operating in an unrepresentative state (Section 3.1), continuous monitor data are not used to determine emission reduction performance. Instead, manual measurements are used. Most manual measurements were collected following the completion of rod and other engine/compressor maintenance operations and, as such, should be reasonably representative of what most sites experience during normal operations.

In Section 4.1, the accuracy of the manual Flow Tube measurements and the in-line flow meters is discussed in detail. It is clear that each of the measurement devices met the accuracy and data quality goals stated in the Test Plan. The Center determined that the instrument and sampling bias for each was –3.5 percent for the Flow Tubes, -3.9 percent for the SAS discharge meter (Q7), and –5.0 percent for the motive gas meter (Q8). Since the bias of each instrument was similar, incorporating the error into the results has little effect on the difference between the two approaches that are summarized in Figure 3-5.

3.3.2 Emission Capture Results

Natural gas emission capture performance is defined as the percent reduction in rod packing emissions achieved by SAS. It is determined by calculating net gas savings; i.e., the rod packing emissions minus the gas leaking from the SAS. Both values are measured using the Flow Tube, but their determination is not simultaneous since the SAS must be operational to measure ECG leak rates, then disabled to measure rod packing emissions. Only measurements that were nearly simultaneous are used. Specifically, rod packing emissions and SAS leak rates measured within about 30 minutes of each other are used. Once determined, the net gas savings are divided by the rod packing emissions and multiplied by 100 to yield an estimate of the natural gas emission capture performance.

Table 3-3 summarizes natural gas emission capture performance over the Phase I and II periods. The table contains the same SAS leak rates presented earlier in Table 3-2, and includes the near-simultaneous rod packing emissions data determined using the Flow Tube. Columns are gray shaded when no near-simultaneous uncontrolled emission rate is available. As the table shows, emission capture performance varies widely from -34 percent (a net emission increase) to 95 percent. Negative emission reductions are possible because the SAS can leak both rod packing emissions and motive gas introduced into the SAS from the station's pipeline. The overall average emission capture is estimated to be 50 percent. A normality test on the emission capture data set was inconclusive because of the small number of data points (13 samples). However, the standard deviation of the data set is approximately 36.8 percent.

Efforts to correlate emission capture performance with rod packing emissions, ECG suction pressure, and ECG recycle rates were unsuccessful. In general, the strongest correlation exists with ECG suction pressure but, as noted earlier, low or negative ECG pressures do not always yield high capture rates. In the early stages of the verification, high capture rates and low suction pressures correlated well, but during Phase II, the correlation is not as strong. Capture performance did not exceed 80 percent during Phase II where, as during Phase I, values as high as 95 percent occurred. Although not conclusive, this may be evidence that ECG seal wear accelerated in Phase II, increasing emission levels during that period.

Table 3-3. Natural Gas Emission Capture Performance

		3/25/99		3/26/99		4/27/99			4/28/99					9/29/99	2/9/00	2/10/00	2/11/00
	Flow Tube ID.	2	2	2	2	2[b]	2	2	2	2	2	2	2	2[b]	2[b]	5	5
	Sampling Time	1004-1010	1515-1520	1500-1505	1530-1545	1009-1032	1306-1318	1640-1709	925-937	1027-1035	1227-1235	1326-1341	1431-1447	910-1005	1025-1126	833-904	1428-1500
Rod 1	Leak rate (scfm natural gas)	1.36	0.08	0.08	0.08	1.68	1.68	2.25	1.79	1.85	1.56	1.17	0.33	1.38	-0.84[a]	-1.05[a]	-1.09[a]
	Uncontrolled (scfm natural gas)	0.89	0.84	1.39	1.39		0.71	0.61	1.06	1.06	0.79	0.79	0.43			0.00	0.10
Rod 2	Leak rate (scfm natural gas)	0.78	0.08	0.08	0.08	0.60	0.46	0.32	0.67	0.64	0.15	0.08	0.08	1.42	2.22	3.45	3.35
	Uncontrolled (scfm natural gas)	0.46	0.59	0.43	0.43		1.60	0.78	0.74	0.74	0.90	0.90	0.76			6.33	5.70
Rod 3	Leak rate (scfm natural gas)	2.87	0.55	0.23	0.08	0.86	0.70	1.53	1.15	1.27	1.36	0.54	0.33	2.23			
	Uncontrolled (scfm natural gas)	2.38	2.25	2.57	2.57		5.32	2.63	4.80	4.80	2.95	2.95	2.54				
	Total leak rate (scfm natural gas)	5.01	0.71	0.39	0.24	3.14	2.84	4.10	3.61	3.76	3.07	1.79	0.74	5.03	1.38	3.45	3.35
	Total uncontrolled (scfm natural gas)	3.73	3.68	4.39	4.39		7.63	4.02	6.60	6.60	4.64	4.64	3.73			6.33	5.80
	Natural gas capture (%)	-35	81	91	95		63	-2	45	43	34	62	80			45	42

a. Gas flowing back into the SAS system past the tertiary seal.
b. Gray shaded columns represent periods when no near-simultaneous rod packing emission rate is available.

The overall emission capture efficiency used to characterize SAS performance is represented as the overall average value derived from the Phase I and II evaluations (50 percent). Without more conclusive data on the factors influencing emission performance of the SAS, the use of other emission capture efficiency relationships isn't justified.

3.4 METHANE EMISSION REDUCTION

3.4.1 Industry Average Engine/Compressor

As discussed in Section 3.1, the host site test unit experienced unusual operational and maintenance problems throughout the verification period, and these problems resulted in significant engine/compressor down time, subsequent data loss, and extreme operating conditions for SAS to respond to. These problems, coupled with abnormally high rod packing emissions, suggest the engine/compressor system was not operating in a representative state during the verification period. Given this, the annual methane emission reduction determined for the SAS is based on the emission and operational characteristics of a generic average engine/compressor system. Important assumptions made to define the generic system include the rod seal emission rate, the number of compressors used per engine, and the annual hours of operation.

The uncontrolled rod seal emission rate assumed is a key parameter used to estimate annual methane emission reductions. Based on the EPA/GRI and Pipeline Research Committee studies described earlier, average leak rates for reciprocating compressors vary between 0.98 and 1.86 scfm of natural gas per rod (GRI 1997, Hummel et al., 1996). Emission reductions are estimated for compressors that liberate emissions at both of these levels. The SAS was designed for installation on all compressors attached to an engine, so an industry average number of compressors per engine must be determined. Based on the EPA/GRI study, there are an average of 3.3 compressors used per engine in the natural gas transmission industry. To estimate annual methane emission reductions, three compressors per engine are assumed, the same as existed at the host site.

The SAS is designed to collect gas during normal operations, and the vendor claims it may also operate and collect emissions during pressurized standby mode when the engine is not running. However, testing in this mode was not encountered (the host unit never operated in this mode) so, for the purpose of determining annual emission reductions, it is assumed that pressurized standby operations do not occur during the year. Given this, the unit is assumed to operate continuously with the exception of downtime for scheduled maintenance and emergency shutdowns and repair. The amount of time compressors spend in this mode is not defined in the available literature but, based on the Center's experience, the time spent in these modes is generally small in the transmission sector: roughly 2 to 3 weeks a year or less. Three weeks of downtime is assumed here, resulting in an operating time of 8,232 hours per year.

3.4.2 Annual Emission Reductions

An important assumption used to estimate annual emission reductions is the natural gas leak capture efficiency used for the SAS. Based on testing conducted over about 1 year, an overall average capture efficiency of 50 percent is used. In general, this value is derived from two parameters measured at the host site: rod packing emissions and ECG leak rates. The ECG leak rates were determined over a wide range of rod packing emission rates (0.43 to 6.28 scfm) and, as such, should be applicable to units operating throughout the industry (especially the average unit). Rod packing emissions also include a broad range of values, and are representative of most normally operating units found in industry.

Although the host site experienced unusual operating problem and high emission levels, most of the manual measurements used to determine natural gas capture efficiency were collected following the completion of rod and other maintenance operations. As such, the emission reduction values derived from those measurements should be reasonably representative of sites operating normally. Although excessive ECG seal wear may have occurred, reducing the average leak capture estimate used here, it is unclear if this wear resulted from extreme operations at the host site, SAS design deficiencies, or both. Nevertheless, low SAS leak capture efficiencies occurred early in the study, suggesting seal wear was only one of several factors contributing to the low leak capture efficiencies achieved by the SAS.

Annual emission reductions of natural gas are determined using the following multiplication: rod packing emissions (scfm) * number of compressors * annual operating time (minutes) * leak capture efficiency (%). Emission reductions of methane are then calculated using the methane content of the pipeline gas determined by the pipeline operator. The pipeline monitoring station is approximately 400 miles upstream of the host site operation. At the monitoring station, a gas chromatograph is used to determine 24-hour average gas composition every day (calibration conducted daily also). Gas composition measured at the station is generally constant and, based on daily averages from the days when manual sampling was conducted, methane concentrations ranged from 96.6 to 97.0 percent. An average value of 96.8 percent methane is applied to determine methane emission reductions.

Table 3-4 summarizes the annual emission reductions of natural gas and methane determined for the test engine and generic average transmission compressor stations. Based on global warming potentials published by the Intergovernmental Panel on Climate Change (IPCC 1996), methane emission reductions range from 84 to 159 tons carbon equivalents per year (76 to 145 metric tons carbon equivalents per year).

Table 3-4. Annual Emission Reductions for Test Site and Industry Average Engine/Compressor Systems[a]

Rod Packing Emissions (scfm natural gas/compressor)	Emission Reduction (10^6 scf/yr)	
	Natural Gas	Methane
1.54 (test site average)	1.14	1.10
0.98	0.73	0.70
1.86	1.38	1.33

a. Natural gas emission capture performance 50%; operating 8232 hrs/yr.

3.5 SAS PAYBACK PERIOD

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 was compiled during Phase I, and estimates of annual gas savings were determined in Phase II. The total capital equipment cost for this standard system was estimated to be $30,933 in Phase I, and total installation cost for the standard system was estimated to be $11,841. Thus, the capital and installation cost for the SAS is estimated to be $42,774.

Payback was calculated based on the total capital and installation cost and the annual emission reductions measured at the site. Other assumptions included in calculation of payback period are a discount rate of return on investment of 10 percent, and an assumed gas price of $\$2/10^3\ ft^3$. The gas price was identified by the Oil and Gas Stakeholders as the average monetary value of natural gas for their industry in the past decade. The Center recognizes that recent increases in natural gas prices are likely to result in a change in this assumption. Payback is the expected length of time required for the future cash inflows from a capital investment to fully repay the original capital cost. Future incomes and expenses are discounted to the beginning of the analytical period, using an interest rate that represents the minimum acceptable rate of return for the industry. The stakeholders have identified this rate of return to be 10 percent. Payback is calculated using Equation 1 as follows:

(1) Estimating the costs (capital investment in the beginning year; operations, maintenance, overhead, etc. in all later years) and benefits (cost savings, revenues earned, etc.) for each year of the device's useful life.

(2) Discounting each year's net value (benefits minus costs) to the beginning year using an appropriate discount rate and formula.

(3) Sequentially adding each year's discounted value of its cash flows to the beginning year value until the discounted net present value of the device is no longer negative.

(4) Identifying the year that causes the aggregated net present value in (3) to be zero or greater as the payback period.

$$NPV = Capital\ Cost - \sum \frac{Gas\ Savings\ in\ Year\ t}{(1+r)^t} \qquad \text{(Eqn. 1)}$$

$$Payback\ Period\ (yrs) = first\ year\ when\ PV \geq 0$$

$Where:$

$NPV = net\ present\ value$

$t = year$

$r = discount\ rate\ of\ return, 10\%$

Under these assumptions, SAS payback is not achievable because the gas savings rate observed on the test engine (average of 50 percent) cannot overcome the investment cost of money. The highest gas savings rate observed during the verification period was 95 percent during Phase I. If station operators were able to maintain a gas recovery rate of 95 percent continuously, payback could be achieved in approximately 4 years assuming an average rod emission rate of 4.5 scfm period.

Design modifications are currently under way to reduce the capital cost of SAS and improve gas recovery performance. Cost of the device will be significantly reduced by incorporating the system directly into the packing case (rather than attaching a separate gland). Modifications have also been made to the jet manifold system to ensure better efficiency under adverse conditions such as those experienced at the test site.

4.0 DATA QUALITY

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 ($\pm$ 3 to 4 months of a target payback period of 3 to 4 years). Inherent in this objective is documentation of the SAS emission reduction performance.

The Test Plan specified that long-term SAS gas recovery and performance were to be evaluated using continuous metering of gas flows. To meet the maximum desirable error in the payback period estimate of 10 percent, manual leak rate measurements and the gas flow meters are required to be accurate within $\pm$ 10 percent. Mass flow meters capable of providing accuracy within $\pm$ 1 percent were used throughout the verification. As described earlier, station shutdowns and unfavorable engine operations precluded the collection of sufficient continuous gas flow metering to make a valid long-term evaluation of SAS performance. Therefore, the results presented and discussed in Section 3.0 were based largely on manual measurements conducted by the Center.

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 Leak Monitoring

Manual leak testing is required to determine the SAS emission reduction 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 55 to 6,800 fpm with an instrument rated accuracy of $\pm$ 1 percent of reading. Four different flow tubes were used during the manual sampling events. More detail regarding the design, use and calibration of the flow tubes is presented in the Flow Tube Standard Operating Procedure (SOP) of Appendix A.

Measured gas velocities were converted to volumetric flow rates by calibrating the anemometer against two laminar flow elements (LFEs). One LFE was used for low flow rate calibrations (up to approximately 3 scfm methane) and another was used for high flow conditions (up to approximately 10 scfm). The low flow LFE was calibrated with a NIST traceable reference dry gas meter, and a calibration curve was developed that provided flow rates in acfm air as a function of pressure drop across the element. The high flow LFE was factory calibrated with a NIST traceable master LFE, and a calibration curve was supplied by the manufacturer that provided flow rates in acfm air as a function of pressure drop. LFE calibration certificates tracing the accuracy of these devices to primary standards are presented in Appendix B.

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-inch incline oil manometer. Gas temperature, barometric pressure, absolute line 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 actual cubic feet per minute of methane as a function of measured gas velocity (Appendix A).

The SOP requires calibration of the Flow Tube at a minimum of four points over the operating range to determine its accuracy. The SOP also requires repeating the calibration at least 2 times to enable determination of precision. The replicate measurements required for precision are based on findings that precision does not vary significantly if the calibration is repeated 3 times, versus 2 times. Once the Center determined that the precision achieved using two replicates was similar to the precision achieved using three, the procedure of using only two replicates was adopted to reduce the amount of methane needed to conduct the calibrations.

A non-zero intercept for the linear regression plot is desired because the instrument is known to perform non-linearly at low gas velocities. In the field, the regression correlation is only used to interpolate between gas velocities observed in the laboratory. Thus, the Flow Tube velocities at low flow conditions are not extrapolated.

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	Were goals met?		
Fugitive Leak Monitoring						
Gas Velocity	Vane Anemometer	55 to 6800 fpm	1% reading	no[a]	Multiple calibrations with LFEs resulted in an average overall sampling error of –3.5% .	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						
SAS Discharge (Q7)	Mass Flow Meters – Integral Orifice	0 to 50 scfm	1% FS	yes	Performance checks[c] , calibrations in field and Center laboratory	Meets QA goals
Jet Motive Gas (Q8)	Mass Flow Meters – Laminar	0 to 20 scfm	1% FS	yes	Performance checks[c] , calibrations in field and Center laboratory	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] Data quality indicator goal for instrument was not met, but the overall DQO of 10% was met.

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

FS = Full Scale

Table 4-2 summarizes calibration results for the Flow Tubes, and shows the bias and precision values developed from these data. The average Flow Tube mean bias values presented for each run were calculated from the individual measurements in a run. Each run consisted of a series of comparisons at five or six different flow rates ranging from 0 to 3.0 scfm methane for low flows and 0 to 8.0 scfm for high flows (see Appendix A for an illustration of a calibration curve for a vane anemometer). Precision is calculated as the average of the CV (coefficient of variation which, for paired measurements, is equivalent to 0.707 times the absolute value of the difference divided by the mean value of the pair) at each of the velocity values for the run. Individual measurement accuracy values were calculated by determining the difference between the Flow Tube and LFE flow rates (Flow Tube minus LFE), dividing this value by the LFE flow rate, and then multiplying by 100. As the table shows, the average accuracy (bias) of the Flow Tubes equipped with vane anemometers ranged from –7.3 to 0.0 percent of the value measured by the LFE. The overall average accuracy of all four tubes used was –3.23 percent, well within the goal of 10 percent. This value includes instrument error and any error introduced by the sampling procedure. The lower detection limits presented in the table were determined by applying the lowest possible velocity reading for the anemometers (55 fpm) to each of the calibration curves.

Table 4-2. Summary of Flow Tube Calibrations

Calibration Date	Flow Tube ID	Calibration Run No.	Calibration Range (scfm)	Lower Detection Limit (scfm)	Mean Bias (%)	Precision as CV RSD (%)
4/2/99	ID-2 CH_4	1	0.00 to 3.47	0.19	-3.0	$\pm$ 3.18
		2	0.80 to 2.73	0.17	-5.0	
2/2/00	ID-3 CH_4	1	0.00 to 2.94	0.20	-3.3	$\pm$ 0.14
		2	0.00 to 3.23	0.20	-5.3	
9/27/99	ID-2 CH_4	1	0.00 to 3.08	0.19	-2.5	$\pm$ 1.92
		2	0.38 to 3.07	0.23	-2.5	
12/2/99	ID-4 CH_4	1	1.99 to 7.67	0.18	-4.5	$\pm$ 1.12
		2	2.11 to 8.00	0.18	-7.3	
1/10/00	ID-5 CH_4	1	0.00 to 3.14	0.14	-0.8	$\pm$ 0.83
		2	0.00 to 3.16	0.13	0.0	
6/27/00[a]	ID-5 Air	1	0.00 to 2.15	0.33	-3.0	$\pm$ 4.83
		2	0.00 to 2.00	0.34	-1.5	

[a] This calibration was conducted with air to determine the flow rate of air going into the Rod 1 doghouse vent during the February 2000 sampling event.

4.1.2 SAS Gas Flows

Total gas flow directed from the SAS to the fuel header (Q7) was metered using a Rosemount Model 1195 orifice meter equipped with a Model 3095 transmitter. Motive gas introduced to the SAS to energize the system was metered using Q8, which was a Universal Flow Monitors Flowstream mass flow meter. Gas recovery by the SAS was defined as the difference between meters Q7 (SAS discharge total flow) and Q8 (SAS motive gas flow). As described in Section 3.0, the frequently occurring extreme operating conditions observed on the test compressors precluded the ability to use the continuous data to form long-term evaluations on the SAS. However, to ensure that the accuracy and precision goals of 1 percent of full scale are met, the Plan called for following all manufacturer 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 & Startup 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 DP and flow with the EA software. In this condition, the flow output should read zero, and the DP measured should be zero. A small DP at zero can be corrected by offsetting the transmitter output, provided the DP is stable. The meter was zeroed at the beginning of the verification, and confirmed in September 1999 and February 2000 to be reading zero when isolated from the flow. 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.

- Q8 (Jet Motive Gas Flow)

Setup & Startup Checks: This laminar flow meter was 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 by an over-range at +21 mA. During installation, the meter was checked to ensure that it was reading properly.

Sensor Function Checks: Reasonableness checks were made daily while reviewing the data to ensure that valid data were being obtained. In addition, five tests were conducted in the field to evaluate the comparability of the Q7 and Q8 meters. These tests were conducted by isolating the flow of gas while the SAS system was off, and directing the gas through both meters simultaneously. Results of these tests are summarized in Table 4-3 and indicate an average percent difference in the two meters of approximately –3.9 percent, which is within the standard error of each instrument.

Calibration: Manufacturer-supplied calibration certificates were obtained and reviewed for the flow meter. In addition, the flow meter was field-calibrated with a newly calibrated sensor.

- Post Test Activities

At the conclusion of the test, the meter was returned to the Center for examination. Laboratory calibrations showed a consistent low bias in the Q8 meter. After investigating the discrepancy in calibration values, it was determined that the factory calibrations had a 7 percent error. The Center discovered that the factory used a methane viscosity of 116 micropoise when converting calibration flow rates from air to methane. The published experimental values at 70°F range between 108.7 and 109.2 micropoise (Perry et al., 1984; and CRC, 1979). In response to this difference, the Q8 values reported in Section 3 were corrected for the 7 percent bias.

Additionally, the flow rate comparability tests that were conducted on Q7 and Q8 in the field were repeated in the laboratory, along with a laminar flow element as a reference. The differences observed between the three flow measurement devices are summarized in Table 4-3. Results indicate the Q7 and Q8 were in close agreement in the laboratory with an average difference of only 1.6 percent. The average absolute differences between Q7 and Q8 were 0.28 scfm during the field comparison tests, and 0.32 scfm in the laboratory. The average absolute differences between the meters and the reference LFE were 0.44 scfm for Q7 and 0.63 scfm for Q8. These differences are well within the uncertainty associated with each meter: ± 0.50 scfm for Q7 and ± 0.20 scfm for Q8, and therefore meet the data quality goals for these measurements.

Table 4-3. Summary of Flow Meter Comparisons

Test Location	Date	Measured Flow Rates (scfm methane)			Percent Differences		
		Reference LFE	Q7	Q8	LFE vs. Q7	LFE vs. Q8	Q7 vs. Q8
Field Checks (meters in line)	2/8/00	--	15.70	15.73	--	--	-0.2
	2/10/00	--	9.39	10.24	--	--	-9.1
	2/11/00	--	2.95	3.04	--	--	-3.1
		--	4.16	4.34	--	--	-4.3
		--	9.61	9.87	--	--	-2.7
Average Difference							**-3.9**
Laboratory Checks	7/10/00	10.95	10.58	10.45	-3.38	-4.6	-1.23
	7/11/00	12.20	12.04	11.39	-1.31	-6.6	-5.40
		15.23	14.53	14.47	-4.60	-5.0	-0.41
	7/17/00	11.44	10.90	10.99	-6.47	-3.9	0.83
Average Difference					**-3.9**	**-5.0**	**-1.6**

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 operating 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. The P4 and P5 transmitters were compared to an oil manometer in the laboratory at the conclusion of the verification test. At 1.0 psig, both transmitters were within approximately 0.02 psig of the manometer indicating that the meters were operating well within the goal of 0.5 percent of full scale (0.1 psig). 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 Determination of Fugitive Emissions From SAS Component Leaks

In one instance during the Phase II testing, two small leaks were discovered by the soap screening process. Both leaks were in pipe thread connections upstream of the SAS jets. To determine if the leaks were significant with respect to total SAS flow, the larger of the two was measured and quantified. The leaking joint was enclosed with a Tedlar bag. A vacuum pump was used to pull clean air through a small hole in the bag and to a rotameter and methane sensor. The component leak rate was calculated using the air flow measured with the rotameter and the measured methane concentration at the pump outlet. The leak was determined to be approximately 0.0005 scfm, or 0.003 percent of the total SAS flow.

The rotameter used to measure air flow was calibrated against a laminar flow element using the same procedures used to calibrate the Flow Tubes and was found to have an accuracy of 7.68 percent which is well within the $\pm$ 15 percent accuracy expected in the procedure.

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APPENDIX A

Flow Tube Measurement Procedures

Appendix A-1: Flow Tube Standard Operating Procedure (SOP)

STANDARD OPERATING PROCEDURE
FOR USING THE FLOW TUBE
TO CONDUCT DOGHOUSE VENT MEASUREMENTS

Contents:

SOUTHERN RESEARCH
INSTITUTE

I. Instrument Descriptions

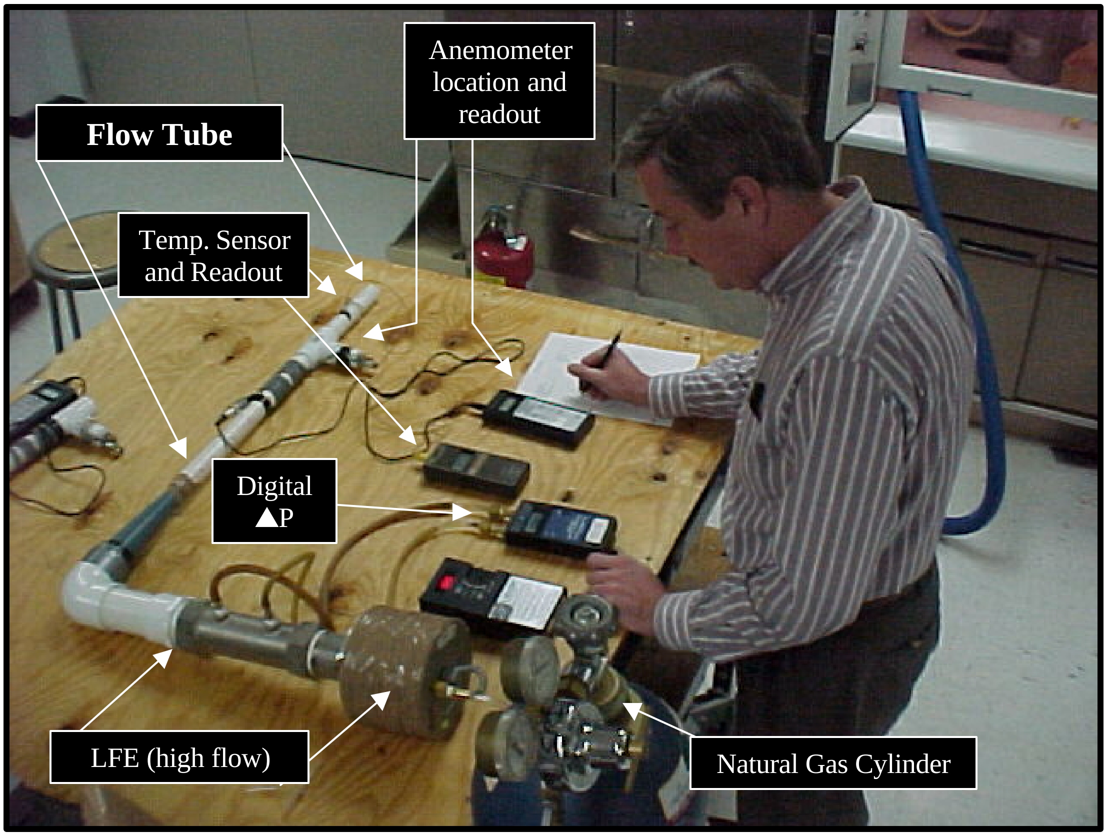
Flow Tube

The Flow Tube, shown in Figure A-1, consists of a vane anemometer housed in a flow straightening PVC tube with an inside diameter of about 1-inch (7/8 inch ID) and an overall length of approximately 30 inches. An anemometer is placed in the tube (Omega Model HH-31A) to measure gas velocity in the range of 60 to 6,800 feet per minute (fpm).

Measured gas velocities are converted to volumetric flow rates by calibrating the anemometer against a laminar flow element (LFE), made by Merriam Company. The Flow Tube calibration is a direct comparison with the laminar flow element, which is traceable to NIST. The calibration is performed prior to each measurement trip at the Center's Research Triangle Park, NC laboratory. It consists of no fewer than five points spanning the flow rate of interest (0.15 scfm to 4 scfm methane for doghouse vents; up to 20 scfm for other sources). A properly calibrated flow tube will provide accurate and reliable readings above flows of about 0.3 scfm of natural gas. Accuracy values ranging from about 0.5 percent to less than 3 percent of actual readings should be anticipated for the Flow Tube based on the Center's experience. Similar accuracy values have been observed at flows as high as about 10 scfm.

As a function of instrument sensitivity, the Flow Tube has a lower detection limit (LDL) ranging from about 0.14 to 0.20 scfm of natural gas, depending on the calibration curve for a specific tube. If during low flow testing it can be visually confirmed that the vane within the Flow Tube is not moving during testing, then the emissions should be reported as zero. If the vane is moving during low flow testing but no reading is reported by the anemometer, a value of one-half of the LDL is assigned.

Figure A-1. Flow Tube Calibration Operation



Hydrocarbon Analyzer

A Bascom-Turner CGI-201 hydrocarbon analyzer is used to determine hydrocarbon concentrations. It is capable of detecting 4 to 100 percent total hydrocarbon concentration, with an accuracy of $\pm$ 2 percent of reading. The CGI-201 is calibrated prior to each measurement trip. Calibrations are performed in the laboratory using certified methane standards at 2.5, 25, 50, 75, and 100 percent methane. Calibrations are performed using the calibration apparatus provided by the manufacturer (Part numbers MC-105 and PCA-001), and by following the manufacturer's calibration procedures.

II. PRE-TEST SETUP AND CALIBRATION PROCEDURES

Prior to each field measurement trip, perform laboratory calibrations on the Flow Tube and the hydrocarbon analyzer as described below. It is recommended that calibrations be performed upon return from the field, to ensure instrument damage did not occur in transport.

Flow Tube Calibration Procedures

This procedure is specific to the use of a Laminar Flow Element. Other reliable calibration standards are available, and procedures may vary from those presented below if they are used. Materials required include a Flow Tube, Laminar Flow Element or LFE, Omega HH-25 KC temperature transmitter and thermocouple, oil manometer or calibrated digital manometer, pressure transducer, miscellaneous fittings and hardware.

- Assemble the Flow Tube in-line with the LFE so that the calibration gas can be regulated to flow through both instruments.

- Connect a manometer to the LFE. Zero the manometer when no flow is occurring. When gas is allowed to flow through the LFE, the manometer will display a pressure drop across the instrument. Connect a pressure transducer or second manometer to the inlet of the LFE to record inlet absolute pressure. Connect the temperature transmitter to the in-line thermocouple.

- Record the barometric pressure and the ambient temperature on the log sheet.

- Open the flow regulator on a gas cylinder of methane (about 95 percent) or natural gas, and initiate gas flow into the Flow Tube and the LFE.

- Observe the point where the vane anemometer begins to turn, allowing the readings to stabilize (typically 15 to 20 seconds). Push the 16-sec average button on the vane anemometer transmitter. Record the velocity displayed and the pressure drop shown on the manometer in the log sheet. Record the LFE inlet absolute pressure, and record the exit gas temperature.

- Increase the gas flow until pressure drop increases are at intervals of 2.0, 4.0, 5.0, 6.0, and 8.0 inches of water. Record the 16 second average velocity and the temperature of the gas at each pressure interval. A minimum 5 point calibration will be conducted, and this result will be useful for methane gas flows ranging from about 0.5 to 3 scfm. If higher flows are anticipated, a larger LFE should be obtained and the procedure above repeated.

- Repeat the above procedures a second time to achieve a duplicate calibration result (i.e., match the LFE pressure drops from the previous runs). These data will be used to determine precision.

- Determine the slope and y-intercept of the equation that relates gas flows as a function of velocity readings (see analytical procedures below). A straight line relationship has been observed in calibrations conducted by the Center up to flows of about 10 scfm of natural gas. Typical calibration charts are shown in Figure A-1 and A-2. Calculate the accuracy of these measurements, using the calculations presented later in this SOP.

FLOW TUBE CALIBRATION LOG FORM

Anemometer Make/Model:_______________________
Anemometer Serial Number:_______________________
LFE ID: ____________________
LFE Calibration Value: Delta P (in H2) = __________
ACFM air = __________

Barometric Pressure: ____________
Ambient Temp (K): ____________
Calibration Gas: ____________
Operator: ____________
Date: ____________

Run 1

Run 2

Velocity (fpm)	Delta P (in. H_2O)	Temp.	Anemometer (fpm)	Delta P 2	Tube (K)

Figure A-1. Example Flow Tube Calibration (Low Flows - 2/2/00)

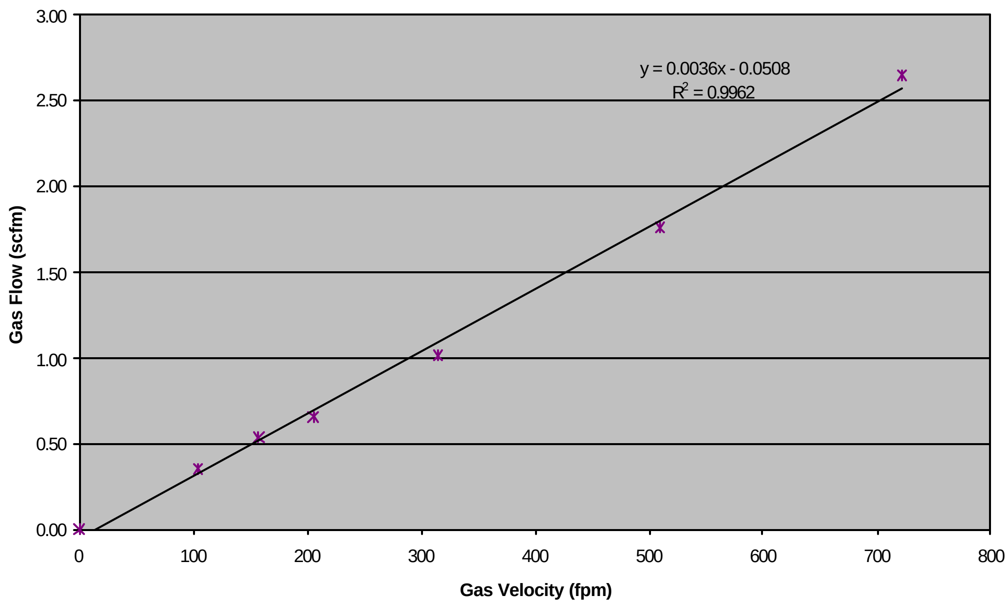
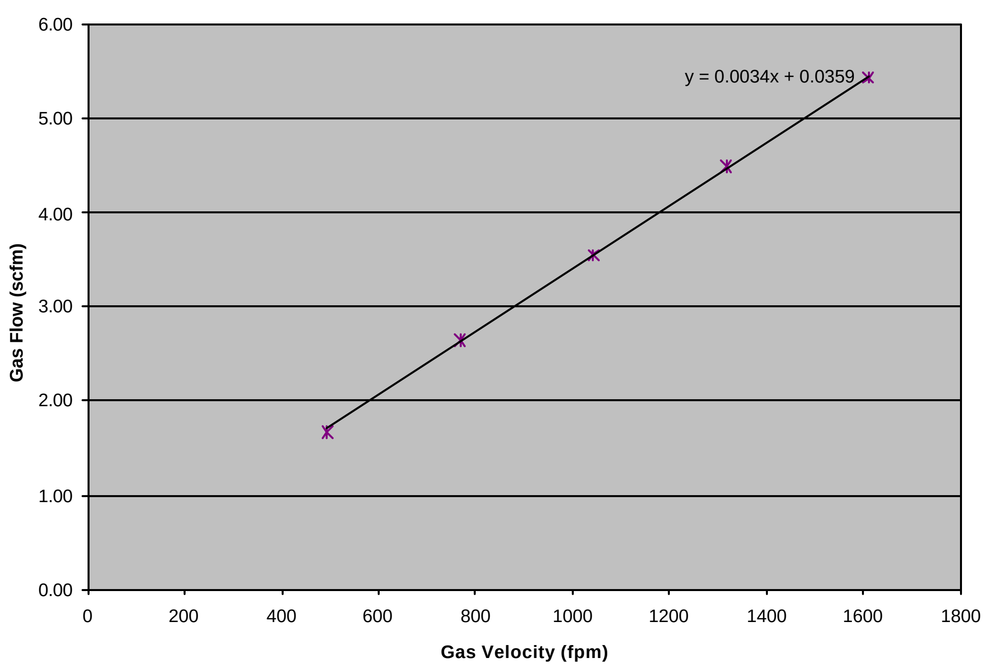


Figure A-2. Example Flow Tube Calibration (High Flows - 8/11/99)



CALCULATION OF CALIBRATION FLOWS AND FLOW TUBE ACCURACY

1. Using the following equations, determine the flow of air, and then of natural gas (nat gas) at standard conditions for each set of LFE pressure drop readings measured during a calibration.

$$\textbf{LFE ACFM}_{\textbf{air}} = [\textbf{LFE Delta P}]\ [\textbf{LFE Cal. ACFM}_{\textbf{air}} / \textbf{LFE Cal. Delta P}]$$

Where:
LFE Delta P = pressure drop measured by the digital manometer for the LFE
LFE Cal. ACFM $_{air}$ = obtained from calibration certificate of NIST traceable LFE
LFE Cal. Delta P = obtained from calibration certificate of NIST traceable LFE, in H_2O

$$\textbf{LFE ACFM}_{\textbf{nat gas}} = [\textbf{ACFM}_{\textbf{air}}]\ [\textbf{u}_{\textbf{nat gas}} / \textbf{u}_{\textbf{air}}]$$

Where:
$u_{nat\ gas}$ = viscosity of methane (the major constituent in natural gas) at the test gas temperature (110 centipoise @ 20 ^{o}C based on Perry's Chemical Engineer's Handbook)
u_{air} = viscosity of air at 20 ^{o}C (185 centipoise based on Perry's Chemical Engineer's Handbook)

$$\textbf{LFE SCFM}_{\textbf{nat gas}} = [\textbf{ACFM}_{\textbf{nat gas}}]\ [\textbf{P}_{\textbf{a}} / 14.7]\ [298 / \textbf{Tube T}]$$

Where:
P_a = absolute pressure at LFE inlet, psia
Tube T = gas exit temperature, K

2. Generate a linear plot through the calibration points similar to those shown in Figures A-1 and A-2. Plot measured anemometer velocity (**fpm**) on the x-axis and the measured flow of natural gas (**LFE SCFM $_{nat\ gas}$**) on the y-axis. Perform a least-squares linear regression to obtain the slope (m) and the y-intercept (b). The r-squared values for this equation should be 0.95 or better.

3. The following linear equation describes the natural gas flows at the observed anemometer velocity readings. Flow Tube accuracy is determined based on this value and the measured value as shown below.

$$\textbf{Flow Tube SCFM}_{\textbf{nat gas}} = \textbf{m}\ [\textbf{Anemometer Velocity}] + \textbf{b}$$

$$\textbf{Accuracy (\%)} = [\textbf{Flow Tube SCFM}_{\textbf{nat gas}} - \textbf{LFE SCFM}_{\textbf{nat gas}}] / \textbf{LFE SCFM}_{\textbf{nat gas}} * 100$$

4. Convert flows of natural gas measured in the field into flows of methane using gas compositional data routinely collected by the pipeline operators.

5. Precision is calculated as the average of the CV (coefficient of variation, which for paired measurements is equivalent to 0.707 times the absolute value of the difference divided by the mean value of the pair) at each of the velocity values for the run.

Hydrocarbon Analyzer Calibration Procedures

These methane meters actually have two sensors: one for low-range methane concentrations (up to 2.5 percent) and another for high-range (up to 100 percent). The two sensors are calibrated separately using clean air (compressed zero air) as a zero reference and five levels of certified methane reference gas including approximately 2.5, 25, 50, 75, and 100 percent methane in balance nitrogen.

Gases are introduced to the meter using a pressure controlled regulator and Teflon tube. The tubing incorporates a "T" so that excess calibration gas is dumped to the atmosphere to prevent overpressurizing the meter. The calibration procedure is to zero the sensors first using clean air and adjust (using potentiometer) if necessary. Next, the 2.5 percent reference is introduced and the meter self adjusts its low range sensor response to that gas. The 100 percent reference is next introduced to span the high range sensor. Again, adjustments are made using a potentiometer if necessary to obtain the correct response. Finally, the remaining reference gases are introduced sequentially without making adjustments to the meter to verify linearity.

If proper responses are unobtainable using the potentiometer or the responses are not linear, then either the sensor is replaced or the meter is sent to the manufacturer for service or repair. Calibrations are conducted each time prior to being used in the field.

In the field, the meters are used to determine methane concentrations. Prior to use, the instrument is turned on in the "zero instrument" mode, exposed to clean outdoor air, and allowed to self zero the sensors. The meter is then turned to "read gas" mode and allowed to read the outdoor air to verify the zero reading. The probe tip is manually plugged until the meter displays "bloc" to ensure that the probe is leak free. The meter is then ready for use. Methane concentrations are determined by inserting the probe tip into vent pipes where appropriate, or near suspected leak locations (e.g., flanges, valves, fittings).

HYDROCARBON ANALYZER CALIBRATION LOG FORM

Date of Calibration:____________________

Operator:____________________________

Barometric Pressure:__________________

Ambient Temp:________________________

Make/Model:________________________

Serial Number:______________________

Calibration Gas:_____________________

Reference Concentration	Sensor Response Before Adjustments	Sensor Response After Adjustments

III. Leak Rate Measurement Field Procedures
(Compressor Doghouse Vents)

1. Follow manufacturer's procedures for the hydrocarbon analyzer (auto-zero away from the engine room).
2. 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

3. Disconnect doghouse vent union. Directly attach hydrocarbon analyzer inlet to the open doghouse vent using a leak free connection. Check for leaks by soap screening all connections with a 1 percent diluted soap solution (place about ¼ cup of dish soap into a spray bottle, then fill with water). Tighten or repair any leaking fittings before proceeding. Plumb all drains.
4. Allow a minimum of 30 minutes to purge the doghouse of air, and ensure the exiting gas has a composition which is close to pure natural gas (i.e., between 92 to 98 percent total hydrocarbons). Measure and record hydrocarbon concentration after the purge period is complete. If gas composition is too low, continue the purge and record hydrocarbon readings at 5 minute intervals. Use extreme caution if gas concentration is in the explosive range (5 to 15 percent of methane in air). If pure natural gas is not measured at the end of the purge period, this is evidence that air is leaking into the doghouse. Locate and repair any leaks before proceeding.
5. Remove the hydrocarbon analyzer and insert temperature probe into the doghouse vent. Measure and record the gas temperature after stable readings are achieved.
6. Remove the temperature probe and attach the Flow Tube to open doghouse vent with a leak tight connection. Again, soap screen all connections.
7. Program the anemometer display to provide 16 sec average velocity readings following the manufacturer's instructions.
8. Record 16 sec velocity readings, until a minimum of 10 readings are recorded. Continue collecting and recording velocity readings until three adjacent readings are within 5 FPM of each other.
9. Remove the Flow Tube and repeat the procedure if results are highly variable, or trend upward or downward. (Consult Section 3.0 for example data.) Continue repeating until a reasonably steady state flow rate data set is collected (i.e., the standard deviation from a series of measurements, divided by the average emission rate, is about 7 percent or less).
10. Use Flow Tube calibration data collected prior to the test to convert these velocity readings directly into natural gas flow rates (scfm). Plot the data and, if normally distributed, determine the average natural gas emission rate.
11. Use natural gas compositional data routinely collected by the pipeline operator, to convert natural gas values determined in step 10 above into methane emission values. Obtain the pipeline operator's calibration data used to determine gas composition.
12. Insert the hydrocarbon analyzer, and measure and record the final hydrocarbon concentration.
13. Repeat above procedures for remaining doghouse vents.

DOGHOUSE VENT MEASUREMENT USING FLOW TUBE
LOG FORM

Engine ID:________________________________
Flow Tube ID:________________________
Flow Tube Calibration Date:_____________

Date:_________________________
Ambient Temp:_________________
Barometric Pressure: ___________
Operator:_____________________

Time:_____________
Rod Number:_____________
Compressor Operating Pressure:______________

Initial Total Hydrocarbons (%):_________________
Gas Temp (^{O}C):_______________________

Leak Rates (16 Sec Avg FPM):

____________	____________	____________
____________	____________	____________
____________	____________	____________
____________	____________	____________
____________	____________	____________

Final Total Hydrocarbons (%):_________________

APPENDIX B

Laminar Flow Element Calibrations

Meriam Instrument
a Scott Fetzer company

FILE NO. 040FB:001-19
PAGE 1 OF 1

LETTER OF CERTIFICATION
LAMINAR FLOW ELEMENT

CUSTOMER NAME: SOUTHERN RESEARCH INSTITUTE

CUSTOMER ORDER NUMBER: 30584

MERIAM ORDER NUMBER: 779480

Meriam Instrument certifies that the completed LFE unit has been calibrated and correlated at several points of flow rate using a Meriam Standard, which is controlled per the calibration system requirements of ANSI Z540-1 and traceable to the National Institute of Standards and Technology. The collective uncertainty of the measurement standards has a 1:1 ratio to the acceptable tolerance for the flow rate being calibrated.

The total rss uncertainty of the completed laminar flow unit is +/- .72 % of reading.

MODEL NO.: 50MW20-2 SERIAL NO.: 720140-A2

FLOW CURVE/TABLE NO.: 32161 , 32162

DATE OF CALIBRATION 02-04-2000 BY GEORGE ROBOTKAY

AS RECEIVED CONDITION: ____In Tolerance ____Out of Tolerance ✓ NA

AS LEFT CONDITION : ✓ In Tolerance ____Out of Tolerance ____NA

CALIBRATION INTERVAL: TO BE DETERMINED BY CUSTOMER BASED ON USAGE OF LFE.

FLOW STANDARD SERIAL NO.	DATE OF LAST CAL	DATE OF NEXT CAL
WMMH10-2	MAY 1999	MAY 2000

The LFE unit listed hereon has been successfully calibrated in accordance with Meriam Instrument Procedure A-35822.

Christine McCutcheon
FLOW DATA TECHNICIAN
MERIAM INSTRUMENT

Daniel P. Milligan
QUALITY ASSURANCE MANAGER
MERIAM INSTRUMENT

10920 Madison Avenue • Cleveland, Ohio 44102 • (216) 281-1100 • FAX (216) 281-0228
www.meriam.com

Standard
LAMINAR.BAS VER 1.38 MARCH 1999

CALIBRATION DATE 02-04-2000 PLOT NUMBER 112

LAMINAR MODEL # 50MW20-2 WORKING MASTER SERIAL # WMMH10-2

SERIAL # 720140-A2 MASTER MASTER SERIAL # MMMH10-2

CURVE # 32161 JOB # 779480

uut = Unit Under Test

DATA AS INPUT FROM DATA SHEET mas = Master

RH %	Tuut DEG F	Tmas DEG F	PSuut PSIA	PSmas PSIA	DPuut In H2O	DPmas In H2O
27.0	68.6	69.0	14.223	14.181	1.011	0.986
26.7	68.6	69.1	14.220	14.142	2.011	1.960
26.3	68.7	69.2	14.217	14.102	3.007	2.932
26.1	68.7	69.4	14.212	14.063	4.011	3.912
25.8	68.7	69.4	14.206	14.020	5.004	4.887
25.6	68.8	69.5	14.199	13.980	6.003	5.875
25.3	68.8	69.6	14.193	13.937	6.998	6.862
25.2	68.8	69.6	14.187	13.894	8.005	7.869

Master LFE coefficients
A1 = 1.04483E+03
B1 = -3.40485E+06
C1 = -1.62140E+10

REDUCED DATA, BASED ON MASTER LFE COEFFICIENTS:

DATA POINT	DP uut InH2O@4C	FLOW IN ACFM BASED ON MASTER	CFM* (DATA) BASED ON MASTER	CFM* (CURVE) B*DP+C*DP^2	PERCENT ERROR**
1	1.011	5.613474	5.601402	5.591904	-0.17
2	2.011	11.044104	11.020738	11.018240	-0.02
3	3.007	16.350414	16.316963	16.330672	0.08
4	4.011	21.595029	21.551602	21.581707	0.14
5	5.004	26.694927	26.642177	26.676022	0.13
6	6.003	31.756490	31.694847	31.698463	0.01
7	6.998	36.685782	36.617131	36.609373	-0.02
8	8.005	41.609874	41.533460	41.471940	-0.15

*CFM = ACFM x (Flowing viscosity in Micropoise / 181.87)

** PERCENT ERROR = ((CURVE-DATA) / DATA) * 100

A Least Squares Fit of the CFM(DATA) yields the following formula and LFE uut coefficients used to generate the CFM(CURVE) values:

CFM(CURVE) = (B x DP) + (C x DP^2) Where B = 5.58000E+00
C = -4.98592E-02

A Flow of 41.449001 CFM produces a UUT DP of 8.00 In H2O

TERMINAL NON-LINEARITY = 3.568 %
INDEPENDENT NON-LINEARITY = 1.165 %

FOR DETAILS SEE FILE NO. 501:440

PRINTOUT DATE :02-04-2000

Filename : 72014002.2AP

HPPOLY.BAS VER A

TODAY'S DATE 02-04-2000

REPORT TIME:11:44:36

MODEL# :50MW20-2

SERIAL# :720140-A2

JOB# :779480

TERM	COEFFICIENT
0	1018.26458740234
1	-5052554.60739136
2	42117524892.0918

(RHO*DP)/ MU^2	(Q*MU)/ DP	Y-CALC	DIFF	PCT-DIFF
2.23090E-06	1007.29999	1007.2024584	0.0975294	0.0097
4.42290E-06	996.77002	996.7415476	0.0284719	0.0029
6.59520E-06	986.64001	986.7739508	-0.1339361	-0.0136
8.77100E-06	976.96002	977.1887511	-0.2287291	-0.0234
1.09070E-05	968.04999	968.1667883	-0.1168005	-0.0121
1.30440E-05	960.08002	959.5251921	0.5548250	0.0578
1.51570E-05	951.33002	951.3588736	-0.0288565	-0.0030
1.72800E-05	943.35999	943.5326669	-0.1726815	-0.0183

THE AVERAGE Y IS = 973.81122

STANDARD ERROR OF ESTIMATE = 0.29418

INDEX OF DETERMINATION = 0.99988

Standard
HPLFE.BAS VER 1.21 OCTOBER 1993

CALIBRATION DATE	02-04-2000	PLOT NUMBER	112
LAMINAR MODEL #	50MW20-2	WORKING MASTER SERIAL #	WMMH10-2
SERIAL #	720140-A2	MASTER MASTER SERIAL #	MMMH10-2
CURVE #	32162	JOB #	779480

DATA POINT	TUUT DEG F	DP uut InH2O@4C	FLOW IN ACFM BASED ON MASTER	(RHO*DP)/ MU^2	(Q*MU)/ DP
1	68.6	1.011	5.6133	2.2309E-06	1.0073E+03
2	68.6	2.011	11.0433	4.4229E-06	9.9677E+02
3	68.7	3.007	16.3486	6.5952E-06	9.8664E+02
4	68.7	4.011	21.5919	8.7710E-06	9.7696E+02
5	68.7	5.004	26.6900	1.0907E-05	9.6805E+02
6	68.8	6.003	31.7493	1.3044E-05	9.6008E+02
7	68.8	6.998	36.6759	1.5157E-05	9.5133E+02
8	68.8	8.005	41.5968	1.7280E-05	9.4336E+02

RHO = FLOWING DENSITY IN LBS/F^3
MU = FLOWING VISCOSITY IN MICROPOISE
DP = INCHES OF H2O @ 4 DEG C
Q = FLOW IN ACTUAL CUBIC FEET PER MINUTE

Filename : 72014002.2AP

CHEROKEE INSTRUMENTS, INC.
Flow Rate Calibration
Laminer Flow Element
Air Calibration Data

SRI ID #: Laminer Flow Element
Model #: NA
Serial #: 713920-V1

Date: 8/6/99
Barometric Pressure: 29.94 in. Hg

CALIBRATION DEVICE INFORMATION

Delta H (in. H_2O)	Time (minutes)	Initial (ft^3)	Final (ft^3)	Total (ft^3)	Temperature (°F) Initial	Temperature (°F) Final	Temperature (R)	Element Flow Rate (scf)	Element Flow Rate (scfm)
1.00	36.0	160.886	168.804	7.918	93	94	553.5	7.575	0.210
2.50	19.0	169.278	179.120	9.842	94	94	554.0	9.442	0.497
4.00	27.0	179.667	201.568	21.901	95	95	555.0	21.050	0.780
6.50	32.0	202.516	242.464	39.948	95	95	555.0	38.629	1.207
8.00	21.5	243.392	276.102	32.710	95	95	555.0	31.745	1.477
9.50	21.5	278.392	315.282	36.890	95	95	555.0	35.931	1.671
15.00	18.0	415.929	458.929	43.000	95	95	555.0	42.435	2.357
21.00	33.0	317.223	414.981	97.758	99	99	559.0	97.144	2.944
34.00	15.0	461.950	520.150	58.200	99	99	559.0	59.590	3.973

Calibration Gamma = $\boxed{0.9998}$

*Device is reference dry gas meter (Rockwell Model , S/N)

S-110, 300395

8/6/99
(FZ)

Measurement Controls, Inc.

107 Center Lane
P.O. Box 997
Huntersville, NC 28070

Telephone (704) 875-2034
Fax (704) 875-3480

6-23-99

CALIBRATION RECORD
REFERENCE METER
ROCKWELL S-110 SERIAL # 300395

$$Y = \frac{Vs \times Ys\ (460+T)\ Pb}{Vt\ \left(\frac{dH}{13.6} + Pb\right)(460+T)}$$

T= 68 F. Pb= 29.56

FLOW RATE	dH(WC)	AVE. VOLUME	AVE. Y
106 CFH	.75"	1.9965	.9999
60 CFH	1.20"	1.9950	.9995
48 CFH	2.10"	1.9890	1.0003
36 CFH	1.35"	1.9946	.9994
30 CFH	1.40"	1.9930	1.0000
OVERALL AVERAGE Y=			.9998

Calibration performed on American Bell Prover # 2989, certification dated 10-23-95, certified to 0.00% error, and traceable to the N.I.S.T.

By
Measurement Controls, Inc.

Larry B. Lane

STDLFE - REV D. - 3/18/86

TODAY'S DATE IS 4/7/86
THE MODEL # IS 50MJ10 TYPE 10
THE SERIAL # IS 713920-Y1
THE CURVE # IS 16448
THE LCR PLOT # IS 140
THE WORKING MASTER SERIAL # IS WMMJ10-10
THE MASTER-MASTER SERIAL # IS PSMJ10-10
DATA AS INPUT FROM DATA SHEET

BARO	PS	PM	DIFF	PA
29.45	.130	7.878	8.000	8.080
29.45	.120	6.873	7.000	7.050
29.45	.090	5.884	6.000	6.030
29.45	.060	4.900	5.000	5.030
29.45	.030	3.914	4.000	4.020
29.45	.020	2.930	3.000	3.020
29.45	.010	1.951	2.000	2.010
29.45	0.000	.973	1.000	1.000

E= .227120
F= -.002545

B= .2207901503
C= -.0026277468

I	%ERROR	SLOPE	CFM(DATA)	CFM(CURVE)
8.000000	-.039841	.199848	1.598782	1.598145
7.000000	.072896	.202248	1.415739	1.416771
6.000000	.038190	.204945	1.229672	1.230142
5.000000	-.040485	.207736	1.038678	1.038257
4.000000	-.040624	.210365	.841458	.841117
3.000000	-.008195	.212924	.638773	.638721
2.000000	-.042154	.215626	.431251	.431069
1.000000	.060463	.218031	.218031	.218162

PERCENT TERMINAL NON-LINEARITY 4.999
PERCENT INDEPENDENT NON-LINEARITY -3.631

.2208
-.0026

B-8