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September 2000

Environmental Technology Verification Report

C. Lee Cook Division, Dover Resources, Inc.
Static-Pac^{TM} System

Phase II Report

Prepared by:

Southern Research Institute

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

EPA REVIEW NOTICE

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Greenhouse Gas Technology Verification Center

A U.S. EPA Sponsored Environmental Technology Verification Organization

C. Lee Cook Division, Dover Resources, Inc.
Static-Pac^{TM} System

Phase II
Technology Verification Report

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Under EPA Cooperative Agreement   CR 826311-01-0

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1.0 INTRODUCTION

1.1 BACKGROUND

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

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), and conducts verification testing of promising GHG mitigation and monitoring technologies. This Center's verification process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other data, obtaining independent peer review input, and reporting findings. Performance evaluations are conducted according to externally reviewed Verification Test Plans and established protocols for quality assurance.

The Center is guided by volunteer groups of Stakeholders. These Stakeholders offer advice on specific technologies most appropriate for testing, help disseminate results, and review test plans and verification reports. The Center's Executive Stakeholder group consists of national and international experts in the areas of climate science, and environmental policy, technology, and regulation. It also includes industry trade organizations, environmental technology finance groups, various governmental organizations, and other interested groups. The Executive Stakeholder Group helps identify and select technology areas for verification. For example, the oil and gas industry was one of the first areas recommended by the Executive Stakeholder Group as having a need for high quality performance verification.

To pursue verification testing in the oil and gas industries, the Center established an Oil and Gas Industry Stakeholder Group. The group consists of representatives from the production, transmission, and storage sectors. It also includes technology vendors, technology service providers, environmental regulatory groups, and other government and non-government organizations. This group has voiced support for the Center's mission, identified a need for independent third-party verification, prioritized specific technologies for testing, and identified broadly acceptable verification strategies. They also indicated that technologies that reduce methane leaks from compressor rod packing are of great interest to technology purchasers. In the natural gas industry, interstate gas pipeline operators use large gas-fired engines to provide the mechanical energy needed to drive pipeline gas compressors. In the U.S., fugitive natural gas leaks from these compressors represent a major source of methane emissions, and a loss of economic and natural resources.

To pursue verification testing on compressor rod packing technologies, the Center placed formal announcements in the Commerce Business Daily and industry trade journals to invite vendors of commercial products to participate in independent testing. C. Lee Cook Division of the Dover Resources, Inc. responded, and committed to participate in a medium-term independent verification of their static sealing technology. The technology is referred to as the Static-Pac™ and is designed to reduce methane leaks from compressor rod seals during periods when the compressor is in a standby and pressurized state.

Performance testing of the Static-Pac was carried out at a compressor station operated by ANR Pipeline Company (ANR) of Detroit, Michigan. The verification test was planned to be executed in two phases where: Phase I evaluates short-term gas savings and documents installation costs; and Phase II addresses additional performance parameters including medium-term technical and economic performance factors. The Phase I performance results are documented in a separate report titled *Environmental Technology Verification Report for the C. Lee Cook Division, Dover Corporation Static-Pac™ System – Phase I* (SRI 1999*)*. The Phase I report may be downloaded from the Center's Web site at www.sri-rtp.com. This report presents the results of the Phase II test, using data collected during both phases of testing spanning the period of July 15, 1999 to January 24, 2000.

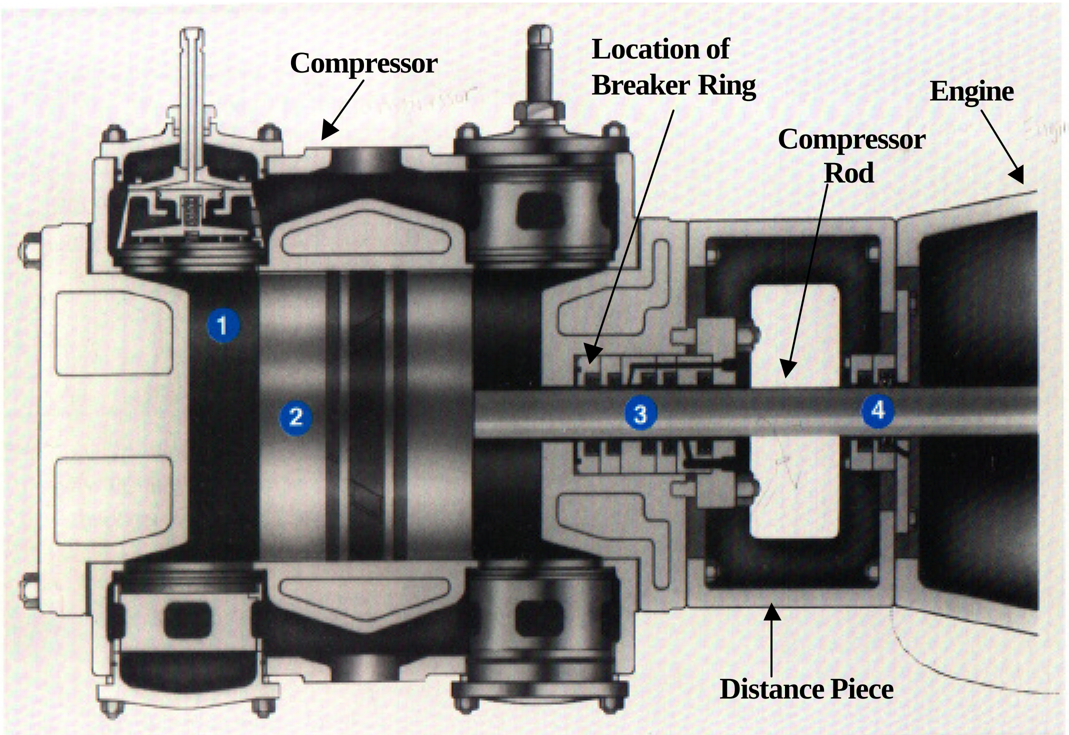
Details on Phase I and II verification test design, measurement test procedures, and Quality Assurance/Quality Control (QA/QC) procedures can be found in the *Testing and Quality Assurance Plan for the C. Lee Cook Division, Dover Corporation Static-Pac™ System* (SRI 1999*)*. It can be downloaded from the Center's Web site. The Test Plan describes the rationale for the experimental design, the testing and instrument calibration procedures planned for use, and specific QA/QC goals and procedures. The plan was reviewed and revised based on comments received from C. Lee Cook, ANR Pipeline, selected members of the Oil and Gas Industry Stakeholder Group, and the EPA Quality Assurance Team. The plan meets the requirements of the Center's Quality Management Plan (QMP), and conforms to EPA's standard for environmental testing. In some cases, deviations from the Test Plan were required. These deviations, and the alternative procedures selected for use, are discussed in this report.

The remainder of this section describes the Static-Pac technology and the goals of the verification. Section 2 describes methane emissions from natural gas compressors, and describes the test site and measurement system employed. Section 3 presents Phase II test results, and Section 4 assesses the quality of the data obtained.

1.2 THE STATIC-PAC TECHNOLOGY

One of the largest sources of fugitive natural gas emissions from compressor operations is the continuous leakage associated with operating and idle-mode compressor rod packing. When a compressor is in standby mode, natural gas can leak into the atmosphere from the packing case and other compressor emission sources. Based on an EPA/GRI study, reciprocating compressors in the gas transmission sector were operating 45 percent of the time in 1992, but were in standby or off-line mode for the remaining 55 percent (Hummel et al., 1996). If rod leaks during standby operations are reduced or eliminated, significant gas savings and emissions reductions could occur. The C. Lee Cook Static-Pac device is intended to provide this benefit.

In general, compressor packing provides a seal around the rod shaft, keeping high-pressure gas contained in the compressor from leaking out into the atmosphere. A typical compressor packing case is shown in Figure 1-1 (location No. 3). It consists of one or more sealing rings contained within a case that serves several functions. These functions include: lubrication, venting, purging, cooling, temperature and pressure measurement, leakage measurement, rod position detection, and on occasion, sealing for standby mode operations (GRI 1997). In conventional packing, the sealing rings are configured in series to successively restrict the flow of gas into the distance piece between the compressor and the engine. The sealing rings are held in separate grooves or "cups" within the packing case, and are free to move laterally along with the rod and "float" within the grooves. The distance piece, shown between locations 3 and 4 in Figure 1-1, is sealed and typically vents rod packing leaks to the atmosphere.



1 Compressor Valves and Unloaders
2 Piston & Rider Rings
3 Packing Rings & Case
4 Oil Wiper Rings & Cases

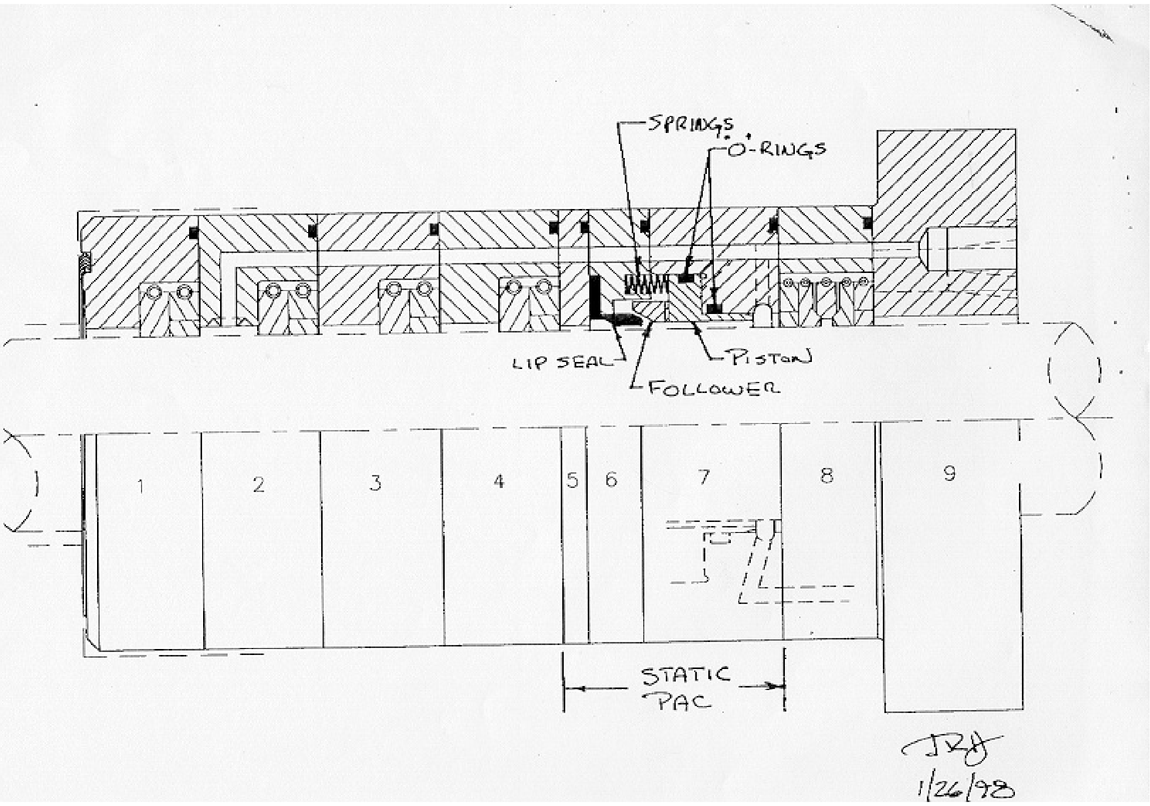
A conventional packing case usually contains seven to nine cups. Each cup houses one or more seal rings, which restrict the flow of natural gas into the distance piece. Each ring seals against the piston rod and also against the face of the packing cup. The first cup is occupied by the breaker ring (Figure 1-1), designed to reduce the pressure on the packing rings by providing an orifice restriction to flow. A second function of the breaker ring is to regulate the reverse flow of gas from the packing case into the cylinder. This reverse flow occurs as the piston begins the intake stroke, and the pressure is rapidly reduced in the cylinder.

The remaining cups are occupied by conventional three-ring packing sets which consist of a radial cut ring, a tangent cut ring, and a backup ring and are designed to reduce the amount of gas leaking from the compressor into the distance piece. The final cup houses a vent control ring which can be used to transport the leaking gas for subsequent use or discharge into the distance piece. A detailed description of rod packing is given in GRI's report documenting existing compressor rod packing technology and emissions (GRI 1997).

During idle periods on units that remain pressurized, rod packing leaks usually continue when the rod motion has stopped. The leakage encountered during idle periods can be due to the loss of lubrication oil which normally fills the leak paths, changes in the shape of the ring as it cools, and changes in rod alignment as the temperature changes (GRI 1997).

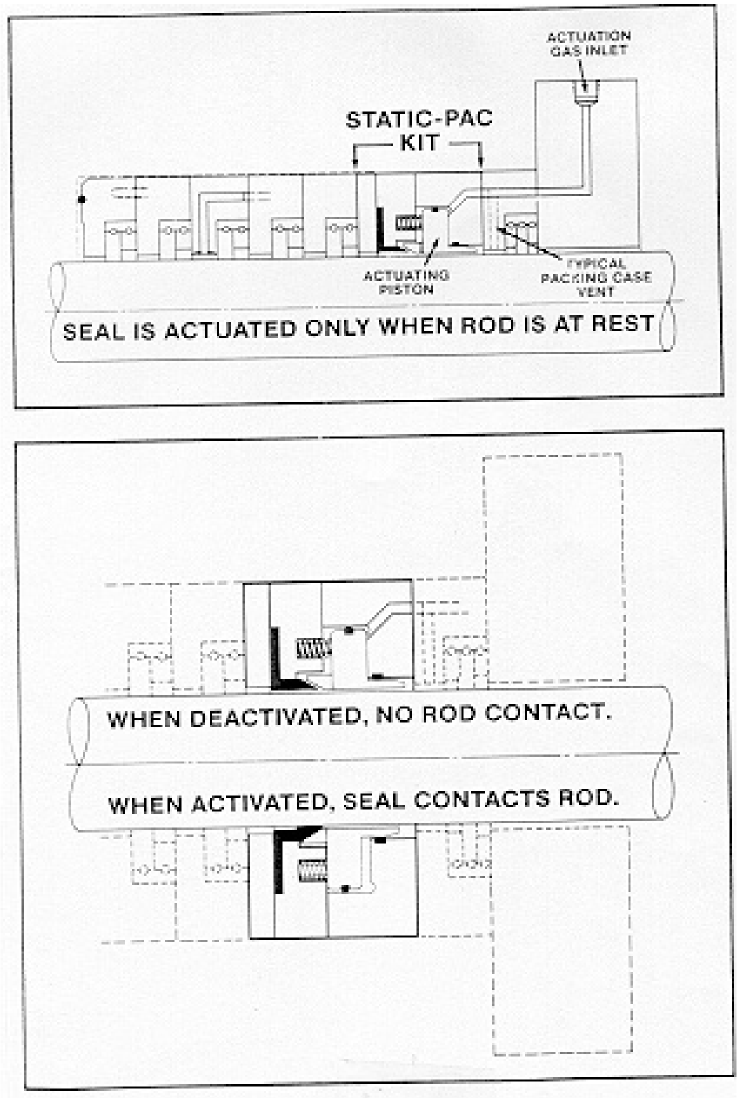
The Static-Pac is a gas leak containment device designed to prevent rod packing leaks from escaping into the atmosphere during compressor shutdown periods. The Static-Pac system is installed in a conventional packing case by typically replacing two cups in the low-pressure side of the packing case (Figure 1-3). When the compressor shuts down, an automatic actuation valve is opened, admitting pressurized gas behind the internal piston. As shown in Figures 1-2 and 1-3, the movement of the piston wedges a lip seal into contact with the rod. When the actuating pressure is lowered during compressor startup, the piston retracts, causing the Static-Pac seal to lift from the rod surface.

Figure 1-2. Rod Packing Cutaway with Static-Pac



To allow room for the addition of the Static-Pac, a packing case with the Static-Pac contains one less ring set than conventional packing. It is speculated that this “missing seal” can cause increases in rod emissions while the compressor is in operating mode. However, industry experience suggests that the Static-Pac should not affect normal sealing during compressor operation. The Center was unable to locate reliable data to verify this claim. Therefore, the verification test approach, described in Section 2.2, assesses the effect (if any) of the Static-Pac on normal sealing performance during compressor operation. This was accomplished by fitting one rod on a test engine with a Static-Pac and the second rod with new conventional packing. A second engine was fitted in the same manner to provide duplicate measurements.

Figure 1-3. Static-Pac Actuation and Deactuation Process



“Static-Pac” is a registered trademark of C. Lee Cook covered by Patent No. 4469017.

1.3 VERIFICATION GOALS

Compressor shutdown and standby procedures vary from station to station. Some operators depressurize and blow down all pressure from a compressor before placing the unit into standby mode. Others depressurize the compressor to a lower but elevated pressure, while still others maintain full pressure during standby. Adding the Static-Pac to a compressor may result in varying levels of net gas savings and emission reductions depending on the shutdown procedure used.

The evaluation of the Static-Pac focused on two shutdown procedures that represent the most common approaches to compressor shutdown: remain pressurized during idle; and depressurized (blowdown) before idle. These shutdown modes are discussed in Section 2.1. The Phase I and II verification goals and parameters associated with these two compressor shutdown scenarios are outlined below.

Phase I Evaluation:
Verify gas savings
Verify installation and shakedown requirements
Verify capital and installation costs

Phase II Evaluation:
Verify annual gas savings
Verify annual methane emission reduction
Calculate and document Static-Pac payback period

Phase I goals were achieved through observation, collection and analyses of direct gas measurements, and the use of site logs and vendor supplied cost and operational data. The evaluation was completed after about a 3-week period of measurements. Gas savings were based on two sets of manual emission measurements. The number and duration of shutdowns were determined from site records provided by ANR Pipeline Company for the testing period. Measured emission rates, site operational data, estimated gas savings, and installation requirements were documented and verified in the Phase I report.

The primary goal of the Phase II evaluation was to determine the Static-Pac payback period. As a practical matter, the Center could not conduct testing for the number of years that would be required to determine payback from direct measurements. Thus, the Phase II goals were accomplished through a combination of the measurements conducted during the Phase I test period and 3 additional months of Phase II measurements.

2.0 TECHNICAL BACKGROUND AND VERIFICATION APPROACH

2.1 METHANE EMISSIONS FROM NATURAL GAS COMPRESSORS

Fugitive natural gas emissions from compressor stations account for a significant loss in revenue and natural resources. These emissions also contribute to the release of methane, a potent greenhouse gas, into the atmosphere. Prior EPA and Gas Research Institute studies estimated that reciprocating compressors emitted approximately 21 percent of the total gas emissions (314 x 10^9 ft^3) from the natural gas industry in 1992 (Harrison et al., 1996).

Methane emissions from compressors are liberated from a variety of different sources. These sources include leaks from the rod packing, unit valves, blowdown valve, pressure relief valve, and miscellaneous valves, fittings, and other devices. Emissions are also significant from blow-down operations that occur prior to placing a compressor into standby mode or taking it off-line. Fugitive natural gas emissions associated with compressor rod packing occur from operating compressors, but emissions also occur when some compressors are placed into a standby or idle mode while remaining pressurized.

According to an ongoing, multiyear fugitive emissions study conducted by the Pipeline Research Committee (PRC), very little difference was observed between compressor rod packing emissions during normal operations and during pressurized standby or idle mode operations. The overall average leak rate was approximately 1.86 cfm per rod (GRI 1997). This emission rate is higher than the 0.86 cfm per rod reported previously in an EPA/GRI study (Hummel et al., 1996). The PRC results are based on data collected from nine compressor stations, containing 56 reciprocating compressors and readings taken at 365 individual rod packing, compared to 135 measurements at six compressor stations in the EPA/GRI study. Nevertheless, both data sets are very useful in quantifying average rod emission rates throughout the natural gas industry.

Fugitive emissions from standby or idle mode compressors are affected by the compressor shutdown mode. This varies from station to station and, in general, the following procedures are used:

- Maintain full operating pressure when idle (either with or without the unit isolation valves open),
- Depressurize and blow down all pressure when idle (except a small residual pressure to prevent air in-leakage) and vent the gas, either partially or completely, to the atmosphere,
- Depressurize to a lower pressure, venting the gas either to the atmosphere or to the station fuel system, or
- A combination of these procedures.

Based on the EPA/GRI study, the first two operating procedures represent the most common approaches to compressor shutdown (Harrison et al., 1996). The study estimated that about 57 percent of idle transmission compressors are maintained at operating pressures and 38 percent are blown down to the atmosphere. A smaller percentage (less than 5 percent) are blown down to a lower pressure, in some cases venting to the station's fuel system.

2.2 DESCRIPTION OF THE TEST SITE AND STATIC-PAC INSTALLATION

Reciprocating compressors are the type most commonly used within the gas industry, and are a primary source of compressor-related emissions. Thus, the Static-Pac verification was conducted at a transmission station that uses reciprocating compressors. ANR Pipeline Company expressed interest in hosting the verification, and assisted the Center in identifying an appropriate compressor station within their pipeline system. ANR reviewed its operations and identified facilities where: the Static-Pac was not currently used; at least one compressor operates in a shutdown mode several times a year; and site operators could cooperate in support of the short- and long-term evaluations.

The natural gas transmission station selected to host the Static-Pac verification operates six Cooper-Bessemer engines (8-cylinder, 2000 hp), each equipped with two reciprocating compressors operating in series (4,275 in.^{3} displacement, 4-inch diameter rods). The low-speed engines at the site are typical of many used in the industry, but may not be typical of newer, high-speed engines in use. The rods and packing cases have the same basic design and function as most reciprocating compressors currently used and planned for use in the future in the transmission sector. The rod packing is essentially a dry seal system, using only a few ounces of lubricant per day. Wet seals, which use high-pressure oil to form a barrier against escaping gas, have traditionally been employed. According to the Natural Gas STAR partners, dry seal systems have recently come into favor because of lower power requirements, improved compressor and pipeline operating efficiency and performance, enhanced compressor reliability, and reduced maintenance. The STAR industry partners report that about 50 percent of new seal replacements consist of dry seal systems.

Two engines, designated as Engines 801 and 802, were selected to verify the performance of the Static-Pac system. These two engines are the same age and have similar operating hours. Actual operating hours on each engine are logged continuously. Each engine contains two compressor rods, and nine cups are contained in each packing case. All rods are made of chrome-plated steel.

The Static-Pac was installed on one compressor rod on each of the two engines and included a new packing case and seals. This rod is referred to as the Test Rod. The packing material on the second rod on each engine was replaced with new packing at the same time the Static-Pac was installed. The second rod used conventional packing and served as a Control Rod against which Static-Pac performance could be compared. The conventional packing normally used at the site is manufactured by C. Lee Cook. The comparisons were conducted both for idle periods and while the engine was running to determine if the elimination of one of the seals in the Static-Pac design affects normal sealing performance during compressor operation.

2.3 VERIFICATION APPROACH

According to C. Lee Cook, the Static-Pac can provide static sealing during idle periods, provided the compressor remains pressurized while idle. The gas savings achieved by the rod packing depend on the emission characteristics of the compressor's packing, both before and after installation of the Static-Pac. Savings also depend on the shutdown procedures used, and the number and duration of shutdowns experienced. A station that currently leaves compressors pressurized during shutdown will achieve net savings from the decrease in rod packing leaks during idle periods. Alternatively, a station that currently blows down compressors before shutdown would change to a pressurized shutdown procedure, and this change in operating practice would result in both increases and decreases in emissions from various compressor components. A likely scenario for such a change would be that the station wishes to eliminate blowdown emissions, and employs a static sealing system at the same time to reduce or eliminate any additional emission from the newly pressurized, rod packing. In this case, gas savings occur by eliminating blowdown emissions and unit valve leaks. However, there is a potential for increases in emissions from components now exposed to high pressure during shutdown, including the rod packing.

This section presents the approach used to calculated gas savings associated with the Cook Static-Pac for Engines 801 and 802. Two base-case shutdown/idle modes are assumed. Case 1 represents the original use of a pressurized shutdown (same as Static-Pac requires), and Case 2 represents the original use of compressor depressurization and blowdown. As a result of changing the packing, and possibly the shutdown/idle mode, a variety of emission changes occurred in both cases. Each change was quantified during the verification through measurement of the values listed below:

- Case 1 rod seal savings while idle;
- Case 1 rod seal losses due to emissions increases while running;
- Case 2 rod seal increases while idle;
- Case 2 rod seal losses due to emissions increases while running -- same as in Case 1;
- Blowdown volume savings;
- Blowdown valve leak losses;
- Unit valve leak savings; and
- PRV and miscellaneous component losses.

2.3.1 Determining Gas Savings and Payback

For the two most commonly used compressor shutdown scenarios described in Section 2.1, Table 2-1 shows the relationship between compressor shutdown procedures and emissions. Because use of the Static-Pac system is associated with pressurized compressor standby operation, the table indicates how compressor emissions may change from the emissions that occurred during the original standby mode. Using this table as a guide, a verification plan was developed to characterize all the emissions changes that may occur with the installation of the Static-Pac and the possible adoption of a different shutdown procedure.

The evaluation of the Static-Pac performance at ANR Pipeline Company focused on the two shutdown scenarios that collectively represent practices employed by about 95 percent of the transmission compressors (Shires and Harrison 1996). Case 1 represents compressors that remain pressurized when idle, and Case 2 represents compressors that completely depressurize and blow down all gas. The host site was asked to follow these practices during testing, although their normal practice is to maintain idle pressures of about 120 psig and recover all blowdown gas into the engine fuel system. The following discussion highlights the verification issues for each case and outlines measurements and data collection activities implemented in the verification test.

2.3.1.1 Case 1

The baseline for Case 1 is a compressor that normally maintains full operating pressure during idle periods. For this case, a change in emissions was anticipated to occur only at the rod packing due to the static sealing action of the Static-Pac. To quantify this potential change in rod packing leaks, direct gas emission rate measurements were conducted on the distance piece or doghouse vent pipes associated with the Control Rods and Test Rods for each of the two engines. Because the unit pressure is essentially unchanged during both operating and idle periods, all leak rates from other components (pressure relief valve, blowdown valve, unit valves, and miscellaneous flanges, valves, and fittings) can be assumed to remain constant after installation of the Static-Pac. The idle-mode emissions from the two Control Rods are compared to idle-mode emissions from the two Test Rods. The difference between these two values is determined, and used to quantify the static sealing abilities of the Static-Pac.

Table 2-1. Common Shutdown Scenarios and Emissions

Matrix of Shutdown Procedure Changes		
Shutdown Procedure or Emission Source	**CASE 1**	**CASE 2**
Current shutdown procedure	Pressurized shutdown with unit valves open or closed[a]	Blowdown/100% vent to atmosphere
New procedure with Static-Pac	n/c[b]	Pressurized shutdown
Matrix of Possible Emissions Changes Due to Shutdown Procedure Changes or Installation of the Static-Pac		
Rod seals	Decrease	Little or no increase
Blowdown volume	n/c	Decrease
Unit valve seat (via open blowdown line)	n/c	Decrease
Blowdown valve	n/c	Increase
Pressure relief valve	n/c	Increase
Misc. valves, fittings, flanges, stems etc.	n/c	Increase

[a] Most sites leave the unit valves closed for safety reasons (i.e., sites may not want problems in the shutdown engine to affect the integrity of the entire station).

[b] n/c - no change/effectively no change.

For Case 1, the savings consist solely of gas prevented from leaking from the rod packing during idle periods. This is the difference between the average leak rate without the Static-Pac (measured for the Control Rods) and the average leak rate with the Static-Pac (measured for the Test Rods). Average uncontrolled leak rate is defined as the average of all measurements made on the two Control Rods and average controlled leak rate is the average of all measurements made on the two Test Rods. Equation 1 states how gas savings will be calculated for each test engine.

$$G1 = [Q_u - Q_s] * t \qquad \text{(Eqn. 1)}$$

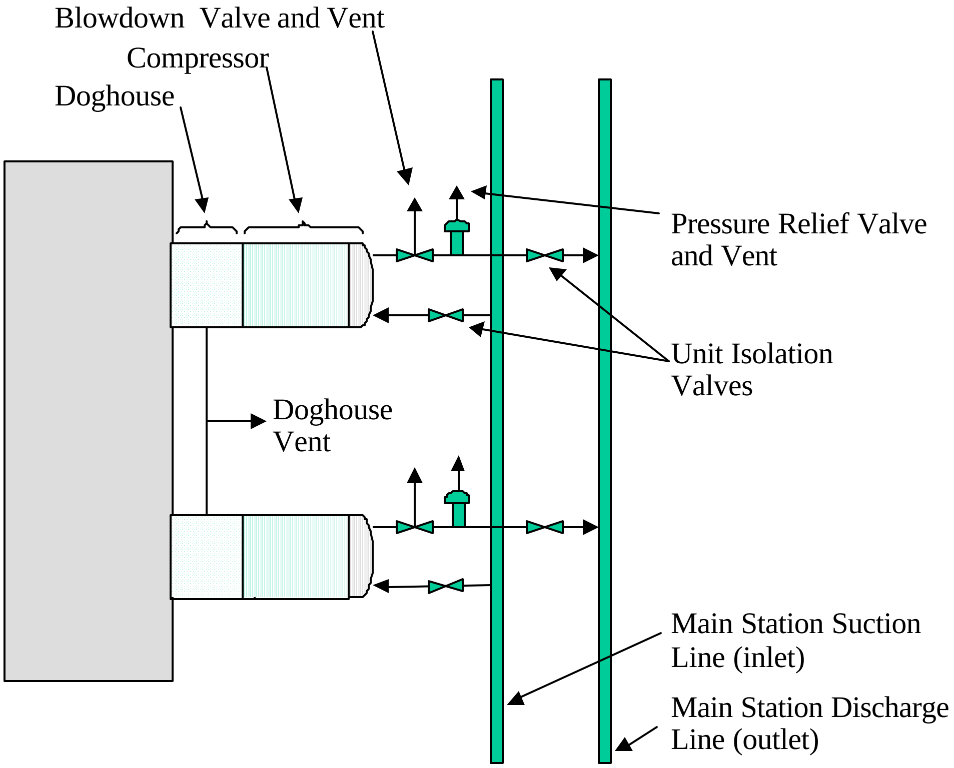
where,

G1 = average gas savings for each engine (Case 1), scf
Q_u = average uncontrolled leak rate while idle (Control Rods), scfm
Q_s = average controlled leak rate while idle (Test Rods), scfm
t = total shutdown or idle time during verification period, minutes

2.3.1.2 Case 2

The baseline for Case 2 is a compressor that normally blows down from operating pressure to a minimum pressure during idle periods. At such times the pressure on compressor components is reduced to near atmospheric. Consequently, leaks from rod packing, pressure relief valves, and blowdown valves cease to exist. However, leaks from the unit valves, which are closed to isolate the compressor from the pipeline, are liberated into the atmosphere. This gas leaks past the unit valves, into the compressor system, and out into the atmosphere via the open blowdown valve. Figure 2-1 is a simplified diagram of these emission sources. Because emissions associated with leaking unit valves can be substantial, measurements were made to quantify these emissions after blowdown was completed. In addition, the compressed gas contained in the compressor and associated piping is lost during blowdown. These savings were calculated based on known volumes of compressor components, the measured operating pressure, and the measured gas composition. All of these emission savings are added together to calculate a total gas savings as a result of changing from a blowdown practice to remaining pressurized.

Figure 2-1. Compressor/Engine Configuration and Emissions Sources



In contrast, emissions can increase from several components that are now exposed to high pressure. This includes increase in leaks from the pressure relief valve, blowdown valve, various flanges, connectors, and valves, and the rod packing where the Static-Pac is installed. The Static-Pac serves to reduce the increase in rod packing emissions relative to a conventional packing when the unit remains pressurized when idle. Ultimately, these leaks decrease the total gas savings associated with the blowdown practice. To verify the emission contribution of these sources, gas emission rate measurements were conducted (during pressurized idle-mode) on all components newly exposed to elevated pressures. Emissions from these devices are subtracted from the total savings above, to yield the net savings associated with changing the operating practice and installing a Static-Pac.

For Case 2, gas savings consist of the blowdown volume (times the number of blowdown events) and the unit valve leak rate (times the duration of idle periods). In addition, there could be gas leakage from the blowdown valve, pressure relief valves, and miscellaneous components. Additionally, any gas that escapes past the Static-Pac is lost (i.e., pressurized conditions may result in packing case leaks which are essentially zero during non-pressurized/blowdown conditions). For Case 2, the gas savings for each idle period were calculated as follows.

$$\mathbf{G2 = BDV + Q_{uv} * t - [Q_{prv} + Q_{bdv} + Q_{misc} + Q_{s}] * t} \qquad \text{(Eqn. 2)}$$

where,

G2 = gas savings for each engine (Case 2), scf
BDV = blowdown volume times the number of blowdowns during the verification period, scf
Q_{uv} = unit valve leak rate, scfm
t = idle time over the verification period, minutes
Q_{prv} = pressure relief valve leak rate, scfm
Q_{bdv} = blowdown valve leak rate, scfm
Q_{misc} = aggregate leak rate for miscellaneous components, scfm
Q_s = rod leak rate with Static-Pac, scfm

2.3.1.3 Impact on Normal Running Emissions

With the Static-Pac system, the packing case is modified, resulting in one less set of rings than conventional packing cases. With this change, there is a potential to alter the emission sealing performance of the overall packing system (i.e., cause an increase or decrease in packing emissions compared to the standard packing). To address this, measurements were conducted on the Test and Control Rods during normal operations and the emission rates were then compared. It is assumed that, after installation of the Static-Pac, the unit valve position (i.e., closed or open) would remain the same as before the Static-Pac was installed.

If the Static-Pac caused any increase in emissions during normal compressor operation, these emissions were subtracted from the gas savings. The following equation states how the total gas savings were calculated for each case. The total gas savings, $G1_T$ and $G2_T$, for Case 1 and Case 2, respectively, are given in Equations 3 and 4.

$$G1_T = G1 - V_m \qquad \text{(Eqn. 3)}$$

Where, V_m is any increase in operating emissions that occurred over the test period due to the Static-Pac. V_m is the difference in operating emissions (i.e., emissions during non-idle periods) between the Test and Control Rods, times the number of minutes the compressor operated during the verification period.

$$G2_T = G2 - V_m \qquad \text{(Eqn. 4)}$$

2.3.1.4 Annual Gas Savings and Payback Period

Annual Gas Savings

Case 1 and Case 2 gas savings rates for the verification period are computed using Equations 1 and 2. Since the test did not span an entire year, it was necessary to project gas savings over this longer period. During the development of the Test Plan, it was expected that compressor rod emission rates would increase over time due to wear on the packing. To account for this, the initial testing strategy proposed extrapolating the measured data to project increasing leak rate trends over time. The projected annual gas savings rate was to be projected as a likely case and a conservative case. The likely case would extrapolate future increases in leak rates based on increases observed during the test period. The conservative case assumes that the gas savings rate will not follow an increasing trend, but will be the same as the rate measured at the conclusion of the test.

As discussed in Section 3.4.2, the measurements data collected during the test did not reveal increasing trends in rod leak rates over time. As a result, the initially planned extrapolation routine for the likely case could not be executed, and the conservative approach was followed. The annual gas savings rate was determined as the average gas savings rate (Control Rod minus Test Rod) measured during the testing period (July 14, 1999, to January 26, 2000). This average savings rate was multiplied by the average annual engine idle time as reported by ANR. The monetary value associated with the use of the Static-Pac for Case 1 was calculated by multiplying this average saving by an assigned value of \$2 per 1,000 ft^3 of gas saved.

Annual Methane Emission Reductions

The calculated annual gas savings were also used to determine annual methane emission reductions. This was accomplished by multiplying the natural gas savings (discussed above) with the average methane content of the natural gas at the site. The methane content data were obtained from gas sampling analyses routinely collected by ANR.

Static-Pac Payback Period

The Center's Stakeholder group has identified payback as an indicator of economic performance for technologies verified under the ETV program. Under the payback method of analysis, purchases with shorter payback periods are ranked higher than those with longer paybacks. The theory is that devices with shorter paybacks are more liquid, and thus less risky (i.e., they allow initial investment to be recouped sooner such that the money can be reinvested elsewhere). Projects with longer payback periods can bring uncertainty in economics over time due to potential changes in market conditions, interest rates, or the economy. Generally, a payback period of less than 3 years is considered favorable by the gas industry stakeholders, and the chances of its implementation are high. If the payback is less than 5 years, the technology is likely to receive some consideration.

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 5 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.

Appendix A displays the payback calculation in tabular form. Payback is one of many ways of examining the economic viability of a technology, including internal rate of return and net present value over the life of the device. Unlike the latter two methods, payback has several drawbacks. First, it ignores any additional costs that may be incurred after the payback period, so a technology that has a shorter useful life may be favored over a technology that lasts longer but has a longer payback period. Payback also ignores additional benefits that may occur after the payback period.

$$NPV = Capital\ Cost - \sum \frac{Gas\ Savings\ in\ Year\ t}{(1+r)^t} \qquad \text{(Eqn. 5)}$$

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

$Where:$

$NPV = net\ present\ value$

$t = year$

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

2.3.2 Emission Measurements and Calculations

The following discussion provides an overview of the measurements made, instruments used, field procedures followed, and key calculations made in the Phase I and II tests. For more detail on these topics, the reader should consult the Test Plan titled *Testing and Quality Assurance Plan for the C. Lee Cook Division, Dover Corporation Static-Pac^{TM} System* (July 1999). It can be downloaded from the Center's web site at www sri-rtp.com.

To characterize the running emissions and Case 1/Case 2 idle emissions, manual emission measurements were collected on the following sources: doghouse vent, unit valve seat (via the open blowdown line), pressure relief valve vent, blowdown valve vent, and miscellaneous components (e.g., fittings, connections, valve stems). The measurements made and operating conditions under which testing was performed are listed below. One full day was needed to conduct this suite of measurements on both engines.

- With both units shut down and pressurized: natural gas leak rates for the pressure relief valve, blowdown valve, miscellaneous components, and rod packing vents (test rod and control rod)
- With both units blown down: natural gas leak rates for the unit valve and unit valve stem
- With both units running: natural gas leak rates for the rod packing vents (Test Rod and Control Rod)

Measured natural gas leak rates were converted to methane leak rates using natural gas compositional measurements provided by ANR Pipeline (about 97 percent methane). The measurements are conducted using a gas chromatograph located along the pipeline at 4-hour intervals.

The station agreed to a limited number of unscheduled shutdowns for the purpose of conducting the measurements described above. Results from these tests were used to characterize emission rates at the time of testing, and to characterize emissions differences between Cases 1 and 2, above. Net gas savings were calculated based on the number and duration of idle periods encountered at the site for the test period.

2.3.2.1 Rod Leak Rate Measurements

Emissions from the packing case vent and leaking rod seals are both vented into the distance piece or doghouse described in Section 1.2. Both emission sources vent gas that has escaped the sealing action of the packing, and are included together when measuring emissions. After emissions are discharged into the doghouse, they are vented to the atmosphere through the doghouse vent. Soap screening all doghouse seals and connections, and monitoring the long-term compositional trends of the gas exiting the doghouse, was done to ensure that no other gas was entering the doghouse during the testing. The doghouse vent and oil drain are the only paths by which emissions escape into the atmosphere and for the test, the doghouse oil drain was sealed using ball valves. This forced all emissions to exit through the doghouse vent.

To measure these emissions, a Flow Tube was used to measure vent gas velocity, and a hydrocarbon analyzer was used to measure vent gas total hydrocarbon (THC) concentration before flow measurement started. In the original Test Plan, sensitive, low-pressure-drop continuous flow meters were planned for use, but after their installation, it was determined that the pressure in the doghouse vents was so low that reliable flow detection could not be established. With this discovery, the decision was made to proceed with manual testing, and to use sensitive manual methods to conduct the measurements.

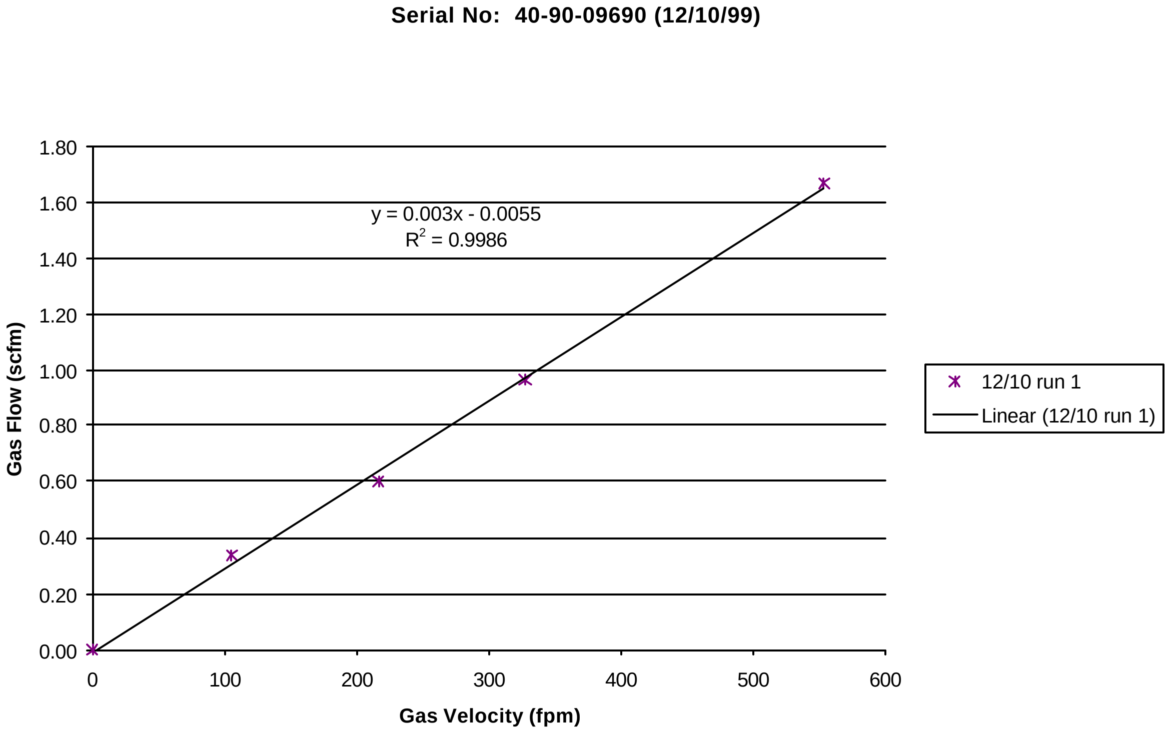
The Flow Tube consists of a sensitive 1-inch vane anemometer mounted on the inside walls of a polyvinyl chloride (PVC) tube that measures 30 inches in length and 1 inch in diameter. During the Phase I testing, it was determined that idle emissions with the Static-Pac engaged were sometimes below the level of detection of the vane anemometer (which is approximately 0.12 scfm natural gas). Therefore, the vane anemometer in the Flow Tube was replaced with a thermal anemometer for Phase II testing and used in cases where emissions were below the detectable level of the vane anemometer. The thermal anemometer is an intrinsically safe device capable of detecting low level flow rates (detection limit of approximately 0.01 scfm). Table 2-2 provides the ranges of the two types of anemometers used for the testing.

Table 2-2. Anemometer Range of Detection in Flow Tube

Type of Anemometer	Lower Detection Limit		Upper Range[a]	
	fpm	scfm[b]	fpm	scfm[b]
Vane	60	0.12	6800	20
Thermal	25	0.01	NA	NA

[a] The thermal anemometer was only used at or near its lower detection limit.
[b] The scfm values are for methane and represent the average flow rates determined through laboratory calibrations using methane (99.9 percent pure).

Before each manual measurements campaign at the site, the Flow Tube was laboratory-calibrated using a NIST-traceable Laminar Flow Element and a wide range of simulated gas flow rates (99 percent methane, 0.3 to 4 scfm for the vane anemometer and 0.02 to 1 scfm for the thermal anemometer). These calibrations were used to generate calibration curves that spanned the range of flow rates anticipated for the site. These curves were used to select a gas flow rate based on the indicated velocity from the flow tube. An example calibration chart is shown in Figure 2-2 for a flow tube equipped with the vane anemometer.



For each doghouse vent, one testing event consisted of a minimum of 10 separate gas velocity readings measured with the Flow Tube. These readings were made after the doghouse emissions were observed to stabilize (15 to 20 minutes after the vents were opened). In most cases, the 10 readings showed stable emissions. Each reading represents a 16-second average value and, after completion, all values were averaged to yield an overall average total gas flow rate in feet per minute. Using this value, a natural gas flow rate was selected from the flow tube calibration curve.

With the thermal anemometer inserted in the Flow Tube, the device had a Lower Detectable Limit (LDL) of 0.010 scfm (i.e., flow rates below this value cannot be reliably detected with the instrument). When gas flows lower than the LDL were encountered, a gas flow rate equal to half the LDL (0.005 scfm) was assigned.

It should be noted that, after opening the doghouse vent for measurement, air typically enters and mixes with the natural gas leaking from the rod packing. Just before taking velocity readings, the hydrocarbon concentration in the doghouse vent was measured using a portable hydrocarbon analyzer. The analyzer used was a Bascom-Turner CGI-201, with a 4-100 percent total hydrocarbon range, and an accuracy of 2 percent of the measured concentration. The CGI-201 measures all primary hydrocarbon compounds found in natural gas including methane, ethane, propane, and butane (over 90 percent is methane).

Given sufficient time, the rod leaks would completely purge all air from the doghouse, allowing direct measurement of pure natural gas with the Flow Tube. As a practical matter, this could not be done routinely. Based on the Center's experience with characterizing doghouse vent emissions at several compressor facilities, it is believed that the rod packing leak and vent is the driving force which results in gas escaping through the vents (i.e., only one outlet stream is present for the gas to escape and no other gas can enter the doghouse). As such, it is assumed that the flow rate measured during testing is representative of the flow rate of pure natural gas leaking from the packing. This assumption was verified by monitoring composition on two vents over time (about 1 hour), and verifying that the composition eventually reached 92 to 94 percent THC.

2.3.2.2 Component Leak Rate Measurements

Manual measurements were made for the pressure relief valve, unit valve, blowdown valve, and miscellaneous components on each engine. The Center was unable to obtain a license to use the GRI Hi-Flow device as described in the Test Plan. Consequently, the Flow Tube, proven to be reliable on other similar measurements conducted by the Center, including the Phase I test, was used for the Phase II testing.

The pressure relief valve vents through a 6-inch diameter standpipe extending to the roof of the compressor building. Access to the roof was limited, and posed a hazard to the testing personnel. Thus, a hydrocarbon analyzer was first used to determine if leaks were present and if detected, the Flow Tube was to be used to quantify the gas flow rates. With the exception of making a direct connection to the 6-inch standpipe outlet, the sampling and calibration procedures described in the previous section apply to this emission source as well.

For the unit valves, flow measurements were conducted at an existing port, located immediately downstream of the unit valves in the suction line of each compressor. During compressor shutdown, any leaks from the seats of the unit valves will exit through this opened port. The leak rate for the unit valves was the highest flow measured at the host site. The leak rate was measured using the same Flow Tube applied to the rod packing vents. The anemometer mounted within the tube has the capacity to measure the high flows that occurred (e.g., a maximum of 6,800 fpm or about 20 cfm of natural gas could be measured). A different calibration chart with a greater range was used to determine emission rates at the higher flows encountered with unit valves leaks (Section 4 has additional information on calibration).

During the Phase I testing, the leak rate for the blowdown valve was measured at the flange located at the exit of the valve. To make this measurement, it was necessary to unbolt the flange, then separate the two sides by about 1 inch and then insert a disk. A sensitive low-flow-rate rotameter (Dwyer VB Series, 0 to 1000 mL/min with a published accuracy and precision of ±3 percent) was used to measure flows. No leaks were detected from either unit during Phase I. Because this measurement required significant host facility labor and leak rates were consistently found to be negligible, the measurements were not repeated during Phase II. It is assumed that the blowdown valves were not leaking.

The miscellaneous components at the test site consist of pressure and temperature metering taps, fittings that connect the taps to data transmitters, and valves used to recover gas for the fuel recovery system. The host station normally vents to a specially designed gas recovery system during shutdown, but performed a blowdown procedure for this verification, allowing an assessment of the Case 1 and Case 2 shutdown scenarios described above. Significant leaks were not expected at these locations; however, all components were soap screened and any leaks identified were to be quantified using the EPA protocol tent/bag method.

2.3.2.3 Natural Gas Composition Measurements

On-site natural gas compositional analysis is performed by ANR personnel. The site operators use a gas chromatograph (Daniel Model #2251) to determine the concentration of methane, hydrocarbons, and inert gas species present in the pipeline gas. The gas chromatograph is capable of measuring 0 to 100 percent methane, with an instrument accuracy and precision of ±0.02 percent of full range. The instrument is calibrated each month using 97.0 percent certified methane gas.

The Center obtained copies of the fuel gas analyses results and their calibration records that corresponded to the Phase II measurements. An average methane concentration was calculated for those days when sampling was conducted.

2.3.2.4 Blowdown Volume Determination

The blowdown volume represents gas contained in the test compressor, engine, auxiliary piping, and all components located downstream of the unit valves. Based on records obtained from ANR, the total volume present in this equipment is 176 ft^3. ANR engineers determined that at 600 psig blowdown pressure, 9,200 scf of natural gas occupies this volume (corrected for the methane compressibility factor). Because it is not feasible or safe to directly measure blowdown volume, 9,200 scf was used to represent the total gas released into the atmosphere each time the test compressor is depressurized from 600 to 0 psig.

2.3.3 Engine Operational Data

The number and duration of shutdown/idle periods must be specified to calculate the gas savings that occurred during the test period, and to estimate total idle hours anticipated at the site during a single year. Site records, provided by ANR pipeline from January 1999 through March 2000, were used to determine the number and duration of shutdowns for the test period and throughout a typical year. The ANR records identify daily compressor operating hours and the total hours the compressor was available (i.e., scheduled shutdown for maintenance is not included in the available hour values). Subtraction of the total available hours from the total operating hours yields the number of hours each unit was in standby or idle mode operations. Because the number and duration of shutdowns were manipulated by the Center to ensure collection of the necessary measurements, those shutdowns that occurred at the Center's request were subtracted.

The number of blowdowns was determined by accounting for each occurrence of an idle period. It should be noted that this is an estimated value because the test site does not normally blow-down, but rather maintains a minimum pressure of 120 psig on the compressors during idle periods. The number of blowdown occurrences assigned for the Case 2 evaluation was determined based on the average number of engine shutdown occurrences for the two engines during the verification period.

3.0 RESULTS

The verification testing was conducted during five separate visits to the station beginning on July 15, 1999, and ending on January 26, 2000. Results of all of the tests conducted during both Phases of the verification are presented in this section and include:

Section 3.1 – Rod Packing Emissions
Section 3.2 – Other Emission Sources
Section 3.3 – Net Gas Savings
Section 3.4 – Annual Gas Savings
Section 3.5 – Payback Period

Each of the results sections presents the results of the verification and the performance of the Static-Pac as measured on the test engines. As the results will show, the uncontrolled rod leak rates on the test engines were much lower than the industry averages reported in past GRI studies (Section 2.1). Moreover, the test engines were equipped with only two compressors while the GRI study found the industry average to be 3.3 rods per engine (GRI 1997). The overall gas leaking from the two test engines was unusually low. To provide a representative assessment of Static-Pac performance, Sections 3.4 and 3.5 also include projected annual gas savings and payback for industry average rod leak rates using the GRI data.

Variability in these measurements was determined using a student t distribution test based on a confidence coefficient of 95 percent and the variability is reported with each of the average measurement results reported. Section 4.0 discusses Data Quality and will show that the variability was primarily a result of process variability (and not instrument or procedure related).

3.1 ROD PACKING EMISSIONS

3.1.1 Emissions During Idle/Shutdown

Table 3-1 presents the measured rod packing leak rates for Engines 801 and 802 during pressurized idle states. The table includes all data collected during Phase I and three more field campaigns conducted during the Phase II testing. Each campaign consisted of approximately 3 days of testing each. These data span a time range of just over 6 months and include the period from when the packing was first installed to about 4,000 hours of wear. Measurements were generally started 20 minutes after shutdown occurred, and required about 30 minutes to complete. Thus, the values reported below are representative of average emissions that occurred within about 45 minutes of compressor shutdown (unless the engine had been shut down overnight).

For all of the Phase II tests, the thermal anemometer was used in the Flow Tube to detect emissions from the Test Rod with the Static-Pac engaged. Idle emissions from the Control Rods were detectable with the vane anemometer. For all but one of the Test Rod measurements, the anemometer detected flows of 0.028 scfm or less.

Table 3-1. Rod Seal Leak Rate (Units Idle and Pressurized)

Date	**Approx. Run Time on New Seals (hrs) Control Rod / Test Rod**	**Engine Idle, Pressurized @ ~600 psi**		**Difference Between Control Road and Test Rod,[a] scfm natural gas**	**Natural Gas Emissions Reduction (%)**
		Control Rod With Conventional Packing, scfm natural gas	**Test Rod With Static-Pac, scfm natural gas**		
ENGINE 801					
7/15/99	17 / 1340	0.920	0.020	0.900	97.8
7/16/99	37 / 1365	0.720	0.020	0.700	97.2
8/4/99	520/ 1850	0.020[b]	0.010[b,d]	na	na
8/5/99	540 / 1870	0.020[b]	0.010[b,d]	na	na
8/6/99	563 / 1893	0.500	0.010[d]	0.490	98.0
9/21/99	1206 / 1536	0.527	0.022	0.505	95.8
9/21/99	1209 / 1539	0.634	0.024	0.610	96.2
9/22/99	1230 / 1560	0.507	0.024	0.483	95.3
12/7/99	2502 / 3833	0.581	0.023	0.558	96.0
12/7/99	2505 / 3836	0.544	0.023	0.521	95.8
12/8/99	2512 / 3842	0.036[b]	0.024[b]	na	na
12/9/99	2526 / 3856	0.226	0.022	0.204	90.3
12/9/99	2528 / 3858	0.021[b]	0.021[b]	na	na
1/26/00	3186 / 4516	0.686	0.021	0.665	96.9
1/26/00	3187 / 4517	0.740	0.019	0.721	97.4
1/26/00	3189 / 4519	0.755	0.018	0.737	97.6
1/27/00	3191 / 4521	0.592	0.020	0.572	96.6
801 Average		**0.610**	**0.020**	**0.590**	**96.2**
801 Standard Deviation		**0.170**	**0.004**	**0.170**	**2.0**
801 Confidence Coefficient[c]		**0.101**	**0.002**	**0.101**	
ENGINE 802					
7/16/99	19 / 19	0.790	0.020	0.770	97.5
8/4/99	509 / 509	0.020[b]	0.020[b]	na	na
8/5/99	533 / 533	1.130	0.010[d]	1.120	99.1
8/6/99	559 / 559	0.400	0.010[d]	0.390	97.5
9/22/99	1527 / 1527	0.318	0.025	0.293	92.1
9/22/99	1529 / 1529	0.365	0.016	0.349	95.6
9/23/99	1537 / 1537	0.497	0.027	0.470	94.6
9/23/99	1539 / 1539	0.535	0.023	0.512	95.7
12/7/99	2885 / 2885	0.287	0.030	0.257	89.5
12/8/99	2900 / 2900	0.431	0.005[d]	0.426	98.8
12/8/99	2903 / 2903	0.490	0.011	0.479	97.8
1/25/00	3597 / 3597	0.349	0.014	0.335	96.0
1/25/00	3599 / 3599	0.369	0.028	0.341	92.4
1/25/00	3602 / 3602	0.373	0.010	0.363	97.3
1/26/00	3605 / 3605	0.288	0.019	0.269	93.4
1/26/00	3607 / 3607	0.301	0.017	0.284	94.4
1/26/00	3609 / 3609	0.316	0.013	0.303	95.9
802 Average		**0.452**	**0.017**	**0.435**	**95.5**
802 Standard Deviation		**0.220**	**0.008**	**0.220**	**2.6**
802 Confidence Coefficient[c]		**0.118**	**0.004**	**0.119**	

(continued)

Table 3-1. Rod Seal Leak Rate (continued)
(Units Idle and Pressurized)

Date	Approx. Run Time on New Seals (hrs) Control Rod / Test Rod	Engine Idle, Pressurized @ ~600 psi		Difference Between Control Road and Test Rod,[a] scfm natural gas	Natural Gas Emissions Reduction (%)
		Control Rod With Conventional Packing, scfm natural gas	Test Rod With Static-Pac, scfm natural gas		
Overall Average		**0.523**	**0.019**	**0.504**	**95.8**
Overall Standard Deviation		**0.210**	**0.006**	**0.210**	**2.4**
Overall Confidence Coefficient[c]		**0.080**	**0.002**	**0.080**	

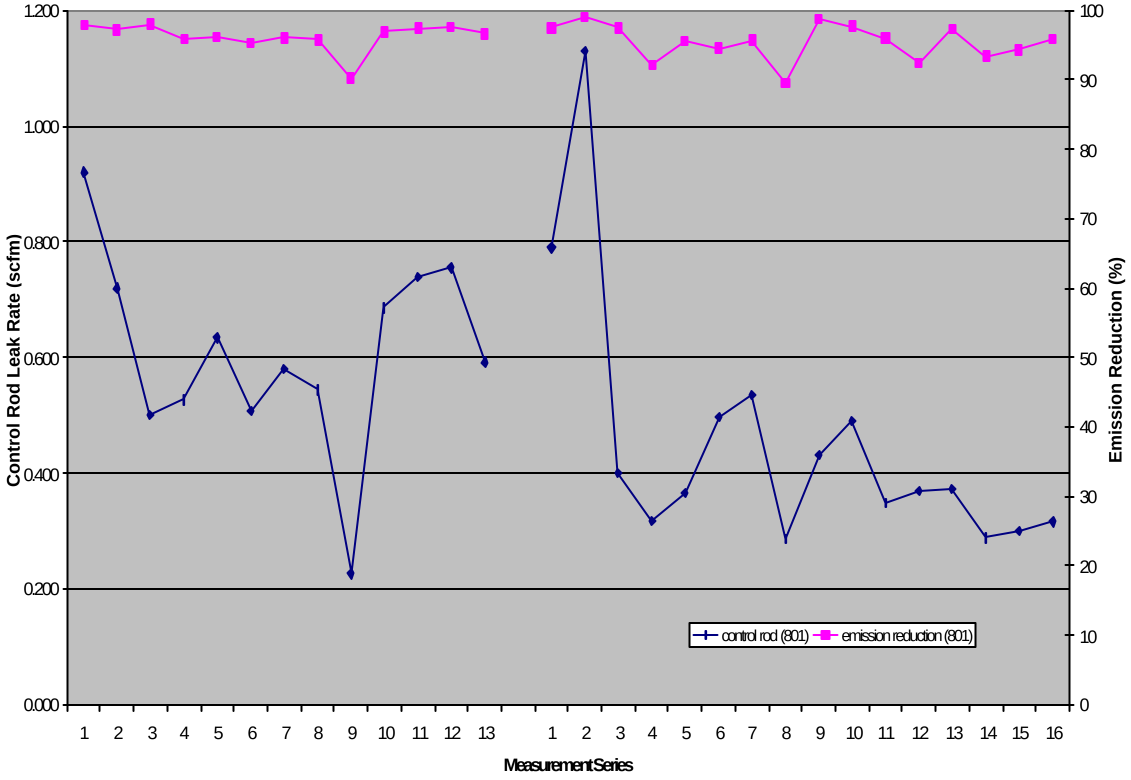
[a] Difference = (Control Rod Leak Rate – Test Rod Leak Rate).
[b] Anomalous measurements were not used to calculate averages.
[c] Student t distribution statistical analyses were used. Results are reported at 95% confidence level.
[d] Represents Non-detectable values. For these samples, a Lower Detectable Limit of 0.010 scfm for the vane anemometer and 0.005 for the thermal anemometer was assigned.

Four of the tests conducted on Engine 801 and one on 802 were invalidated because the emission rates measured on the control rods were extremely low compared to the overall data set and were considered atypical for these compressors. These tests were not used in calculating the overall average emissions, emission differences, and percent emission reductions reported in Table 3-1.

The average leak rate for the conventional rod packing was determined to be 0.61 scfm for Engine 801 and 0.45 for Engine 802. The Static-Pac equipped test rod reduced these leaks to 0.02 scfm for both engines. Variability in the measurements data was determined using a student t distribution test based on a confidence coefficient of 95 percent. All data, with the exception of percent emission reductions, were found to be normally distributed. The average emission reduction with the Static-Pac on Engine 801 and 802 was 0.590 +/- 0.083 scfm and 0.44 +/- 0.10 scfm, respectively. This equates to an overall emission reduction efficiency of 96 percent for both engines.

As discussed in Section 2, the Center was unable to conduct continuous monitoring for Control and Test rods as originally planned due to low leak rates encountered at the test site. In lieu of continuous measurements, the number of manual measurements conducted by the Center was increased to achieve a larger data set. Figure 3-1 illustrates the percent reduction in leak rates achieved through use of the Static-Pac. The figure illustrates that leak reductions due the Static-Pac are relatively consistent for both engines, and its performance and leak rate variability over time are adequately captured by the manually measured data. The figure illustrates that, over a series of 13 to 16 different measurement samples (sampling over a 6 month period), a wide range of Control Rod leak rates were encountered (0.23 to 1.13 scfm natural gas). At each one of these leak rates, the Static-Pac reduced a minimum of 90 percent of the rod packing leak rates. It is believed that further sampling would not alter these conclusions.

Figure 3-1. Static-Pac Performance Over Time



As described in Section 2.3.1, the approach for determining emission reductions was to compare the average Control Rod emissions to the average Test Rod emissions with the Static-Pac engaged. During all of the tests, the Static-Pac was manually disengaged allowing the comparison of emissions in both the engaged and disengaged position. However, since the Static-Pac requires the removal of the last set of rings from the packing case, the disengaged emissions may not be fully representative of conventional packing emissions. The data collected with the Static-Pac disengaged are not presented in this report for simplicity, but analysis of the data resulted in an average emissions reduction of 96 percent, the same that was measured using the Control Rod data.

3.1.2 Emissions During Compressor Operation

Tables 3-2a and 3-2b present the measured packing vent leak rates for Engines 801 and 802 during compressor operation. These data were collected to evaluate if removal of the last set of rings (to accommodate the Static-Pac) had an effect on emissions during operation. As before, these data were collected during five trips to the facility and span the range of time of just over 6 months and up to about 4000 hours of wear on the packing.

For Engine 801, the Static-Pac equipped packing had leak rates while running that averaged 1.31 scfm of natural gas lower than the conventional packing. Conversely, on Engine 802, the Static-Pac equipped packing had running leak rates that were about 0.23 scfm of natural gas higher than the conventional packing. Figure 3-2 plots the running leak rates for both engines. The running leak rates on the 801 control rod are much higher than those observed during Phase I indicating that the standard packing is starting to leak more during engine operation, while the leak rate with the Static-Pac equipped rod remained relatively stable. This trend is not present for Engine 802. Here, both rods are following the same general trend in emission rates over time.

Clearly, removal of the last set of rings would not cause emissions to be lower as indicated on Engine 801. This suggests that variation in emissions, caused by inherent differences between compressors such as rod alignment and the condition or effectiveness of primary seals, is more important than the missing seal associated with the Static-Pac. Some increase in emissions was measured on Engine 802, although the increase was slight. When the variability of these measurements is taken into account, the increase in emissions is within the range of measurement error. The Center therefore concluded that there is not strong evidence suggesting that removal of the last set of rings causes a significant increase in emissions and for this reason, a running emissions increase of 0 was used to calculate Case 1 gas savings.

Figure 3-2. Operating Emissions

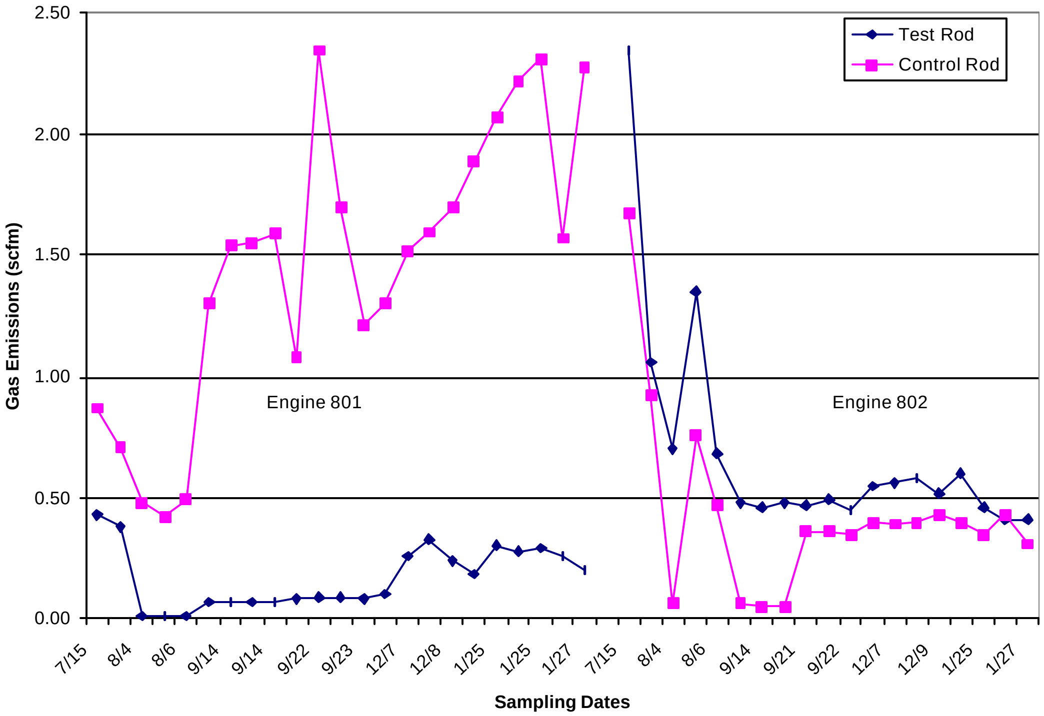


Table 3-2a. Rod Packing Leak Rates
Engine 801 – Operating

Date	**Approx. Run Time on New Seals, hrs Control Rod / Test Rod**	**Engine Running @ ~700 psi**		**Difference Between Control Rod and Test Rod,[a] scfm natural gas**
		Control Rod With Conventional Packing, scfm natural gas	**Test Rod With Static-Pac, scfm natural gas**	
ENGINE 801				
7/15/99	17 / 1340	0.87	0.43	0.44
7/16/99	37 / 1365	0.71	0.38	0.33
8/4/99	520 / 1850	0.48	0.01	0.47
8/5/99	540 / 1870	0.42	0.01	0.41
8/6/99	563 / 1893	0.49	0.01	0.48
9/14/99	1038 / 2368	1.30	0.05	1.25
9/14/99	1040 / 2370	1.54	0.05	1.49
9/14/99	1042 / 2372	1.55	0.05	1.50
9/14/99	1044 / 2374	1.59	0.05	1.55
9/21/99	1206 / 1536	1.08	0.06	1.02
9/22/99	1230 / 1560	2.35	0.06	2.29
9/22/99	1232 / 1562	1.70	0.06	1.64
9/23/99	1254 / 2584	1.21	0.06	1.15
9/23/99	1256 / 2586	1.30	0.07	1.23
12/7/99	2502 / 3833	1.52	0.26	1.26
12/8/99	2510 / 3840	1.60	0.33	1.27
12/8/99	2512 / 3842	1.70	0.24	1.46
12/8/99	2514 / 3844	1.89	0.18	1.71
1/25/00	3163 / 4493	2.07	0.30	1.77
1/25/00	3166 / 4496	2.22	0.28	1.94
1/25/00	3168 / 4498	2.31	0.29	2.02
1/26/00	3186 / 4516	1.57	0.26	1.31
1/27/00	3191 / 4521	2.28	0.20	2.08
801 Average		**1.47**	**0.16**	**1.31**
801 Standard Deviation		**0.59**	**0.13**	**0.57**
801 Confidence Coefficient[b]		**±0.26**	**±0.06**	**±0.25**

[a] Difference = (Control Rod Leak Rate – Test Rod Leak Rate), positive values indicate gas savings are achieved.

[b] Student t distribution statistical analyses were used. Results are reported at 95% confidence level.

Table 3-2b. Rod Packing Leak Rates
Engine 802 - Operating

Date	Approx. Run Time on New Seals, hrs Control Rod / Test Rod	Engine Running @ ~700 psi		Difference Between Control Rod and Test Rod,[a] scfm natural gas
		Control Rod With Conventional Packing, scfm natural gas	Test Rod With Static-Pac, scfm natural gas	
7/15/99	1 / 1[b]	1.67	2.35	-0.68
7/16/99	19 / 19	0.92	1.06	-0.14
8/4/99	509 / 509	0.06	0.70	-0.64
8/5/99	533 / 533	0.76	1.35	-0.59
8/6/99	559 / 559	0.47	0.68	-0.21
9/14/99	1348 / 1348	0.05	0.48	-0.42
9/14/99	1350 / 1350	0.04	0.46	-0.41
9/14/99	1352 / 1352	0.04	0.48	-0.43
9/21/99	1517 / 1517	0.36	0.47	-0.11
9/21/99	1519 / 1519	0.36	0.49	-0.13
9/22/99	1527 / 1527	0.35	0.45	-0.10
12/7/99	2883 / 2883	0.40	0.55	-0.15
12/7/99	2885 / 2885	0.39	0.56	-0.17
12/7/99	2887 / 2887	0.40	0.58	-0.18
12/9/99	2910 / 2910	0.43	0.52	-0.09
12/9/99	2912 / 2912	0.40	0.60	-0.20
1/25/00	3597 / 3597	0.35	0.46	-0.11
1/27/00	3609 / 3609	0.43	0.41	0.02
1/27/00	3612 / 3612	0.31	0.41	-0.10
802 Average		**0.36**	**0.60**	**-0.23**
802 Standard Deviation		**0.23**	**0.24**	**0.19**
802 Confidence Coefficient[c]		**±0.11**	**±0.12**	**±0.09**
Overall Average (801 and 802 Combined)		**0.98**	**0.35**	**0.63**
Overall Standard Deviation		**0.72**	**0.29**	**0.89**
Overall Confidence Coefficient[c]		**±0.23**	**±0.09**	**±0.28**

[a] Difference = (Control Rod Leak Rate – Test Rod Leak Rate), positive values indicate gas savings are achieved.
[b] Due to insufficient packing break-in time, this test was not included in the averaging.
[c] Student t distribution statistical analyses were used. Results are reported at 95% confidence level.

3.2 OTHER EMISSION SOURCES

3.2.1 Valve Leaks and Blowdown Volume

Measurements were conducted to quantify the leaks associated with the closed and pressurized blowdown valve, pressure relief valve, and unit valves. Seven measurements were made on the pressure relief and unit valves on each engine. Three measurements were conducted on each of the blowdown valves. These measurements represent the natural gas leaking past the valve seats on each device. Estimates of natural gas venting associated with compressor blowdown operations are also presented, and are based on ANR-supplied gas pressures and equipment volumes. The sources addressed in this section are among the most significant fugitive emission sources associated with compressor operations. Measurements associated with the remaining minor sources (e.g., valve stems, fittings, and other minor fugitive sources) are addressed in Section 3.2.2.

The results of these measurements are presented in Table 3-3. There were no detectable leak rates for both the blowdown valve and the pressure relief valve. Natural gas leak rates for the unit valves ranged from 1.99 to 6.46 scfm. The overall average unit valve leak rate between the two test engines was 4.48 ±0.91 scfm. As with the rod leak rate measurements, variability in the unit valve measurements was assessed using the student t test. The blowdown volume is constant (9,200 scf/event) because the operating pressure and equipment volume remained the same.

3.2.2 Miscellaneous Fugitive Sources

Once each trip, miscellaneous fugitive emission sources were soap screened to identify components that were leaking significantly and in need of leak-rate measurement. Seven screenings were conducted on each engine. The types of components screened include:

- Valves, meters, pipes, and flanges
- Miscellaneous fittings (tees, elbows, couplings, drains, ports, small valves)
- Blowdown gas recovery system components

The soap screening revealed no leaking components. This is not surprising, because most of these components are located in confined working areas, and any leaks could result in a significant safety hazard or triggering of the gas detection alarm system located at the site.

Table 3-3. Component Leak Rates

Date	Blowdown Valve, scfm natural gas	Pressure Relief Valve, scfm natural gas[a]	Unit Valve,[b] scfm natural gas	Blowdown Volume,[c] scf natural gas/event
ENGINE 801				
7/15/99	0.00	0	3.31	9,200
8/4/99	0.00	0	6.22	9,200
8/5/99	0[d]	0	6.46	9,200
8/6/99	0[d]	0	5.39	9,200
9/21/99	0.00	0	6.03	9,200
12/9/99	0[d]	0	6.06	9,200
1/26/00	0[d]	0	4.78	9,200
801 Average	na	na	5.46	na
801 Standard Deviation	na	na	1.11	
801 Confidence Coefficient[e]	na	na	±1.03	na
ENGINE 802				
7/16/99	0.00	0	2.82	9,200
8/4/99	0.00	0	5.49	9,200
8/5/99	0[d]	0	5.00	9,200
8/6/99	0[d]	0	4.20	9,200
9/22/99	0.00	0	2.43	9,200
12/8/99	0[d]	0	1.99	9,200
1/25/00	0[d]	0	2.50	9,200
802 Average	na	na	3.49	na
Standard Deviation	na	na	1.39	
802 Confidence Coefficient[e]	na	na	±1.29	na
802 Overall Average	na	na	4.48	na
Overall Standard Deviation	na	na	1.58	
Overall Confidence Coefficient[e]	na	na	±0.91	na

[a] Zero leak rates are assigned because screening with a hydrocarbon analyzer did not detect measurable levels.

[b] Represents total leak rates from both unit valves on the engine.

[c] Based on calculations performed by ANR engineers. This value represents the total volume of gas present in the test compressor, piping, and all equipment located downstream of the unit valves (at 700 psig).

[d] Zero values were assigned based on previous measurements.

[e] Student t distribution statistical analyses were used. Results are reported at 95% confidence level.

na Not applicable

3.3 NET GAS SAVINGS

The primary verification parameters for the Phase II evaluation are annualized gas savings and payback period. Both are based on the net gas savings measured throughout the Phase I and II testing. The Phase II test period began on September 21, 1999, after about 1,200 hours of operation on Engine 801 seals and about 1,500 hours on 802. Phase II testing ended on the last day of sampling (January 27, 2000). Net gas savings for the entire test period were calculated for the Case 1 and Case 2 baseline shutdown scenarios based on the engine specific average leak rates presented in Sections 3.1 and 3.2 and engine operational data presented in the next section.

3.3.1 Compressor Operational Characteristics

To calculate net gas savings for the verification period, the operational characteristics of both engines were determined on a daily basis. These operating characteristics include the number of shutdowns, the number of hours in the idle mode, and the number of hours in the running or operating mode. These operating characteristics, presented in Appendix B, were defined for Engines 801 and 802 using data supplied by ANR Pipeline. All periods when the station was off-line or the engines were in the out-of-service mode (i.e., non-idle-mode such as maintenance and repair) were not included in the determination of gas savings. The gray areas in the table correspond with sampling conducted by the Center, and operating or idle periods on these days are also not included in the verification. Although several engine shutdowns occurred on these days, they are not included in the determination of gas savings because these shutdowns were performed at the request of the Center. During the Phase I and II test period, Engine 801 was idle about 32 percent of the time, while Engine 802 was idle about 23 percent of the time.

3.3.2 Case 1 and Case 2 Gas Savings During the Verification Period

This section presents calculated gas savings associated with the Cook Static-Pac for Engines 801 and 802. Savings are computed by comparing compressor rod leak rates when the Static-Pac is installed, with compressor rod leak rates without the Static-Pac. The Static-Pac requires that a pressurized shutdown/idle mode is used, and the shutdown and idle mode operations used prior to installing the Static-Pac will affect the gas savings achieved. As discussed in Section 3.1, it was determined through direct measurement of uncontrolled emissions that leak rates on the Control Rods were significantly lower than the industry average. This issue will be addressed in Sections 3.5 and 3.6 where annual gas savings and payback periods are presented.

Two base-case compressor standby operating modes are evaluated. Case 1 represents the original use of a pressurized shutdown (same as Static-Pac requires), and Case 2 represents the original use of compressor depressurization and blowdown practice. As a result of changing the packing, and possibly the shutdown/idle mode, a variety of emission changes will occur in both cases. Each change is quantified here, and the bullets below describe how each value is determined. The emission factors referred to below were described in Sections 3.1 and 3.2, and are summarized in Table 3-4.

CASE 1 (no change in shutdown/idle mode; i.e., pressurized shutdown practice continues):

- Rod seal savings while idle:
  Description: Rod packing leaks that are reduced by the Static-Pac during idle periods
  Calculation: Idle hours*(Control Rod leak rate - Test Rod leak rate)

CASE 2 (change from blowdown mode to a pressurized mode):

- Rod seal leaks increase while idle:
  Description: Idle-mode rod packing leak rates from Static-Pac (with new pressurized shutdown/idle mode, these leaks, although very low, must now be added)
  Calculation: Idle hours*(Test Rod leak rate)

- Blowdown volume savings:
  Description: Gas contained in the compressor and piping released during shutdown (with new pressurized shutdown/idle mode, these emissions are no longer released)
  Calculation: Number of shutdowns*(blowdown volume emission factor)

- Blowdown valve emission increases:
  Description: Gas released from the closed blowdown valve (with new pressurized shutdown/idle mode, these emissions must now be added)
  Calculation: Idle hours*(blowdown valve leak rate)

- Unit valves leak savings:
  Description: Gas released from the closed unit valves (with new pressurized shutdown/idle mode, these emissions are no longer released)
  Calculation: Idle hours*(unit valves leak rate)

- PRV and miscellaneous component losses
  Description: Gas released from the pressure relief valve and miscellaneous fugitive sources (with new pressurized shutdown/idle mode, these leaks must now be added)
  Calculation: Idle hours*(PRV + Miscellaneous component (leak rates)

Table 3-4. Average Leak Rates Used to Compute Gas Savings (scfm natural gas)

Engine 801 Control Rod $_{\text{idle/pressurized}}$	0.610
Engine 802 Control Rod $_{\text{idle/pressurized}}$	0.452
Engine 801 Test Rod $_{\text{idle/pressurized}}$	0.020
Engine 802 Test Rod $_{\text{idle/pressurized}}$	0.017
Blowdown Volume	9,200 scf / shutdown event
Blowdown Valve	0.00
Unit Valve	4.48
Pressure Relief Valve and Misc. Components	0

Tables 3-5a and 3-5b present the actual Case 1 and 2 gas savings, respectively, that occurred during the entire verification test period from July 15, 1999, to January 27, 2000. Gas savings were calculated using average leak rates summarized in Table 3-4 and the engine operating data for the period as summarized in Appendix B. The Case 1 and Case 2 savings are reported on a per engine basis assuming that Static-Pacs are applied to each of the two engine's compressors.

Total natural gas savings for both engines under Case 1 were calculated to be 148,780 scf of natural gas, or savings of about 31 scf natural gas/standby hour for each Test Rod. These gas savings occurred because the Static-Pac reduced emissions by 96 percent during idle mode and the engines averaged 28 percent idle time during the verification.

Total natural gas savings for both engines under Case 2 were calculated to be 1,129,603 scf of natural gas. For this case, changing from a base case or blowdown practice to a pressurized condition resulted in significant gas savings from the blowdown volume and unit valves (Table 3-5b). However, the change in operating practice also resulted in emission increases from other components now exposed to high pressures. This includes packing leaks from the Static-Pac equipped rod. With the Static-Pac, some leaks are occurring from the engaged Static-Pac, but it is still inhibiting higher leak rates (total of 148,780 scf) that would have occurred if it was not installed.

Table 3-5a. Case 1 Gas Savings for the Test Period
(scf natural gas)

	CASE 1		
	Rod Seal Savings While Idle	Rod Seal Increases While Running	Total Savings
Engine 801	97,107	0	97,107
Engine 802	51,673	0	51,673
Total	148,780	0	148,780

Table 3-5b. Case 2 Gas Savings
(scf natural gas)

	Gas Savings Due To Change From Blow-Down Mode To Pressurized Mode					
	Blow-down Volume Savings	Unit Valve Leak Savings	Blowdown Valve Emission Increases	Pressure Relief Valve And Misc. Comp. Increases	Rod Seal Increases (Static-Pac Installed and Engaged)[a]	Total Savings Minus Emission Increases[b]
Engine 801	257,600	362,853	0	0	-3,078	617,375
Engine 802	248,400	266,085	0	0	-2,257	512,228
Total	506,000	628,938	0	0	-5,335	1,129,603

Note: Base case scenario is defined as a compressor that changes from a blowdown practice to a pressurized practice.

[a] The rod packing continues to leak slightly with the Static-Pac installed, but it is still inhibiting higher leak rates that would have occurred if the Static-Pac was not installed. Had Static-Pac not been installed, an additional increase of 154,115 scf of natural gas would be liberated.

[b] Total gas savings are a result of elimination of blowdown and unit valve releases, not the Static-Pac. The rod seal increases emissions slightly because it is now exposed to pressurized conditions. However, the increase with the Static-Pac is lower than the increase without the Static-Pac.

From a greenhouse gas emissions standpoint, the natural gas savings and emission increases cited above were converted into methane savings/increases by using natural gas compositional data routinely measured by ANR pipeline (Section 2.3.2.3). An average methane composition of 97.28 percent was measured during the Phase I and II test periods by ANR and, based on this value, total methane savings were:

Case 1: Net methane decrease of 144,733 scf for both engines

Case 2: Net methane decrease of 961,216 scf from eliminating the blowdown practice and not installing a Static-Pac, and net methane decrease of 1,098,878 scf from eliminating the blowdown practice and installing a Static-Pac.

3.4 ANNUAL GAS SAVINGS

3.4.1 Annual Case 1 and Case 2 Gas Savings

One of the goals of the Phase II testing was to calculate the gas savings associated with the use of the Static-Pac on an annual basis. Section 2.3.1.4 discussed in detail the procedures used for this determination. As mentioned, the data collected during Phases I and II of this verification indicated that there was no trend in increases in idle mode emissions over time as initially expected. Therefore, the conservative approach was used in annualizing gas savings by using the engine-specific average control rod leak rates minus the average emission rates from the Static-Pac observed throughout the entire test period. This average gas savings rate was used to calculate annual savings for an engine with two compressor rods equipped with the Static-Pac by multiplying it by the expected number of idle hours during a typical calendar year.

Table 3-6 summarizes the running and idle hours for the 1999 and early 2000 operating period. Also included in the table is the total number of shutdowns logged for each engine.

Table 3-6. Operating and Idle Hours for Engines 801 and 802 – 1999/2000

Month	Engine 801			Engine 802		
	Running	Idle	Shutdowns	Running	Idle	Shutdowns
February	442	230	3	345	327	2
March	661	83	0	282	462	3
April	159	561	1	262	458	3
May	159	585	3	262	482	3
June	618	102	1	236	484	1
July	572	172	1	440	304	1
August	418.6	190.7	6	526.5	83.8	5
September	430	218	2	572.2	75.8	3
October	605	91	6	583	113	5
November	425	295	6	614	106	6
December	586.1	85.9	3	394.7	277.3	3
January	164.6	411.4	34	412.7	163.3	3
Total	**5240.3**	**3025**	**35**	**4930.1**	**3336.2**	**38**
Percent of Total	**63.4**	**36.6**		**59.6**	**40.4**	

The data do not include periods of station shutdowns, engine maintenance, or verification testing. All data were obtained from ANR records.

Engines 801 and 802 averaged approximately 63.4 and 59.6 percent operating time, respectively, corresponding to an overall average idle time for both engines of 38.5 percent. The two engines averaged 37 shutdowns during the 12-month period. Using the average idle time of 38.5 percent, each rod would average a total of 3,373 idle hours per year. The annual gas savings for Case 1 and Case 2 operating scenarios are summarized in Tables 3-7a and 3-7b, respectively. Briefly, the Case 1 annual savings are 204,000 scf per engine or 102,000 scf per compressor rod. The Case 2 annual savings are 1,239,372 scf per engine. It should be noted that the majority of the Case 2 savings are due to the elimination of blowdown volume and unit valve emissions, not the Static-Pac.

TABLE 3-7a. Annual Gas Savings for Case 1 (February 1999 to January 2000)
(scf natural gas)

	CASE 1		
	Rod Seal Savings While Idle	**Rod Seal Increases While Running**	**Total Savings**
Engine With Two Compressor Rods Equipped With Static-Pacs	204,000	0	204,000

Table 3-7b. Annual Gas Savings for Case 2 (February 1999 to January 2000)
(scf natural gas)

	Gas Savings Due To Change From Blowdown Mode To Pressurized Mode					
	Blowdown Volume Savings	**Unit Valve Leak Savings**	**Blowdown Valve Emission Increases**	**Pressure Relief Valve And Misc. Comp. Increases**	**Rod Seal Increases (Static-Pac Installed and Engaged)[a]**	**Total Savings Minus Emission Increases[b]**
Engine with two compressor rods equipped with Static-Pacs	340,400	906,662	0	0	-7,690	1,239,372

Note: Base case scenario is defined as a compressor that changes from a blowdown practice to a pressurized practice.

[a] The rod packing continues to leak slightly with the Static-Pac installed, but it is still inhibiting higher leak rates that would have occurred if the Static-Pac was not installed. Had Static-Pac not been installed, an additional annual increase of 211,690 scf natural gas would be liberated.

[b] Total gas savings are a result of elimination of blowdown and unit valve releases, not the Static-Pac. The rod seal increases emissions slightly because it is now exposed to pressurized conditions. However, the increase with the Static-Pac is lower than the increase without the Static-Pac.

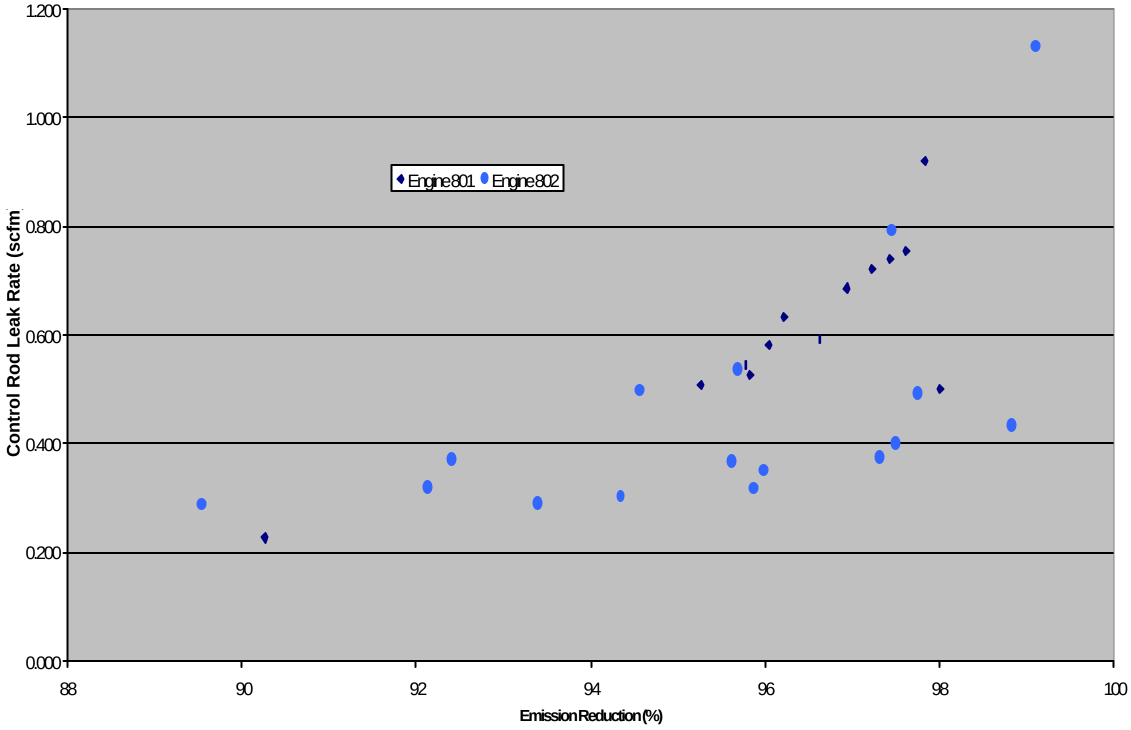
3.4.2 Estimated Annual Gas Savings For Other Compressors and Engines

The natural gas emission rates encountered at the test site were lower than the typical emission rates reported for rod packing leaks in the natural gas industry. Specifically, an EPA/GRI study reported an average leak rate of about 0.9 scfm per rod (Hummel et al., 1996). A study conducted by the Pipeline Research Committee (PRC) reported an average leak rate of about 1.9 scfm per rod (GRI 1997). These studies suggest that rod leak rates can vary significantly from one site to another and that the compressor leak rates tested under this verification are atypical. For this reason, the rod leak rate data collected under this verification program are believed to represent sites with low leak rates, and additional gas savings could be achieved for rods with industry average leak rates. To provide results more useful to the industry, annual gas savings for rods exhibiting industry average leak rates are estimated.

The measurements data collected during the test provide an understanding of Static-Pac performance for a range of rod leak rates, and allow extrapolation of measured data to industry average leak rates. The uncontrolled rod leak rates encountered at the site ranged between 0.23 and 1.13 scfm. The data collected clearly show that emissions from Static-Pac equipped rods do not vary over the range of uncontrolled emission rates observed at the site. As shown in Table 3-1 and Figure 3-1, the Static-Pac performance was relatively consistent, with emission reductions ranging from 89.5 to 99.1 percent (average reduction of 96 percent). Based on this, it is reasonable to assume that rods leaking at the GRI published industry average leak rate of 0.9 scfm are likely to achieve a 96 percent reduction in emissions.

Direct measurements data were not available for the PRC published industry average leak rate of 1.9 scfm. The highest uncontrolled leak rate measured at the site was 1.13 scfm, and the emission reduction associated with this leak rate was 99.1 percent. This one data point does not indicate performance output at the PRC reported leak rate. However, a plot of leak rate versus emission reduction (see Figure 3-3) clearly shows that Static-Pac leak reduction potential continues to improve at higher leak rates. For the PRC reported leak rate, it is assumed this trend continues, and the 96 percent emission reduction verified during the test can be extrapolated to the 1.9 scfm industry average leak rate. The reader is cautioned with limitations with this assumption because it is based on observed trends in the data.

Figure 3-3. Emission Reduction Performance at Varying Rod Leak Rates



Different compressor stations will also vary in average annual engine standby times. To account for such variability, annual gas savings were estimated for two engine standby rates: the rate of 38.5 percent that was determined during this test, and the rate of 55 percent that was cited as the average in the GRI study (Hummel et al., 1996). The number of compressors on an engine can also affect gas savings and payback. The test engines were equipped with only two compressor rods. The average number of compressor rods per unit tested in the PRC study was 3.3 (GRI 1997).

In the annual gas savings matrix presented in Table 3-8, annual gas savings are estimated for each of these variations in idle time and number of compressors using each of the varying rod leak rates referenced above (0.523, 0.9, and 1.9 scfm). The matrix assigns a Static-Pac emission reduction rate of 96 percent to each of the rod leak rates. The intent of the matrix is to provide a representative assessment of Static-Pac performance based on leak rates and engine operational data documented by the gas transmission industry at a wide range of gas processing facilities.

Table 3-8. Case 1 Annual Gas Savings Matrix for Varying Rod Leak Rates and Engine Idle Periods

Conventional Packing Case Leak Rate (cfm Natural Gas)	Annual Natural Gas Savings per Engine (Mscf)[b]			
	2 Compressors per Engine		3 Compressors per Engine	
	38.5 % Idle	55 % Idle (Industry Avg.)	38.5 % Idle	55 % Idle (Industry Avg.)
0.523 (Test Site)	204[a]	290	305	435
0.9 (GRI Industry Average)	350	500	525	749
1.9 (PRC Industry Average)	738	1,055	1,107	1,582

[a] Actual gas savings measured during this verification

[b] Mscf = thousand standard cubic feet

3.5 STATIC-PAC PAYBACK PERIOD

3.5.1 Capital, Installation, and Operation and Maintenance Costs

Table 3-9a presents the equipment and labor costs for the Control Rod packing material and all costs related to the Static-Pac system. These costs were obtained from C. Lee Cook and station operators. On a per-rod basis, the capital cost for the Static-Pac system was $4,088 in 1999. This is about $2,638 higher than the conventional packing case installed on the Control Rod. The Static-Pac system required 48 hours to install on each Test Rod (about 13 hours more than the Control Rod). Installation of the Static-Pac seals was similar to that of a conventional packing case, with the exception that the conventional packing case is modified to accept Static-Pac components. This involves milling/modifying the last cups to enable the Static-Pac seals and piston apparatus to be accommodated in the packing case. The costs associated with this activity (5 labor hours) are a one-time requirement that are accrued as a result of upfitting a conventional packing case. This task is not repeated during routine maintenance and operation, because the packing case is already modified to accept replacement Static-Pac seals. In addition to this, an automatic activator system is installed to provide pressurized gas to the piston. The installation and operating procedures, as submitted by C. Lee Cook, are provided in Appendix C as a reference. No deviations from these procedures were observed in the field.

Based on the data presented in Table 3-9a, the difference in costs for a rod equipped with the Static-Pac and a rod equipped with a conventional packing case is $3,483 for an engine with one compressor rod and one system actuator. The engines tested have two compressors and rods. Normally, Static-Pacs would be installed on both rods and be controlled by one common actuator at a cost of $4,808. This scenario is applicable to the host site and is used to calculate payback. The industry average for number of compressors on a single engine is three. This scenario (one actuator and three rods equipped with Static-Pacs) has a cost increase of $6,133 and is also used to estimate payback.

Table 3-9a. Static-Pac Equipment and Installation Costs

Test Rod		**Control Rod**		**Increase in Packing Case Cost for Upgrading to a Static-Pac $ / rod**
Description	**Cost $**	**Description**	**Cost $**	
Capital Equipment				
Packing Case with Static-Pac	2,200	Conventional Packing Case	1,450	750
Automatic Actuator System	1,638	--	--	1,638
Miscellaneous Materials	250	--	--	250
Installation Labor				
Packing Case With Static-Pac	2,600[a] (40 hrs)	Conventional Packing Case	2,275[a] (35 hrs)	325
Actuator System	520[a] (8 hrs)	--	--	520
Total Capital Cost	**$7,208**		**$3,725**	**$3,483**

[a] Installation costs of $65 per hour are assumed.

Note: For multiple rod installations, only the costs for packing case and miscellaneous materials are increased by the number of rods (i.e., actuator costs remain the same).

Static-Pac Operation and Maintenance (O&M) cost assumptions are based on observations at the ANR host site and discussions with two other ANR operators. Table 3-9b contains a summary of O&M cost findings for the three ANR sites which collectively represent a history of 57 Static-Pacs operating between 1 and 16 years. No repairs, replacement parts, or maintenance were needed on either of the Static-Pac systems tested throughout the test period. In addition, discussions with ANR operators at two other sites indicate that O&M costs for the Static-Pac were negligible for representative compressors experiencing normal operation. Specifically, 83 percent of the Static-Pacs installed experienced negligible O&M costs. Based on this and similarities observed between the three sites, annual O&M costs for the test site are assumed to be negligible.

The remaining 17 percent of the Static-Pacs installed at the two sites were found to require replacement parts in the latter years, mostly due to malfunctioning compressors. It is likely that other factors are causing this, but sufficient information was not available to form definitive conclusions. This small population of compressors are included in the payback analyses using O&M cost findings reported in Table 3-9b. For rods that begin to misalign, excessive wear in the packing case seals can occur. Under these conditions, any worn or damaged conventional seals and the last two Static-Pac seals are usually replaced. The capital costs for a one-time replacement are reported to range from $500 to $800/rod. Both site operators reported that these costs occurred in years 10 through 15. No additional labor costs were reported by ANR operators because replacing the Static-Pac seals required the same amount of time as replacing conventional packing seals that would be present if the Static-Pac was not there. The payback calculations assume that O&M costs are negligible in years 1 through 10 and increase to $160/rod/yr for years 11 through 15 (average of the $800 figure over a 5-year period).

The Static-Pac O&M cost assumptions outlined above are considered representative of ANR type facilities. The reader is cautioned to use these data for unrepresentative compressors, and is encouraged to apply their site specific cost assumptions to develop payback estimates.

Table 3-9b. Summary of Findings for Static-Pac Operation and Maintenance Costs

	ANR Test Site	**ANR Defiance Station**	**ANR Meade Station**
No. of Static-Pacs In Place	2	36	29
Age of Static-Pacs In Place	1 yr	15 yrs	15 yrs
Routine Inspection Costs	Static-Pac inspection conducted simultaneously with other seals in packing case; no additional labor hours expended	Static-Pac inspection conducted simultaneously with other seals in packing case; no increase in labor was reported	Static-Pac inspection conducted simultaneously with other seals in packing case; no additional labor hours expended
Parts Replacement Costs	No O&M costs occurred	**For about 6 Static-Pacs** Year 1-10: O&M costs were "essentially negligible[a]" Year 11-15: one time cost of $600/rod[c]	**For 5 Static-Pacs** Year 1-10: 0 to $1.60/yr/rod[b] Year 11-15: one time cost of $500 to $800/rod[c]
		For remaining 30 Static-Pacs Year 1-15: O&M costs were "essentially negligible[a]"	**For remaining 24 Static-Pacs** Year 1-15: 0 to $1.60/yr/rod[c]
Proposed O&M Cost Factors for Payback Calculations	Paybacks will be discussed for 2 scenarios: • Well maintained, properly functioning compressors: costs are negligible • Compressor rods that malfunction: Year 1-10 costs are negligible; Year 11-15 costs are $160/rod/yr		

[a] Site operators defined negligible as being so small that records were not maintained

[b] Consists of $1.50 for springs and $0.10 for O-rings. Site reports that these parts were replaced as a precautionary measure, not because of failures in Static-Pac components

[c] Due to compressor malfunctioning, damage to Static-Pac seals occurred. New Static-Pac seals were added at the same time new conventional seals were replaced.

3.5.2 Payback Period for the Test Engines

Payback was determined for Case 1 only, which represents compressors that normally maintain full operating pressure during idle periods. Payback for Case 2 was not determined due to concerns raised by several peer reviewers. The reviewers indicated that readers could inappropriately associate all of Case 2 savings to the Static-Pac, where in actuality, significant savings are occurring due to a change in the operating practice (i.e., converting from blowdown practice to pressurized conditions). Using the equations specified in Section 2.3.1.4, the annualized gas savings measured at the test facility, the initial costs outlined in Table 3-9a, and O&M costs assumptions discussed above, the Case 1 payback period is greater than 30 years for the test site.

3.5.3 Payback Period for Other Compressors and Engines

As mentioned earlier, uncontrolled rod leak rates at this facility were much lower than industry averages. Thus, the economic performance for a low-emitting site that remains pressurized is not favorable, but acceptable paybacks can be achieved for sites with industry average leak rates. In order to determine Static-Pac payback period for more typical facilities, the same data sources used to estimate potential gas savings (Section 3.4.3) were used to develop Table 3-10. All of the payback periods were calculated using the procedures presented in Section 2.3.1.4 and include the 10 percent discount rate of return on capital. These tables summarize potential payback periods for each of the gas savings scenarios presented in Table 3-8.

Table 3-10. Case 1 Payback Period Matrix

Conventional Packing Case Leak Rate (cfm Natural Gas per Rod)	Payback Period (years)			
	2 Compressors per Engine		3 Compressors per Engine	
	38.5 % Idle (Test Site)	55 % Idle (Industry Avg.)	38.5 % Idle (Test Site)	55 % Idle (Industry Avg.)
0.523 (Test Site)	>30[a]	18.5	>30	12.8
0.9 (Industry Avg.)	12.2	6.9	9.2	5.5
1.9 (Industry Avg.)	4.1	2.7	3.4	2.3

[a] Actual payback estimated for test site

As shown in Table 3-10, the Case 1 payback period can vary significantly depending on an engine's standby rate, rod packing leak rates, and number of compressors. The extremely low gas leak rates measured at the test facility, combined with the assumed 10 percent rate of return discount on capital, make payback essentially unattainable under those conditions. However, with higher leak rates more typical of conventional rod packing, reasonable payback periods can be achieved depending on average engine idle times. A payback period of less than 4 years can be achieved when the rod leak rates are near the PRC-reported industry average of 1.9 scfm and the engine standby rate is greater than 38 percent. If these compressor rods require Static-Pac replacement parts as stated in the O&M cost discussion, the payback period increases by about 3 months. The user is cautioned that gas savings associated with this leak rate are based on extrapolation of measured data, and potential for alternate gas savings exists. This means that payback estimates for the 1.9 leak rate could be lower or higher than the values reported in Table 3-10.

3.5.4 Limitations to the Verification Conclusions

In the Phase I report, the Center reported that the continuous emissions monitoring originally planned for this verification could not be conducted because of the low leak rates encountered at the test site. In lieu of continuous measurements, the Center increased the number of manual measurements to achieve a larger data set. Nevertheless, the data set collected is much smaller than originally planned. In addition to the small data set, uncontrolled leak rates at the test facility were somewhat atypical when compared to the industry average in that they were much lower than emissions documented for many other gas transmission stations.

Because the uncontrolled rod packing leaks at the test site were low, the calculated emission reductions achieved by the Static-Pac were also low. As explained earlier, the percent decrease in emissions measured at the test site was extrapolated to apply to average compressor emissions documented in other studies. The data collected during this study showed that emission reductions were steady throughout the range of uncontrolled leak rates measured. In most cases, emission reductions were highest when uncontrolled emissions were highest because emissions with the Static-Pac engaged did not increase proportionally to uncontrolled emissions. It was on this basis that the data were extrapolated to the industry average. However, since no actual measurements were conducted at the higher industry average leak rates, and the data set presented in this report is much smaller than originally planned, the payback periods presented in the payback matrix are estimates only.

4.0 DATA QUALITY

4.1 BACKGROUND

Information on data quality is used to characterize the level of uncertainty in measured values and verification parameters. The process of establishing data quality objectives starts with determining the desired level of confidence in the primary verification parameters. A primary parameter was the establishment of idle-mode gas savings for the Static-Pac. These gas savings were used to help quantify the primary Phase II verification parameter which is the Static-Pac payback period. The data quality objective that was established for the payback period is based on input from gas industry and other Stakeholder Group members and allows for an error in payback values of about ±3 to 4 months, or approximately 10 percent of a favorable payback period of 3 to 4 years. This objective was used to set data quality indicator goals for the following key measured values: rod packing emissions; valve emissions (unit, blowdown, and pressure relief valves); miscellaneous source emissions; and natural gas quality measurements. This section identifies the data quality indicator goals and discusses whether they were met to satisfy the data quality objectives.

Table 4-1 summarizes the data quality indicators assigned for primary measurement variables. Throughout the test period, field and laboratory measurements were collected in an effort to quantify instrument and sampling errors associated with these measured values. For example, the accuracy and precision of the Flow Tube measurements were quantified with frequent calibrations and replicate samples, and these data were used to quantify uncertainty in the rod packing emission rates. The resulting data sets were analyzed to determine if significant variability was present. The instrument calibrations and replicate sample results, along with accuracy and precision data provided by instrument vendors, were used to determine if the data quality indicator goals were met, and thus, the data quality objective was satisfied. The following subsections discuss the data quality assessment of the primary measurement variables, and the overall uncertainty associated with the final results.

4.2 ROD PACKING EMISSION RATE MEASUREMENTS

The continuous flow metering devices initially planned for use on the doghouse vents did not function properly in the field. As a result, these meters were replaced by manual Flow Tube measurements. The maximum instrument error anticipated for the Flow Tube was ±2 percent according to manufacturer specifications. The error due to sampling (i.e., configuring the anemometers inside the flow tube) was established through laboratory calibration of the Flow Tube. A combined error of 5 percent was anticipated, which would have allowed the achievement of the data quality objectives set for the payback period. The error due to variability encountered in the process (i.e., rod leak rate for each compressor) was not addressed in the Test Plan because such data were not available to establish reasonable bounds. The uncertainty associated with the process was discussed in Section 3.0. The following paragraphs discuss whether data quality indicator goals (i.e., accuracy, precision, completeness) were met, and how these affected the overall quality of the Static-Pac performance data.

Table 4-1. Data Quality Indicator Goals

Measurement	Method	Range	Instrument and Sampling Error		How Determined	Frequency Goal
			Accuracy	Precision		
Rod Packing (Doghouse Vent) Emissions	Flow Tube with Vane Anemometer	0.20 to 3.0 scfm	0.18 scfm	10 %	Calibration against certified laminar flow element	90 % of hourly data over test period
	Flow Tube with Thermal Anemometer	0.02 to 0.10 scfm	0.006 scfm	20 %	Calibration against certified laminar flow element	
Unit Valve Leak Rate	Flow Tube with Vane Anemometer	0.30 to 6.0 scfm	0.36 scfm	10 %	Calibration against certified laminar flow element	9 Repetitions
Leaks From All Other Components	THC Detector	Dual range: 0.05 to 4.0 % 4 to 100 %	2 % of reading	Not Specified	Certified Calibration Gases	9 Repetitions

Four Flow Tubes were used to measure rod leak rates during the testing. Three of these were vane anemometers (two were damaged during testing and replaced by new anemometers) and the fourth contained the low-flow thermal anemometer. The Flow Tubes were calibrated with a laminar flow element (LFE), which itself was calibrated with an NIST-traceable primary standard. Table 4-2 summarizes calibration results for the Flow Tubes, and shows the accuracy and precision values developed from these data.

The average Flow Tube accuracy 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 (see Figure 4-1 for an illustration of a calibration curve for the vane anemometer). Individual measurement accuracy values were calculated by determining the absolute value of the difference between the Flow Tube and LFE flow rates (Flow Tube minus LFE), and averaging this value over the rates of each calibration run. As the table shows, the average accuracy of the Flow Tubes equipped with vane anemometers ranged from 0.012 to 0.086 scfm. The overall average accuracy with regards to sampling error for all three tubes used was 0.040 scfm, or 1.35 percent of the calibration range.

Table 4-2. Summary of Flow Tube Calibrations (Low Flows)

Calibration Date	Flow Tube ID	Calibration Run No.	Calibration Range (scfm)	Accuracy (scfm)	Precision (%)
6/2/99	ID-1 Vane	1	0.34 to 2.75	0.036	0.24
		2	0.34 to 2.75	0.037	
7/2/99	ID-1 Vane	1	0.35 to 3.47	0.028	0.66
		2	0.36 to 3.46	0.037	
7/23/99	ID-1 Vane	1	0.38 to 2.75	0.031	2.8
		2	0.38 to 2.75	0.049	
8/11/99	ID-1 Vane	1	0.39 to 2.69	0.037	0.23
		2	0.39 to 2.69	0.038	
8/11/99	ID-2 Vane	1	0.18 to 1.55	0.086	0.87
		2	0.18 to 1.55	0.012	
11/9/99	ID-3 Vane	1	0 to 1.63	0.032	0.07
		2	0 to 1.63	0.020	
12/10/99	ID-3 Vane	1	0 to 1.63	0.052	0.12
		2	0 to 1.63	0.048	
2/2/00	ID-3 Vane	1	0 to 2.42	0.038	0.09
		2	0 to 2.67	0.066	
12/13/99	Thermal	1	0 to 0.08	0.0049	1.5
		2	0 to 0.07	0.0029	
1/21/00	Thermal	1	0 to 0.10	0.0029	4.8
		2	0 to 0.10	0.0022	
2/2/00	Thermal	1	0 to 0.09	0.0015	3.6
		2	0 to 0.08	0.0040	
2/24/00	Thermal	1	0 to 0.10	0.0007	1.9
		2	0 to 0.10	0.0015	

The calibration curves for the thermal anemometer are not linear, but when the nonlinear calibration is applied, average accuracy over the calibration range was 0.0026 scfm, corresponding to 2.6 percent of the calibration range. Because the thermal anemometer was used to measure only extremely low flow rates in the range of 0.01 to 0.03 scfm, the sampling errors corresponding to these rates are very small. The thermal anemometer was first used in the field in September 1999, but was not calibrated prior to that sampling episode. The calibration curve from the December calibration was used for the September tests. This was considered acceptable after documenting that the calibrations are very consistent through February 2000 and measured flow rates (with Static-Pac engaged) were also consistent throughout the test period.

Conducting two replicate calibrations each time the flow tubes were calibrated assessed precision and/or repeatability. The calibration curves developed from replicate calibration series were compared at several velocity readings over the calibration range. 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. Figures 4-1 and 4-2 are examples of Flow Tube calibrations

Figure 4-1. Flow Tube Calibration - Vane Anemometer
Serial No: 40-90-09690

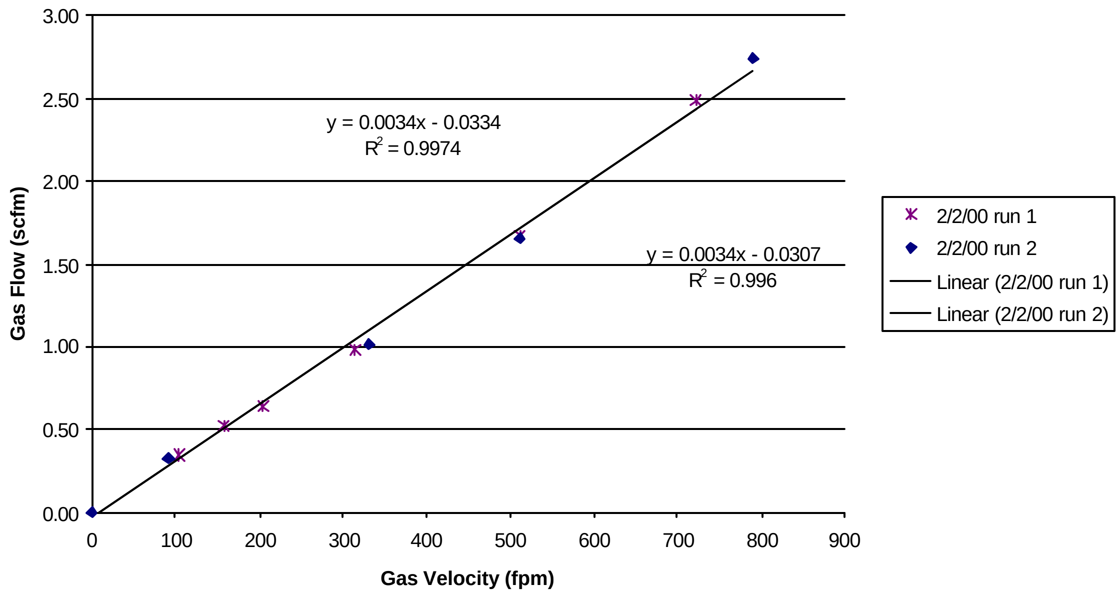
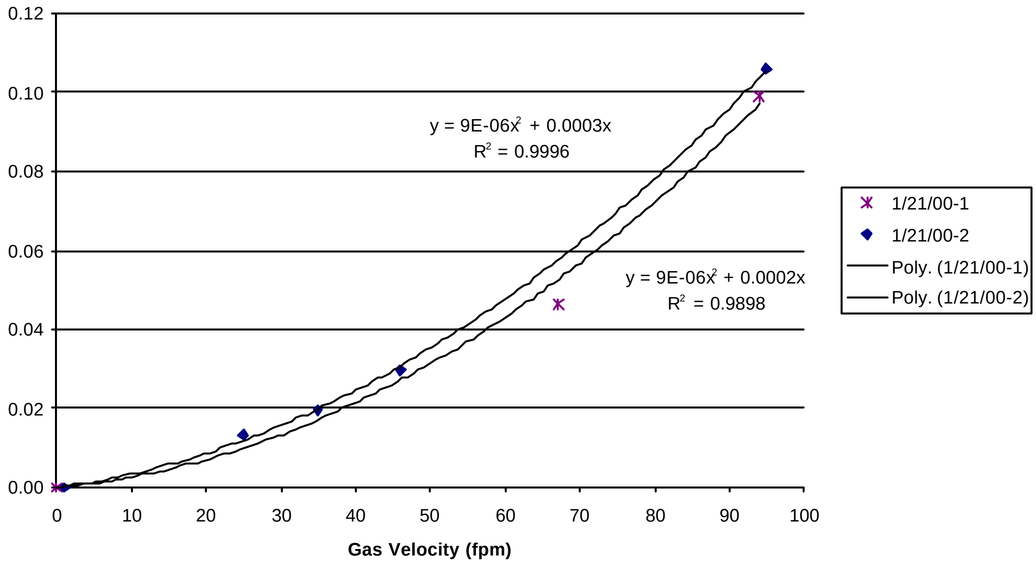


Figure 4-2. Flow Tube Calibration - Thermal Anemometer
Serial No: 91070385



with both a vane anemometer (Figure 4-1) and a thermal anemometer (Figure 4-2). Through previous laboratory tests conducted by the Center, it has been determined that the precision using two calibration curves is similar to precision results that would be obtained with three separate calibration curves. The calibration results indicate that close agreement between replicate readings can be achieved and show the close agreement of example replicate calibration runs. The means of the precision values in Table 4-2 are 0.64 percent for the vane anemometer runs, and 2.95 percent for the thermal anemometer runs.

In conclusion, the data quality indicator goals for accuracy and precision were met for all rod leak rate measurements.

Similar to the Phase I test, the original completeness goal for rod packing emissions measurements required the completion of 90 percent of hourly measurements using continuous flow monitoring throughout Phase II. As discussed in Section 3.1, continuous measurements were not feasible, and an alternate method of manual sampling was used. The manual measurement data collected during Phases I and II represent 14 days of sampling, and cover a 6-month period. Clearly, the data set collected is much smaller than originally planned, and the completeness goals were not met as a result of changing the sampling procedure from continuous to manual sampling. Close examination of the data set collected reveals that emission reductions due to the Static-Pac are relatively consistent for both Control rods, indicating that both performance and emission rate variability over time are adequately captured in the data set. Figures 3-1, 4-3, and 4-4 illustrate that, over a series of 13 to 16 different measurement samples taken, a wide range of control rod emission rates were encountered. At each of these emission rates, the test rod with the Static-Pac consistently reduced leaks by at least 90 percent. Further sampling within these intervals would likely not alter verification conclusions.

Figure 4-3. Compressor Rod Emissions Data

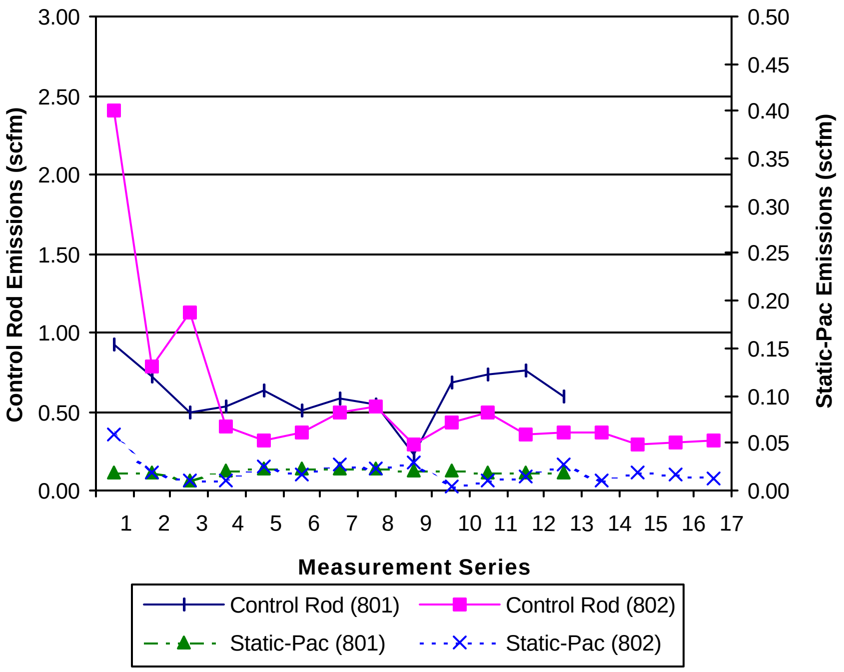
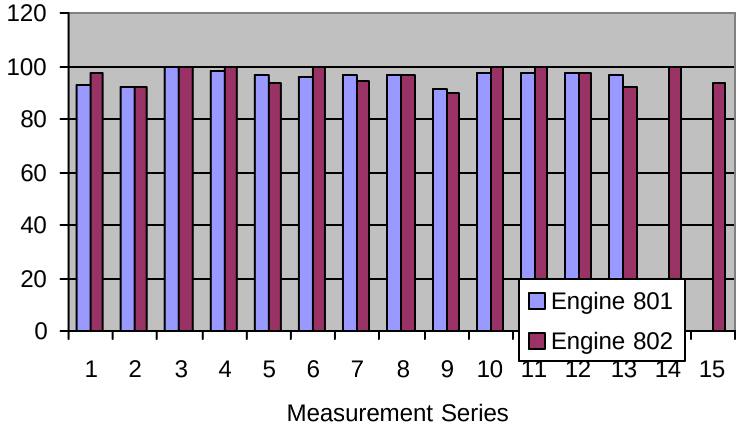


Figure 4-4 Emission Reduction Determinations For Pacs



4.2.1 Unit Valve, Blowdown Valve, and Pressure Relief Valve

The Test Plan specified using the Hi-Flow device and/or EPA's protocol tent/bag method for manual testing of the blowdown valve, pressure relief valve, and unit valves. As discussed earlier, the Center was unable to obtain a license in time to use the Hi-Flow device, and the tent/bag procedure would not have provided the desired level of accuracy needed at this facility. Therefore, measurements were made using the Flow Tube equipped with a vane anemometer. In all cases, the data quality achieved with the Flow Tube was better than the 10 percent accuracy and precision goals set for the Hi-Flow device. QA results for the three flow tubes used for these measurements are summarized below. Data quality considerations for the estimated blowdown volume are also discussed.

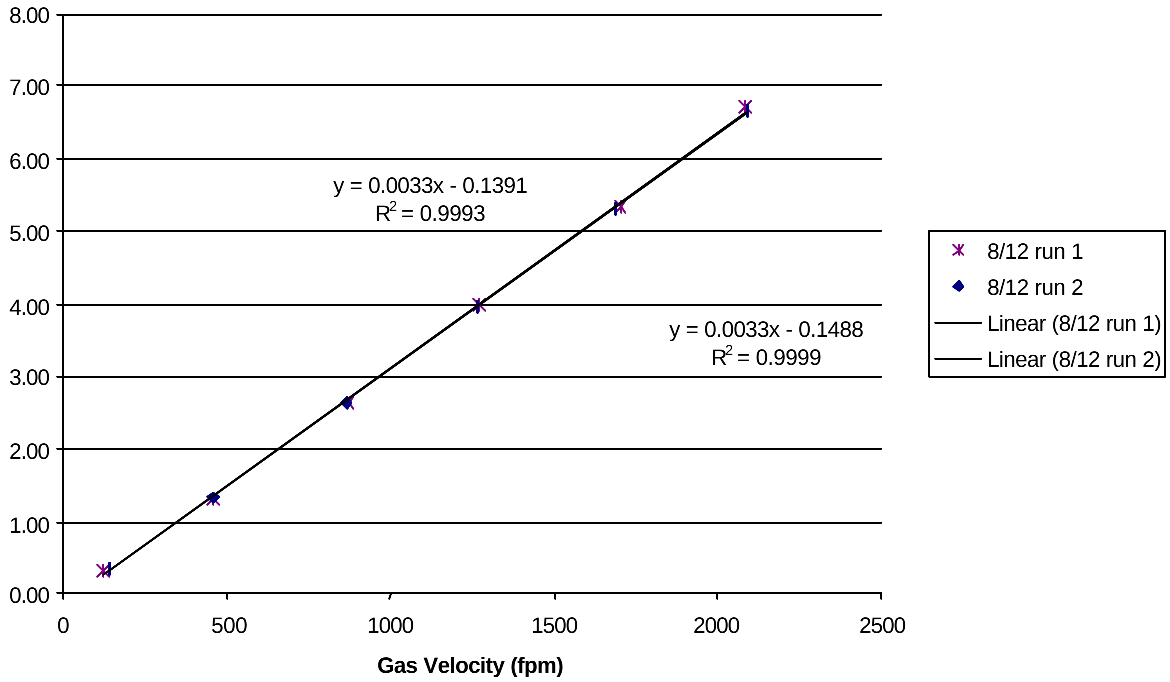
The pressure relief and unit valve leak rates were measured using the same Flow Tubes discussed earlier. Because flow was not detected for any pressure relief valves, QA and calibration data are not presented for them. For the unit valves, gas velocities higher than those measured during rod leak measurements were recorded. For this reason, a high-flow calibration chart was developed to convert measured gas velocities into natural gas flow rates. The same Flow Tube calibration procedures described for the rod packing vent measurements were followed here, and the calibration data developed at high flows are presented in Table 4-3.

Table 4-3. Summary of Flow Tube Calibrations (High Flows)

Calibration Date	Flow Tube ID	Run No.	Calibration Range (scfm)	Accuracy (scfm)	Precision (%)
8/11/99	1	1	2.14 to 7.59	0.065	1.16
		2	0.60 to 6.61	0.043	
8/12/99	2	1	0.32 to 6.72	0.075	0.12
		2	0.33 to 6.67	0.057	
9/27/99	2	1	0.26 to 3.31	0.041	2.81
		2	0.26 to 3.66	0.027	
12/2/99	3	1	1.67 to 5.43	0.034	2.17
		2	1.79 to 5.47	0.064	
1/20/00	3	1	1.65 to 5.36	0.034	0.64
		2	1.76 to 5.39	0.028	

A high flow calibration chart, similar to the Flow Tube calibration chart presented in Section 2 for the rod packing vent measurements, is shown in Figure 4-5. The average Flow Tube accuracy (0.047 scfm) and precision (1.38 percent) at high-flow regimes were found to be comparable to the values observed at lower flow regimes. Figure 4-5 clearly shows that the natural gas flow rate is linearly proportional to the gas velocity measured with the Flow Tube. The accuracy and precision of the Flow Tube exceeded the goals set for high flows such as those encountered with the unit valves. The completeness goal for the unit valve measurements was nine measurements (three sets of three). Unit valve leak rate measurements were made on 3 consecutive days in August 1999 and revealed little variability on consecutive days. Therefore, only one measurement was made during every subsequent visit to the site (to minimize blowdown gas losses) for a total of seven unit valve leak rate measurements. Further sampling within these intervals or continuous sampling would likely not alter the average leak rates determined through manual sampling.

Figure 4-5. Flow Tube Calibration - Vane Anemometer at High Flows
Serial No: 40-98-11431/5960



The Flow Tube was originally planned for use on blowdown valve leaks as well. However, Phase I field results suggested that the flow rates from the blowdown valve leaks were very low and well below the detectable limits of the flow tubes. Therefore, a low-flow rotameter was used to conduct measurements on the blowdown valves. Those tests indicated that the blowdown valve leak rates were either zero or an extremely low level that was negligible with respect to the verification goals. Additionally, the test location required separation of a flange that was very labor intensive and had to be conducted using host facility resources. For these reasons, the blowdown valve leak rates were measured only once during Phase II of the verification.

For the miscellaneous components such as flanges and valve stems, it was not possible to effectively channel the leaking gas to the flow tube. For these types of fugitive sources, soap screening was used to identify significant leaks and, when flow rate determination was needed, EPA's protocol tent/bag method was planned for use. Since significant leaks were not found, the tent/bag method was not applied, and the data quality information is not presented.

The average accuracy values presented here are used in Section 4.3 to assess how these measured values may contribute to overall uncertainty in the natural gas savings estimated for Cases 1 and 2.

4.2.2 Gas Composition

Based on average gas compositional data supplied by ANR, the average methane concentration in the natural gas for the Phase I and II testing was determined to be 97.28 percent. The average was calculated based on daily average values that were provided for each day that testing was conducted (14 total). The reported daily averages were a function of the readings made by ANR at 4-hour intervals. The accuracy of these readings was determined by ANR using calibration gases and was reported to be 0.12 percent.

4.2.3 Blowdown Volume

Blowdown volume was quantified based on the volume of piping and manifolds in the compressor system, and is accurate to within the piping specifications (assumed to be 100 percent accurate). The unit pressure, which was measured at the station by ANR engine monitors, was used to convert the calculated volume into a volume of natural gas at standard conditions. Generally, the host site operated at about 600 psig suction pressure. Unfortunately, calibration records for the pressure monitor are not maintained by ANR, so accuracy estimates for this measured parameter could not be determined. However, the accuracy of the pressure sensor was not required because the blowdown volume was calculated based on a typical suction pressure of 600 psig.

4.3 OVERALL UNCERTAINTY IN THE MEASUREMENTS, NET GAS SAVINGS, AND METHANE EMISSIONS VALUES

The errors associated with key measurement variables for this verification were determined and are summarized in Table 4-4. The data quality indicator goals listed in Table 4-1 address the desired accuracy of the measurement instrumentation and sampling procedures. However, the pretest accuracy goals do not incorporate errors associated with process variability. As discussed in Section 3.1, variability analyses were conducted on all of the compressor rod and unit valve leak rate measurements to account for process variability. The net measurement errors summarized in Table 4-4 include the instrument/sampling errors and the process variability.

Reviewing the data in Table 4-4, it is clear that the sampling errors documented for the testing are all well within the data quality objectives specified in the plan. For the control rod and unit valve measurements, the total net errors were 15 and 20 percent, respectively when the process variability is included.

Table 4-5 propagates the measured instrument/sampling error and process variability to obtain the overall uncertainty in the primary verification parameters. The primary objective of the verification was to determine the payback period with an uncertainty of 10 percent. Sampling errors and process variability were propagated based on the verification parameters listed in Table 4-5. Specifically, the average errors (from Table 4-4) associated with each of the measurements used to determine the verification parameters were totaled to determine the overall uncertainty due to instrument error. These errors were then combined with the process variability to obtain overall measurement uncertainty for each of the verification parameters.

Table 4-4. Summary of Errors Associated With Key Measurement Variables

Measurement Variable	Instrument and Sampling Errors (%)		Net Error (includes instrument, sampling, and process variability)	
	Goal	Actual	Performance Range	Error (%)
Control Rod (Idle)	2% of full scale (0.06 scfm)	1.34 % of calibration range (0.04 scfm)	0.523 ± 0.080 scfm	15
Test Rod (Idle)	2% of full scale (0.002 scfm)	2.95 % of calibration range (0.0026 scfm)	0.019 ± 0.002 scfm	13
Unit Valve	10% of full scale (0.40 scfm)	-0.78 % of calibration range (0.047 scfm)	4.48 ± 0.91 scfm	20
Gas Chromatograph	NA	0.12 % of reading	97.28 ± 0.12%	0.12

Table 4-5. Error Propagation and Overall Measurement Uncertainty

Verification Parameter	Uncertainty Due to Instruments and Sampling		Net Uncertainty (includes instrument, sampling, and process variability)	
	Performance Range	Error (%)	Performance Range	Error (%)
Natural Gas Emission Reductions	96 ±0.05 % reduction	0.05	95.8 ± 0.90 % reduction	0.94
Methane Emission Reductions	96 ±0.05 % reduction	0.05	95.8 ± 0.90 % reduction	0.94
Annual Gas Savings – Case 1	204,000 +28,529 scf [a]	1.39	81,642 ± 13,029 scf [a]	16
Annual Gas Savings – Case 2	617,213 +2,407 scf [a]	0.39	617,375 ± 74,417 scf [a]	12
Payback period – Case 1 [b]	2.42 ± 0.08 years	3.30	2.26 ± 0.42 years	18

[a] Based on gas savings measured on Engine 801 during the verification test period.

[b] Based on the Case 1 payback scenario of an average rod leak rate of 1.9 scfm and an average engine standby rate of 55 percent where the payback period was 2.26 years.

As shown in the table, the overall sampling and instrumental errors for all of the parameters were very low and well within the 10 percent goal. Incorporation of process variability was not included in the Data Quality Objectives, but was conducted to achieve a better understanding of measurement uncertainty. Once process variability is factored into the uncertainty analyses, the payback period errors exceed the objective.

Documentation of the uncertainty in the Case 1 payback period determinations was further complicated because, as reported in Section 3.5, Case 1 payback was unobtainable on the test engines due to the extremely low leak rates measured on the Control Rods. Therefore, the error in payback was calculated based on the hypothetical typical industry case where rod emissions average 1.9 scfm per rod, the engines are configured with three compressors, and engine standby averages 55 percent (Table 3-8). The 16 percent uncertainty in the current Engine 801 Case 1 gas savings measurements was applied to this hypothetical case to calculate the payback uncertainty. The data quality of results corresponding to the 1.9 scfm industry average leak rate is not certain because directly measured data were not available at the higher leak rates. The trends observed in Static-Pac performance as a function of rod leak rate suggest that the extrapolation performed based on measured data is legitimate. Nevertheless, the user is cautioned with potential limitations for higher leak rate rods.

In summary, all of the data quality objectives were met with regards to the instrumentation and sampling procedures used throughout the verification. Variability in the processes tested could not be predicted prior to conducting the testing and therefore were not included in the data quality objectives. The variability was determined through posttest data analyses and presented to provide overall verification uncertainty.

5.0 REFERENCES

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SRI 1999. *Testing and Quality Assurance Plan for the C. Lee Cook Division, Dover Corporation Static-Pac^{TM} System,* SRI/USEPA-GHG-QAP-04, Greenhouse Gas Technology Verification Center, Southern Research Institute, Research Triangle Park, NC, July 1999.

APPENDIX A

Example Payback Calculations For Case 1

Appendix A. Example Payback Calculations For Case 1 (2 compressors per engine, 55% idle time)

Total Capital Cost (Year 0)	**$4,808**	from Table 3-9
Discount Rate (r)	**10**	%
Annual O&M Costs	**$0**	
Annual Natural Gas Emissions Reduced	**290,000**	std. ft3/yr, from Table 3-8
Gas Cost	**2.00**	$/1000 std. ft3
Annual Gas Savings	**$580**	

Year	**Annual O&M Costs**	**Annual Gas Savings**	**Net Annual Savings**	**Discount Factor**	**Annualized Savings**	**Net Present Value**	
t				1/(1+r)^t			
1	$0	$580	$580	0.91	$527	$4,281	
2	$0	$580	$580	0.83	$479	$3,801	
3	$0	$580	$580	0.75	$436	$3,366	
4	$0	$580	$580	0.68	$396	$2,969	
5	$0	$580	$580	0.62	$360	$2,609	
6	$0	$580	$580	0.56	$327	$2,282	
7	$0	$580	$580	0.51	$298	$1,984	
8	$0	$580	$580	0.47	$271	$1,714	
9	$0	$580	$580	0.42	$246	$1,468	
10	$0	$580	$580	0.39	$224	$1,244	
11	$0	$580	$580	0.35	$203	$1,041	
12	$0	$580	$580	0.32	$185	$856	
13	$0	$580	$580	0.29	$168	$688	
14	$0	$580	$580	0.26	$153	$535	
15	$0	$580	$580	0.24	$139	$396	
16	$0	$580	$580	0.22	$126	$270	
17	$0	$580	$580	0.20	$115	$155	
18	$0	$580	$580	0.18	$104	$51	<---payback (between
19	$0	$580	$580	0.16	$95	-$44	years 18 and 19)
20	$0	$580	$580	0.15	$86	-$130	

Using Microsoft Excel, "NPER" function: **Payback:** **18.5**

APPENDIX B

Engine Operating Schedule for Phases I and II

Engine Operating Schedule for Phase I and II

Date	Engine 801 Operational Data (Hrs)				Engine 802 Operational Data (Hrs)			
	Shut-downs	Running	Out of Service	Idle	Shut-downs	Running	Out of Service	Idle
15-Jul			Testing				Testing	
16-Jul			Testing				Testing	
17-Jul		24	0	0		0	0	24
18-Jul		24	0	0	1	0	0	24
19-Jul	1	15.2	0.1	8.7		0	0	24
20-Jul		13.8	2.8	7.4		14	0.1	9.9
21-Jul		24	0	0		24	0	0
22-Jul		24	0	0		24	0	0
23-Jul		24	0	0		24	0	0
24-Jul		24	0	0		24	0	0
25-Jul		24	0	0		24	0	0
26-Jul		24	0	0		24	0	0
27-Jul	1	13.9	0	10.1		24	0	0
28-Jul		9.7	6.4	7.9		24	0	0
29-Jul		23.7	0.3	0		24	0	0
30-Jul		24	0	0		24	0	0
31-Jul		24	0	0		24	0	0
1-Aug		24	0	0		24	0	0
2-Aug		24	0	0		24	0	0
3-Aug		24	0	0		24	0	0
4-Aug			Testing				Testing	
5-Aug			Testing				Testing	
6-Aug			Testing				Testing	
7-Aug	1	13.6	0	10.4		10.2	0	13.8
8-Aug		24	0	0		0	0	24
9-Aug		24	0	0		0	0	0
10-Aug	1	20.8	0	3.2		11.1	0	12.9
11-Aug		24	0	0	1	7.9	0	16.1
12-Aug		24	0	0		15	0	9
13-Aug		24	0	0		24	0	0
14-Aug		24	0	0		24	0	0
15-Aug		24	0	0		24	0	0
16-Aug	1	19.2	0	4.8		24	0	0
17-Aug		0	0	24		24	0	0
18-Aug		0	0	24		24	0	0
19-Aug		9.6	0	14.4		24	0	0
20-Aug	1	10	0	14		24	0	0
21-Aug		24	0	0		24	0	0
22-Aug	1	9.3	14.7	0	1	10.3	13.7	0
23-Aug		0	24	0		0	24	0
24-Aug		16.2	0	7.8	1	16.5	0	7.5
25-Aug		24	0	0		23.5	0	0.5
26-Aug		24	0	0		24	0	0
27-Aug	1	7.9	0	16.1		24	0	0
28-Aug		0	0	24		24	0	0
29-Aug		0	0	24		24	0	0
30-Aug		0	0	24		24	0	0
31-Aug		0	0	24		24	0	0

(continued)

Engine Operating Schedule for Phase I and II (continued)

Date	Engine 801 Operational Data (Hrs)				Engine 802 Operational Data (Hrs)			
	Shut-downs	Running	Out of Service	Idle	Shut-downs	Running	Out of Service	Idle
1-Sep		10.1	0	13.9		24	0	0
2-Sep	1	11.3	0	12.7		24	0	0
3-Sep		0	0	24		24	0	0
4-Sep		0	0	24		24	0	0
5-Sep		0	0	24		24	0	0
6-Sep		0	0	24		24	0	0
7-Sep		0	0	24		24	0	0
8-Sep		0	0	24		24	0	0
9-Sep		0	0	24		24	0	0
10-Sep		12.7	0	11.3		24	0	0
11-Sep		24	0	0		24	0	0
12-Sep		24	0	0		24	0	0
13-Sep		24	0	0		24	0	0
14-Sep		24	0	0		24	0	0
15-Sep		24	0	0	1	23.7	0	0.3
16-Sep		24	0	0		24	0	0
17-Sep		24	0	0		24	0	0
18-Sep		24	0	0		24	0	0
19-Sep		24	0	0		24	0	0
20-Sep		24	0	0		24	0	0
21-Sep			Testing				Testing	
22-Sep			Testing				Testing	
23-Sep			Testing				Testing	
24-Sep		24	0	0	1	9.1	0	14.9
25-Sep		24	0	0		0	0	24
26-Sep		24	0	0		0	0	24
27-Sep		24	0	0		12.3	0	11.7
28-Sep		24	0	0		24	0	0
29-Sep		24	0	0		24	0	0
30-Sep	1	11.8	0	12.2	1	23.1	0	0.9
1-Oct		0	24	0		0	24	0
2-Oct		0	24	0		0	24	0
3-Oct		24	0	0		24	0	0
4-Oct	1	9.7	0	14.3	1	18.3	0	5.7
5-Oct		0	0	24		0	0	24
6-Oct		16.1	0	7.9		16.3	0	7.7
7-Oct		24	0	0		24	0	0
8-Oct		24	0	0		24	0	0
9-Oct	1	22.6	0	1.4	1	22.3	0	1.7
10-Oct	1	9.8	0	14.2		12.3	0	11.7
11-Oct		11.3	0	12.7		24	0	0
12-Oct		24	0	0		24	0	0
13-Oct		24	0	0		24	0	0
14-Oct	1	16.4	0	7.6		24	0	0
15-Oct		16.4	0	7.6		24	0	0
16-Oct		24	0	0		24	0	0
17-Oct		24	0	0		24	0	0
18-Oct		24	0	0		24	0	0
19-Oct		24	0	0		24	0	0
20-Oct		24	0	0		24	0	0

(continued)

Engine Operating Schedule for Phase I and II (continued)

Date	Engine 801 Operational Data (Hrs)				Engine 802 Operational Data (Hrs)			
	Shut-downs	Running	Out of Service	Idle	Shut-downs	Running	Out of Service	Idle
21-Oct		24	0	0		24	0	0
22-Oct		24	0	0		24	0	0
23-Oct		24	0	0		24	0	0
24-Oct		24	0	0		24	0	0
25-Oct		24	0	0		24	0	0
26-Oct		24	0	0		24	0	0
27-Oct		24	0	0	1	11.6	0	12.4
28-Oct		24	0	0		5.4	0	18.6
29-Oct		24	0	0		24	0	0
30-Oct		24	0	0	1	13.2	0	10.8
31-Oct	1	22.3	0	1.7		11	0	13
1-Nov		12.3	0	11.7		24	0	0
2-Nov	1	20.1	0	3.9		24	0	0
3-Nov		24	0	0		24	0	0
4-Nov		24	0	0		24	0	0
5-Nov	1	15.7	0	8.3	1	15.7	0	8.3
6-Nov		0	0	24		0	0	24
7-Nov		0	0	24		0	0	24
8-Nov		14	0	10		13.5	0	10.5
9-Nov		24	0	0		24	0	0
10-Nov		24	0	0		24	0	0
11-Nov	1	9.2	0	14.8	1	8.4	0	15.6
12-Nov		0	0	24		8.5	0	15.5
13-Nov		0	0	24	1	10.7	0	13.3
14-Nov		8.3	0	15.7		0	0	24
15-Nov		24	0	0		10.8	0	13.2
16-Nov		24	0	0		24	0	0
17-Nov	1	23.1	0	0.9	1	18.5	0	5.5
18-Nov		24	0	0		24	0	0
19-Nov		24	0	0		24	0	0
20-Nov	1	17.9	0	6.1		24	0	0
21-Nov		0	0	24	1	20.1	0	3.9
22-Nov		13.1	0	10.9		13.2	0	10.8
23-Nov		24	0	0		24	0	0
24-Nov	1	14.5	0	9.5		24	0	0
25-Nov		0	0	24		24	0	0
26-Nov		0	0	24	1	23.6	0	0.4
27-Nov		0	0	24		0	0	24
28-Nov		12.5	0	11.5		14.8	0	9.2
29-Nov		24	0	0		24	0	0
30-Nov		24	0	0		24	0	0
1-Dec		24	0	0		24	0	0
2-Dec	1	4.6	0	19.4		24	0	0
3-Dec		10.3	0	13.7		24	0	0
4-Dec		24	0	0		24	0	0
5-Dec		24	0	0		24	0	0

(continued)

Engine Operating Schedule for Phase I and II (continued)

Date	Engine 801 Operational Data (Hrs)				Engine 802 Operational Data (Hrs)			
	Shut-downs	Running	Out of Service	Idle	Shut-downs	Running	Out of Service	Idle
6-Dec	1	0.6	0	23.4		24	0	0
7-Dec			Testing				Testing	
8-Dec			Testing				Testing	
9-Dec			Testing				Testing	
10-Dec		23.9	0	0.1		24	0	0
11-Dec		24	0	0		24	0	0
12-Dec		24	0	0		24	0	0
13-Dec		24	0	0		24	0	0
14-Dec		24	0	0		24	0	0
15-Dec		24	0	0		24	0	0
16-Dec		24	0	0		24	0	0
17-Dec		24	0	0		24	0	0
18-Dec		24	0	0		24	0	0
19-Dec		24	0	0	1	12.6	0	11.4
20-Dec	1	20.3	0	3.7		0	0	24
21-Dec		0	0	24		0	0	24
22-Dec		22.4	0	1.6	1	22.1	0	1.9
23-Dec		24	0	0		0	0	24
24-Dec		24	0	0		0	0	24
25-Dec		24	0	0		0	0	24
26-Dec		24	0	0		0	0	24
27-Dec		24	0	0		0	0	24
28-Dec		24	0	0		0	0	24
29-Dec		24	0	0		0	0	24
30-Dec		24	0	0		0	0	24
31-Dec		24	0	0		0	0	24
1-Jan	1	23.3	0	0.7		0.3	0	23.7
2-Jan		2.8	0	21.2	1	22.6	0	1.4
3-Jan		24	0	0		24	0	0
4-Jan		24	0	0		24	0	0
5-Jan	1	22.8	0	1.2		24	0	0
6-Jan		0	0	24		24	0	0
7-Jan		0	0	24		24	0	0
8-Jan		0	0	24		24	0	0
9-Jan		0	0	24		24	0	0
10-Jan		15.1	0	8.9	1	8.9	0	15.1
11-Jan		24	0	0		15.9	0	8.1
12-Jan	1	17	0	7		24	0	0
13-Jan		0	0	24		24	0	0
14-Jan		0	0	24		24	0	0
15-Jan		0	0	24		24	0	0

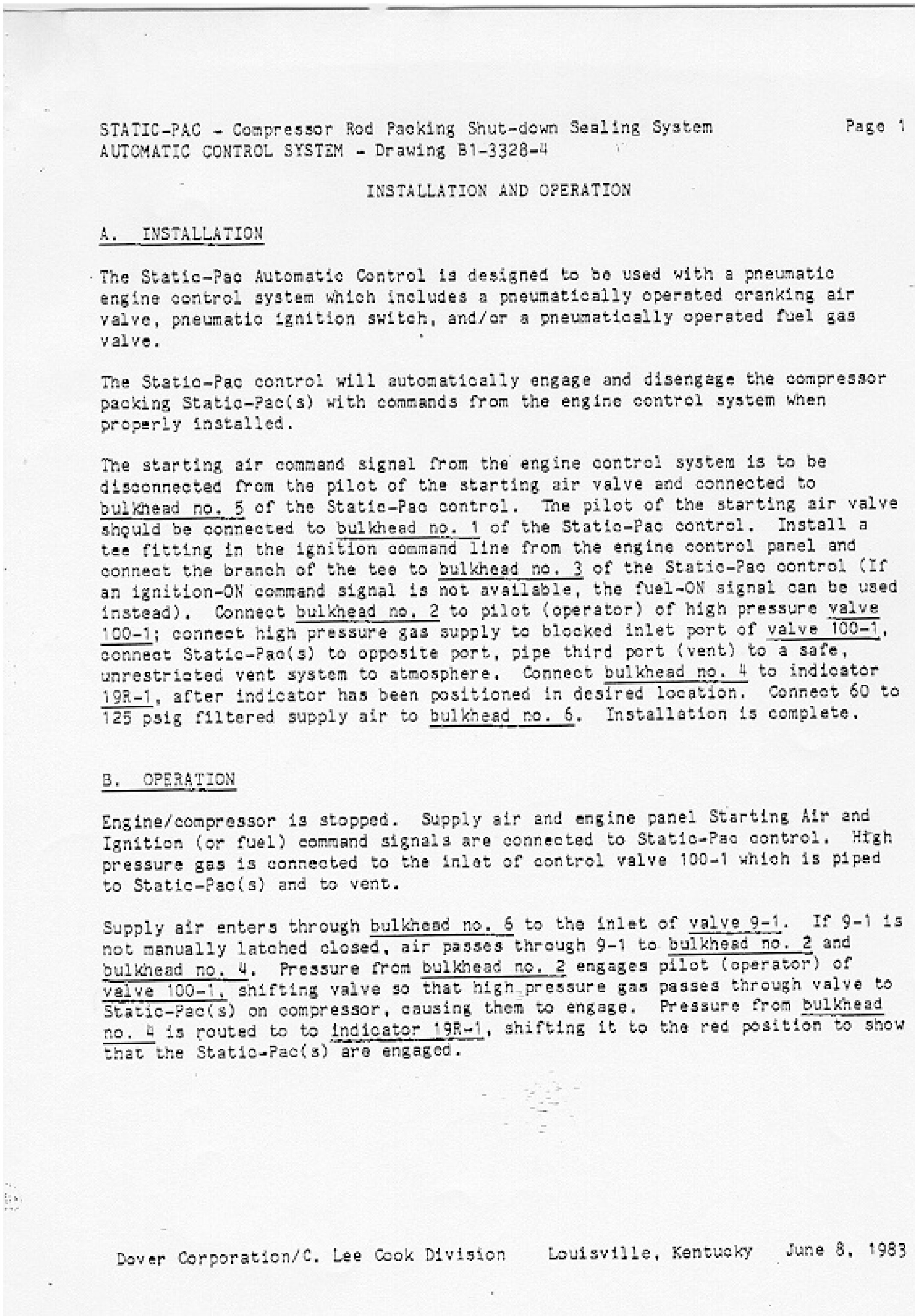
(continued)

Engine Operating Schedule for Phase I and II (continued)

Date	Engine 801 Operational Data (Hrs)				Engine 802 Operational Data (Hrs)			
	Shut-downs	Running	Out of Service	Idle	Shut-downs	Running	Out of Service	Idle
16-Jan		0	0	24		24	0	0
17-Jan		0	0	24		24	0	0
18-Jan		0	0	24		24	0	0
19-Jan		0	0	24	1	14	0	10
20-Jan		0	0	24		0	0	24
21-Jan		0	0	24		0	0	24
22-Jan		0	0	24		0	0	24
23-Jan		0	0	24		0	0	24
24-Jan		11.6	0	12.4		15	0	9
25-Jan			Testing				Testing	
26-Jan			Testing				Testing	
27-Jan			Testing				Testing	
Totals	**27**	**2944.8**	**96.3**	**1350.9**	**22**	**3292.3**	**85.8**	**989.9**

APPENDIX C

Static-Pac^{TM} Operator's Manual
Automatic Control System



AUTOMATIC CONTROL SYSTEM - Drawing B1-3328-4

INSTALLATION AND OPERATION

A. INSTALLATION

The Static-Pac Automatic Control is designed to be used with a pneumatic engine control system which includes a pneumatically operated cranking air valve, pneumatic ignition switch, and/or a pneumatically operated fuel gas valve.

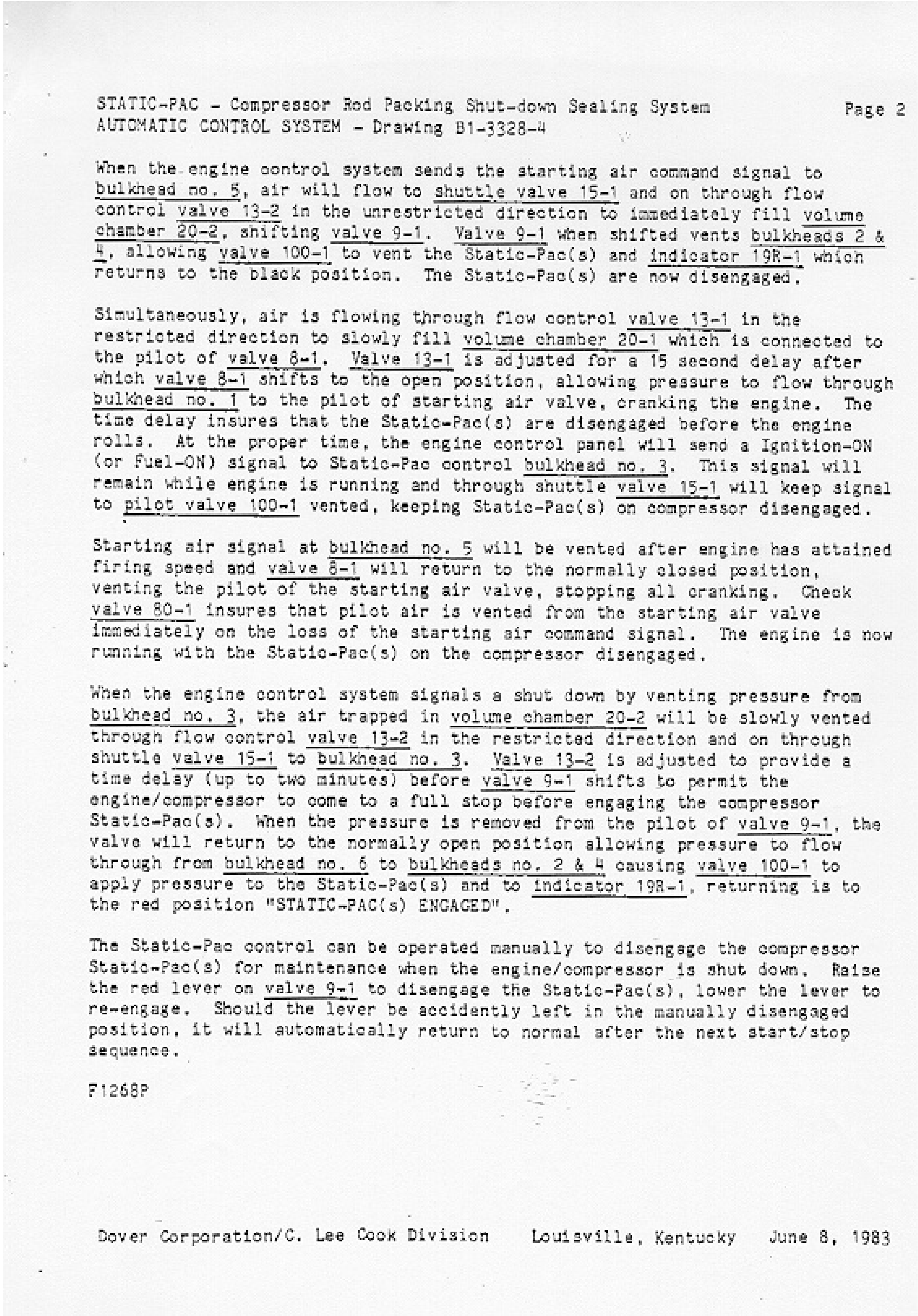
The Static-Pac control will automatically engage and disengage the compressor packing Static-Pac(s) with commands from the engine control system when properly installed.

The starting air command signal from the engine control system is to be disconnected from the pilot of the starting air valve and connected to bulkhead no. 5 of the Static-Pac control. The pilot of the starting air valve should be connected to bulkhead no. 1 of the Static-Pac control. Install a tee fitting in the ignition command line from the engine control panel and connect the branch of the tee to bulkhead no. 3 of the Static-Pac control (If an ignition-ON command signal is not available, the fuel-ON signal can be used instead). Connect bulkhead no. 2 to pilot (operator) of high pressure valve 100-1; connect high pressure gas supply to blocked inlet port of valve 100-1, connect Static-Pac(s) to opposite port, pipe third port (vent) to a safe, unrestricted vent system to atmosphere. Connect bulkhead no. 4 to indicator 19R-1, after indicator has been positioned in desired location. Connect 60 to 125 psig filtered supply air to bulkhead no. 6. Installation is complete.

B. OPERATION

Engine/compressor is stopped. Supply air and engine panel Starting Air and Ignition (or fuel) command signals are connected to Static-Pac control. High pressure gas is connected to the inlet of control valve 100-1 which is piped to Static-Pac(s) and to vent.

Supply air enters through bulkhead no. 6 to the inlet of valve 9-1. If 9-1 is not manually latched closed, air passes through 9-1 to bulkhead no. 2 and bulkhead no. 4. Pressure from bulkhead no. 2 engages pilot (operator) of valve 100-1, shifting valve so that high pressure gas passes through valve to Static-Pac(s) on compressor, causing them to engage. Pressure from bulkhead no. 4 is routed to to indicator 19R-1, shifting it to the red position to show that the Static-Pac(s) are engaged.



When the engine control system sends the starting air command signal to bulkhead no. 5, air will flow to shuttle valve 15-1 and on through flow control valve 13-2 in the unrestricted direction to immediately fill volume chamber 20-2, shifting valve 9-1. Valve 9-1 when shifted vents bulkheads 2 & 4, allowing valve 100-1 to vent the Static-Pac(s) and indicator 19R-1 which returns to the black position. The Static-Pac(s) are now disengaged.

Simultaneously, air is flowing through flow control valve 13-1 in the restricted direction to slowly fill volume chamber 20-1 which is connected to the pilot of valve 8-1. Valve 13-1 is adjusted for a 15 second delay after which valve 8-1 shifts to the open position, allowing pressure to flow through bulkhead no. 1 to the pilot of starting air valve, cranking the engine. The time delay insures that the Static-Pac(s) are disengaged before the engine rolls. At the proper time, the engine control panel will send a Ignition-ON (or Fuel-ON) signal to Static-Pac control bulkhead no. 3. This signal will remain while engine is running and through shuttle valve 15-1 will keep signal to pilot valve 100-1 vented, keeping Static-Pac(s) on compressor disengaged.

Starting air signal at bulkhead no. 5 will be vented after engine has attained firing speed and valve 8-1 will return to the normally closed position, venting the pilot of the starting air valve, stopping all cranking. Check valve 80-1 insures that pilot air is vented from the starting air valve immediately on the loss of the starting air command signal. The engine is now running with the Static-Pac(s) on the compressor disengaged.

When the engine control system signals a shut down by venting pressure from bulkhead no. 3, the air trapped in volume chamber 20-2 will be slowly vented through flow control valve 13-2 in the restricted direction and on through shuttle valve 15-1 to bulkhead no. 3. Valve 13-2 is adjusted to provide a time delay (up to two minutes) before valve 9-1 shifts to permit the engine/compressor to come to a full stop before engaging the compressor Static-Pac(s). When the pressure is removed from the pilot of valve 9-1, the valve will return to the normally open position allowing pressure to flow through from bulkhead no. 6 to bulkheads no. 2 & 4 causing valve 100-1 to apply pressure to the Static-Pac(s) and to indicator 19R-1, returning is to the red position "STATIC-PAC(s) ENGAGED".

The Static-Pac control can be operated manually to disengage the compressor Static-Pac(s) for maintenance when the engine/compressor is shut down. Raise the red lever on valve 9-1 to disengage the Static-Pac(s), lower the lever to re-engage. Should the lever be accidently left in the manually disengaged position, it will automatically return to normal after the next start/stop sequence.

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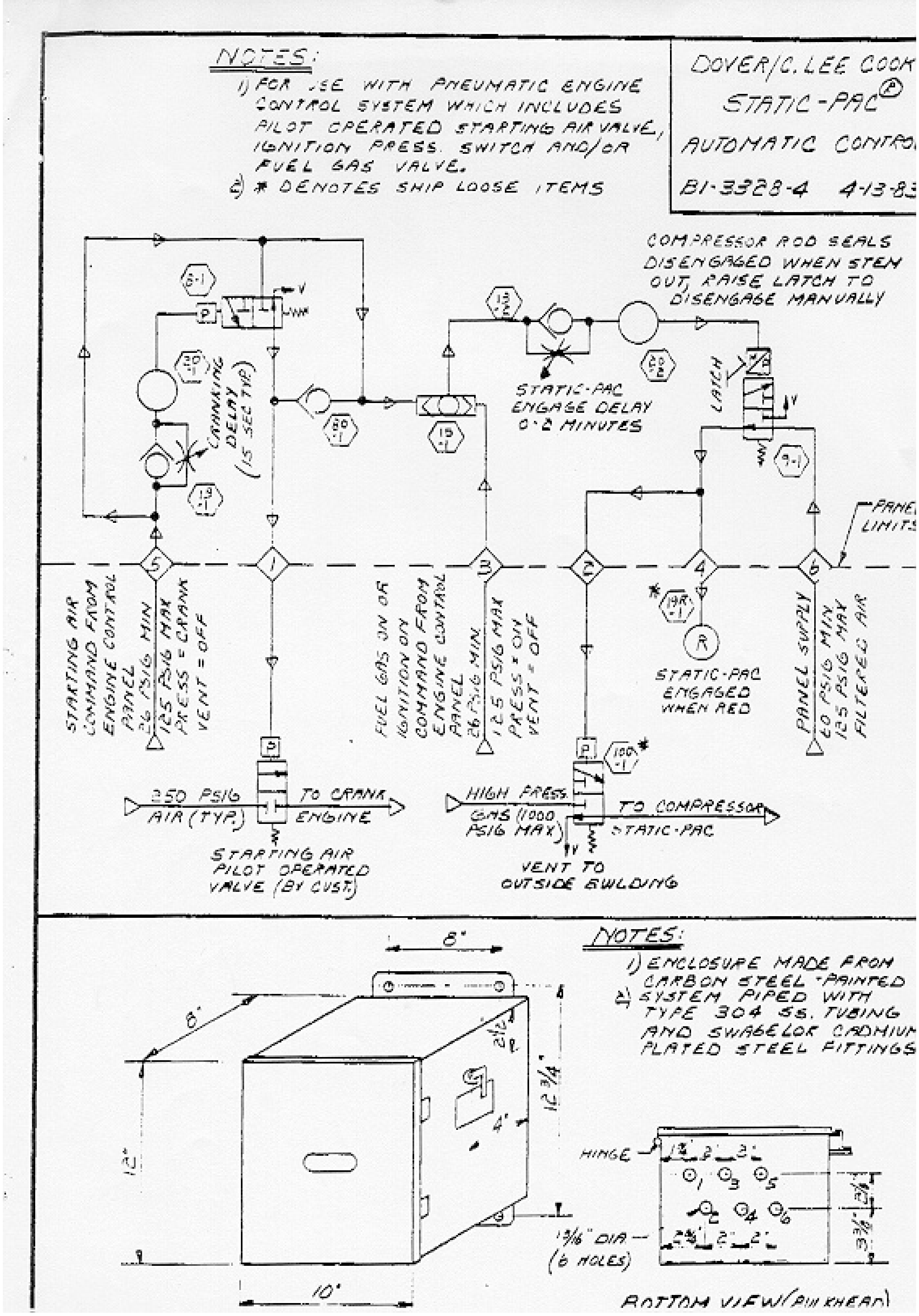
NOTES:
1) FOR USE WITH PNEUMATIC ENGINE CONTROL SYSTEM WHICH INCLUDES PILOT OPERATED STARTING AIR VALVE, IGNITION PRESS. SWITCH AND/OR FUEL GAS VALVE.
2) * DENOTES SHIP LOOSE ITEMS
DOVER/C. LEE COOK
STATIC-PAC®
AUTOMATIC CONTROL
B1-3328-4 4-13-83
COMPRESSOR ROD SEALS DISENGAGED WHEN STEM OUT, RAISE LATCH TO DISENGAGE MANUALLY
8-1
P
V
20-1
CRANKING DELAY (15 SEC TYP)
19-1
80-1
15-1
13-2
STATIC-PAC ENGAGE DELAY 0-2 MINUTES
20-2
LATCH
V
9-1
PANEL LIMITS
5
1
3
2
4
6
STARTING AIR COMMAND FROM ENGINE CONTROL PANEL 26 PSIG MIN 125 PSIG MAX PRESS = CRANK VENT = OFF
FUEL GAS ON OR IGNITION ON COMMAND FROM ENGINE CONTROL PANEL 26 PSIG MIN. 125 PSIG MAX PRESS = ON VENT = OFF
* 19R-1
R
STATIC-PAC ENGAGED WHEN RED
PANEL SUPPLY 60 PSIG MIN 125 PSIG MAX FILTERED AIR
P
250 PSIG AIR (TYP.)
TO CRANK ENGINE
STARTING AIR PILOT OPERATED VALVE (BY CUST.)
P
100-1 *
HIGH PRESS. GAS (1000 PSIG MAX)
TO COMPRESSOR STATIC-PAC
V
VENT TO OUTSIDE BUILDING
NOTES:
1) ENCLOSURE MADE FROM CARBON STEEL - PAINTED
2) SYSTEM PIPED WITH TYPE 304 SS. TUBING AND SWAGELOK CADMIUM PLATED STEEL FITTINGS
8"
8"
2½"
12¾"
4"
12"
10"
HINGE
1⅝"
2"
2"
1
3
5
2
4
6
13/16" DIA. (6 HOLES)
3⅞"
3⅞"
BOTTOM VIEW (BULKHEAD)