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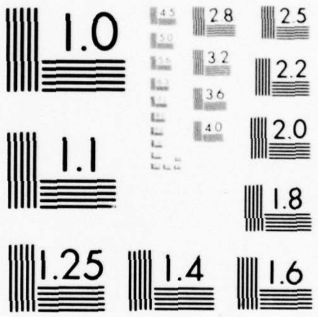
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ESL-TR-79-05

CASING LEAK DETECTION STUDY

LEVEL II

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JULY 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this study was to investigate the feasibility of using tracer gas technology to locate leaks in underground RIC-WIL steam pipe casings. A series of controlled model experiments at the contractor's plant demonstrated that one or more leaks in a buried steel pipe could be detected by surface measurement of tracer gas concentrations. A full-scale demonstration test was conducted at Naval Air Station-North Island on a 400-foot casing with suspected leaks. Two leaks were localized to within three feet using the hardware and procedure developed during the controlled experiments. Simplification

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) would be required before this tracer gas technique could be used on a routine service basis at Air Force bases.

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PREFACE

This report was prepared for the Air Force Civil and Environmental Engineering Developement Office (CEEDO) under Job Order Number 20545012. The report summarizes work done between December 1977 and February 1979 by Systems, Science, and Software (S^3) under Contract Number F08635-78-C-0025.

This effort was initiated by Mr. Thomas F. Lewicki, AFESC/DEMM. The CEEDO Technical Monitors were Maj Roger J. Girard and 2Lt Robert J. Gunning. The S^3 Principal Investigator was Dr Peter L. Lagus.

Effective 1 March 1979 CEEDO was inactivated and became the Engineering and Services Laboratory (ESL) a directorate of the Air Force Engineering and Services Center on Tyndall AFB Florida 32403.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION 1

INTRODUCTION

Water leakage of buried tri-service steam pipe casings (RIC-WIL) results in considerable expense to the U.S. Air Force both from the standpoint of increased energy requirements and from repair/replacement costs. The ability to locate and/or localize a leaking area of an expansive run of steam pipe would greatly facilitate the economical repair of these casings.

Systems, Science and Software (S^3) investigated the feasibility of using tracer gas technology to localize leaks in underground RIC-WIL steam pipe casings. To accomplish this goal a series of model experiments were performed at the Green Farm Test Site. These experiments were performed with steel pipes which possessed controlled leaks. These pipes were 14 inches in diameter and possessed no central steam pipe.

These pipes were buried under a variety of soil types. The purpose of these experiments was three-fold: (1) to ascertain whether a leak could be located utilizing compressed air and tracer gas in conjunction with surface measurements; (2) to determine to what degree along the length of a pipe this leak could be localized; and, (3) to validate gas diffusion rates through various soils. If, on the basis of these model experiments, it appeared possible to localize the area(s) of leakage in a buried RIC-WIL steam casing, an experiment was to be designed and experimental hardware fabricated to allow conduct of such a test at a military installation.

The controlled leak experiments at the Green Farm Test Site demonstrated that one or more leaks in a buried steel pipe could be detected with surface measurements of tracer gas concentration. Furthermore, it was necessary to utilize three distinct tracer gases, SF_6, Freon® 13B1 and Freon® C-318 to perform all the controlled leak experiments in a comprehensive, timely, and cost effective manner.

On the basis of these experiments, it was concluded that a field test under actual unknown conditions in a leaking RIC-WIL steam pipe casing should be undertaken to demonstrate the feasibility of locating, or at least localizing, area(s) of leakage in such a pipe.

Accordingly, a full-scale demonstration test was conducted at Naval Air Station-North Island (NAS-NI) on a 400-foot section of pipe. This pipe was buried approximately 3 feet beneath the surface of the ground. Two experiments were performed on this section of pipe. In the first experiment SF_6 was introduced with compressed air into the casing, and a reconnaissance surface sampling was made along the surface trace of the centerline of the buried pipe for the entire 400 feet. On the basis of this test, three areas appeared to be likely candidates for further study as they evidenced strong concentrations of SF_6. Accordingly, on the second day an additional test using Freon® 13B1 as a tracer was undertaken with a 3-foot sample spacing above those areas suspected of leaking. Two of these areas gave evidence of strong Freon® 13B1 concentrations suggesting the presence of leaks.

Section 2 contains a discussion of the technical background required for understanding the measurement program undertaken. In Section 3 the measurements and experimental technique are presented. In Section 4 we present a discussion of the results which we provide in Section 3. Section 5 of this report contains significant conclusions of our experimental undertakings. In Section 6 we present some recommendations for further work which may lead to a tracer technology program suitable for Air Force use in routine underground steam casing leak detection.

SECTION 2

BACKGROUND

In this section mean diffusion times required for tracer gas plus compressed air to propagate through a variety of soil conditions are calculated. These calculations form the basis for attempting the tracer gas tests which are documented later in this report. In addition, a brief discussion of the gas chromatographic instrumentation utilized in the experimental portion of this study is provided.

2.1 EXPECTED DIFFUSION TIMES

A brief derivation of the mean diffusion time required for tracer gas to reach the surface through a variety of types of soil follows. This is an order of magnitude calculation using highly idealized geometry. It does, however, suggest that times on the order of minutes, hours, or at most a few days, as opposed to months or years, would be expected for tracer gas diffusion through soils. This, in turn, suggests that a series of experiments under controlled conditions could be undertaken to verify that underground leaks are locatable and localizable using tracer gas detection techniques.

In order to estimate diffusion time for a buried pipe, a model problem using a spherical source in spherical geometry is solved. For a spherical steady-state source (see Figure 1) with

P = pressure at radius r from source
r = radial distance from source
P_o = driving pressure
P_∞ = pressure far from source
r_o = radius of source
r_∞ = radius at which P_∞ is measured,

the following equation is presented:

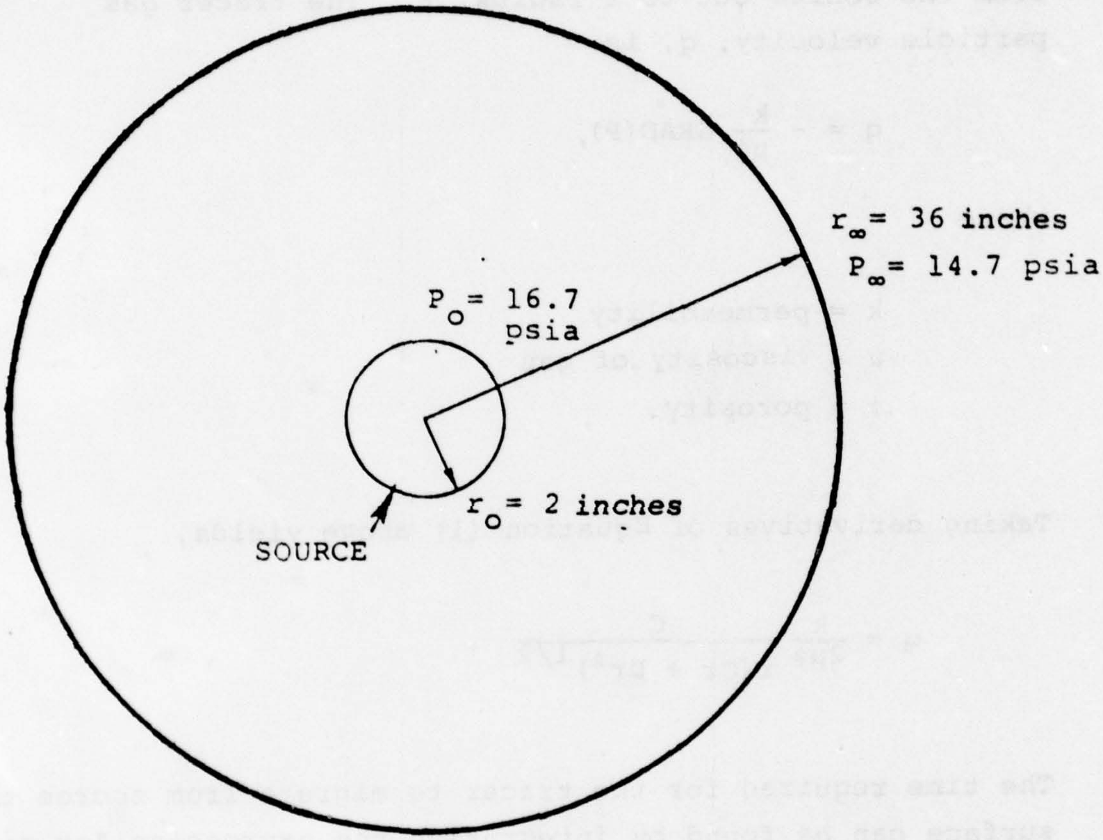

Figure 1. **Representation of Spherical Source Geometry for Tracer Diffusion Calculation With Values for Pressures and Radii Used in Example Calculation**

$$P^2 = -\frac{1}{r}\,\frac{P_o^2 - P_\infty^2}{\frac{1}{r_\infty} - \frac{1}{r_o}} + \frac{\frac{P_o^2}{r_\infty} - \frac{P_\infty^2}{r_o}}{\frac{1}{r_\infty} - \frac{1}{r_o}} \equiv \frac{C}{r} + D\,. \tag{1}$$

Since diffusion time is being sought, gas must be followed from the source out to a radius, r. The tracer gas particle velocity, q, is

$$q = -\frac{k}{\mu\phi}\,\mathrm{GRAD}(P),$$

where

k = permeability
μ = viscosity of gas
ϕ = porosity.

Taking derivatives of Equation (1) above yields,

$$q = \frac{k}{2\mu\phi}\,\frac{C}{r(Cr + Dr^2)^{1/2}}\,. \tag{2}$$

The time required for the tracer to migrate from source to surface can be found by integrating the expression for q:

$$q = \left.\frac{dr}{dt}\right|_{\text{tracer}}$$

$$\frac{dr}{dt} = \frac{k}{2\mu\phi}\,\frac{C}{r(Cr + Dr^2)^{1/2}}$$

$$\frac{kC}{2\mu\phi}\int_0^T dt = \int_{R_o}^{R_\infty} r(Cr + Dr^2)^{1/2}\,dr.$$

Taking and performing the integration we obtain

$$\chi = Cr + Dr^2$$

$$\frac{kC}{2\mu\phi} T = \frac{\chi^{3/2}}{3D} - \frac{C(2Dr + C)}{8D^2} \chi^{1/2}$$

$$\left. + \frac{C^3}{16D^2} \frac{1}{D^{1/2}} \ell n \; 2(D\chi)^{1/2} + 2DR + C \right| \Bigg\}_{R_o}^{R_\infty} . \qquad (3)$$

Using values for pressure and radius given in Figure 1 we calculate

$$C = - \frac{P_o^2 - P_\infty^2}{\frac{1}{r_\infty} - \frac{1}{r_o}} = 3.38 \times 10^{14}$$

$$D = \frac{\frac{P_o^2}{r_\infty} - \frac{P_\infty^2}{r_o}}{\frac{1}{r_\infty} - \frac{1}{r_o}} = 2.124 \times 10^{14} .$$

Plugging in values for C and D in Equation (3), it is found that only the first term in the expression need be considered. All the rest are much smaller, hence,

$$\frac{kC}{2\mu\phi} T \approx \frac{(CR_\infty + DR_\infty^2)^{3/2}}{3D} = 3.81 \times 10^{12} . \qquad (4)$$

For air flow through the ground:

$$\mu_{air} = 1.8 \times 10^{-4} \text{ dyne-sec/cm}^2$$

$\phi_{soil} \simeq 0.3$ (This number is really smaller since much of the void space may be filled with water).

If representative values for k are taken, i.e.,

$$k_{\text{sandstone}} \approx 0.01 \text{ darcy and}$$

$$k_{\text{sand or sand + gravel}} \approx 100 \text{ darcy.}$$

Then, for the worst case (sandstone)

$$T = \frac{(3.8 \times 10^{12})(2)(1.8 \times 10^{-4})(0.3)}{(0.01)(9.87 \times 10^{-9} \text{ cm}^2/\text{darcy})(3.38 \times 10^{14})}$$

$$= 1.23 \times 10^4 \text{ sec} \quad \underline{\underline{3.5}} \text{ hours.}$$

For the best case (sand or sand + gravel)

$$T = 1.2 \text{ seconds;}$$

as an average (k ∿ 1 darcy)

$$T \approx 2 \text{ minutes.}$$

The preceding calculation determines the length of time required for a gaseous tracer to travel from the buried source to the surface assuming that a steady-state pressure gradient has been established. It is of interest to determine the length of time required to establish this profile. Since the total time for tracer to appear is the sum of the transient plus steady-state diffusion times, it is useful fo make the following definitions for analytical simplicity:

$$K = \frac{kP_\infty}{\mu\phi}$$

$$\nu_o = P_o - P_\infty$$

$$\nu = P - P_\infty$$

$$\frac{\nu}{\nu_o} = \frac{R_o}{r} \operatorname{erfc} \frac{r - R_o}{2\sqrt{Kt}} \qquad (5)$$

(non-linear terms neglected).

As shown graphically in Figure 2, the steady-state gradient is established by the time $\nu(R_\infty)/\nu_o \approx 0.01$, then

$$\frac{\nu}{\nu_o}\,\frac{R_\infty}{R_o} = 0.18 .$$

Then, putting numerical values in Equation (5) yields

$$\text{erfc } Z = 0.18 \rightarrow Z \approx 0.8$$

and

$$K_{worst} = 1.8$$

$$K_{best} = 1.8 \times 10^4$$

$$K_{average} = 1.8 \times 10^2 .$$

Since

$$0.8 = \frac{r - R_o}{2\sqrt{Kt}} ,$$

then

$$t = \left(\frac{r - R_o^2}{2}\right)^2 \cdot \frac{1}{K}\,\frac{1}{(0.8)^2}$$

$$t = (43.2)^2 \cdot \frac{1}{1.8}\,\frac{1}{0.64}$$

$$t_{worst} = 27 \text{ minutes} .$$

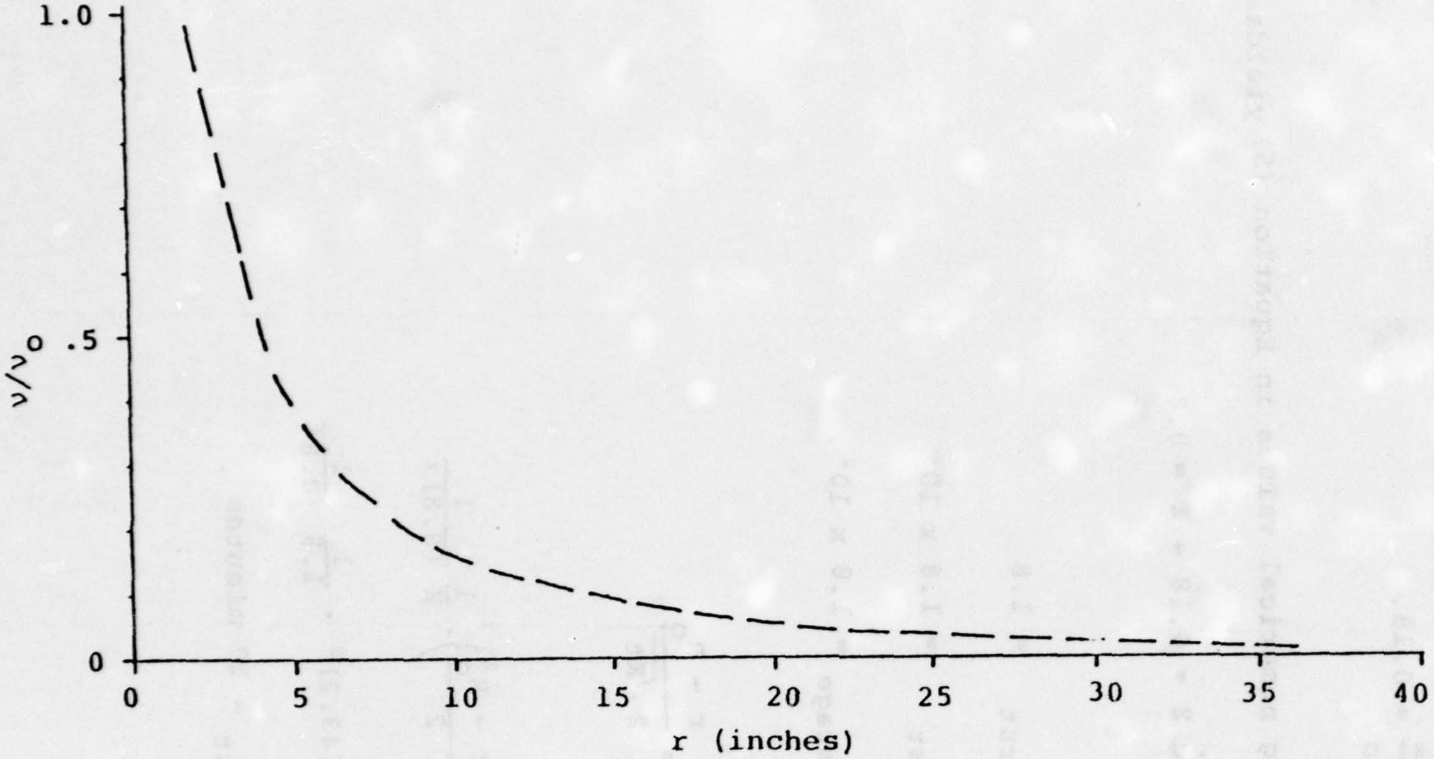

Figure 2. Plot of Equation (5) Showing Onset of Steady-State Gradient

2.2 WATER SATURATION

If the soil is completely saturated, then it will be difficult to have the tracer penetrate to the surface. If it is assumed that the water must be displaced before tracer gas reaches the surface, then for steady-state with

$$\mu_{water} \sim 1 \times 10^{-2}$$

we have

$$T_{avg} = \frac{(3.8 \times 10^{12})(2)(1 \times 10^{-2})(0.3)}{(1)(9.87 \times 10^{-9})(3.38 \times 10^{14})} = 6859 \text{ seconds } (\sim 2 \text{ hours})$$

T_{worst} = 200 hours (Cracks probably exist, so this case would not really occur).

In Section 3, a table is presented in which diffusion times calculated by Equation (4) are compared to those measured in the pit experiments at Green Farm.

2.3 MONITORING INSTRUMENTATION AND GASES USED IN THIS STUDY

The S^3 tracer gas monitor is an electron capture gas chromatograph shown schematically in Figure 3. The electron capture gas chromatograph utilizes the high electron affinity of gases with halogen group elements to provide a measurable signal. A sample to be analyzed is injected into the instrument by means of a disposable syringe. Injection is through a rubber septum located on the sample port. This septum prevents spurious contaminants from diffusing into the chromatograph and producing anomalous signals.

The heart of the instrument is the column. It separates the various gaseous components of a sample by selectively slow-

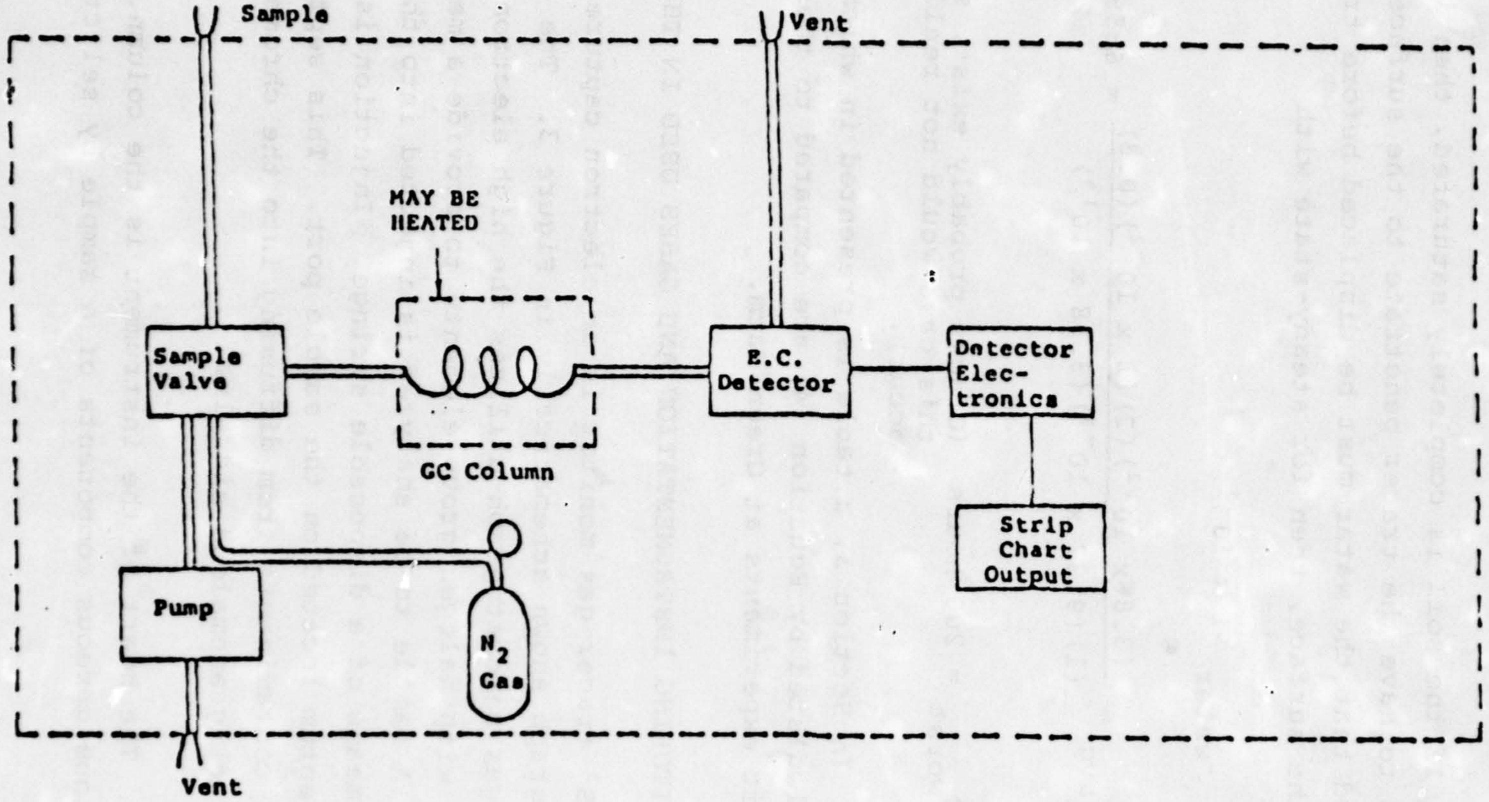

Figure 3. Schematic of an Electron Capture Gas Chromatograph

ing down some gases relative to others. The column can be thought of as a device to elute the distinct components in a gas sample in a definite order.

When monitoring SF_6 plus selected Freons®, experience has shown that a column (stationary phase) consisting of one of the Porapaks® provides excellent separation. This separation is illustrated in Figure 4 for the tracer gases used in tests reported herein. Porapak® is a porous polymer composed of ethylvinylbenzene cross-linked with divinylbenzene to form a uniform structure of distinct pore size. The columns and detector are generally operated at elevated temperatures to increase detector sensitivity to tracer peaks and to allow a complete measurement to be performed in a relatively short time. Care must be exercised in the choice of operating temperature since the relative arrival time (elution time) is a function of Porapak® type as well as column temperature and chemical species (see Figure 5). Incorrect operating temperature could provide erroneous or confusing data output due to peak arrival overlap.

The detector portion of the chromatograph consists of a tritiated foil encased within an electrically conductive housing. Specific pulse-generator circuitry energizes the detector, initiating a flow of electrons from the tritium foil. A collector wand within the detector receives the electrons and establishes a current flow which is amplified through an electrometer circuit. Should an "electron-capturing gas", such as SF_6 or one of the Freons®, flow through the stream of electrons, the current is decreased in proportion to the concentration of the gas.

The gas commonly used in electron capture gas chromatographs is so-called "carrier grade" nitrogen, which means that

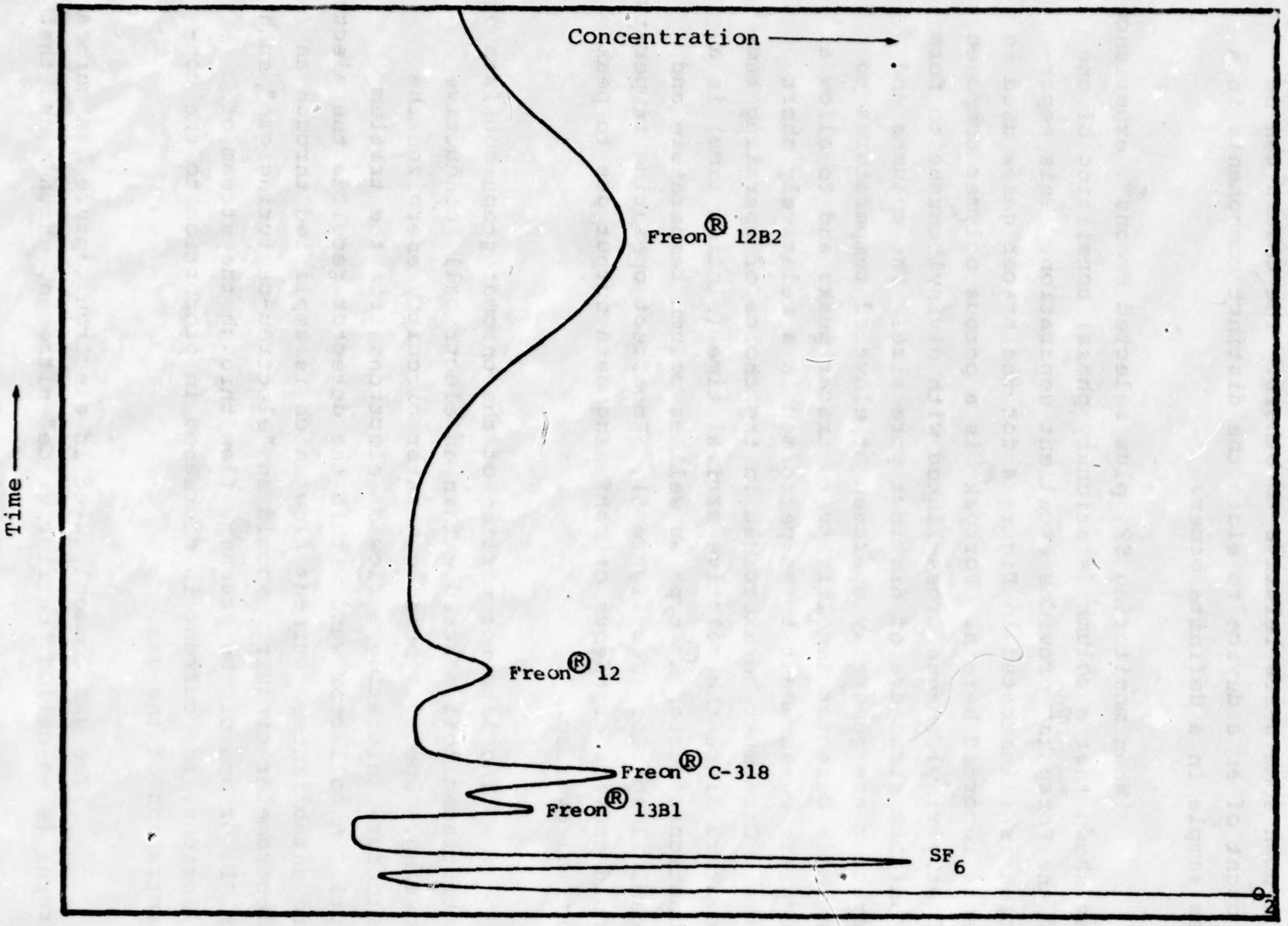

Figure 4. Chromatograph Response Showing Separation of Various Tracer Gases on a One-Meter Porapak® Q Column (Column Temperature = 100°C; Carrier Flow Rate = 50 cc/min)

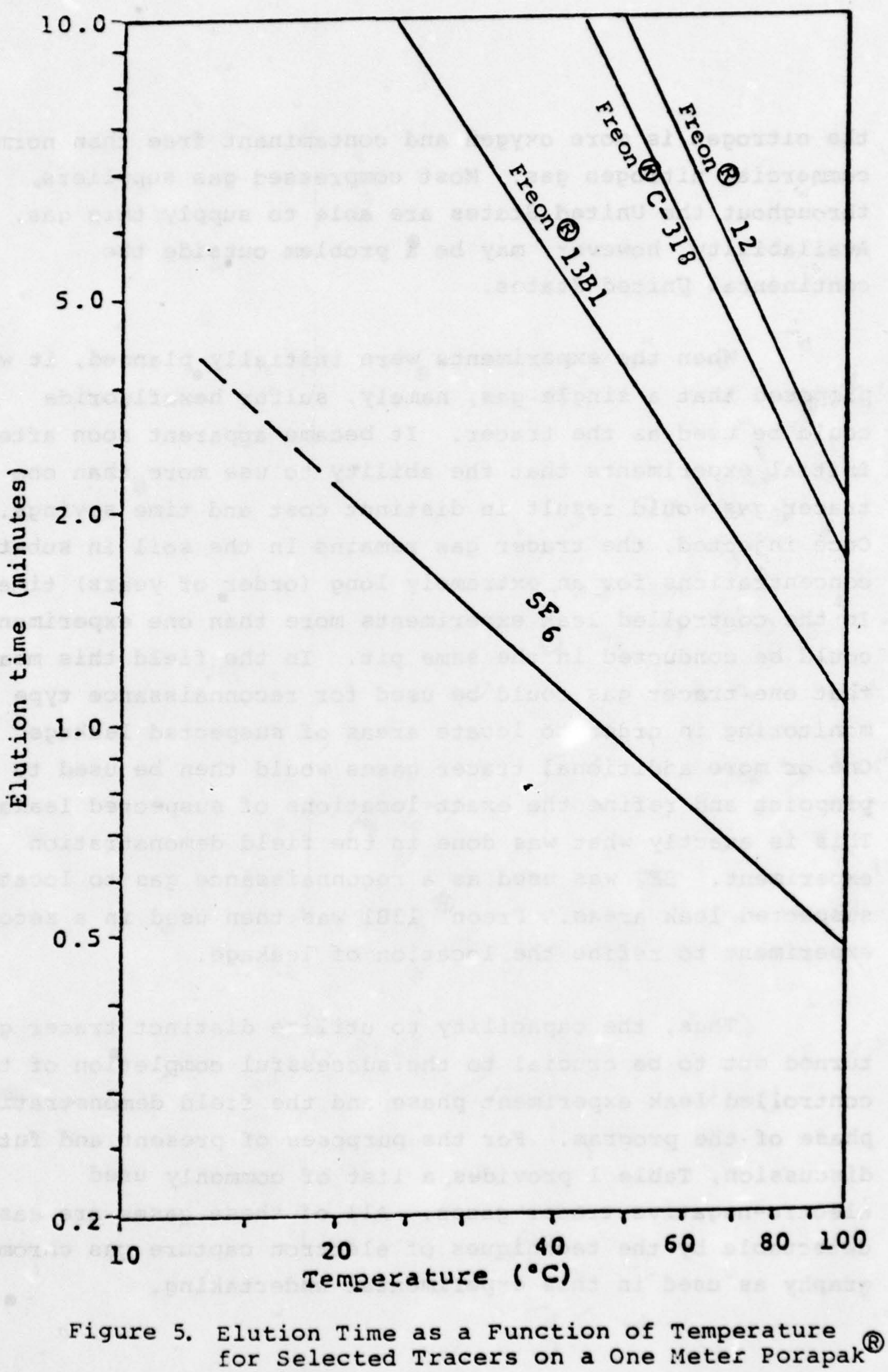

Figure 5. Elution Time as a Function of Temperature for Selected Tracers on a One Meter Porapak® Q Column.

the nitrogen is more oxygen and contaminant free than normal commercial nitrogen gas. Most compressed gas suppliers throughout the United States are able to supply this gas. Availability, however, may be a problem outside the continental United States.

When the experiments were initially planned, it was proposed that a single gas, namely, sulfur hexafluoride could be used as the tracer. It became apparent soon after initial experiments that the ability to use more than one tracer gas would result in distinct cost and time savings. Once injected, the tracer gas remains in the soil in substantial concentrations for an extremely long (order of years) time. In the controlled leak experiments more than one experiment could be conducted in the same pit. In the field this meant that one tracer gas could be used for reconnaissance type monitoring in order to locate areas of suspected leakage. One or more additional tracer gases would then be used to pinpoint and refine the exact locations of suspected leakage. This is exactly what was done in the field demonstration experiment. SF_6 was used as a reconnaissance gas to locate suspected leak areas. Freon® 13B1 was then used in a second experiment to refine the location of leakage.

Thus, the capability to utilize distinct tracer gases turned out to be crucial to the successful completion of the controlled leak experiment phase and the field demonstration phase of the program. For the purposes of present and future discussion, Table 1 provides a list of commonly used electro-negative tracer gases. All of these gases are easily detectable by the techniques of electron capture gas chromatography as used in this experimental undertaking.

In the controlled leak portion of this study, two System, Science and Software Model 215BGC Laboratory Tracer Gas Monitors were used for SF_6 detection. Detection of Freons® 13B1 and C-318 was performed utilizing a proprietary electron capture chromatograph (Model 430DCD). This instrument is a heated dual column, dual detector device. Equipped with two Porapak® columns, this instrument is suitable for monitoring all the gases listed in Table 1.

TABLE 1. ELECTRONEGATIVE GASES USABLE AS TRACERS

TRACER	SYMBOL	TRADE NAME*
Sulfur Hexafluoride †	SF_6	--
Dibromodifluoromethane	CF_2Br_2	Freon® 12B2
Trichlorofluoromethane	$CFCl_3$	Freon® 11
1,1,2-Trichlorotrifluoroethane	$C_2Cl_3F_3$	Freon® 113
Bromotrifluoromethane †	CF_3Br	Freon® 13B1
Octafluorocyclobutane †	C_4F_8	Freon® C-318
Dichlorodifluoromethane	CCl_2F_2	Freon® 12
1,2-Dichlorotetrafluoroethane	$C_2Cl_2F_4$	Freon® 114
Chlorodifluoromethane	$CHClF_2$	Freon® 22

* Freons® also known as Genetrons and Halocarbons

† Used in Air Force Leak Study

In the field demonstration test, in addition to the above instrumentation, two Systems, Science and Software Model 215AUP Envirometers were used. The two Model 215BGC monitors and two Model 215AUP Envirometers were fitted with special molecular sieve columns which afforded detection capability for both SF_6 and Freon® 13B1.

The requirement for additional instrumentation arose due to throughput requirements in testing a substantial interval of buried pipe. For SF_6 only, each instrument is capable of analyzing roughly 20 samples per hour. When other gases, such as Freon® 13B1, are used, this number falls to between 12 and 15 samples per hour.

In the initial phase of the demonstration test, 240 samples per hour were taken, although only 1/3 to 1/2 of these had to be analyzed for the presence of tracer gas. Thus, the need for five machines was driven by sample analyses throughput requirements.

SECTION 3

CONTROLLED LEAK EXPERIMENTS

The initial controlled leak experiments were performed at the Green Farm Test Site on a series of five steel pipes 14 inches in diameter and roughly 20 feet long which were buried at a nominal depth of 3 feet. A flat, slightly cobbled area was chosen for these tests. This area is adjacent to the machine shop at Green Farm and provides ready access for power and shop support.

Each steel pipe had a steel plate welded on each end. A 2-inch vent pipe was also welded to one end to allow a vent protrusion above ground surface when the pipe was buried. Welding was done by certified pipeline welders, and all welds were leak checked prior to installation in the ground. At several locations along the top of the pipe, electrically operated solenoid valves were installed to provide a controllable leak at known locations.

The steel pipes were laid out in a hexagonal pattern around an approximately 6 foot in diameter pit. The bulkheads forming the pit were 4 feet on the side. Figure 6 gives a cross section of typical buried pipe while Figure 7 shows a general layout of the leak experiment facility. The hexagonal shape allowed for installation of five steel pipes, one on each of the five sides, with a clear section for mounting manifolds and associated plumbing.

Each steel pipe was installed so that it protruded several inches into the hexagonal pit. Thus, each pipe terminated in a manner similar to termination in an actual

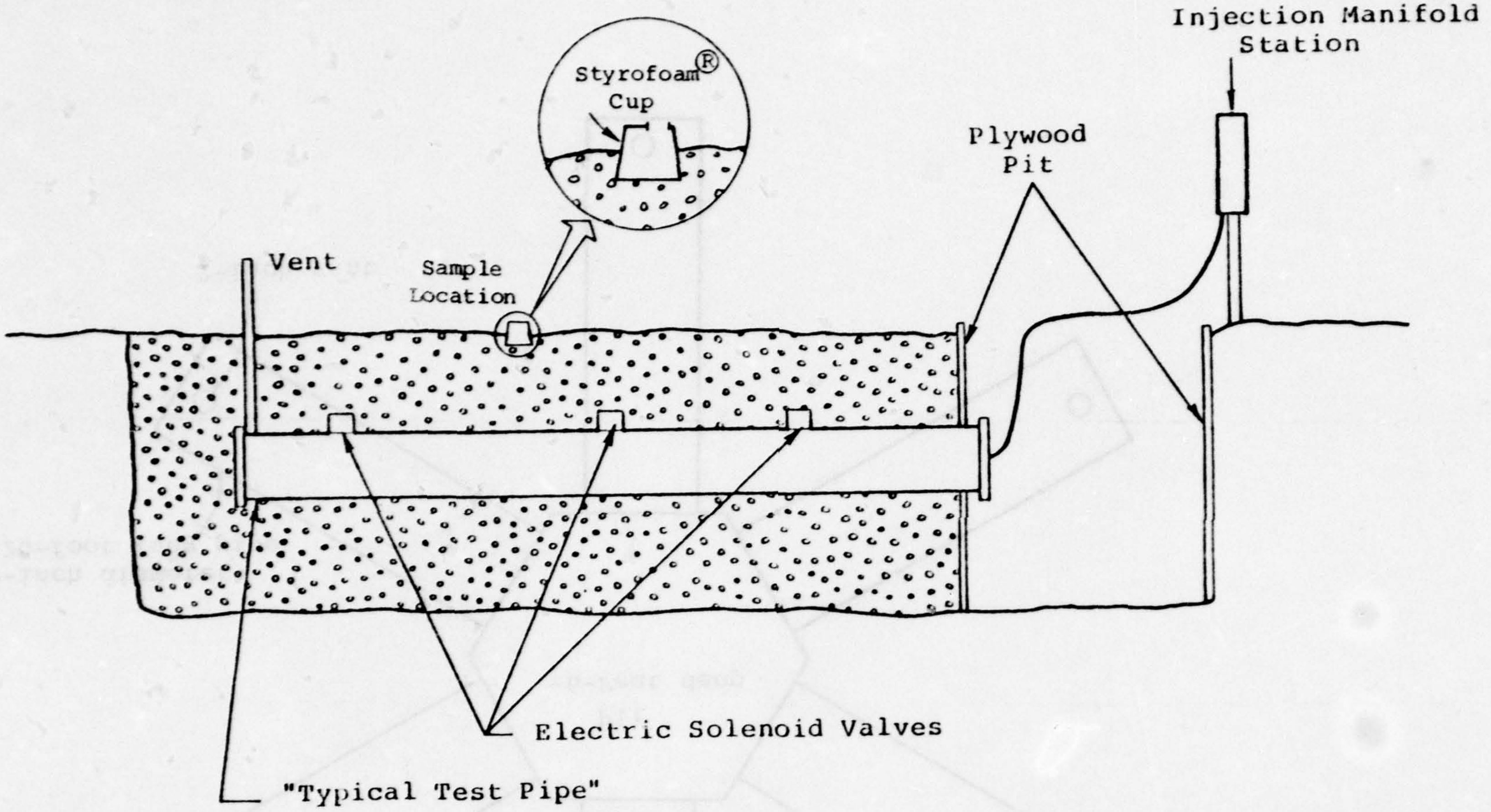

Figure 6. Typical Experimental Arrangement Showing Buried Pipe, Typical Surface Sample Location, Injection Monitoring Station and Approximate Positions of Solenoid Valves

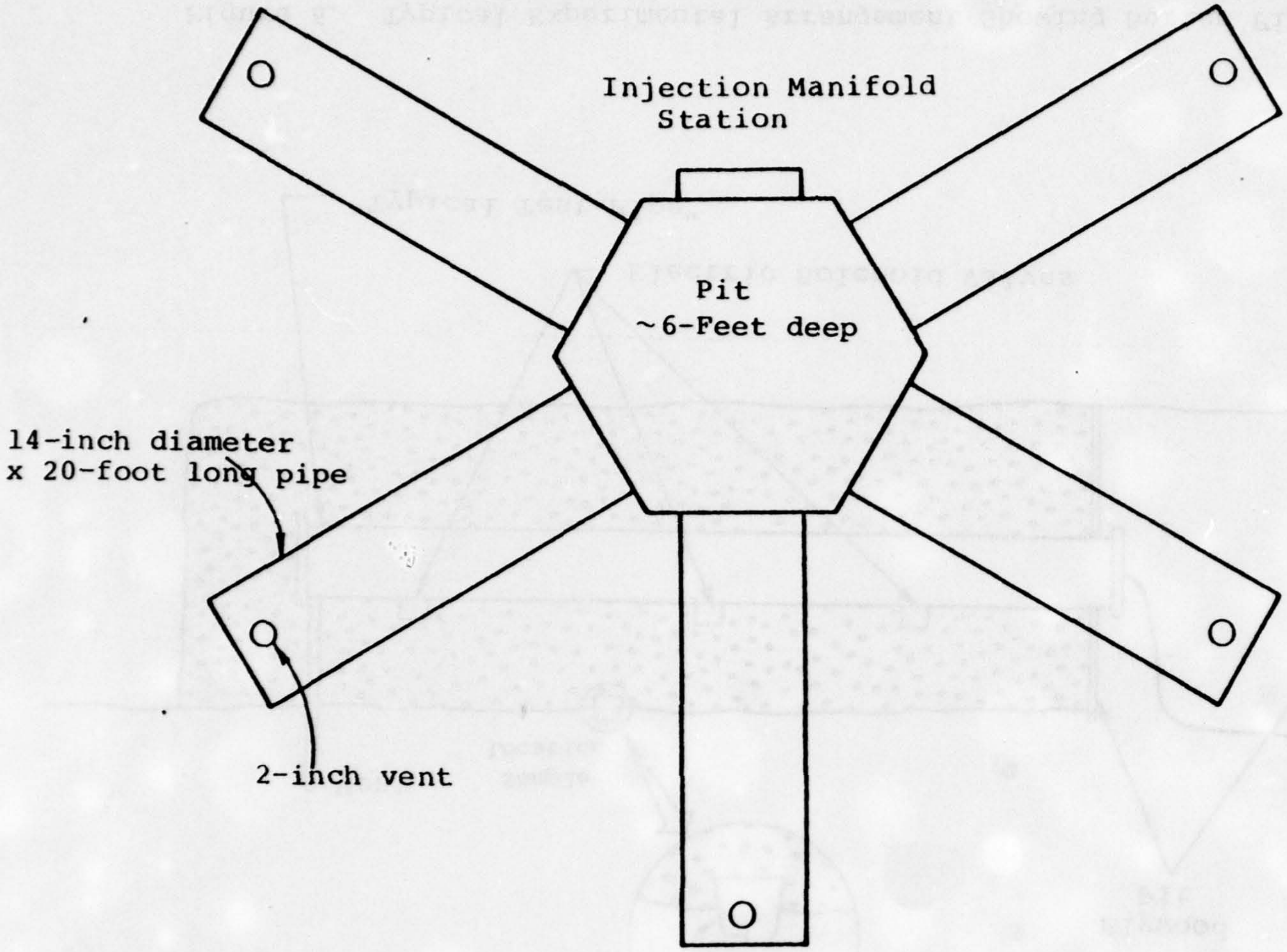

Figure 7. General Site Configuration - Leak Experiment Facility

manhole. A pressure gauge and a pressurization port were installed on the steel pipe end which protruded into the hexagonal pit. The vent pipe had a manually actuated valve installed so that the buried pipe could be vented as required.

An instrumentation and mixing manifold was placed in a shelter on the sixth side of the hexagonal pit. This manifold shown in Figure 8 provided metering of tracer gas, individual shut-off valves for tracer gas and compressed air, injection flow rate monitoring, leaking solenoid control panel, and an electronic pressure transducer to monitor injection manifold pressure. Manifold pressure is needed to correct flow measured with rotometers to standard flow rates. Tracer gas control was effected using a critical orifice metering valve in conjunction with compressed gas bottles filled with diluted tracer gas in nitrogen at an initial concentration of 10^{-4}. A small electric spray paint compressor with a pressure regulator provided compressed air.

Each steel pipe was set up with specified leak(s) by placing a copper tube on the downstream side of the solenoid valve and running the tubing to the required location. The leak type and location were then varied by changing the placement and hole pattern of sections of 1/4-inch (O.D.) x 0.035-inch wall copper tubing attached to the outlet of the solenoid valve. Figure 9 is a typical installation to simulate a top leak. For a simulated leak at the bottom of the pipe, this tubing was routed around to the underside of the pipe. A simulated leak in a weld was obtained by routing a piece of plugged tubing one-quarter of the circumference around the pipe. A series of small holes was drilled into the copper tubing to allow gas to escape along the circumference of the steel pipe.

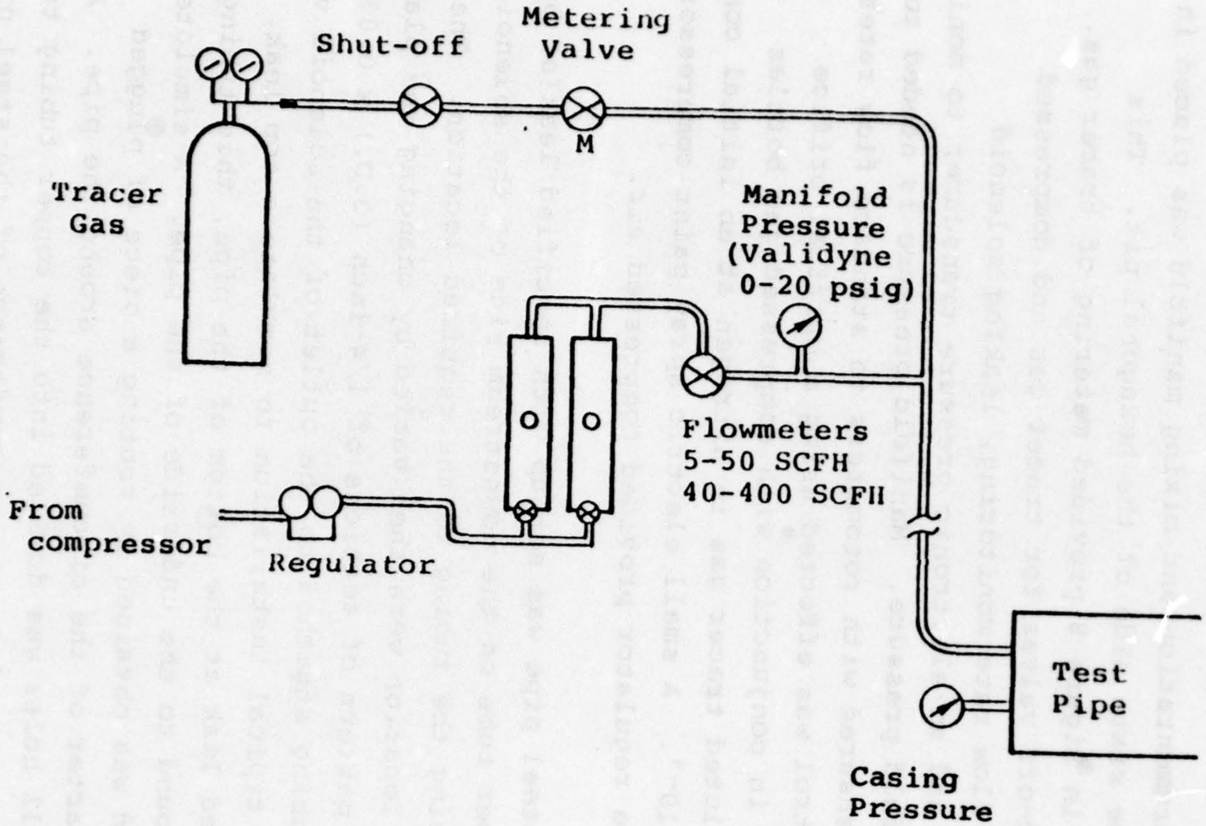

Figure 8. Test Manifold - Green Farm Test Facility

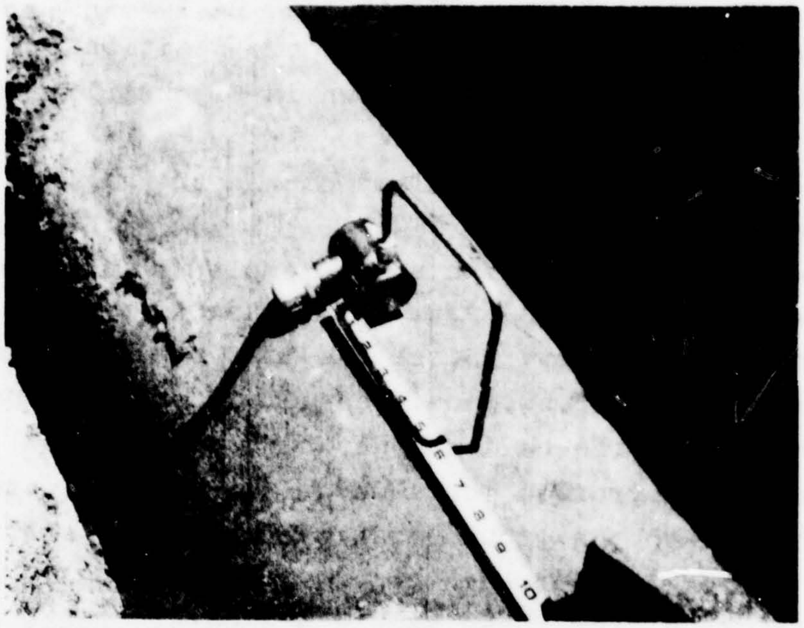

Figure 9. Typical Installation of Solenoid Controlled Leak (Top Leak Shown)

Steel pipes were placed in trenches approximately 2-feet wide and 5-feet deep leading out from the hexagonal pit. A photograph of one is shown in Figure 10. The small pipe extending vertically from the large diameter steel pipe is the vent line previously mentioned. Electric solenoids were connected to the control panel and rechecked prior to burial. After being checked, the pipe was covered with fill, either sand or dirt or a combination of the two. Line drawings showing the routing of tubing and the positions of leaks for all five test pipes are shown in Figures 11 and 12.

Sample grids were laid out on the surface with a known relationship to the leak or leaks. In general, the grids were three rows with seven sample stations per row. The rows were 7 inches apart with a sample station every 21 inches in each row. Since the test pipe was a nominal 42 inches below the surface, the sample station spacing in each row was one-half the depth of burial (DOB). As shown in Figure 6, Styrofoam® cups were inverted and inserted two inches into the ground to act as sampling stations. One-half of the bottom side of each cup was then removed. Gas samples were withdrawn from these sample chambers. These cups served as reservoirs to keep surface winds from diluting the tracer gas diffusing through the ground to the surface and distorting the results. The gas samples were taken at the ground surface using disposable 12-cc polypropylene syringes. Two samples were taken from each sample station at predetermined time intervals. These samples were analyzed by the previously mentioned electron capture gas chromatographs as the test progressed.

A test sequence was initiated by filling the pipe with compressed air and tracer gas. When the pressure rise within the pipe indicated that a substantial quantity of compressed air mixed with tracer gas had been injected into a test pipe,

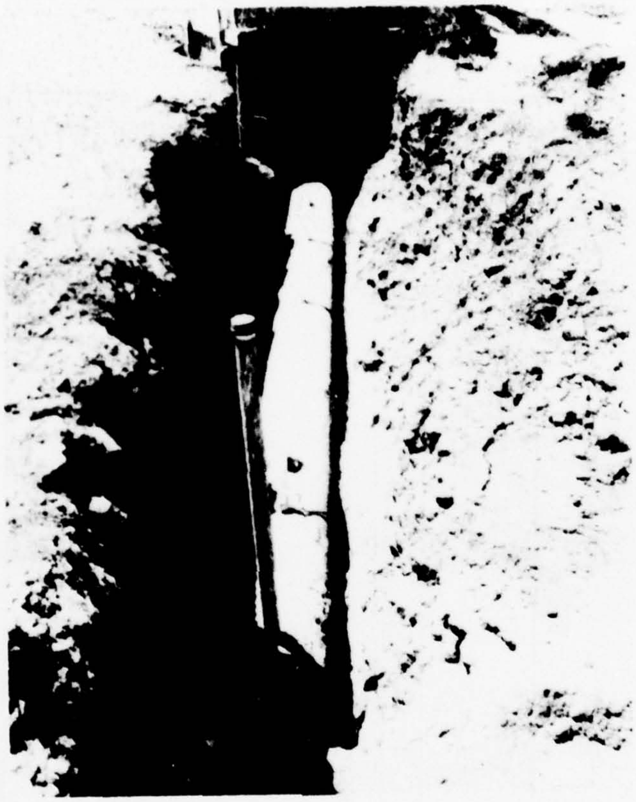

Figure 10. Typical Pipe in Trench Prior to Burial

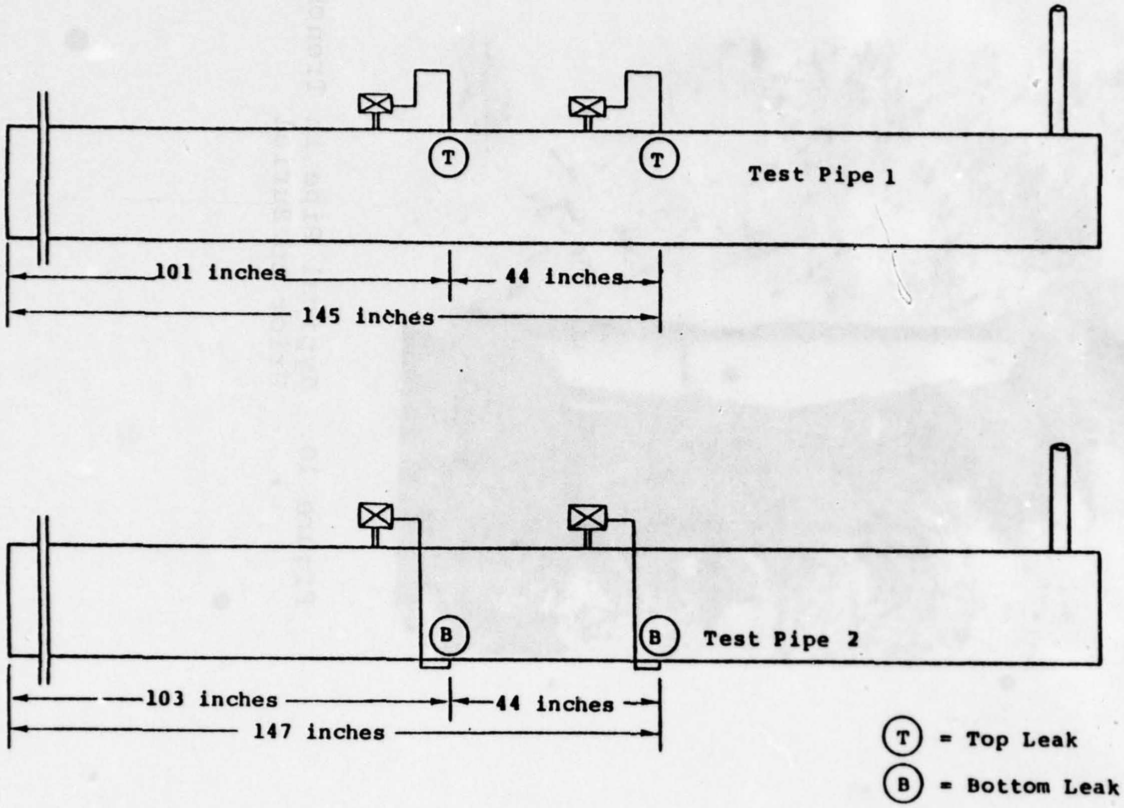

Figure 11. Test Pipe Configurations for Pipes 1 and 2

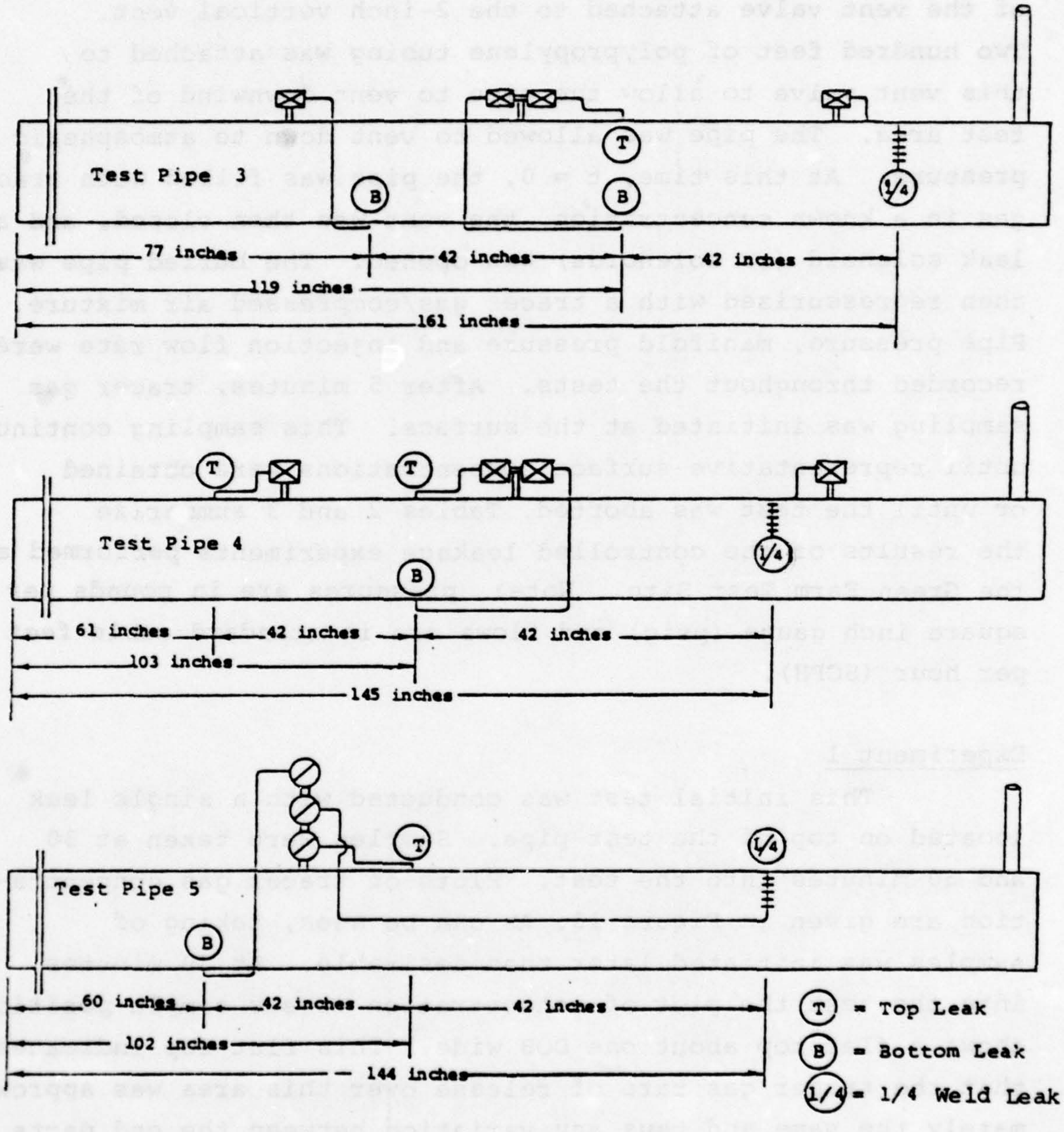

Figure 12. Test Pipe Configurations for Pipes 3, 4, and 5

the pressurization was stopped and the pipe was vented by means of the vent valve attached to the 2-inch vertical vent. Two hundred feet of polypropylene tubing was attached to this vent valve to allow the pipe to vent downwind of the test area. The pipe was allowed to vent down to atmospheric pressure. At this time, t = 0, the pipe was filled with tracer gas in a known concentration, the vent was then closed, and a leak solenoid (or solenoids) was opened. The buried pipe was then repressurized with a tracer gas/compressed air mixture. Pipe pressure, manifold pressure and injection flow rate were recorded throughout the tests. After 5 minutes, tracer gas sampling was initiated at the surface. This sampling continued until representative surface concentrations were obtained or until the test was aborted. Tables 2 and 3 summarize the results of the controlled leakage experiments performed at the Green Farm Test Site. Note: pressures are in pounds per square inch gauge (psig) and flows are in standard cubic feet per hour (SCFH).

Experiment 1

This initial test was conducted with a single leak located on top of the test pipe. Samples were taken at 30 and 50 minutes into the test. Plots of tracer gas concentration are given in Figure 13. As can be seen, taking of samples was initiated later than desirable. At 30 minutes into the test the plot of concentration versus sample position shows a flat top about one DOB wide. This flat top indicates that the tracer gas rate of release over this area was approximately the same, and thus any variation between the end parts of the flat top cannot be seen. However, even with this simple initial test, it is apparent that the leak is localized to within ± one DOB (42 inches).

TABLE 2. SUMMARY OF CONTROLLED LEAK EXPERIMENTS CONDUCTED AT GREEN FARM TEST SITE

Experiment	DOB (inches)	Fill Material(s)	Leak Type
1	42	Sand	Top
2	42	Sand	Top
3	42	Sand	Top 2 each 2 DOB apart
4	42	Sand	Bottom
5	42	Sand	Top
6	42	Sand	1/4 weld leak
7	42	12 inches sand/ 30 inches dirt fill	Top
8	42	12 inches sand/ 30 inches dirt fill	1/4 weld leak
9	42	6 inches sand/dirt in 6 inch compacted lifts	Top
10	42	12 inches sand/ 25 inches dirt fill/ 4 inches concrete	Top

TABLE 3. SUMMARY OF PARAMETERS IN CONTROLLED LEAK EXPERIMENTS AT GREEN FARM TEST SITE

Experiment	Manifold Pressure (psig)	Casing Pressure (psig)	Flow Rate (SCFH)	Gas and Initial Concentration
1	10.0	8.0	40	SF_6 5 x 10^{-7}
2	13.0	9.5	60	Freon® 13B1 1 x 10^{-7}
3	12.8	9.0	68	Freon® C318 5 x 10^{-7}
4	10.0	3.8	74	Freon® 13B1 1 x 10^{-7}
5	13.3	12.0	32	SF_6 5 x 10^{-7}
6	13.4	7.0	87	Freon® C318 5 x 10^{-7}
7	Experiment aborted due to equipment malfunction			
8	13.0	7.0	82	SF_6 5 x 10^{-7}
9	13.2	7.5	81	SF_6 5 x 10^{-7}
10	13.2	8.5	70	Freon® 13B1 1 x 10^{-7}

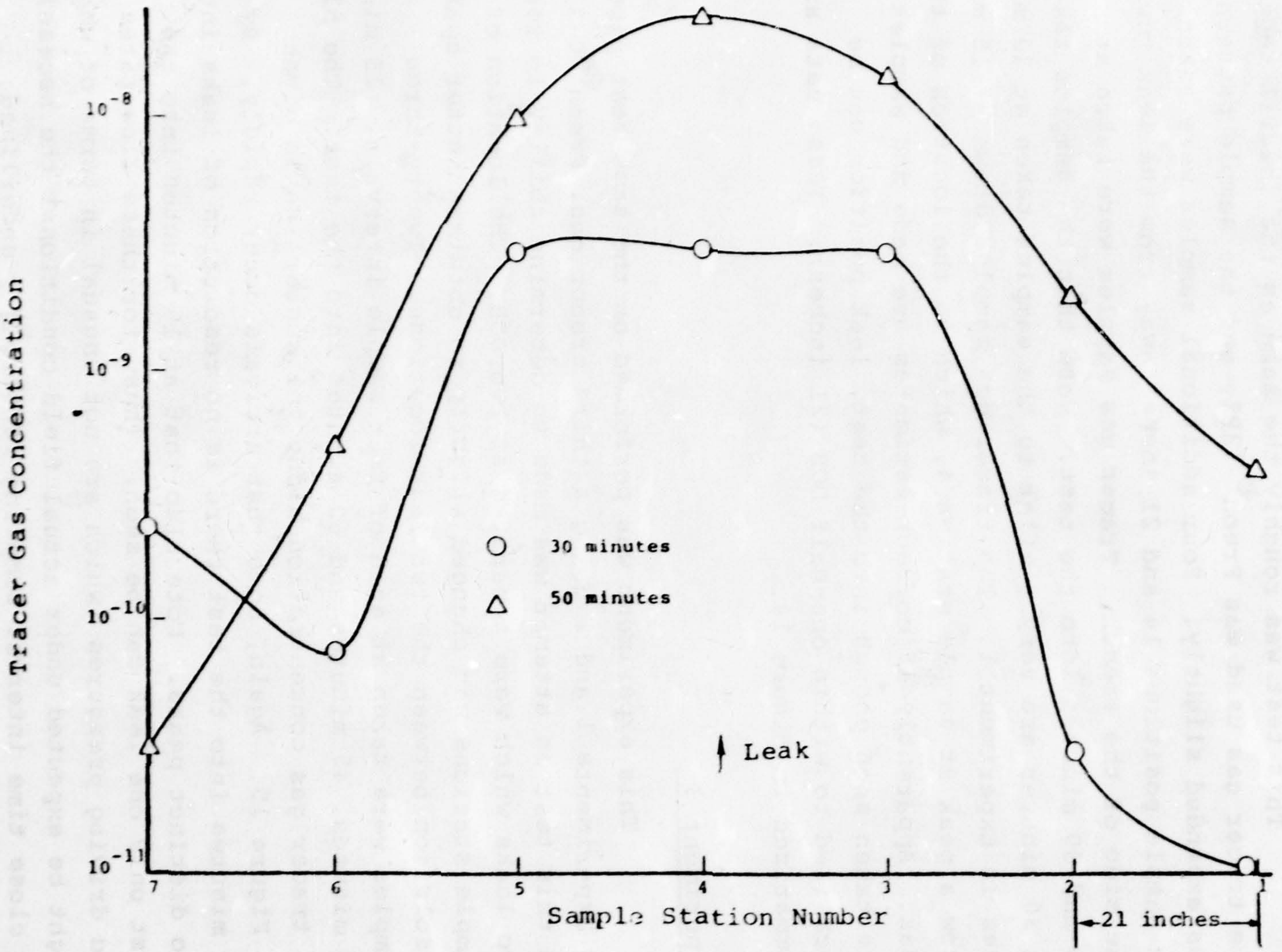

Figure 13. Experiment 1 Tracer Gas Concentration on the Surface Along Pipe Centerline

Experiment 2

This test was roughly the same as the initial test. The tracer gas used was Freon® 13B1, and the sample pattern was expanded slightly. Four additional samples were taken at sample positions 14 and 21 inches away from the leak toward the side of the trench. Tracer gas samples were taken at 15 and 30 minutes into the test. Note that the samples taken at 30 minutes are very similar to the samples taken at 30 minutes in Experiment 1. The tracer gas samples drawn at 15 minutes show a peak at sample station 4, which is the location of the leak. Apparently if correct estimates are made and samples are taken soon enough into the test, leak position can be localized to within one-half DOB (21 inches). These data are summarized in Figure 14.

Experiment 3

This experiment was performed on the same test pipe as Experiments 1 and 2 using a third tracer gas, Freon® C-318. In this test an attempt was made to determine ability to resolve two leaks which were separated at two DOB. The location of the sample stations was changed slightly to obtain a better spatial resolution between the two leak locations. Twenty-three samples were taken at each of four sample intervals; 15 minutes, 30 minutes, 45 minutes and 60 minutes into the test. The plot of tracer gas concentration along the centerline is given in Figure 15. Again, note that arrivals occur rapidly. By 45 minutes into the test there is no resolution of leaks into two distinct peaks. Note also that at 15 minutes into the test only one leak can be seen. Thus, for these flow rates and driving pressures (which are not unusual in terms of what might be expected under actual field conditions) the necessity of close time interval sampling is strongly underlined.

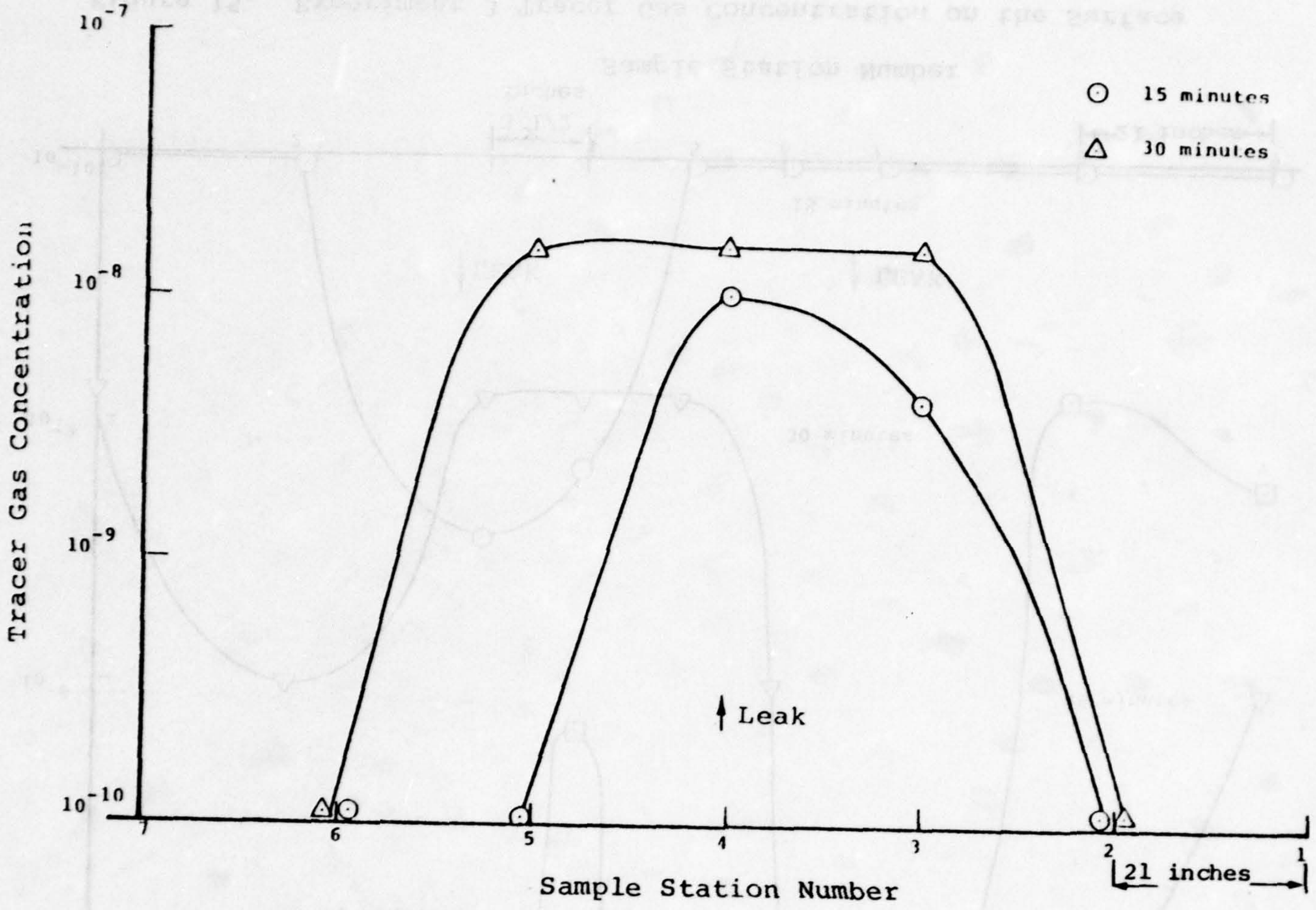

Figure 14. Experiment 2 Tracer Gas Concentration on the Surface Along the Pipe Centerline

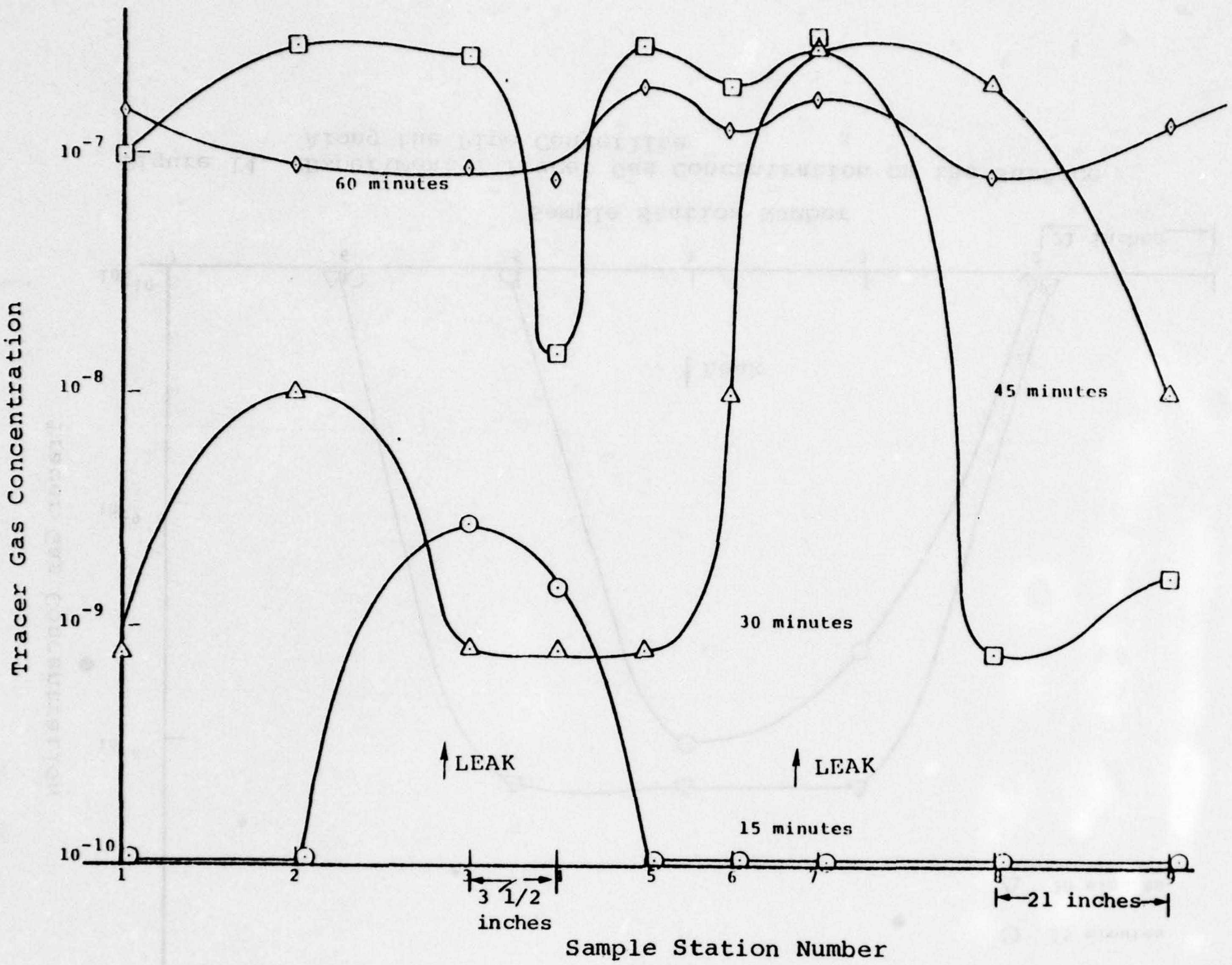

Figure 15. Experiment 3 Tracer Gas Concentration on the Surface Along the Pipe Centerline

Experiment 4

In this experiment we tested a single leak located at the bottom centerline of a buried pipe. This test serves as one of the worst case possibilities since there is no clearly defined leak path to the top of the pipe and then upward to the ground surface. The sampling pattern is identical to that in Experiment 2. Nineteen samples were taken during each of eight sampling intervals; 15 minutes, 30 minutes, 45 minutes, 60 minutes, 90 minutes, 105 minutes, 120 minutes, and 135 minutes into the test. The tracer gas concentrations obtained along the pipe centerline as a function of time are shown in Figure 16. Initial tracer gas arrivals were not discovered until 90 minutes into the test. Three earlier (60-minute) tracer gas concentrations were found at scattered points within the sample pattern. Samples were also drawn around the circumference of the test pipe where it enters the hexagonal pit. Substantial amounts of tracer gas were found at this location. It appears that much of the tracer gas traveled along the pipe rather than directly to the surface. However, what is significant here is that tracer gas was eventually discovered at the surface near the expected leak position of the pipe.

Experiment 5

This experiment evaluated a leak at the top of the pipe and used SF_6 as a tracer gas. The sample pattern is the same as that in Experiments 1, 2 and 3. Three sets of samples were drawn at 10-minute intervals. A plot of tracer gas concentration along the pipe centerline is shown in Figure 17. At 10 minutes into the test no tracer gas was detected. At 20 minutes there was an arrival with the peak being one DOB away from the actual leak location. At 30 minutes, the tracer gas peak has spread out over a wider range but has its maximum

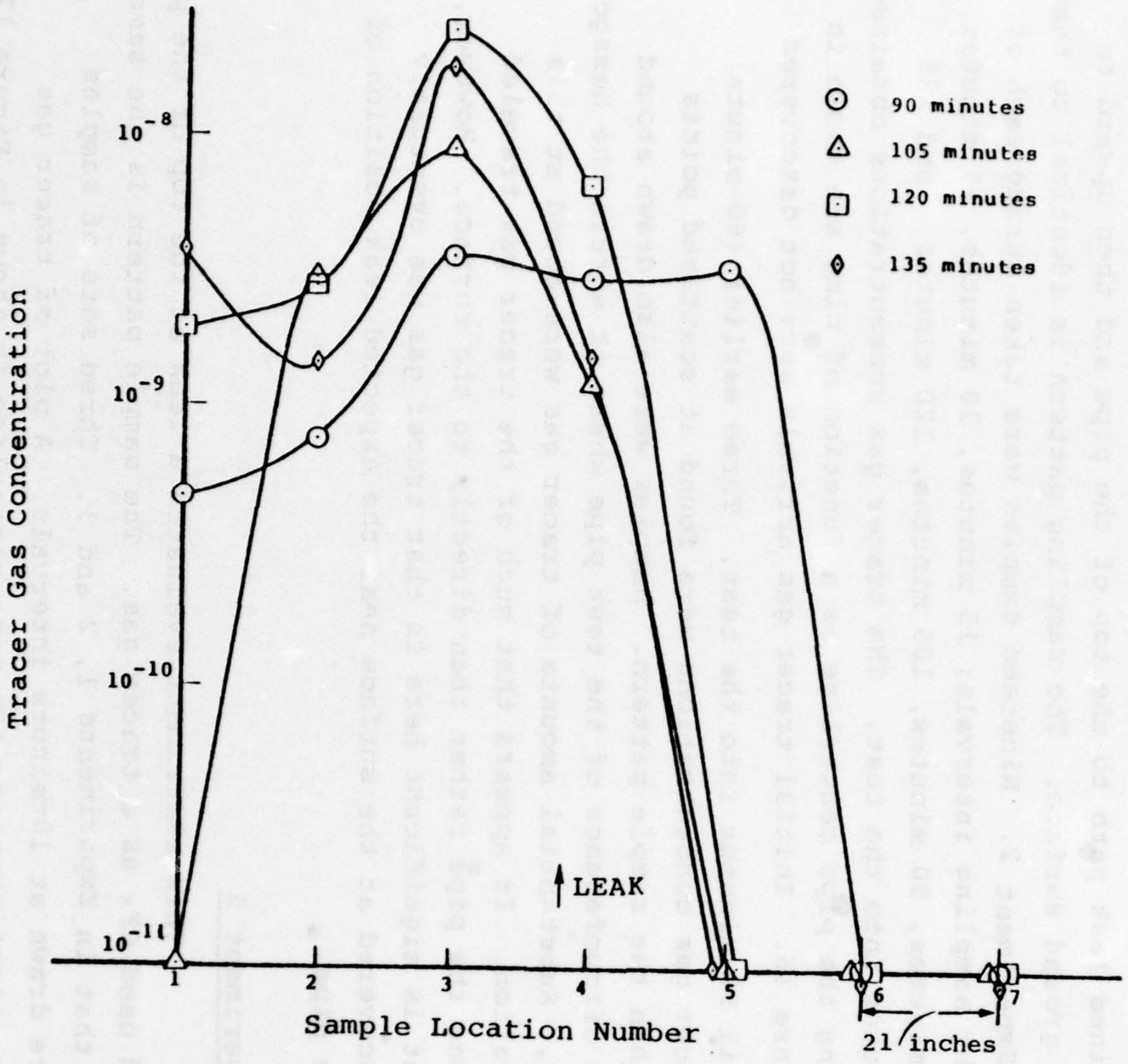

Figure 16. Experiment 4 Tracer Gas Concentration on the Surface Along the Pipe Centerline

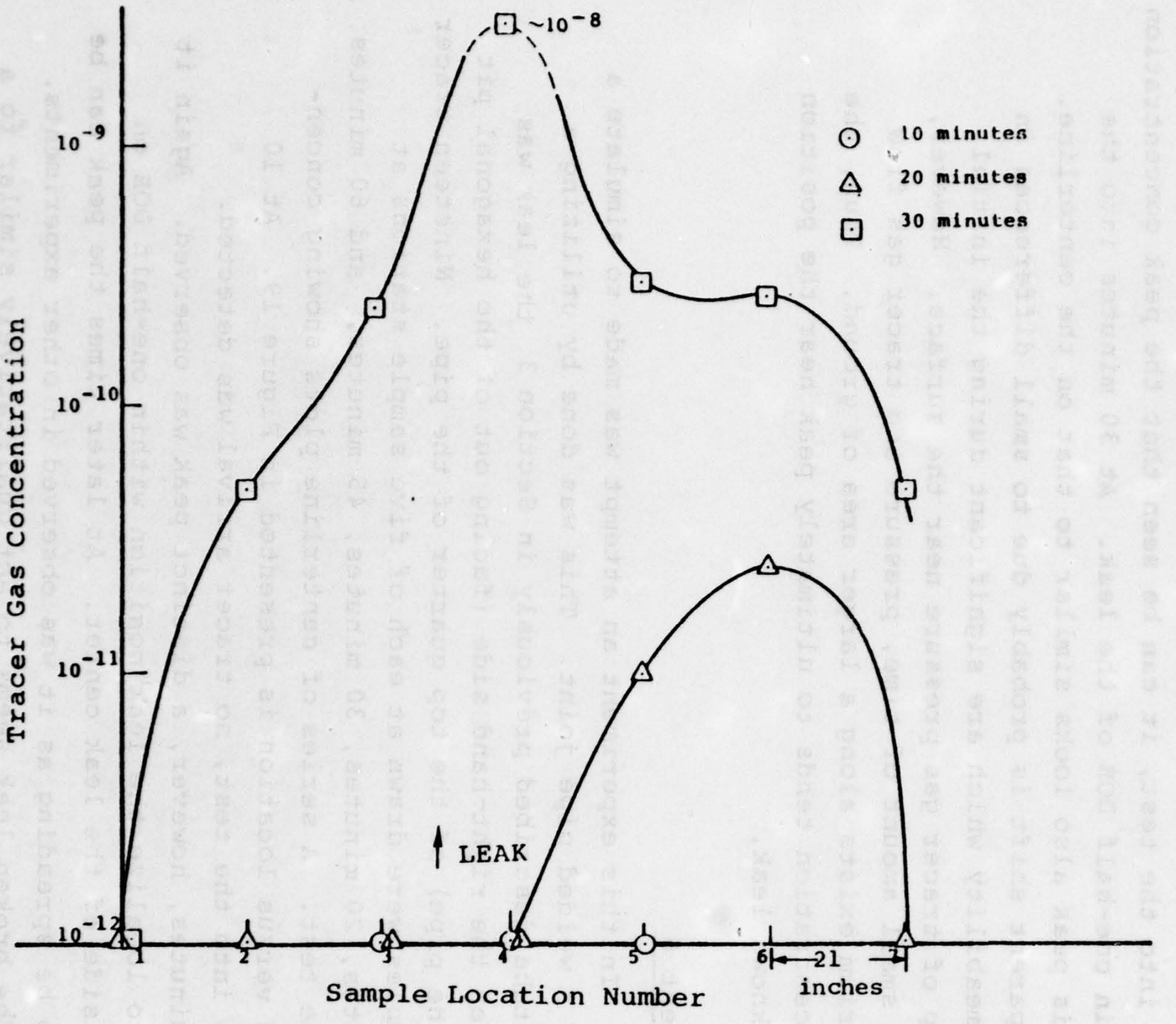

Figure 17. Experiment 5 Tracer Gas Concentration on the Surface Along the Pipe Centerline

concentration directly above the known leak. Looking also at samples taken off the centerline (see Figure 18) at 20 minutes into the test, it can be seen that the peak concentration is within one-half DOB of the leak. At 30 minutes into the test this peak also looks similar to that on the centerline. This apparent shift is probably due to small differences in gas permeability which are significant during the initial build-up of tracer gas pressure near the surface. However, after a small amount of time, pressure and tracer gas flow equilibrium exists along a larger area of ground. Thus, the gas concentration tends to ultimately peak near the position of the known leak.

Experiment 6

In this experiment an attempt was made to simulate a leak in a welded pipe joint. This was done by utilizing a copper tube described previously in Section 3 the leak was placed on the right-hand side (facing out of the hexagonal pit along the pipe) of the top quarter of the pipe. Nineteen tracer gas samples were drawn at each of five sample stations at 10 minutes, 20 minutes, 30 minutes, 45 minutes, and 60 minutes into the test. A series of centerline plots showing concentration versus location is presented in Figure 19. At 10 minutes into the test, no tracer arrival was detected. At 20 minutes, however, a distinct peak was observed. Again it tends to localize the leak position within one-half DOB on either side of the leak center. At later times the peak can be seen to be spreading as it was observed in other experiments. Thus, the broken leak seems to act qualitatively similar to a single leak located near the top of the pipe.

Experiment 7

In this experiment a single leak on top of a pipe was used with Freon® 13B1 tracer gas. The pipe was covered

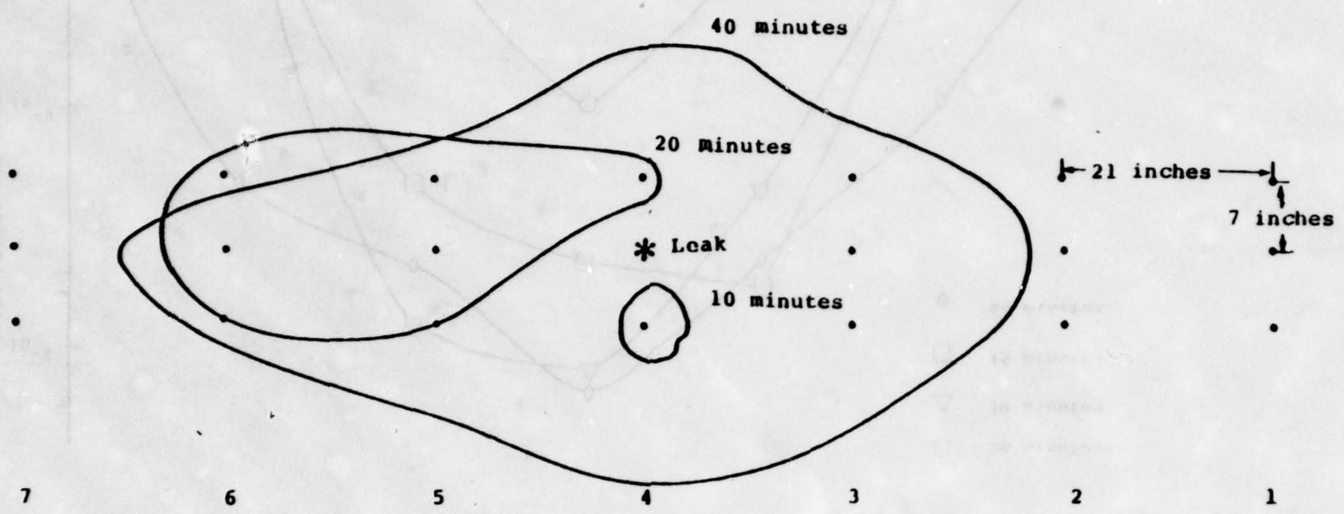

Figure 18. Experiment 5 Isoconcentration Plot (10^{-11} Conc) Versus Time

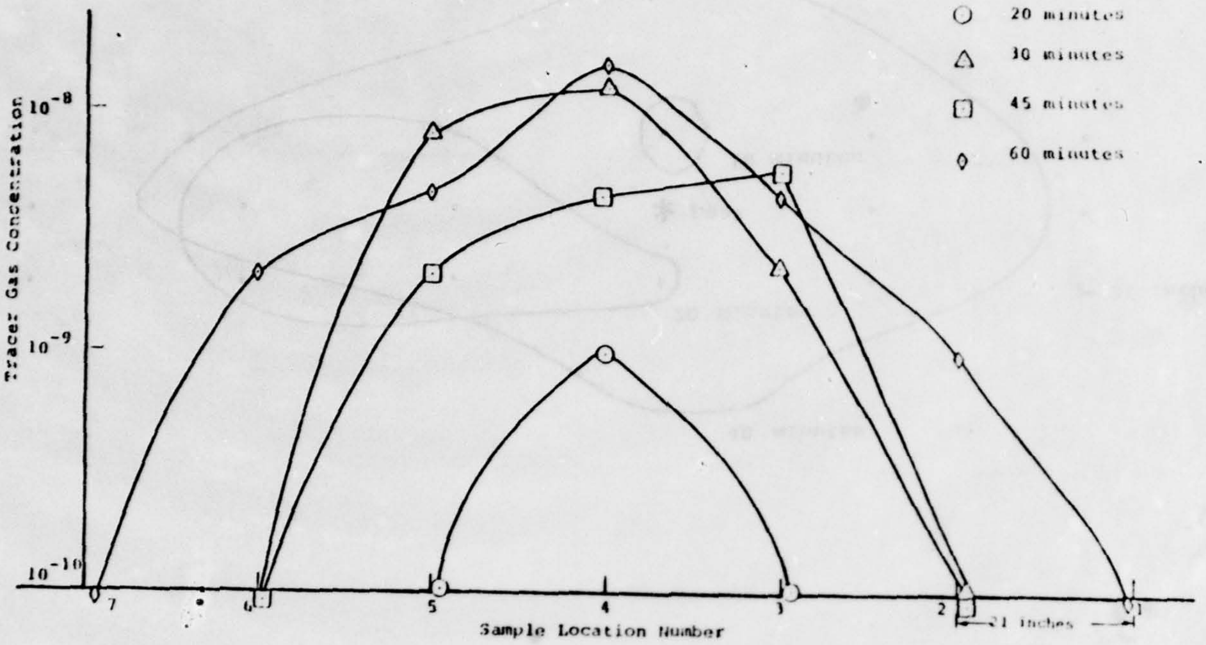

Figure 19. Experiment 6 Tracer Gas Concentration on the Surface Along the Pipe Centerline

with one foot of fill sand and then buried with native dirt. In this experiment an attempt was made to bury a pipe in a manner in which many construction contractors might attempt pipe burial. A series of 25 samples was taken each from 6 sample stations at 15-minute intervals. There were no tracer gas arrivals at the surface up to 105 minutes after test initiation. Shortly after this sampling run the compressed air pump failed and required that the test be aborted.

Experiment 8

In this experiment a quarter leaking weld simulation as described in Experiment 6 was used. Tracer gas was SF_6. The pipe was buried as in Experiment 7. One foot of fill sand was used to cover the pipe and the remainder of the fill was made with native dirt. A series of 25 samples was taken during each of 4 sample periods: 30, 50, 70, and 90 minutes into the test. Figure 20 is a plot of the concentration of tracer gas along the centerline of the pipe. A very sharp peak begins to appear at 50 minutes into the test. If a check is made of tracer gas concentrations off the centerline on the side of the pipe with the weld leak, an arrival of tracer gas somewhat earlier than the sharp peak discovered along the centerline at 50 minutes can be seen. Figure 21 presents contoured SF_6 data with contour lines of 10^{-10} SF_6 plotted as isoconcentration versus time. This figure shows graphically how the tracer gas rises from the leak and spreads out with time. A significant observation here is that a distinct tracer gas peak along the centerline of the pipe was visible although at a somewhat later time than the initial arrival at the surface.

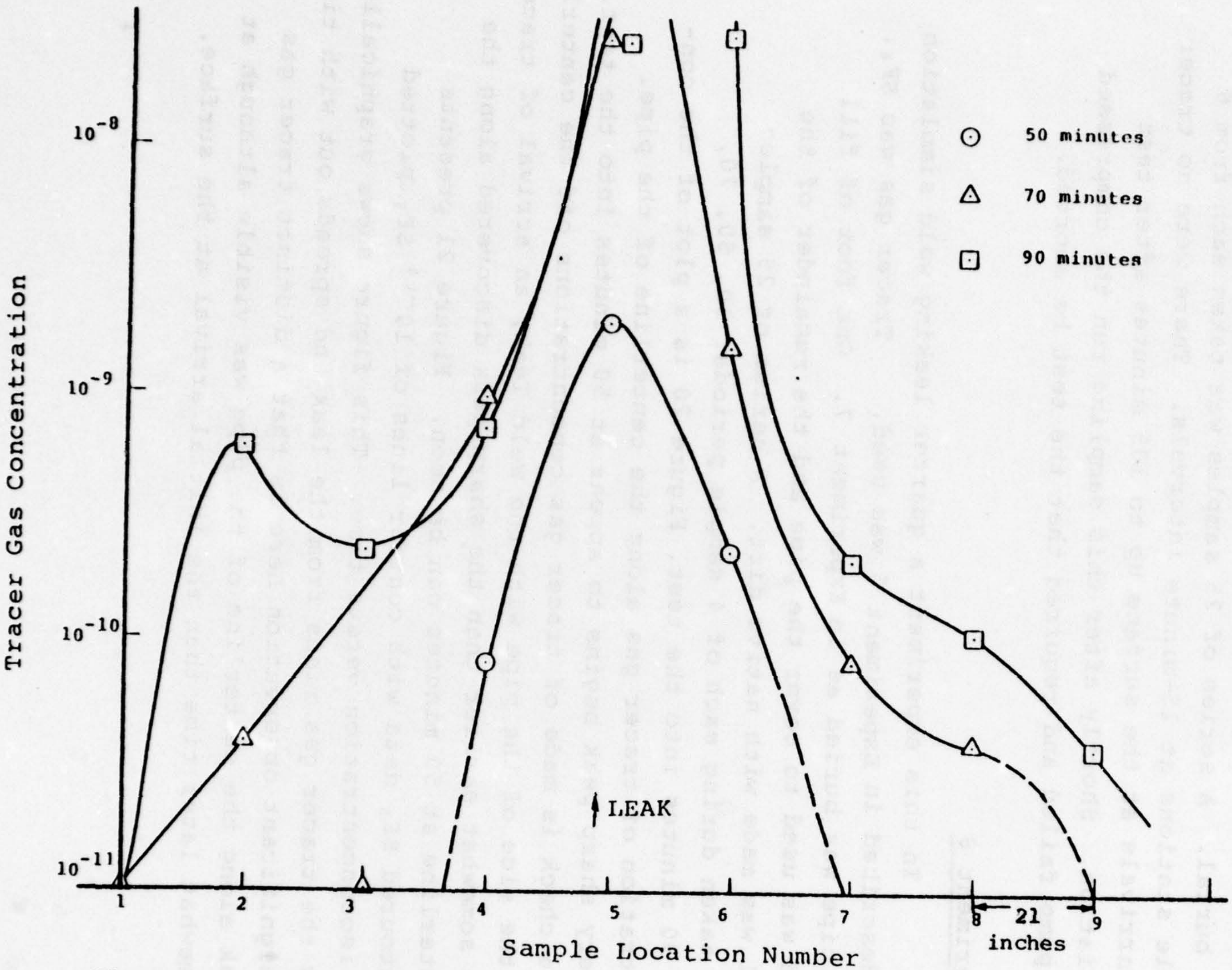

Figure 20. Experiment 8 Tracer Gas Concentration on the Surface Along the Pipe Centerline

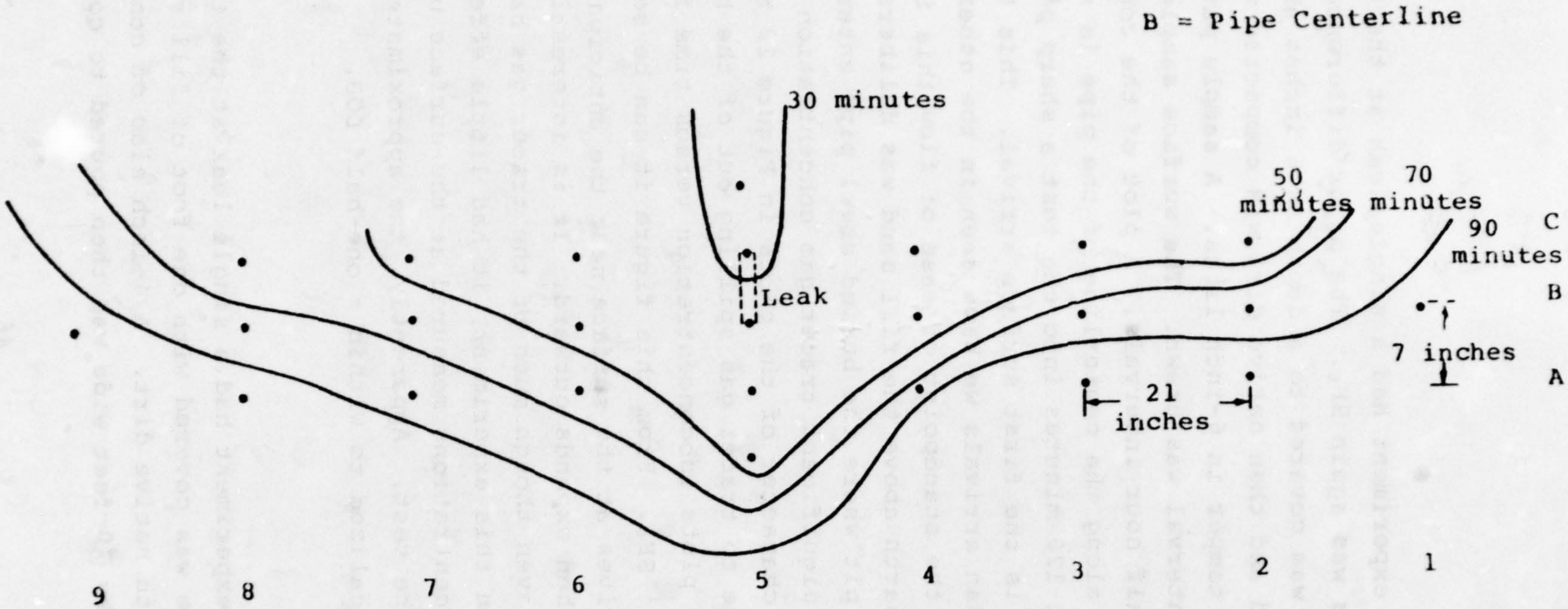

Figure 21. Experiment 8 Isoconcentration Plot (10^{-10} Conc) Versus Time

Experiment 9

This experiment had a single leak at the top of the pipe; the tracer gas was again SF_6. The major difference here was that the pipe was covered to a depth of 6 inches above it with fill sand and then native dirt was compacted with a gasoline-powered tamper in 6-inch lifts. A sample pattern of 25 samples per interval was drawn. The surface samples were drawn over 11 one-half hour intervals. A plot of the concentration of tracer gas along the centerline of the pipe is shown in Figure 22. At 120 minutes into the test a sharp peak is observed. This is the first surface arrival. This time is somewhat longer than arrivals we have seen in the other experiments. However, from the standpoint of ease of flow this is a worst case, as the earth above the fill sand was deliberately compacted. The hexagonal pit where the buried steel pipe entered was sampled and a significant tracer gas concentration was found. The change in character of the plots in Figure 22 at 210 minutes is probably due to tracer gas spilling out of the hexagonal pit. Figure 23 plots isoconcentration versus time for a reference of 10^{-11} SF_6. From this figure it can be seen that the tracer gas arrives at the surface near the anticipated leak location and then expands outward. It is interesting and significant that even though much of the tracer gas has leaked into the pit in this experiment, it had little effect on the tracer gas concentrations measured at the surface until 210 minutes into the test. Apparently, the approximate leak location can be localized to within ± one-half DOB.

Experiment 10

This experiment had a single leak at the top of the pipe. The pipe was covered with one foot of fill sand and then buried with native dirt. A 4-inch slab of concrete 5 feet across by 20-feet wide was then poured to cover the

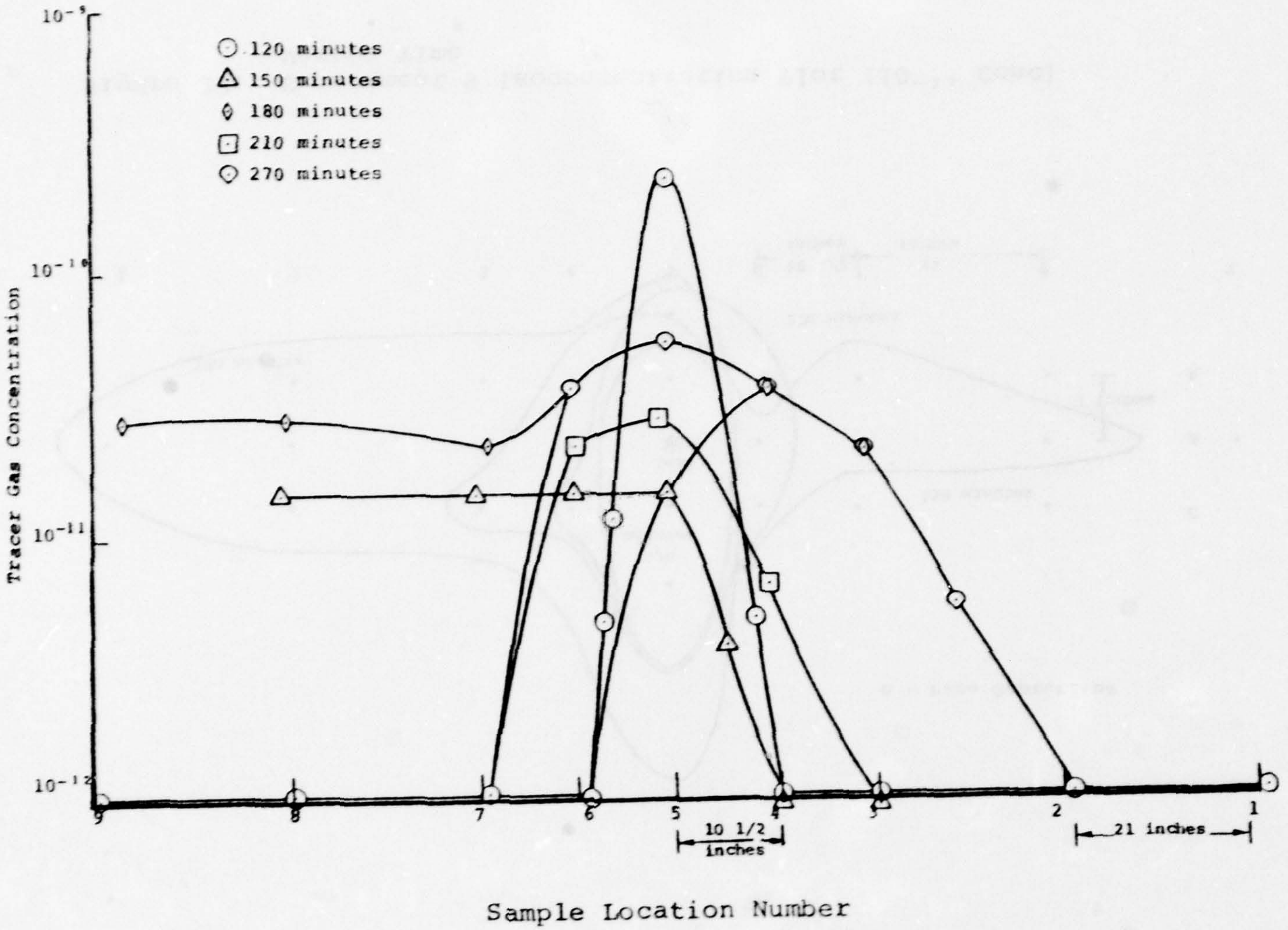

Figure 22. Experiment 9 Tracer Gas Concentration on the Surface Along the Pipe Centerline

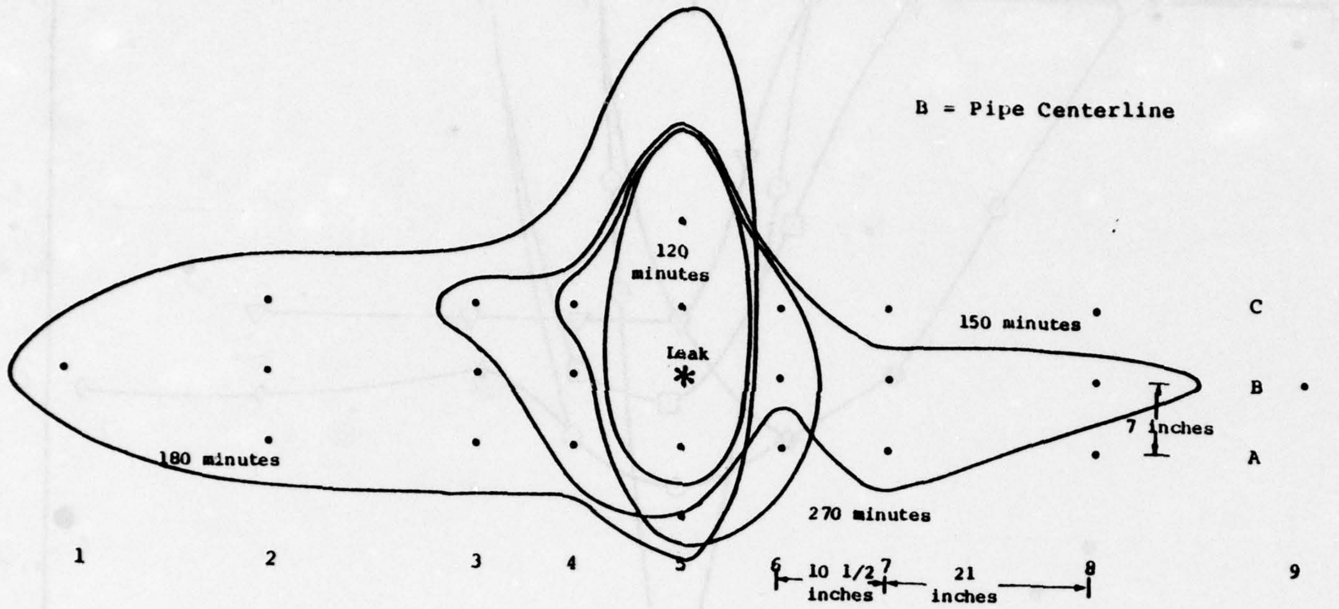

Figure 23. Experiment 9 Isoconcentration Plot (10^{-11} Conc) Versus Time

area immediately overlying the pipe. In this way it was planned to simulate a road, sidewalk, or other impermeable barrier overlying a buried pipe. A prearranged sampling pattern was laid out in the concrete utilizing two-inch plastic pipe set into the concrete. In practice, it is relatively straightforward to drill small holes in concrete or asphalt using diamond core drills. The sampling pattern used 20 samples arranged in 5 rows parallel to the pipe, spaced one-half a pipe width, with four sample stations each. In each row sample stations were one DOB apart and were centered about the leak. Note that in this particular test there is no sample station centered directly above the leak. Figure 24 presents a plot of tracer gas concentration along the pipe centerline. At 120 minutes into the test a distinct tracer gas arrival is seen. As time progresses after this arrival, the broadening and peak flattening of the tracer gas concentration is visible. Figure 25 depicts isoconcentration plots versus time for an SF_6 concentration of 10^{-10}. Note that the late time samples which demonstrate the saturation of SF_6 concentration as the flow impinges the impermeable concrete boundary have been omitted. It appears that localization of the leak is a relatively straightforward matter.

In Section 2, a simple theoretical model was described which allows prediction of tracer diffusion times. In Table 4, calculated and measured diffusion times for the nine successful pit experiments are presented. Most of the calculated values agree with measured arrival times to within a factor of 3 or better.

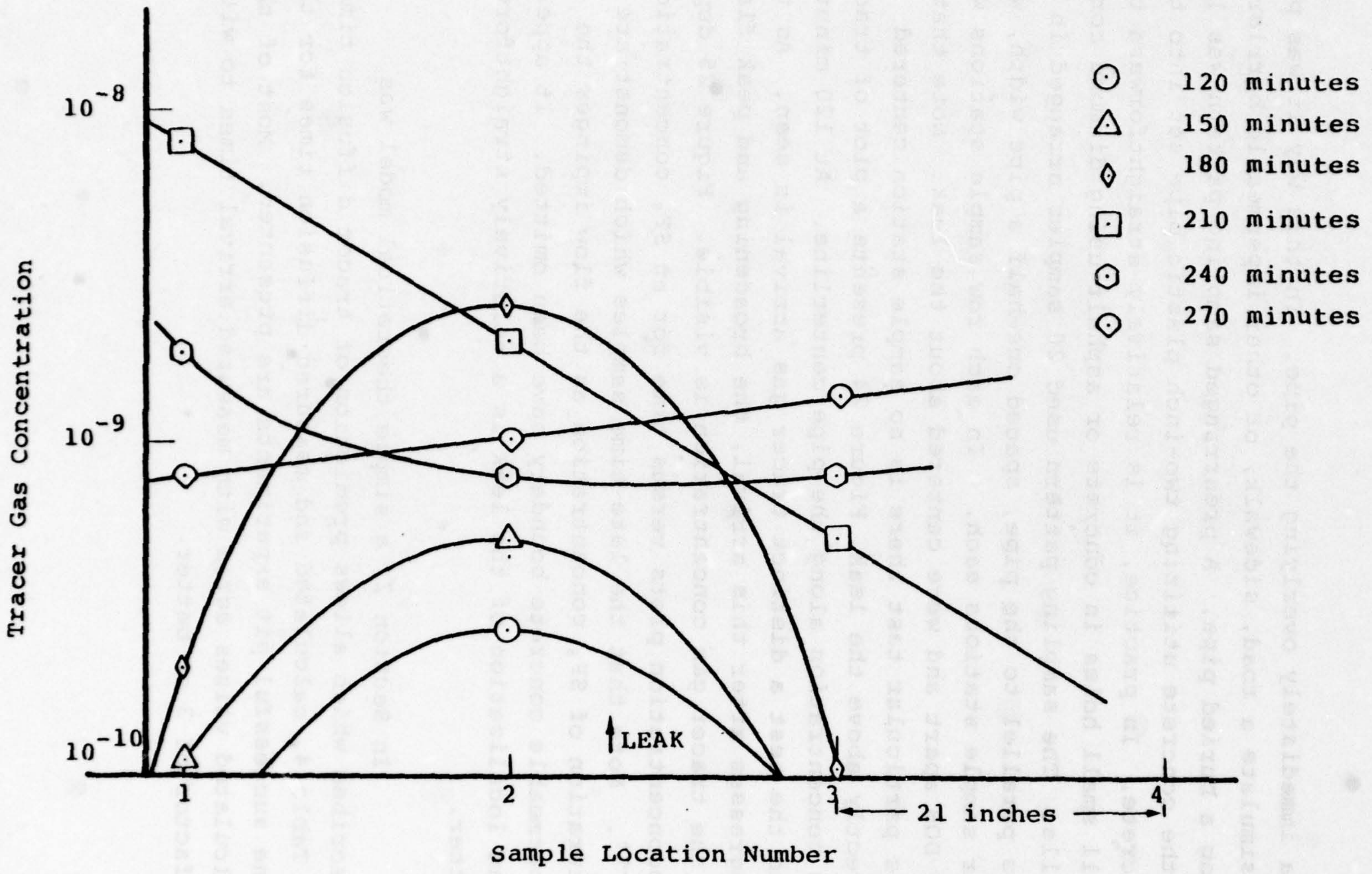

Figure 24. Experiment 10 Tracer Gas Concentration on the Surface, Under Concrete, Along the Pipe Centerline

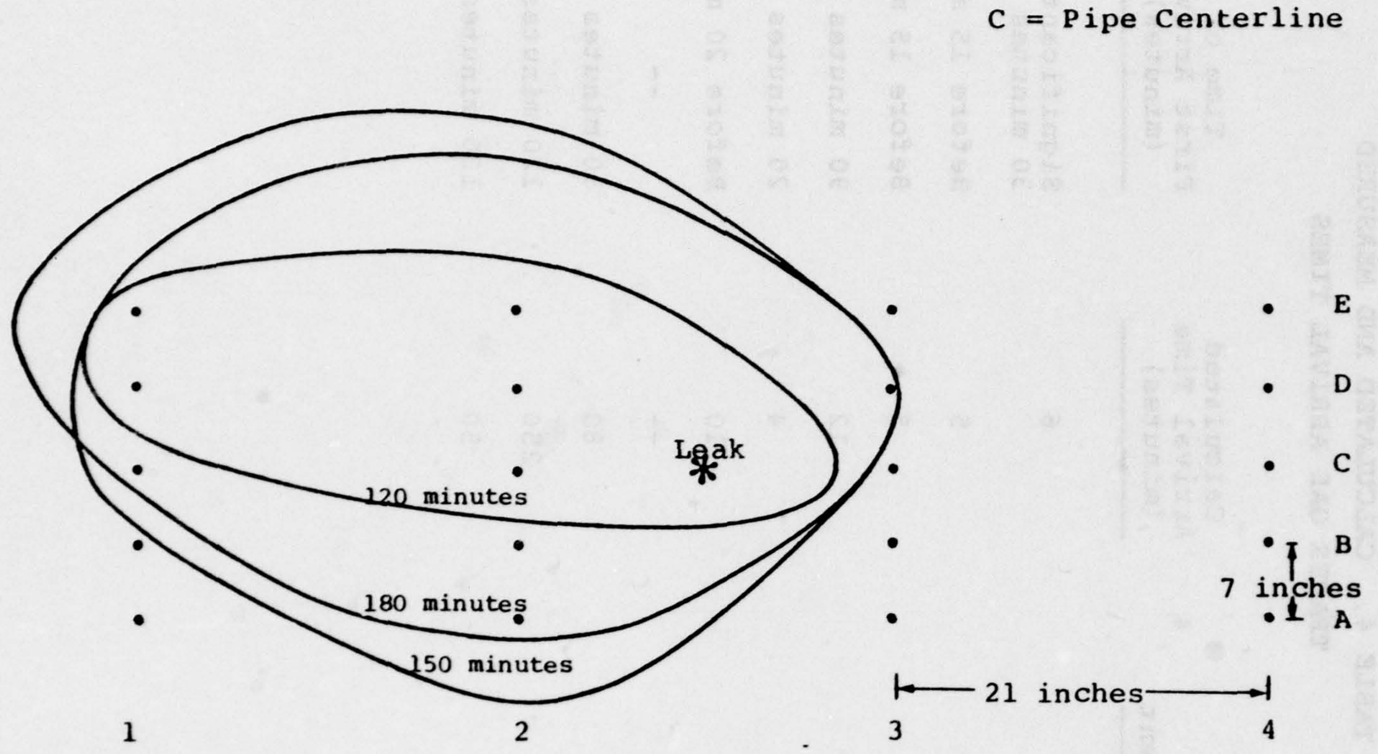

Figure 25. Experiment 10 Isoconcentration Plot (10^{-11} Conc) Versus Time

TABLE 4. CALCULATED AND MEASURED TRACER GAS ARRIVAL TIMES

Experiment	Calculated Arrival Time (minutes)	Time of First Arrival (minutes)
1	6	Significantly before 30 minutes
2	5	Before 15 minutes
3	5	Before 15 minutes
4	12	90 minutes
5	4	20 minutes
6	10	Before 20 minutes
7	--	--
8	80	50 minutes
9	250	120 minutes
10	50	120 minutes

SECTION 4

FIELD DEMONSTRATION TESTS

4.1 FIELD TEST

A field test was conducted during the month of December 1978 at Naval Air Station, North Island (NAS-NI) in San Diego, California. The use of this site was offered by the Naval Civil Engineering Center in conjunction with NAS-NI and approved by the Air Force Civil Engineering Center. The site was deemed suitable for the needs of a field demonstration as it possessed RIC-WIL steam casing and was close to the offices of S^3. The facilities office of NAS-NI informed S^3 that several lengths of underground steam casing possessed casing leaks as determined by routine pressure decay measurements on the casings.

On November 29, 1978, a reconnaissance survey of NAS-NI examined likely sections of leaking steam casing. The most suitable section of casing was a dog-leg section 390-feet long on McCain Boulevard adjacent to Building 614. This location is a few hundred feet inside the main gate. This section was deemed most suitable for the demonstration since it possessed: (1) ease of access, (2) a variety of surface features, i.e., roads, sidewalks, and grass overlying the pipe, and, (3) relatively shallow burial, in this case 31 inches at one end deepening to 44 inches near the other end.

A plot plan of the demonstration area is presented in Figure 26. Also shown are the initial sample stations as they were laid out for the first day's testing.

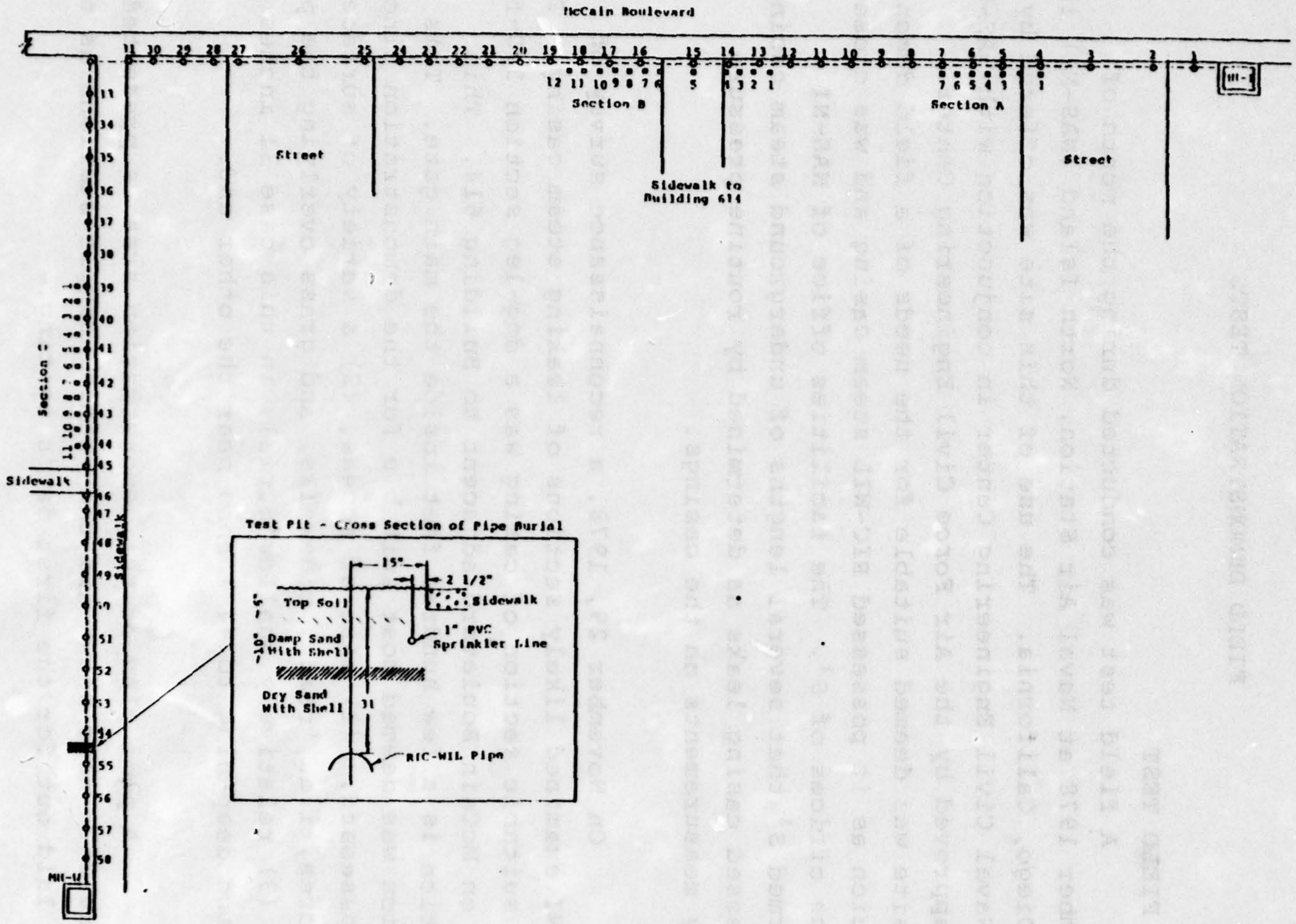

Figure 26. Sample Station Plan -- Naval Air Station North Island (Circles are Initial Test Sample Locations; Squares are Sample Stations for Second Test)

Prior to the start of pressurization, a small pit was excavated near Manhole MH-W in order to obtain a cross section of the underlying soil. It was found that the casing depth was 31 inches from the top of the soil. The casing was buried in sand except for the top 6 inches which were topsoil covered by grass. A cross section of this test pit is also presented as an insert to Figure 26.

On December 4, 1978, a pressurization decay test of the chosen section of steam casing was carried out. This test indicated that the casing would leak at a rate of 130 SCFM with a manifold pressure of 13 psig and a casing pressure of 5.2 psig. The pressure within the pipe decayed fairly quickly when the compressor was shut off. The time required for pressure to decay to 1/e (e is the base of the natural logarithms) of its initial value was about 60 seconds. Leakage at this rate suggested that there were substantial leaks within the system. The pressure injection manifold is similar to the one used in the controlled leak experiments at the Green Farm test site with the exception of a wider range of flowmeters. The flowmeter and pressure monitor are shown in Figure 27. Figure 28 is a line drawing of the injection manifold. Compressed air for these experiments was provided by a standard jackhammer compressor capable of approximately 100 cubic feet per minute at 100 psi driving pressure.

The vent line (in this case three-quarter inch garden hose) was approximately 200-feet long and was attached to the vent valve of the end casing in Manhole W (MH-W). This vent line was then placed far downwind from the measurement area, thereby insuring that any tracer gas being vented was at least 200-feet downwind from the test area.

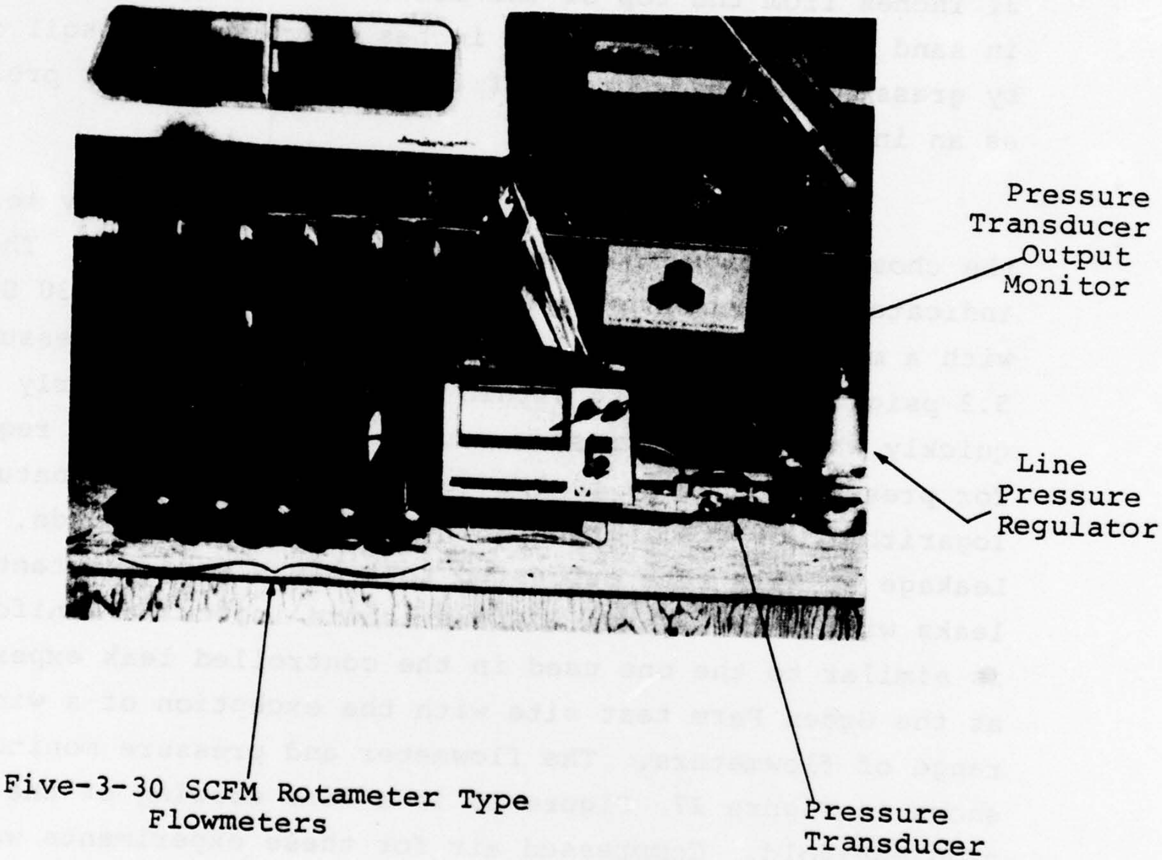

Figure 27. Injection Manifold at NAS-NI
(Official Photograph U.S. Navy)

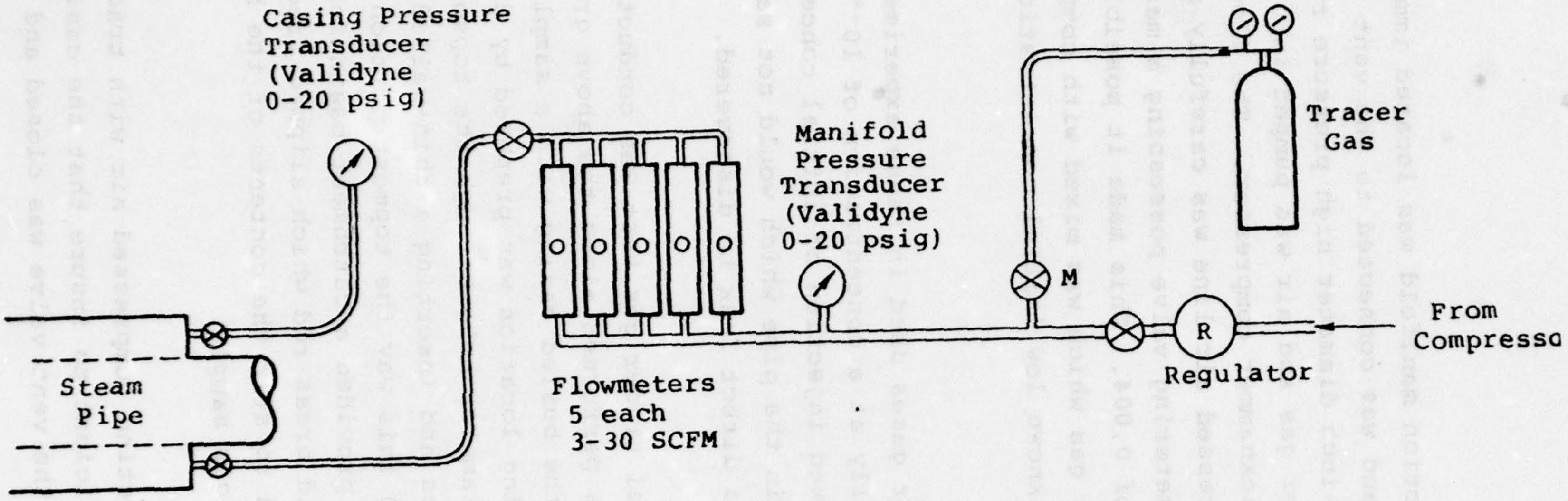

Figure 28. Test Manifold Naval Air Station, North Island

The injection manifold was located immediately above Manhole I (MH-I) and was connected to the vent valve in the casing end by a 1-inch diameter high pressure rubber hose. A mixture of tracer gas and air was pumped into the casing by means of the jackhammer compressor. The flow of tracer gas into the compressed air line was carefully metered by a critical orifice metering valve possessing a maximum flow coefficient (C_v) of 0.004. This made it possible to control the flow of tracer gas which was mixed with compressed air in order to obtain a known low initial concentration within the pipe.

The tracer gases used in these experiments were all obtained commercially at a concentration of 10^{-4} in nitrogen. This dilution allowed injection of initial concentrations of tracer gas within the pipe which would not saturate the instrument should a direct leak be discovered.

The initial tracer gas test was conducted on December 6, 1978. Sampling was performed along the above ground trace of the centerline of the buried casing with a sample spacing of 6 feet. Each sampling location was prepared by drilling a one-quarter inch diameter hole through the topsoil to a depth of roughly 6 inches and inserting a thin-walled brass tube into this hole. In this way the topmost portion of the ground was penetrated and provided a catchment basin for the upcoming tracer gas. A solid brass rod which slipped freely inside the brass tube was used to stir the contents of the hole immediately prior to drawing a gas sample.

After injecting compressed air with tracer gas for a period of time sufficient to insure that the casing was filled (about 20 minutes) the vent valve was closed and above-ground sampling was initiated. Replicate samples were drawn from each of the brass tubes at 20-minute intervals utilizing 12-cc disposable polypropylene syringes. To ensure that samples at a given interval were drawn at roughly the same time, four technicians each drew samples from 15 sample locations; this took less than 2 minutes.

The initial SF_6 concentration was 3×10^{-7}. The compressed air flow rate was 130 SCFM with a driving pressure of 13 psig and a casing pressure of 5.2 psig.

Three sample runs were taken 20 minutes apart initiating 10 minutes after the vent valve was closed. A total of five electron-capture chromatographs was utilized to analyze the large number of samples which were drawn. Upon analysis of the gas samples, several areas of suspected leakage were discovered. A plot of SF_6 concentration versus sample location is presented in Figure 29. Note that the SF_6 concentration is presented on a logarithmic scale encompassing six orders of magnitude.

The suspected areas of leakage were adjacent to the street by Manhole I denoted by Section A; under the sidewalk in front of Building 614 denoted by Section B; and, around the corner midway toward Manhole W denoted by Section C. For two reasons these results suggested that a second test was in order. Rapid arrival of SF_6 in such high a concentration was not anticipated and in many instances, therefore, instruments were overranged. These data can only show a lower value of the maximum concentration. In addition, due to the rapid communication from these leaks, there is a nonzero background (on the order of 10^{-11}) which can be seen at many sample locations. However, it was fairly certain that there were three areas which required further study. They all had SF_6 peaks with concentrations of 10^3 to 10^5 times higher than the background.

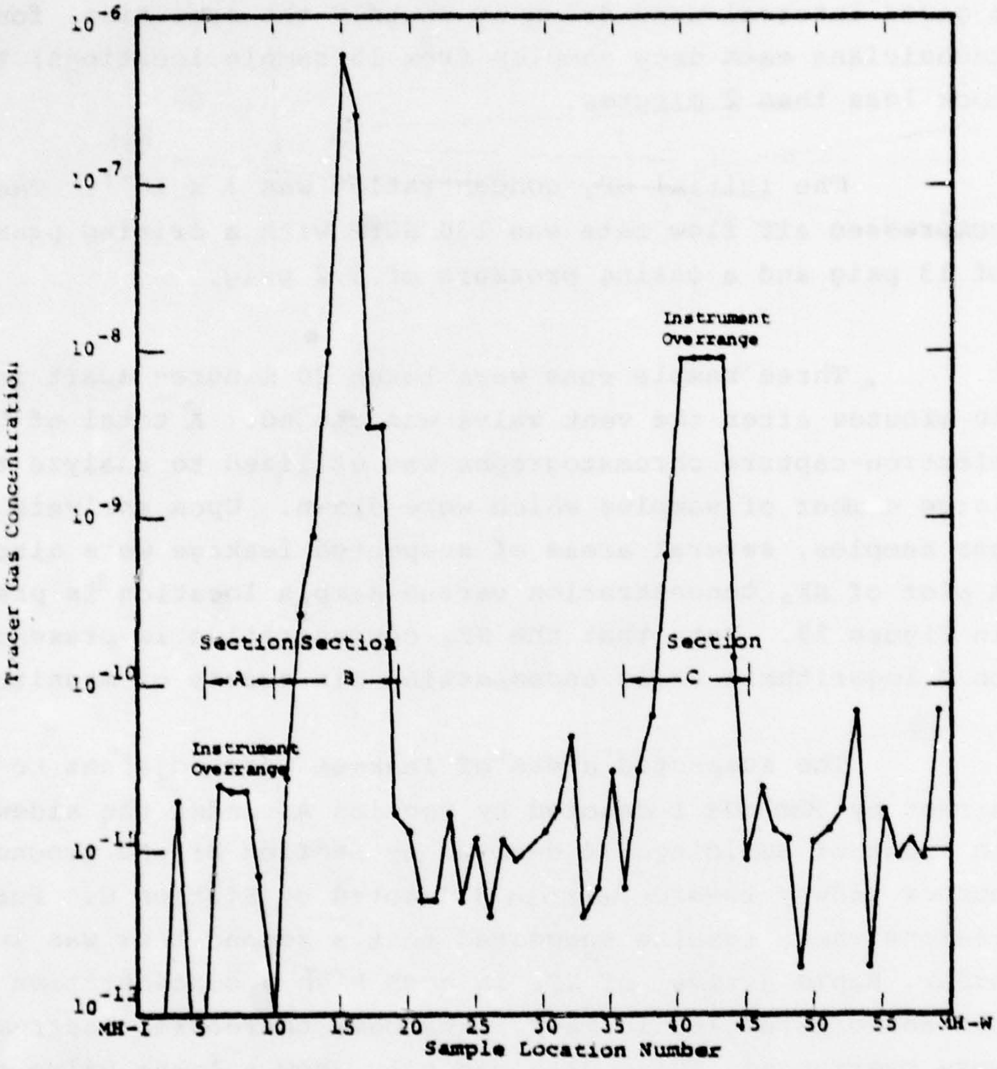

Figure 29. NAS-NI Test 1 - Tracer Gas Concentration on the Surface Along Estimated Pipe Centerline

On the next day (December 7, 1978), a second test using an additional tracer gas, in this case Freon® 13B1 was conducted. The second test concentrated only on the three areas of leakage. The sample station pattern was set up as denoted by squares in Figure 26. The sampling interval here was 3 feet, except for the area crossing the concrete sidewalk in front of Building 614. Due to the non-availability of a diamond core drill on short notice, a single sampling station in this sidewalk had to suffice.

Freon® 13B1 was injected into the casing at a concentration of about 8 x 10^{-7}, with an initial flow rate of 10 SCFM with a casing pressure of 0.5 psig. After sampling for 3 hours without finding evidence of tracer gas arrival, it was decided to increase the flow rate in the casing while maintaining the Freon® 13B1 injection concentration at the same relative level. Accordingly, the casing and driving pressures were increased until a flow rate of 83 SCFM was obtained with a casing pressure of 3.4 psig. Soon thereafter tracer gas arrivals were measured at two of the locations. These data are presented in Figure 30.

The section immediately under the street adjacent to Manhole I showed no sign of Freon® 13B1 during the second test. Section B showed a first arrival of tracer at new stations B6 and B7 just east of the sidewalk near Building 614. Note that several sample intervals elapse before the tracer gas appears to spread along the underside of the sidewalk. There is little doubt that the apparent center of the leakage lies between station B5 and B7.

Section C also showed a substantial Freon® 13B1 arrival. The initial detection of Freon® 13B1 was at station C7; however, as time increased, the position of maximum concentration began

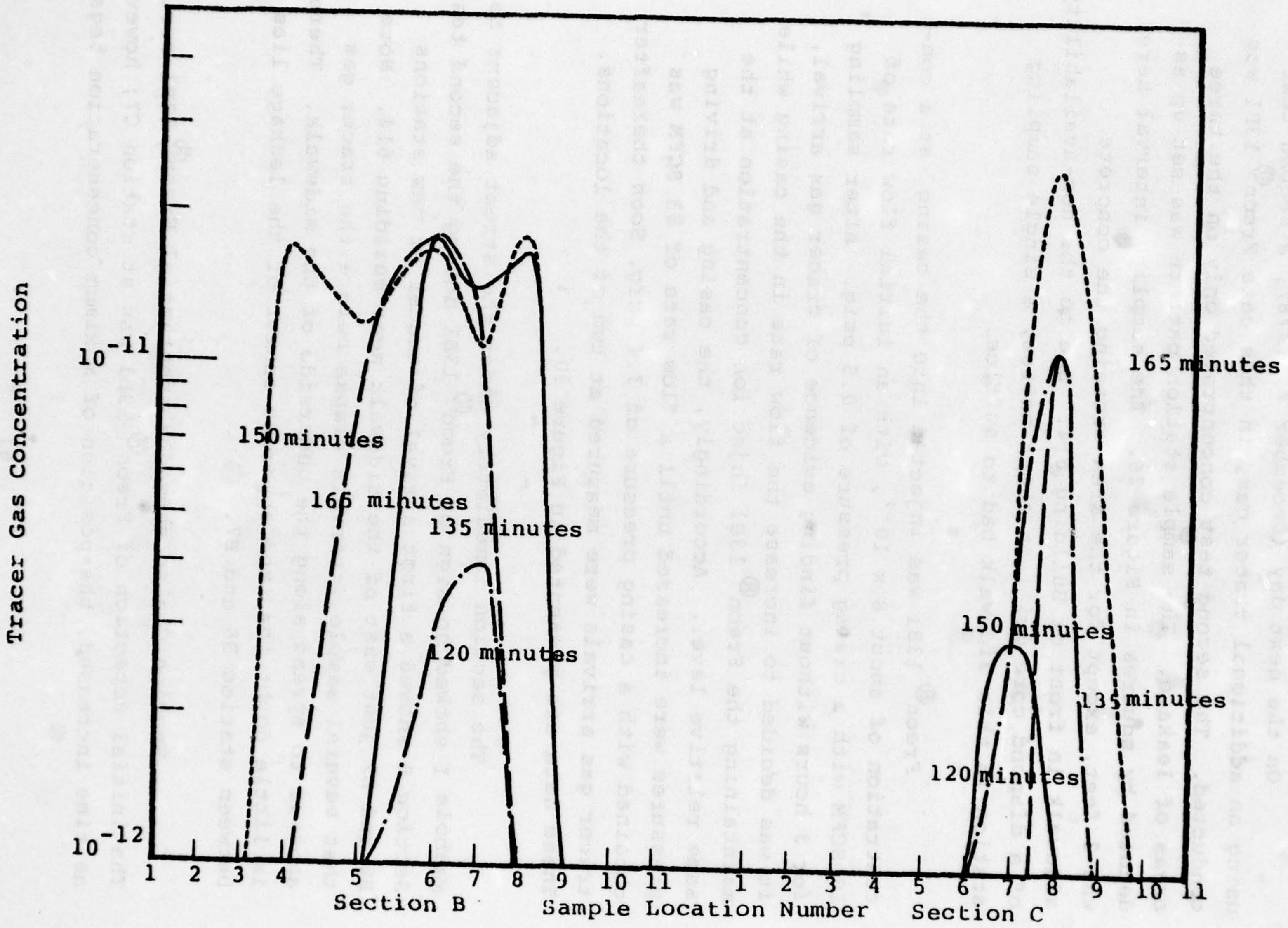

Figure 30. NAS-NI Test 2 Tracer Gas Concentration on the Surface Along Estimated Pipe Centerline at Section B and Section C

shifting toward station C8. Whether this is due to channeling or due to the concentration building up to the maximum value is not clear. However, the concentration maximum is within two sample stations (6 feet) of station C7.

After completion of this test, the tracer gas flow was turned off and initial data analysis was undertaken on-site. During this time the compressor was allowed to continue pumping. This turned out to be fortuitous since immediately before the compressor was to be shut down (roughly five hours after beginning of test), wisps of warm air were noted rising from the ground near station C6. Inspection of the ground with the hand near the area of C6 indicated the ground was quite warm. These tests were conducted during a time in which it was unseasonably cold in San Diego. The temperatures hovered near the freezing mark. It is unlikely that this change in warmth of the ground would have been noted during an average day in San Diego.

No evidence of warmth over the suspected leak near Building 614 was ever discerned. In this one case, at least, it appears fortuitous that data collectors were near the point in question when warm air began escaping from the ground. This escape of warm air, however, supported the tracer gas findings that a substantial leak was in evidence beneath the area of station C6.

4.2 EXCAVATION OF SUSPECTED LEAKS

On April 17, 1979, the RIC-WIL pipe was uncovered near the suspected leak at Section B. A substantial leak was found within one foot of the tracer peak location illustrated in Figure 30. A significant additional fact is that the axis of the steam casing is four feet closer to the street than was thought in December, 1978. Thus, surface measurement of tracer gas was able to localize a leak whose location was roughly one DOB laterally away from the measured line. A photo of the excavated leak is presented in Figure 31.

Conversations with Messers. D. Guaderrama and W. Toles of the Public Works Office (PWO) at NAS-NI revealed that PWO was unaware of the measurements taken in December, 1978. In February, 1979, excavation in Section C by the PWO uncovered a leak whose location was localized to within one foot by the measurements in December. Apparently the steam casing possesses an expansion loop which has an elbow at this location. This elbow possessed a one-foot section of badly rusted pipe which was replaced. The other elbow of this loop (roughly 10-feet north) and the dog-leg elbow of the 400-foot casing run (roughly 60-feet north) were also excavated since "conventional wisdom" is that such places are likely leakage locations. Neither of these two additional excavations uncovered casing leaks.

The findings of areas of leakage and regions with no leaks are very significant in terms of the utility of using surface measurements of tracer gas to localize such leaks. Leaks were discovered where the tracer gas technique suggested that leaks were present. Perhaps more significantly, leaks were not found in two places where the tracer gas technique suggested that leaks were not in evidence.

Figure 31. Excavated Steam Casing Showing Location of Leak Detected by Surface Measurement of Tracer Gas (Official Photograph U.S. Navy)

SECTION 5

CONCLUSIONS

On the basis of the experiments performed during the course of this research, several major conclusions may be drawn:

- Injection of metered amounts of compressed air tagged with tracer gas of a known concentration provides a means of localizing leaks in a buried pipe by means of surface measurements.

- Credible localization of suspected leaks in buried pipes is possible for a wide variety of soil and surface conditions.

- Detection of leaks in buried RIC-WIL steam line casing utilizing surface measurements of tracer gas was successfully demonstrated in a field test at a government installation.

- The ability to utilize multiple tracer gases significantly increases the accuracy and credibility of the steam leak location technique.

- The technology and equipment needed to perform tracer gas leak detection of leaking steam pipe casings either exists or is easily fabricated from commercially available components.

SECTION 6

RECOMMENDATIONS

As was apparent to the Air Force personnel involved in monitoring the demonstration test, the experiment as undertaken at North Island Naval Air Station was labor-intensive. In a research type operation this, of course, is acceptable and probably necessary. However, for the tracer gas technique to be a useful service technique for the United States Air Force, the number of personnel required must be reduced.

The technology exists to automate both the sampling of the ground for tracer gas at particular locations and the analysis of the samples. The development and use of automated sampling and analysis techniques would greatly reduce the manpower required to perform these tests. Such development would greatly enhance the utility of the tracer gas technique in the overall Air Force program for monitoring steam casings.

For reconnaissance type investigation a simple pressure testing schedule would be useful. The manifold shown in Figure 28 without the tracer gas injection line would be ideal for such testing. In practice, the manifold pressure would be set to 15 psig. The flow rate and casing pressure would be noted after 30 minutes of flow. Leaks could be ranked in severity by casing pressure. The lower the casing pressure, the greater the leak. For two leaks with the same casing pressure, that with the highest indicated flow would would be the greater leak.

In actual tracer gas testing of buried casings, a single tracer such as SF_6 may be made to serve double, triple, or quadruple duty by undertaking tests with stepped initial concentration. On-going studies at S^3 suggest that initial casing concentrations of 10^{-11}, 10^{-9}, 10^{-7} and possibly 10^{-5} provide differentiatable surface concentrations. A larger testing period is required to ensure that the surface concentration measured is essentially that injected into the casing initially.

An additional area of endeavor which may be profitably pursued would be a more thorough analysis of the diffusion times through various types of soil by means of numerical computer models. Utilizing such models, a series of nomographs could readily be constructed relating soil type, depth of burial and various other properties to expected tracer gas diffusion times. Such a nomograph would be extremely useful in implementing a field program under non-research conditions.

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