

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

HEALTH AND ENVIRONMENTAL AFFAIRS DEPARTMENT
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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

PREPARED UNDER CONTRACT BY:

JAIRUS D. FLORA, JR., PH.D.
WILLIAM D. GLAUZ, PH.D.
JOE HENNON
MIDWEST RESEARCH INSTITUTE
425 VOLKER BOULEVARD
KANSAS CITY, MO 64110-2299

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API STAFF CONTACTS

Dee Gavora, Health and Environmental Affairs Department
Andrew Jaques, Health and Environmental Affairs Department

MEMBERS OF THE LEAK DETECTION WORKGROUP

Allan Wolf, Chairperson, Exxon
Ronald M. Bass, Shell Development Company
Nimish Dhuldhoya, Texaco
Frank Furillo, Mobil Technology Corporation
Jerry Horak, Exxon
Laurence Hudson, Texaco
Eugene P. Milunec, Mobil
Philip E. Myers, Chevron Products Company
Anh N. Nguyen, Colonial Pipeline Company

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 through 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

Comparison Item	Technology			
	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.

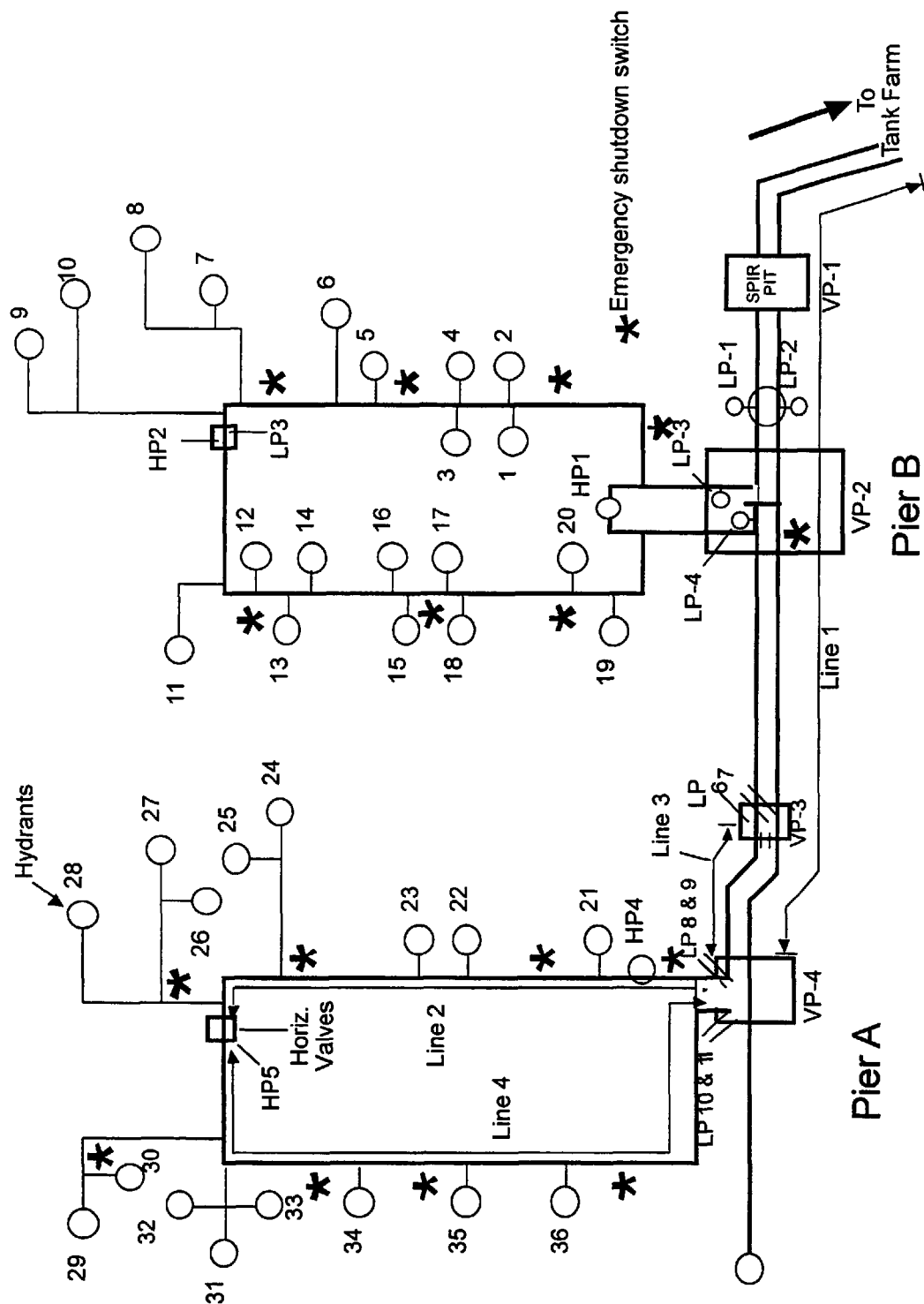


Figure 1. Test Facility

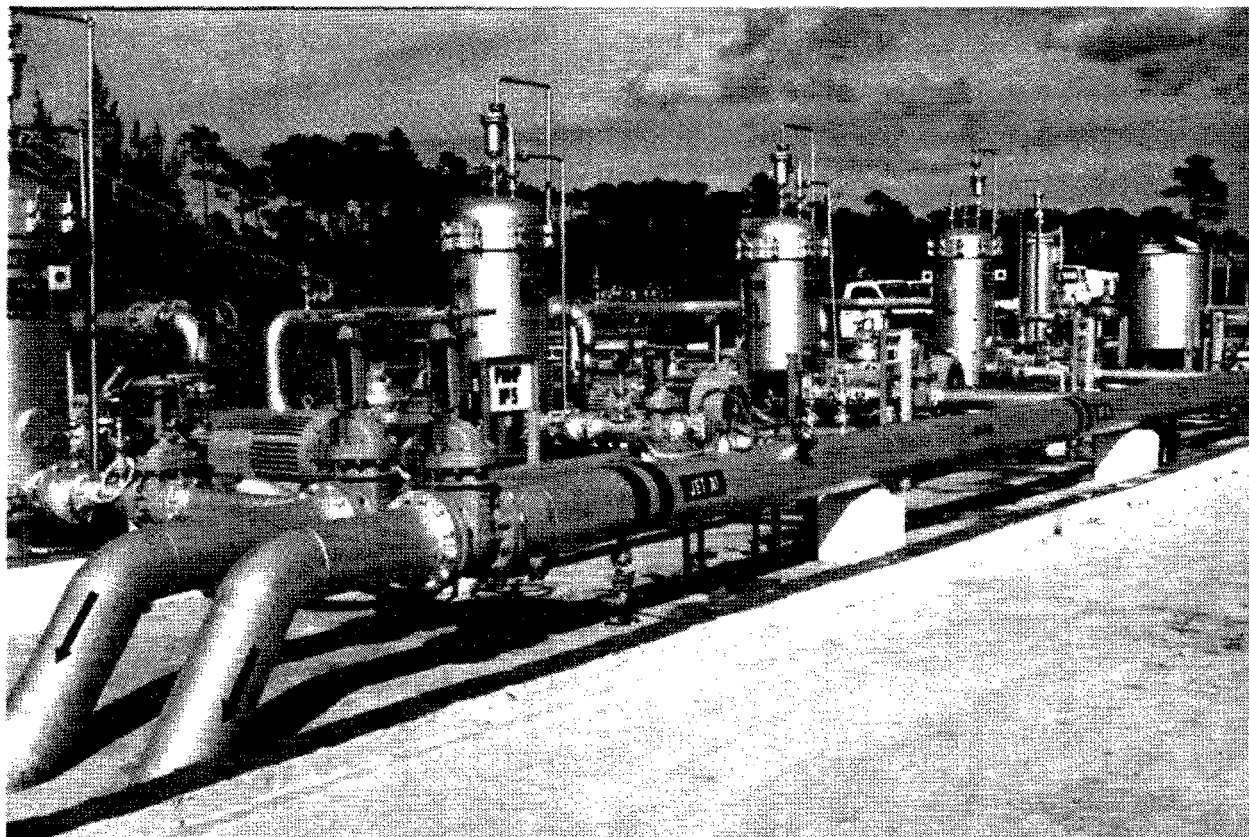


Figure 2. Pumps and Location of the End of Line 1

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

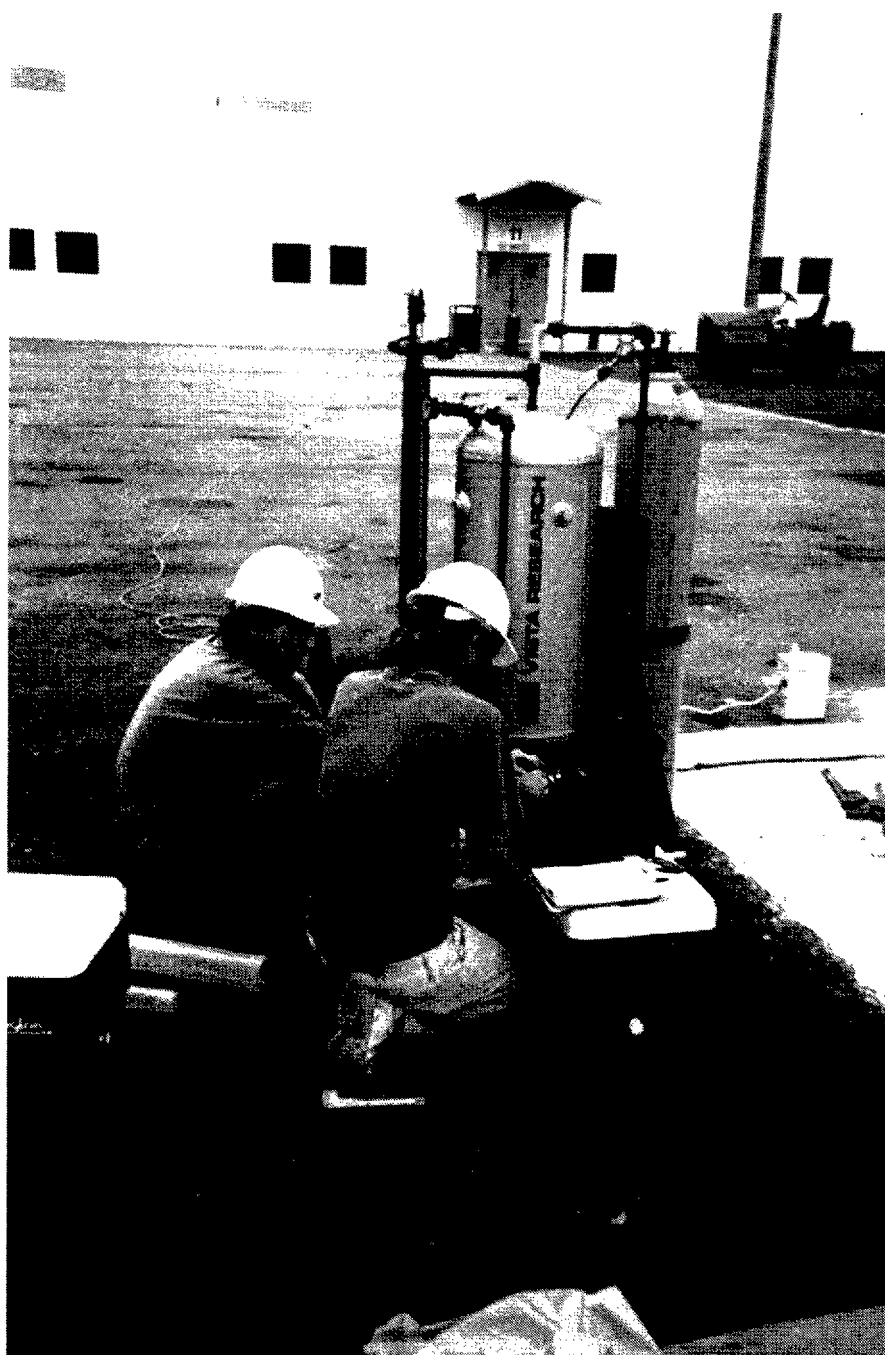


Figure 4. The Smaller Volumetric Unit Conducting a Test

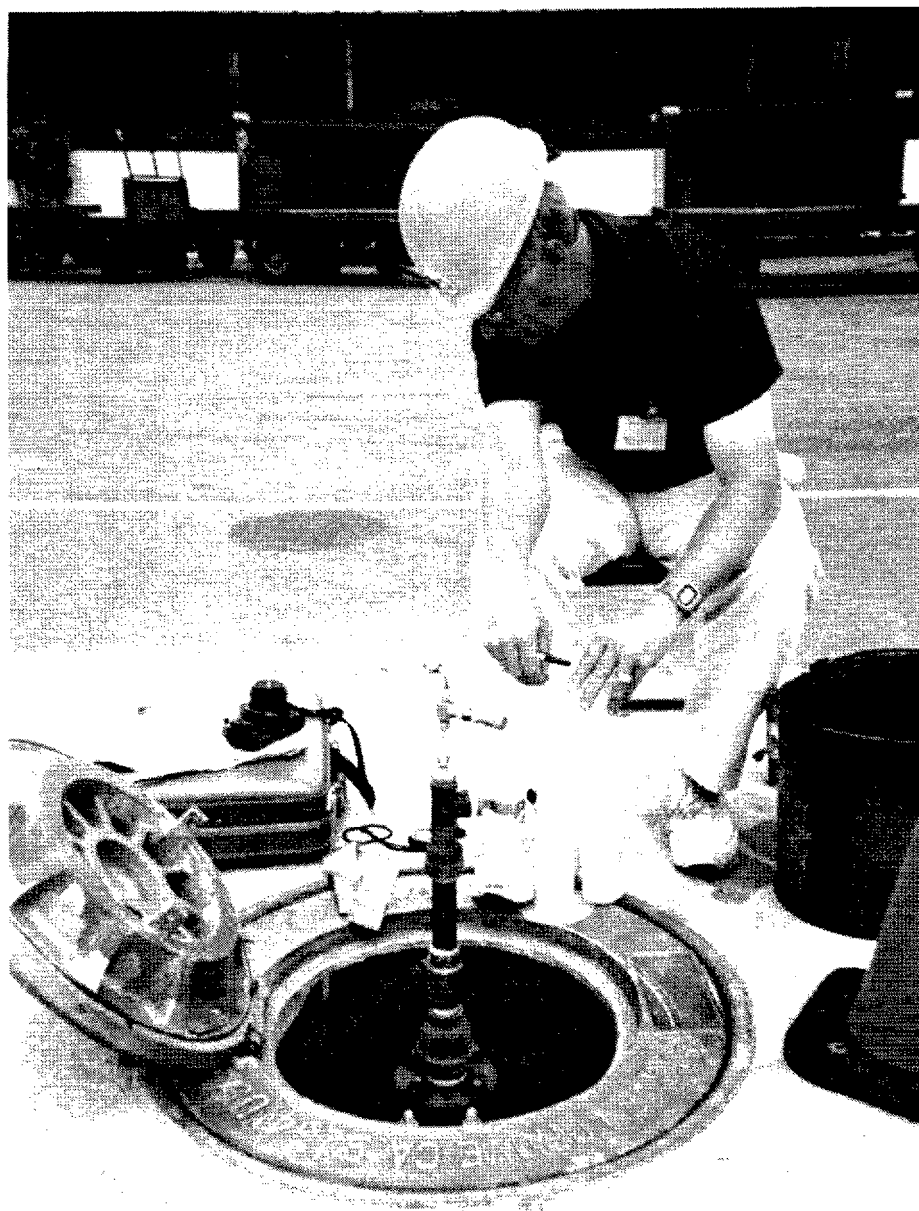


Figure 5. MRI Conducting a Leak Simulation

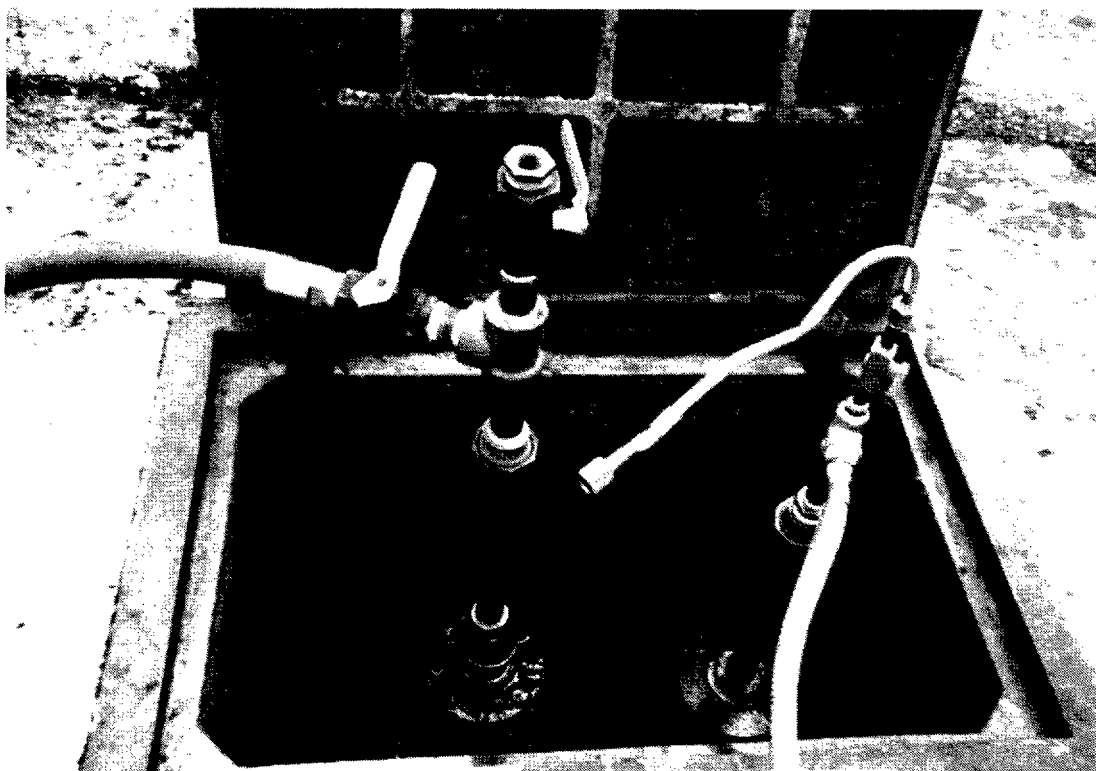


Figure 6. Connections of the Larger and Smaller Volumetric System at High Point 4

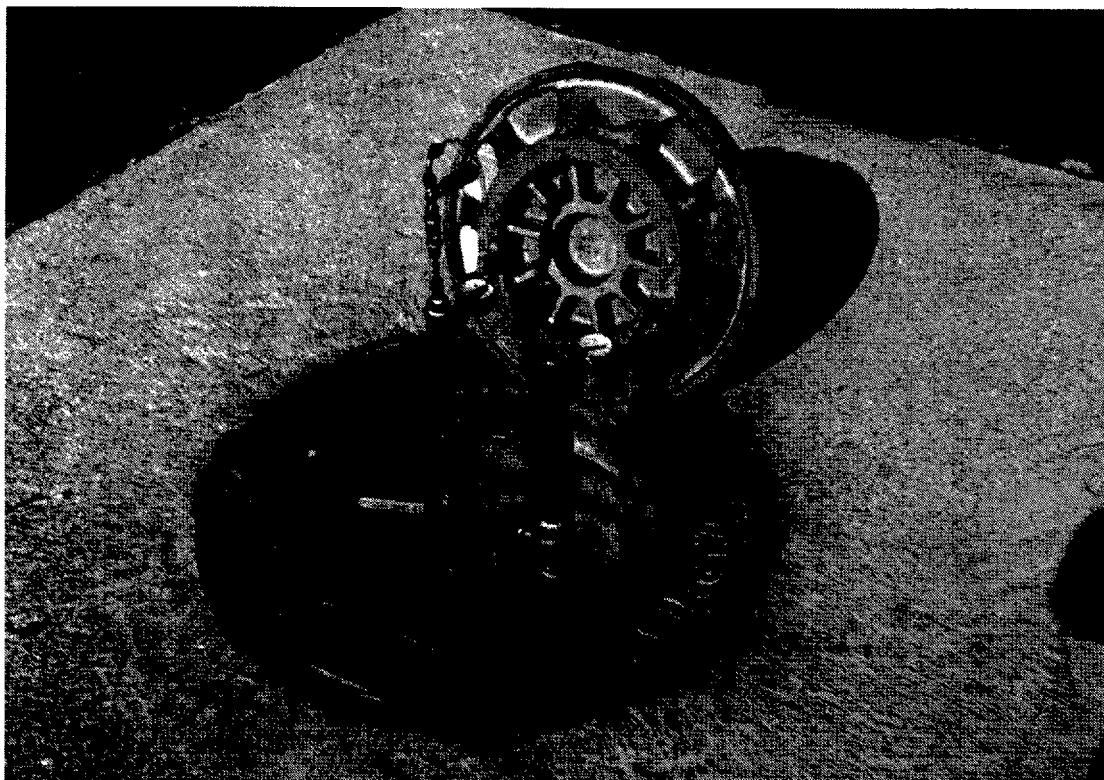


Figure 7. Leak Simulators at High Point 3

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.

Pressure Decay Method

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 under-

ground 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

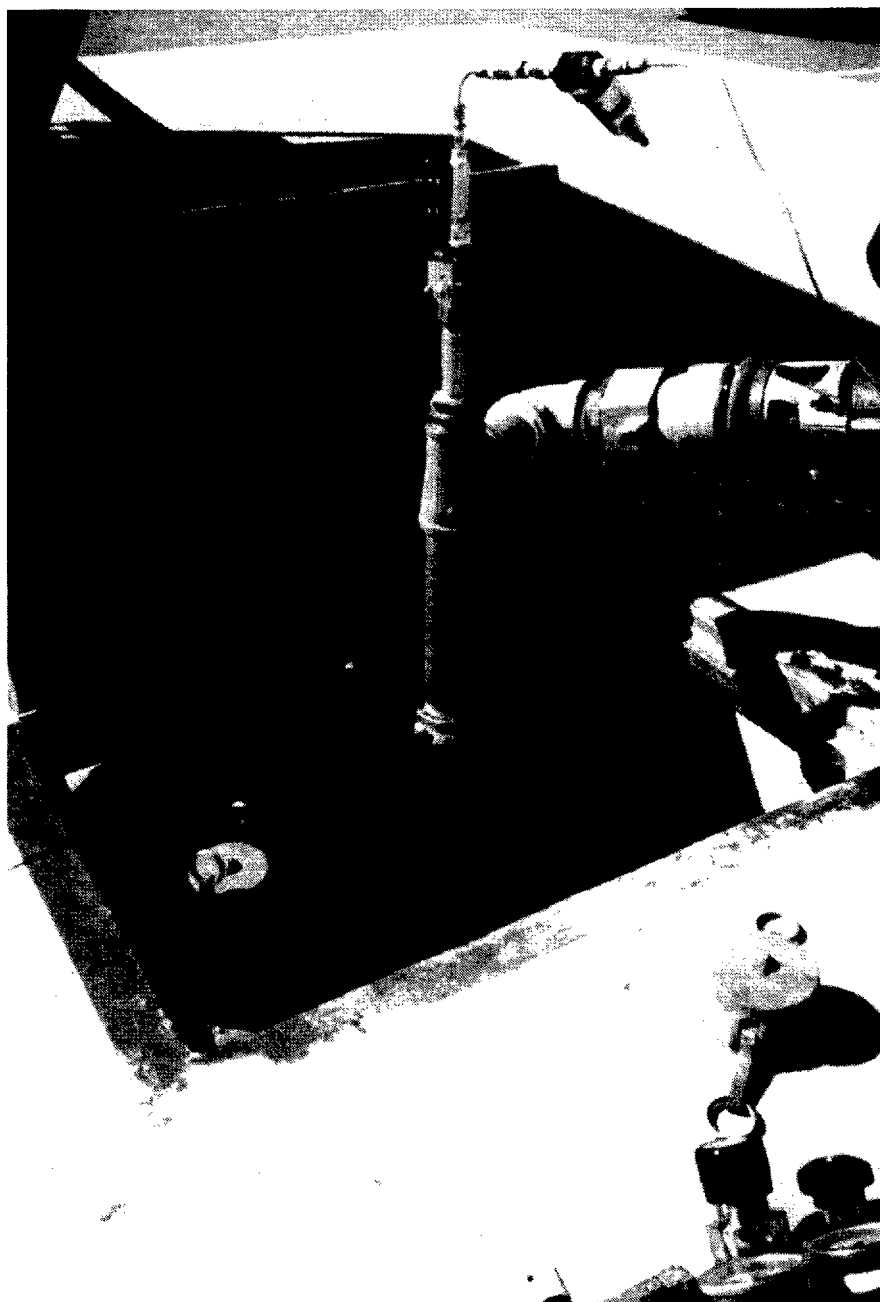


Figure 9. Injecting Tracer in Product as the Line is Filled



Figure 10. Installing Sampling Ports for Tracer

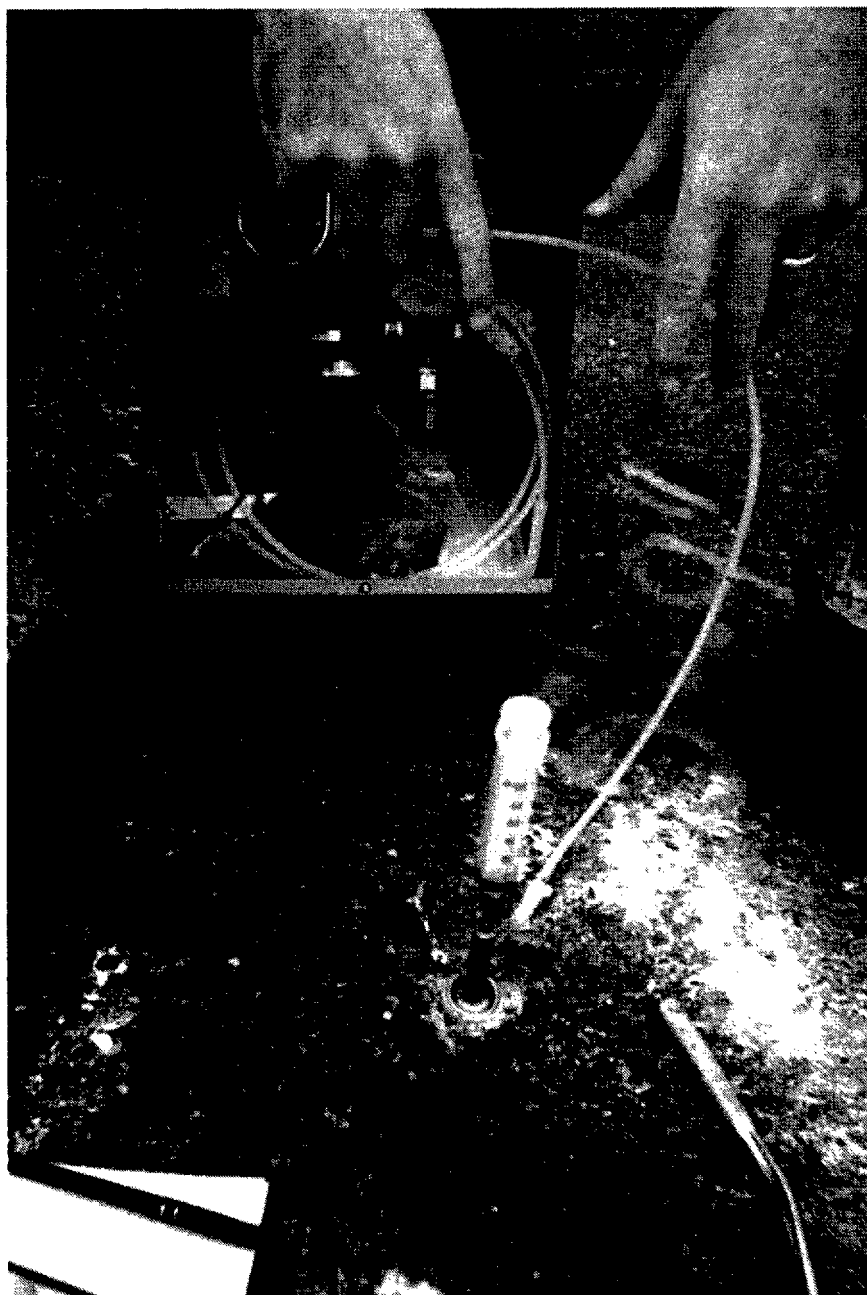


Figure 11. Sampling Soil Gas for Tracer

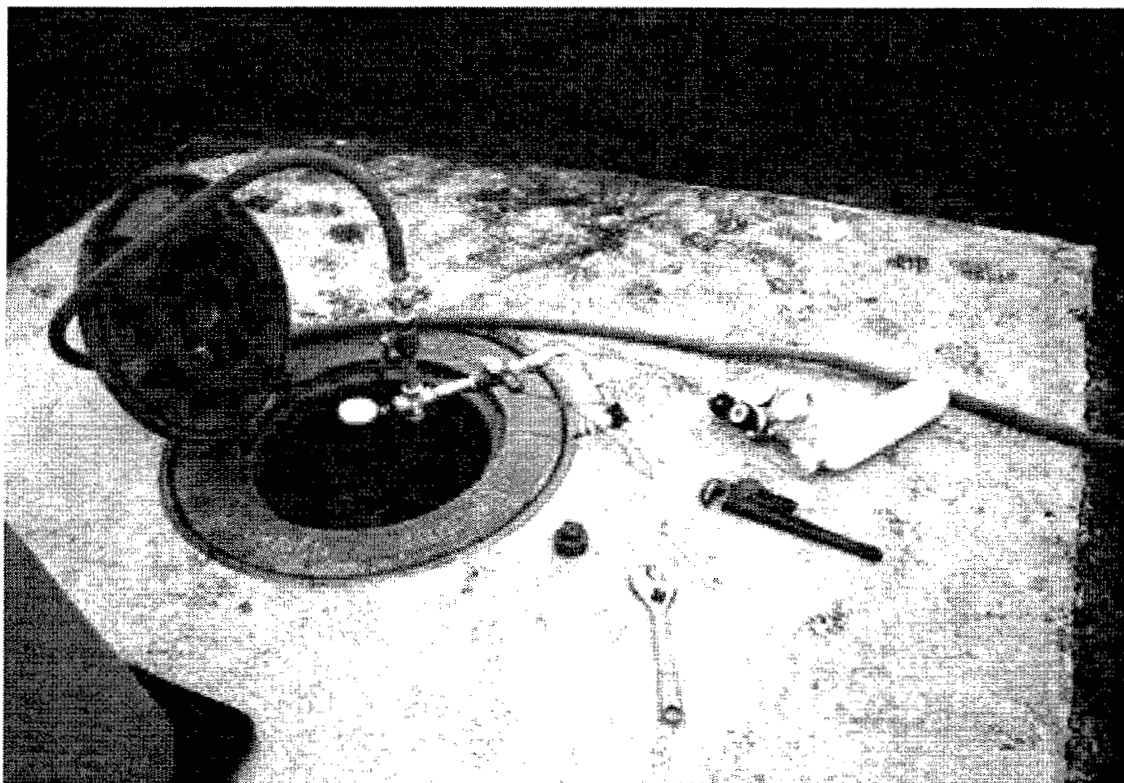


Figure 12. Injecting Tracer with Compressor Air in Line 4



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.

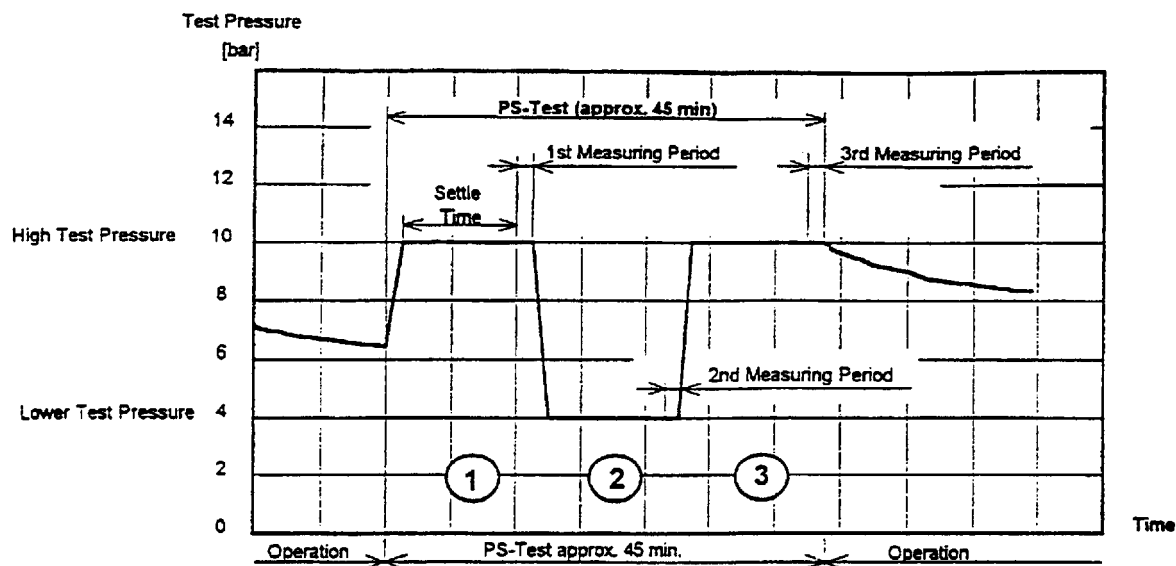


Figure 14. Procedure of a Pressure Decay Test with Its Three Test Cycles (test pressure high–low–high)

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 $0.0 \pm 0.02 \text{ l/h/m}^3$. 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.

Acoustic Emissions Method

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.

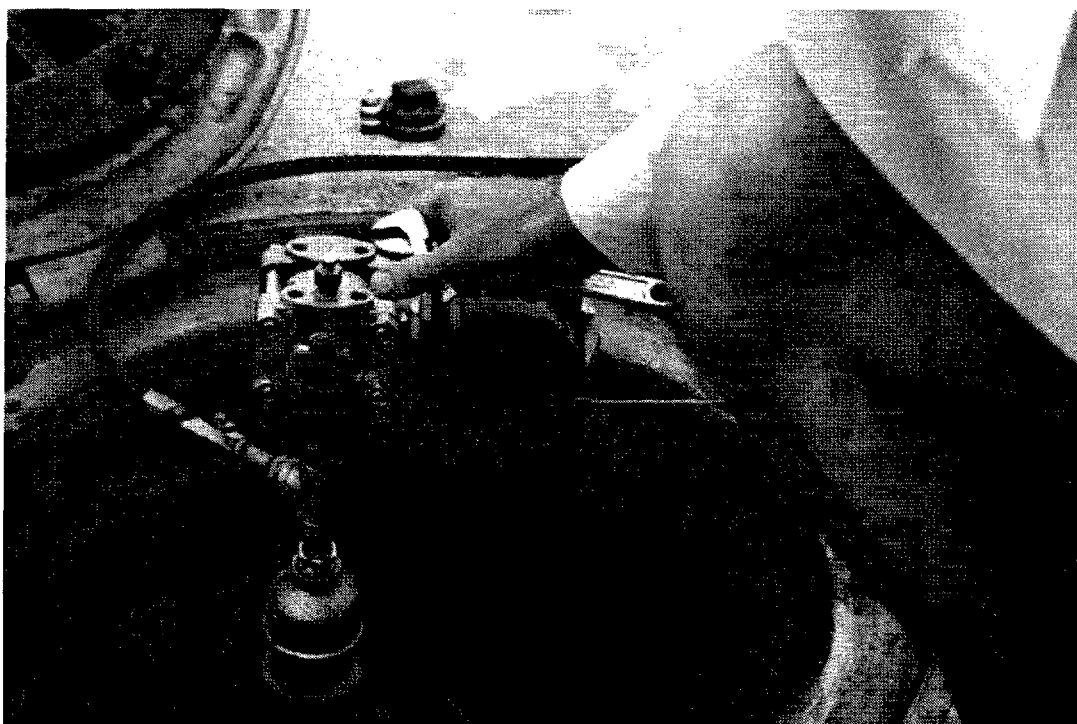


Figure 15. Installing the Pressure Sensor for the Pressure Decay Method

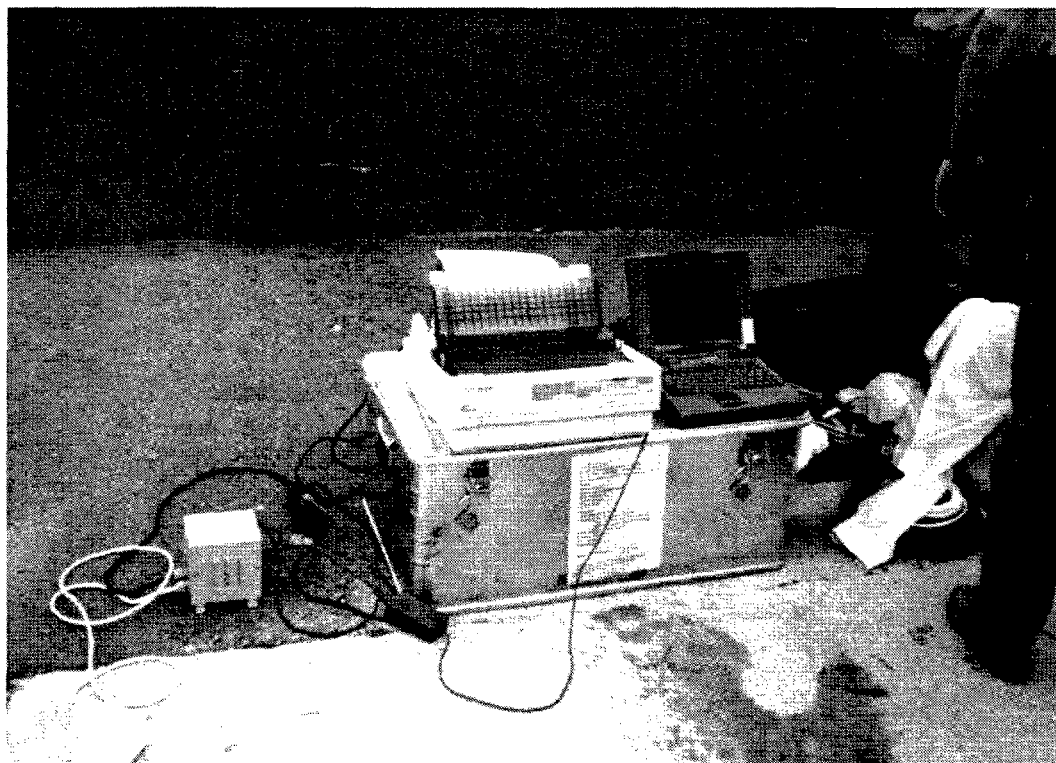


Figure 16. The Power Supply, Computer, and Printer Connected to the Pressure Decay System



Figure 17. The Pressure Decay System Installed

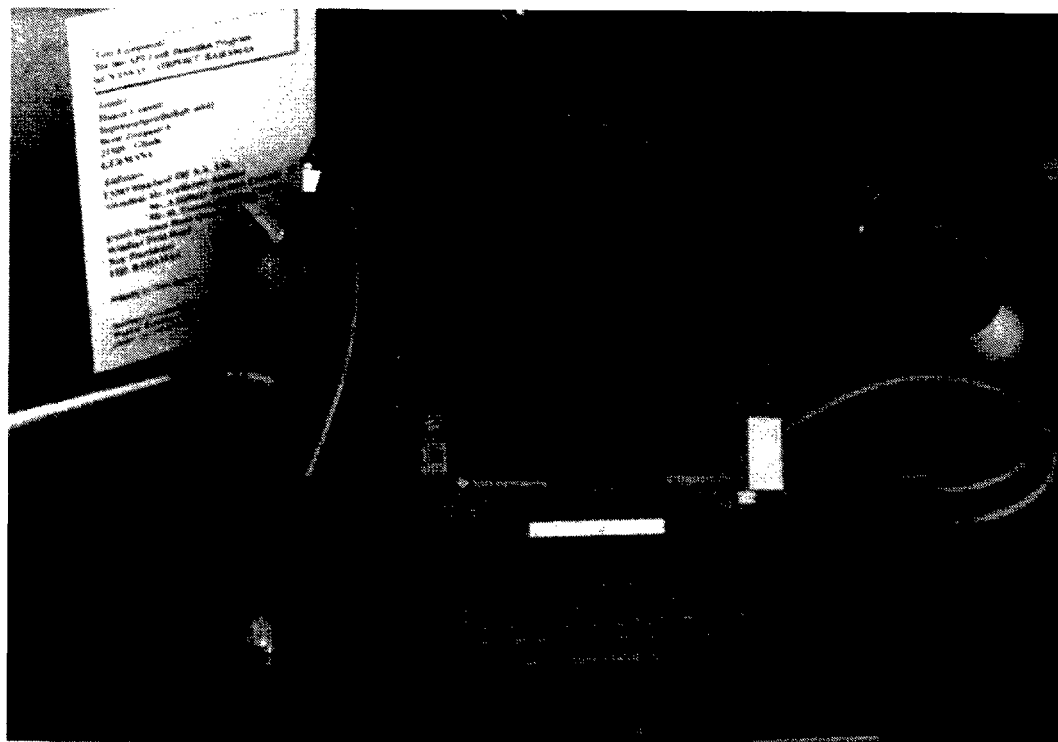


Figure 18. Computer Used for Collecting and Analyzing Data for Pressure Decay System

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 $\pm 5\%$ 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