American Petroleum Institute

STEP Strategies for Today's Environmental Partnership

RESULTS OF RANGE-FINDING TESTING OF LEAK DETECTION AND LEAK LOCATION TECHNOLOGIES FOR UNDERGROUND PIPELINES

HEALTH AND ENVIRONMENTAL AFFAIRS DEPARTMENT
PUBLICATION NUMBER 346
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American Petroleum Institute

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Results of Range-Finding Testing of Leak Detection and Leak Location Technologies for Underground Pipelines

Health and Environmental Affairs Department

API PUBLICATION NUMBER 346

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ABSTRACT

This study reviewed the leak detection and leak location methods for pressurized underground piping. The review selected candidate methods for testing underground piping of diameters of 6 to 18 inches and lengths of 250 feet to about 2 miles. Such underground piping is commonly found at airports, refineries, and fuel terminals. Methods that appeared promising were further reviewed, and four technologies were selected for field demonstration in range-finding tests. The four technologies were constant-pressure volumetric testing, pressure-decay testing, chemical tracer testing, and acoustic emission testing. Range-finding tests were conducted at an operating facility, using pipeline sections of different volumes. The methods were tested on tight lines, lines with induced leaks, and one line with an operational leak. The approximate size of a leak that each method could detect was estimated. Methods that could locate leaks were used to identify the operational leak, which was confirmed by excavation and repair.

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EXECUTIVE SUMMARY

This study reviewed the available literature and other sources to identify methods of leak detection and leak location for pressurized underground piping. The size of the piping that was the subject of this research was larger than that found in retail fueling applications but smaller than cross-country transmission pipelines. The population of pipelines targeted ranged from about 6 to 18 inches in diameter and from about 250 feet to 2 miles long. Such piping is commonly found at airports, refineries, bulk plants, and fuel terminals.

The technologies that were identified were constant-pressure volumetric testing, pressure-decay tests, chemical tracer tests, acoustic emission tests, radioactive tracer tests, product inventory reconciliation analysis, and computerized pressure-flow analysis. Vendors of four different technologies (constant-pressure volumetric tests, pressure-decay testing, chemical tracer testing, and acoustical emission tests) were identified and invited to participate in the research study. The first two technologies purport to detect a leak and measure its size, while the latter two methods purport to detect leaks and identify their location.

The four methods were subjected to range-finding tests at an operating facility. Up to four different line sections of different volumes ranging from 1,600 gallons to 9,700 gallons were used in the testing. Tests were done on tight lines, on lines with simulated leaks, and on one line with a large operational leak.

The volumetric test method demonstrated the capacity to detect and measure leaks ranging from about 0.2 gallon per hour (gph) to 0.6 gph. The size of the leak that it can detect is a function of the volume of the line tested, in a fixed duration test. The system is designed for rapid mobilization to a test site and use as a point-in-time test. It has the potential to be permanently installed at a site and used for periodic testing. It requires that the sections of line to be tested be isolated with tight valves or blind flanges and tested in a static condition. The system checks the bulk modulus of the line. In the tests observed, the operators required that the line be nearly air-free. Once set up, a test requires about 2 hours. There are two differently sized systems designed for differently sized lines. This method identified the large operational leak and gave an approximate leak rate—the actual leak was too large for the system to measure without an additional source of fuel to keep the line under constant pressure. It tested a line with an unknown leak of about 0.2 gph, identified that the line was leaking, and estimated the leak rate as about 0.2 gph.

The chemical tracer method demonstrated the ability to detect a leak of 0.05 gph that persisted for at least 36 hours with tracer-labeled material. The tracer method can be used in a variety of different operating conditions: tracer inoculated product can be placed in the line under pressure in a static condition, the product can be inoculated with tracer and circulated through the line, or the line can be emptied and pressurized with tracer-labeled air. The choice depends on the operating conditions at a site. The tracer method was tested with liquid product in a static condition, and with tracer in air in a static test. The tracer method gave no false alarms on a tight line. It identified the operational leak and identified three suspect areas, one of which was confirmed by excavation and repair. The tracer method requires inoculation with tracer, installation of sampling probes, then sampling and analysis several days after inoculation, depending on site conditions. Special procedures were used for these tests since introduction of the tracer material in fuel is not yet approved by the FAA for commercial aircraft.

The pressure-decay method was found to be designed for permanent installation. As such, it requires calibration to each section of pipe to be tested—performing a number of calibration tests with the line tight and with known simulated leak rates. It is not intended for use as a one-time test method. Once calibrated, it detected simulated leaks and measured them. It uses a threshold for leak detection that is proportional to the volume of the pipeline, equivalent to 0.004% of the volume of the line per hour. When tested on a line with a large operational leak, it identified the leak quickly through the line's failure to hold pressure. When tested on a line with an unknown leak of about 0.2 gph, the operators were unable to calibrate the system. After about a day and a half of testing, they concluded that the line must have a leak, which was then confirmed as leaking past a blind flange. The method requires absolutely tight valves to isolate line sections for testing. It also requires the lines to be essentially air-free. In permanent installation, it requires remotely operated double-block-and-bleed valves. A pipe section can be tested in about 45 minutes, once the system is calibrated.

The acoustic emission test requires physical access to the pipe about every 50 feet. At the test site, access was accomplished with existing valve pits and hydrants. Testing with simulated leaks showed that the system could detect leaks though a needle valve of about 0.4 gph at 150 feet and leaks of 1.8 gph through an orifice into air at that distance. The vendor stated that the leak into backfill created a different signal because of the interaction of the leaking liquid and the soil particles. The method tests quite rapidly once there is access to the pipe, taking about 5 minutes at each point. The vendor knew from site personnel that one line had an operational leak and identified a signal the vendor said appeared to locate the leak near one end of the section. However, upon excavation, the actual leak was found at the opposite end of the line. The vendor had one test point within 20 feet of the operational leak and did not find it. The leak was found to be in a pipe in a sleeve, and the area was saturated with liquid. Thus, the leak did not directly interact with soil, and the area was saturated with liquid, which attenuates the acoustic signal. Testing on another section of pipe identified a signal resulting from the cathodic protection system. Thus, the range-finding tests showed that the system is sensitive to the geometry of the source of the leak, as well as the conditions around it. The location capability of the system was not confirmed upon excavation.

No single leak detection system was found that works in all situations. Site-specific conditions may affect any method, and combinations of methods may provide the most effective approach.

Table 1. Comparison of Technologies

	Technology			
Comparison Item	Volumetric	Pressure Decay	Tracer	Acoustic
Installation time	One day	About 1 week for permanent installation; 1 day for test	1-2 days	Half a day
Test duration	2 hours	45 minutes	Up to 14 days	About 2 hours per 1000 feet
Type of installation	Temporary (could be permanent)	Permanent (can be temporary for demonstration)	Temporary (probes can be permanent for re-testing)	Temporary (access points could be permanent)
Impact on operation	Shut down for check out and tests	Shut down for calibration (at installation) and tests	Varies, can test in service	Tests in service or static with pressurized line
Requirements	120V and 230V electricity at site Fuel connection to line	If installed, uses system pumps to pressurize line, needs 120V at site or needs pumps and air-free line	Sampling probes, GC and computer	Access to line every 50 feet or closer
Detectable Leak	Varies with line size	Varies with line size	Independent of line size	Varies with conditions, distance from probe
Observed results estimated detectable leak rates in gph	Line 1: 0.62 Line 2: 0.32 Line 3: 0.16	Line 1: 0.60 Line 2: 0.34 Line 3: 0.13	Simulated rate of 0.05 gph in 36 hours	Needle: 0.4 at 150 feet Orifice: >1.8 at 150 feet
Real Leak	Detected, size estimated	Detected, too large for estimation	Detected, found at one of three suspect locations	Incorrectly detected, but location not correct
Leak Location	Only to line section tested	Only to line section tested	Location estimate provided	Location estimate provided
Comments	Several interference sources: vapor, vibration, rain	Designed for large systems; assumes turbulent flow in leak	Requires tracer in product or in empty line; needs sampling ports	Requires physical contact with pipe every 50 feet; detection varies with distance

Section 1

INTRODUCTION

A number of leak detection methods and systems have been developed for pipelines at retail fueling outlets. These pipelines are typically 2 or 3 inches in diameter and 200 to 300 feet long, operating at 30 psi or less. Many of these methods have had their performance evaluated according to the U.S. Environmental Protection Agency protocol (U.S. Environmental Protection Agency, 1990). However, that protocol is limited to pipelines of approximately that same size. The pipelines at facilities of interest to the American Petroleum Institute (API) in this research are those typically associated with aboveground storage tank (AST) facilities or airports and are substantially larger and operate at higher pressures (up to 150 psi) than those found at retail fueling outlets. These pipelines may be up to 18 inches in diameter and a mile long or more. Thus, the leak detection methods commercially available for underground storage tank (UST) facilities may not be applicable.

Underground pressurized piping, particularly large pipes operating at high pressure, may be a potential source of soil and groundwater contamination should a leak develop. Examples of such systems include airport hydrant systems and pipelines at refineries, terminals, and transportation facilities. The performance of leak detection methods for such large pipelines is not well established. A 1990 study by Midwest Research Institute (MRI) and Burns & McDonnell for the Air Transport Association of America (Air Transportation Association of America, 1990; Flora *et al.*, 1993) reviewed the available technology for leak detection for pressurized pipelines in airport hydrant systems and provided performance estimates based on engineering judgment without the benefit of actual data.

MRI is an independent, not-for-profit research institute. MRI has no vested interest in any of the technologies investigated in this research or in other related technologies. Moreover, MRI is not developing any leak detection methods, nor is MRI a service provider for leak detection testing or leak location. Thus, MRI is an impartial and objective reviewer of the performance of these technologies.

HISTORY

In 1994, a survey by API at terminal, refining, and transportation facilities identified leaks from underground pressurized pipelines as a major contributor to contamination at those sites. One approach to assessing line tightness from those sources could be the application of periodic leak detection to the lines. However, outside of vendor literature or vendor-generated tests, limited data are available to assess the capabilities and limitations of various approaches to leak detection for this application.

The EPA regulations (U.S. Environmental Protection Agency, 1988) specify performance standards for leak detection for underground pressurized piping under the UST regulations. Testing on an annual basis is required to detect a leak rate of 0.1 gph with at least 95% probability and no more than a 5% false alarm rate. Monthly monitoring must be capable of detecting leaks of 0.2 gph with at least 95% probability with no more than a 5% false alarm rate. The EPA has published a standard test plan for evaluating line leak detection systems (U.S. Environmental Protection Agency, 1990). However, because of the considerably larger volume of the pipes and the higher operating pressures, these requirements are unlikely to be appropriate for the terminal-sized piping. Other factors to be considered in evaluating leak detection methods for underground piping were considered by MRI (Glauz *et al.*, 1993).

PROJECT BACKGROUND

With the larger pipelines typically associated with AST facilities or airports, not only is there interest in detecting the presence of a leak but also in locating the leak. Location of leaks is not as critical when the pipeline is only 100 feet long. However, for pipelines that are up to a mile or more long, locating the leak so that repairs can be made at the point of the problem is much more important. Consequently, this study addressed the capability of systems to identify a leak of specified size and to locate the leak. This study also addressed the degree of accuracy with which systems performed these two tasks.

TECHNOLOGIES THAT WERE REPRESENTED IN THE PROJECT

MRI identified 20 companies that appeared to have expertise in the area of leak detection for large underground pipelines of the type typically found at refineries, bulk plants, and terminals. MRI contacted these companies to ascertain their level of expertise and their interest in the project. A three-page information summary was sent via facsimile to each company, giving basic information about the study and inviting each company to submit a letter of interest and any relevant technical information. The information summary also invited questions from companies about the project.

MRI received written responses with information from eight companies. Collectively, these companies use 11 different leak detection methods for pipelines, although some of the methods are based on common technology. Leak detection methods were identified that were based on the following technologies:

- Volumetric changes
- Pressure decay
- Tracer substance
- Acoustic emission
- Product-sensitive cable
- Metering/inventory reconciliation
- Computer-based flow and pressure monitoring
- Acoustic wave (pressure pulse)
- Visual inspection

Based on technical discussions with the API work group, four general types of leak detection technologies were selected for testing: volumetric, pressure decay, chemical tracer, and acoustic emission. These four technologies were selected as being commercially available and having the potential to provide the precision and accuracy desired. They also appeared to be the most widely applicable with existing installations. They will be described in subsequent sections.

Product-Sensitive Cable

Product-sensitive cable must be laid in close proximity to the underground pipelines. When the cable comes in contact with hydrocarbons, it reacts, giving a signal to its console. After any contamination has been cleaned up, the cable, or at least the affected section, must then be replaced for further use. It is difficult to install as a retrofit and is not applicable if there are existing hydrocarbons.

Metering/Inventory Reconciliation

Metering/inventory reconciliation coupled with a statistical analysis of the inventory data have shown some promise in preliminary trials. However, this technology requires that the pipelines be equipped with meters and that all inventory be tracked. Many pipelines do not have meters and some operations use product in tanks, trucks, and pipelines, making this technology cumbersome or not applicable.

Computer-Based Flow and Pressure Monitoring

Computer-based flow and pressure monitoring requires special installation of flow and pressure sensors to provide data to a computer. The computer uses proprietary algorithms to process the data. This method monitors an ongoing flow process for any changes and takes a baseline period as defining the stable condition. It is applicable to special installations but is a process monitoring method rather than a leak test.

Acoustic Wave

Acoustic wave or pressure pulse technology relies on monitoring the pipeline in process. A change or start of a leak would generate an acoustic wave or a pressure pulse that would be detected as a change from a steady-state condition. It appeared to be in the development stage and to be designed to detect changes in an ongoing process rather than the existence of a leak.

Visual Inspection

The visual inspection technique was found to be used for cross-country pipelines. It involved inspecting the line for dead vegetation or other visual evidence of a leak. It does not seem likely to have the desired sensitivity and is not applicable for pipelines that are located mostly under pavement.

Section 2
SCOPE AND OBJECTIVES

The project objectives were to:

- identify different technologies available for leak detection and location for the selected type of pipelines,
- identify vendors of each technology,
- select vendors for testing,
- conduct range-finding tests of the technologies, and
- assess potential impacts on operations.

The scope of the project was limited to range-finding tests; testing was not intended to provide a complete evaluation of any specific system. Rather, the objective was to identify technologies and obtain information on the performance of each technology, together with the field considerations or limitations for applying each.

GENERAL PROJECT OBJECTIVES

The project identified the different technologies available for leak detection and leak location for underground pipelines of the sort used at refineries, fuel terminals, airports, and transportation facilities. Four different technologies were identified and representative vendors of each were reviewed. Based on that review, a vendor of each technology was selected and invited to participate in field trials. The purpose of the field tests was to provide information on the state of the technology in terms of its suitability for use in the field and to provide and estimate each technology's sensitivity and accuracy in application.

SCOPE OF THE TESTING

The scope of the testing of each technology was designed to observe the operation of the technology and provide an approximate estimate of its performance. To this end, several features of each technology were documented as part of the testing:

- The amount of and types of equipment employed
- The time for setup and calibration (if necessary)
- The site support and preparation required
- General operational considerations
- Impact on operations
- Test procedures
- Test duration
- Test results for tight lines and for simulated leaks
- Leak location results (when applicable)

Testing was conducted with different lengths of lines and with different simulated leak rates. Testing was conducted at an operating site, which included one line with a suspected leak and another line with a known substantial leak as well as two lines of different sizes that were supposed to be tight. Thus, the tests included both real leaks and simulated leaks and different length of lines, providing different volumes of product in the lines.

The vendors were provided with a description of the facility, including a sketch of the configuration of the lines. The approximate length of each identified segment was provided as well as the diameter and, when applicable, the number of hydrants. The vendors were told that the lines would be taken out of service and isolated from the rest of the system by blind flanges so that there would be no question about possible leakage past valves into other sections of the pipeline. MRI told the vendors that they were being asked to test each section of line as a commercial test and report the results. Vendors were told that all work performed would be considered their typical commercial protocol. If the vendors identified a leak in the lines as they found them, and had the capability of locating the leak, they would be asked to locate the leak.

MRI also told the vendors that they would be asked to test each line multiple times. MRI would simulate a number of leaks of various sizes during some of the testing and would ask the vendors to conduct a number of tests under both tight and simulated leak conditions. The simulated leak rates would be kept blind to the vendors.

TECHNOLOGY-SPECIFIC OBJECTIVES

Four technologies were investigated: volumetric, pressure decay, tracer, and acoustic emission. The objectives for each technology are discussed separately in the following sections.

Volumetric

The volumetric method is a quantitative method that provides an estimated leak rate at a specific line pressure in addition to an interpretation of the results in terms of whether the line is tight or leaking. The volumetric method uses product addition or removal from the line at a constant pressure as the basic procedure. The testing was designed to estimate the operational characteristics of the method in terms of setup time, test duration, and demobilization time. In addition, the method performance was estimated by comparing the method's reported leak rates to the induced leak rates. Limited information on the role of interference (i.e., temperature, vapor, vibration, etc.) was expected because the use of the field site did not allow for control of these variables.

Pressure Decay

This method is similar to the volumetric method in its application, in that both use the pressure-volume relationship. However, the volumetric method holds the pressure constant and measures volume change while the pressure decay method measures pressure change over time, resulting from a volume change. The pressure decay method also provides a quantitative measure of the estimated leak rate at a specific line pressure in addition to an interpretation of the results in terms of whether the line is tight or leaking. The testing was designed to estimate the operational characteristics of the method in terms of setup time, test duration, and demobilization time. In addition, the method performance was estimated by comparing the method's reported leak rates to the induced leak rates. Limited information on the role of interference (i.e., temperature, vapor, vibration, etc.) was expected because the use of the field site did not allow for control of these variables.

Tracer

This method is primarily semi-quantitative, providing a result that indicates if a line is leaking or tight. In addition, it provides a delineation of the location of the leak based on probe spacing. The tracer method can provide a semi-quantitative estimate of the size of a leak, based on the concentration of tracer and the time lapse required before observing the presence of the tracer. Testing included simulated leak tests conducted by the vendor to determine the time needed for the tracer to migrate different distances. Testing was done on a tight line to confirm that it was tight and that no false alarm was observed. Testing was done on a suspected leaking line and a leak was detected. The objective was to demonstrate the ability to detect leaks and to assess the accuracy in locating leaks. The actual location of the leak found was documented when the line was repaired.

Acoustic Emission

Acoustic emission is a qualitative method, measuring the acoustic signature of a leak of a liquid under pressure to detect the leak. It also provides a location estimate based on one of two methods. As testing moves from point to point along the pipeline, an approximate location is determined based on the magnitude of the acoustic signature. A refined estimate of location is made by testing simultaneously at two points, bracketing the suspected leak and then statistically analyzing the signals received.

The accuracy of the method both for detection and location is a function of the spacing of the test points on the pipe. Other factors, such as backfill composition, defect shape, and liquid saturation can also affect accuracy. Testing was conducted on tight lines (documented to be tight by other test methods) to document that the method did not provide excessive false alarms. A simulated leak also was introduced to determine whether the method could detect leaks at two different distances and of different sizes. The system was used to test a leaking line to detect the leak and provide an estimate of its location. The results were compared against the findings of the actual location of the leak after the line was repaired.

Section 3

PROTOCOLS AND TEST METHODS

The vendor of each test methodology was asked to provide a summary of its testing protocol. The MRI scientists then observed the testing and documented procedures relative to the protocol. Deviations or adaptations required by the specific site were noted. Each vendor was asked to test each of the four line segments. After testing in the lines' normal mode of operation, leaks were simulated on three of the four line segments, and they were retested with the simulated leaks. The fourth line segment had an operational leak that was too large to accommodate additional leak simulation. Results of the test methods were compared to the simulations.

TEST SITE

Testing was conducted at a facility provided by an API member company. The field tests were conducted on portions of an airport hydrant system. The facility was made available and local support provided by an API member company.

A sketch of the pipelines at the facility is provided in Figure 1. Four portions of the system were isolated and used as separate test beds (indicated on Figure 1). As can be seen in the figure, two parallel pipes extend from the fuel facility. This allowed for part of the hydrant system to remain in service while testing was being conducted on portions of the system that were isolated.

Line 1 was a section of 10-inch diameter pipe that ran from the fuel facility to valve pit 4, a distance estimated as 3,500 feet. This line was blanked at the pumps and at valve pit 4. There were intermediate valve pits, low point drains, and high point drains along this length. A parallel pipe, also 10 inches in diameter, can be found adjacent to line 1. Line 1 was thought to be tight. Later measurement of line 1 from a scaled drawing gave a length of 2,370 feet, resulting in a volume of 9,700 gallons. Figure 2 shows the pumps and the flange where line 1 was isolated at the fuel terminal.

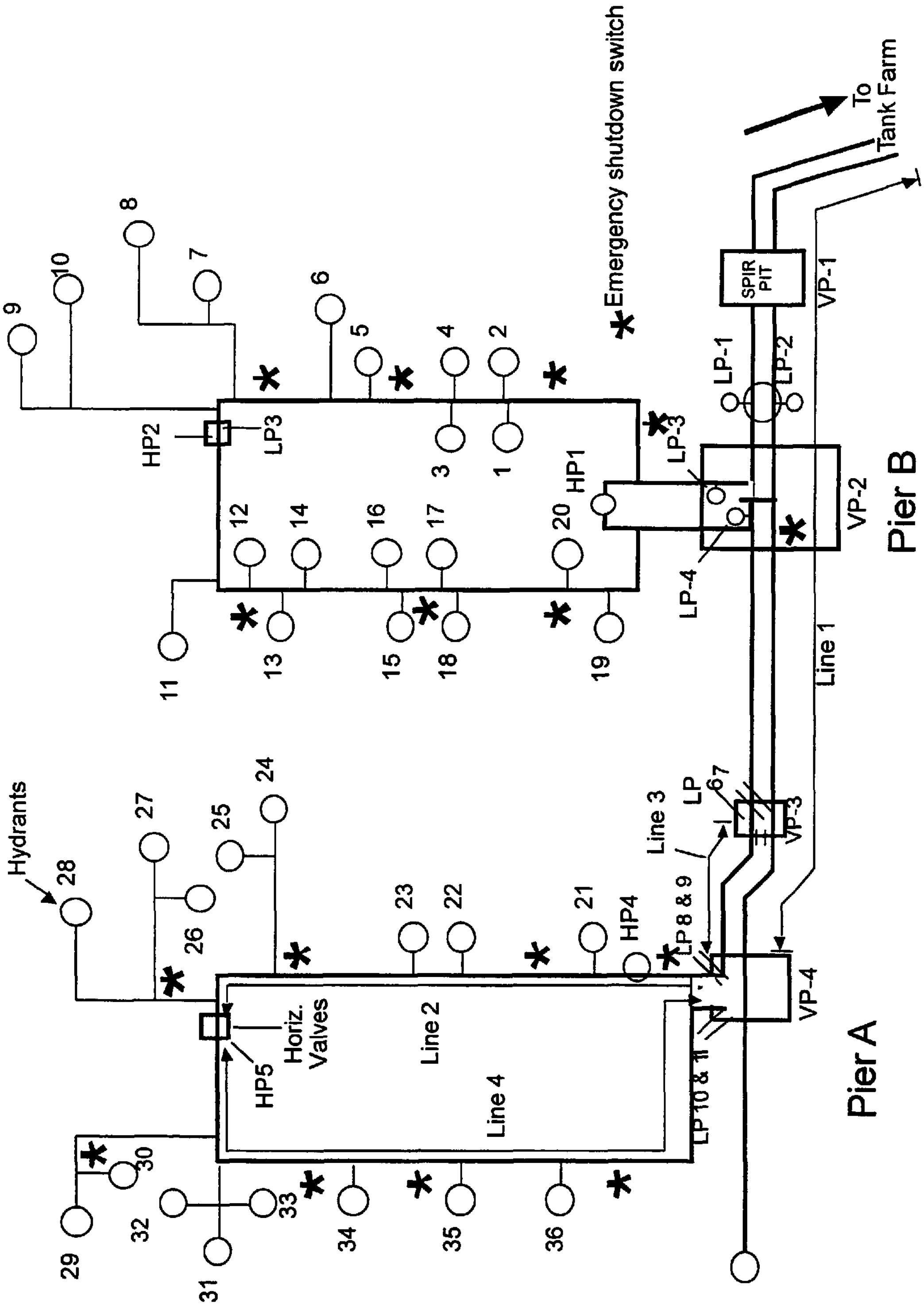


Figure 1. Test Facility

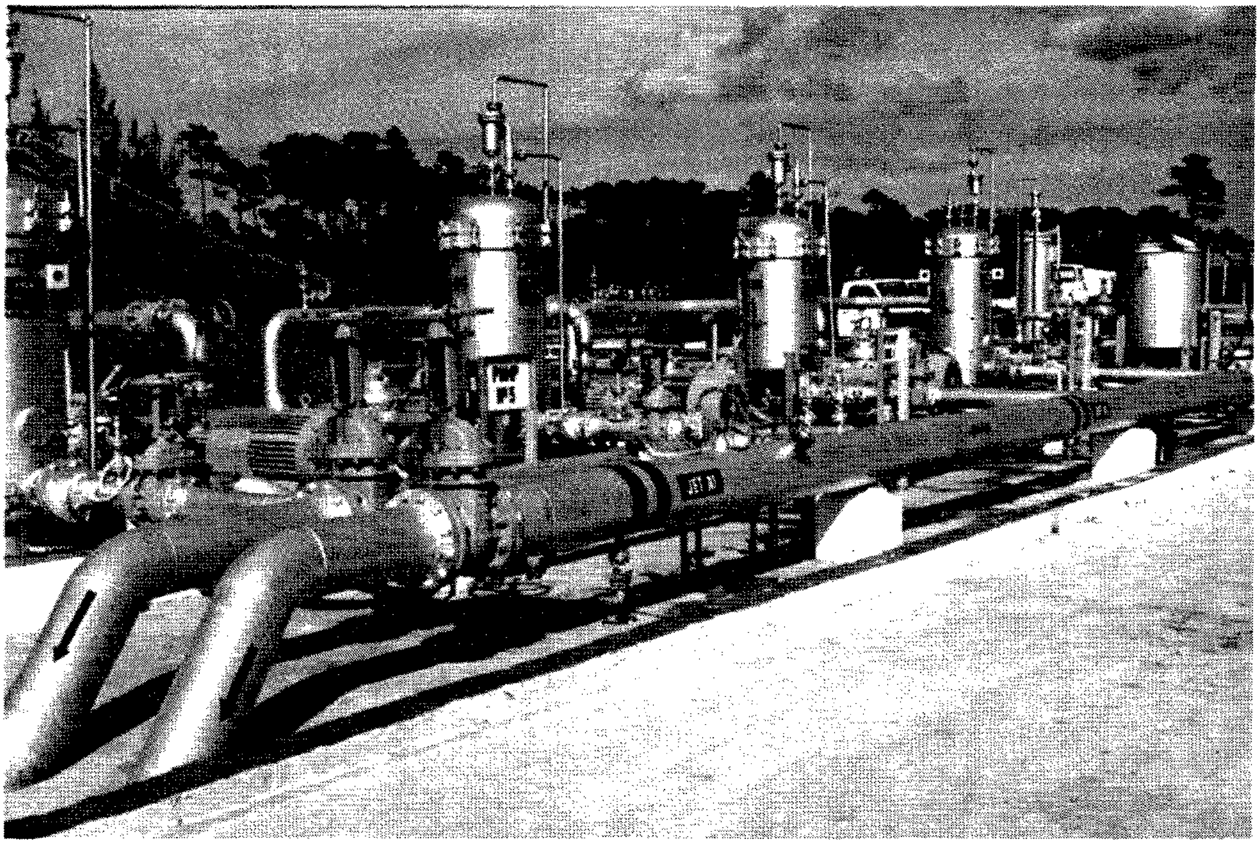


Figure 2. Pumps and Location of the End of Line 1

Line 2 was a section of 10-inch diameter pipe that ran from valve pit 4 to valve pit 5 along the interior side of Pier A. This line ended at a spectacle blind to isolate that section of the line in valve pit 5. For testing, a blind flange was installed at valve pit 4. In addition to the main line, eight hydrants branched off from the line. Each hydrant was on a 6-inch diameter lateral pipe. High point 4 was located about 20 feet from valve pit 4. Line 2 consisted of approximately 600 feet of 10-inch pipe and approximately 300 feet of 6-inch laterals to the hydrants. Line 2 was thought to be tight but during testing by both the volumetric and the pressure decay methods was found to have a leak of approximately 0.2 gallon per hour. This leak was found visually at the spectacle blind and was eliminated by tightening the bolts on the spectacle blind after the volumetric method had completed testing. Later, measurement of line 2 on a scaled drawing resulted in a length of 580 feet of 10-inch pipe with 260 feet of 6-inch laterals, resulting in a volume of 2,800 gallons.

Line 3 was a section of 10-inch diameter pipe running adjacent to line 1 from valve pit 3 to valve pit 4. This line was 400 feet long and had a high point vent about 150 feet from valve pit 4. It was isolated from the other lines with blind flanges in valve pit 3 and valve pit 4. Line 3 was suspected to have a small leak, but testing indicated that it was actually tight. Its volume was 1,660 gallons.

Line 4 was a 10-inch diameter line with 6-inch laterals to hydrants. It ran from valve pit 4 to high point 4, then made a 90° turn left and ran under the Pier A building. It then made another 90° turn right on the other side and ran to valve pit 5, ending at the spectacle blind. Line 4 had 8 hydrants and consisted of approximately 800 feet of 10-inch line and about 300 feet of 6-inch laterals. It was known to have a large leak, which testing confirmed. Measurement on a scaled drawing gave the length of line 4 as 726 feet of 10-inch pipe with 240 feet of 6-inch laterals for a volume of 3,330 gallons.

GENERAL PROJECT PROTOCOLS

When invited to participate in the test program, each line test technology vendor was provided with sketches and written information about the lines to be tested. Each vendor arrived on location for the field tests and was briefed on the facility. Vendors then began installation of their equipment. A test plan was prepared with each vendor in conjunction with the facility operator, scheduling tests on the different line segments. Generally, operational considerations required substantial modification of the initial test plan.

Each test plan initially called for testing each of the four different line segments of different sizes and configurations. In addition, simulated leak tests were planned on three of the four line segments. The fourth had an operational leak that was too large to accommodate additional leak simulation. The approximate size of the leak rates was chosen based on the line volume and the size that the vendors expected to be able to find. Leak rates larger and smaller than the approximate size were selected by MRI and kept blind to the vendors until they reported the results of their tests. All vendors knew that line 4 had a probable leak.

TECHNOLOGY-SPECIFIC PROTOCOLS

Volumetric Method

A volumetric method of leak detection is commercially available from, and testing was done by, Vista Research, Mountain View, California. Two systems are based on this technology, a large-volume and a small-volume system. Both systems use essentially the same technology; however, one system is designed to test larger lines than the other. The smaller system has a manual test mode that utilizes volume measurements based on a sight glass. It pressurizes the line with nitrogen and also can be used with a computer to record and store volume change data determined from differential pressure transducers. The larger system is completely computer controlled and uses a pump and product reservoir to pressurize the line. Both systems were used in the testing; however, all test results with a simulated leak were based on the smaller system. The larger system was used to test line 4 and to attempt to quantify the large leak discovered on that line. Figure 3 shows the larger volumetric system setup at valve pit 4.

Because the technical approach is essentially the same for both the large and small volumetric systems, they are discussed together. The systems are used to perform a static leak detection test with existing product in the line. The line is packed with product and then isolated from the tank(s) or other lines. During a test, the volumetric system measures the change in volume of fuel in the line at two different pressures, each of which is held constant while the measurement is taken.

Once the system has been installed and checked out, a formal test requires 2 hours of data. Typically the first hour of data is collected at low (generally atmospheric) pressure. This is followed by 1 hour of data at high (operating) pressure. The low pressure test was conducted at near atmospheric pressure but with a slight head pressure because the product in the test reservoir was elevated a few feet above the line. The high pressure test was conducted at 50 psi for the smaller and 150 psi for the larger system. For both stages, the last 20 minutes of data were used.

Figure 3. The Large Volumetric System

Since the rate of volume change from thermal changes is independent of line pressure, while the rate of leak depends on the pressure, this comparison results in a leak rate estimate that accounts for any thermal changes. A leak rate and an associated error estimate can both be provided by the systems.

The steps in the volumetric method are as follows:

1. Take the line to be tested out of service and isolate it. (Lines need to be isolated to ensure that there is no leakage past valves. This can be done with blind flanges or double-block-and-bleed valves.)

2. Pack the line with product.

3. Set up and check equipment.

4. Fill reservoir tank with the same product that is in the line.
5. Connect the system to the line.
6. Measure the bulk modulus of the line by adding volume in increments and recording the pressure change.
7. If the bulk modulus is too small, purge the line of vapor (however, line does not have to be air-free).
8. After bulk modulus is satisfactory, collect 1 hour of data at low pressure.
9. Raise the pressure of the line and collect 1 hour of data at high pressure.
10. Analyze the data from the last 20 minutes of low and high pressure tests and interpret the results.

Figure 4 shows the smaller volumetric system setup and conducting a test. The large diameter cylinder is the product reservoir. The taller cylinder is compressed nitrogen used to maintain the constant pressure. The notebook computer is used to collect the data (and later may be used to analyze the data). Figure 5 shows MRI staff conducting a leak simulation during the testing.

Figure 6 shows the connections of the volumetric system to the line. The larger volumetric system is connected to the line (line 4) at the left of the picture, and the smaller is connected to a different line (line 2) at the right of the picture. Figure 7 shows the leak simulators installed on line 3 (left) and line 1 (right) at high point 3.

Tracer Method

A tracer method of leak detection and location is commercially available from, and tracer testing was done by, Tracer Research Corporation, Tucson, Arizona. Tracer Research has used this method commercially since 1985 to test pipelines, ASTs, and USTs.

The protocol calls for introducing a volatile nonhazardous, nontoxic chemical concentrate, a tracer, into the pipeline, followed by the detection of the tracer underground in the vapor phase. The tracer is used in very low concentrations and has no impact on the chemical or physical

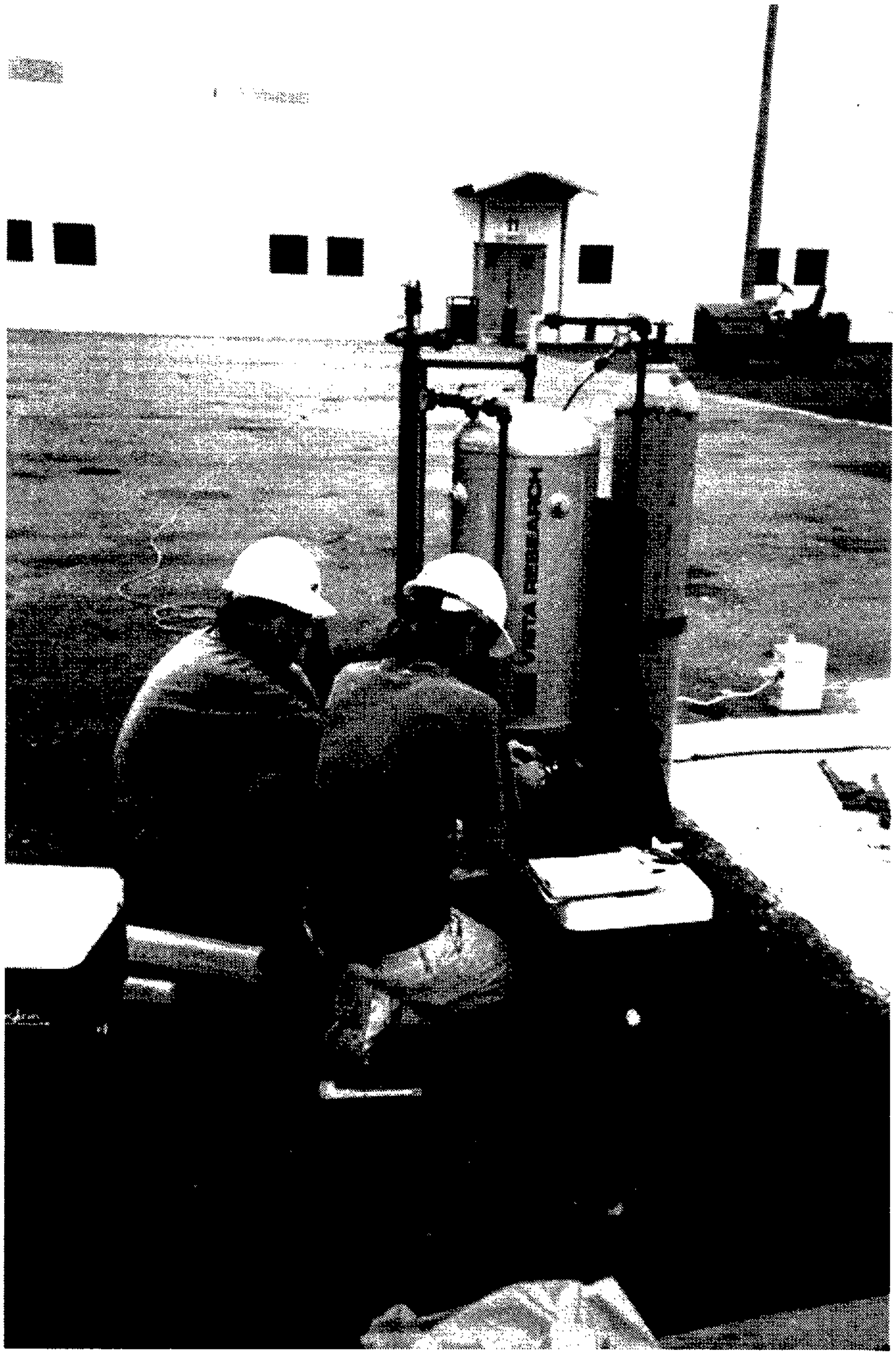


Figure 4. The Smaller Volumetric Unit Conducting a Test

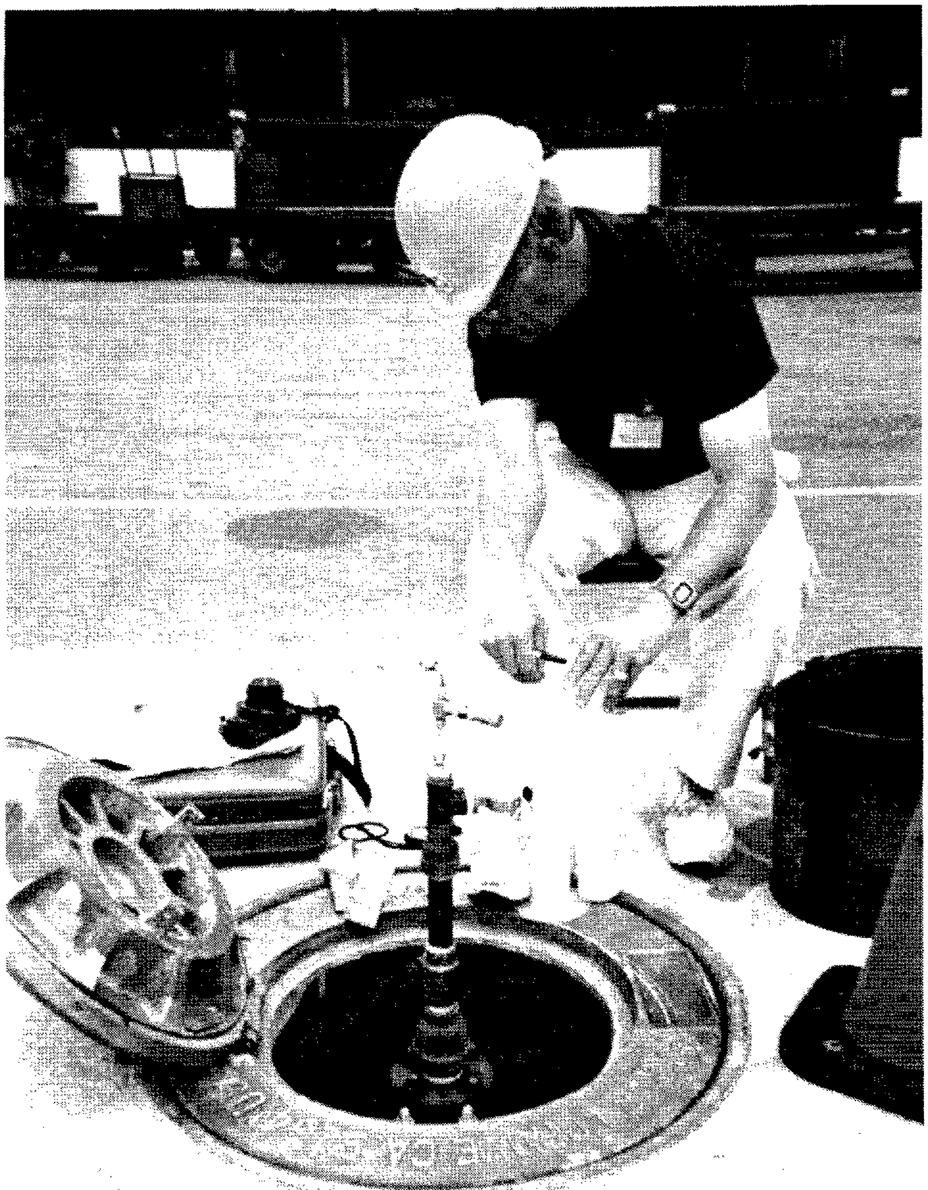


Figure 5. MRI Conducting a Leak Simulation

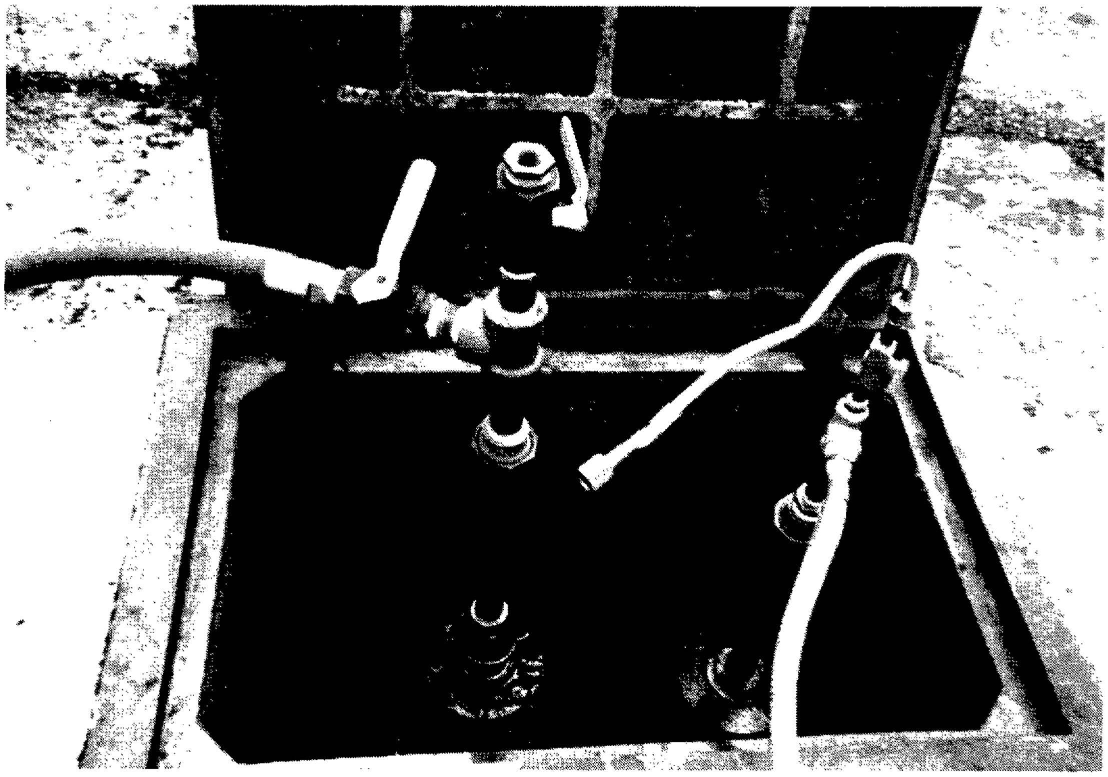


Figure 6. Connections of the Larger and Smaller Volumetric System at High Point 4

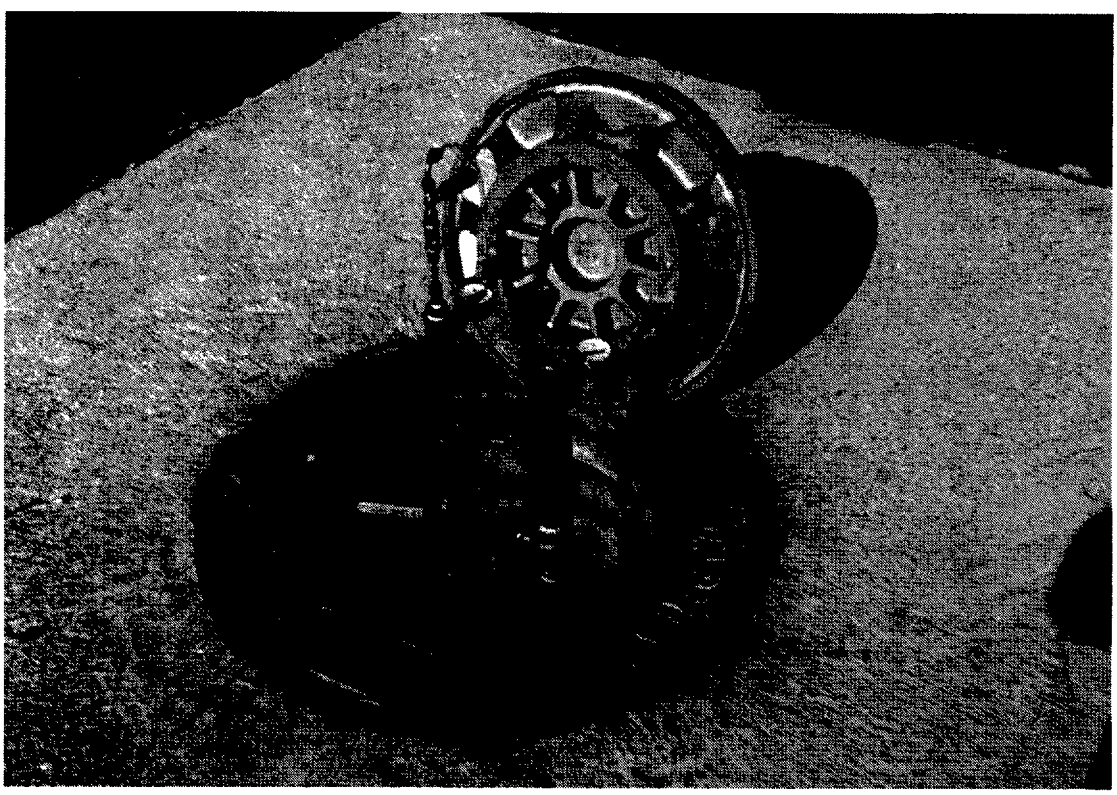


Figure 7. Leak Simulators at High Point 3

properties of the pipeline products. Special procedures were implemented for this testing since the introduction of tracer material is not yet approved by the FAA for commercial aircraft. The tracer chemical, being highly volatile, distributes itself both into the product and into the vapor space above the product.

If a pipeline leaks fuel, the tracer is released from the product into the soil and disperses in all directions through the air porosity of the soil by molecular diffusion. The tracer also can travel by convection when a pipeline is emptied of liquid product and tested under pressure with a mixture of tracer and nitrogen or air. When product leaks below the saturated zone or water table, the product rises to the surface of the water table and then releases the tracer into the vadose or unsaturated zone above the water table.

After the tracer has had time to diffuse and migrate through the soil away from the leak, soil gas samples are collected from the area surrounding the pipeline. Probes are placed in the backfill above the pipeline to collect the tracer vapors that might appear in the soil. The probes are inserted into holes drilled in the soil, asphalt, or concrete, and a small amount of soil gas is pulled by vacuum through each probe. Samples of this soil gas are collected and analyzed for the presence of the tracer and hydrocarbons. Timing for sample gathering is based on leak simulations at the site.

The protocol calls for initially conducting a leak simulation test to determine the suitability of the site and to validate the effectiveness and sensitivity of the method at the testing site. The simulation results also are used to determine recommended spacing of probes and timing of sample collection.

The leak simulation was proceeded by installing a number of probes in the soil at the site of the line to be tested. One probe was used to inoculate the soil with a simulated leak at the pipe depth using one particular chemical tracer. The other probes were 16 inches deep (6 inches below the asphalt) at varying distances (e.g., 2.5 feet, 5 feet, and 10 feet in each direction) from the spiking location. After the simulated leak was introduced, soil gas samples were taken from the other probes at different time intervals and analyzed for presence of the tracer. The simulation was conducted by introducing the amount of tracer that would be released from the pipeline with a leak rate of 0.05 gph over a 72-hour period, corresponding to a loss of 3.6 gallons of product. The information from the leak simulation allows the technician to adjust the timing for initial sample collection or tracer concentration appropriately for site conditions should a deviation from standard operating procedures be required.

After the leak simulation was completed, probes were installed at the recommended spacing. The probes were placed in the backfill above the pipeline to collect the tracer vapors that might appear in the soil. The probes are driven into the ground in loose soil or are placed in holes drilled for that purpose if the area is paved. Since the area was paved, the probes were sealed with caulking to the paving flush with its surface. After the probes are installed, tracer is introduced into the line, either in the liquid product, or, if the line is empty, with compressed air or nitrogen. Samples are collected from the line at the extremes from the point of tracer insertion to confirm that the entire line has a concentration of tracer. After the tracer has been in the line for a sufficient time, soil gas samples are taken from the probes and analyzed for the tracer. Presence of the tracer indicates a leak. Continued absence after a suitable period indicates that the line is tight.

If a leak is found, its location is indicated by the relative concentrations at different probe locations. The location may be refined by installing additional probes near the suspected location. A soil depth profile of tracer concentration obtained by sampling at different depths to the line at probes near the suspected leak also may be used to provide a more definitive location of the leak.

The steps in the tracer method are as follows:

1. Locate the pipelines and mark the locations. (This may be done from plans or magnetically.)

2. Drill a hole and insert an injection probe for leak simulation to about 6 inches above the top of the pipe.

3. Install sampling probes for leak simulation at varying distances from the injection port.

4. Inject tracer for leak simulation.

5. Take soil gas samples from sampling ports at various times after injection and analyze for tracer.

6. On the basis of the simulation results, select spacing for sampling probes and time after inoculation for testing.

7. Install sampling probes along line.

8. Inoculate line with tracer.

9. Sample line at both extremes to confirm tracer is present throughout line.

10. Take soil gas samples from sampling ports.

11. Analyze soil gas samples for the tracer.

12. Interpret results.

13. Use a second tracer to confirm findings or to more precisely locate a suspected leak (may require adding sampling ports).

Figure 8 shows a photo of the crew drilling holes for the simulation and sampling ports. Figure 9 shows the connection as the tracer is added to liquid product as a line is filled. This was done on line 3, replacing the product in the line with tracer-inoculated product. Figure 10 is a picture of the crew installing the soil gas sampling probes. Figure 11 shows a soil gas sample being taken. Figure 12 shows line 4 being inoculated with tracer and air, and Figure 13 shows the gas chromatograph system used for analyzing the samples.

<u>Pressure Decay Method</u>

A pressure decay method is commercially available from, and pressure decay testing was conducted by, Hansa Consult Ingenieurgesellschaft mbH, Glinde, Germany, which has a U.S. office in Houston, Texas. The system was first developed in 1982 for installation on the underground hydrant system at Frankfurt International Airport; dozens of installations now exist throughout the world, mostly in Europe. Systems are installed in the United States at airports in Anchorage, Alaska, and Atlanta, Georgia.

The Tightness Control System (TCS) uses what is called a pressure-step or pressure-jump method. The pipeline section to be tested is first isolated from other sections and placed under high pressure. The pressure decay is then monitored. Following a certain test cycle time, the section pressure is lowered and again monitored. Finally, the pressure is again raised and monitored. The theory is that a leak rate (if there is a leak) will be pressure dependent, but the effect of thermal gradients is not pressure dependent. Thus, pressure changes due to thermal effects can be separated from pressure changes due to a leak.

The normal operating procedure for the pressure decay method is as follows:

1. The hydrant system to be monitored is first divided into convenient sections.

2. The individual sections are separated by tightly closing valves or by blanks. Double Block and Bleed valves are recommended since the pressure decay method is unable to distinguish a leak into the ground from a leak through a valve into another portion of the hydrant system.

3. Each section has a pressure transducer and transmitter installed.

4. A computer is set up to run the tests, log the data, and do the leak calculations.

5. A means of pressurizing and depressurizing is identified. Typically the line would be pressurized by the airport's main fuel pumps or a jockey pump.

6. Excess air is bled from the lines. (The line must be fully packed and air-free.)

7. A series of calibration tests is run, with both a tight line and with simulated leaks. (This enables the method to quantify its results depending upon the size and compressibility of the pipeline section.)

8. For an actual test (as for a calibration test), the section being tested must be taken out of service for the test duration, which is approximately 45 minutes.

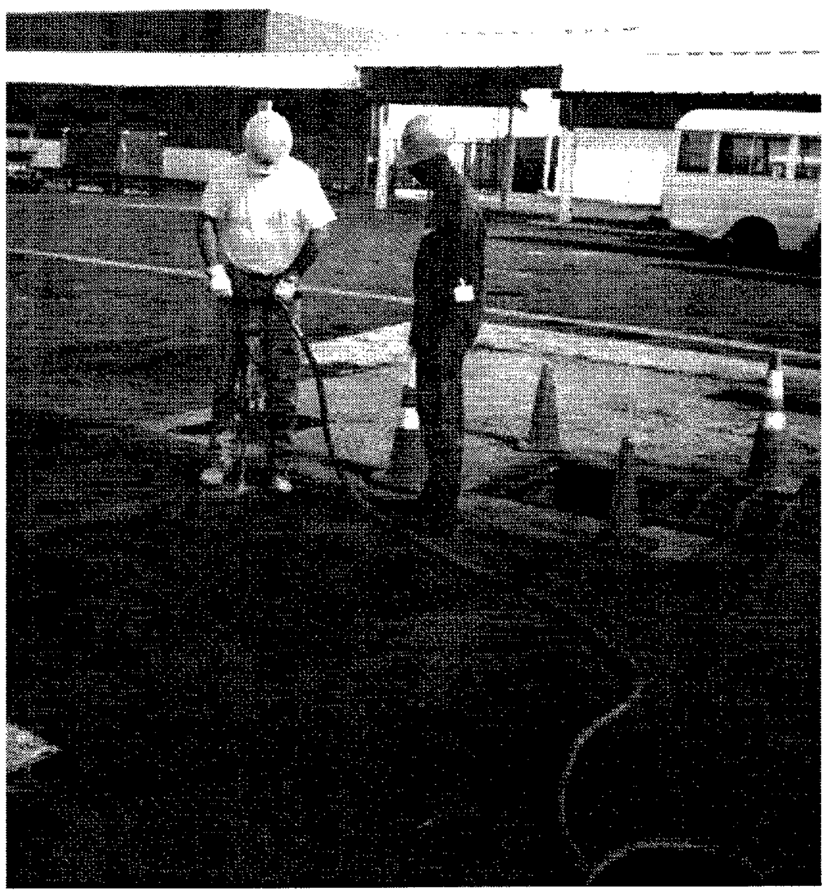


Figure 8. Drilling to Install Tracer Ports

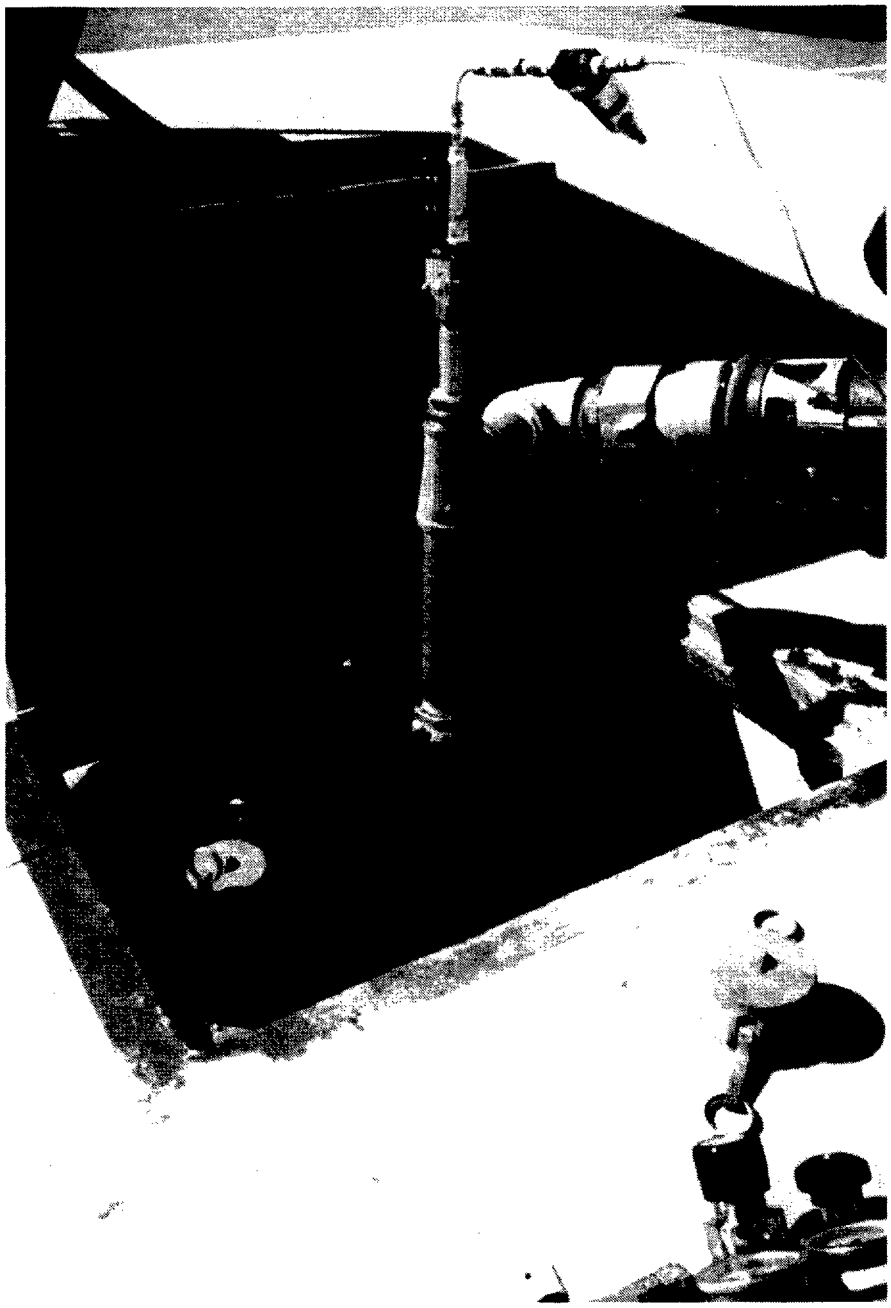


Figure 9. Injecting Tracer in Product as the Line is Filled

Figure 10. Installing Sampling Ports for Tracer

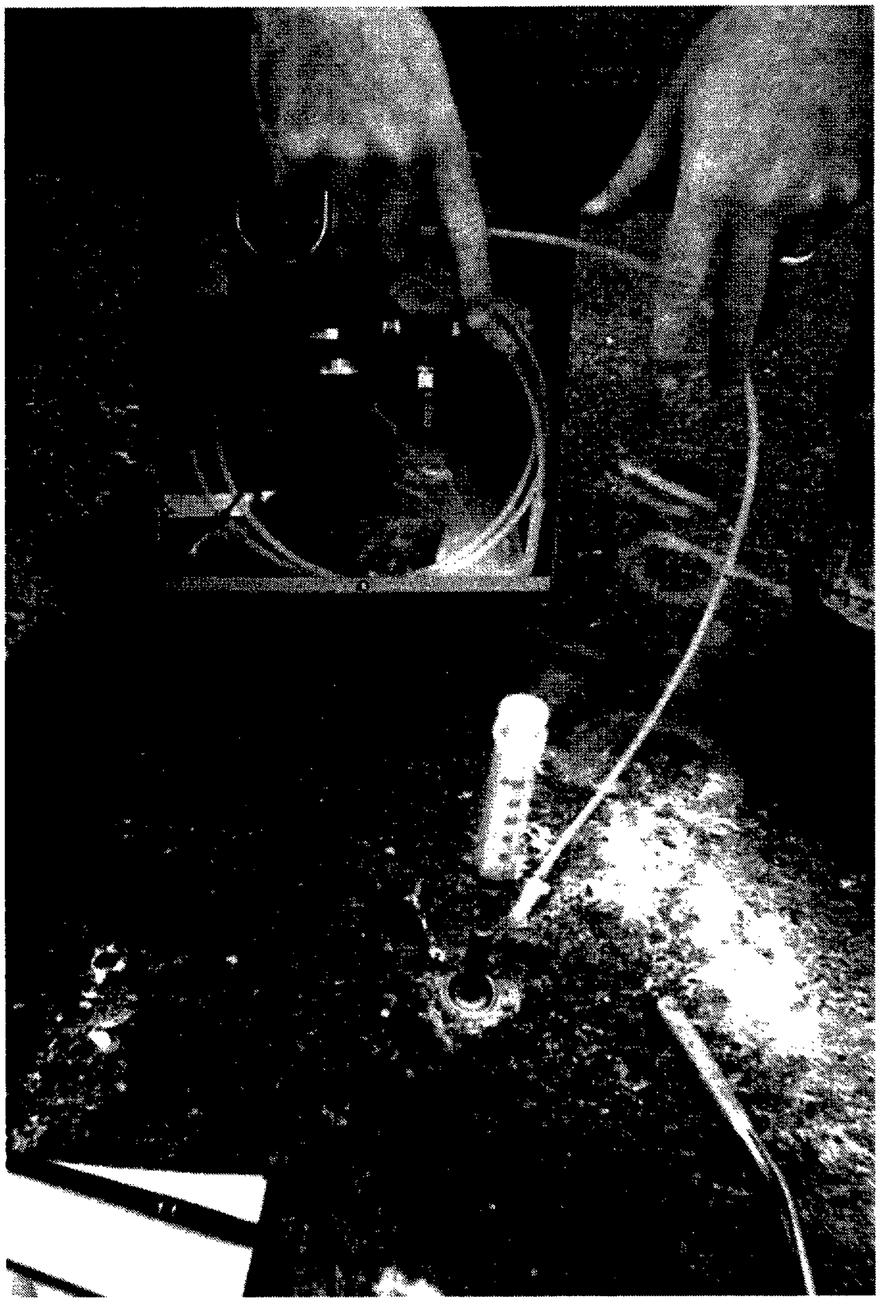


Figure 11. Sampling Soil Gas for Tracer

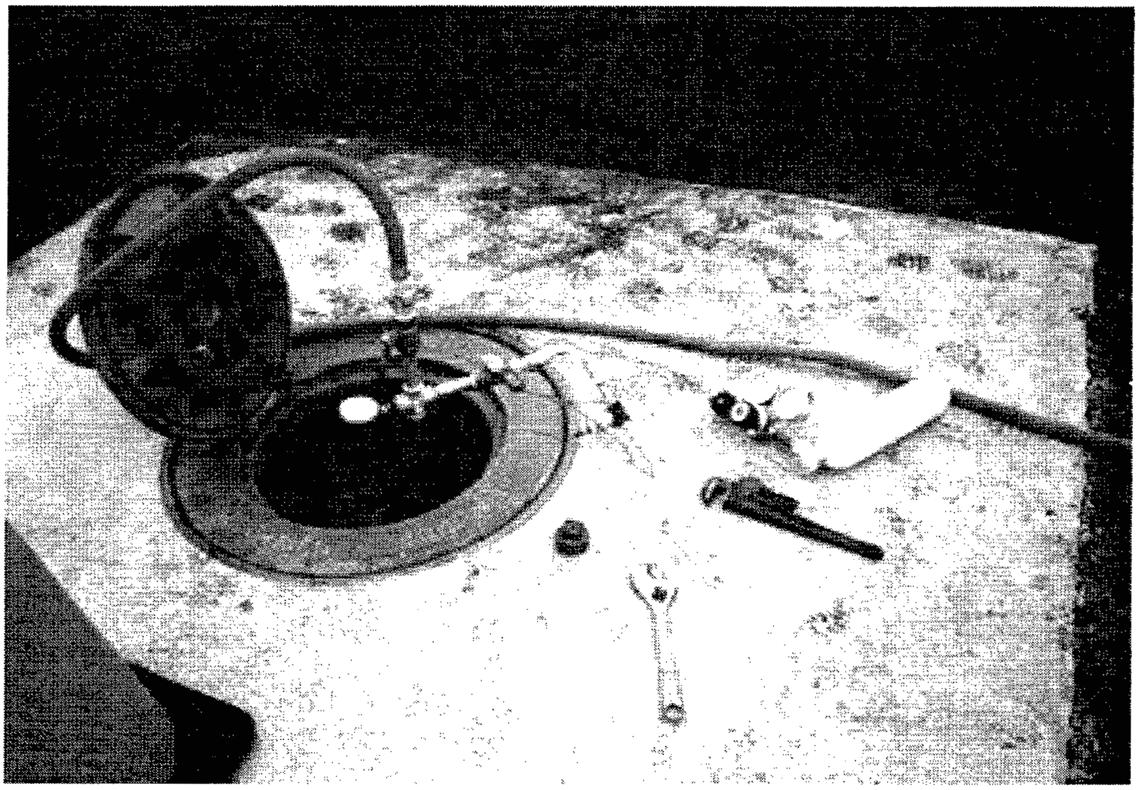


Figure 12. Injecting Tracer with Compressor Air in Line 4

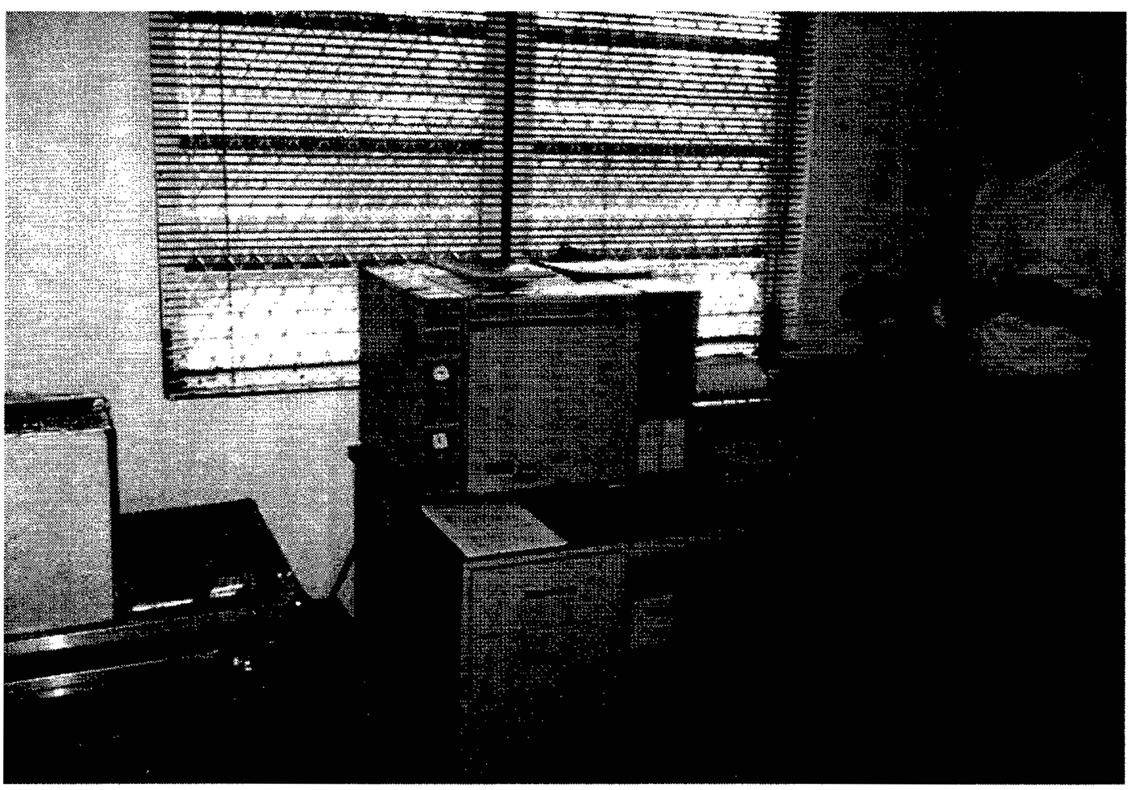


Figure 13. The Gas Chromatograph Used to Analyze Soil Gas Samples for Tracer

The calculations are performed based on certain constants for the system that include the input data and two calibration factors, k_1 and k_2, that are calculated based on calibration tests. The input data are related to the volume of the line being tested, the liquid's compressibility, the pipe radius and wall thickness, and the normal operating pressure.

In a normal setup, a minimum of five calibration tests with a tight line are run to determine k_2, and a minimum of three tests with a known, simulated leak are run to calculate k_1. This would require about 8 hours for each line section, although with multiple sections some calibration tests could be conducted simultaneously. At the test site, all of these tests were not conducted due to time constraints imposed by the vendor's schedule so the vendor shortened its normal procedure to three calibration tests with a tight line and one with a known simulated leak.

The pressure decay system is designed to be installed on a new line system. It assumes that the line is tight and does its calibration once when it is installed. When it is used on an existing line, it does a number of calibration tests on the line in its assumed tight condition, then follows those with calibration tests at a known leak rate to estimate the parameters that it uses with its data analysis. If it attempts to calibrate on a line with an existing leak, it identifies that there is a problem with the line in a number of ways, depending on the size of the leak. For a large leak, it may not be able to pressurize the line (this was the case with line 4) and so the operators conclude that there is a leak. When it attempted to calibrate on line 2 (which had a leak on the order of 0.2 gph at the blind) they were unable to get stable or reasonable values for their parameters and so the operators concluded that there was a problem with the line. They confirmed this with an overnight pressure decay test and then visually observed the product dripping from the blind the next day. Thus, the testing confirmed anecdotally that their calibration tests can identify lines with existing leaks at least down to about 0.2 gph.

Figure 14 helps demonstrate the procedure for an actual test. As seen, each test consists of three cycles. The first cycle is conducted at approximately 10 bar (atmospheres, or about 150 psi). A 10-minute waiting time allows for stabilization of the line after pressurization, and then there is a 2-minute data collection period. The pressure is dropped to about 4 bar and again a 10-minute waiting period occurs to allow the line to relax following the pressure drop. The 10-bar test is then repeated. A total time of about 45 minutes is required, assuming each pressurization/depressurization activity requires only 2 to 3 minutes.

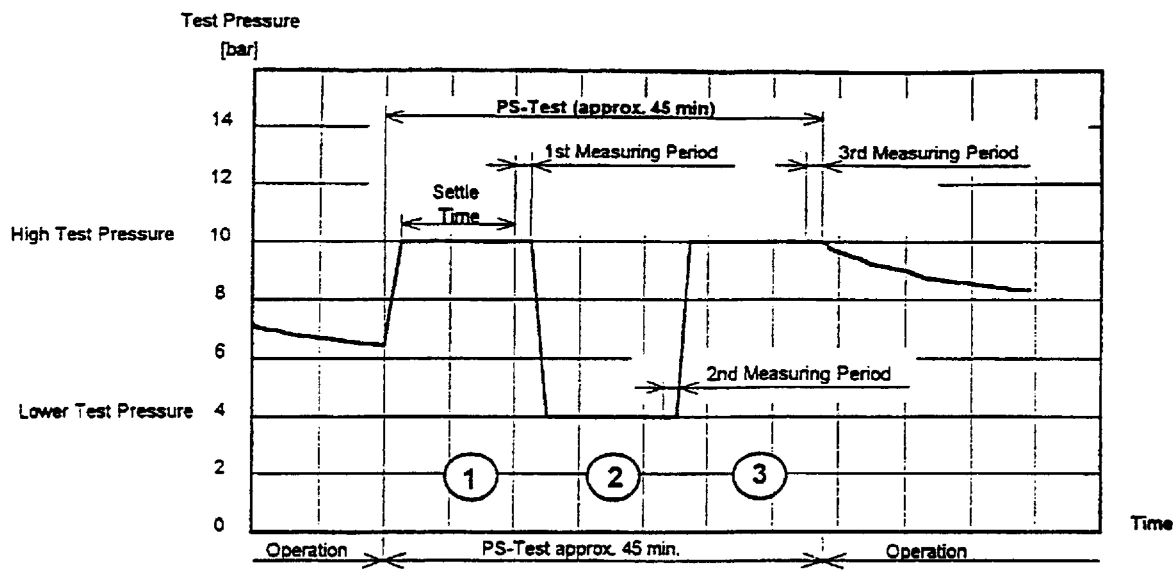


Figure 14. Procedure of a Pressure Decay Test with Its Three Test Cycles
(test pressure high–low–high)

The pressure step system reports leak rates as "tightness factors," measured in units of $l/h/m^3$ (i.e., the leak rate in liters per hour divided by the pipeline section volume in m^3). The vendor guarantees a leak detection accuracy of 0.04 $l/h/m^3$ or 0.004% of the line volume. Thus, for example, if the line section has a volume of 100 m^3 (about 26,400 gallons), the company would guarantee to find a leak of 4 l/h. If the line is tight, it would expect to obtain results of 0.0 ± 0.02 $l/h/m^3$. If a test result is in this range, the vendors declare the line to be tight. If a measured leak rate is greater than 0.02 $l/h/m^3$, it reports that as a leak. Thus, 0.02 $l/h/m^3$ is used as its threshold and 0.04 $l/h/m^3$ is its detectable leak rate, according to the vendor's literature. In the field tests the vendor used the value of 0.04 $l/h/m^3$ as the threshold.

In its calculations, the vendor corrects all indicated pressure drops during the 2-minute data collection periods to exactly 10 bar. This adjustment is made assuming turbulent flow through the leak (actual or simulated), using the theory that turbulent flow rates are proportional to the square root of the pressure.

Figure 15 shows the system's pressure sensor being installed. Figure 16 is a picture of the power supply, computer, and printer connected to the pressure sensor for the system. Figure 17 shows the complete installation. In the foreground is a hand pump that was used to pressurize the line for the system. In normal installation where the system is installed as part of the facility, that pressurization is accomplished by the system pumps shown in Figure 2, but since the line section under test was isolated by blind flanges, the system pumps could not be used. The pressure sensor is visible in the pit, with the computer and printer in the box in the background. Figure 18 is a close-up of the computer and interface for the system.

<u>Acoustic Emissions Method</u>

An acoustic emissions method is commercially available from the Physical Acoustics Corporation (PAC), Princeton, New Jersey, who tested using the acoustic emission method. The general method is applied to a number of structural integrity investigations; the present application is to detect and locate leaks in pressurized piping.

The vendor hypothesizes that when leakage occurs through a hole in a pressurized pipe, the fluid escapes with turbulent flow into the surrounding soil. This produces acoustic waves in the sonic and ultrasonic frequency range. The waves propagate through the fluid in the pipe and along the pipe walls. The sound waves produced at the leak are attenuated as they propagate, especially within the fluid and less so along the pipe walls. A remotely located piezoelectric sensor can detect these acoustic waves if the noise is intense enough or if the sensor is located close enough to the source.

The acoustic emissions method defines a leak as a detection of an acoustic signal that is 6 dB or greater above the normal background noise. The company claims that, with sensing performed at 50-foot intervals along the pipeline, its system is sensitive enough to detect leaks in the 2- to 3-gallons per hour range.

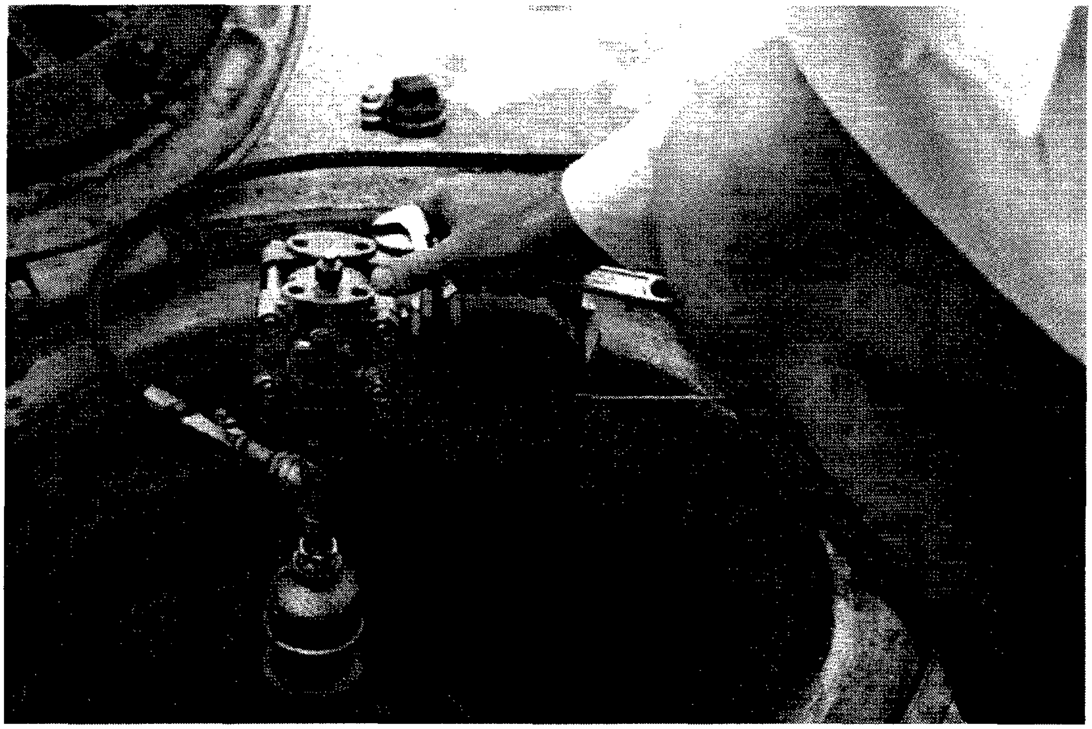


Figure 15. Installing the Pressure Sensor for the Pressure Decay Method

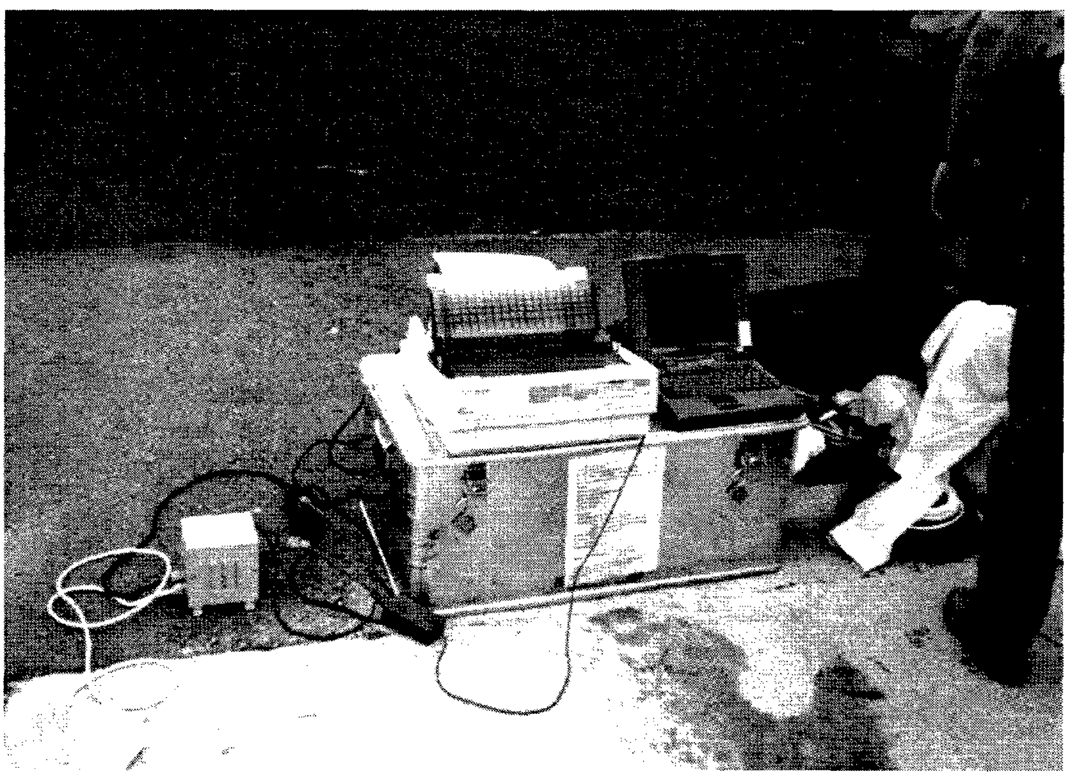


Figure 16. The Power Supply, Computer, and Printer Connected
to the Pressure Decay System

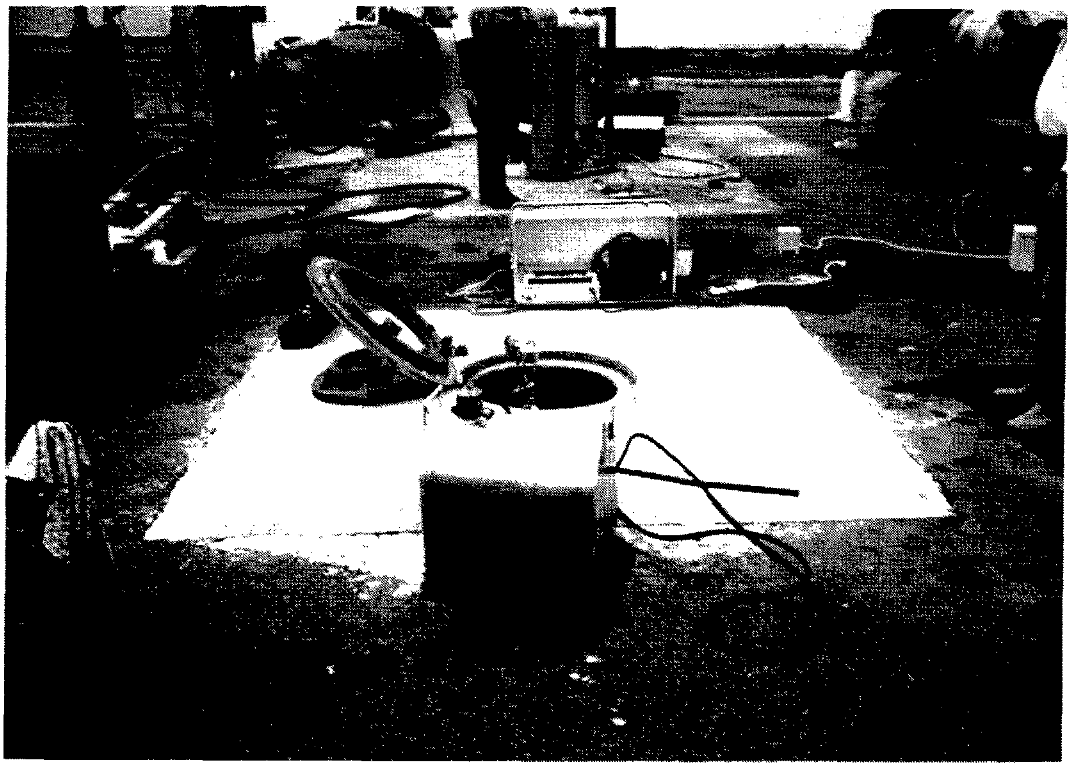


Figure 17. The Pressure Decay System Installed

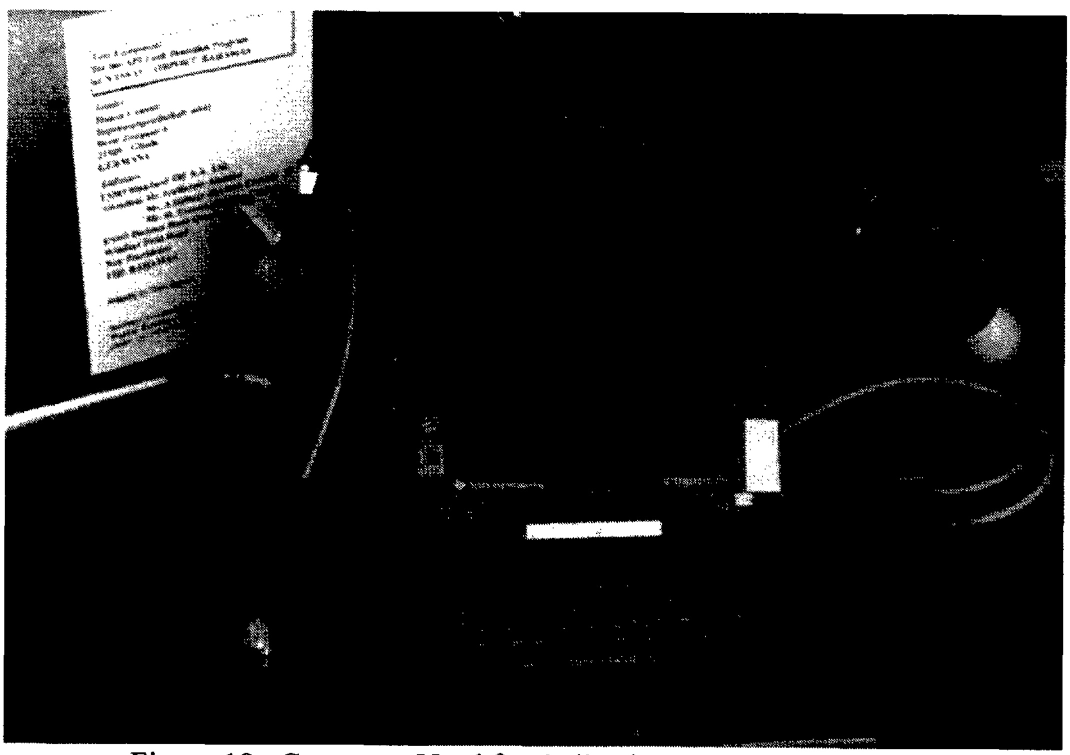


Figure 18. Computer Used for Collecting and Analyzing Data
for Pressure Decay System

Once a leak is detected, the vendor next attempts to determine the location of the leak. Two different methods are used to accomplish this. The first, and crudest, called the "Signal Difference" or "Amplitude Difference" method, requires signals to be detected at two different locations; their levels are compared with an attenuation curve. They claim to be able to locate leaks to within ±5% of the sensor spacing using this method. The second method, called the "Delta Time" or "Time Difference" method, acquires signals from two locations simultaneously and then processes them in a computer. One of three approaches is used—a conventional time-of-arrival comparison, cross-correlation techniques, or coherence analysis. The ability to locate a leak to within a foot is claimed.

Leak detection and location are accomplished through a six-step process:

1. The sensor or a wave guide is placed in contact with the pipe wall, using a couplant to enhance acoustic transmission from the pipe wall. The pipe surface must be cleaned of contaminants and pipe coating removed, if present. The sensor is magnetic to enhance its placement firmly against the pipe. A wave guide, rather than the sensor, is pushed through the soil and placed in contact with the pipe in the typical situation when the pipe is buried in the soil, to avoid the necessity of excavating the pipe. Drilling may be necessary for hard soils or when the pipeline is under pavement.

2. The sensor is connected to the instrumentation and the instrument is calibrated. Calibration includes obtaining the background signal level. PAC uses its Model 5120 two-channel portable acoustic emission leak monitor for this purpose.

3. The line is pressurized, either hydrostatically or pneumatically. (This step is not necessary if the line being tested is under normal operating conditions, and is already pressurized. The line does not have to be taken out of service for acoustic emission testing.) The line can be tested in either a static, pressurized condition, or with product flowing. However, different sensitivities result.

4. A signal measurement is taken.

5. After several readings at different locations are obtained, the results are reviewed. The readings are compared to each other as well as to the background noise. If an increase in signal level is detected, an initial estimate of the leak location is made by comparing the signal amplitudes, as described earlier.

6. If more precise leak location is desired, simultaneous measurements are made at the two sensor locations nearest the leak and the time difference method is used. A four-channel system with a built-in 486 computer, which contains leak location software and which performs data logging and post-data processing, was used for this leak location.

Figure 19 is a picture of a staff member attempting to drill to the pipe for access with a wave guide for the acoustic emissions sensor. The employee was unsuccessful in drilling because he did not have the needed bit extension. Instead, the company used available access to the pipe at the hydrant and valve pits. Figure 20 shows the acoustic emissions equipment used to detect the acoustic signal and perform the data processing for the detection and location of a leak. As a result of using existing access to the lines at valve and hydrant pits, data were taken at intervals ranging from 20 feet to about 100 feet.

TEST METHODS

Volumetric

The volumetric method was set up on a line segment. For line segments 1 and 3, the test equipment was connected to the lines at valve pit 4. For lines 2 and 4, the connection was made at high point 4, about 20 feet from valve pit 4. A leak simulator was installed at a high point along the line but at a different location. For tests on lines 1 and 3, the simulator was installed at high point 3, about 150 feet away from valve pit 4. For tests on line 2, the simulator was installed at valve pit 5, several hundred feet away from high point 4.

The leak simulator consisted of a ball valve, piping, and a micrometer-needle valve. The leak was calibrated by setting the needle valve, opening the ball valve, and collecting product in a graduated cylinder while the line pressure was maintained constant. The collected product was measured and used with the time of collection to establish a leak rate corresponding to settings of the micrometer valve. The leak simulations were conducted by setting the micrometer valve at a value to obtain approximately the desired leak rate, then collecting and measuring the product over the period of the test. Product was measured every 5 minutes, and the data from the last 20 minutes of each test were used to compute the induced leak rate.

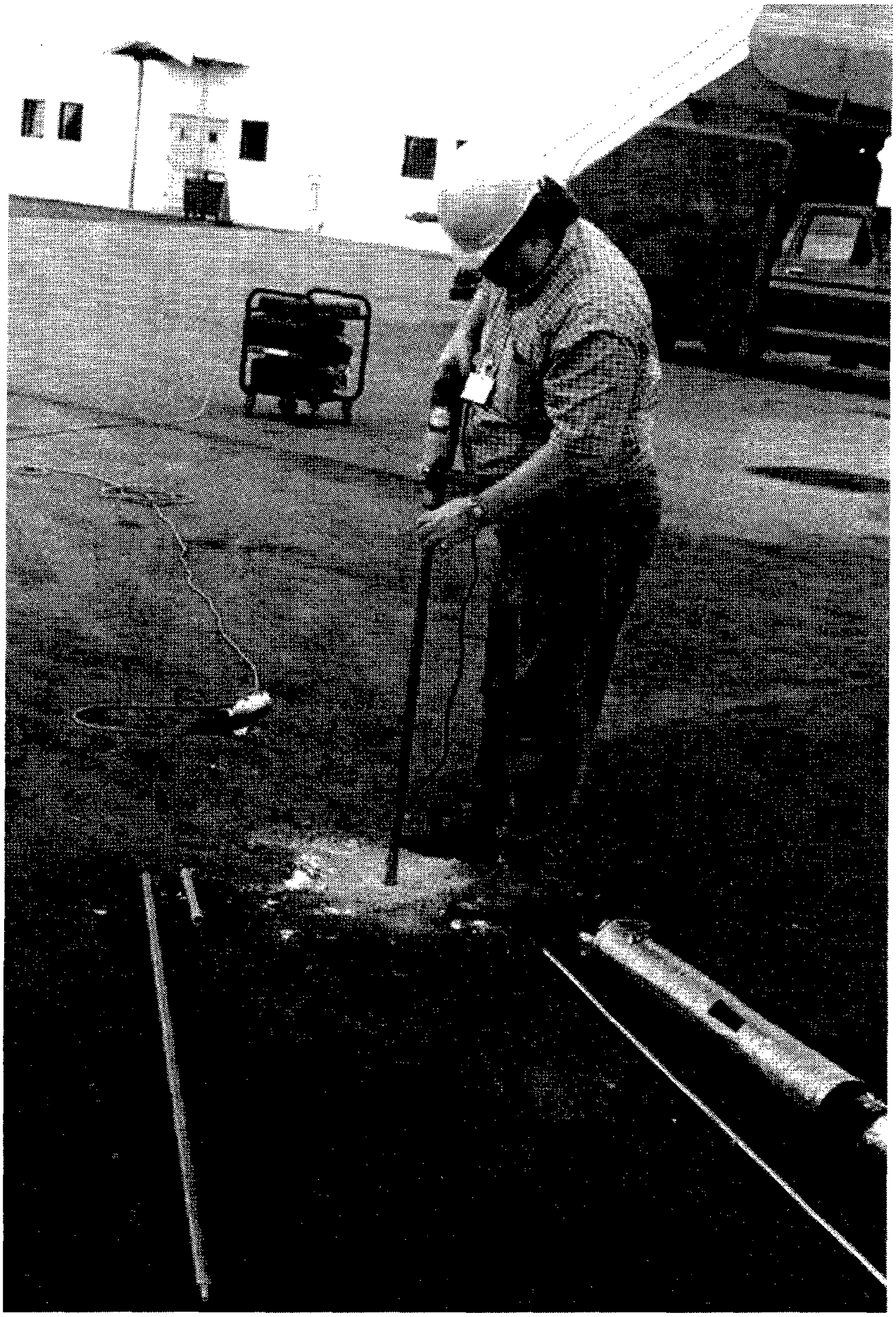


Figure 19. Drilling to Get Access to Pipe for Acoustic Emissions System

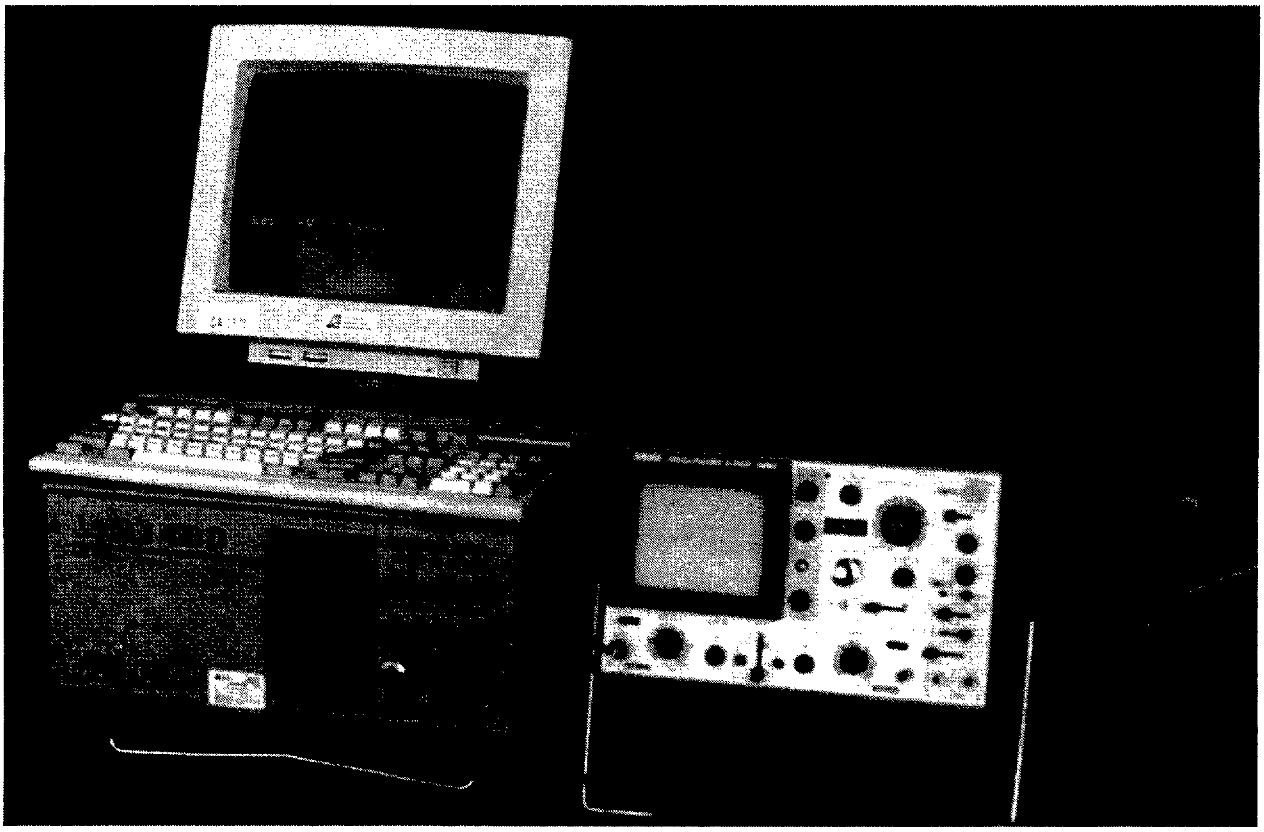


Figure 20. Equipment Unit for the Acoustic Emissions System

Leak rates were induced blind to the vendor. After a test was complete, the vendor provided an oral estimate of the measured leak rate to MRI and an approximate induced leak rate was communicated to the vendor. No leak simulation was attempted on line 4. The vendor had intended to test line 4 with their larger system. However, foreign material (dirt or corrosion product) came into contact with the pump bearings, rendering the pump unusable. The vendor modified its larger system using a fuel reservoir and a nitrogen cylinder to pressurize the line. One test was started at 150 psi, and the line lost enough product to empty the reservoir tank before the test could be completed. A second test was started at 50 psi, and again line 4 lost enough product to empty the reservoir before the full hour of data could be obtained. Estimates of the leak rate were made by the vendor based on the duration of the test and the volume lost before the test was terminated. However, these estimates are based on a test that did not meet the normal operating protocol and so are subject to more variability than usual. With the pump and an adequate supply of fuel, the larger system should have been able to complete a test on line 4.

Tracer

Three leak simulation tests were run at different locations by the vendor as standard procedure. They were observed and reported by MRI but were not blind to the vendor. One leak simulation location was along line 3 (part of line 1 was located parallel to this location). A second leak simulation location was just east of the Pier A building along line 4, and the third leak simulation location was near valve pit 5.

At each leak simulation location, one inoculation hole was drilled halfway between two test probes. Additional test probes were installed at 2.5 feet and 5 feet from the simulation probe along the line in each direction. The inoculation probe was installed to a depth of 6 inches above the fuel pipe, approximately 4 to 5 feet below the surface. The leak simulations were done to simulate a leak rate of 0.05 gallon per hour over a 72-hour period. The amount of tracer that would be present in the product with a leak of this size was injected into the inoculation port. Soil gas samples were taken from the sampling probes at various time periods and analyzed with a gas chromatograph to determine when tracer was detected at concentrations above the test threshold.

At each location the amount of tracer injected was equivalent to the amount in 3.6 gallons of product. The three leak simulations were conducted under the soil conditions found at each location. At location 3, the inoculation point was below the water table, which had several inches of free product floating on it.

Tracer was detected within 24 hours 10 feet away from the inoculation at locations 1 and 2. At location 3, tracer was detected 2.5 feet from the inoculation point after 27 hours.

Installation of the three leak simulation probes proved difficult with a pneumatic rock drill. Drilling through the wet/damp limestone plugged the ports in the drill bit through which air passes to clear the hole of cuttings. An auger type of drill was obtained from a local source, for the purpose of drilling the three leak simulation probes to the proper depth above the pipe. The annular space around the probe was sealed using a concrete slurry. The results of the leak simulations indicated that it was possible to provide a valid test with shorter-than-normal probes installed.

The vendor personnel then proceeded with the installation of the sampling probes at a normal spacing but to a depth of 16 inches below the surface of the pavement. All probes were at least 2 inches deeper than the ramp. The normal depth of the sampling probes is 24 inches along pipelines unless the depth of the pipeline is less. Drilling through the concrete ramp for the installation of sampling probes was normal. Probes were installed by drilling a 1½-inch hole through the concrete pavement followed by the installation of a sampling probe. Probes were installed flush with the pavement and sealed with caulking to ensure a gas-, water-, and fuel-tight seal around the probe.

Lines 3 and 4 were tested twice. Line 3 was tested with liquid tracer in the liquid product. Two different tracers were used on each line at two different times. Line 4 was tested using tracer in gas form with compressed air. Testing of lines 1 and 2 was not included in the scope of work for tracer testing.

<u>Pressure Decay Method</u>

The vendor was asked to calibrate its system on lines 1, 2, and 3, and then to conduct a series of tests on these lines with blind (to the vendor) leak rates set and measured by MRI.

The vendor was handicapped by the lack of an automated system at the airport that could be used for pressurization/depressurization. The test sections of the hydrant system had been blind-flanged off and isolated from the system pumps, which still supplied pressure to the remaining, operational portions of the system. Instead, the API member supplied a hand-operated manual pump and a laborer to operate it. For lines 2 and 3, with volumes of 9.6 and 5.3 m^3, respectively, about 4 minutes were required to pump the lines up to pressure, which was considered satisfactory to the vendor. For line 1, however, with a volume of 46.3 m^3, 20 minutes were required, which the vendor stated was outside the acceptable range of its operating parameters and would influence the results. Nevertheless, tests were run and results obtained and reported. For this method to be used as a one-time test (instead of being a permanent facility installation), it needs to provide equipment to pressurize the lines.

The vendor's system is designed for testing lines with volumes of several hundred m^3, and the literature suggests that the volume should be greater than 75 m^3 if the guarantee of detecting 0.04 $l/h/m^3$ is to hold. Later communication from the vendor indicated a preferred minimum volume of 50 m^3. For lesser volumes, the vendor indicates the system can detect leaks not smaller than 2 to 3 l/h. At the test site, the largest line (line 1) had a volume of about 46.3 m^3, so was marginal for the vendor's system. Lines 2 and 3, with much smaller volumes, were clearly too small to be reliably tested. Part of the difficulty stems from the fact that the small leak rates simulated (to be on the order of 0.04 $l/h/m^3$) no longer produced turbulent flow; it was laminar. Thus, the vendor's algorithm, which is based on turbulent flow, was known to be inaccurate.

It was not possible to pressurize line 4 to 10 bar, because of the magnitude of its leak. Therefore, the API member personnel connected a fueling truck to the line and pumped it up to the maximum capability of the truck, about 45 psi (3 bar). Since this was not sufficient to meet the vendor's protocol (and could not be held at a steady value), the vendor was asked to simply perform a single pressure decay measurement and determine if there was a leak, and if so, of approximately what magnitude.

All of the vendor's measurements were made at access points at valve pit 4 or high point 4. Leak simulations were done at high point 3 for lines 1 and 3, and at valve pit 5 for line 2. Leaks were simulated by opening a micrometer valve and measuring the amount of product flowing through it per unit of time. Once a leak rate was established, the micrometer valve was not adjusted, but a ball valve upstream of the micrometer valve was opened and closed to start and stop the leaks. In normal operation, the vendor's method is to bring the section of pipe to the test pressure, then isolate it with double-block-and-bleed valves. After the section is brought to the test pressure, it is allowed to stabilize for 10 minutes, followed by a 2-minute period of collecting data, which is a measurement of the pressure decay rate. At the test site, the line sections were isolated with blind flanges. After the section to be tested was brought to pressure, it was allowed to stabilize for 10 minutes. The leak simulation was only started to run during the data collection period after stabilization. This was done to keep the leak simulation blind to the vendor. If the leak simulation were run during the stabilization period, a substantial drop in pressure would occur before the data collection period. This, in itself, would be sufficient to identify the fact that a non-zero leak was being simulated. Thus, for each test, the line segment remained at the set pressure (except for any thermal changes) until the data collection period began.

Acoustic Emissions Method

The vendor was invited to make a preliminary site visit in preparation for the testing. A representative arrived on-site on November 12, 1996. It was decided that the acoustic emission vendor would test lines 2 and 4 to see if acoustic emissions could detect/locate any leaks. The vendor reluctantly agreed to test line 3 with simulated leaks but doubted that the leak simulations could be detected because the leaks would not consist of turbulent flow into backfill. Line 1 would not be tested because of its length (2,370 feet) and the fact that about half of it is under the tarmac or paved roads. A substantial amount of drilling, to sample each 50 feet, would be required and little additional information about the performance of the acoustic emission system would be obtained.

It was determined to attempt leak simulation using two methods. The first was to use the micrometer-needle valve used with the volumetric and pressure decay methods. The second leak simulation method used small orifices supplied by the vendor. A short section of 2-inch pipe was drilled and tapped to receive quarter-inch plugs containing the orifices. A number of orifices of different sizes were available to simulate different leak rates. By the vendor's own statement these leak simulation mechanisms may not adequately represent a true operational leak.

TESTING LIMITATIONS

The use of the operating fuel facility provided a unique opportunity to observe the technologies and vendors under actual conditions. On the other hand, it imposed some limitations on the testing program in that temperature changes could not be introduced as would be possible at a special test facility. It also meant that isolating lines, packing them with fuel, changing pressure, etc., had to be coordinated with fueling operations. These real-world conditions did not affect actual testing but did make the research work more time consuming. The employees at the site were very accommodating in accomplishing this work, within the limits of maintaining operations.

The volumetric and pressure decay technologies can be affected by temperature changes. If warm product is pumped into lines at a cooler temperature, the product will cool and contract according to its thermal coefficient of expansion. This could be mistaken for a leak. On the other hand, if cool product is pumped into warmer pipes, the product will warm and expand. This expansion could mask a leak. With the test site operating facility, no artificial temperature changes in the fuel could be introduced to challenge the technologies with temperature effects. Thus, testing was conducted under static conditions with fuel in the lines. For test methods affected by temperature changes, this represents the best test conditions. Fuel did not circulate since the lines were isolated with blind flanges. Results must be interpreted with the caution that, while the descriptions of the technologies recognize thermal effects and are designed to accommodate such effects, the ability of each system to do so was not directly tested in this project.

The tracer method and the acoustic method can be affected by the soil conditions. For the tracer method, the porosity of the soil and the location of the water table are important factors in the diffusion of the tracer from release through a leak. These affect how far the tracer will travel and how long it will take for the tracer to be detected. The nature of the soil and location of the water table affect the acoustic signal. Granular size of the soil affects the production of one type of acoustic signal, while flow from a leak into unsaturated or saturated soil also changes the signal. The soil along the pipe sections was generally similar, so that the testing did not address effects due to different soil types or water table depths. However, some differences were observed. The water table was closer to the surface near valve pit 5, and there was free product above the water table. This affected lines 2 and 4. Lines 1 and 3 had lower water tables and little if any free product. A longer breakthrough time was observed for the leak simulation with the tracer method near valve pit 5 than at the other two locations.

Section 4

OBSERVATIONS AND RESULTS

VOLUMETRIC

The data report supplied by the vendor is in Appendix A. Its report consisted of a series of four tables, corresponding to the 4 line test sections. Each table shows the tests that the vendor reported on that line section. The table shows the date and time of the test, the equipment, the leak rate that the vendor estimated, and the pass/fail conclusion. The tables are annotated with notes about special conditions.

The vendor also supplied a description of the small and large systems used in the testing. On reviewing this document, MRI determined that the actual testing departed from the summary information on several important technical issues.

- The method of estimating the leak rate presented in the document supplied by the vendor was not the method used in the testing observed in the field.
- The document states that the compressibility characteristics of the pipeline system do not need to be known to conduct a test or interpret the results; yet the vendor spent a great deal of time documenting the compressibility of the lines and complained repeatedly about excessive trapped vapor.
- The document states that tests can be conducted with trapped vapor present, but in operation the field crew invalidated some tests because of this and required purging of the lines.
- The document stresses successful application of the systems in many cases; many difficulties were encountered in the field and the system appeared to be very sensitive to vibration, power line fluctuations, small amounts of trapped vapor, and other disturbances.

Installation/Setup

The equipment was unpacked and set up in about 4 hours. It was not ready to run at that time due to the lack of electricity available. The setup time included repairing damage that occurred to the smaller system in shipping. After electricity was available, the vendor spent about 8 hours checking the two systems and trying to get them to function properly. Some of the difficulty turned out to be the electrical supply, which had excessive line noise and voltage fluctuations. This interfered with the computers used to collect data and control the test. This electrical problem was specific to the particular location and was solved by using a generator. However, it should be anticipated in the field and could have been solved with an uninterruptible power supply (UPS) quite simply. The larger system requires electrical power to operate its pump. The smaller system can operate using battery power for its computer.

Preliminary tests were done on all lines to estimate the compressibility or the amount of trapped vapor in the lines. This was perceived as a significant problem by the vendor's field crew, in distinction to the vendor literature, which stated that tests could be conducted with trapped vapor. The lines were vented at the high points and MRI observed little or no vapor escaping, only small bubbles in a liquid stream. Line 3 was purged of vapor by pumping product in at valve pit 3 and out at high point 3, followed by pumping product in at valve pit 4 and releasing it at high point 3. This took approximately 1 hour after arranging for the fuel truck and recovery. The procedure was viewed as improving the condition, but the vendor still reported excessive vapor. Thus, setup may include purging the lines of vapor.

Test Duration

Once the system has been set up and checked out, a preliminary test of system compressibility took 1 to 2 hours. If the results are acceptable, a test of the line takes an additional 2 hours. One hour of the test was at low pressure (atmospheric in the tests observed, although the vendor stated that any 2 pressures could be used). The second hour of the test was at high pressure (50 psi for the small system, about 150 psi for the large system). Thus, a test has a 2-hour duration, with about a total of a half hour to establish and release the pressure before and after the test period.

Relation to Operation of the Line

The line can be operational during the setup of the equipment, even during connection of the system to the line, provided that the connection can be made to a valved location. Once testing is to start, the line must be taken out of service for the duration of the test—slightly more than 2 hours. A period of time out of service is also required for compressibility tests, another 2 hours or so, preferably immediately before the leak test. The section of the line to be tested must be isolated. If valves are used, the valves must be completely tight, as seeping of product past a valve would be detected by the system as a loss of product and classified as a leak.

Other Operational Aspects

The system is designed to be transported to the site and used for a one-point-in-time test. Electrical power of both 120 volts (for the computer) and 220 volts (for the pump) is needed for the large system. A battery-powered computer can be used.

During the testing observed, the system did not appear to be as field hardened as one would expect. The system was sensitive to a number of external factors. It was sensitive to the electrical power, but this could be corrected with a UPS. The system was sensitive to vibration. Drilling approximately 150 feet from the location of the equipment (but close to a line under test) was stated to have interfered with the test and made the data invalid. A rain overnight caused difficulty with the system, requiring extensive maintenance in trying to get it back on line. Dirt or corrosion product got into the pump for the larger system, taking it out of service.

Product literature states that the system can be permanently installed. However, to date it has not been permanently installed, to our knowledge. Use of it as a permanently installed monitoring system would appear to be a potential development in the future.

Results

The large system was stated as the preferred system to test larger lines, including line 1 because of its size (approximately 9,700 gallons). It was also the preferred system to test a line with a large leak rate because of its larger product reservoir. It was used on the tests of line 4. However, the vendor experienced considerable operating difficulties with the large system. Two attempts were made to test line 1 with the large system on November 11, 1996. The first was recorded in the field as giving data that was too "noisy" and did not meet the data quality. The second was reported verbally as tight, but no estimated leak rate was reported. Neither of these tests was included in the vendor's data report. One problem was dirt or corrosion product got into the pump bearing, rendering the pump unusable. After spending a considerable amount of time trying to fix the system, testing with the large system for this project was abandoned except for the tests on line 4. All of the other tests and the conclusions relate exclusively to the smaller system.

Line 1. Line 1 was tested on November 12, 1996 with the small system. Table 1 summarizes the data. It includes the two attempts with the large system. The times in the table are starting times from MRI's field notes. These differ by a few minutes from those of the vendor's report due to difference in watches or imprecise notification of the starting time in the field. In the field, MRI asked for a report of the leak rate as soon as the test was completed. An approximate leak rate was given to MRI verbally after the data were analyzed. This is reported as the "Verbal Leak Rate." MRI then provided an approximate induced leak rate to the vendor. The vendor conducted additional analyses of the data prior to sending the official report with the leak rate as indicated. Both the verbally reported leak rate and the officially reported leak rate are tabulated.

Table 1. Volumetric Test Results on Line 1

Date	Time	Test system	Result	Verbal leak rate	Reported leak rate	Induced leak
Nov. 11	1530	Large	NR	Invalid	NR	None
Nov. 11	1730	Large	NR	Tight	NR	None
Nov. 12	1030	Small	Pass	Pass	0.174	0.0
Nov. 12	1335	Small	Fail	0.512	0.695	0.820
Nov. 12	1550	Small	Fail	0.570	0.623	0.539
Nov. 12	1750	Small	Fail	0.308	0.305	0.184

NR: Not Reported

An inspection of Table 1 shows that the volumetric system did not report any false alarms when the line was tight. It indicated "Pass" in the valid tight test. It also identified correctly the three leak simulations as leaks, indicating "Fail." The verbally reported leak rates were reasonably close to the simulated leak rates. Thus, as a range-finding experiment, these tests indicate that the small volumetric system can detect leaks on the order of 0.5 gph on this line, which had a volume of about 9,700 gallons.

Line 2. The tests conducted by the volumetric method on line 2 are summarized in Table 2. All of the valid tests reported a fail, indicating that the line had a leak. The average leak rate reported for the test at 50 psi with no induced leak was 0.204 gph. After these tests were conducted, the pressure decay method was used on this line. It also identified a problem with the line. During that testing, a leak was visually observed from this line at the spectacle blind. The bolts on the blind were tightened and the visible leak stopped. The pressure decay tests then indicated a tight line. Later testing with the volumetric method for the API member (not as part of this project) reported a small seep past a valve into another part of the line at hydrant pit 25. After that was also corrected, tests with the volumetric method also indicated that line 2 was tight.

All of the tests reported in Table 2 except for the November 9 test were conducted at 50 psi. The test on November 9 was conducted at 140 psi. That is the reason for the larger leak rate. The tests with zero induced leak averaged 0.204 gph, excluding the test at higher pressure. The standard deviation of these tests was 0.053 gph. In comparing the results of the volumetric tests, MRI assumed that during the testing at 50 psi, the line had a base leak of 0.204 gph.

Inspecting Table 2 shows that the volumetric system failed the line, indicating a leak, on every valid test. This line was, in fact, later found to have a small leak with product dripping from the spectacle blind. The visually observed drip was consistent with the average measured leak rate of 0.204 gph (for the tests at 50 psi without an induced leak). This line had a volume of about 2,800 gallons. Thus, as a range-finding test, it is reasonable to conclude that the volumetric system can detect leaks on the order of 0.2 gph in a line of this size under stable conditions.

Table 2. Volumetric Test Results on Line 2

Date	Time	Test system	Result	Verbal leak rate	Reported leak rate	Induced leak
Nov. 8	1300	Small	Invalid	Operator Error	NR	0.0
Nov. 8	1647	Small	Fail	NR	0.180	0.0
Nov. 8	1747	Small	Fail	NR	0.156	0.0
Nov. 8	1855	Small	Fail	0.15 to 0.2	0.216	0.0
Nov. 8	1940	Small	Fail	Suspicious	0.178	0.0
Nov. 9	1230	Small @ 140 psi	Fail	NR	0.451	0.0
Nov. 10	1445	Small	Abort	Bubble in Line	NR	0.0
Nov. 10	1645	Small	Abort		NR	0.0
Nov. 10	1715	Small	Fail	0.5	0.555	0.197
Nov. 10	2000	Small	Fail	NR	0.291	0.0
Nov. 11	1730	Small	No Test	Operator Error	Operator Error	0.0

Line 3. Testing and checking out of both the small and large systems began on line 3. Three tests were conducted on line 3 with the large system, one of which was used to measure the bulk modulus (compressibility of the system). On the basis of these tests, the vendor concluded that the line contained excessive trapped vapor. The remaining tests were done with the small system. Those tests with the small system after the vapor was purged were reported by the vendor and are included in Table 3. MRI has reported some tests that were attempted by the vendor and were declared invalid for the reasons indicated.

No formal report was received for the large system tests. The verbal report was excessive vapor with an unreliable leak rate on the order of 1 to 1.5 gph for the first test and 0.5 gph for the second test. In fact, the large system would not normally be used on a line as small as line 3. MRI has not included the large system results in the table as they appear to have been primarily attempts to troubleshoot the large system's operation.

Table 3. Volumetric Test Results on Line 3

Date	Time	Test system	Result	Verbal leak rate	Reported leak rate	Induced leak
Nov. 6	1235	Small	Aborted	Battery failed	NR	0.0
Nov. 6	1945	Small	Pass	Tight	–.031	0.0
Nov. 7	1015	Small	Pass	Pass	0.021	0.0
Nov. 7	1340	Small	Valve wrong	Operator Error	NR	0.703
Nov. 7	1540	Small	Fail	1.1	1.108	1.181
Nov. 7	1750	Small	Fail	0.255	0.201	0.187
Nov. 7	1944	Small	Fail	0.55	0.556	0.530
Nov. 8	0900	Small	Invalid	Vibration from Jackhammer	NR	None
Nov. 11	1430	Small	Pass	Tight	0.017	0.00

The tests reported showed one test that was lost due to operator error when a valve on the test equipment was incorrectly set during the test. One test was aborted due to a battery failure on the portable computer. A third test was declared invalid because of interference from vibrations resulting from drilling holes in the concrete about 160 feet from the system but close to part of the pipe.

As seen in Table 3, the small volumetric system correctly identified the tight lines and the leak simulations for the valid tests. This line was about 1,660 gallons in volume. The verbally reported leak rates matched the induced rates well. As a range-finding demonstration, these tests indicated that the volumetric system could find leaks down to about 0.2 gph on a line of this size, at least under the test conditions, in which the line was isolated for an extended period of time.

Line 4. The volumetric method was used to test line 4 with the large system. Two tests were attempted on November 6. The first was attempted at the normal operating pressure of 150 psi. The test continued for 6 minutes, at which time the line had required so much product to maintain pressure that the system's product reservoir was empty and the test had to be stopped. Based on the amount of product lost and the time, it was concluded that the line had a leak and an attempt to quantify it was made. A second test was begun at a pressure of 50 psi. This test lasted for 30 minutes until the reservoir was empty. Again, the qualitative result was a significant leak, with an attempt to quantify the rate. The data are summarized in Table 4. It should be noted that neither test completed its required duration. Consequently, while the conclusion is clear, the precision and accuracy of the leak rate should not be expected to be as good as when a full test is conducted. Probably the test at 50 psi has a somewhat more reliable result. It would extrapolate to 190 gph at 150 psi using the square root rule, which is in approximate agreement with the measured rate at 150 psi.

Table 4. Volumetric Test Results on Line 4

Date	Time	Test	Result	Leak rate	Induced leak
Nov. 7	0954	6 min @ 150 psi	Fail	230 gph	None
Nov. 7	1250	30 min @ 50 psi	Fail	110 gph	None

Line 4 was considered to be leaking on the basis of a number of pressure tests. This information was not presented to the vendors by MRI, so that they would test line 4 without prior knowledge of its assumed condition. However, the vendors all appeared to assume that line 4 had a problem, so they apparently received information about line 4 from the facility operator. When each vendor attempted to pressurize line 4, difficulty achieving or maintaining pressure was encountered. This observation indicated a problem with the line to each vendor as the testing began. All vendors did identify a major leak on line 4, which was later confirmed by excavation. Thus, the volumetric method correctly identified a leak on line 4 and provided probably the best estimate of its size.

Analysis of Volumetric Results Data

The purpose of this test program was to conduct range-finding tests to give an indication of the size of a leak that could be detected by the different technologies. That has been accomplished. The testing that was conducted was not as extensive or as controlled as testing for an EPA evaluation of leak detection. However, the testing was done under real-world conditions, and a substantial number of tests was completed. There were 16 tests with officially reported test results conducted under standard conditions with the volumetric method. There were eight such tests with verbal reports on-site. Since the results are quantitative, the numerical value of the estimated leak rate can be compared with the induced leak rate actually measured. A statistical analysis of these data can provide additional insight into the performance to be expected of the method. However, the relatively small number of tests and, even more so, the limited set of test conditions, mean that the results must be interpreted with caution and viewed as indicative, not conclusive, estimates of the performance.

The vendor of the volumetric test method provided verbal results for some tests at the time of the testing. Despite repeated requests, the vendor declined to provide official test results until after returning to the office and performing additional analyses of the data. The vendor asked for and received approximate simulated leak rates after providing verbal test results. However, verbal results were not provided for all tests, and for tight tests, the report was "Pass" or "Tight," without a numerical result. The data tables in the previous sections show both the verbal report and the official report. The verbal report is probably the more representative of field performance. The officially reported results, some of which were determined with knowledge of the approximate induced leak rate data, probably represent a somewhat optimistic estimate of the performance.

The statistical analysis consists of first forming the difference between the measured and reported leak rates. The mean and standard deviation of these differences are computed. If the method is unbiased, the mean difference should be close to zero, and this can be tested using a t-test. If the mean is not significantly different from zero, the method is judged to be unbiased. The standard deviation is used to compute a threshold for a probability of false alarm set at 5 percent. The threshold, standard deviation, and sample size are then used to compute the size of a leak that should be detectable with probability of 95 percent. The analysis is illustrated using the data from the verbally reported leak rates for line 1. The data from line 1 are reproduced in Table 5. The results of the analysis for the other lines are presented in Table 6.

Table 5. Verbally Reported Leak Rates for Line 1

Reported rate (gph)	Induced rate (gph)	Difference (gph)
0.512	0.820	-0.308
0.520	0.539	-0.031
0.308	0.185	0.123

The arithmetic mean of the differences in the third column of Table 5 was computed as

$$\text{Mean} = -0.051 \text{ gph.} \qquad \text{(Equation 4-1)}$$

The standard deviation of those differences was computed as

$$SD = 0.227 \text{ gph.} \qquad \text{(Equation 4-2)}$$

A t-test was used to test whether the mean difference was significantly different from zero. The t-statistic was computed as

$$t = (-0.051)\sqrt{3}/(0.227) \qquad \text{(Equation 4-3)}$$

$$t = -0.389. \qquad \text{(Equation 4-4)}$$

This computed t-value was compared with the critical value from a t-table with 2 degrees of freedom of 2.92. Since the computed t-value was less in absolute value than the critical value, the mean difference was not significant at the 5 percent level and the method did not exhibit a significant bias. For a 5 percent false alarm rate, test of the null hypothesis that the leak rate is zero against the alternative that it is positive (positive numbers for leak rates represent leaks out of the line) would be done. This would be done by comparing the measured leak for a given test with a critical value. The critical value was computed as the estimated standard deviation times the critical value from the t-table with the number of degrees of freedom determined by the number of valid tests on a given line. For line 1, there were three valid tests, so the degrees of freedom is 2.

The critical value at the one-sided 5 percent level from the t-table is 2.92. Thus, the threshold for the test at a 5% significance level would be given by

$$\text{Threshold} = 2.92 * 0.227 \text{ gph}, \qquad \text{(Equation 4-5)}$$

$$\text{Threshold} = 0.66 \text{ gph}. \qquad \text{(Equation 4-6)}$$

Thus, leak rates in excess of 0.66 gph on line 1 would be judged to be significant, based on the verbally reported test data.

The leak rate must be large enough that there is a 95 percent probability of detecting it. This occurs if the actual leak rate is at least twice the threshold, or 1.32 gph in this example.

Table 6 contains the results of these computations for both the verbally reported leak rates and the written officially reported leak rates in the vendor's report.

Table 6. Statistical Results for Volumetric Tests

		Verbally reported data			
Line	Volume	No. of tests	SD (gph)	5% Threshold (gph)	Detectable leak at 95% (gph)
1	9,700	3	0.227	0.66	1.32
2	2,800	2	0.091	0.57	1.14
3	1,660	3	0.077	0.22	0.45
		Officially reported data			
Line	Volume	No. of tests	SD (gph)	5% Threshold (gph)	Detectable leak at 95% (gph)
1	9,700	4	0.131	0.31	0.62
2	2,800	6	0.079	0.15	0.30
3	1,660	6	0.039	0.08	0.16

Some cautionary notes are in order in regard to Table 6. The vendor reported thresholds and detectable leak rates for the three line sections. The vendor's threshold was 0.3 gph for line 1, with a detectable leak rate of 0.6 gph, in good agreement with the results from the officially reported data. The vendor's reported threshold was 0.06 gph for lines 2 and 3, with corresponding detectable leak rates reported as 0.10 gph. All of these were stated to be for a 5 percent false alarm rate and a 95 percent probability of detection. The basis for these thresholds and detectable leak rates was not stated by the vendor but is presumed to be the vendor's own tests, which would presumably have larger sample sizes. A larger sample size would reduce the value from the t-table that is used in computing the thresholds and the detectable leak rates. To achieve the vendor's stated thresholds for the smaller lines would also require a smaller standard deviation of the differences between the measured and induced leak rates.

The data and results from line 2 must be viewed with special reservations. This line had a real leak when this vendor tested the line. The size of the leak was unknown, but was probably on the order of 0.2 gph. The results were adjusted using the vendor's estimated leak rate based on all tests at 50 psi of the line in its original condition. However, this adjustment is approximate and may not be adequate.

With these cautions, some observations can still be made. The size of the leak that can be detected with this method is related to the volume of the line. The standard deviations were larger for the larger volume lines, and the vendor's stated threshold and detectable leak were also larger for line 1 than for the other two lines, which were similar in volume. While the general nature of the increase in detectable leak rate with the volume of the line seems clear, no specific form for this relationship can be obtained from these data. If the standard deviations were modified by dividing them by the line volume, the results increase as the line volume becomes smaller. Thus, assuming that the results were proportional to the line volume is too much of a correction.

TRACER

The detailed report of the tracer method is in Appendix B. A summary of those results, along with a discussion of the activities observed, problems encountered and their solutions, and findings are presented in this section.

Once the equipment was on-site and the crew was ready to begin, some difficulties were encountered in drilling through the concrete paving and underlying soil to install the three leak simulation probes. The tracer method requires installing an inoculation port and six sampling probes for the leak simulation test that is required. The results of this test are used to determine the probe spacing. At this site, there was initially difficulty in drilling the holes for the leak simulation probes. Rather than the typical engineered backfill material generally used, the trench was apparently backfilled with broken limestone rock that had been excavated for the pipeline installation. As discussed earlier, this proved difficult to drill through using a pneumatic rock drill. Probes were installed along a total of 1,500 feet of piping.

The vendor used three tracers: tracer 1, tracer 2, and tracer 3. Probe installation and leak simulation with tracer 2 began on November 8 and concluded on November 11, 1996. Once the rock drill was available, Tracer punched holes for probes to 16 inches about one per minute. The second phase, tracer inoculation, sample collection and sample analysis, began on December 1 and concluded on December 12.

The tracer sampling points are documented completely in the vendor's report in Appendix B. Figure 21 shows the location of the sampling probes.

<u>Installation/Setup</u>

Testing generally requires two steps. The first step is to conduct leak simulations and install sampling probes. The second step is to collect and analyze the samples. Leak simulations are conducted to establish the soil porosity and conditions at the specific site. The leak simulations also demonstrate the sensitivity of the technology at the specific site. Sampling probes must be installed along the line. The spacing may vary depending on site conditions.

Installation of the probes depends on the length of the line and the difficulty in installation. It requires that the line be located so the probes can be installed in the line trench either directly above or within a foot or two of the line. This typically takes 1 or 2 days, longer for long lines.

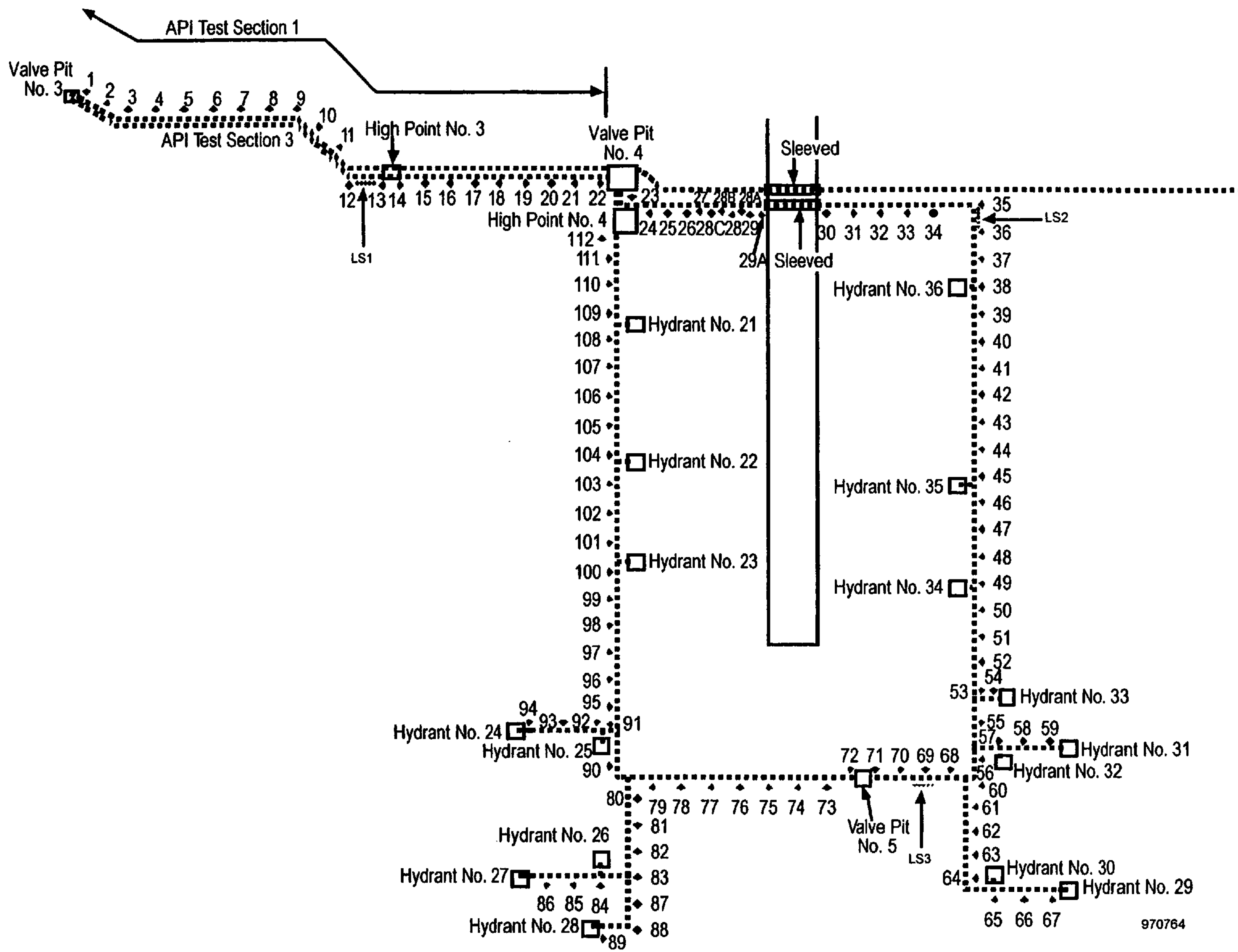


Figure 21. Location of Sampling Probe for Tracer

Test Duration

Once the tracer is inoculated into the line, it must remain there for a sufficient period for leakage to diffuse to the sampling ports. When the test was performed with product in the line, the tracer-labeled product remained in the pipeline for 48 hours after inoculation. Typically, test samples are collected from probes 7 to 14 days after the 48-hour inoculation period. When the test was performed with the line emptied of product, the line is pressurized with tracer-labeled air, which stayed in the line for only 24 hours. However, the tracer-labeled air cannot be released into the air in the vicinity of the test section of the pipe. It must therefore either remain in the pipe until after the test samples are collected and analyzed, or be moved through the piping and away from the test section with product. It may then be released from the pipe a safe distance from the test section. (This prevents possible contamination of the sampling probes.) Test samples are collected from the probes 24 hours after the 24-hour inoculation period.

Once samples are collected, they are analyzed in a gas chromatograph. Because the leak simulations at the test site performed along the test sections of piping indicated a very porous soil with the tracer diffusing very rapidly to the sample probes, the duration of the test was shortened to 2 days in the case of line 3.

Two tests were conducted with liquid product on line 3. The vendor first inoculated the line with tracer 1 on December 3 and conducted sampling and analysis on December 6. The line was inoculated with tracer 3 on December 10 and sampling and analysis were conducted on December 12. Thus, the first test lasted 4 days, the second 3. Two tests were conducted with air and tracer on line 4. The line was first inoculated with tracer 1 on December 3, and one round of samples was collected about 24 hours later with a second round after 72 hours. Secondly, the line was inoculated with tracer 3 on December 12, and one round of samples was collected after 2 hours.

Relation to Operation of the Line

There are four scenarios of the tracer test in relation to line operation. Often the tracer is inoculated into the liquid product as the line is packed. The test would require that the line be taken out of service from the period of inoculation until sampling and analysis are complete and the line left under pressure with tracer-labeled product. This would take the line out of service for up to 14 days, depending on the site.

A second scenario would be to inoculate the tracer into all the product in a tank for a period of time. Under that condition, the line could continue to function normally, assuming that it would then contain tracer-labeled liquid under pressure. This would require a larger amount of tracer, depending on the use of the line. It also assumes that the addition of the tracer does not interfere with originally intended use of the product.

Where the intended product usage is not affected by the addition of tracer or where the necessary approval can be obtained prior to inoculation, a third scenario would be to inoculate the product flowing through the pipeline at a given concentration through an opening to the line, while that line remains in service.

A fourth scenario would be to drain the line of liquid and use a tracer and compressed air (or nitrogen) to pressurize the line. In this case, the line would be out of service for the duration of the test, about 2 to 4 days. Additional time would be needed to drain the line at the beginning (unless the line were already empty) and refill the line at the end (unless repairs were needed). The most frequent applications of this method are the second and third scenarios.

Other Operational Aspects

This system is well-established with a documented protocol and experienced operators. It has been used commercially with success at many different sites. It provides both identification of a leak when one exists and location of that leak. Location of a leak usually involves installing additional sampling probes at closer spacing in the vicinity of probes where tracer was found and conducting additional sampling. A second tracer may be used to confirm findings and assist in locating the leak after additional sampling probes are installed.

Results

Line 3 Results. On December 3, 1996, 1,459 gallons of aviation fuel were pumped from a fuel pumper truck into the empty pipeline at valve pit 3. Tracer 1, the inoculation tracer, was metered into the fuel as it was pumped into the pipeline. After inoculation, two fuel samples were collected at valve pit 4 and analyzed for tracer. The analysis indicated that the pipeline was not sufficiently inoculated, so an additional 118 gallons of fuel and tracer 1 were added and the displaced fuel collected into a fuel bowser. Analysis of the collected fuel samples indicated that the fuel was properly inoculated. Test section 3 was then blocked in for the duration of the test.

On December 6, 22 samples were collected from test section 3 and analyzed for tracer 1. Elevated concentrations were found in probes 17 to 22, in the areas adjacent to test section 4 (which was also inoculated with tracer 1). A summary of analytical results is in Table 7. The concentration units for the tracer method were µg/L.

Due to the proximity of the section 4 piping, test section 3 was retested with tracer 3 to confirm the initial results. On December 10, 1,800 gallons of fuel was pumped from a pumper truck into line test section 3 at valve pit 3 while tracer 3 was injected into the fuel. The displaced fuel was collected on a defuel truck at valve pit 4. The inoculation effectively displaced the tracer 1 inoculated fuel and replaced it with tracer 3 inoculated fuel.

On December 12, samples were collected from section 3 and analyzed for tracers 3 and 1. Decreased concentration levels of tracer 1 were detected in probes 10 and 13 through 22. Tracer 3 was not detected at significant levels. The conclusion was drawn that test section 3 was tight and passed the leak test. A summary of the analytical results is in Table 8. The small reading of tracer 3 at probe 1 was due to a small amount of tracer-labeled product released in valve pit 3 when disconnecting a hose.

Table 7. 48-Hour Test with Tracer 1 on Line 3 (μg/l) (December 6, 1996)

Probe number	Analytical results
1 through 16	ND
17	0.02
18	0.08
19	1.0
20	12
21	3
22	7
Air, Lab	ND
Air, Valve Pit 4	ND

Test section 4 did not contain any fuel and was empty at the time of the inoculation. Using a compressor, a mixture of tracer 1 and compressed air was introduced into the pipeline on December 3, 1996. The tracer/air mixture was added at the high point adjacent to valve pit 4 (high point 4). Samples were collected at valve pit 5 at the furthest end of the piping from the injection point and analyzed for tracer. Once the tracer 1 was confirmed at valve pit 5, the pipeline was blocked in at 30 psi. A hydrant outlet adapter was used to release air from the pipe until tracer labeled air arrived at hydrant outlets 29 to 36. Test section 4 was pressurized up to a final pressure of 42 psi at 1800 hours on December 3.

On December 4 at 0900, 15 hours after final pressurization, gauge readings were 0 psi, indicating that the piping had lost all pressure. The pipe was recharged with tracer 1 and compressed air for 3.5 minutes, bringing the pipeline pressure up to 10 psi before a malfunction in the locally rented compressor stopped the inoculation event.

Table 8. 48-Hour Test with Tracer 3 on Line 3 (µg/l) (December 12, 1996)

Probes	Analytical results tracer 1, residual from previous test	Analytical results
1	ND	0.00006
2 through 9, 11 and 12	ND	ND
10	0.001	ND
13	0.001	ND
14	0.004	ND
15	0.006	ND
16	0.01	ND
17	0.2	ND
18	0.2	ND
19	0.7	ND
20	1	ND
21	1	ND
22	1	ND

On December 4, approximately 24 hours after initial inoculation, 48 samples were collected from section 4 and analyzed for tracer 1. Concentrations of tracer 1 high enough to fail the line were detected in probes 25 though 29, the area between high point 4 and Pier A. The highest concentration of tracer (13 µg/L) was detected at probe 28. The analytical results are summarized in Table 9.

Table 9. 48-Hour Test with Tracer 1 on Line 4 (µg/l) (December 4, 1996)

Probe	Analytical results
30 through 71	ND
29	0.8
28	13
27	5
26	4
25	2
24	0.001

On December 6, in an effort to determine the location of the leak(s), four leak delineation probes (28A, 28B, 28C, and 29A) were installed on 5-foot centers in the area of probe 28, between probe 27 and Pier A. These probes were installed only 16 inches deep because of concern about buried high voltage and radar cables in the vicinity. Deeper probes would have been useful in performing depth profiling, which is instructive in conducting a leak delineation. Probe 23 was also installed at this time.

Approximately 72 hours after inoculation, another round of samples was collected from probes 23 through 71 and analyzed for tracer 1. Concentrations of tracer 1 high enough to fail the line were observed in probes 23 through 29A. The analytical results are summarized in Table 10.

Table 10. 72-Hour Test with Tracer 1 on Line 4 (µg/l) (December 6, 1996)

Probes	Analytical results
31 through 71	ND
30	0.001
29A	3
29	.2
28A	8
28	6
28B	5
28C	4
27	5
26	9
25	6
24	0.005
23	11

To confirm the findings and further delineate the leak location(s), test section 4 was retested with tracer 3. On December 12, test section 4 was pressurized to 20 psi with a compressor. Tracer 3 was then injected into the air stream over the next 16 minutes until the line pressure reached 62 psi.

Two hours after inoculation with tracer 3, samples were collected between valve pit 4 and the international pier. These were analyzed for tracer 3 and tracer 1. Tracer 3 was detected in probes 23 through 28A with the highest concentration at probes 23, 26, and 28A. Decreased residual concentrations of tracer 1 were detected in probes 23 through 29A. The analytical results are summarized in Table 11.

Table 11. 2-Hour Test with Tracer 3 on Line 4 (μg/L) (December 12, 1996)

Probes	Analytical results tracer 1 (residual)	Analytical results tracer 3
29A	1	ND
29	0.4	ND
28A	1	2
28	1	0.003
28B	1	0.001
28C	1	0.003
27	2	0.1
26	2	3
25	0.9	.2
24	0.02	0.0006
23	0.2	13

As a result of the tests, the portion of test section 4 between valve pit 5 and the east side of Pier A (probes 30-71) tested tight and passed the leak test. The portion of test section 4 between valve pit 4 and Pier A (probes 23-29A) failed the leak test.

The leak location was stated to be more difficult to determine than usual. The reason for this was the high level of groundwater and the thick, overlying concrete cover. This formed two horizontal boundaries with a relatively thin layer of permeable fill between them. Tracer released with a large volume of air into this permeable layer resulted in a rapid lateral tracer transport around the site.

The data indicated at least one leak. According to the vendor, the most probable location is in the vicinity of probe 28A. There may be leaks at locations of probe 23 and 26 as well, but the results there could also be due to tracer migration. Significant tracer migration was demonstrated by the detection of tracer 1 in probes 17 through 22, since the test with tracer 3 confirmed no leak in this area. Consequently, the vendor was not confident in identifying leaks at probes 23 and 26, feeling that those might turn out to be false positive locations.

PRESSURE DECAY METHOD

The detailed report from the vendor is in Appendix C. A comparison of those results with the measured leak rates induced on the various lines is given in this section, along with a discussion of activities observed, problems encountered, and possible explanations for anomalies.

First, a few comments are needed relative to the organization of the material in Appendix C. The first few pages provide a narrative description of the vendor's major points. Next is a theoretical determination of the point of transition to laminar flow from turbulent flow, a phenomenon expected to have occurred on some tests and which probably affected the accuracy of the reported results. This is followed by graphs of long term (overnight) pressure decay tests for section 1 and for section 2 (twice, before and after the leak had been discovered and repaired). Following that information are two-page summaries of all the tests on lines 1, 2, and 3, respectively, and a one-page summary of the pressure decay test on line 4. The remainder of the material is field logs for all of the tests, including the pressure test on line 4 and the overnight pressure decay tests on lines 1 to 3.

Note that clock time reported by the vendor was the time from the computer, which was set on Glinde (Hamburg), Germany, time. The corresponding U.S. Eastern time zone time is 7 hours earlier, which is the time used in this report.

The vendor reported its findings to MRI in the field in real time; these are the results shown on the field forms. However, since those results were based on a shortened series of calibration tests, it was known that the values of k_1 and k_2 were only approximate, as would therefore also be the reported leak rates. Later, the vendor recalculated the k-factors based on all the usable data (including the tests performed blind but later reported to them). The adjusted k-factors were then used to refine the leak rate estimates. In the following tables, we give both the field-reported results and the adjusted results.

For each test, the vendor compared the computed leak rate with the value computed from the 0.04 $l/h/m^3$ tolerance limit or threshold (called "Tolerable Tightnessfactor" in its reports) to determine whether to pass or fail the line.

Installation/Setup

The HANSA system is meant to be permanently installed, a process that the vendor states takes on the order of a week or two. Testing on a one-time basis as in this program is only done as a demonstration. The system is not intended as a one-time test method for lines of unknown condition but rather as a monitoring method. This assumes that the facility has previously installed the necessary valves and pumps. The time includes performing all of the calibrations, final software modifications, and training of the local personnel in the system operation. The time will vary with the number of test sections.

Setup for the testing operations required 2 days. Most of this time was spent acquiring supplementary, site-specific equipment. The electrical supply at this location is notoriously troublesome, with voltage fluctuations and line noise. Computers cannot operate with such power. The vendor therefore locally procured an uninterruptible power supply for its computer. There was no means of automatically pressurizing the test segments because they had been isolated from the system pumps. A manual pump was then provided by the airport fueling contractor, although it required mechanical repairs.

Calibration testing for a test section would normally require eight tests of 45 minutes each and about eight 30-minute periods of calculations and decision making. For these tests, the vendor reduced the calibrations to four tests to complete the tests within their travel schedule.

Test Time

A test normally requires 45 minutes from start to finish. This total time includes the time to pressurize the test section twice and depressurize it once. For our tests, because an automated pumping system was not available, the line had to be manually pressurized, which required about

20 minutes each time on line 1, less on lines 2 and 3. Under these conditions, a test on line 1 required about 1 1/2 hours, about twice as long as the vendor normally plans.

Relation to Operation of the Line

In normal testing, a test section of the line would need to be taken out of service for the duration of the test, which is 45 minutes. The method would also require the test section to be taken out of service for about two days during the calibration tests, but these are generally done only during installation of the system.

Other Operational Aspects

This system is well established and is permanently installed at many airport hydrant systems around the world. It requires double block and bleed valves for isolating the different test sections, to assure that product cannot leak from one section to another during a test. It is normally meant to be installed on larger test sections than were used in our tests. On larger sections, leaks in the advertised detection range (0.04 $l/h/m^3$) would be great enough to produce turbulent flow, which the software assumes. On the smaller test sections, some of the simulated leaks were small enough that the flow was probably laminar, reducing the accuracy of the vendor's measurements.

Power requirements for the system include 120 volts for the computer system and probably 220 volts or more for the hydrant pumps. The vendor assumes that the line is initially tight so that he can properly run his calibration tests. If the line has a leak, and the vendor assumes it to be tight, the k-factor calculations will be invalid. This was the situation found with line 2, as will be discussed. The vendor is able to use his equipment to determine if a line is tight by operating it in a different mode. Instead of the usual test mode, the vendor uses his equipment to simply track the pressure and its drop over an extended period of time (ideally 12 to 24 hours). This was done on line 2, with a 10-hour test, and it was determined that it had a leak on the order of 0.4 to 0.5 l/h (0.10 to 0.13 gal/h) at 10 bar (about 150 psi).

Results

Line 1 Results. Table 12 contains the results of the testing on line 1. The vendor declared the third test to be invalid because it required an excessive amount of time to repressurize the line between the second and third cycles. The manual pump used for these tests failed on occasion. During the first test following the calibration runs, the simulated leak rate increased substantially for unknown reasons. Both the MRI observer and the system detected and reported this discrepancy. The system operator, not the system, declared the run to be aborted. Being unable to determine an accurate leak rate when it is varying represents a possible shortcoming in any system, although that shortcoming may not be of practical significance if real-world leaks do not vary significantly over a short time period (45 minutes). In the last test, the system accurately measured the leak rate, but because it was below the threshold, the system did not declare the line to be leaking.

Table 12. Results from Pressure Decay Method on Line 1

Date	Time	Simulated leak rate (l/h)	Field-reported leak rate (l/h)	Adjusted leak rate (l/h)	Pass/ fail
11-13-96	10:42	0.000	3.803[a]	0.250	NA
11-13-96	11:31	0.000	3.692[a]	0.143	NA
11-13-96	12:24	0.000	4.683[a]	1.222	[b]
11-13-96	13:41	0.000	3.481[a]	–0.085	NA
11-13-96	14:58	2.862	5.686[a]	2.283	NA
11-13-96	15:59	Aborted[c]			
11-13-96	17:35	5.29	4.359	4.458	Fail
11-13-96	18:51	0.000	0.554	–0.300	Pass
11-13-96	20:04	0.83	0.494	0.997	Pass[d]

[a] Calibration run. Reported leak rate is artificial until k-factors are defined.
[b] Vendor discarded this test as a valid calibration test because 35 minutes were required to pressurize between cycles 2 and 3, a value deemed excessive.
[c] Leak simulator failed to maintain a steady leak rate.
[d] Line not declared leaking because measured leak rate was less than the threshold of 1.851 l/h.

The results from line 1 showed that the pressure decay method was able to detect a leak on the order of 1 gph. It measured an induced leak rate of about 0.2 gph fairly accurately, but the size of the leak was below its threshold, so it indicated a "pass," meaning that the line was judged to be tight. For this line of about 9,700 gallons volume, the vendor's threshold was 0.39 gph, although the vendor used a threshold of 0.49 gph, based on an approximate size of the line. Thus, it appears that the method could reliably find leaks in excess of about 0.5 gph.

Line 2 Results. Table 13 contains the results of the testing on line 2. The vendor tried, unsuccessfully, to determine the k-factors all day on November 12, 1996. Its attempts, based on all valid tests of the day, produced "unusual factors in an unstable situation." The vendor suspected that the line had a leak. That night, equipment was set up to run an all-night pressure drop test. The following morning the vendor reported a suspected leak rate of 0.4 to 0.5 l/h.

On November 14, 1996, the vendor again tried to calculate k-factors for line 2 using the first three tests of the day. But, the next three tests, using these calculated values, produced error messages from the system. (The reported leak rates were negative, implying leakage *into* the line.) At that point, the vendor reported that line 2 definitely had a leak and could not be tested further. Subsequently, it was discovered that a spectacle valve at one end of line 2 was not tight and fuel was dripping into valve pit 5.

After the valve was tightened, the vendor again ran a calibration test (at 17:44). Although the system again produced an error message (it was still using the old k-factors), the vendor calculated trial k-factors based on this single test and used them on the subsequent (calibration) tests. All of the adjusted leak rates in Table 13 are based on the final k-factors from the last four successful runs.

The results from the line 2 tests illustrated the fact that the system is not designed to test a line in unknown condition. The system requires a calibration with known conditions on each line to establish its test. When the line has an existing leak, as was the case with line 2, the system cannot achieve a calibration. This means that it cannot reliably estimate a leak rate, although the fact that it cannot calibrate the system led to the conclusion that there was a problem with the line and that it was suspected to be leaking. After the leak was observed at the blind flange and corrected by tightening the bolts, the system was able to detect a simulated leak of about 0.6 gph

Table 13. Results from Pressure Decay Method on Line 2

Date	Time	Simulated leak rate (l/h)	Field-reported leak rate (l/h)	Adjusted leak rate (l/h)[b]	Pass/ fail
11-12-96	10:01	0.000	2.420[a]	1.744	NA
11-12-96	10:49	0.000	2.169[a]	1.512	NA
11-12-96	11:33	0.000	2.194[a]	1.533	NA
11-12-96	14:32	0.650	2.168[a]	1.500	NA
11-12-96	15:18	0.000	1.715[a]	NR[c]	NA
11-12-96	16:43	0.988	3.635[a]	2.893	NA
11-12-96	17:58	0.000	1.652[a]	1.016	NA
11-12-96	18:50	0.000	1.595[a]	0.958	NA
11-14-96	09:26	0.000	3.348[a]	2.631	NA
11-14-96	10:15	0.000	3.521[a]	2.786	NA
11-14-96	11:17	1.810	4.386[a]	3.601	NA
11-14-96	12:19	0.600	–0.397[a]	2.596	Error
11-14-96	13:28	0.000	–2.747[a]	1.457	Error
11-14-96	14:25	0.000	–2.609[a]	1.500	Error
11-14-96	17:44	0.000	–5.785[a]	0.017	Error
11-14-96	18:34	0.000	–0.034	–0.016	Pass[d]
11-14-96	19:17	0.000	–0.019	–0.002	Pass[d]
11-14-96	20:42	Aborted[e]			
11-14-96	21:27	2.420	2.553	2.420	Fail[d]

[a] Calibration run. Reported leak rate is artificial until k-factors are defined. Vendor could not obtain satisfactory k-factors on 11-12-96. Tried to determine k-factors from first three tests on 11-14-96, but system declared Errors on subsequent tests.
[b] Adjusted based on final k-factors from final 4 good tests on 11-14-96 after leak was repaired.
[c] Not reported by vendor in Summary Table.
[d] Based on trial k-factors determined from single calibration run at 17:44 on 11-14-96.
[e] Leak simulator failed to maintain a steady leak rate.

based on a single point calibration. The vendor's threshold would calculate to about 0.12 gph on this line. However, depending on the shape of the hole in the line, leak rates of less than about 0.2 gph may produce laminar rather than turbulent flow. The vendor's algorithms assume turbulent flow and would overestimate leak rates if the flow is small enough to be laminar. Thus, with a line of this volume (about 2,800 gallons), the method could probably detect a leak on the order of 0.2 gph after calibration.

Line 3 Results. The data for line 3 are given in Table 14. Testing on this line went very well, with no unusual problems. The vendor calculated a trial k_2 factor after only one calibration test, and used it to make pass/fail decisions on the remaining three calibration tests. Then, new k-factors were calculated based on all four calibration tests and used for the rest of the tests.

Table 14. Results from Pressure Decay Method on Line 3

Date	Time	Simulated leak rate (l/h)	Field-reported leak rate (l/h)	Adjusted leak rate (l/h)	Pass/ fail
11-15-96	08:58	0.000	0.393[a]	–0.003	NA
11-15-96	09:43	0.000	–0.002[a]	–0.005	Pass[b]
11-15-96	10:26	0.000	0.010[a]	0.007	Pass[b]
11-15-96	11:40	0.660	1.001[a]	0.949	Fail[b]
11-15-96	12:36	0.680	0.515	0.730	Fail
11-15-96	14:00	1.480	1.217	1.486	Fail
11-15-96	16:14	0.990	0.878	0.943	Fail
11-15-96	17:09	1.440	1.437	1.543	Fail
11-15-96	18:02	0.580	0.853	0.917	Fail

[a] Calibration run. Reported leak rate is artificial until k-factors are defined.
[b] Based on k_2-factor from first calibration test, only.
[c] Actual leak rate expected to be too small to support turbulent flow, according to vendor, so calculated leak rates stated to be overestimates based on turbulent flow assumption.

Line 3 had a small volume (estimated at 5.3 m^3 or 1,660 gallons), so detectable leak rates were projected to be quite small (0.2115 l/h). However, the vendor estimated that at leak rates less than 0.7 l/h the flow would become laminar. As the system assumes leaks are turbulent, the vendor expected that the leak rate was over estimated when it was less than 0.7 l/h. This was true of the leaks simulated at 11:40, 12:36, and 18:02.

The system detected induced leaks ranging from about 0.38 gph down to 0.14 gph based on four calibration tests (three tight and one simulated leak). This line is small enough that the vendor's threshold would be below the turbulent flow rate. Consequently, the leak rate that the method could detect is somewhat higher than would be expected based on the size of the line. A leak rate of about 0.2 gph should be detectable after calibration.

Line 4 Results. Testing on line 4 was very limited. Because it could not be pressurized to 10 bar, the method could not be applied in its normal fashion. Instead, the airport fueling contractor applied pressure on the line from a fueling truck, raising the pressure to about 45 psi. The vendor then used its system to simply track the pressure drop in the line with time. In a single measurement over about 5 minutes of time, the vendor tracked a pressure drop from 2.7 to 1.5 bar. Using these data, the vendor estimated a leak rate of 50 to 60 l/h at 10 bar. However, it was also indicated that the true leak rate was probably greater because (the vendor suspected) there was a significant amount of trapped air in the line, which would require great amounts of fuel to flush it from the line. The vendor felt that it was not necessary to do this to obtain greater accuracy; there was obviously a large leak.

Analysis of Pressure Decay Results Data

The purpose of this test program was to conduct range-finding tests to give an indication of the size of a leak that could be detected by the different technologies. That has been accomplished. The testing that was conducted was not as extensive or as controlled as testing for an EPA evaluation of leak detection. However, the testing was done under real-world conditions, and a substantial number of tests was completed. There were 11 valid tests with the pressure decay method performed after vendor calibration. These tests were conducted blind to the vendor. Since the results are quantitative, the numerical value of the estimated leak rate can be compared with the induced leak rate actually measured. A statistical analysis of these data can provide additional insight into the performance to be expected of the method. However, the relatively small number of tests and, even more so, the limited set of test conditions, mean that the results must be interpreted with caution and viewed as indicative, not conclusive, estimates of the performance.

The method of analysis is the same as used for the volumetric method and the description is not repeated here.

The pressure decay method requires that the system be calibrated on a known tight line and with a known leak rate. Once this is done, it is capable of detecting a leak in a section of a line. However, this limits its applicability as a test method for lines of unknown condition. The vendor calibrated the system and then tested lines 1, 2, and 3. After calibrating the system on each line, a number of blind tests were run with simulated leaks unknown to the vendor. The vendor reported leak rate results for these tests on site. After leaving the site, the vendor computed adjusted parameters using all of the test data and then reported adjusted leak rates for all tests. As with the volumetric vendor, the statistics have been computed and reported for both sets of data. The blind tests are judged to be more representative of what the vendor's system could do in practice. However, they were based on fewer calibration tests than usual, so they may not be as accurate as the vendor could achieve. Table 15 contains the results of the statistical computations for the pressure decay system.

Note that the vendor's stated threshold is related to the volume of the line in that the vendor's threshold is 0.004% of the volume of the line.

Table 15. Statistical Results for Pressure Decay Data

		Blind test results			
Line	Volume	No. of tests	SD (gph)	5% Threshold (gph)	Detectable leak at 95%
1	9,700	3	0.132	0.28	0.56
2	2,800	3	0.017	0.05	0.10
3	1,660	5	0.039	0.12	0.23
		Adjusted Test Results			
Line	Volume	No. of Tests	SD (gph)	5% Threshold (gph)	Detectable Leak at 95%
1	9,700	8	0.109	0.21	0.41
2	2,800	14	0.133	0.24	0.47
3	1,660	9	0.036	0.07	0.14

The vendor's computed threshold would be 0.39 gph for line 1, 0.11 gph for line 2, and 0.07 gph for line 3. Some caution is required in interpreting the data in Table 15. When originally tested, line 2 had a real, unknown leak. The vendor concluded that the line probably had a leak because he was unable to calibrate the system on the line. The leak was observed visually in valve pit 5 during the second day of testing on that line. After the leak was found, it was corrected. The blind tests reported in Table 15 were done after the leak had been corrected. The revised data for line 2 in Table 15 included tests with the existing leak, with an adjustment for the estimated leak rate. The fact that the standard deviation for these tests was larger than for the tests on line 1 suggests that the adjustment was not adequate and the estimated leak rate was not accurate.

This system states its threshold as directly proportional to the volume of the line under test. The results of these tests showed a higher standard deviation for the largest line. The two smaller lines were comparable in their standard deviations. Thus, it seems reasonable to conclude that the size of the leak rate that can be detected does increase with the size of the line, but the current testing was not detailed enough to establish the actual form of this relationship.

ACOUSTIC EMISSIONS METHOD

The detailed report of the vendor is in Appendix D. A summary of the results, along with a discussion of activities observed, problems encountered, and possible explanations for anomalies are given in this section.

The vendor decided to bring drilling equipment the week of November 18, 1996, when it did its testing. The equipment included a hammer drill, a 1-inch bit about 6 inches long, and bit extension rods. The vendor proceeded to attempt drilling a 1-inch hole through the tarmac above line 4 but was unsuccessful. The extension rods were found to be 1 1/8 inch in diameter, so they could not be forced into the 1-inch drilled hole. No replacement rods or larger bits were available locally. Therefore, it was decided to test only at the hydrant pits, valve pits, and high points. Arrangements were made to bring a local contractor on site the evening of Tuesday, November 19, to drill a few holes in the vicinity of any suspected leak. (As it turned out, the contractor did not appear, but the acoustic emission vendor did not require his services.)

Installation/Setup Time

The vendor required about a one-half day to unpack and check out its electronic equipment. This checkout process also included changing out some components, such as electronic filters, of which a number of versions were shipped to the site, from which the proper ones for the site conditions were selected.

Test Time

The testing to determine whether there is a leak is very rapid, requiring on the order of 5 minutes per test point assuming there is access to the pipe. If a leak is suspected, additional measurements are made to determine an approximate leak location, requiring another 15 or 20 minutes. If more precise leak location is desired, an additional leak-location system is placed into operation. About 1 hour is required to set up and adjust this equipment, and about an hour of data collection and field analysis is needed. Later, the data are analyzed further in the laboratory, to refine the leak location determination.

Relation to Operation of the Line

The acoustical emission method is routinely used with the line in normal operation. In an airport environment, aircraft taxiing nearby create enough background noise that testing is suspended until the aircraft either taxis away from the test site or shuts down its engines. The system compares acoustical emissions from various parts of the line to background levels. The background is what the instrument measures when the probe is not in contact with the pipe. Areas with acoustical emissions in excess of the background are suspected of leaking if the signal is consistent with that of a leak in the judgment of the operator.

Other Operational Aspects

The method is qualitative, not quantitative, so it cannot produce an accurate estimate of the leak rate, although a skilled operator might make an educated guess.

The method requires access to the pipe at about 50-ft intervals. This normally means that some method of drilling through the soil and/or pavement is required. This was not done for these tests, as the hydrants and valve pit access points were deemed to be adequate and accepted by the vendor. Drilling would have been very time consuming at this location because the backfill under the pavement was the native limestone or coral rock, which had apparently cemented itself together after the pipe was installed. Locating the pipe accurately is mandatory when accessing it because the wave guide must be placed in contact with the pipe. Any coating must be locally removed to assure metal-to-metal contact between the pipe and the wave guide. Excellent operator skill is also required to accomplish this.

The method might have different performance if the pipe to be tested were plastic (PVC, fiberglass, etc.) rather than steel.

Ambient noise of an intermittent nature, such as a nearby taxiing aircraft, is not a significant deterrent for the method; the operator just waits a few minutes for the noise to subside. The acoustical emission signals from different parts of the pipeline are compared. A significant increase over the baseline signal indicates a suspect area. If the nature of the increased level is consistent with the emissions from a leak, a problem is declared and a location is estimated.

There are no external power requirements; all of the equipment is battery operated.

Results

Line 1 Results. The acoustical method requires contact with the pipe approximately every 50 feet. Line 1 was thought to be about 3,500 feet long; later, measured drawings indicated its length to be about 2,800 feet. Because of the length of line 1 and the difficulty of drilling through the pavement and rock, line 1 was not tested. It would have required drilling for access to the pipe at many points, since line 1 had no hydrants and few pipe access points.

Line 2 Results. Testing proceeded on line 2 the afternoon of November 18. The results obtained are given in Table 16. The data are given in the order that the tests were conducted. The actual testing, once it was begun, required about 1 hr. The testing was performed with the line manually pressurized to about 150 psi. No indications of leakage were obtained. (This finding confirmed that of the other vendors after the leaking spectacle valve in valve pit 5 was corrected.)

Table 16. Results from Acoustic Emissions Method on Line 2

Test location	Background (volts)	On-pipe signal (volts)
High Point 4	0.36	0.36
Hydrant 21	0.35	0.35
Hydrant 22	0.35	0.35
Hydrant 23	0.35	0.35
Hydrant 24	0.34	0.34
Hydrant 25	0.34	0.34
Hydrant 26	0.34	0.34
Hydrant 27	0.34	0.34
Hydrant 28	0.34	0.34
Valve Pit 5	0.34	0.34

Line 3 Results. Line 3 was tested on the morning of November 20, 1996. Leak simulation was performed at high point 3, and leak detection was attempted at valve pits 3 and 4, and at high point 3, where the leaks were simulated. The results are shown in Table 17. The tests with the vendor at valve pit 3 and valve pit 4 were blind to the vendor as far as presence or absence of leak and leak rate. The vendor knew the location of the leak simulation but not the leak condition (tight or leaking). Tests at high point 3 were not blind as the vendor was testing where the leak simulation was located.

For all the tests on line 3, two detection sensitivities were used: a normal frequency (NF) setting and a low frequency (LF) setting. With a zero leak rate simulated, essentially no detection occurred at either frequency at the two valve pits. However, detections were made at the source of the leak simulator at both frequencies. Further investigation revealed a slight leak through the pipe threads below the leak simulator. This piping was tightened and the sound level decreased to background, indicating that the leak had been repaired.

A leak of about 0.40 gph was then established through a needle valve. It was detected (slightly) at valve pit 4, and at valve pit 3 it was stated to be a "borderline detect." The vendor felt that detecting this at valve pit 4, a distance of about 150 feet away from the simulated leak on a straight section of pipe, was at about the upper limit of the method's capability. Valve pit 3 was a little farther

Table 17. Results from Acoustic Emissions Method on Line 3

Test location	Simulation method	Leak rate (gph)	Background (volts)		On-pipe signal (volts)		Detect/No detect
			Norm freq	Low freq	Norm freq	Low freq	
Valve Pit 4	Needle Valve	0.00	0.34	0.19	0.34	0.19-0.21	N
Valve Pit 3	Needle Valve	0.00	0.35	0.19	0.36	0.20	N
High Point 3	Needle Valve	0.00	0.34	0.24	0.53	0.10-1.20	D
Valve Pit 4	Needle Valve	0.36	0.35	0.19	0.36-0.50	0.20-0.41	D
Valve Pit 3	Needle Valve	0.40	0.39	0.20	0.40-0.44	0.21-0.24	N
High Point 3	Needle Valve	0.38	0.35	0.19	0.60-0.80	1.10-2.30	D
Valve Pit 4	Orifice	1.60	0.46	0.19	0.48-0.51	0.19	D
Valve Pit 3	Orifice	1.80	0.46	0.19	0.46-0.48	0.19	N
High Point 3	Orifice	1.50	0.52	0.24	0.70-0.80	3.90-4.60	D

away, about 250 feet, and the line has two 45° bends along the way, further degrading the acoustic transmission.

An orifice was then placed in the line at high point 3 for simulating leaks. The first orifice tended to become plugged easily, so another was installed. It produced a steady flow of about 1.5 to 1.8 gph, dropping somewhat as the line pressure dropped during the testing. This leak was also detected at valve pit 4 and marginally at valve pit 3, both at the normal frequency setting. The leak was not detected at either valve pit with the low frequency setting.

Line 4 Results. Testing of line 4 was initiated the afternoon of November 19, 1996. Prior to testing at each test point, the fueling contractor for the airport brought the line up to the maximum pressure producible by the fueling truck, about 45 psi. The actual pressure during each test fluctuated between about 38 psi and 45 psi, at a frequency of several cycles per minute, a function of the truck's fueling pump. When the pressure reached its maximum, the pump stopped. Then, the pressure would drop as product leaked from the line. When the pressure dropped to about 38 psi, the pump automatically restarted. The results of the testing on line 4 are given in Table 18, again, in the order that the tests were conducted.

Table 18. Results from Acoustic Emissions Method on Line 4

Test location	Background (volts)	On-pipe signal (volts)
Hydrant 36	0.34	0.35
Hydrant 35	0.33	0.35
Hydrant 34	0.33	0.34
Hydrant 33	0.33	0.34
Hydrant 32	0.33	0.38
Hydrant 31	0.34	0.34
Hydrant 30	0.33	0.39-0.49
Hydrant 29	0.33	1.2-1.9
High Point 4	0.33	0.34

Note that the last line of Table 18 indicates the test location to be at High Point 4, whereas the vendor report (Appendix D) states it to be at High Point 5. The original data sheet, a copy of which was provided to MRI in the field while testing was being conducted, identifies this point as simply "High Point" without a number. The MRI field notes state: "No noise [observed] at HP4; no test conducted @ HP5 in VP-5."

Most of the test points in Table 15 provided essentially no sound levels above background. A slight signal was detected at Hydrant 32, and a somewhat greater signal was detected at Hydrant 30. Significant noise was heard at Hydrant 29. The range of signal levels for Hydrants 29 and 30 corresponds to the pressure variations between 38 and 45 psi.

Sensors were then mounted on both Hydrants 29 and 30 and wired to the location equipment, and data collection was conducted for about 30 minutes. Then, a sound filter with a different sensitivity was placed on the signal line from Hydrant 30, and about 5 more minutes of data were collected. At that point, data collection ceased because the fueling truck was recalled to fuel a plane that had just landed.

In-the-field review of the data by the vendor led to the conclusion that there was a significant leak between Hydrants 29 and 30, about 10 to 12 feet from Hydrant 29. The straight-line distance between these two hydrants was estimated at about 43 feet, by pacing. The length of pipe between the two test points is somewhat longer, perhaps about 50 feet.

Further examination and refinement of the data analysis by the vendor (see Appendix D) led to the conclusion that the leak was 14 feet along the pipe from the test point on Hydrant 29, or about 12 feet in a straight line from Hydrant 29 to Hydrant 30.

Other Test Results. At about 11:40 a.m. on November 20, the vendor began testing line 5, a different portion of the hydrant system in service at another part of the airport. This was not a previously scheduled set of tests, but because the vendor had additional time (partially since line 1 was not tested), it was agreed to run these tests. The results from those tests are shown in Table 19. The line was pressurized to 150 psi by the hydrant system pumps. Testing went rapidly, with only slight pauses because of ambient noise levels when an aircraft taxied nearby.

The overall set of tests on line 5 required about 2 hours. No leaks were detected in this line. The only anomaly noted was at hydrant 18. Initial testing at this location determined that there was an acoustic signal but not one that was consistent with a leak. Further investigation found that the line's impressed current cathodic protection system was turned on. When that system was turned off, the acoustic signal disappeared. It was not determined why this effect was present.

Table 19. Results from Acoustic Emissions Method on Line 5

Test location	Background (volts)	On-pipe signal (volts)
Hydrant 20	0.46	0.44
Hydrant 19	0.48	0.48
Hydrant 18[a]	0.46	0.53-1.00
Hydrant 18[b]	0.46	0.46
Hydrant 17	0.46	0.46
Hydrant 16	0.47	0.48
Hydrant 15	0.46	0.46
Hydrant 14	0.47	0.47
Hydrant 13	0.47	0.47
Hydrant 12	0.47	0.47
Hydrant 11	0.47	0.47
Hydrant 10	0.46	0.46
Hydrant 9	0.46	0.46
Hydrant 8	0.47	0.47
Hydrant 7	0.48	0.46
Hydrant 6	0.47	0.46
Hydrant 5	0.47	0.47
Hydrant 4	0.48	0.45
Hydrant 3	0.48	0.45
Hydrant 2	0.48	0.46
Hydrant 1	0.52	0.47

[a] With cathodic protection system on.
[b] With cathodic protection system off.

Section 5

FIELD INSPECTION RESULTS

FIELD INSPECTION

A field inspection of the test site was conducted on Tuesday, May 20, 1997, by G. Joe Hennon for MRI. The facility personnel had found a hole and repaired it with a clamp on Thursday, May 15, 1997. After the clamp was in place, they pressurized the line to 120 psi with air and found that the pressure continued to hold on Friday, May 16, 1997.

Mr. Hennon and the facility crew arrived on site at 9:30 am on May 20, 1997. The line was still holding pressure at 120 psi, so the single hole appears to be the only hole. It was high tide, so the liquid level was at the top of the pipe in the three excavations referred to as bell holes. The line was holding air pressure at 120 psi and no air bubbling was observed in any of the pits.

Figure 22 indicates the locations of the excavations. Bell hole 1 was located 15 feet from the wall of the terminal building. The excavation was 4 feet by 4 feet square. It was 11 feet from an underground electrical line running parallel to the building about 4 feet from the wall. The excavation was 15 feet from an underground electrical line perpendicular to the building and 6 feet from another underground electrical line parallel to the building, about 21 feet out. The distance from the top of the tarmac to the top of the pipe was measured at 5 feet, 4½ inches. The distance was 3 feet, 8 inches from the top of the tarmac to the top of the stained backfill. Figure 23 is a picture of the backfill in bell hole 1. The backfill was very hard and compacted for the first 20 inches below the 4-inch tarmac, then was finer and more porous below that. The demarcation between the two types of backfill can be clearly seen in Figure 23. This difference in backfill may be relevant in interpreting the results from some of the vendor location results.

Bell hole 2 was located 40 feet out from the edge of bell hole 1. It was also 4 feet square. The distance from the top of the tarmac to the top of the pipe was 5 feet, 1 inch. It was 40 feet from the edge of bell hole 2 to the edge of the high point pit. The pipe makes a right angle in the high point pit. The excavation next to valve pit 4 (denoted bell hole 3) was begun 6 feet from the edge of the

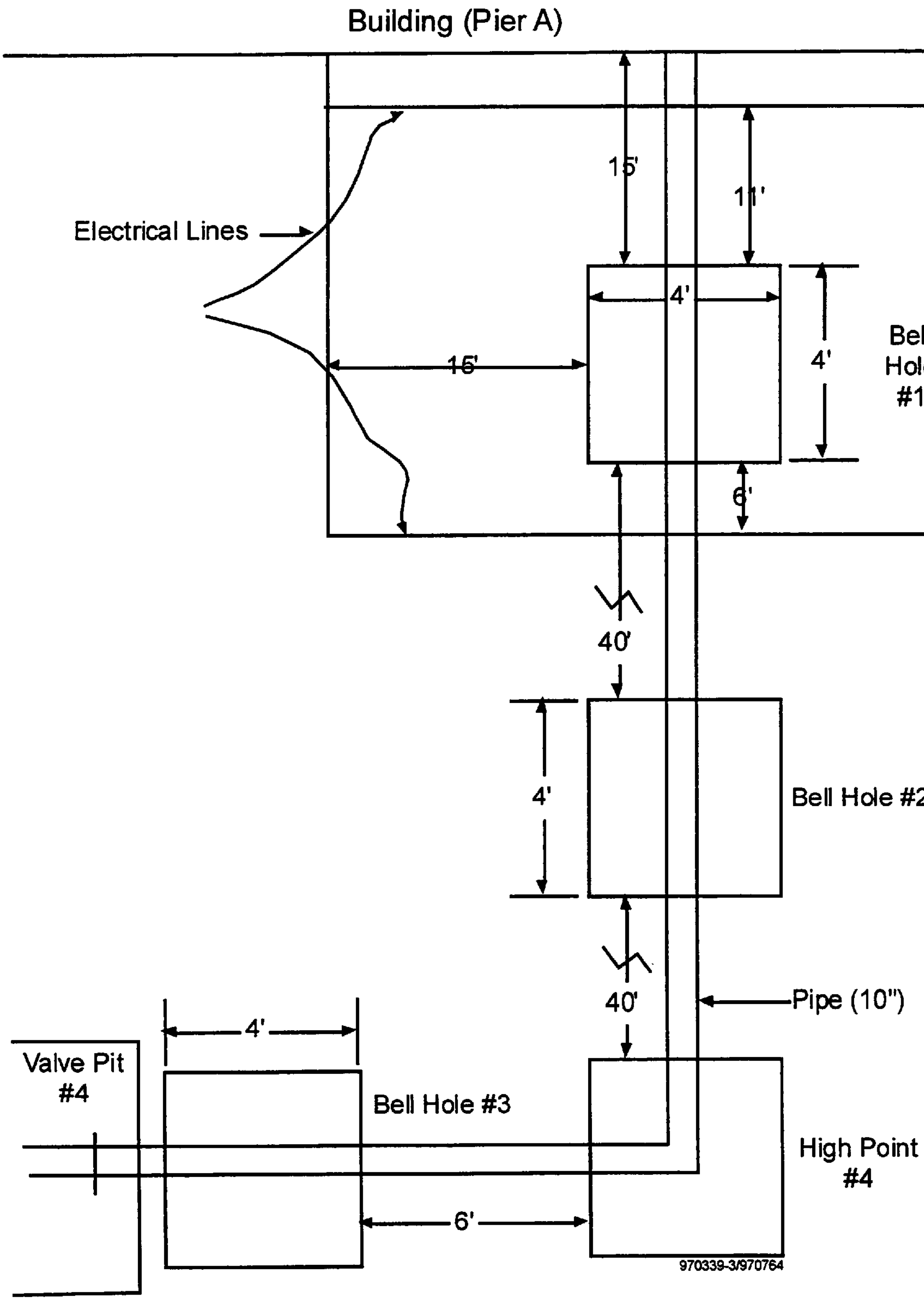


Figure 22. Location of Excavations

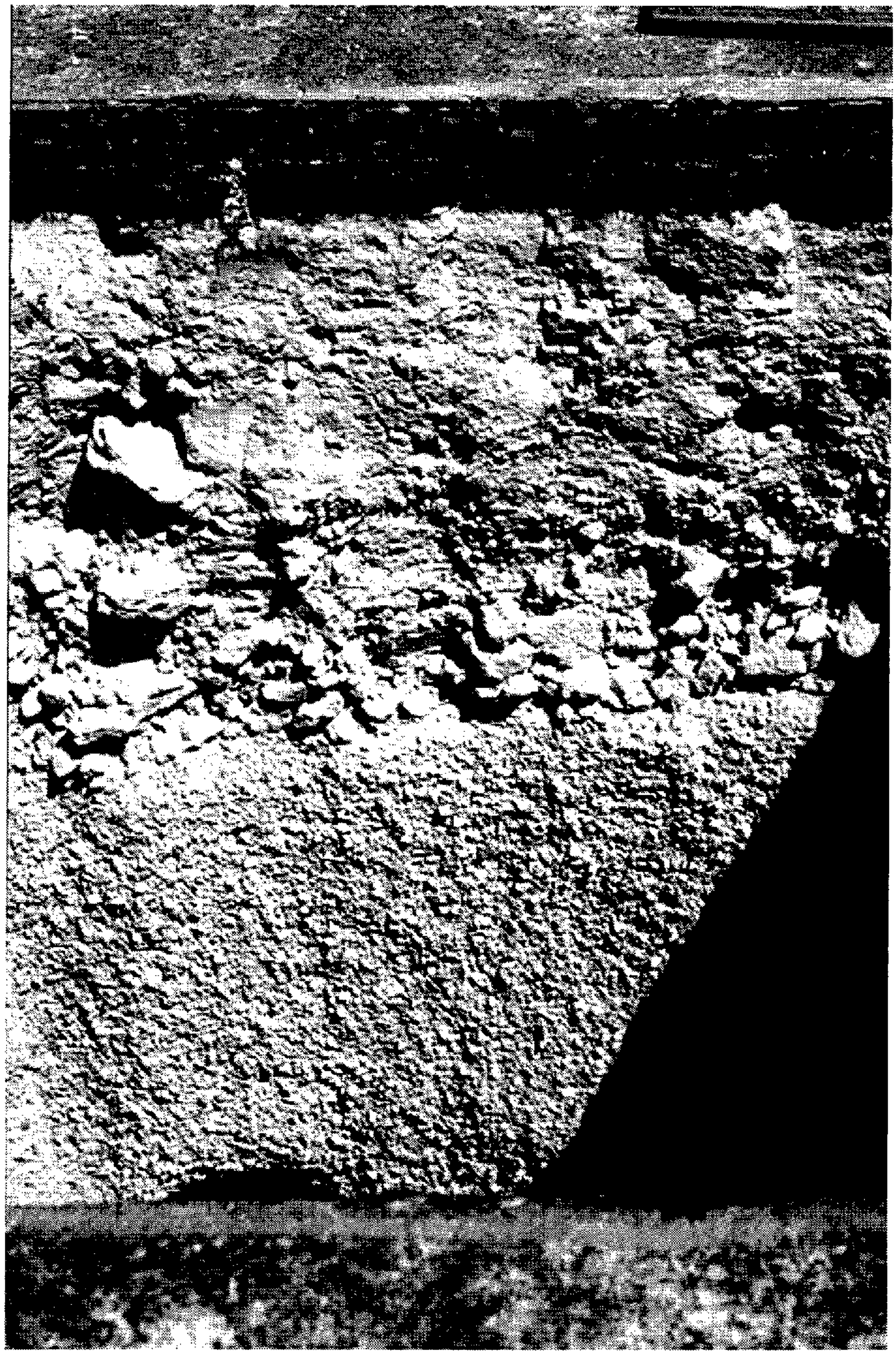


Figure 21. Fill Material in Bell Hole 1

high point pit. The excavation on the outside of valve pit 4 was also 4 feet square. Thus, there was a distance of 10 feet from the outer wall of valve pit 4 to the wall of the pit around the high point.

After low tide, the water and fuel mixture was pumped out of valve pit 4 beginning around 3:50 p.m. The water and product mixture was removed to allow people to enter the valve pit to do the inspection. The pressure was released from the line and the clamp was removed so that the pipe could be observed.

The valve pit area was dark and hot and it was difficult to see. The valve pit sleeve had been slid toward the excavation side since it could not be removed over the flange of the pipe in the valve pit. There was very limited access to the damaged area of the pipe as it was located where the pipe went through the valve pit wall. There was not enough room to position the cameras to obtain good photographs of the pitting. However, photographs were attempted, both directly and with a mirror. The best possible photographs were obtained, given the limitations caused by lack of space and lack of light.

A single perforation was found on the bottom of the pipe at the location where the valve pit seal went around the pipe. The perforation was about 1/8-inch in diameter and was located at the bottom of a pit in the pipe wall about 5/8 inch in diameter. There was no weld close to the pit nor any sign of mechanical damage. There was a circumferential line of pits with the perforation at the bottom of the pipe and the other pits extending about a quarter of the way around the circumference of the pipe. This line of pits was 4 inches into the sleeve from the inner wall of valve pit 4 and corresponded with the end of the link seal. Considering a clock for reference, the perforation was located at 6 o'clock. Pitting extended to about 4:30 o'clock in one direction and to about 7:30 o'clock in the other direction. The pit with the perforation measured 0.16 inch deep from the surface of the pipe to the edge of the perforation. The largest of the other pits was at 7:00 o'clock and measured 0.11 inch deep. These pit depths should be considered minimums because the lack of space made it difficult to position the pit gauge properly under the pipe. The diameters of the other pits ranged from 3/16 to 3/8 inch.

Figure 24 is a sketch of the location of the perforation and the other pits along the bottom of the pipe. Figure 25 is a photograph of the pit with the perforation. The photograph was taken in a mirror, which is the square approximately in the middle of the picture. A stream of liquid can be seen coming from the perforation. The reflection of this liquid stream can be seen in the mirror image of the pit, in the square approximately in the center of the picture. The liquid stream itself can be seen as a horizontal line adjacent to the square mirror.

The crew stated that the line of pits corresponded to the edge of the link seal that had been between the sleeve and the pipe. The rubber/plastic/metal bolted seal was found in the bottom of the valve pit and inspected. Figure 26 is a picture of this link seal after it was removed. Figure 27 is a copy of the design drawing of the pipe and sleeve installation compared to a drawing of the installation as found by actual inspection. The location of the pitting is indicated on the drawing from the inspection.

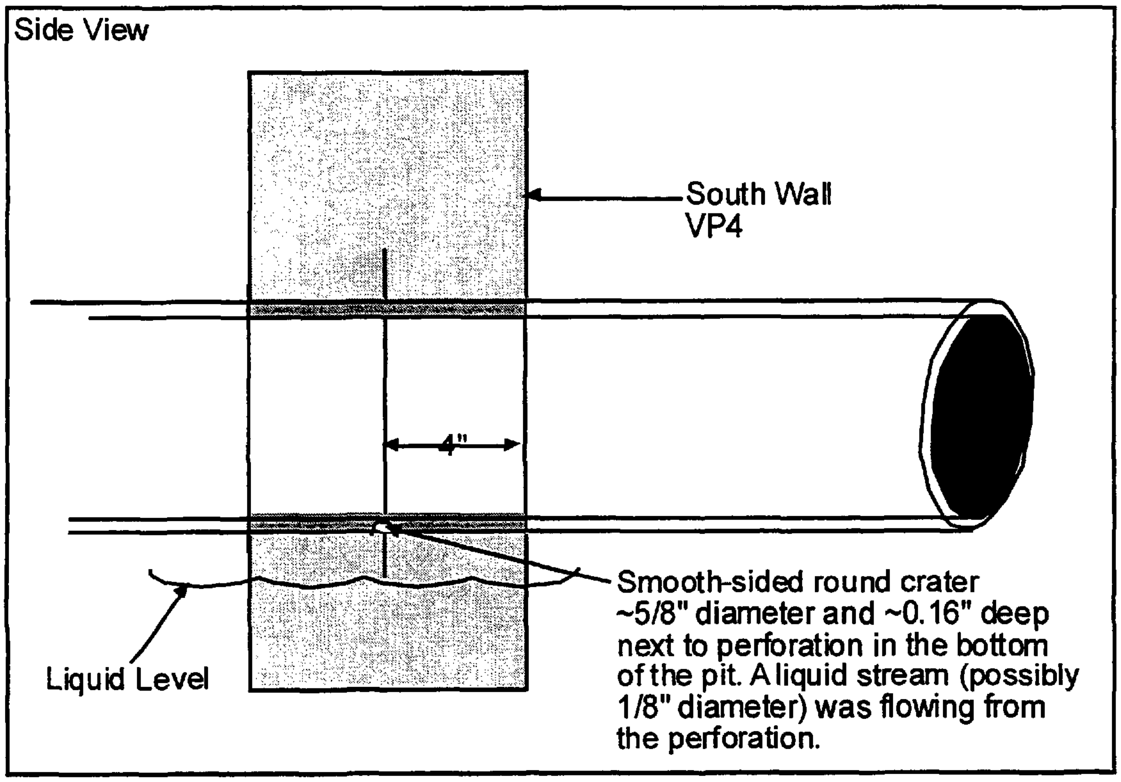
The pitting was isolated to the one circumferential area. From its location, the pitting appears to be related to the valve pit seal. Apparently this was the only perforation in the pipe, as evidenced by the line holding pressure of 120 psi for several days when the repair with the clamp was effected. The rest of the pipe that was visible appeared to be in good shape with only this isolated damage.

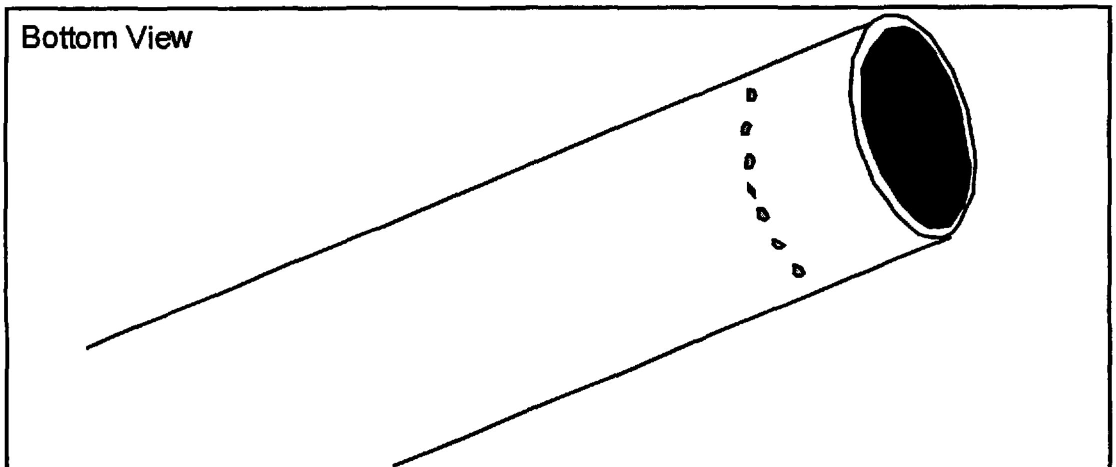
COMPARISON TO LEAK LOCATION ESTIMATES BY VENDORS

Two methods, the tracer method and the acoustical emission method, have techniques to pinpoint the location of the leak as well as to identify the presence of a leak. Each of these vendors provided an estimate of leak location. These location estimates are compared to the inspection results below.

Tracer Method Estimates

The tracer method identified three areas as possibly having leaks. These are the three locations where the bell holes were dug. The vendor identified the location next to the terminal (bell hole 1) as the location of the leak. The vendor stated in its report that there might be leaks at the other two locations (bell holes 2 and 3) as well, but did not identify those locations as definite leaks because to do so might lead to a false alarm error at those locations.





The deep pit with the perforation was at the 6 o'clock (bottom) position and a line of pits in a circumferential pattern was evident. The second largest pit was at the ~7 o'clock position and was measured to be 0.11" deep. The diameter of the secondary pits was judged to be 3/16" to 3/8".

Crew stated that circumferential line pattern corresponds to edge of insulating seal that had been between the sleeve and the pipe.

Figure 24. Location of Pits

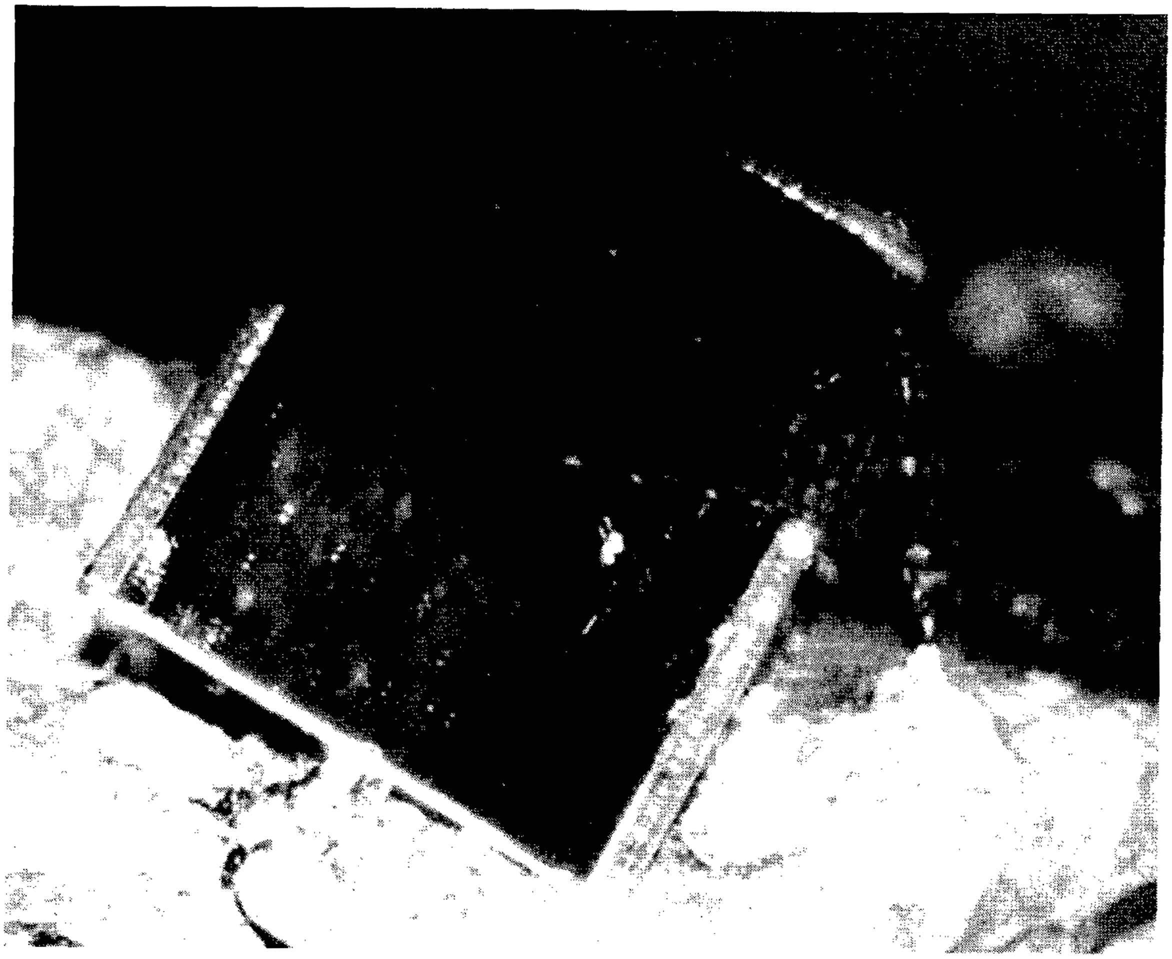


Figure 21. Perforation of Pipe

Figure 21. Link Seal after Removal

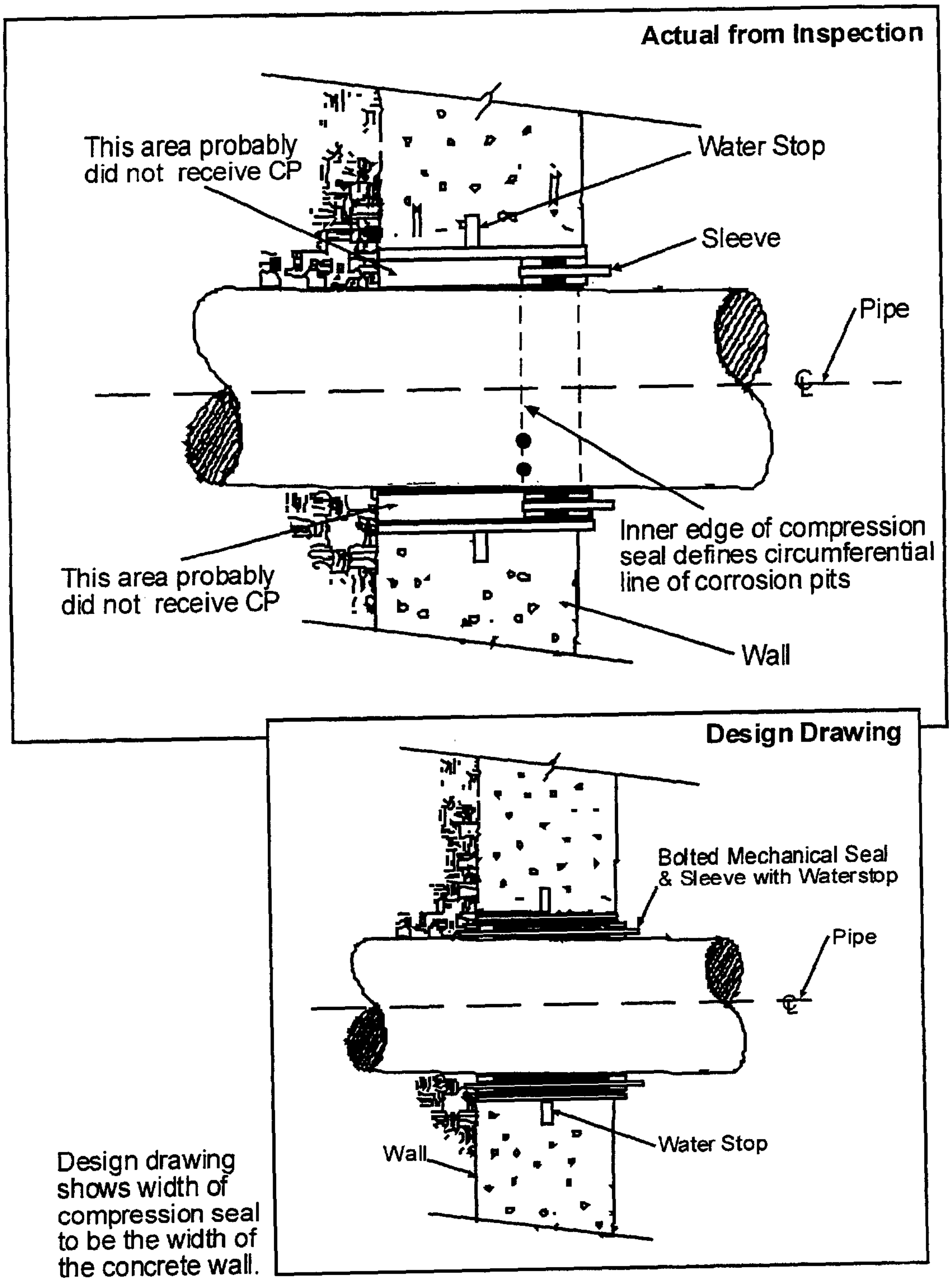


Figure 27. Detail of Pipe and Sleeve

The location where the leak was found is consistent with one area identified as suspicious by the tracer vendor. However, it is not the area identified by that vendor as the primary location of the leak. Bell hole 3, adjacent to valve pit 4 is the leak location that was confirmed as the source by this inspection. Thus, the tracer results located the leak in an area identified as a possible leak but also identified two other areas of potential leaks that were not confirmed.

The perforation that was found was rather large, about 1/8 inch in diameter. It was also located in an open area between the pipe and wall sleeve. This allows for the possibility that the tracer dispersed very rapidly along the pipe. The hardness of the upper portion of the backfill resulted in the sampling probes being installed to only about 14 inches—not quite as deep as usual. The hardness and compaction of the upper part of the backfill may have led to the rapid dispersion of the tracer along the pipe, trapped between the liquid level below and the compacted backfill layer above. The areas of high tracer concentration that were found at the sampling points might correspond to areas of the upper backfill that had a crack or a porous area, allowing the tracer to reach the surface under the pavement and intersect a probe. Sampling the probes a shorter time after inoculating the line with tracer might have identified the location better. Repeated sampling at different times after inoculating the line might have showed this dispersion pattern.

Acoustic Emission Method

The acoustic emission vendor estimated the location of the leak between hydrant pits 29 and 30. This location was at the far end of the line from valve pit 4. Since the line held pressure at 120 psi for several days after the installation of a repair clamp on the identified perforation, it was concluded that there was no other perforation or leak. Thus, the location estimated by the acoustic method was not confirmed.

Further, the acoustic method missed the location of the perforation. The vendor was able to test at valve pit 4 and at high point 4, quite close to the perforation that was found. MRI's field notes from the testing state: "No noise [observed] at HP4; no test conducted @ HP5 in VP-5." Thus, the notes indicate that a test was conducted at high point 4, approximately 10 to 12 feet from the leak. The vendor did not test at valve pit 4, through its own choice. Thus, the test at high point 4 did not find the leak.

The perforation in the pipe was located where the pipe was in a sleeve. Consequently, flow through the perforation would not interact immediately with soil particles, since the flow was into the area between the pipe and sleeve and only reached the soil after flowing a foot or so through the sleeve. The velocity of the liquid would be much reduced by the time it reached the soil or backfill material. Moreover, the sleeve and the backfill were saturated with liquid, a combination of the hydrocarbon product and the groundwater. When the area adjacent to a pipe perforation becomes saturated with liquid, this attenuates the acoustic signal. This attenuation may be the reason that the leak at this location was not detected by the acoustic method.

However, the conclusion from the field test is that the acoustic method did not detect the leak nor correctly locate the leak in the pipe. Its location between hydrants 29 and 30 was a false alarm in terms of location. It is questionable whether the method would have identified the real leak in the absence of information that the pipe had a problem. While the actual leak was not in a location where the pipe was directly buried in backfill, it was a real leak and an operational problem. This suggests that the acoustic method needs to be able to find such leaks to be practical and reliable.

Section 6
RESULTS/FINDINGS

This section summarizes the results in the previous sections and presents conclusions and recommendations.

Each of the four technologies investigated has advantages and disadvantages. All appear capable of detecting leaks under some conditions; however, none of the technologies is a panacea that can be used in all situations. Combinations of ambient and site conditions exist that could cause any of the technologies to make an error of either a false alarm or missing an existing leak. No one technology appears best for all applications. In fact, users may want to consider a combination of technologies. One technology might be selected and used periodically as a screening to check that the line has not developed a problem since the last investigation. Another technology might be used if a problem with the line is suspected, to define the problem or pinpoint its location.

The volumetric approach is designed to provide a test of a line or section of a line at a specified point in time. It currently requires skilled operators, and the line must be out of service during the testing. It provides an estimated leak rate with good accuracy for small to moderate leak sizes. The larger version of the system should provide testing for larger leaks. The size of the leak that it can reliably detect is related to the size of the line, increasing as the volume of the line increases. The only provision for locating a leak is to divide the line into separate sections and test each separately, thus isolating the leak to a particular section of the line between two valves or blanks. The volumetric test method demonstrated the capacity to detect and measure leaks as small as about 0.2 gph on the smaller lines to as small as about 0.6 gph on the largest line tested. The volumetric system is designed for rapid mobilization to a test site and for use as a point-in-time test. It has the potential to be permanently installed at a site and used for periodic testing, but such installation would require that it be permanently connected to several parts of a large line system and that these sections be isolated for testing. The volumetric method requires that the line section to be tested be isolated with tight valves of blind flanges and tested in a static condition. The system checks the bulk modulus of the line and estimates the amount of trapped vapor. In the tests observed, the operators required that the lines be nearly vapor-free. Once set up, a test requires 2 hours of data collection. There are two different sized systems designed for different sizes of lines. The system correctly identified an operational leak and gave an estimate of its rate. It also correctly identified a leak at a valve and estimated its rate. When tested, the volumetric system experienced some weather-related problems with rain.

The pressure decay approach is designed for permanent installation and automatic operation to provide periodic testing. As part of its installation, it requires calibration on the specific line or line sections intended for its use. The system requires that the line or section be out of service during the testing. After calibration upon installation, the out-of-service time would be 45 minutes to one hour for a test. In the permanently installed mode, it requires double block and bleed valves, and for automatic operation, these must be capable of being closed and opened automatically. In addition, when permanently installed, the system uses the line's pumps to pressurize the portion of the line being tested. It provides an estimated leak rate with good accuracy and is designed for pipeline sections of about 50 m^3 (13,000 gallons) or more. The size of the leak that it can detect is related to the line volume in a linear fashion. The system uses a threshold of 0.004% of the line's volume as the volume per hour to identify a leak. Its only way of locating a leak is to test sections of a line separately, thus isolating the leak to a specific portion of the line between two valves.

The pressure decay system is not intended for use as a one time test. It is used in that mode only as a demonstration. It requires a calibration on a tight line and on a line with a known leak rate. This is a drawback for using it on a line with unknown condition or a suspected leak. When tested on a line with an unknown leak, the system could not be calibrated. After a day of testing, the vendor suspected a leak in the line and performed an overnight pressure decay test to confirm the leak. A leak was subsequently found at a blind flange. The system also correctly found a large operational leak. The system requires that the line be out of service for calibration and testing and that the line be nearly air-free. When tested on lines after it was calibrated, it demonstrated the potential to find leaks as small as about 0.2 gph on the small line. However, the system uses a threshold that is equivalent to 0.004% of the line volume per hour, so this represents the smallest leak that it would identify in practice. These results suggest that the threshold could be lowered somewhat without increasing the probability of a false alarm excessively. The system was not adversely affected by rain. However, it does require support equipment from the site to pressurize the lines.

The tracer method incorporates a validation test with a leak simulation to demonstrate the sensitivity in the specific location. The leak simulation is based on detecting a leak rate of as small as 0.05 gph over about 2 days. The key factor is the amount of tracer released and its dispersion through the soil for interception at soil gas probes. The tracer method is capable of locating a leak to within a foot or two. A requirement of the method is that the tracer must be added to the line. The line can be emptied and tracer added in air, or tracer can be added to the product. This may not pose a problem in some applications, but in others (e.g., aircraft fuel) its presence is not yet accepted by the aviation authorities. The line can be tested empty or full, and it can be tested in service or out of service, depending on the application. In-service testing requires that the line remain under pressure with tracer-inoculated product for 2 to 3 days.

The acoustic emissions technology is the fastest way to test a large amount of pipe, provided that there is access to the pipe about every 50 feet. The sensor or waveguide is placed in contact with the pipe, and the acoustic signal monitored briefly at each location. This takes about 5 minutes per location. However, obtaining access to the pipe can be a drawback. For underground pipes, a hole must be drilled to the pipe and a waveguide inserted and placed in contact with the pipe. Any coating would interfere with acoustical transmissions and is generally removed. The acoustic technology can locate a leak by noting the points on the pipe where an acoustic signal indicative of a leak was above background. This is judged by comparing the acoustic signal at different portions of the pipe, some of which are assumed to be tight and provide a baseline. The size of the leak that is detectable depends on the conditions in the soil around the pipe, the geometry of a hole, the size of the leak, and the distance from the probe.

The acoustic emissions technology incorrectly estimated the location of the large operational leak. Further, it failed to detect the leak when tested about 20 feet from the leak that was later found by excavation.

For ease of comparison, Table ES-1 summarizes the characteristics of the technologies tested. The entries in the table are based on the observations and tests conducted during this project. The results and estimated sensitivities are based on these field tests conducted at a single site under existing ambient and site conditions. Only a single vendor of each technology was involved; other vendors might have different results. Testing included leaking lines, tight line conditions, and simulated leaks. However, there was no experimental control allowing systematic variation of other important factors such as temperature gradients or soil conditions that might affect the performance of these technologies. In some cases, the technology was operated in a nonroutine mode. For example, the pressure decay technology was operated in a one-time test mode with limited calibration tests instead of its normal permanently installed mode. Similarly, the acoustic emission technology used available access to the pipe at hydrants rather than special pipe access through holes drilled at a set 50 foot spacing.

Both the acoustic emissions technology and the tracer technology estimated the location of the leak. However, these two technologies disagreed on the location of the leak, placing the estimated location at approximately opposite ends of the line section. The tracer location was correct.

The testing conducted under this project was of limited scope. It provided range-finding results in terms of the performance of the four technologies investigated. Future work could provide more definitive estimates of the performance through a more complete series of tests. Such tests could include experimental variation of test conditions appropriate to each technology, such as variations in temperature, amount of trapped air, and bulk modulus for the volumetric and pressure decay technologies. Variations in soil conditions, particle size, moisture, and permeability would be important considerations for both tracer and acoustic technologies. The characteristics of the fluid, pipe material, and hole size and geometry, as well as distance from the sensor, could affect the performance of the acoustic emission technology and should be investigated further. A larger number of tests with additional simulated leak rates and different ambient and site conditions would provide more definitive information on the operating envelope for the different technologies.

Other technologies could be considered for future work. Some of these are currently in use, and others may still be developed. One additional technology is based on monitoring the flow at each end of the pipe. Another monitors flow and pressure and detects changes inconsistent in the usual relationship. One question with these technologies is whether they are restricted to new installations or how difficult it would be to retrofit them to existing installations. Another question is the sensitivity available with these technologies. Still another possibility is based on inventory reconciliation. These additional techniques could be tested to see what magnitude of leak they could detect in what time period.

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Appendix A

DATA REPORT FROM VISTA RESEARCH

Test Results
API Demonstration Test Program

Line #1: From the fuel terminal to Valve Pit 4. 14,300 gallons.

Test Threshold:	0.3 gal/h
Minimum Leak rate detectable with a $P_D > 95\%$ and a $P_{FA} < 5\%$:	0.6 gal/h

The following tests were conducted on Line #1:

Date	Time	Test	Results	
11/12	0910	Measurement of line compressibility and volume of trapped air	B/V = 130 ml/psi	1810 ml air at 0 psi
11/12	1030	LT-100 Test	Pass	0.17 gal/h (1)
11/12	1333	LT-100 Test	Fail	0.70 gal/h
11/12	1547	LT-100 Test	Fail	0.62 gal/h
11/12	1750	LT-100 Test	Fail	0.31 gal/h

(1) A positive number indicates outflow from the line under test.

Line #2: From Valve Pit 4 to Valve Pit 5 along the international terminal. 2,900 gallons.

Test Threshold:	0.06 gal/h
Minimum Leak rate detectable with a $P_D > 95\%$ and a $P_{FA} < 5\%$:	0.1 gal/h

The following tests were conducted on Line #2:

Date	Time	Test	Results	
11/11	1934	Measurement of line compressibility and volume of trapped air	B/V = 56 ml/psi	271 ml air at 0 psi
11/08	1647	LT-100 Test - 50 psi	Fail	0.18 gal/h
11/08	1747	LT-100 Test - 50 psi	Fail	0.16 gal/h
11/08	1850	LT-100 Test - 50 psi	Fail	0.22 gal/h
11/08	1950	LT-100 Test - 50 psi	Fail	0.18 gal/h
11/09	1217	LT-100 Test - 140 psi	Fail	0.45 gal/h
11/10	2000	LT-100 Test - 50 psi	Fail	0.29 gal/h
11/11	1730	LT-100 Test - 50 psi	No Test	Operator Error

Two leaks were discovered on Line #2. The first leak was observed at the flange at Valve Pit 5. This leak was repaired. A second leak was measured at one of the pneumatic hydrant valves (Hydrant Pit #25) which had a small weep that would allow the section between the pneumatic valve and the hydrant valve to slowly pressurize and/or depressurize during testing. This resulted in an apparent line leak of 0.1 to 0.2 gal/h which persisted for approximately 30 minutes following a pressure change. After both of these sources of leakage were addressed, tests conducted by Vista Research for indicated that the line was tight.

Line #3: From Valve Pit 3 to Valve Pit 4. 1,630 gallons.

Test Threshold:	0.06 gal/h
Minimum Leak rate detectable with a $P_D > 95\%$ and a $P_{FA} < 5\%$:	0.1 gal/h

The following tests were conducted on Line #3:

Date	Time	Test	Results	
11/11	1634	Measurement of line compressibility and volume of trapped air	B/V = 45 ml/psi	18 ml air at 0 psi
11/06	1951	LT-100 Test - 50 psi	Pass	-0.03 gal/h
11/07	1009	LT-100 Test - 50 psi	Pass	0.02 gal/h
11/07	1540	LT-100 Test - 50 psi	Fail	1.11 gal/h (2)
11/07	1751	LT-100 Test - 50 psi	Fail	0.20 gal/h (3)
11/07	1955	LT-100 Test - 50 psi	Fail	0.56 gal/h
11/11	1432	LT-100 Test - 50 psi	Pass	0.02 gal/h

(2) Induced leak rate is too large to accurately quantify rate. Pressure drop exceeded acceptable threshold indicating that measured leak rate understates actual.
(3) The ball valve on the leak maker was opened during the low pressure measurement period. Measurement period duration reduced by 25% to attempt to minimize the effect of this on the test result.

Line #4: From Valve Pit 4 to Valve Pit 5 along east side of international terminal. 3,700 gallons.

Test Threshold:	0.08 gal/h
Minimum Leak rate detectable with a $P_D > 95\%$ and a $P_{FA} < 5\%$:	0.15 gal/h

The following tests were conducted on Line #4:

Date	Time	Test	Results	
11/07	0948	HT-100 - 6 min. at 150 psi	N/A	230 gal/h (4)
11/07	1247	HT-100 - 30 min. at 50 psi	N/A	110 gal/h (4)

(4) Due to the magnitude of the leak in this line, the full 2-hr test could not be performed. The above results are estimates of the leak rate based on the available data.

Appendix
Vista's Volumetric Pipeline Leak Detection Technology

1 Description of the LT-100 and the HT-100

Vista Research has developed and operationally demonstrated an innovative volumetric technology for the detection of small leaks in the underground piping found at bulk fuel storage facilities, hydrant fuel distribution systems, and marine terminal transfer lines. The two leak detection systems based on this technology, the LT-100 and the HT-100, achieve a high level of performance against small leaks because of a novel method of temperature compensation that is achieved as part of the test. The compensation is accomplished, moreover, without the need for a *pre-test waiting period* to allow for temperature changes in the fuel to dissipate, and without the need to measure temperature anywhere in the line. A leak detection test can be completed in 2 h. High reliability is assured, because the *accuracy of the temperature compensation* is also measured during each test. Thus, the technology overcomes the major operational and performance problems associated with conventional pressure and volumetric tests. If a leak is detected, both systems give a direct measurement of the flow rate of the leak in gallons per hour, the quantity of regulatory interest.

Both the LT-100 and the HT-100 can be permanently installed for online monitoring or can be moved from line to line to conduct tightness tests. They can be integrated into the design of new lines or retrofitted to existing ones. Retrofitting is easy because these systems require only a single hose connection to the line, at any convenient location along the line. No online calibration of the equipment is necessary. While the LT-100 and HT-100 can be used to measure the onset of a leak, their principal use is in the testing of lines whose integrity is unknown. (Determining the onset of a leak is accomplished with a difference measurement approach, and determining line integrity is accomplished with the absolute measurement approach described below).

A static leak detection test is performed with the existing fuel in the line. The line is first isolated from the tank(s) and other lines with which it is associated. During a test the LT-100/HT-100 measures the volume of fuel in the line at two different pressures, each of which is maintained constant while the measurement is taken. Because the LT-100 and HT-100 are volumetric systems, a leak detection test can be conducted even with surge suppressors and/or trapped vapor in the line. Both systems are capable of measuring the volume of trapped vapor; although this is not required as part of the test, it is another unique feature of the technology and a useful measurement tool during normal pipeline operations (for example, during line packing).

The technology has been successfully demonstrated numerous times at operational facilities. The LT-100 was demonstrated on four occasions as part of the Naval Environmental Leadership Program (NELP) at the Naval Air Station, North Island, Coronado, California [1-4]. The HT-100 was demonstrated on a 2-mile hydrant fuel distribution line at the Miami International Airport [2,5], on several high-pressure, oil-filled underground cable transmission lines 4 to 8 miles in length owned/operated by Public Service Electric & Gas (New Jersey) and Boston Edison [6], and on bulk underground piping at a variety of military and commercial aboveground storage tank (AST) facilities [7]. Several more demonstrations of the HT-100 will be conducted on airport hydrant lines during the next two months, and the system has been included in the design of at least one major metropolitan airport. In addition to these demonstrations, both the LT-100 and HT-100 are being used to tightness test lines for military and commercial clients. Finally, both the LT-100 and HT-100 were recently evaluated by the American Petroleum Institute (API) in controlled operational field tests at the international airport in

Since many of the bulk lines at military fuel farms are regulated as part of the underground storage tank (UST) regulations, a third-party evaluation of the LT-100 was performed by Ken Wilcox Associates. The performance of the LT-100 was determined experimentally and was reported in accordance with the procedures for evaluating leak detection methods set forth in ASTM Standard Practice E 1596-93 [8] and EPA Standard Test Procedure EPA/530/UST-90/010 [9]. The LT-100 meets the regulatory performance standards established by the EPA for both tightness tests and monthly monitoring tests (i.e., 0.1 gal/h and 0.2 gal/h, respectively, with a $P_D \geq 95\%$ and a $P_{FA} \leq 5\%$) on pressurized lines associated with underground storage tanks [10]. When the LT-100 is used as a monthly monitoring system, the probability of false alarm is much less than 1%. This third-party evaluation has been reviewed and approved by the National Review Board.

For up-to-date information about state and local regulatory certifications for both systems, please contact Vista Research directly. At the present time, the LT-100 is certified in California by the State Western Resources Control Board (SWRCB) for testing lines associated with the bulk fuel UST's. Both the LT-100 and HT-100 systems are approved by the Florida Department of Environmental Protection (FDEP) as satisfying the annual testing requirement for bulk storage and airport hydrant fueling system piping. Both systems are also acceptable substitutes for the pressure tests required by the California State Fire Marshal and the California State Lands Commission.

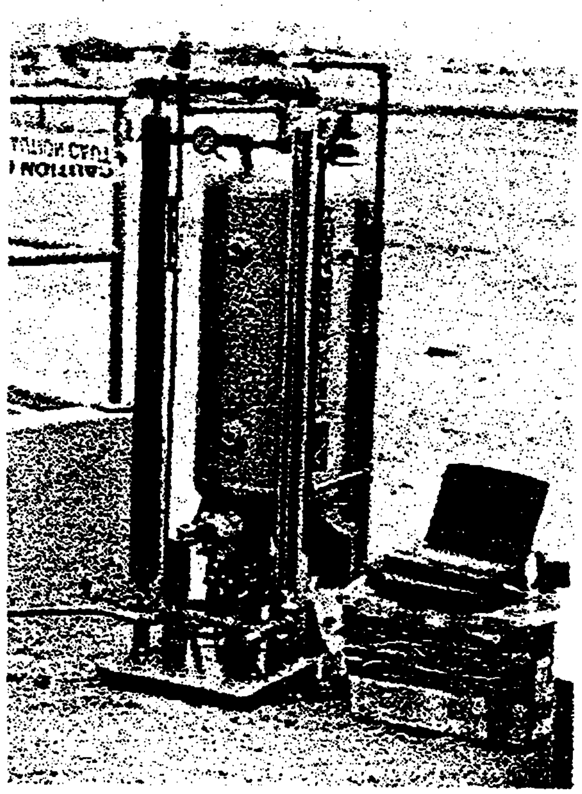

Figure 1. The "Vista" LT-100, photographed at NAS North Island.

LT-100. The LT-100, which is shown in Figure 1, tests underground bulk piping used to transfer product into and out of underground or aboveground fuel storage tanks. The LT-100 is a totally self-contained leak detection system and requires no special site preparation or utilities. A battery-operated computer notebook is used to power the sensors and the data acquisition system. Since the test data can be collected either manually or with the notebook computer, the LT-100 is easily used at remote sites or parts of the fuel farm where electrical power is not available or safety considerations preclude the use of electrical outlets. The LT-100 is intrinsically safe, incorporating a standard ASTM pressure vessel with fire-proof valves and fittings; no special safety precautions need be taken when it is being operated.

The *LT-100 volumetric sensor unit* looks very similar to a surge suppressor and consists of (1) a 16-in.-diameter pressure cylinder, (2) a 2-1/2-in.-diameter measurement cylinder, (3) a means of measuring level changes in the measurement cylinder both visually (with a sight glass) and electronically (with a differential pressure sensor), and (4) three valves that are opened or closed to operate the unit, connect/isolate the unit from the line, and adjust the line pressure. The cylinders are approximately 48 in. in height. The system includes a pressure relief valve and a check valve to ensure safe operation of the device. Very small changes in volume can be easily measured. For example, a change of 1/16-in. in the level of liquid in the measurement cylinder (and sight glass) is equal to a change of 0.0012 gal (4.5 ml) in the volume of liquid in the line.

The *LT-100 data acquisition unit* makes a permanent record of all test operations. In addition to reporting the test results, the electronic record is used for quality control, quality assurance, and test auditing.

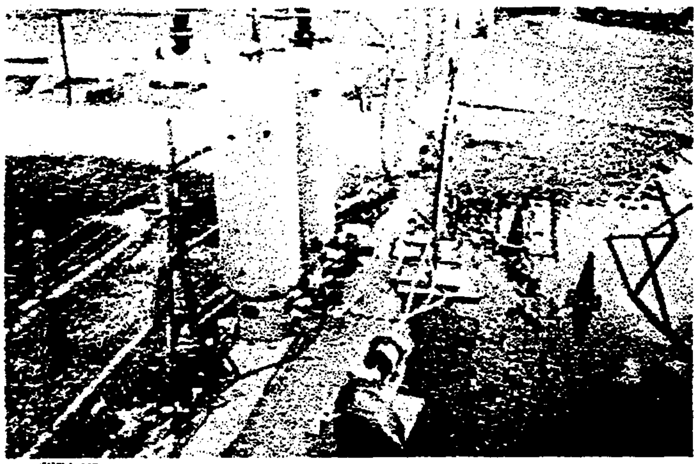

Figure 2. Photograph of the HT-100, an implementation of the "Vista" technology designed for hydrant fuel distribution systems.

HT-100. The HT-100, which is shown in Figure 2, is used to test long, large-diameter underground lines found in military hydrant fuel distribution systems, marine terminal transfer lines, feeder lines, and very long bulk fuel farm piping. It is typically used to test lines up to several miles in length. The HT-100 is a fully automatic, computer-controlled system. This system can also be fully integrated into both existing and new aviation fueling lines and SCADA systems.

The HT-100 consists of two storage reservoirs, two differential pressure sensors (one for each reservoir), and a *pressure management system* comprised of the pump, the pressure regulating valves, the pressure gauge, the solenoid valves, and a computer and electronics control unit. The storage reservoirs are used for changing and/or maintaining pressure during a leak detection test. These containers are 24 in. in diameter and over 60 in. in height. Unlike the LT-100, these containers are not pressurized and serve only to store sufficient product to complete a test. (When the HT-100 is used on smaller lines or when it is integrated directly in to the fueling system, one of the storage containers can be eliminated and the second can be made smaller.) The HT-100 is connected to the line by means of a valve; when open, this valve allows the exchange of fuel between one of the reservoirs (the measurement cylinder) and the line. The volume of fuel that must be removed from or added to the measurement cylinder in order to maintain a constant pressure is measured by a differential pressure sensor. The other reservoir stores the excess fuel used in attaining the two specified pressures. Pressure in the line is increased, decreased or maintained constant by the pressure management system.

1.1 Test Methodology

Vista's technology uses a novel data collection and analysis algorithm to compensate for changes in the temperature of the product. The systems based on this technology measure volume changes in the pipeline at two different pressures, each one constant. This approach makes use of the fact that (1) the leak rate changes depend on line pressure and (2) the rate of thermally induced volume change is not affected by line pressure.

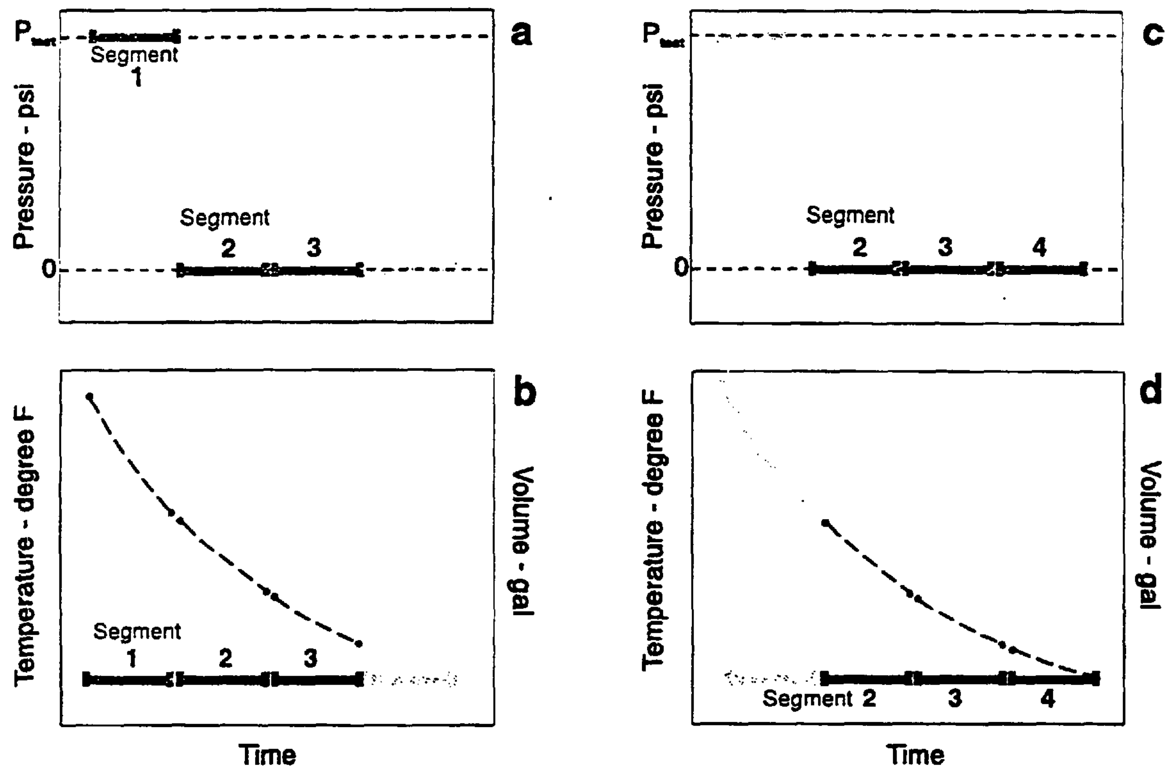

Figure 3. *Testing methodology.* Plots **a** and **b** illustrate how the test result is obtained, and the plots **c** and **d** illustrate how the test error is obtained. **A** and **b** show the pressure at which the volume measurements are made, while **c** and **d** illustrate the volume changes induced by the temperature changes.

Typically the two pressures selected for a test are the normal operating pressure of the line ("test pressure") and, in most cases, atmospheric pressure (0 psig). However, any two pressures can be used. The order of the two pressures is not critical. The LT-100 (as well as the HT-100) generates both a *test result*, which is an estimate of the leak expressed as a rate in gallons per hour, and a *test error*, which is an estimate of the accuracy of the temperature compensation achieved during the test. There are a number of ways to analyze the "volume" data used in computing the test result and the test error. One way, which is illustrated in Figure 3, to divide the 2-h test into a minimum of three equally spaced segments, all of the same duration, such that one of the three segments of data is taken at a different pressure than the other two. During each segment, changes in the volume of the liquid in the line are measured.

The test result, TR, which is equal to the leak rate, if one exists, is estimated by appropriately averaging the data collected during the first three segments in Figure 4 and is computed by

$$TR = [(V_1 + V_3)*0.5 - V_2]/\Delta t$$

where V_i is the measured volume change during each segment of duration Δt; the subscript i denotes the segment number. That there is a nonzero estimated test result, TR, does not mean that the piping is not tight. A nonzero flow rate may be produced, for example, by residual fluctuations in temperature remaining after compensation.

If the pressure during three of the segments is the same, then an estimate of the error in the temperature compensation can also be made; this is the test error. The test error, TE, is estimated by appropriately averaging the data from the last three segments in Figure 4 and is computed by

$$TE = [(V_2 + V_4)*0.5 - V_3]/\Delta t$$

1.2 System Attributes

Several attributes of the LT-100 and the HT-100 are summarized below.

- The output of a leak detection test (i.e., the *test result*) is easy to interpret, because it is a direct measurement of the leak rate in gallons per hour at the test pressure, and is the quantity of regulatory and operational interest.
- The LT-100 and HT-100 compensate for the thermal expansion or contraction of the fuel in the line during a test. This means that accurate tests can be conducted without long, pre-test waiting periods to assure thermal stabilization.
- The output of a leak detection test includes a measure of the "goodness" of that test (i.e., the *test error*) that establishes the credibility of each test result and minimizes the chance of a false alarm or a missed detection. The test error is a direct estimate of the accuracy of temperature compensation achieved during the test.
- The compressibility characteristics of the pipeline system do not need to be known in order to conduct a test or to interpret the results of a test; thus, the LT-100 and HT-100 can be used to test existing lines (for which this information may not be available) as well as newly constructed ones (for which this information can be obtained with measurements).
- The HT-100 can be used to test pipelines containing surge suppressors, which are commonly found in many hydrant fuel distribution systems.

- Both systems can be used to conduct a test even when vapor is trapped in the line.

There are a number of additional measurements that can be easily made with the LT-100 and HT-100 that may be of interest either as part of the test or as part of routine operational maintenance.

- The LT-100 and HT-100 can be used to measure the volume of trapped vapor in the line.
- Both systems can be used to measure the average temperature and the average thermally induced volume changes that occur during a test.
- Both systems can be used to measure the compressibility of the line, with (and without) the effects of trapped vapor included in the compressibility estimate.

1.3 For More Information

Vista Research offers a wide range of LT-100/HT-100 products and services to meet your pipeline leak detection and leak location needs. Vista will test lines under a service contract or will sell stand-alone systems. Vista also provides the necessary design services to integrate either of these systems into an existing or new line. Vista Research has published a number of articles and technical reports on the technology. These documents and product brochures can be provided upon request. For additional information, contact Vista Research directly by phone (415-966-1171, fax (415-969-4348) or e-mail (info@vrinc.com). Mr. Michael R. Fierro is the Product Manager. Pictures of the LT-100 and HT-100 and the latest information about Vista's products and services can be found on our web page (http://www.aimnet.com/~vrinc/).

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Appendix B

REPORT FROM TRACER RESEARCH

TRACER TIGHT® LEAK TEST
of
Test Sections 3 and 4, Fuel Distribution Piping
at
Nassau International Airport
Nassau, P.I., Bahamas

November 4-12 - December 1-12, 1996

Tracer Tight® Leak Test

Test Section Pipelines 3 and 4, Aviation Fuel Distribution Piping

Nassau International Airport
Nassau. P.I, Bahamas

November 4-11 - December 1-12, 1996

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1.0 Project Description

Tracer Research Corporation (Tracer Research) performed *Tracer Tight®* leak testing of 1,500 linear feet of six to ten inch diameter aviation fuel distribution piping at Bahamas International Airport, Nassau, P.I., Bahamas. Advanced project planning and implementation were conducted to ensure that aircraft operations were not affected in any way during the test. The piping test was conducted under contract with API, under a project entitled, "Participate in the API Study on Leak Detection Methods for Underground Piping Providing Tracer Tight Leak Detection Services". Exxon Research and Engineering Corporation and Midwest Research Institute (MRI) provided on-site, third party technical oversight during all phases of the leak simulation and piping tests.

The testing was conducted in two phases. The first phase of testing, the leak detection sample probe installation and leak simulation phase, began on November 4 and was completed by November 11, 1996. The second phase of testing, the piping inoculation, leak detection probe sample collection and analysis began on December 1 and was completed on December 12, 1996.

2.0 Background

The purpose of this project was to test the aviation fuel piping for leaks and investigate and evaluate leak detection technologies for underground petroleum pipelines. In an effort to evaluate several different leak detection technologies, API contracted with four companies offering four different leak detection technologies: pressure testing, volumetric testing, acoustic testing and tracer testing. Tracer Research was selected to provide the tracer testing. MRI provided on-site, third party technical oversight and evaluation for all four technologies.

3.0 Objectives

The purpose of this *Tracer Tight®* leak test was to identify any sources of product leakage associated with API identified sections of piping at Nassau International Airport. Any leakage detected during the initial testing would be further investigated to determine the approximate leak location point on the pipeline so that repairs could be made and the pipeline(s) returned to normal operation.

4.0 *Tracer Tight®* Concept

Tracer Tight® leak testing is a patented process performed by introducing a volatile chemical concentrate, a tracer, into the pipeline followed by the detection of tracer underground in the vapor phase. The tracer is used in very low concentrations. The tracer has no impact on the chemical or physical properties of the pipeline products. The tracer chemical, being highly volatile, distributes itself, both into the product and into the vapor space above the product.

If a pipeline leaks fuel, the tracer is released from the fuel into the soil and disperses in all directions through the air porosity of the soil by molecular diffusion. Tracer can also travel by convection when a pipeline is emptied of fuel and tested under pressure with a mixture of tracer and nitrogen or air. When fuel leaks underwater, it rises to the surface of the water table and releases the tracer into the air above the water.

After the tracer has had time to diffuse and migrate through the soil away from the leak, soil gas samples are collected from the area surrounding the pipeline. Probes are placed in the backfill above the pipeline to collect the tracer vapors that might appear in the soil. The probes are driven into the ground and a small amount of soil gas is pulled by vacuum through each probe. Samples of this soil gas are collected and analyzed for the presence of tracer and hydrocarbons.

5.0 Site Description

The aviation fuel distribution system begins at the Esso Standard Oil, bulk fuels storage facility located on Windsor Field Road. The fuel distribution system then extends to a fuel hydrant system which encircles both the U.S. Pier and the International Pier, Concourse "C". The piping was arranged in two sections by American Petroleum Institute (API), as Test Section #3 and Test Section #4. Test Section #3 (400 feet) extends from valve pit #3, between the U.S. Pier and the International Pier, Concourse "C", to valve pit #4. Test Section #4 (1100 feet) extended from valve pit #4 to valve pit #5, just south of the International Pier. The pipeline depth ranges from approximately four feet to six feet below ground surface (bgs). The depth to groundwater was reported to be in the range of four to six feet bgs. The ground cover over the piping right of way consists of reinforced concrete topped with a layer of asphaltic concrete. The thickness of this concrete and asphaltic concrete ground cover varies from twelve to fourteen inches. A section of Test Section #4 piping is encased in a piping sleeve. The sleeved pipe passes under the foundation of the International Pier, Concourse "C", and is approximately 40 feet in length.

6.0 Leak Detection System Installation

Installation of the initial 72 sampling probes on Test Sections #3 and #4 began on November 6, 1996. Probes were installed adjacent to the approximately 1,500 feet of piping tested. All probes were 16 inches in length. All probes were installed to a depth of at least 2 inches below the bottom of the ramp. Probes were installed by first drilling a one and one half inch hole through the concrete ramp followed by the installation of a sampling probe. All probes were installed flush with the ground surface and sealed with caulking to insure a gas, water and fuel tight seal around the probe.

7.0 Leak Simulation

Leak simulations were completed to validate the effectiveness and sensitivity of the *Tracer Tight®* method at the testing site and confirm that a *Tracer Tight®* leak test would detect any leak exceeding the 0.05 gallon per hour (gph) minimum detection criteria mandated by the United States Environmental Protection Agency (EPA) for tightness testing methods. One leak simulation was performed on Test Section #3 and two leak simulations were performed on Test Section #4. The leak simulation probes were installed and the leak simulations performed on November 10-11, 1996 (see Appendix D, Figures 2A-C).

A leak simulation is performed by introducing a tracer different from the one used for the hydrant loop leak testing into the soil through an injection probe installed at a point equi-distant between two sampling probes. This spacing represents the farthest distance a leak could occur from any given sampling location. Additional leak detection probes were installed at 2.5 feet and 5 feet on either side of the leak simulation injection probe. The leak simulation probe was installed to a depth of six inches above the fuel pipe (approximately 4 to 5 feet bgs).

The minimum leak rate specified by the EPA for leak detection is 0.05 gph. Therefore, the amount of tracer used for the simulations was determined by the amount of tracer expected to leak out of a pipeline leaking at 0.05 gph for 72 hours or the amount of tracer released with 3.6 gallons of product. This procedure provides a field test to confirm the leak detection sensitivity achieved at the site. This information allows the technician to adjust the test duration or the tracer inoculation concentration appropriately for site conditions should a deviation from standard operating procedures be required.

The first leak simulation was performed on Test Section #3 just west of the high point between valve pit #3 and valve pit #4. The leak simulation was designed to simulate a liquid product leak because Test Section #3 was tested with aviation fuel in the pipeline. The results of the leak simulation indicate that significant concentrations of tracer could be detected ten feet from the leak simulation probe in 22 hours.

The second simulation was performed northeast of Hydrant #36, Gate 10, between probe locations #36 and #37 on Test Section #4. This leak simulation was designed to simulate a tracer/air mixture leak because Test Section #4 was inoculated with a mixture of tracer and air. As with leak simulation #1, the leak simulated was a 3.6 gallon product release.

The results of this leak simulation indicate that significant concentrations of tracer could be detected ten feet from the leak simulation probe in 22 hours.

The third simulation was performed southeast of valve pit #5, between probe locations #69 and #70. The same amount of leak simulation tracer was added to the leak simulation probe. Significant tracer concentrations were detected in the probe 2.5 feet away from the leak simulation probe after 27 total hours had passed. The leak simulation tracer appeared to migrate a little more slowly here because the leak simulation tracer was injected under water and floating product. Once the tracer finally reached the unsaturated vadous zone it would move rapidly to a distance of 10 feet from the leak simulation probe as it did with leak simulations #1 and #2.

The results of the leak simulations confirmed that the soil is highly permeable and that the tests could be conducted in the time allotted.

8.0 Test Sections #3 and #4

8.1 Test Section #3 - Inoculation

On December 3, 1996, 1,459 gallons of aviation fuel was pumped from a fuel pumper truck into the empty pipeline at valve pit #3. Tracer A, the inoculation tracer, was metered into the fuel as the fuel was pumped into the pipeline. After the inoculation, two fuel samples were collected at valve pit #4. The analysis of two fuel samples indicated that the pipeline was not sufficiently inoculated to a 1 part per million (ppm) concentration. An additional 118 gallons of fuel and tracer A were added to the pipeline and the displaced fuel was collected into a fuel bowser. Analysis of the collected fuel samples indicated that the fuel was properly inoculated to 1 ppm. Test Sections #3 was then blocked in for the duration of the test.

8.2 Test Section #3 - Sampling and Analysis

On December 6, 22 samples were collected from Test Section #3 and analyzed for Tracer A. Elevated tracer concentrations were detected in Probes 17-22, in the area adjacent to Valve Pit 4 (see Appendix C, Table #2). Due to the proximity of this piping to Test Section #4 piping (also inoculated with Tracer A), Test Section #3 was retested with Tracer W to confirm the initial results.

On December 10, 1,800 gallons of fuel was pumped from a pumper truck into valve pit #3 while Tracer W was injected into the fuel. The displaced fuel from the inoculation of Test Section #3 was collected into a defuel truck at valve pit #4. This inoculation effectively displaced the Tracer A inoculated fuel and replaced it with Tracer W inoculated fuel. Fuel sample analysis confirmed a satisfactory concentration of Tracer W (see Appendix C, Table #1).

On December 12, samples were collected from Test Section #3 and analyzed for Tracer W and A. Decreased concentration levels of Tracer A were detected in probes 10 and 13 through 22. Tracer W was not detected at significant levels (see Appendix C, Table #3).

8.3 Test Section #4 - Inoculation (Tracer A)

Test Section #4 did not contain any aviation fuel and was completely empty at the time of inoculation. Using a compressor, a mixture of Tracer A and compressed air was introduced into the pipeline on December 3, 1996. The tracer/air mixture was added at the high point adjacent to valve pit #4. Confirmation that the Tracer A had been distributed throughout the piping was accomplished by collecting and analyzing air samples at the furthest end of the piping from the injection point at valve pit #5. Once the Tracer A was confirmed at the furthest end of the piping, the pipeline was blocked in at 30 p.s.i.. A hydrant outlet adapter was used to release air from the pipe until tracer labeled air arrived at hydrant outlets 29-36. This insured complete inoculation of each hydrant lateral. Air samples were collected and analyzed from hydrant outlets 29-32 in order to verify the presence of tracer at the furthest downstream points (see Appendix C, Table #1). Test Section #4 was pressurized up to a final pressure of 42 p.s.i. at 1800 hours on December 3.

On December 4, at 0900, 15 hours after final pressurization, gauge readings were 0 p.s.i., indicating that the piping had lost all pressure. The pipe was recharged with Tracer A and compressed air for 3.5 minutes bringing the pipeline pressure up to 10 p.s.i. before a malfunction in the compressor stopped the inoculation event.

8.4 Test Section #4 - Sampling and Analysis

On December 4, approximately 24 hours after inoculation, 48 samples were collected from Test Section #4 and analyzed for Tracer A. Failing concentrations of Tracer A were detected in probes 25 through 29, the area between the high point at valve pit #4 and the International Pier building (see Appendix C, Table #4). The highest concentration of tracer was detected at probe 28 (13 µg/L).

On December 6, in an effort to determine the leak location(s), four leak delineation probes (28A, 28B, 28C and 29A) were installed on 5 foot centers in the area of probe 28, between probe 27 and the International Pier building. Due to the proximity of buried high voltage and radar cables, Exxon personnel determined it hazardous to install leak delineation probes deeper than 16 inches. Deeper probes are useful in performing depth profiling which is instructive when conducting leak delineation. Probe 23 was also installed at this time (it had not been installed during the original probe installation because test equipment from another leak detection contractor was set up at that site).

Approximately 72 hours after inoculation, another round of samples were collected from probes 23 through 71 and analyzed for Tracer A. Failing concentrations of Tracer A were detected in probes 23 and 25 through 29A (see Appendix C, Table #5).

8.5 Test Section #4 - Inoculation (Tracer W)

To further delineate the leak location(s) on Test Section #4, the test section was retested with Tracer W. On December 12, Test Section #4 was pressurized to 20 p.s.i. with a compressor. Tracer W was then injected into the air stream over the next 16 minutes until the line pressure reached 62 p.s.i.

8.6 Test Section #4 - Sampling and Analysis (Tracer W)

Two hours after inoculation with Tracer W, samples were collected between valve pit #4 and the International Pier and analyzed for Tracer W and Tracer A. Tracer W was detected in probes 23 through 28A, with the highest concentrations at probes 23, 26 and 28A (see Appendix C, Table #6). Decreased residual concentrations of Tracer A were detected in probes 23 through 29A.

9.0 Sampling Parameters

All samples were collected from installed probes in pre-evacuated sample canisters. The samples were analyzed onsite immediately following collection. All samples were analyzed utilizing a laboratory grade Hewlett-Packard gas chromatograph (GC) and data plotting integrators. The GC was calibrated daily, before sample collection and analysis. Approximately 98% percent of the vacuum readings observed during sampling were less than five inches of mercury (in/Hg). The observed readings indicated favorable soil porosity and tracer migration was therefore optimal for detection of possible leaks.

10.0 Conclusions

10.1 Test Section #3

Test Section #3, piping between valve pit #3 and valve pit #4, tested tight and passes the *Tracer Tight®* leak test.

10.2 Test Section #4

The portion of Test Section #4 between valve pit #5 and the east side of the International Pier building (probes 30-71), tested tight and passes the *Tracer Tight®* leak test. The portion of Test Section #4 between valve pit #4 and the International Pier building (probes 23-29A), failed the *Tracer Tight®* leak test.

It is difficult to determine the specific quantity and location of leak(s) between valve pit #4 and the International Pier building. Tracer can spread great distances laterally at a site where a shallow water table exists with a thick, overlying concrete cover. The water table and the concrete effectively form two horizontal boundaries with a relatively thin layer of permeable soil between them. Tracer released with a large volume of air into this permeable layer (i.e. from the leak in the depressurizing pipe) will result in rapid lateral tracer transport around the site. This tends to mask the exact leak location because it becomes difficult to measure a reliable concentration gradient in the vicinity of the leak. This type of site condition can be addressed with deeper sampling probes and a more sensitive inoculation technique. Potential underground hazards and project schedule did not accommodate additional investigation.

Based on our experience, the data indicate the existence of at least one leak. The most probable location is in the vicinity of probe 28A. In the initial Tracer A test results (see Appendix C, Table #4), the tracer concentrations decreased away from the probe as expected. However, higher than expected tracer concentrations exist at some probes that are a considerable distance from probe 28A, particularly probes 23 and 26. There may be leaks at these locations as well, or the data may be a manifestation of tracer migration. Significant lateral tracer migration is demonstrated by the detection of Tracer A in probes 17 through 22 (Test Section #3 Tracer W test confirmed no leak in this area). Based on our experience, we are not confident that leak(s) exist at probes 23 and 26. Identifying individual leaks at these locations risks identifying leaks where they do not exist (false positive). Exxon personnel have indicated the area between valve pit #4 and the International Pier building will be excavated. During the excavation, we recommend particular attention be paid to the piping in the vicinity of probes 23, 26 and 28A.

The analytical results of the leak test are condensed and presented in Appendix C. The locations of the leak detection probes can be found on the map located in Appendix D.

APPENDIX A: Results of EPA Standard Evaluation

Results of U.S. EPA Standard Evaluation

Nonvolumetric Tank Tightness Testing Method

This form tells whether the tank tightness testing method described below complies with the performance requirements of the federal underground storage tank regulation. The evaluation was conducted by the equipment manufacturer or a consultant to the manufacturer according to the U.S. EPA "Standard Test Procedure for Evaluating Leak Detection Methods: Nonvolumetric Tank Tightness Testing Methods." The full evaluation report also includes a form describing the method and a form summarizing the test data.

Tank owners using this leak detection system should keep this form on file to prove compliance with the federal regulations. Tank owners should check with State and local agencies to make sure this form satisfies their requirements.

Method Description

Name: Tracer Tight®

Version: ______

Vendor: Tracer Research Corporation

(address) 3855 North Business Center Drive

(city) Tucson (state) Arizona (zip) 85705 (phone) 602/888-9400

Evaluation Results

This method, which declares a tank to be leaking when tracer is detected outside the tank at concentrations greater than 3×10^{-5} times the tracer concentration in the tank has an estimated probability of false alarms [P(FA)] of a 0.0 % based on the test results of 0 false alarms out of 22 tests. A 95% confidence interval for P(FA) is from 0 % to 13 %

The corresponding probability of detection [P(D)] of a 0.05 gallon per hour leak is 100 % based on the test results of 45 detections out of 45 simulated leak tests. A 95% confidence interval for P(D) is from 92.4 % to 100 %

The corresponding probability of detection [P(D)] of a 0.1 gallon per hour leak is 100 % based on the test results of 93 detections out of 93 simulated leak tests. A 95% confidence interval for P(D) is from 96.2 % to 100 %

Does this method use additional modes of leak detection? ☒ Yes ☐ No If Yes, complete additional evaluation results on page 3 of this form.

Based on the results above, and on page 3 if applicable, this method ☒ does ☐ does not meet the federal performance standards established by the U.S. Environmental Protection Agency (0.10 gallon per hour at P(D) of 95% and P(FA) of 5%).

Test Conditions During Evaluation

The evaluation testing was conducted outside a 55 -gallon ☒ steel ☐ fiberglass tank that was 22 inches in diameter and 34 inches long, installed in silty clay native soil backfill.

The ground-water level was 0 inches above the bottom of the tank.

Nonvolumetric TTT Method Tracer Tight®
Version ______

Test Conditions During Evaluation (continued)

The tests were conducted with the tank 38/0.0 percent full.

The temperature difference between product added to fill the tank and product already in the tank ranged from NA °F to NA °F, with a standard deviation of NA °F.

The product used in the evaluation was regular leaded gasoline

This method may be affected by other sources of interference. List these interferences below and give the ranges of conditions under which the evaluation was done. (Check None if not applicable.)

☒ None

Interferences	Range of Test Conditions

Limitations on the Results

The performance estimates above are only valid when:

- The method has not been substantially changed.
- The vendors instructions for using the method are followed.
- The tank contains a product identified on the method description form.
- The tank capacity is NA gallons or smaller. *NO SIZE LIMITATION*
- The difference between added and in-tank product temperatures is no greater than + or - NA degrees Fahrenheit.

☒ Check if applicable:

Temperature is not a factor because Tracer Tight is an external leak detection method

- The waiting time between the end of filling the test tank and the start of the test data collection is at least NA hours.
- The waiting time between the end of "topping off" to final testing level and the start of the test data collection is at least NA hours.
- The total data collection time for the test is at least NA hours.
- The product volume in the tank during testing is NA % full.
- This method ☒ can ☐ cannot be used if the ground-water level is above the bottom of the tank.

Other limitations specified by the vendor or determined during testing:

Soil must be permeable enough to yield at least 0.15 cfm of air through a 3/4" nominal diameter probe under a vacuum of 15" of Hg.

Nonvolumetric TTT Method Tracer Tight®
Version ______

>Safety disclaimer: This test procedure only addresses the issue of the methods ability to detect leaks. It does not test the equipment for safety hazards.

Additional Evaluation Results (if applicable)

This method, which declares a tank to be leaking when water ingress is detected has an estimated probability of false alarms [P(FA)] of N/A % based on the test results of false alarms out of N/A tests. Note: A perfect score during testing does not mean that the method is perfect. Based on the observed results, a 95% confidence interval for P(FA) is from 0 % to N/A %.

The corresponding probability of detetecton [P(D)] of a N/A gallon per hour leak is N/A % based on the test results of N/A detections out of N/A simulated leak tests. Note: A perfect score during testing does not mean that the method is perfect. Based on the observed results, a 95% confidence interval for P(D) is from N/A % to 100 %.

>Water detection mode (if applicable)

Using a false alarm rate of 0% the minimum water level that the water sensor can detect with a 100% probability of detection is 0.008 inches.

Using a false alarm rate of 5% the minimum change in water level that the water sensor can detect with a 95% probability of detection is 0.19 inches.

Based on the minimum water level and change in water level that the water sensor can detect with a false alarm rate of 5% and a 95% probability of detection, the minimum time for the system to detect an increase in water level at an incursion rate of 0.10 gallon per hour is 1836 minutes in a 75,000 - gallon tank.

Certification of Results

I certify that the nonvolumetric tank tightness testing method was installed and operated according the the vendors instructions. I also certify that the evaluation was performed according to the standard EPA test procedure for nonvolumetric tank tightness testing methods and that the results presented above are those obtained during the evaluation.

Curtis W. Bryant
(printed name)

Control Strategies Engineering
(organization performing evaluation)

Curtis W. Bryant
(signature)

12550 West Manville Road
Tucson, Arizona 85743
(city, state, zip)

May 20, 1992
(date)

(602) 682-8726
(phone number)

APPENDIX B: Certification

TRACER TIGHT® LEAK DETECTION CERTIFICATION

Nassau International Airport
Nassau, P.I., Bahamas

Date: December 1996
Job: R0008-000.H

Pipeline	Length	Product	Tracer	Pass/FAIL
Test Section #3	400 Feet	Jet A	W	Pass
Test Section #4 Probe Locations 30-71	990 Feet	Jet A	A	Pass
Test Section #4 Probe Locations 29A-23	110 Feet	Jet A	A, W	FAIL

Tracer Research Corporation hereby certifies that the above listed pipeline(s) have been tested by means of *Tracer Tight®*, which meets the criteria set forth in NFPA 329 for a precision leak test. According to United States Environmental Protection Agency (EPA) standard test procedures for evaluating leak detection methods, the *Tracer Tight®* method is capable of detecting leaks of 0.05 gallons per hour with a Probability of Detection (PD) of 0.97 and a Probability of False Alarm (PFA) of 0.029.

Submitted by: Tracer Research Corporation

The classification of leakage is based on the presence or absence of tracer.

Pass Criteria: NO tracer detected less than 0.1 ug/L.
Fail Criteria: Tracer detected equal to or greater than 0.1 ug/L.

APPENDIX C: Analytical Data

1ANALYTICAL DATA
API/MRI STUDY
Nassua Int'l Airport
Nassua, P.I., Bahamas Job #R0008-000.H

Probe #	Tracer A

TABLE #1 Tracer Verification Line #3, Line #4 December 3, 1996	
Line #3, Fuel	Tracer Verified
Line #4, Valve Pit #5	Tracer Verified
Line #4, Hydrant #29	Tracer Verified
Line #4, Hydrant #30	Tracer Verified
Line #4, Hydrant #31	Tracer Verified
Line #4, Hydrant #32	Tracer Verified
Air, Valve Pit #5	ND
Line #3, Fuel (Dec. 10)	Tracer W Verified

TABLE #2 48 Hour Test Tracer A Line #3 December 6, 1996	
1	ND
2	ND
3	ND
4	ND
5	ND
6	ND
7	ND
8	ND
9	ND
10	ND
11	ND
12	ND
13	ND
14	ND
15	ND
16	ND
17	0.02
18	0.08
19	1
20	12
21	3
22	7
Air, lab	ND
Air, valve pit #4	ND

All concentrations shown in µg/L

ND = Not Detected
NA = Not Analyzed
NS = Not Sampled

1

2ANALYTICAL DATA
API/MRI STUDY
Nassua Int'l Airport
Nassua, P.I., Bahamas Job #R0008-000.H

Probe #	Tracer A	Tracer W
TABLE #3 **48 Hour Test** **Tracer W** **Line #3** **December 12, 1996**		
1	ND	0.0006**
2	ND	ND
3	ND	ND
4	ND	ND
5	ND	ND
6	ND	ND
7	ND	ND
8	ND	ND
9	ND	ND
10	0.001 *	ND
11	ND	ND
12	ND	ND
13	0.001 *	ND
14	0.004 *	ND
15	0.006 *	ND
16	0.01 *	ND
17	0.2 *	ND
18	0.2 *	ND
19	0.7 *	ND
20	1 *	ND
21	1 *	ND
22	1 *	ND

* Residual Tracer A from previous test.

** Probe location #1 is located very close to where Line #3 was inoculated at valve pit #3. A small amount of inoculated fuel was released when disconnecting the inoculation hose from the valve which caused a this very small elevated concentration of Tracer W.

All concentrations shown in µg/L

ND = Not Detected
NA = Not Analyzed
NS = Not Sampled

3ANALYTICAL DATA
API/MRI STUDY
Nassua Int'l Airport
Nassua, P.I., Bahamas Job #R0008-000.H

Probe #	Tracer A	Probe #	Tracer A
TABLE #4 **24 Hour Test** **Line #4** **December 4, 1996**		**24 Hour Test (Cont.)** **Line #4** **December 4, 1996**	
Air, Lab	ND	63	ND
30	ND	64	ND
31	ND	65	ND
32	ND	66	ND
33	ND	67	ND
34	ND	Air, 67	ND
35	ND	68	ND
36	ND	69	ND
37	ND	70	ND
38	ND	71	ND
39	ND	29	0.8
40	ND	28	13
41	ND	27	5
42	ND	26	4
43	ND	25	2
44	ND	24	0.001
45	ND	23 (not yet installed)	NS
46	ND		
47	ND		
48	ND		
Air, 48	ND		
49	ND		
50	ND		
51	ND		
52	ND		
53	ND		
54	ND		
55	ND		
56	ND		
57	ND		
58	ND		
59	ND		
60	ND		
61	ND		
62	ND		

All concentrations shown in µg/L

ND = Not Detected
NA = Not Analyzed
NS = Not Sampled

4ANALYTICAL DATA
API/MRI STUDY
Nassua Int'l Airport
Nassua, P.I., Bahamas Job #R0008-000.H

Probe #	Tracer A	Probe #	Tracer A
TABLE #5 72 Hour Test Line #4 December 6, 1996		72 Hour Test Line #4 (Cont.) December 6, 1996	
30	0.001	63	ND
31	ND	64	ND
32	ND	65	ND
33	ND	66	ND
34	ND	67	ND
35	ND	Air, 67	ND
36	ND	68	ND
37	ND	69	ND
38	ND	70	ND
39	ND	71	ND
40	ND	29A	3
41	ND	29	0.2
42	ND	28A	8
43	ND	28	6
44	ND	28B	5
45	ND	28C	4
46	ND	27	5
47	ND	26	9
48	ND	25	6
Air, 48	ND	24	0.005
49	ND	23	11
50	ND		
51	ND		
52	ND		
53	ND		
54	ND		
55	ND		
56	ND		
57	ND		
58	ND		
59	ND		
60	ND		
61	ND		
62	ND		

All concentrations shown in µg/L

ND = Not Detected
NA = Not Analyzed
NS = Not Sampled

5ANALYTICAL DATA
API/MRI STUDY
Nassua Int'l Airport
Nassua, P.I., Bahamas Job #R0008-000.H

Probe #	Tracer A	Tracer W
TABLE #6 **2 Hour Test** **Tracer W** **Line #4 (Leak Locate)** **December 12, 1996**		
29A	1 *	ND
29	0.4 *	ND
28A	1 *	2
28	1 *	0.003
28B	1 *	0.001
28C	1 *	0.003
27	2 *	0.1
26	2 *	3
25	0.9 *	0.2
24	0.02 *	0.0006
23	0.2 *	13

* Residual Tracer A from previous test.

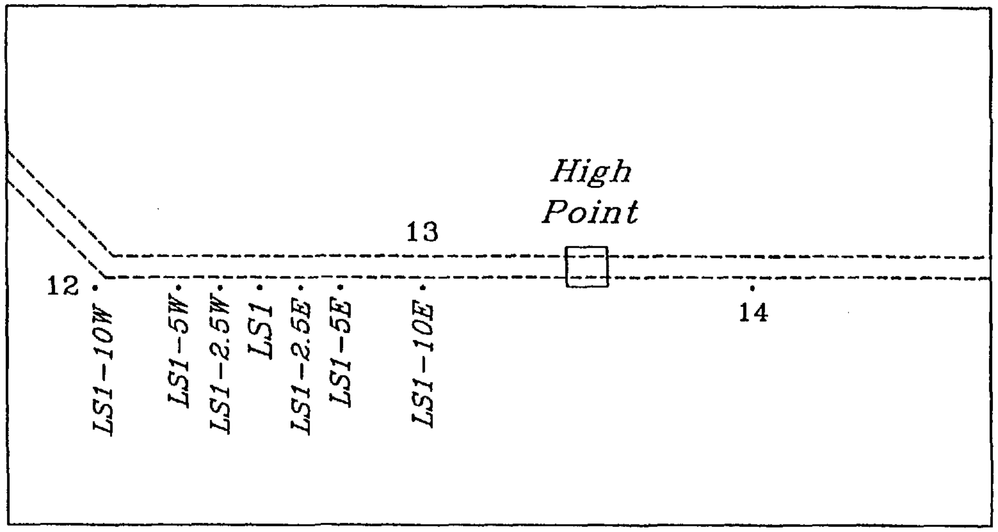
All concentrations shown in µg/L

ND = Not Detected
NA = Not Analyzed
NS = Not Sampled

APPENDIX D: Map of Pipeline with Sampling Locations

Tracer Research Corporation

Leak Simulation No. 1



EXPLANATION

• 1	Sampling Probe Location
• *LS1*	Leak Simulation Probe
-------	Approximate Pipeline Location

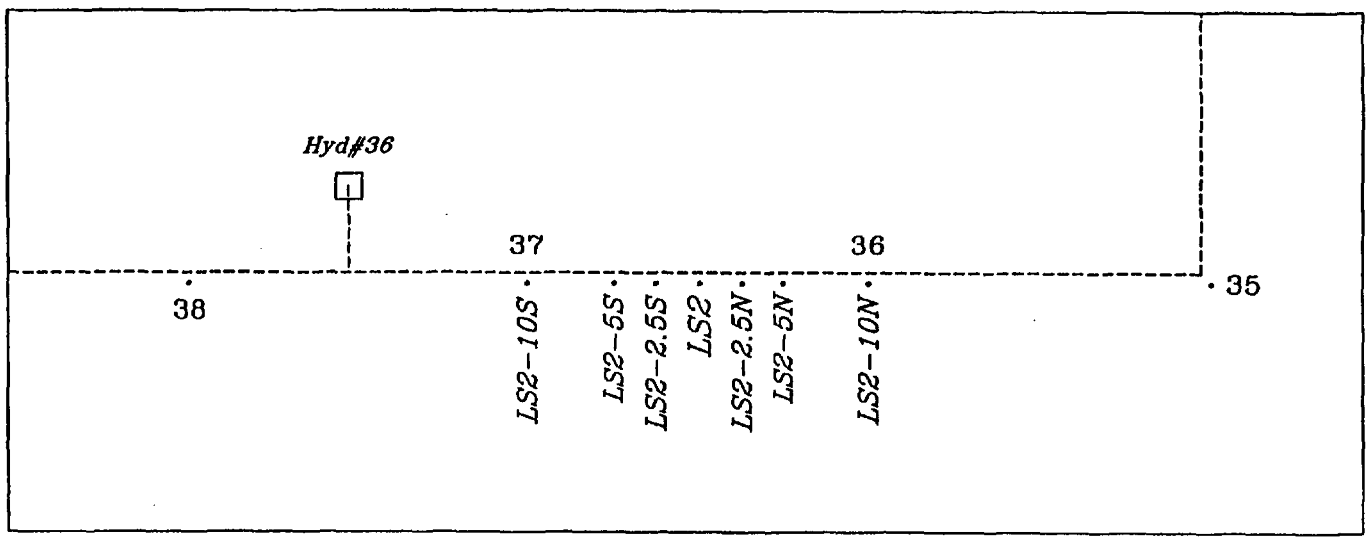
Tracer Job No. R0008-000.P

API/MRI Study - BAHAMAS
Nassau Int'l Airport
Leak Simulation No. 1
NASSAU, P.I., BAHAMAS
Sampling Locations

Figure 2A

Tracer Research Corporation

Leak Simulation No. 2



EXPLANATION

- ·1 — Sampling Probe Location
- ·*LS2* — Leak Simulation Probe
- ------- — Approximate Pipeline Location

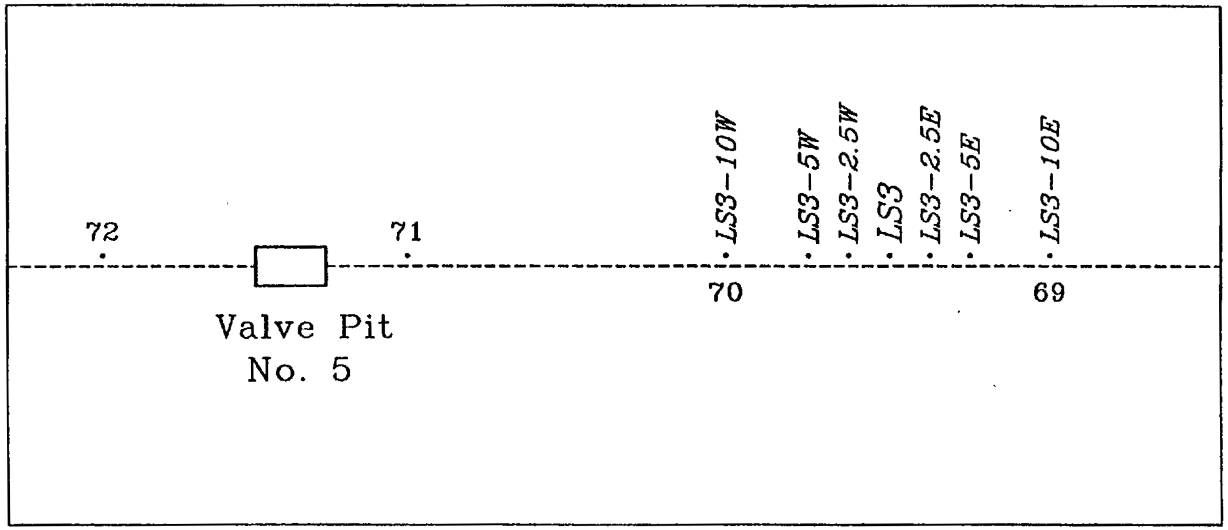
Tracer Job No. R0008-000.P

API/MRI Study – BAHAMAS
Nassau Int'l Airport
Leak Simulation No. 2
NASSAU, P.I., BAHAMAS

Sampling Locations

Figure 2B

Leak Simulation No. 3



EXPLANATION

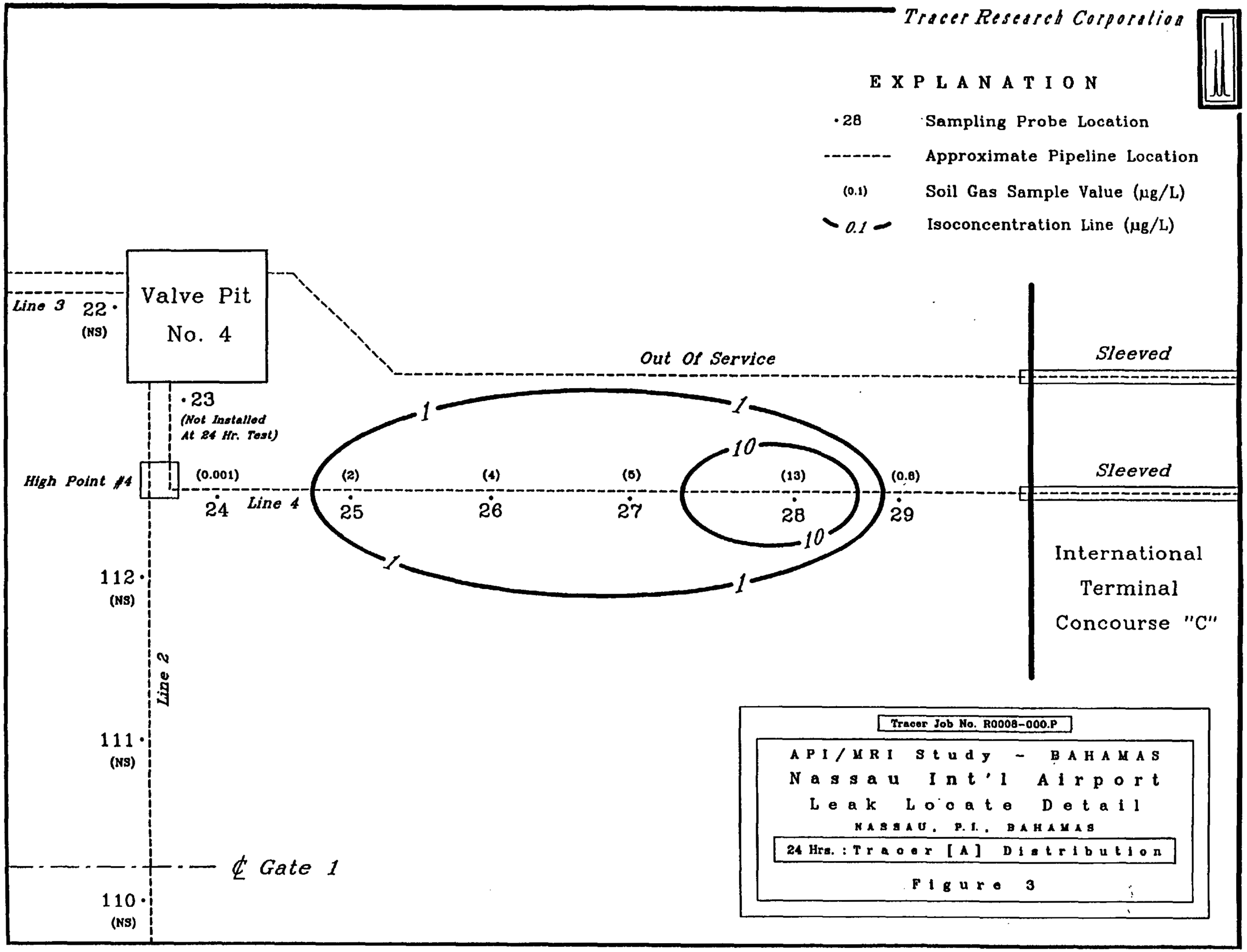
- •1 Sampling Probe Location
- • *LS3* Leak Simulation Probe
- ------- Approximate Pipeline Location

Tracer Job No. R0008-000.P

API/MRI Study – BAHAMAS
Nassau Int'l Airport
Leak Simulation No. 3
NASSAU, P.I., BAHAMAS

Sampling Locations

Figure 2C


Tracer Research Corporation
EXPLANATION
•28 Sampling Probe Location
Approximate Pipeline Location
(0.1) Soil Gas Sample Value (μg/L)
0.1 Isoconcentration Line (μg/L)
Valve Pit No. 4
Line 3
22• (NS)
•23 (Not Installed At 24 Hr. Test)
High Point #4
(0.001) 24
Line 4
(2) 25
(4) 26
(5) 27
(13) 28
(0.6) 29
1
10
Out Of Service
Sleeved
Sleeved
International Terminal Concourse "C"
112• (NS)
Line 2
111• (NS)
℄ Gate 1
110• (NS)
Tracer Job No. R0008-000.P
API/MRI Study - BAHAMAS
Nassau Int'l Airport
Leak Locate Detail
NASSAU, P.I., BAHAMAS
24 Hrs. : Tracer [A] Distribution
Figure 3

Appendix C

REPORT FROM HANSA CONSULT TCS

TCS

Tightness Control System

For

Documentation

Revision 1

November 19th 1996

Hansa Consult Ingenieurgesellschaft mbH
Beim Zeugamt 6 Tel +49 - 40 - 710 918-0
21509 Glinde Fax +49 - 40 - 710 918-20
Germany (Fax +49 - 40 - 710 918-30)

1 Introduction

1.1 General

At   should be tested 4 sections for tightness. It should be done with 4 different measurement-systems to determine their preferences. The sections had sizes of 5 - 50 m3 inner volume.

At 10 bar there will be a change from turbulent to laminar flow by about 0,05 mm diameter for the Leaksize.

1.2 Explanation of words and shorts

Volume	Inner volume of pipeline
ri/s	Proportion of inner pipeline radius to wall thikness
Operating pressure	design pressure of pipeline (the leak-results are based on this pressure)
k1	Correction factor 1 for angle (influences are e.a. compressibility)
k2	Correction factor 2 for zero-line (influences are e.a. time delayed effects)

2 Results

2.1 Section 1

The parameter of section 1 where given us to 3500 feet of 10 inch pipeline. This section was given as possible tight. It was blindflanged on both sides and good settled by temperature.

For pressurizing we needed with the manual pump about 20 minutes. For depressurizing the pressure was released through a small ball-valve within 1 minute. Usual pressurizing and depressurizing should be nearly the same time in the range between 1 and 3 minutes. Therefore the timedelayed effects had more influence than usual.

The first installation of k-factors are based on 3 tests without and 1 test with leak. The average time between cycle 1 an 2 had been about 16±2 minutes, the time between cycle 2 and 3 about 23±7 minutes for no-leaktests and 31±4 for leaktests.

The test 13th Nov at 19:24 had a too long pressurizing-time for cycle 3. Therefore this result was not valuated.

The test 13th Nov at 22:59 had leakrates (calculated for 10 bar) climbing upwards (2.86 l/h to 4.25 l/h calculated for 10 bar) while testphase. That means, the testequipment was not settled for a defined size of leak. Therefore this test was not valuated.

2.2 Section 2

The parameter of section 2 where given us to 600 feet of 10 inch and 300 feet of 6 inch pipeline. This section was given as possible tight. It was blindflanged on both sides and good settled by temperature.

For pressurizing we needed with the manual pump about 4 minutes. That was nearly in the standard of 1 to 3 minutes.

The first installation of k-factors are based on 4 tests without and 2 test with leak. It showed unusual factors in an unstabile situation. Therefore it seemed to be possible, the section was not tight. We made 8 more tests and a pressure-test for only 10 hours over night. It showed a leakrate of roughly about 400-500 ml/h.

Because of the size of leak, the most proability position for it was a leakage on a gasket or similar. Therefore we watched in the valve chanbers. This leakage was found on the blindflange in VP-5 with a driprate of about 1 drips per 1-2 seconds. It was fixed. All measurements until now where deleted.

We made 3 new tests (No 14-16) without leak. The k2-factors where in the standard range and stabil. Therefore the section seemed to be tight. The first test with simulated leak (No 17) failed. The leakrate climbed up (1,49-2,58 l/h calculated for 10 bar) over the time. Therefore this result was not valuabled. The second leaktest (No 18) was ok.

When all results are shown with the correction-factors for the tight pipeline, you see very easy that the results before are wide out of range (above the „Tol.Leak+"-line), even if they have an leakrate of only 400-500 ml/h.

2.3 Section 3

The parameter of section 3 where given us to 400 feet of 10 inch pipeline. This section was given as possible leaking. It was blindflanged on both sides and good settled by temperature.

For pressurizing we needed with the manual pump about 3 minutes. That was in the standard of 1 to 3 minutes.

The k-factors and calculations are based on turbulent flow. The leaks less than 0,7 l/h at 10 bar have laminar flow. If a leakrate is calculated for turbulent flow and you really have laminar flow, the calculated leakrate will be greater, that means an earlier alarm. Therefore the results of test 15th Nov 18:40, 19:36 and 16th Nov 01:02 are not correct.

2.4 Section 4

The parameter of section 4 where given us to 800 feet of 10 inch and 300 feet of 6 inch pipeline. The section was given as possible leaking with a big leakage. It was blindflanged on both sides and good settled by temperature but also possible partly filled with air. Our job was to find out, if there is a leak or not.

A pressurizing with the manual pump was not possible (max. 12 mbar). Therefore it was allowed to connect shortly a truck to pressurize the pipeline to about 2.7 bar and look for the pressurechange. With this method it was possible to say: „There is a leak of >50 l/h. The mass of leakage was dropped down by the amout of air in the line.

To have a better accuracy, you would have to press more than the total pipelinevolume new product in the line (to eliminate the most important influence of air) and watch the trucks meter for liter/hour leakrate. For it you would need 50-times product for testing as used by us.

Leck-Hydraulik

Possible nearest to needlevalve

[illegible]	[illegible]	flat rectangle			
[illegible]		[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	0,0000013			Kinematic viscosity
[illegible]	[illegible]	[illegible]	0,001129969	0,00174038	Leakrate
dP	[illegible]	[illegible]	[illegible]	[illegible]	Pipelinepressure
Rho	[illegible]	800			Density
[illegible]	m	0,001			Length of hole
AzuB	[illegible]	2			Sideproportion of rectangle
Do	m	0,000104983			Hydraulic equivalent diameter
[illegible]	[illegible]				
Lambda	[illegible]	0,048883582	0,0536		Friction coefficient
Zeta	[illegible]	1,965602022	2,010126666		Coefficient of flow-resistance
[illegible]	m/s	29,0344	18,2267	28,0728	Flow-velocity
[illegible]	m	1,48E-04			Leak-diameter
Re	[illegible]	2344,7061	1471,9141	2267,0442	Reynolds number

Calc turbul: sqrt(P4/P10)*L10/L4 1,007478881 0,654121505

Calc lamin: P4/P10*L10/L4 0,637185592 0,413702764

Assumptions: (form of the hole, flow-resistence, ...).

form of hole: flat rectangle

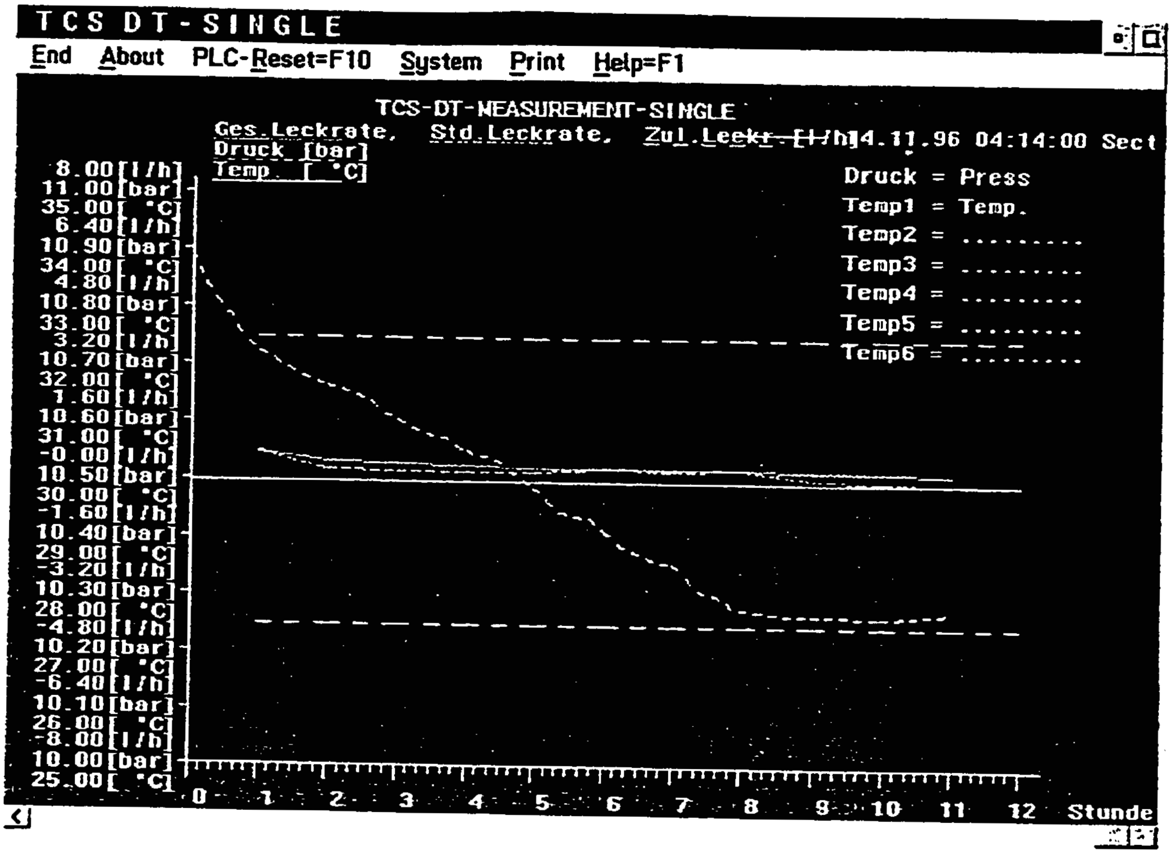
flow-resistance: Altshul´s approximate formula

We see that by a leakrate of less than 1,8 l/h we have turbulent flow at 10 bar and possible laminar flow at 4 bar.

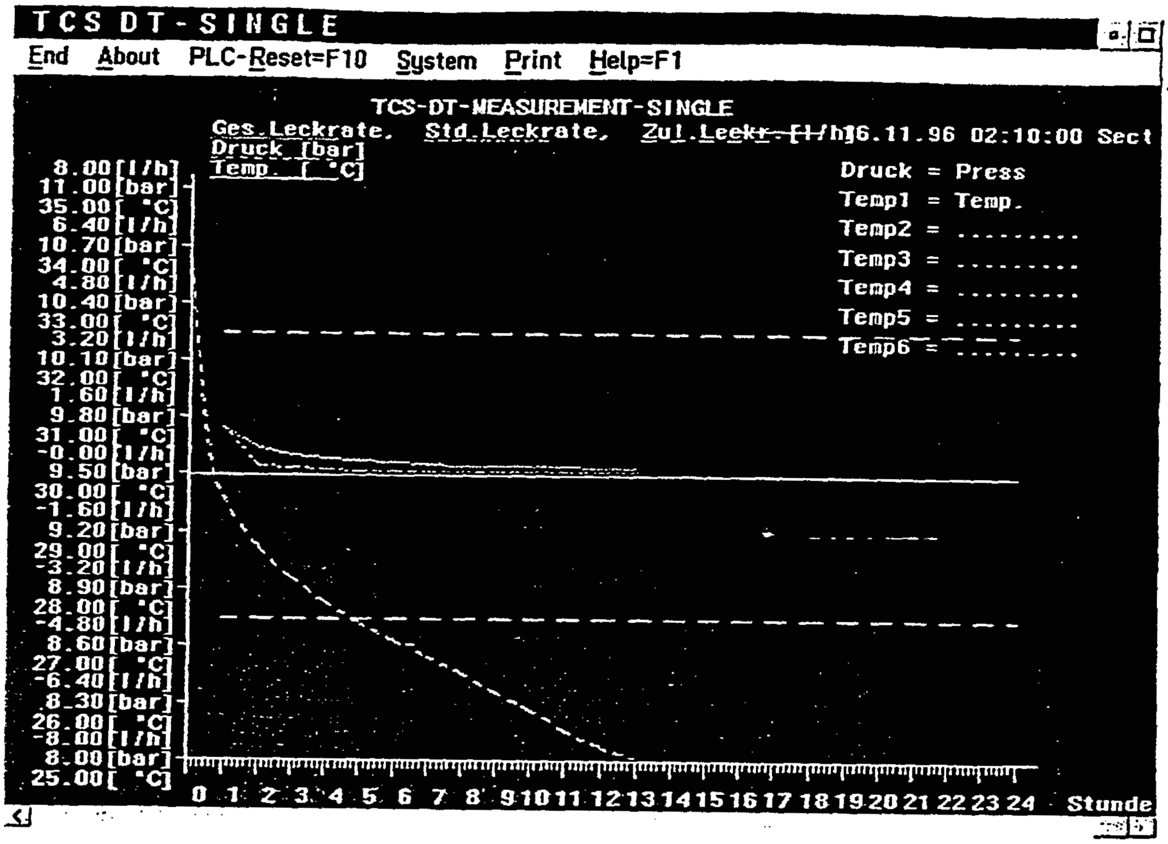
In this case we would make a mistake by calculation for turbulent flow of about 35 %

In the TCS-calculation we would give by laminar flow a greater leakrate than real existing. That means, we would give an alarm a little earlier.

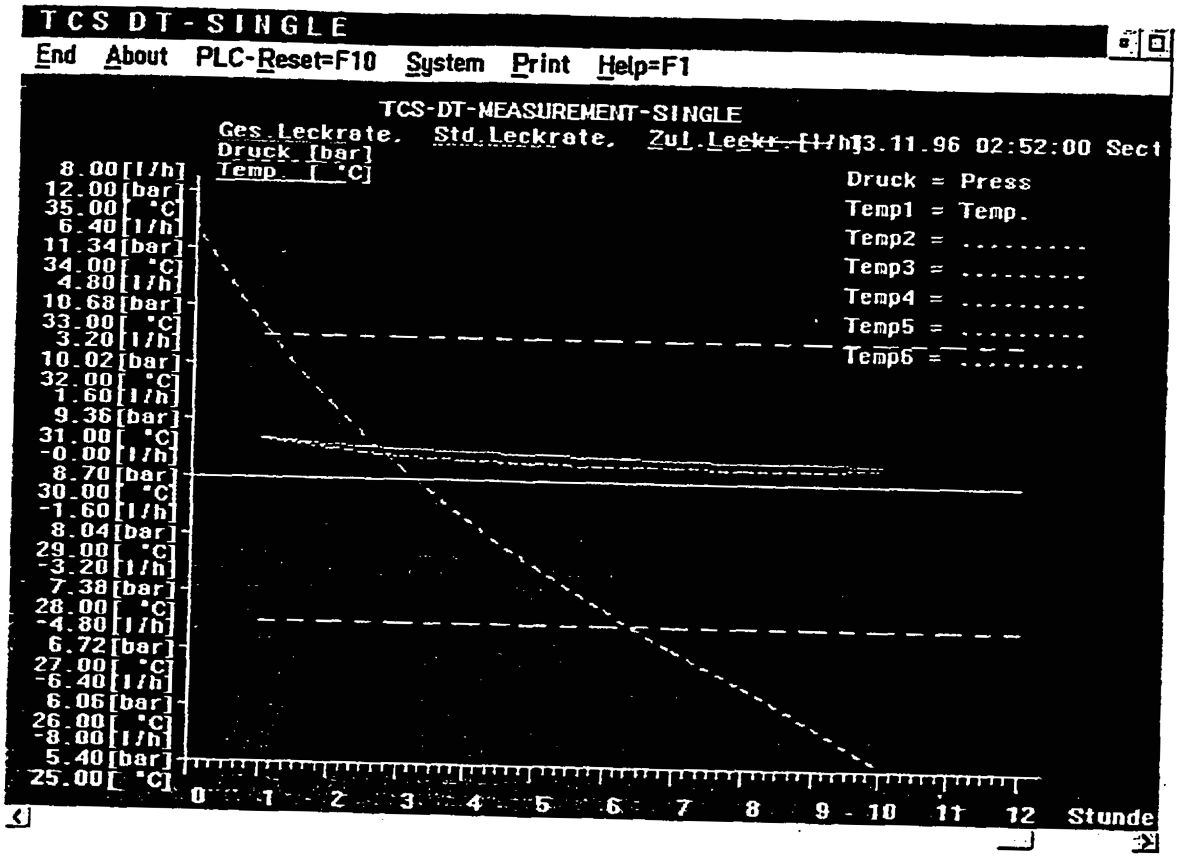
If we would come direct from 10 bar to 4 bar it would possible stay at turbulent flow or go to laminar flow. It is not possible to determine it.



Pressuretest section 1

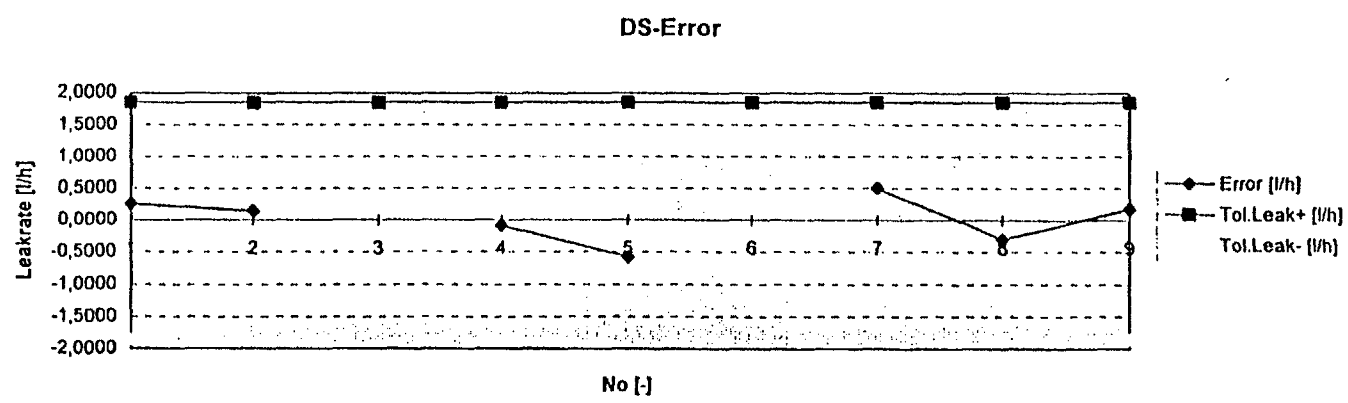


Pressuretest section 2 with fixed leak



Pressuretest section 2 with unknown leak

DS-Section 1



Seite 2

DS-Section 1

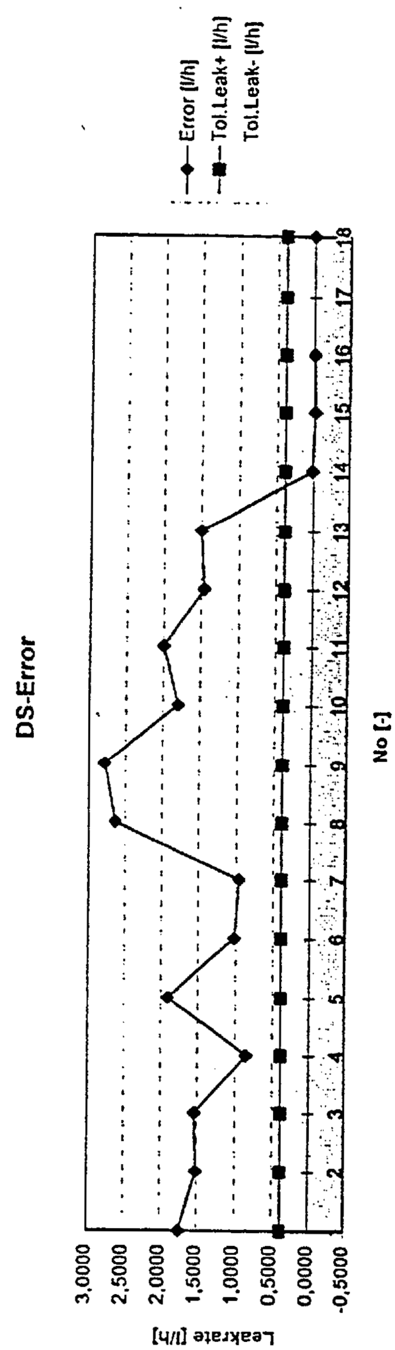
Date	Time	Press1	Press2	Press3	dPress1	dPress2	dPress3	Meas.Leak	Calc.Leak	Error	Tol.Leak+	Tol.Leak-	
		[bar]	[bar]	[bar]	[bar/h]	[bar/h]	[bar/h]	[l/h]	[l/h]	[l/h]	[l/h]	[l/h]	
13. Nov 96	17:42:03	10,473	4,185	10,265	-0,6650	0,2563	-0,6091	0,00	0,2500	0,2500	1,85084	-1,85084	
13. Nov 96	18:31:03	10,269	4,190	10,243	-0,4279	0,3002	-0,7038	0,00	0,1429	0,1429	1,85084	-1,85084	
13. Nov 96	19:24:03	10,104	4,129	10,253	-0,5897	0,4114	-0,5237	0,00	1,2222		1,85084	-1,85084	press3 time too long
13. Nov 96	20:41:03	10,117	4,245	10,261	-0,5361	0,3358	-0,4465	0,00	-0,0851	-0,0851	1,85084	-1,85084	
13. Nov 96	21:58:03	10,050	4,265	10,114	0,8917	0,0636	1,0386	2,86	2,2829	0,5771	1,85084	1,85084	
13. Nov 96	22:59:03	10,123	4,232	10,069	0,9303	0,0654	1,4201	3,29	4,4576	[illegible]	1,85084	1,85084	Error in Leakequipment
14. Nov 96	00:35:03	9,913	4,190	10,006	1,5099	0,2395	1,6605	5,29	5,7824	0,4924	1,85084	1,85084	
14. Nov 96	01:51:03	10,330	4,284	10,336	-0,2747	0,5187	-0,3304	0,00	-0,2998	-0,2998	1,85084	-1,85084	
14. Nov 96	03:04:03	10,148	4,320	10,224	0,3674	0,4593	0,5491	0,03	0,0970	0,1670	1,85084	1,85084	

C-10

[redacted]

Date	Time	Press1	Press2	Press3	dPress1	dPress2	dPress3	Meas.Leak	Calc.Leak	Error	Tol.Leak+	Tol.Leak-	
		[bar]	[bar]	[bar]	[bar/h]	[bar/h]	[bar/h]	[l/h]	[l/h]	[l/h]	[l/h]	[l/h]	
12. Nov 96	17:01:03	10,058	4,095	10,07	-3,1089	-1,2478	-2,736	0	1,7439	1,7439	0,38552	-0,38552	with unknown Leak
12. Nov 96	17:49:03	9,803	4,124	9,665	-2,4137	-1,0269	-2,5724	0,00	1,5123	1,5123	0,38552	-0,38552	with unknown Leak
12. Nov 96	18:33:03	9,896	4,173	9,795	-2,4305	-0,9461	-2,4381	0,00	1,5325	1,5325	0,38552	-0,38552	with unknown Leak
12. Nov 96	21:32:03	10,355	4,231	10,142	1,9101	0,4782	2,1454	0,65	1,4998	0,8498	0,38552	-0,38552	with unknown Leak
12. Nov 96	23:43:03	9,783	4,088	9,847	2,2868	0,6733	2,4565	0,99	2,8927	1,9047	0,38552	-0,38552	with unknown Leak
13. Nov 96	00:58:03	10,213	4,174	10,205	-1,2859	-0,0127	-1,3445	0,00	1,0164	1,0164	0,38552	-0,38552	with unknown Leak
13. Nov 96	01:50:03	10,174	4,403	10,100	-1,1428	-0,0149	-1,2952	0,00	0,9576	0,9576	0,38552	-0,38552	with unknown Leak
14. Nov 96	16:26:03	9,523	3,883	9,689	-4,1838	-2,0621	-4,1109	0,00	2,6309	2,6309	0,38552	-0,38552	with unknown Leak
14. Nov 96	17:15:03	9,772	4,065	9,745	-3,7826	-1,5428	-3,5721	0,00	2,7858	2,7858	0,38552	-0,38552	with unknown Leak
14. Nov 96	18:17:03	9,581	4,172	9,608	4,1207	1,7882	4,3076	1,81	3,6005	1,7905	0,38552	-0,38552	with unknown Leak
14. Nov 96	19:19:03	9,872	4,325	10,292	2,9819	1,0617	3,2052	0,60	2,5959	1,9959	0,38552	0,38552	with unknown Leak
14. Nov 96	20:28:03	10,086	4,354	9,906	-2,0798	-0,7403	-2,2674	0,00	1,4571	1,4571	0,38552	-0,38552	with unknown Leak
14. Nov 96	21:25:03	10,015	4,125	10,005	-2,0654	-0,6239	-2,2276	0,00	1,4955	1,4955	0,38552	-0,38552	with unknown Leak
15. Nov 96	00:44:03	10,371	4,326	10,327	-0,388	0,3518	-0,4566	0,00	0,0165	0,0165	0,38552	-0,38552	Unknown Leak fixed
15. Nov 96	01:34:03	10,396	4,289	10,237	-0,3066	0,3809	-0,4476	0,00	-0,0155	-0,0155	0,38552	-0,38552	
15. Nov 96	02:17:03	10,348	4,136	10,195	-0,3371	0,3752	-0,4698	0,00	-0,0022	-0,0022	0,38552	-0,38552	
15. Nov 96	03:42:03	10,069	4,151	9,789	1,8161	0,9779	2,9187	2,09	1,2867	[illegible]	0,38552	0,38552	Error in Testequipment
15. Nov 96	04:27:03	9,979	4,06	9,889	2,8622	0,908	2,983	2,42	2,4201	0,0001	0,38552	0,38552	

DS-Section 2

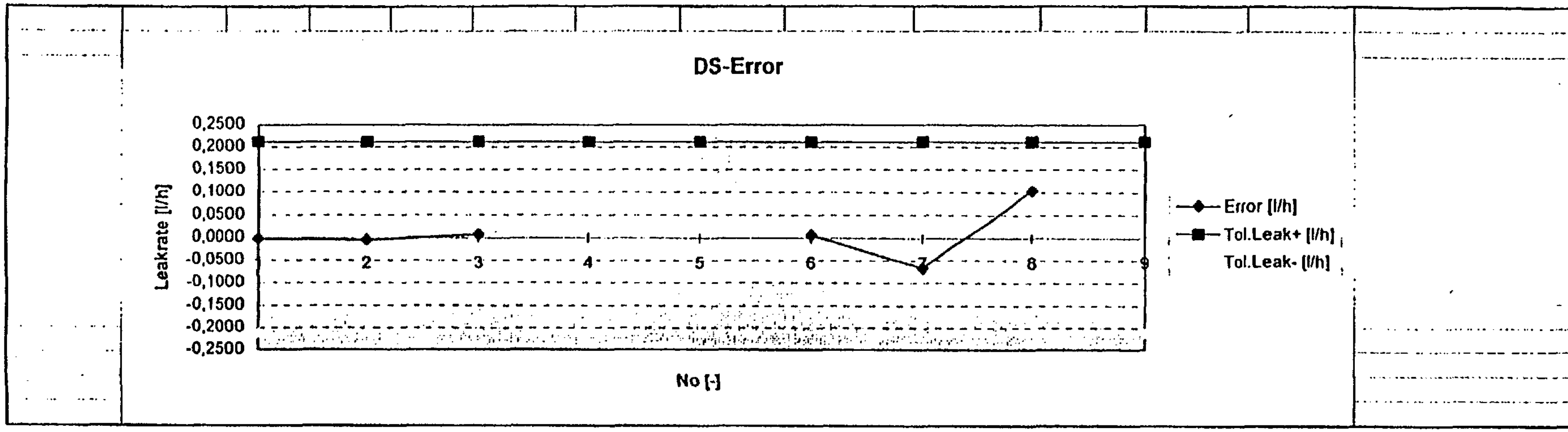


Seite 6

[redacted]

Date	Time	Press1 [bar]	Press2 [bar]	Press3 [bar]	dPress1 [bar/h]	dPress2 [bar/h]	dPress3 [bar/h]	Meas.Leak [l/h]	Calc.Leak [l/h]	Error [l/h]	Tol.Leak+ [l/h]	Tol.Leak- [l/h]	
15. Nov 96	15:58:03	10,422	4,213	10,359	-0,5080	0,3185	-0,5625	0,0000	-0,0025	-0,0025	0,2115	-0,2115	
15. Nov 96	16:43:03	10,241	4,516	10,353	-0,4074	0,3267	-0,5330	0,0000	-0,0048	-0,0048	0,2115	-0,2115	
15. Nov 96	17:26:03	10,245	4,456	10,301	-0,4118	0,3485	-0,5167	0,0000	0,0073	0,0073	0,2115	-0,2115	
15. Nov 96	18:40:03	10,195	4,315	10,223	1,9010	-0,3328	2,1412	0,6700	0,9492	[illegible]	0,2115	-0,2115	Leak too small (laminar)
15. Nov 96	19:36:03	10,253	4,250	10,172	1,6841	-0,3757	2,0796	0,6800	0,7298	[illegible]	0,2115	0,2115	Leak too small (laminar)
15. Nov 96	21:00:03	9,970	4,187	10,117	3,3845	1,2402	3,4608	1,4800	1,4864	0,0064	0,2115	0,2115	
15. Nov 96	23:14:03	9,977	4,185	10,010	-2,5203	0,8868	2,5913	1,0100	0,9431	-0,0669	0,2115	0,2115	
16. Nov 96	00:09:03	9,855	4,043	10,017	3,2669	1,1038	3,4668	1,4400	1,5429	0,1029	0,2115	0,2115	
16. Nov 96	01:02:03	10,293	4,259	10,194	1,6836	0,3079	2,0868	0,5800	0,9163	[illegible]	0,2115	0,2115	Leak too small (laminar)

C-13

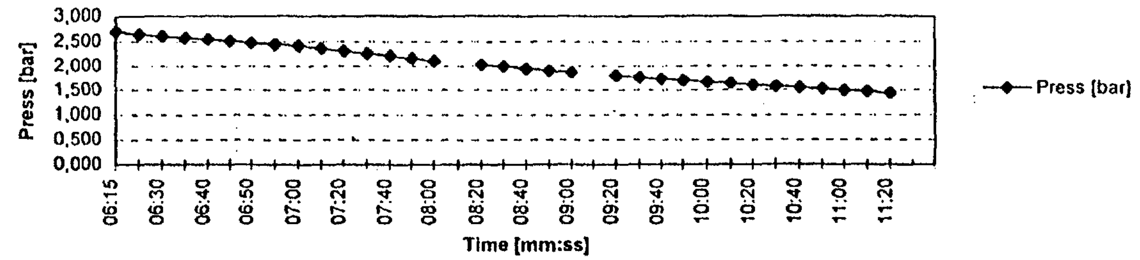

DS-Error
Leakrate [l/h]
0,2500
0,2000
0,1500
0,1000
0,0500
0,0000
-0,0500
-0,1000
-0,1500
-0,2000
-0,2500
2
3
4
5
6
7
8
9
No [-]
Error [l/h]
Tol.Leak+ [l/h]
Tol.Leak- [l/h]

C-14

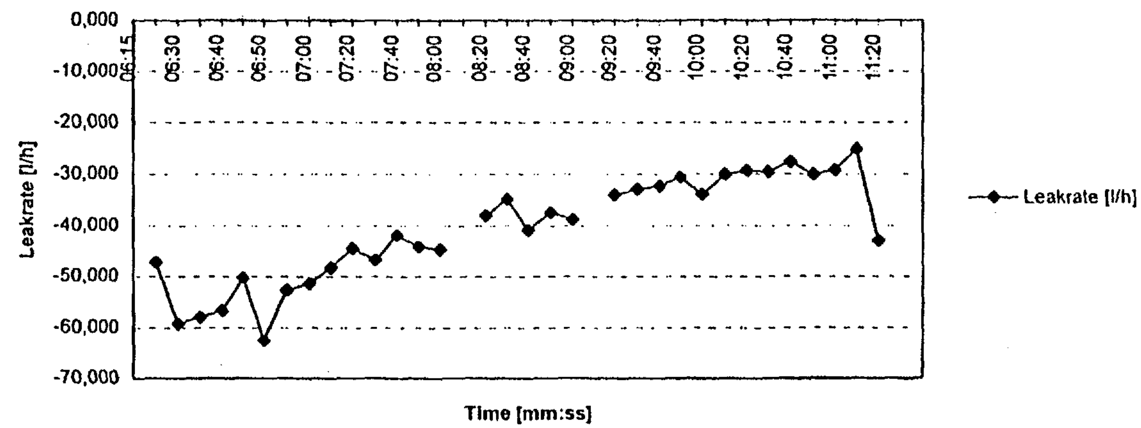
Pressuretest Section4

Time	Press	Time	Leakrate
[mm:ss]	[bar]	[mm:ss]	[l/h]
06:15	2,703	06:15	[illegible]
06:25	2,645	[illegible]	[illegible]
06:30	2,609	06:30	-59,205
06:35	2,574	06:35	-57,953
06:40	2,540	06:40	-56,676
06:45	2,510	06:45	-50,324
06:50	2,473	06:50	-62,482
06:55	2,442	06:55	-52,711
07:00	2,412	07:00	-51,330
07:10	2,356	07:10	-48,938
07:20	2,308	07:20	-44,525
07:30	2,252	07:30	[illegible]
07:40	2,205	[illegible]	[illegible]
07:50	2,156	07:50	[illegible]
08:00	2,107	08:00	-44,731
08:10	[illegible]	08:10	[illegible]
08:20	2,025	08:20	[illegible]
08:30	1,988	08:30	-34,813
08:40	1,945	08:40	-40,867
08:50	1,906	08:50	-37,458
09:00	1,866	09:00	-38,819
09:10	[illegible]	09:10	[illegible]
09:20	1,797	09:20	-33,976
09:30	1,764	09:30	-32,961
09:40	1,732	09:40	-32,258
09:50	1,702	09:50	-30,613
10:00	1,669	10:00	-33,877
10:10	1,640	10:10	-30,048
10:20	1,612	10:20	-29,265
10:30	1,584	10:30	-29,521
10:40	1,558	10:40	-27,647
10:50	1,530	[illegible]	[illegible]
11:00	1,503	[illegible]	[illegible]
11:10	1,480	[illegible]	-25,100
11:20	[illegible]	[illegible]	[illegible]

Section 4: Pressuretest



Section 4: Leakrate @ 10 bar



Seite 13

HANSA CONSULT Beim Zeugamt 6 Tel. 040-710918-0
Ingenieurgesellschaft mbh D-21509 Glinde Fax. 040-710918-20

(C) Hansa Consult Ing.GmbH - TCS - TST

DS RESULT-PROTOCOL - Section--1

Date: 13.Nov.1996 Time: 17:42:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	17:42:03	18:00:03	18:17:03
Stop	[-]:	17:44:03	18:02:03	18:19:03
Test-Pressure	[bar]:	10.473	4.185	10.265
Press.Gradient	[bar/h]:	-0.6650	0.2563	-0.6091
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.082181

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	3.802611

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

k1 := 0,6906

k2 = 0,1466

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______ (1) - 3.802611 ltr/h = _______ ltr/h < 1.850839tr/h

.... Signature of Operator _______ Signature of Supervisor

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Beim Zeugamt 6 D-21509 Glinde
Tel. 040-710918-0 Fax. 040-710918-20

DS RESULT-PROTOCOL - Section--1
===

Date: 13.Nov.1996 Time: 18:31:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	18:31:03	18:48:03	19:10:03
Stop	[-]:	18:33:03	18:50:03	19:12:03
Test-Pressure	[bar]:	10.269	4.190	10.243
Press.Gradient	[bar/h]:	-0.4279	0.3002	-0.7038
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.079781

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	3.691532

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

______(1) - 3.691532 ltr/h = _______ ltr/h < 1.850839tr/h

______ Signature of Operator ______ Signature of Supervisor

HANSA CONSULT Beim Zeugamt 6 Tel. 040-710918-0
Ingenieurgesellschaft mbh D-21509 Glinde Fax. 040-710918-20

DS RESULT-PROTOCOL - Section--1
==

Date: 13.Nov.1996 Time: 19:24:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	19:24:03	19:39:03	20:26:03
Stop	[-]:	19:26:03	19:41:03	20:28:03
Test-Pressure	[bar]:	10.104	4.129	10.253
Press.Gradient	[bar/h]:	-0.5897	0.4114	-0.5237
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.101214

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	4.683274

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - 4.683274 ltr/h = _______ ltr/h < 1.850839tr/h

______ Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--1
==

Date: 13.Nov.1996 Time: 20:41:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	20:41:03	20:56:03	21:26:03
Stop	[-]:	20:43:03	20:58:03	21:28:03
Test-Pressure	[bar]:	10.117	4.245	10.261
Press.Gradient	[bar/h]:	-0.5361	0.3358	-0.4465
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[l/(m3*h)]:	0.040000
Actual Tightnessfactor	[l/(m3*h)]:	0.075225

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	3.480753

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - 3.480753 ltr/h = _______ ltr/h < 1.850839tr/h

______ Signature of Operator ______ Signature of Supervisor

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Ingenieurgesellschaft mbH D-21509 Glinde Fax. 040-710918-20

DS RESULT-PROTOCOL - Section--1
==

Date: 13.Nov.1996 Time: 21:58:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	21:58:03	22:13:03	22:43:03
Stop	[-]:	22:00:03	22:15:03	22:45:03
Test-Pressure	[bar]:	10.050	4.265	10.114
Press.Gradient	[bar/h]:	-0.8917	0.0636	-1.0386
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.122892

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	5.686338

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

Artificial Leak Test: (yes)/no

Leak.run no.1: ..46... ml/min = 2.76 ltr/h => 2.75 ltr/h at Operating press.

Leak.run no.2: ..33... ml/min = 1.98 ltr/h => 3.03 ltr/h at Operating press.

Leak.run no.3: ..47... ml/min = 2.82 ltr/h => 1.80 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 1.86 ltr/h (1)

______(1) - 5.686338 ltr/h = ______ ltr/h < 1.850839tr/h

.... Signature of Operator _____ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--1
===

Date: 13.Nov.1996 Time: 22:59:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	22:59:03	23:14:03	23:46:03
Stop	[-]:	23:01:03	23:16:03	23:48:03
Test-Pressure	[bar]:	10.123	4.232	10.069
Press.Gradient	[bar/h]:	-0.9303	0.0654	-1.4201
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.166764

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	7.716342

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________
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ohne Bewertung ____________________

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Artificial Leak Test: yes/no

Leak.run no.1: ..48... ml/min = 2.88 ltr/h => 2.86 ltr/h at Operating press.

Leak.run no.2: ..30... ml/min = 1.80 ltr/h => 2.77 ltr/h at Operating press.

Leak.run no.3: ..71... ml/min = 4.26 ltr/h => 4.25 ltr/h at Operating press. ← Fehler!

Calculated tightnessfactor at Operating pressure 3.29 ltr/h (1)

_______(1) - 7.716342 ltr/h = _______ ltr/h < 1.850839tr/h

...... Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--1
==

Date: 14.Nov.1996 Time: 00:35:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	00:35:03	00:50:03	01:25:03
Stop	[-]:	00:37:03	00:52:03	01:27:03
Test-Pressure	[bar]:	9.913	4.190	10.006
Press.Gradient	[bar/h]:	-1.5099	-0.2395	-1.6605
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.690600 0.146600

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.094208

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	4.359084

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = 5.40 ltr/h => 5.40 ltr/h at Operating press.

Leak.run no.2: .... ml/min = 3.48 ltr/h => 5.07 ltr/h at Operating press.

Leak.run no.3: .... ml/min = 5.40 ltr/h => 5.40 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 5.29 ltr/h (1)

5.29 (1) - 4.359084 ltr/h = 0.93 ltr/h < 1.850839tr/h

Signature of Operator W.D. [signature] Signature of Supervisor

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DS RESULT-PROTOCOL - Section--1

Date: 14.Nov.1996 Time: 01:51:03 Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	01:51:03	02:06:03	02:34:03
Stop	[-]:	01:53:03	02:08:03	02:36:03
Test-Pressure	[bar]:	10.330	4.284	10.336
Press.Gradient	[bar/h]:	-0.2747	0.5187	-0.3304
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.690600 0.146600

Tolerable Tightnessfactor	[l/(m3*h)]:	0.040000
Actual Tightnessfactor	[l/(m3*h)]:	-0.011968

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	-0.553789

DS Result: Tightnessfactor is ok !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = 0.______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure ______ ltr/h (1)

_______(1) - -0.553789 ltr/h = _______ ltr/h < 1.850839tr/h

_____ Signature of Operator _______ Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--1

Date: 14.Nov.1996   Time: 03:04:03   Operator : hcd

Volume	[m3]:	46.271
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	03:04:03	03:19:03	03:50:03
Stop	[-]:	03:06:03	03:21:03	03:52:03
Test-Pressure	[bar]:	10.148	4.320	10.221
Press.Gradient	[bar/h]:	-0.3674	0.4583	-0.5491
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.690600   0.146600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.010679

Tolerable Leakrate in ltr per hour	:	1.850839
Measured Leakrate in ltr per hour	:	0.494145

DS Result: Tightnessfactor is ok !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = 0.93 ltr/h => 0.92 ltr/h at Operating press.

Leak.run no.2: .... ml/min = 0.92 ltr/h => 0.64 ltr/h at Operating press.

Leak.run no.3: .... ml/min = 0.93 ltr/h => 0.92 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 0.83 ltr/h (1)

0.83 (1) - 0.494145 ltr/h = 0.34ltr/h < 1.850839tr/h

..... Signature of Operator   Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--2
==

Date: 12.Nov.1996 Time: 17:01:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	17:01:03	17:17:03	17:35:03
Stop	[-]:	17:03:03	17:19:03	17:37:03
Test-Pressure	[bar]:	10.058	4.095	10.070
Press.Gradient	[bar/h]:	-3.1089	-1.2478	-2.7360
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[l/(m3*h)]:	0.040000
Actual Tightnessfactor	[l/(m3*h)]:	0.251122

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	2.420208

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

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Artificial Leak Test: yes/no (no circled)

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

...___(1) - 2.420208 ltr/h = _______ ltr/h < 0.385503tr/h

______ Signature of Operator ______ Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--2
==

Date: 12.Nov.1996 Time: 17:49:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	17:49:03	18:03:03	18:19:03
Stop	[-]:	17:51:03	18:05:03	18:21:03
Test-Pressure	[bar]:	9.803	4.124	9.665
Press.Gradient	[bar/h]:	-2.4137	-1.0269	-2.5724
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.225071

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	2.169142

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

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Artificial Leak Test: Yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure ______ ltr/h (1)

___(1) - 2.169142 ltr/h = _______ ltr/h < 0.385503tr/h

______ Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
==

Date: 12.Nov.1996 Time: 18:33:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	18:33:03	18:49:03	19:06:03
Stop	[-]:	18:35:03	18:51:03	19:08:03
Test-Pressure	[bar]:	9.896	4.173	9.795
Press.Gradient	[bar/h]:	-2.4305	-0.9461	-2.4381
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.227643

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	2.193927

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

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Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - 2.193927 ltr/h = _______ ltr/h < 0.385503tr/h

______ Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2

==

Date: 12.Nov.1996 Time: 21:32:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	21:32:03	21:47:03	22:04:03
Stop	[-]:	21:34:03	21:49:03	22:06:03
Test-Pressure	[bar]:	10.355	4.231	10.142
Press.Gradient	[bar/h]:	-1.9101	-0.4782	-2.1454
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.224941

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	2.167885

TDS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

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Artificial Leak Test: (Yes)/no

Leak.run no.1: 9.5 ml/min = 0.57 ltr/h => 0.56 ltr/h at Operating press.

Leak.run no.2: 7 ml/min = 0.42 ltr/h => 0.65 ltr/h at Operating press.

Leak.run no.3: 12.5 ml/min = 0.75 ltr/h => 0.74 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 0.65 ltr/h (1)

______(1) - 2.167885 ltr/h = ______ ltr/h < 0.385503tr/h

____ Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
==

Date: 12.Nov.1996 Time: 22:18:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	22:18:03	22:32:03	22:48:03
Stop	[-]:	22:20:03	22:34:03	22:50:03
Test-Pressure	[bar]:	10.423	4.247	10.308
Press.Gradient	[bar/h]:	-1.4049	-0.0854	-1.4555
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.177904

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	1.714568

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - 1.714568 ltr/h = _______ ltr/h < 0.385503tr/h

_____ Signature of Operator _______ Signature of Supervisor

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DS RESULT-PROTOCOL-Section--2
==

Date: 12.Nov.1996 Time: 23:43:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	23:43:03	23:57:03	00:14:03
Stop	[-]:	23:45:03	23:59:03	00:16:03
Test-Pressure	[bar]:	9.783	4.086	9.847
Press.Gradient	[bar/h]:	-3.2866	-0.6733	-2.4565
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.377184

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	3.635146

DS Result: Tightnessfactor out of limit !

Comment: Signature: ________________________

Artificial Leak Test: (Yes)/No

Leak.run no.1: ..17... ml/min = 10.2 ltr/h => 1.03 ltr/h at Operating press.

Leak.run no.2: .....9.. ml/min = 0.54 ltr/h => 0.84 ltr/h at Operating press.

Leak.run no.3: ...18... ml/min = 10.8 ltr/h => 1.09 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 0.988 ltr/h (1)

_____ (1) - 3.635146 ltr/h = _______ ltr/h < 0.385503tr/h

.. Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
===

Date: 13.Nov.1996 Time: 00:58:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	00:58:03	01:12:03	01:28:03
Stop	[-]:	01:00:03	01:14:03	01:30:03
Test-Pressure	[bar]:	10.213	4.174	10.205
Press.Gradient	[bar/h]:	-1.2859	-0.0127	-1.3445
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.171422

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	1.652096

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = ______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

......_ (1) - 1.652096 ltr/h = _______ ltr/h < 0.385503tr/h

______ Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
==

Date: 13.Nov.1996 Time: 01:50:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	01:50:03	02:03:03	02:20:03
Stop	[-]:	01:52:03	02:05:03	02:22:03
Test-Pressure	[bar]:	10.174	4.403	10.100
Press.Gradient	[bar/h]:	-1.1428	-0.0149	-1.2952
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.165465

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	1.594685

TDS Result: Tightnessfactor out of limit !

Comment: Signature: ________________________

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Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

......(1) - 1.594685 ltr/h = _______ ltr/h < 0.385503tr/h

Signature of Operator ______ Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--2
==

Date: 14.Nov.1996   Time: 16:26:03   Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	16:26:03	16:40:03	16:58:03
Stop	[-]:	16:28:03	16:42:03	17:00:03
Test-Pressure	[bar]:	9.523	3.883	9.689
Press.Gradient	[bar/h]:	-4.1838	-2.0621	-4.1109
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[l/(m3*h)]:	0.040000
Actual Tightnessfactor	[l/(m3*h)]:	0.347373

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	3.347840

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - 3.347840 ltr/h = _______ ltr/h < 0.385503tr/h

_____ Signature of Operator _____ Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--2
===

Date: 14.Nov.1996 Time: 17:15:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	17:15:03	17:34:03	17:51:03
Stop	[-]:	17:17:03	17:36:03	17:53:03
Test-Pressure	[bar]:	9.772	4.065	9.745
Press.Gradient	[bar/h]:	-3.7826	-1.5428	-3.5721
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.365347

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	3.521059

DS Result: Tightnessfactor out of limit !

Comment: Signature: ________________________

____

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Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = ______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = ______ ltr/h => ______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure ______ ltr/h (1)

_______(1) - 3.521059 ltr/h = _______ ltr/h < 0.385503tr/h

...... Signature of Operator ______ Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--2
===

Date: 14.Nov.1996 Time: 18:17:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	18:17:03	18:30:03	18:49:03
Stop	[-]:	18:19:03	18:32:03	18:51:03
Test-Pressure	[bar]:	9.581	4.172	9.608
Press.Gradient	[bar/h]:	-4.1207	-1.7882	-4.3076
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.455088

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	4.385949

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________
----

k1 = -1.5665 ______________________

k2 = 0.3066 ______________________

Artificial Leak Test: yes/no

Leak.run no.1: 31.... ml/min = 1.86 ltr/h => 1.90 ltr/h at Operating press.

Leak.run no.2: 31.5.... ml/min = 1.05 ltr/h => 1.63 ltr/h at Operating press.

Leak.run no.3: 31.... ml/min = 1.86 ltr/h => 1.90 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 1.31 ltr/h (1)

______ (1) - 4.385949 ltr/h = ______ ltr/h < 0.385503tr/h

Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL-Section--2
==

Date: 14.Nov.1996 Time: 19:19:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	19:19:03	19:33:03	19:51:03
Stop	[-]:	19:21:03	19:35:03	19:53:03
Test-Pressure	[bar]:	9.872	4.325	10.292
Press.Gradient	[bar/h]:	-2.9819	-1.0617	-3.2052
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -1.560500 0.369600

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: -0.041211

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	-0.397175

DS Result: Error while Tightness-Control !

Comment: Signature: ________________

Artificial Leak Test: yes/no

Leak.run no.1: 11 ml/min = 0.66 ltr/h => 0.66 ltr/h at Operating press.

Leak.run no.2: 5.5 ml/min = 0.33 ltr/h => 0.50 ltr/h at Operating press.

Leak.run no.3: 11 ml/min = 0.66 ltr/h => 0.65 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 0.60 ltr/h (1)

0.60 (1) - -0.397175 ltr/h = 1.00 ltr/h < 0.385503tr/h

Signature of Operator Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
==

Date: 14.Nov.1996 Time: 20:28:03 Operator : kcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	20:28:03	20:45:03	21:02:03
Stop	[-]:	20:30:03	20:47:03	21:04:03
Test-Pressure	[bar]:	10.086	4.354	9.906
Press.Gradient	[bar/h]:	-2.0798	-0.7403	-2.2674
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -1.560500 0.369600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	-0.285070

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	-2.747389

TDS Result: Error while Tightness-Control !

Comment: Signature: ________ ________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

____ (1) - -2.747389 ltr/h = _______ ltr/h < 0.385503tr/h

___ Signature of Operator _______ Signature of Supervisor

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DS RESULT-PROTOCOL-Section--2
==

Date: 14.Nov.1996   Time: 21:25:03   Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	21:25:03	21:42:03	22:00:03
Stop	[-]:	21:27:03	21:44:08	22:02:03
Test-Pressure	[bar]:	10.015	4.125	10.005
Press.Gradient	[bar/h]:	-2.0654	-0.6239	-2.2276
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -1.560500 0.369600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	-0.270692

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	-2.608818

TDS Result: Error while Tightness-Control !

Comment: Signature: ________________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = ... ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = ________ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _ _ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - -2.608818 ltr/h = _______ ltr/h < 0.385503tr/h

.... Signature of Operator   ____ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
==

Date: 15.Nov.1996 Time: 00:44:03 Operator : hcd

Volume	[m3]:	9.638
ri/s~	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	00:44:03	00:57:03	01:14:03
Stop	[-]:	00:46:03	00:59:03	01:16:03
Test-Pressure	[bar]:	10.371	4.326	10.327
Press.Gradient	[bar/h]:	-0.3880	0.3518	-0.4566
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -1.560500 0.369600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	-0.600284

Tolerable Leakrate in ltr per hour :	0.385503
Measured Leakrate in ltr per hour :	-5.785290

DS Result: Error while Tightness-Control !

Comment: Signature: ______________________

Nach Leck ________________________________

____

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = ______ ltr/h => ______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = ______ ltr/h => ______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = ______ ltr/h => ______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure ______ ltr/h (1)

______(1) - -5.785290 ltr/h = ______ ltr/h < 0.385503tr/h

Signature of Operator ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--2
==

Date: 15.Nov.1996 Time: 01:34:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	01:34:03	01:48:03	02:04:03
Stop	[-]:	01:36:03	01:50:03	02:06:03
Test-Pressure	[bar]:	10.396	4.289	10.237
Press.Gradient	[bar/h]:	-0.3066	0.3809	-0.4476
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.128500

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	-0.003486

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	-0.033597

DS Result: Tightnessfactor is ok !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - -0.033597 ltr/h = _______ ltr/h < 0.385503tr/h

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D S R E S U L T - P R O T O C O L - Section--2
===

Date: 15.Nov.1996 Time: 02:17:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	02:17:03	02:31:03	02:49:03
Stop	[-]:	02:19:03	02:33:03	02:51:03
Test-Pressure	[bar]:	10.348	4.136	10.195
Press.Gradient	[bar/h]:	-0.3371	0.3752	-0.4698
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.128500

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	-0.002008

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	-0.019356

DS Result: Tightnessfactor is ok !

Comment: Signature: ______________________

____

____

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = ______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = ______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = ______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______(1) - -0.019356 ltr/h = _______ ltr/h < 0.385503tr/h

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DS RESULT-PROTOCOL - Section--2
==

Date: 15.Nov.1996 Time: 03:42:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	03:42:03	03:56:03	04:13:03
Stop	[-]:	03:44:03	03:58:03	04:15:03
Test-Pressure	[bar]:	10.069	4.151	9.789
Press.Gradient	[bar/h]:	-1.8161	-0.9779	-2.9187
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.128500

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.140020

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	1.349456

DS Result: Tightnessfactor out of limit !

Comment: Signature: ____________________

Leakrate drauts up! ______________________

____

Artificial Leak Test: yes/no

Leak.run no.1: 25 ml/min = 1,50 ltr/h => 1,49 ltr/h at Operating press.

Leak.run no.2: 23,5 ml/min = 1,41 ltr/h => 2,19 ltr/h at Operating press.

Leak.run no.3: 42,5 ml/min = 2,55 ltr/h => 2,58 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 2,09 ltr/h (1)

.... (1) - 1.349456 ltr/h = _______ ltr/h < 0.385503tr/h

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DS RESULT-PROTOCOL - Section--2
==

Date: 15.Nov.1996 Time: 04:27:03 Operator : hcd

Volume	[m3]:	9.638
ri/s	[-]:	11.863
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	04:27:03	04:41:03	04:59:03
Stop	[-]:	04:29:03	04:43:03	05:01:03
Test-Pressure	[bar]:	9.979	4.060	9.889
Press.Gradient	[bar/h]:	-2.8622	-0.9080	-2.9630
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.128500

Tolerable Tightnessfactor	[l/(m3*h)]:	0.040000
Actual Tightnessfactor	[l/(m3*h)]:	0.264906

Tolerable Leakrate in ltr per hour	:	0.385503
Measured Leakrate in ltr per hour	:	2.553055

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________
----

k1 = -0.7539

k2 = 0.1271

Artificial Leak Test: yes/no

Leak.run no.1: 42.5 ml/min = 2.55 ltr/h => 2.55 ltr/h at Operating press.

Leak.run no.2: 23.0 ml/min = 1.38 ltr/h => 2.16 ltr/h at Operating press.

Leak.run no.3: 42.5 ml/min = 2.55 ltr/h => 2.56 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 2.42 ltr/h (1)

______(1) - 2.553055 ltr/h = _______ ltr/h < 0.385503tr/h

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DS RESULT - PROTOCOL - Section--3
==

Date: 15.Nov.1996 Time: 15:58:03 Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	15:58:03	16:12:03	16:28:03
Stop	[-]:	16:00:03	16:14:03	16:30:03
Test-Pressure	[bar]:	10.422	4.213	10.359
Press.Gradient	[bar/h]:	-0.5080	0.3185	-0.5625
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.080000

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.074376

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	0.393311

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

______ (1) - 0.393311 ltr/h = _______ ltr/h < 0.211524tr/h

______ Signature of Operator ______ Signature of Supervisor

K2 01??

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D S R E S U L T - P R O T O C O L - Section--3
==

Date: 15.Nov.1996   Time: 16:43:03   Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	16:43:03	16:57:03	17:12:03
Stop	[-]:	16:45:03	16:59:09	17:14:03
Test-Pressure	[bar]:	10.241	4.516	10.353
Press.Gradient	[bar/h]:	-0.4074	0.3267	-0.5330
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]:   -0.800000   0.138200

Tolerable Tightnessfactor   [1/(m3*h)]:   0.040000
Actual   Tightnessfactor   [1/(m3*h)]:   -0.000432

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	-0.002283

TDS Result: Tightnessfactor is ok !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = ________ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure   ______ ltr/h (1)

_____ (1) - -0.002283 ltr/h = _______ ltr/h < 0.211524tr/h

_____ Signature of Operator   _______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--3
==

Date: 15.Nov.1996 Time: 17:26:03 Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	17:26:03	17:39:03	17:54:03
Stop	[-]:	17:28:03	17:41:03	17:56:03
Test-Pressure	[bar]:	10.245	4.456	10.301
Press.Gradient	[bar/h]:	-0.4118	0.3485	-0.5167
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.138200

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.001953

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	0.010329

TDS Result: Tightnessfactor is ok !

Comment:

Signature: ________________________

Artificial Leak Test: yes/no

Leak.run no.1: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.2: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Leak.run no.3: .... ml/min = _______ ltr/h => _______ ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure _______ ltr/h (1)

_______ (1) - 0.010329 ltr/h = _______ ltr/h < 0.211524tr/h

_______ Signature of Operator _______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--3
==

Date: 15.Nov.1996 Time: 18:40:03 Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	18:40:03	18:54:03	19:09:03
Stop	[-]:	18:42:03	18:56:03	19:11:03
Test-Pressure	[bar]:	10.195	4.315	10.223
Press.Gradient	[bar/h]:	-1.9010	-0.3328	-2.1412
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.800000 0.138200

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.189276

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	1.000915

DS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________
----

k1 = -0,5368 ____________________

k2 = 0,1386 ____________________

Artificial Leak Test: yes/no

Leak.run no.1: 12,5 ml/min = 0,75 ltr/h => 0,74 ltr/h at Operating press.

Leak.run no.2: 6,0 ml/min = 0,36 ltr/h => 0,55 ltr/h at Operating press.

Leak.run no.3: 12,0 ml/min = 0,72 ltr/h => 0,71 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 0,66 ltr/h (1)

_____ (1) - 1.000915 ltr/h = _______ ltr/h < 0.211524tr/h

Signature of Operator ______ Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--3
==

Date: 15.Nov.1996   Time: 19:36:03   Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	19:36:03	19:49:03	20:06:03
Stop	[-]:	19:38:03	19:51:03	20:08:03
Test-Pressure	[bar]:	10.253	4.250	10.172
Press.Gradient	[bar/h]:	-1.6841	-0.3757	-2.0796
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]:   -0.536800   0.138600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.097353

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	0.514816

TDS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: ..12,5. ml/min = 0,75 ltr/h => 0.74 ltr/h at Operating press.

Leak.run no.2: .0.6..... ml/min = 0.36 ltr/h => 0,55 ltr/h at Operating press.

Leak.run no.3: ..13..... ml/min = 0,75 ltr/h => 0,77 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure   0.68 ltr/h (1)

0,68 (1) - 0.514816 ltr/h = 0,17 ltr/h < 0.211524tr/h

Signature of Operator   ______ Signature of Supervisor

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DS RESULT-PROTOCOL - Section--3
==

Date: 15.Nov.1996 Time: 21:00:03 Operator : hcd

Volume	[m3]:	5.288		
ri/s	[-]:	12.368		
Operating-press.	[bar]:	10.000		
Run No.	[-]:	1	2	3
Start	[-]:	21:00:03	21:13:03	21:29:03
Stop	[-]:	21:02:03	21:15:03	21:31:03
Test-Pressure	[bar]:	9.970	4.187	10.117
Press.Gradient	[bar/h]:	-3.3845	-1.2402	-3.4608
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.622700 0.138600

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.230091

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	1.216746

DS Result: Tightnessfactor out of limit !

Comment: Signature: ________________________

Artificial Leak Test: yes/no

Leak.run no.1: 25.5 ml/min = 1.53 ltr/h => 1.53 ltr/h at Operating press.

Leak.run no.2: 14.5 ml/min = 0.87 ltr/h => 1.34 ltr/h at Operating press.

Leak.run no.3: 26.5 ml/min = 1.59 ltr/h => 1.58 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 1.48 ltr/h (1)

1.48 (1) - 1.216746 ltr/h = 0.26 ltr/h < 0.211524ltr/h

Signature of Operator W. B. [signature] Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--3
==

Date: 15.Nov.1996 Time: 23:14:03 Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	23:14:03	23:28:03	23:45:03
Stop	[-]:	23:16:03	23:30:03	23:47:03
Test-Pressure	[bar]:	9.977	4.185	10.010
Press.Gradient	[bar/h]:	-2.5203	-0.8868	-2.5913
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.708600 0.138600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.166105

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	0.878381

DS Result: Tightnessfactor out of limit !

Comment: Signature: ________________________

Artificial Leak Test: yes/no

Leak.run no.1: 18 ml/min = 1.08 ltr/h => 1.08 ltr/h at Operating press.

Leak.run no.2: 10.5 ml/min = 0.63 ltr/h => 0.97 ltr/h at Operating press.

Leak.run no.3: 16.5 ml/min = 0.99 ltr/h => 0.99 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 1.01 ltr/h (1)

1.01 (1) - 0.878381 ltr/h = 0.13 ltr/h < 0.211524tr/h

Signature of Operator Signature of Supervisor

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D S R E S U L T - P R O T O C O L - Section--3
==

Date: 16.Nov.1996 Time: 00:09:03 Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	00:09:03	00:23:03	00:38:03
Stop	[-]:	00:11:03	00:25:03	00:40:03
Test-Pressure	[bar]:	9.855	4.043	10.017
Press.Gradient	[bar/h]:	-3.2669	-1.1038	-3.4668
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.708600 0.138600

Tolerable Tightnessfactor	[1/(m3*h)]:	0.040000
Actual Tightnessfactor	[1/(m3*h)]:	0.271717

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	1.436870

TDS Result: Tightnessfactor out of limit !

Comment: Signature: ________________________

Artificial Leak Test: yes/no

Leak.run no.1: 25.5 ml/min = 1.53 ltr/h => 1.54 ltr/h at Operating press.

Leak.run no.2: 13.5 ml/min = 0.81 ltr/h => 1.23 ltr/h at Operating press.

Leak.run no.3: 25.5 ml/min = 1.53 ltr/h => 1.52 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 1.44 ltr/h (1)

1.44 (1) - 1.436870 ltr/h = 0.00 ltr/h < 0.211524tr/h

Signature of Operator Signature of Supervisor

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DS RESULT-PROTOCOL-Section--3
==

Date: 16.Nov.1996 Time: 01:02:03 Operator : hcd

Volume	[m3]:	5.288
ri/s	[-]:	12.368
Operating-press.	[bar]:	10.000

Run No.	[-]:	1	2	3
Start	[-]:	01:02:03	01:16:03	01:31:03
Stop	[-]:	01:04:03	01:18:03	01:33:03
Test-Pressure	[bar]:	10.233	4.259	10.194
Press.Gradient	[bar/h]:	-1.8836	-0.3079	-2.0866
Kappa	[1e-6/bar]:	84.7009	84.7009	84.7009

k1-,k2-factors [-]: -0.708600 0.138600

Tolerable Tightnessfactor [1/(m3*h)]: 0.040000
Actual Tightnessfactor [1/(m3*h)]: 0.161346

Tolerable Leakrate in ltr per hour	:	0.211524
Measured Leakrate in ltr per hour	:	0.853213

TDS Result: Tightnessfactor out of limit !

Comment: Signature: ______________________

Artificial Leak Test: yes/no

Leak.run no.1: 11 ml/min = 0.66 ltr/h => 0.65 ltr/h at Operating press.

Leak.run no.2: 5 ml/min = 0.30 ltr/h => 0.46 ltr/h at Operating press.

Leak.run no.3: 10.5 ml/min = 0.63 ltr/h => 0.62 ltr/h at Operating press.

Calculated tightnessfactor at Operating pressure 0.58 ltr/h (1)

0.58 (1) - 0.853213 ltr/h = 0.27 ltr/h < 0.211524tr/h

______ Signature of Operator W. D. [signature] Signature of Supervisor

6 15 2.703]
25 2.645] 0.058

11:00 1,503
10 480
20 441
30 472

$\frac{0.058 \text{ bar}}{10 \text{ sek}} \hat{=} 20.88 \text{ bar/h}$

30 609
35 574
40 540
45 510
50 473
55 442
7:00 2.412

$(0.89 \cdot 11.95 + 84.7) \cdot 10.88 \frac{bar}{h} \cdot 12.28 = 24.44$ l/h
@ 2.743

10 356
20 305
30 2.252
40 205
50 156
8:00 2,107 = 21.42 l/h @ 2.26 bar => 45.08 l/h @ 10 bar

47.26 l/h @ 10

10
20 2.025
30 1.988
40 1.945
50 1.906
9:00 1.866
10
20 1.797
30 1.764
40 732
50 702
10:00 1.669]
10 640] 0.029

$(0.89 \cdot 11.95 + 84.7) \cdot 10.44 \cdot 12.28 = 12.22$ @ 1.6

30.01 l/h @ 10 bar

20 612
30 584
40 558
50 530

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D T - R E S U L T - P R O T O C O L - Section--1
==

Measurement Start Date: 14.11.96 Time: 04:14:00
Measurement Stop Date: 14.11.96 Time: 15:14:00

Volume	[m3]:	46.27097
ri/s	[--]:	12.36842
kappa0	[0^-6/bar]:	84.70085
Temp-coef.exp.Fluid	[10^-6/°C]:	900.00000
Temp-coef.exp. Pipe	10^-6/°C]:	28.860
Module of elast. Pipe	[N/mm2]:	210000.000
Contraction of Area	[--]:	0.250
Initial Pressure	[bar]:	10.87783
Final Pressure	[bar]:	10.27205
Initial Temperature	[°C]:	25.00000
Final Temperature	[°C]:	25.00000

Actual Leakrate per Hour	[l/h]:	-0.03441
Actual Leakrate total	[l/h]:	0.24726
Tolerable Leakrate total	[l/h]:	4.00000

Hour [--]	Measurement Start [--]	Pressure [bar]	Temp.(sel) [°C]	Kappa [10^-6/bar]	Leakr./ Hour [l/h]	Leakr. total [l/h]
0	14.11.96 04:14:00	10.73487	25.00000	84.70085	0.74485	0.74485
1	14.11.96 05:14:00	10.66625	25.00000	84.70085	0.30389	0.50649
2	14.11.96 06:14:00	10.61111	25.00000	84.70085	0.24418	0.41445
3	14.11.96 07:14:00	10.55537	25.00000	84.70085	0.24684	0.37092
4	14.11.96 08:14:00	10.49769	25.00000	84.70085	0.25543	0.34711
5	14.11.96 09:14:00	10.42438	25.00000	84.70085	0.32468	0.34327
6	14.11.96 10:14:00	10.35707	25.00000	84.70085	0.29810	0.33668
7	14.11.96 11:14:00	10.28255	25.00000	84.70085	0.32999	0.33583
8	14.11.96 12:14:00	10.26882	25.00000	84.70085	0.06081	0.30475
9	14.11.96 13:14:00	10.26428	25.00000	84.70085	0.02012	0.27585
10	14.11.96 14:14:00	10.27205	25.00000	84.70085	-0.03441	0.24726

Comment: Signature: ________________________

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D T - R E S U L T - P R O T O C O L - Section--2
==

Measurement Start Date: 13.11.96 Time: 02:52:00
Measurement Stop Date: 13.11.96 Time: 12:52:01

Volume	[m3]:	9.63759
ri/s	[--]:	11.86298
kappa0	[0^-6/bar]:	84.70085
Temp-coef.exp.Fluid	[10^-6/°C]:	900.00000
Temp-coef.exp. Pipe	10^-6/°C]:	28.860
Module of elast. Pipe	[N/mm2]:	210000.000
Contraction of Area	[--]:	0.250
Initial Pressure	[bar]:	11.56293
Final Pressure	[bar]:	5.51138
Initial Temperature	[°C]:	25.00000
Final Temperature	[°C]:	25.00000

Actual Leakrate per Hour	[l/h]:	0.42180
Actual Leakrate total	[l/h]:	0.56403
Tolerable Leakrate total	[l/h]:	4.00000

Hour [--]	Measurement Start [--]	Pressure [bar]	Temp.(sel) [°C]	Kappa [10^-6/bar]	Leakr./ Hour [l/h]	Leakr. total [l/h]
0	13.11.96 02:52:00	10.54303	25.00000	84.70085	1.10157	1.10157
1	13.11.96 03:52:00	9.64240	25.00000	84.70085	0.82684	0.95307
2	13.11.96 04:52:00	8.91984	25.00000	84.70085	0.66336	0.85141
3	13.11.96 05:52:00	8.30577	25.00000	84.70085	0.56376	0.77670
4	13.11.96 06:52:00	7.76591	25.00000	84.70085	0.49562	0.71875
5	13.11.96 07:52:00	7.27629	25.00000	84.70085	0.44951	0.67272
6	13.11.96 08:52:00	6.82617	25.00000	84.70085	0.41323	0.63484
7	13.11.96 09:52:00	6.40579	25.00000	84.70085	0.38594	0.60313
8	13.11.96 10:52:00	5.97083	25.00000	84.70085	0.39933	0.58010
9	13.11.96 11:52:00	5.51138	25.00000	84.70085	0.42180	0.56403

Comment: Signature: ______________________

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D T - R E S U L T - P R O T O C O L - Section--2
===

Measurement Start Date: 16.11.96 Time: 02:10:00
Measurement Stop Date: 16.11.96 Time: 15:10:01

Volume	[m3]:	9.63759
ri/s	[--]:	11.86298
kappa0	[0^-6/bar]:	84.70085
Temp-coef.exp.Fluid	[10^-6/°C]:	900.00000
Temp-coef.exp. Pipe	10^-6/°C]:	28.860
Module of elast. Pipe	[N/mm2]:	210000.000
Contraction of Area	[--]:	0.250
Initial Pressure	[bar]:	10.63681
Final Pressure	[bar]:	8.02398
Initial Temperature	[°C]:	25.00000
Final Temperature	[°C]:	25.00000

Actual Leakrate per Hour	[l/h]:	0.06074
Actual Leakrate total	[l/h]:	0.18667
Tolerable Leakrate total	[l/h]:	4.00000

Hour [--]	Measurement Start [--]	Pressure [bar]	Temp.(sel) [°C]	Kappa [10^-6/bar]	Leakr./ Hour [l/h]	Leakr. total [l/h]
0	16.11.96 02:10:00	9.41633	25.00000	84.70085	1.31821	1.31821
1	16.11.96 03:10:00	9.14383	25.00000	84.70085	0.25017	0.74089
2	16.11.96 04:10:00	8.97456	25.00000	84.70085	0.15540	0.53546
3	16.11.96 05:10:00	8.84312	25.00000	84.70085	0.12068	0.42772
4	16.11.96 06:10:00	8.73390	25.00000	84.70085	0.10027	0.36021
5	16.11.96 07:10:00	8.63981	25.00000	84.70085	0.08638	0.31340
6	16.11.96 08:10:00	8.55400	25.00000	84.70085	0.07878	0.27915
7	16.11.96 09:10:00	8.47434	25.00000	84.70085	0.07313	0.25290
8	16.11.96 10:10:00	8.37381	25.00000	84.70085	0.09229	0.23475
9	16.11.96 11:10:00	8.28591	25.00000	84.70085	0.08071	0.21912
10	16.11.96 12:10:00	8.17843	25.00000	84.70085	0.09867	0.20801
11	16.11.96 13:10:00	8.09015	25.00000	84.70085	0.08105	0.19730
12	16.11.96 14:10:00	8.02398	25.00000	84.70085	0.06074	0.18667

Comment: Signature: ____________________

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DT - RESULT - PROTOCOL - Section--3

===

Measurement Start Date: 15.11.96 Time: 05:39:00
Measurement Stop Date: 15.11.96 Time: 15:39:00

Volume	[m3]:	5.28811
ri/s	[--]:	12.36842
kappa0	[0^-6/bar]:	84.70085
Temp-coef.exp.Fluid	[10^-6/°C]:	900.00000
Temp-coef.exp. Pipe	10^-6/°C]:	28.860
Module of elast. Pipe	[N/mm2]:	210000.000
Contraction of Area	[--]:	0.250
Initial Pressure	[bar]:	10.96803
Final Pressure	[bar]:	7.99096
Initial Temperature	[°C]:	25.00000
Final Temperature	[°C]:	25.00000

Actual Leakrate per Hour	[l/h]:	0.09139
Actual Leakrate total	[l/h]:	0.15297
Tolerable Leakrate total	[l/h]:	4.00000

Hour [--]	Measurement Start [--]	Pressure [bar]	Temp.(sel) [°C]	Kappa [10^-6/bar]	Leakr./ Hour [l/h]	Leakr. total [l/h]
0	15.11.96 05:39:00	10.38101	25.00000	84.70085	0.34953	0.34953
1	15.11.96 06:39:00	9.94324	25.00000	84.70085	0.22157	0.28036
2	15.11.96 07:39:00	9.60032	25.00000	84.70085	0.17356	0.24288
3	15.11.96 08:39:00	9.30710	25.00000	84.70085	0.14840	0.21834
4	15.11.96 09:39:00	9.04832	25.00000	84.70085	0.13098	0.20033
5	15.11.96 10:39:00	8.80875	25.00000	84.70085	0.12125	0.18681
6	15.11.96 11:39:00	8.58016	25.00000	84.70085	0.11569	0.17643
7	15.11.96 12:39:00	8.36863	25.00000	84.70085	0.10706	0.16759
8	15.11.96 13:39:00	8.17154	25.00000	84.70085	0.09975	0.15993
9	15.11.96 14:39:00	7.99096	25.00000	84.70085	0.09139	0.15297

Comment: Signature: ______________________

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Appendix D

REPORT FROM PHYSICAL ACOUSTICS CORPORATION

PHYSICAL ACOUSTICS CORPORATION

A MISTRAS Holdings Company

Sound Technology for Safety & the Environment

DUNEGAN TESTING AND INSPECTION

A PHYSICAL ACOUSTICS CORPORATION

Acoustic Emission Inspection Report

on

BURIED PIPE LEAK DETECTION

at

for

AMERICAN PETROLEUM INSTITUTE
Washington, DC.

DTI Job No: FT97-802A
Test Date: November, 1996

P.O. Box 3135 · Princeton, NJ 08543-3135 • (609) 844-0800 • Fax: (609) 895-9726 • e-mail: sales@pacndt.com

DUNEGAN TESTING AND INSPECTION

A PHYSICAL ACOUSTICS CORPORATION

Acoustic Emission Inspection Report

on

BURIED PIPE LEAK DETECTION

at

for

AMERICAN PETROLEUM INSTITUTE
Washington, DC.

DTI Job No: FT97-802A
Test Date: November, 1996

DUNEGAN TESTING AND INSPECTION
A PHYSICAL ACOUSTICS CORPORATION

Acoustic Emission Inspection Report

on

BURIED PIPE LEAK DETECTION

at

for

AMERICAN PETROLEUM INSTITUTE
Washington, DC.

DTI Job No: FT97-802A
Test Date: November, 1996
Test Method: Leak Detection

Test Operators: Sam Ternowchek
Tom Gandy

Data Analysis: Sam Ternowchek

Final Approval: ____________________

Ronnie K. Miller, Ph.D., Executive Director
Engineering Services and Inspection

For further information concerning this report, contact:

Physical Acoustics Corporation
P.O. Box 3135
Princeton, NJ 08543
1-609-844-0800

APPENDIX

FIGURES

INTRODUCTION

Acoustic Emissions are stress waves generated by the rapid release of energy within a material. Classic sources of AE are defect related deformations such as cracks and plastic deformation. A typical application of AE utilizes a stimulus such as mechanical loading to cause localized yielding. This yielding produces stress waves which radiate out into the material or structure. At some point a piezoelectric crystal detects the mechanical energy and converts it into an electrical signal. This pulse can be amplified, filtered and characterized in terms of features associated with the original source mechanism.

AE testing is routinely applied in evaluating structural integrity for used equipment as well as new equipment. Typical problems detected with AE include, active cracks, corrosion and the effect of corrosion, embrittlement, pitting and gouges. In welds, AE can detect lack of fusion, undercuts, inclusions, porosity and lack of penetration.

In addition to structural integrity, AE has been shown to be a very useful tool in detecting and locating leaks in piping, vessels and other components. When leakage occurs through an orifice, turbulent flow occurs. This turbulence creates high frequency pressure waves which can be detected by the AE sensors. There are also burst emissions which can be associated with structural degradation or pressure variations which enhance the ability of AE to detect the occurrence of leakage. These burst emissions are used to determine the location of leak or structural degradation.

I. BACKGROUND

Acoustic Emission (AE) has been used for many years, in different forms, to detect and locate leaks in pressurized systems. It has been used as a research tool, a continuous monitor and a field testing tool. The technique is based on the principle that leaks in liquid filled, buried pipelines, emit acoustic waves in the sonic and ultrasonic frequency ranges. These acoustic waves can be detected by a piezoelectric sensor placed in contact with the piping. The signals are then amplified and "processed" to produce a measurement which can be used as an indication of the presence of leakage and, with more than one sensor or measurement, where the location of the leak is.

The leak mechanism and artifacts of the leakage generate the acoustic waves. These sources include but are not limited to:

A) Turbulent Flow is the passage of the medium through a complicated path in the pipe wall. It produces high accelerations, which are turbulent in nature. This turbulence generates an acoustic signal which is the primary source of the signal.

B) Cavitation results when gas bubbles and/or various voids in the liquid adjacent to the leak site nucleate, expand and collapse in the liquid generating AE signals. Cavitation produces a burst signal which can be very high in amplitude. It is very useful for locating the leak.

C) Particle Blocking - Particle trapped in the pipe fluid can momentarily block the leak orifice. This in turn causes a build up of pressure which is suddenly released when the blockage is cleared. The resulting "water hammer" produces high amplitude, high energy, AE signals that can be detected, measured and located.

D) Soil Movement - When escaping fluid affects the material around the pipe, this movement can impact the outer diameter and generate an AE signal. While this is a leak artifact mechanism, it can produce high amplitude signals and help in the detection/location.

These above mechanisms produce smooth continuous signals, modulated continuous signals and transient (burst type) signals. The signal detection and processing needs to take into account all three in order to be effective in detecting and locating leaks in buried pipelines. The signal processing used most often in leak detection for field applications include the following:

A) Measurement of RMS, energy rate or average signal level - these techniques are somewhat straight forward and are typically used in battery powered instruments for leak detection.

B) Spectral Analysis - a somewhat simple technique used primarily for leak detection. It has been most useful for detecting leakage in high background noise environments.

C) Crossplots such as counts/amplitude - Another technique which has proven useful when detecting leakage in high background noise environments. It compares one signal characteristic vs another to identify multiple sources.

D) Amplitude difference methods - This technique relies on the fact that attenuation of the leak signals decrease as the distance between the measurement point and the leak source decreases. Thus, as you get closer to the leak, the measured signal level increases. By using the ratio of the change in distance to the change in signal amplitude, an estimate of the leak location is made.

E) Time difference measurement - When the same signal can be measured between two different points on the pipeline, the location of the signal source (leakage) can be calculated based on the time difference of propagation between the two points. This technique is the most often used leak location technique. When used properly it can provide a very accurate measurement of source location.

The above are the most often used methods for detecting and locating a leak source. They are utilized in the field as well as laboratory applications and have been the basis of most of the leak detection work performed to date. There are, however, other digital, signal processing techniques which are beginning to find there way into use. These include: cross correlation function analysis; coherence function analysis; and cross correlation using coherence to select frequency range.

These digital techniques offer additional capabilities in detecting low level leakage and/or leakage in the presence of high structure noise. They are, at this point, somewhat difficult and time consuming to utilize in the field today. There is an on-going project sponsored by SERDP (EPA, DOD & DOE) through the Emission Reduction Research Center of the New Jersey Institute of Technology, to evaluate all types of AE leak detection and location techniques including digital signal processing. They will provide a comprehensive report including recommendations and guidelines sometime in 1997.

The last aspect of AE leak detection and location is the factors which affect the detectability of a leak. Basically these are: the magnitudes of the signal generated by the leakage; the attenuation of the signal between the leak source and the sensor; and the background noise on the structure being tested. These factors affect whether or not a leak signal can be detected/located and at what distance away this detection/location can be made.

A) Leak Signal - The signal generated by the leakage is affected by several factors. It is directly proportional to the differential pressure and leak orifice size and indirectly proportional to the viscosity of the fluid as well as the length of the leak path. The compressibility of the fluid, fluid density and fluid turbulence, also effect the signal magnitude.

B) Attenuation - This is the rate at which the signal decreases as it propagates further away from the source. The rate of attenuation is affected by material type and shape, fluid and back fill. While attenuation takes place in the pipe material at a certain rate, there can be a second signal which propagates through the fluid in the pipe which would have a different, and usually lower, attenuation rate.

C) Background noise - This is a "noise" effect sometimes produced by other operating equipment in contact with the pipeline. Typically, this would be pumps or compressors. Their effect decreases as the distance from the source increases.

The three above factors determine whether or not a leak may generate AE, what magnitude of signal is generated and how detectable and locatable the leak may be. Together with leak artifacts (e.g. soil movement), they form the basis of the Acoustic Emission leak detection/location technique.

Acoustic Emission offers a number of benefits in detecting and locating leaks. It is a fast technique which can often detect and locate a leak in a complex system within a matter of hours. Large sections of piping can be tested quickly. A single test crew can test two miles of pipeline a day. It is a sensitive technique. As noted earlier, the detectability is effected by several factors, however, with good planning, a sensitive test can be performed. It offers the advantage of leak location, with a high degree of accuracy, in addition to leak detection. It is an inexpensive technique. The cost per day for a test crew is very low compared to other techniques. There are no special set-ups or variations of operating conditions required. In most cases, the AE technique is applied with normal process materials and pressure. The testing is accomplished when most convenient for the operator of the pipeline. The AE technique is not effected by changes in environmental conditions. The testing is a function of only the piping and it's contents. Last, but not least, the AE test is not effected by the volume of the line being tested. It's sensitivity is the same whether 100 feet or 10 miles of pipeline are being tested. There is no need to compensate sensitivity for volume variation. AE also has the ability to indicate other problems in the piping system. In the API test, a problem in the Cathodic Protection system was detected.

II. WORK STATEMENT

Physical Acoustics Corporation/Dunegan Testing and Inspection was contracted by the American Petroleum Institute (API) to perform Acoustic Emission leak detection and location on a buried pipeline at the   The line is part of a hydrant system supplying jet fuel to the aircraft terminals. The purpose of the testing was to allow the API task group to observe the capabilities of AE leak detection and location capabilities and comment on it's results. PAC/DTI provided all necessary equipment and man power to perform the above. The testing was performed on several sections of the line, one of which was known to have a large leak. Additional measurements were made with controlled, out of ground leaks, to evaluate sensitivity and minimum detectable levels.

2.1 Pipeline Description

Five (5) sections of the hydrant system were identified as test segments by API. They are shown in Figure 1 and labeled Lines 1 to 5.

Line 1 is approximately 3500 feet long, 10 inches in diameter and has a volume of 14,300 gallons.

Line 2 is approximately 600 feet long of 10 inch line and 300 feet of 6 inch line. It's volume is approximately 2900 gallons. It includes laterals to eight (8) hydrants.

Line 3 is 400 feet of 10 inch line containing 1630 gallons of fuel.

Line 4 is approximately 800 feet of 10 inch line and 300 feet of 6 inch line. It's capacity is 3700 gallons and contains eight (8) laterals to hydrants.

Line 5's total length and capacity are not known at this time. The section is referred to as the U.S. Pier. It contains a 10 inch line looping the terminal as well as 20 laterals to hydrants.

The pipeline is operated between 50 and 150 PSI of pressure, depending on the source. Most testing was performed at 150 PSI, except for Line 4, which was tested at 50 PSI.

The pipe is buried approximately three (3) feet from the surface. Backfill around the pipe is sand. It is then covered with approximately two (2) feet of limestone. Six (6) inches of sand is placed on top of the lime stone which is then covered with six (6) inches of macadam.

The access to the piping system is either through the hydrants, valve pits or high/low points. These are all shown in Figure 1.

2.2 Pressure System and Leak Source

The pipeline was previously prepared for testing by other contractors. It had been filled with jet fuel in all test legs. Access to the piping at valve pit four (4) and HP3 had been installed to allow for pressurization and leak simulation. The test sections were pressurized using either a manual pump (sections 2 & 3), a fuel delivery truck (section 4), or the hydrant system pumps (section 5). Sections 2,3 & 5 were tested at 150 PSI and section 4 was tested at 50 PSI.

Above ground leak simulation was installed at high point 3. Leak simulation was accomplished in two ways. The first was a micrometer controlled needle valve which was used for low leak rates. The second consisted of a section of three (3) inch pipe which had been drilled and taped to accept plugs with high precision, machined holes. These were clean cut, circular holes drilled into a diaphragm. The plugs were used to change leak rates.

2.3 Acoustic Emission Equipment

The following AE equipment was used:

a) Physical Acoustics Corporation Model 5120, a two channel portable acoustic emission leak monitor. This is a battery operated two channel instrument designed for leak detection. It offers several unique features which make it very useful in this particular application. One is a front panel control which allows the operator to tune the system to a given frequency for processing. This helps to eliminate unwanted signals from a source outside the bandwidth of interest. It also allows the operator to maximize the sensitivity, to a given sensor by "tuning" in to that sensors resonant frequency. Another unique feature is the X-Y recorder output which provides for hard copy on a recorder or data logger. This output can also be used as a signal level measurement output to compliment the built in signal meter. This unit provides an audio output which is used in conjunction with a headset. The operator can "hear" the signals being detected by the sensor. This is a very useful tool when differentiating leak signals verses other sources.

b) PAC Model Locan 420D is a four (4) channel, general purpose Acoustic Emission detection and location system. It is the most popular laboratory, multi-channel system in use today. This system provides the ability to detect, characterize and store every signal which is detected by each sensor in use. It also provides the location algorithm through which the source (leak) location is determined. In addition to providing all the AE data logging and location software, this system, with it's built in 486 computer, is used for post data processing and report preparation.

c) PAC Model A3 Sensor - these are low frequency sensors used for both leak detection and location. They are placed in contact with the piping and signals are coupled to the sensor from the piping using an ultrasonic coupling medium.

d) PAC Model 1220A Preamplifier. This is a high gain voltage preamplifier used to increase the signal levels detected by the sensor before being processed by the Locan.

III. TEST METHOD

The test method involves a six (6) step process.

1) The sensor or waveguide with sensor is coupled to the outside wall. In the case of the hydrant system, the sensor was attached just below the flange at the end of the hydrant. This allows for a quick and simple measuring point which was consistent from site to site. Prior to attaching the sensor with a magnetic attachment, the surface was cleaned of dirt and contaminants.

2) The sensor is coupled to the instrument and a calibration is performed. Calibration is usually performed on some area near the piping that is subject to normal background noise but is not within the range of a suspected leak.

3) The line is then statically tested. Pressure, either hydrostatic or pneumatic, is applied to the piping. The pressure level is increased to a magnitude that would insure the required leak rate sensitivity is achieved for the given sensor spacing and soil loading. When testing on-line, under normal operating conditions, this step is not required.

4) Once the pressure is applied, measurements are made at specific intervals along the piping. The intervals will vary depending on leak rate sensitivity, soil loading and accessibility. In the case of this hydrant system, measurements were initially made at the hydrants. If better sensitivity would have been required, additional measurements would have been made at shorter intervals, on the order of 50 feet.

5) After several readings have been taken, the results are reviewed. The readings are compared to each other as well as the background noise. When a leak site is approached, a 5-10% increase in signal level is usually observed.

6) When it is determined a leak occurs between two intervals, one of two methods is used to locate the position of the leak. The first is the Signal Difference method, the second is the Time Difference method. Both have been discussed earlier. In this particular case, the Time Difference method was used.

IV. TEST RESULTS

The following are the results of each test segment and the corresponding data. Any additional comments are also included.

A) Line 2

This line was tested on Monday, November 18, 1996. The line was pressurized to 150 PSI using a manual pump. After pressure was achieved, the gauge was monitored for a short period of time to insure no gross leakage was occurring. The following data was recorded at the eight (8) hydrants and pit locations.

LOCATION	BACKGROUND SIGNAL	ON-PIPE SIGNAL
High Point 4	.36 volts	.36 volts
Hydrant 21	.35 volts	.35 volts
Hydrant 22	.35 volts	.34 volts
Hydrant 23	.35 volts	.34 volts
Hydrant 24	.34 volts	.34 volts
Hydrant 25	.34 volts	.34 volts
Hydrant 26	.34 volts	.34 volts
Hydrant 27	.34 volts	.34 volts
Hydrant 28	.34 volts	.34 volts
Valve Pit 5	.34 volts	.34 volts

No significant changes were observed between the "On-Pipe" measurement and the "Background Signal" measurement. There were no indications of leakage in any of the data taken on this segment. The AE test indicates this line was tight. Total test time was approximately one hour.

B) Line 4 - This line was tested on Tuesday, November 19, 1996. The line was pressurized to 50 PSI from a delivery truck which would increase and decrease the pressure in the line just prior to each measurement.

LOCATION	BACKGROUND SIGNAL	ON-PIPE SIGNAL
Hydrant 36	.34 volts	.35 volts
Hydrant 35	.33 volts	.35 volts
Hydrant 34	.33 volts	.34 volts
Hydrant 33	.33 volts	.34 volts
Hydrant 32	.33 volts	.38 volts
Hydrant 31	.34 volts	.34 volts
Hydrant 30	.33 volts	.39-49 volts
Hydrant 29	.33 volts	.120-1.9 volts
High Point 5	.33 volts	.34 volts

The first increase in signal level occurred at hydrant 32. The measurement at hydrant 29 was by far the highest. Hydrant 30 was the second highest. Using the Amplitude Difference technique would indicate the leakage is between hydrants 29 and 30, a distance of approximately 50 feet. To determine more precisely the leak location, the Time Difference technique was used. This involved mounting sensors at hydrants 29 and 30 and connecting them to the Model Locan 420D. Sensitivity checks were performed prior to the start of data acquisition. The results of the unfiltered data are shown in Figure 2. Clearly, it can be seen that the source of the signal is in the region of sensor 1 (hydrant 29). However, there is a great deal of "splatter" which occurs because of high data rates, reflections and other mechanisms. To minimize this, the data is filtered using parameter filters which eliminate many of these extraneous sources. The results are shown in Figure 3. Here it can be clearly seen where the acoustic source of the signal is located. This result is based on an estimated distance between sensors of 50 feet. At this time, it is uncertain as to what this actual spacing is. Figure's 4 thru 7 are additional graphs which are used in evaluating the data to determine the source mechanism. The total test time for this line was four (4) hours, including location analysis.

C) Line 3 was tested on Wednesday, November 20, 1996. This section was used to evaluate the detectability of different leak rates at two different distances. The test used calibrated leak sources out of ground. Prior to starting the simulated test, the line was measured at the three test points. Valve Pit 4, high point 3 (leak site) and valve Pit 3. These reading are shown below. Also, as part of this test, we decided to evaluate sensitivities at different frequencies. Two measurements were made at NF (normal frequency setting) and LF (a low frequency setting approximately 40% of the NF setting). This would allow us to observe whether there was any impediment to the normal test frequency being used. The following are the pre-test measurements.

LOCATION	BACKGROUND SIGNAL	ON-PIPE SIGNAL
Valve Pit 4	NF - .34 volts	.34 volts
	LF - .19 volts	.19-.21 volts
High Point 3	NF - .34 volts	.53 volts
(leak site)	LF - .24 volts	.4 -1.2 volts
Valve Pit	NF - .35 volts	.36 volts
	LF - .19 volts	.20 volts

The above readings increased at HP 3 due to a slight leak through a fitting at the top of the access pipe. This was retreaded and tightened and the test was re-done.. It decreased to the same as the background, indicating the leak was repaired.

Next, a leak rate of .4 gal/hour at 150 PSI was created and the data recorded. Following are those values:

LEAK RATE	LOCATION	BACKGROUND SIGNAL	ON-PIPE SIGNAL
.38 gal/hr	Valve Pit 4	NF - .35 volts	.36 to .5 volts
		LF - .19 volts	.20-.41 volts
.40 gal/hr	Valve Pit 3	NF - .39 volts	.40 - .44 volts
		LF - .20 volts	.21-.24 volts
.38 gal/hr	High Point 3	NF - .35 volts	.6- .8 volts
	(leak site)	LF - .19 volts	1.1-2.3 volts

The readings at VP4 still give good indications of a leak. The readings at VP3 do not show as significant a change as VP4. There are two reasons for this, which will be discussed later. Next, a larger simulated leak was placed in the system and the values for this leak rate were recorded.

LEAK RATE	LOCATION	BACKGROUND SIGNAL	ON-PIPE SIGNAL
1.6 gal/hr	Valve Pit 4	NF - .46 volts	.48 -.51 volts
		LF - .19 volts	.19 volts
1.8 gal/hr	Valve Pit 3	NF - .46 volts	.46 - .48 volts
		LF - .19 volts	.19 volts
1.5 gal/hr	High Point 3	NF - .52 volts	.7-.8 volts
	(leak site)	LF - .24 volts	3.9-4.6 volts

Again, a larger change in signal level occurred at VP4 for this leak rate. Overall, the change was not as large as the smaller rate. The reason for this is discussed in the conclusions section. Total test time for the above was approximately two (2) hours.

D) Line 5 - This line was tested on Wednesday, November 20, 1996. The line was not originally going to be evaluated, but since the previous testing was completed quickly, it was decided that time would allow for testing of this line also. The line was pressurized to 150 PSI and isolated from aircraft use. The following is the recorded data on this line:

LOCATION	BACKGROUND SIGNAL	ON-PIPE SIGNAL
Hydrant 20	.46 volts	.44 volts
Hydrant 19	.48 volts	.48 volts
Hydrant 18	.46 volts	.53-1.0 volts w/cp .46 without
Hydrant 17	.46 volts	.46 volts
Hydrant 16	.47 volts	.48 volts
Hydrant 15	.46 volts	.46 volts
Hydrant 14	.47 volts	.47 volts
Hydrant 13	.47 volts	.47 volts
Hydrant 12	.47 volts	.47 volts
Hydrant 11	.47 volts	.47 volts
Hydrant 10	.46 volts	.46 volts
Hydrant 9	.46 volts	.46 volts
Hydrant 8	.47 volts	.47 volts
Hydrant 7	.48 volts	.46 volts
Hydrant 6	.47 volts	.46 volts
Hydrant 5	.47 volts	.47 volts
Hydrant 4	.48 volts	.45 volts
Hydrant 3	.48 volts	.45 volts
Hydrant 2	.48 volts	.46 volts
Hydrant 1	.52 volts	.47 volts

The above indicates no leakage was occurring in this loop. A high reading was recorded at hydrant 18. When this reading was made, the type of signal detected was not consistent with a leak signal. Monitoring the signal with the headset confirmed this. In an attempt to identify the noise source, the Cathodic Protection rectifiers were de-energized. This eliminated the signal. To confirm, the rectifiers were re-energized and the signal returned. No further investigation was made to determine exactly what was occurring, only that the CP system was causing a continuous, high level signal on the pipe. It is unclear as to what or how this is occurring but the signal is definitely CP related. The time to perform this test was approximately two (2) hours.

V. CONCLUSIONS

The tests on the hydrant system were very effective in demonstrating the capabilities of acoustic emission leak detection and location. The following comments and conclusions are drawn from this work:

a) On the long straight section of line 3, small leak rates (.4 gal/hr) were detected at distances of 150 to 200 feet. While this may be approaching the upper limit in terms of sensitivity, this level was detected. The section of pipe with the 45 degree bend did affect sensitivity.

b) Bends and other geometrical changes can reduce the spacing interval of the AE test. This is one of the reasons the signals at valve pit 4 and 3 were of different levels. The second reason was, the distances were not exactly the same, hence additional attenuation occurred on the longer leg.

c) Back pressure and/or flow restrictions against the leak, are important when detecting and locating leaks. The out-of-ground simulations performed here, even though detectable, would have produced larger signals had there been flow restriction. This can be seen in the data for the .40 gal/hr. and 1.75 gal/hr. leak rates. The lower leak rate was more of a pulsing/dripping leak where as the higher leak rate was a steady stream. For these two conditions, the signal change at valve pit 4 was between 2% and 42% for the low leak rate but only 4% for the larger leak rate. The un-impeded flow did not produce as much fluctuation in turbulence as the lower leak rate. Had this occurred in a buried pipe the higher leak rate would have experienced larger turbulence, hence higher signal levels.

d) Leak artifacts (e.g. soil movement) are important in enhancing leak detectability and location capability. The out of ground simulations were performed without the artifact.

e) The AE testing was fast and the locations results accurate. Locations within a foot of the actual leak are routinely produced.

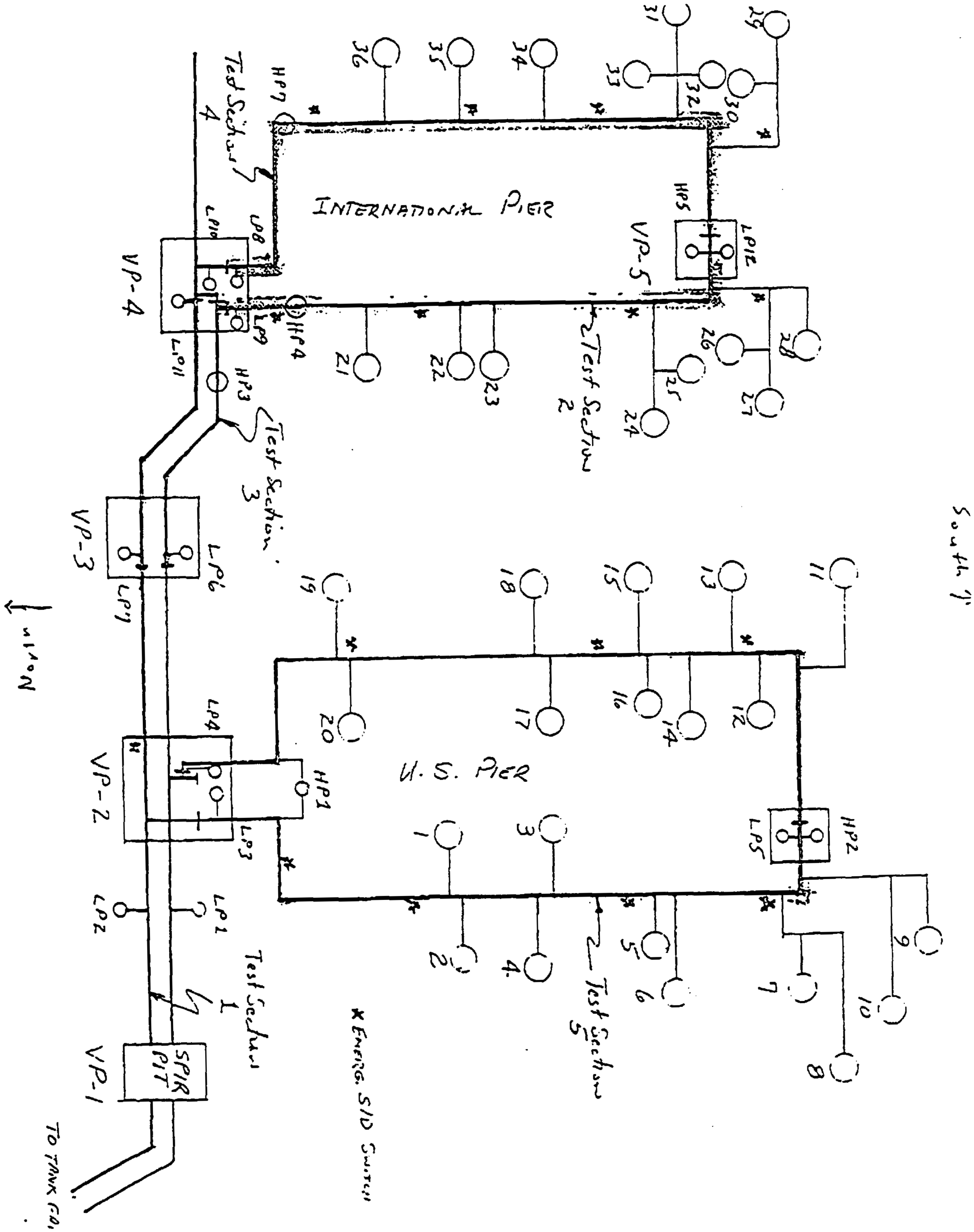
f) The AE test offers additional capabilities in evaluating pipeline conditions. In the testing of Line 5, an abnormality with the cathodic protection system was detected. Other tests have given an indication of active corrosion.

VI SUMMARY

This test has shown the AE technique to be a quick, reliable and sensitive testing method for detecting and locating leaks in buried pipeline. At a distance of 150 feet, a .4 gal./hr. leak was detected. While this test did not have all the benefits of a "real" leak, it was still detectable. The leak location capability was also demonstrated in the test on Line 4. While one AE technique localized the leak site to a 50 foot length of piping, the second AE technique produced a leak location that was defined to 1 foot of the actual distance from the sensor position at the end of the hydrant. This helped reduce the amount of excavation required to repair the pipe. The signals detected were repeatable. Both line 4 and line 3 were pressurized and depressurized several times. The signals detected were similar and repeatable.

And last, but not least, the test was fast. This can be seen from line 5. A 20 hydrant system was tested in two hours. This testing was accomplished while aircraft were entering and departing the area. At only one hydrant was the testing schedule adjusted to accommodate aircraft movement. Otherwise, there were no affects from the environment created by aircraft movement or engine operation. This is very important since the test was performed without affecting airport operations.

While this test may not have taken into account some of the nuances of testing long (several miles) sections of buried piping, it did present other unique aspects which still allowed for a effective evaluation of the technique employed.



" FIGURE 1 TEST SCOPE"

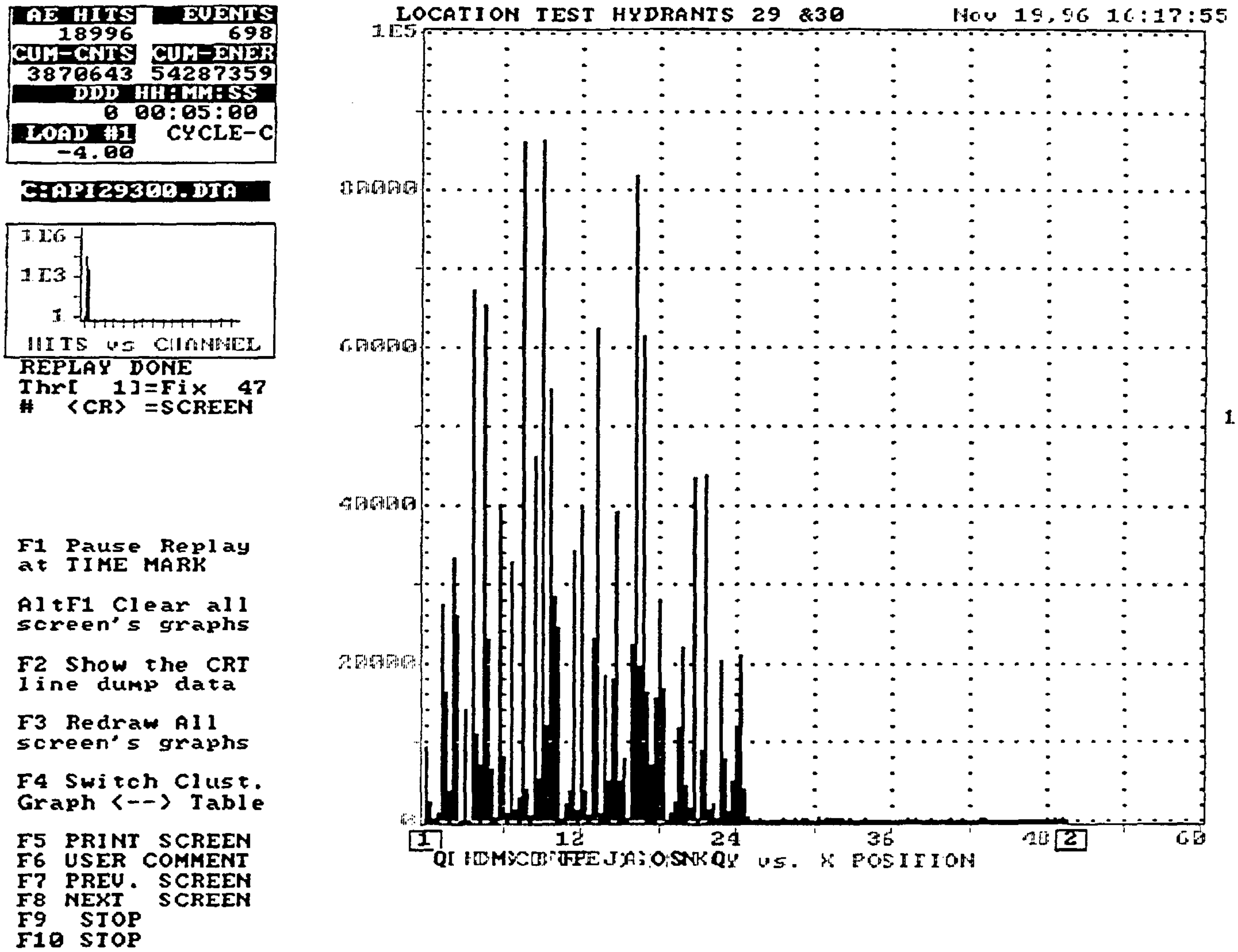


FIGURE 2 - LEAK LOCATION WITH UNFILTERED DATA

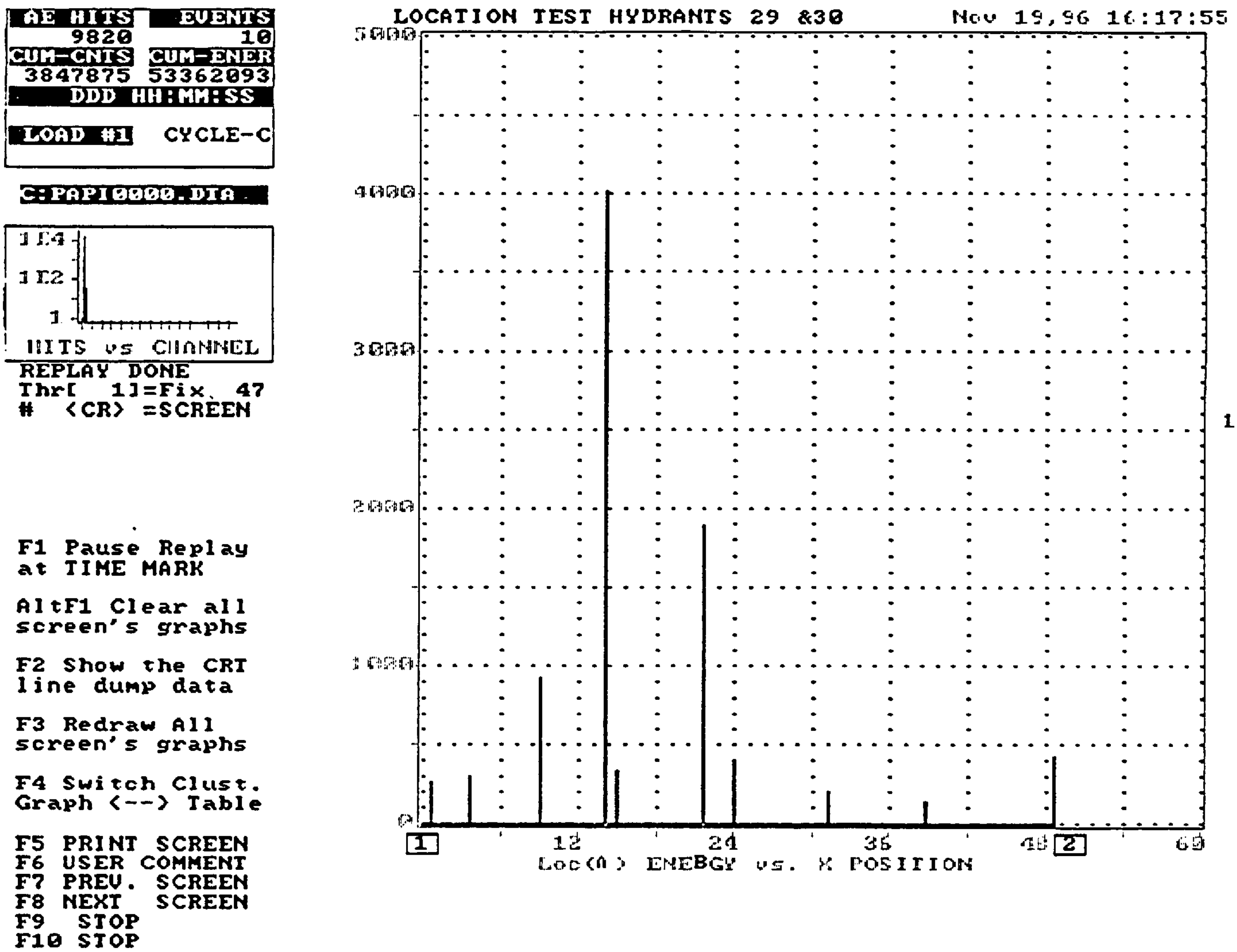


FIGURE 3 - LEAK LOCATION AFTER FILTERING DATA

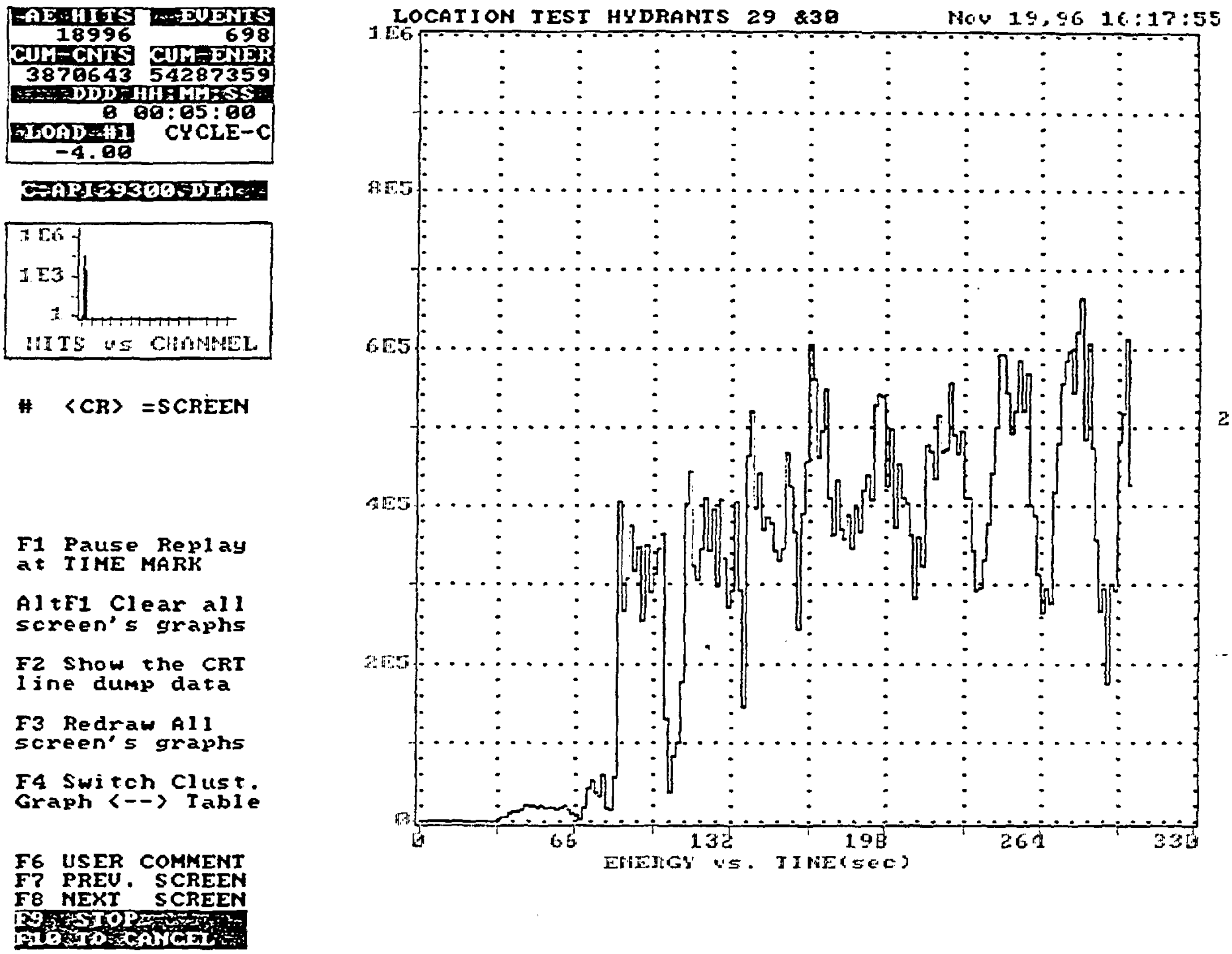


FIGURE 4 - ENERGY RATE OF LEAK

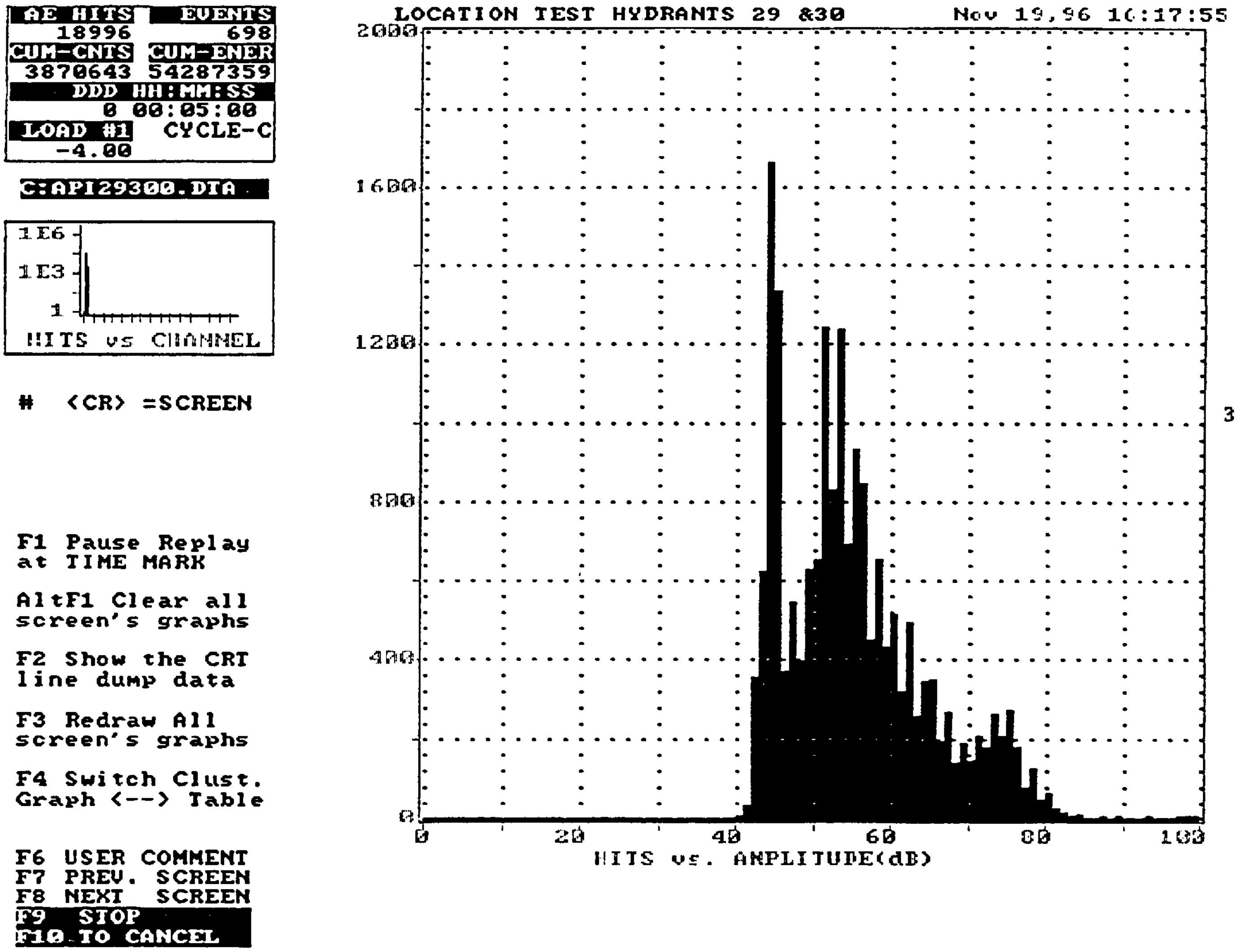


FIGURE 5 - AMPLITUDE DISTRIBUTION OF LEAK DATA

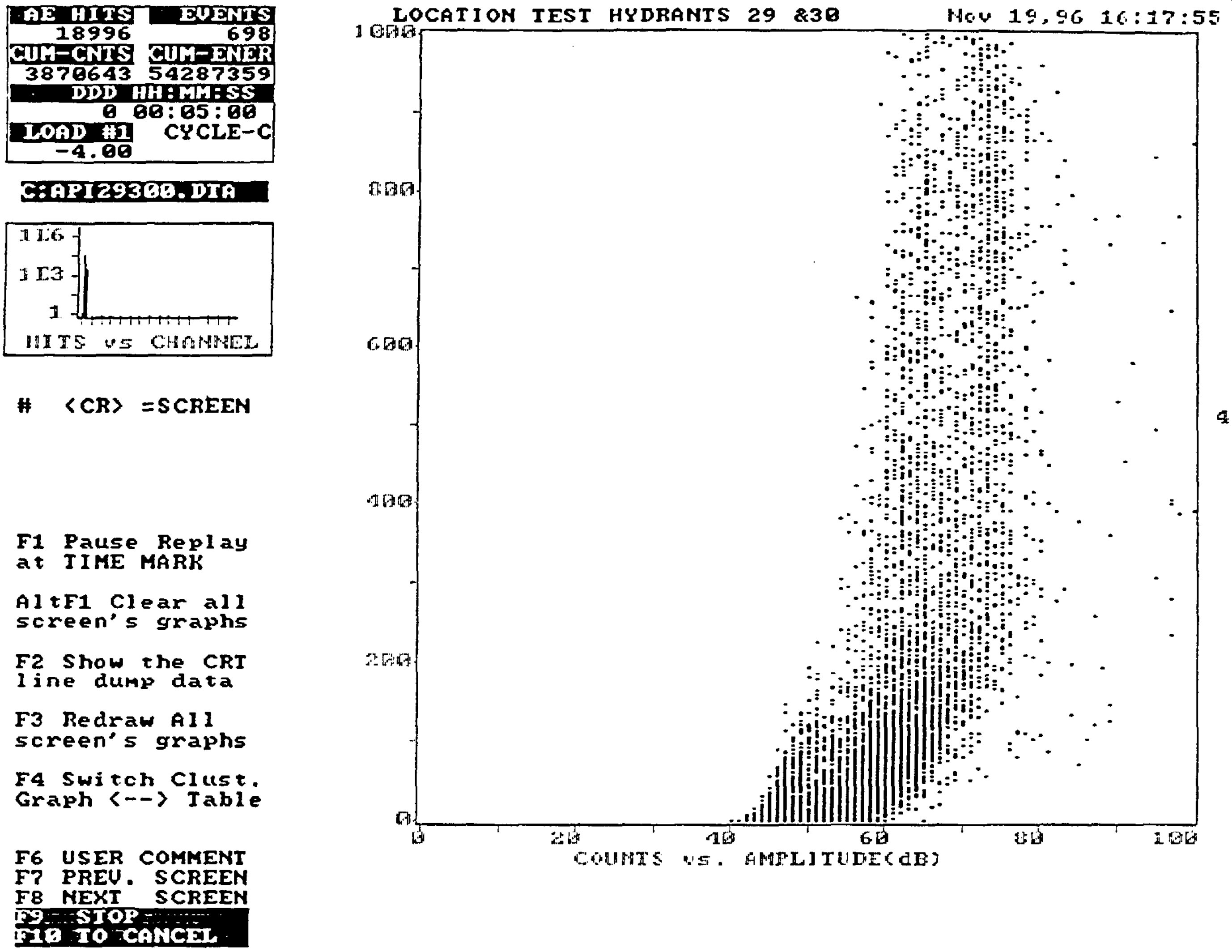


FIGURE 6 - CORRELATION GRAPH OF LEAK DATA

COUNTS vs AMPLITUDE

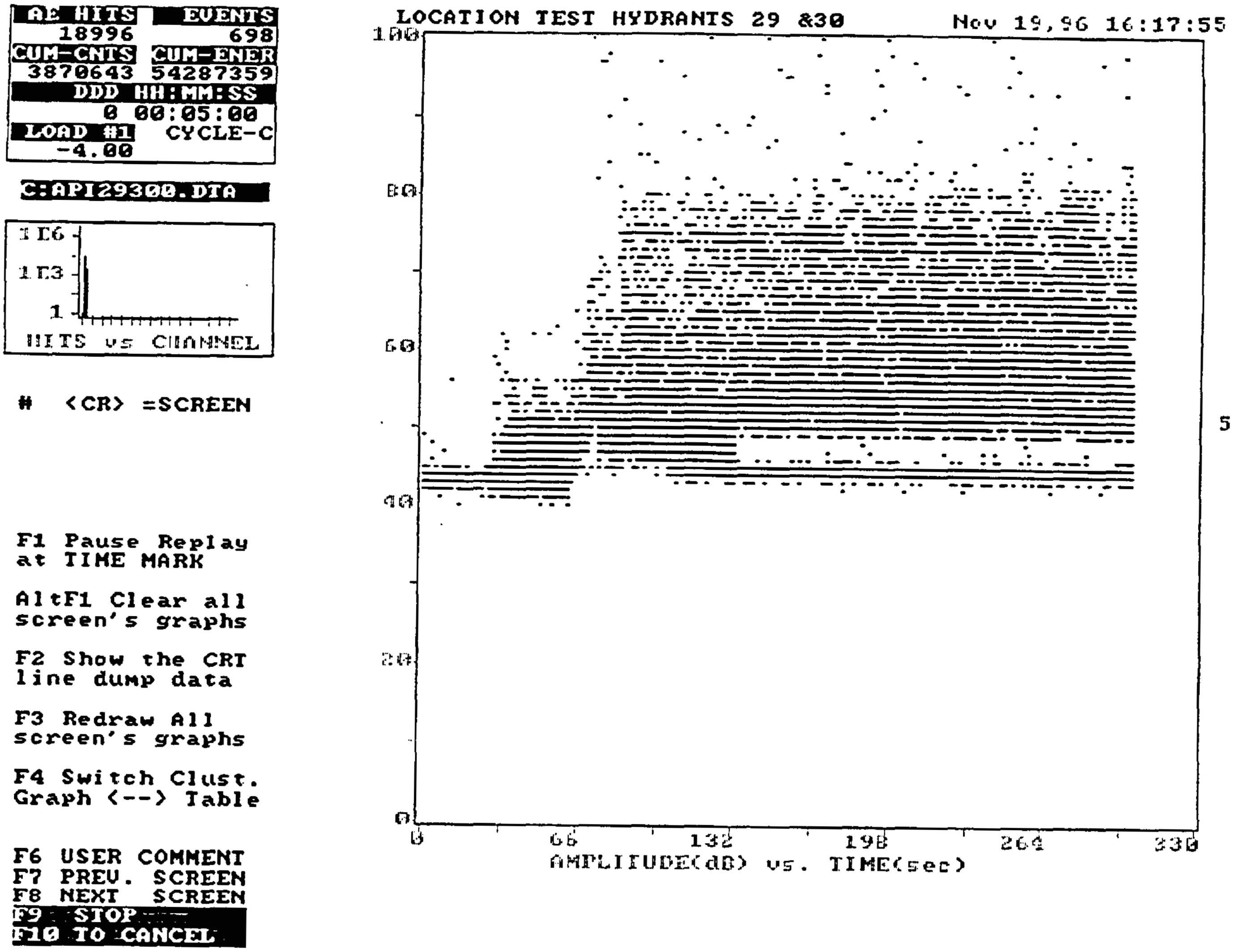


FIGURE 7 - AMPLITUDE vs TIME GRAPH OF LEAK DATA

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