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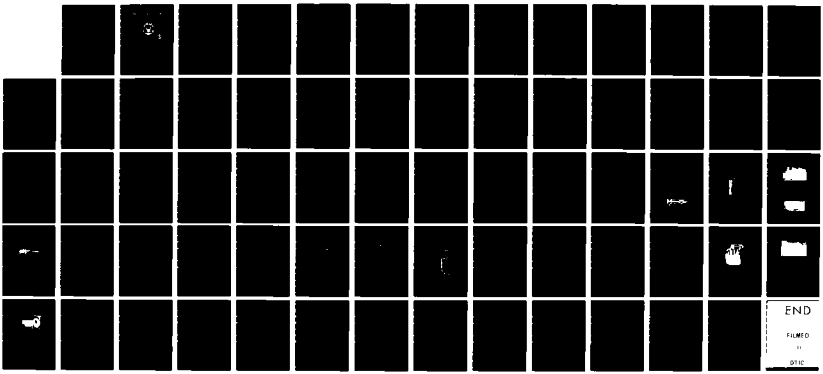

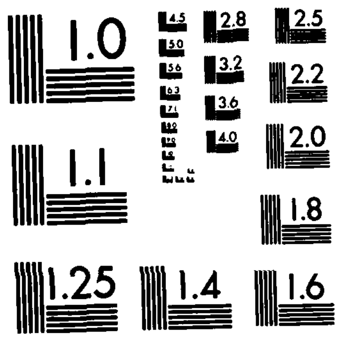

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

FIELD INSPECTION TECHNIQUES FOR BURIED STEAM DISTRIBUTION LINES

by

Walter Neboshynsky

June 1982

Thesis Advisor: James A. Miller

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A practical method of measuring the heat loss in steam lines using a pitot-static flow meter and throttling calorimeters has been developed as well as a method for locating casing failures in buried pressure-testable steam lines using the inert non-toxic gas sulfur hexafluoride as a leak tracer and an ion capture device as a detector. These methods require no knowledge of thermodynamic, mass transfer, or heat transfer theory. They are simple, quick, and inexpensive, and the equipment used is easily portable. Details sufficient for application by untrained field personnel as well as the results of several field tests are described.

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Field Inspection Techniques for Buried Steam Distribution Lines

by

Walter Neboshynsky
Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1982

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ABSTRACT

A practical method of measuring the heat loss in steam lines using a pitot-static flow meter and throttling calorimeters has been developed as well as a method for locating casing failures in buried pressure-testable steam lines using the inert non-toxic gas sulfur hexafluoride as a leak tracer and an ion capture device as a detector.

These methods require no knowledge of thermodynamic, mass transfer, or heat transfer theory. They are simple, quick, and inexpensive, and the equipment used is easily portable. Details sufficient for application by untrained field personnel as well as the results of several field tests are described.

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I. INTRODUCTION

Steam has been used as a medium for energy distribution for many years. Typically, a large central steam generation plant produces steam which is distributed via pipes to many users. An inherent problem in such an energy distribution scheme stems from the large temperature difference between the steam and its surroundings which produces a loss of thermal energy through the transfer of heat from the steam to the surroundings. In order to overcome this problem, insulation is typically applied to the steam line to reduce thermal losses. Installed insulation yields significant savings in thermal energy over a bare pipe carrying the same steam, however, the efficiency of the insulation can deteriorate with time. The problem exists of determining when the insulation around a pipe is no longer effective. This can be simple if the steam line is above ground or otherwise easily accessible throughout all or most of its length. The problem becomes somewhat more difficult if the line is buried in soil or otherwise covered, making access to the line difficult if not impossible without first uncovering the line, usually at some expense. The problem, then, is determining the amount of heat loss in the steam line, and deciding if the magnitude of the loss is acceptable or is indicative of an insulation failure, and, if the latter, where the insulation has failed.

The purpose of this thesis is to develop methods for measuring the thermal energy loss in a given steam distribution line, and locating probable casing failure locations for pressure-testable steam conduits ("Rik-Wil" or similar).

II. BACKGROUND

In general, steam produced at a central plant is distributed via pipeline to many users. After use, the condensate, along with any unused steam, may be returned to the central plant for reheating and redistribution. The steam produced at a central plant is usually low pressure (50-250 psi), and either saturated or slightly superheated.

Distribution of the generated steam can be accomplished via a number of different pipelines. The simplest type of pipe is a bare pipe. It is cheap, but it is also inefficient (due to high losses) and is very susceptible to damage from corrosion. A simple way of improving the bare pipe is to insulate it. The insulation increases the cost of the line, but, if applied correctly, the increased cost will be rapidly returned in the form of lower operating costs due to greatly reduced thermal losses. An important point is that most pipe insulations will retain their insulative qualities only if they are kept dry. Since many insulation materials are hydroscopic, they become wet in the presence of moisture, resulting in losses almost as high as the losses associated with a bare pipe. In effect, wet insulation becomes a "thermal short circuit". A common method of keeping the insulation dry is to enclose the insulated steam pipe and the condensate return pipe, if any, in a larger diameter air-tight casing. If the enclosing casing is air tight, it can be pressure tested for leaks. Also, if it is air-tight, it is most certainly water-tight and will serve to keep the insulation around the carrier pipes dry.

The distribution pipe described above can be below ground, either buried or in a trench or tunnel, or above ground, supported from below or hung from above. A buried line "disappears" after installation; you don't see it, and the high cost of uncovering a buried line discourages any maintenance efforts. A buried line is often (or always) in direct contact with moisture; a situation which encourages corrosion and wet insulation. Lines enclosed in a covered trench or tunnel are more costly to install, but they are easier to maintain, and they overcome the moisture problem (unless the trench itself is flooded). Any above ground pipeline is easy to maintain, but aesthetically unappealing.

No matter what sort of pipe is used, and however it is installed, the ideal situation as far as losses are concerned would be this: all the energy generated by the central plant would be available for use by the users (in other words, no losses). The actual situation is somewhat different. Actual losses are dependent on many factors, among them the presence of insulation, the quality and quantity of insulation, the dryness of the insulation, the difference in temperature between the steam inside the pipe and the surroundings outside the pipe, the size of the pipe, the type of pipe, the installation method, and so on. Since losses in a distribution system are inevitable, a method is needed to measure them.

The method described in Chapter III for measuring losses is applicable to any steam line, as long as access to a few feet of pipe at each end of the line segment in question is available.

If measured losses are unacceptable, and if the line is of a pressure-testable variety (such as "Rik-Wil"), the losses may be due to a casing failure which has allowed moisture to enter the conduit and destroy the insulative qualities of the carrier pipe's insulation. If this is the case, the method described in Chapter IV for casing failure detection may be applied to find the location of the failed casing.

III. MEASUREMENT OF HEAT LOSS IN STEAM LINES

Whatever energy enters a given system, in this case a steam line, must also leave the system, or be stored within the system. Since no energy is stored within a steam line that is operating in a steady state, all the energy entering must equal all the energy leaving. If this energy flow balance is represented mathematically, we can say that

$$q_{in} = q_{out}$$

where q is the energy flow in BTU/hr.

The energy flow (q) into or out of a system can be represented by the product of the mass flow rate and the energy content (per unit mass) of the fluid carrying the energy. Mass flow (m) can be represented in terms of lbs/hr, and the energy content in terms of BTU/lb. The energy content is also known as enthalpy (h), which is a measure of the total thermal energy content of a substance. If the mass flow rate and the enthalpy of the steam within a pipe are known at two points, then the change of energy flow between those two points can be calculated. If the pipe is unbranched between the two measurement points, then the change of energy flow between the two points is the energy loss rate (losses).

The measurement of mass flow rate can be accomplished by several different methods: volumetric, bulk flow, and velocity. Volumetric techniques utilize the positive displacement of a device, such as a water meter or a turbine meter, to indicate the mass flow rate. Bulk flow techniques generally involve the introduction of an obstruction into the flow, with the observed effect of the obstruction on the flow used to infer the mass flow rate (an orifice meter is an example of this). Velocity techniques involve finding the local velocity of the flow, integrating it across the flow to find the bulk velocity, and multiplying by the density of the fluid to find the mass flow rate.

Flow techniques are usually the least expensive, but they often require extensive calibration as well as line shutdown for the installation of the obstructive device. Volumetric techniques are more expensive and either somewhat complex or otherwise unsuitable for field use. The technique chosen for this study is a velocity measuring pitot-static system. Although it is initially more expensive, it is simple, it can be "hot-tapped" (inserted into the line without shutting down the steam line or otherwise interrupting the steam service), it requires little calibration, and it can be connected to a differential pressure transducer to yield instantaneous or continuous readings of the difference between the static and dynamic pressures, which can be converted to mass flow rate.

The enthalpy, or energy content of the steam, can be determined by measuring just the temperature and the pressure of single phase (superheated) steam. Unfortunately, many steam distribution systems are dual phase systems (they contain both steam and liquid water), so knowing just temperature and pressure is not enough to define the enthalpy of the steam. If the steam has a low moisture content, and is under pressure, it can be expanded adiabatically into a superheated state. Since this expansion process is also isenthalpic, the enthalpy of the expanded steam equals the enthalpy of the original unexpanded steam. A throttling calorimeter does this: it adiabatically expands steam from the line pressure to atmospheric pressure. Since atmospheric pressure is known to a high degree of accuracy, and is relatively constant, the measurement of the temperature of the expanded steam within the calorimeter will suffice to define the enthalpy of the steam within the pipe. Since the calorimeter can be hot-tapped, it was chosen for use for enthalpy measurement.

To calculate the total heat loss within a system, consider a schematic of a small steam distribution system (Figure 1). The system consists of steam lines and condensate return lines. Measurement points are numbered for the steam lines and lettered for the condensate return lines. The energy balance for the steam side of the system is:

$$m_1 h_1 = m_2 h_2 + m_3 h_3 + m_{traps} h_{traps} + \text{losses}$$

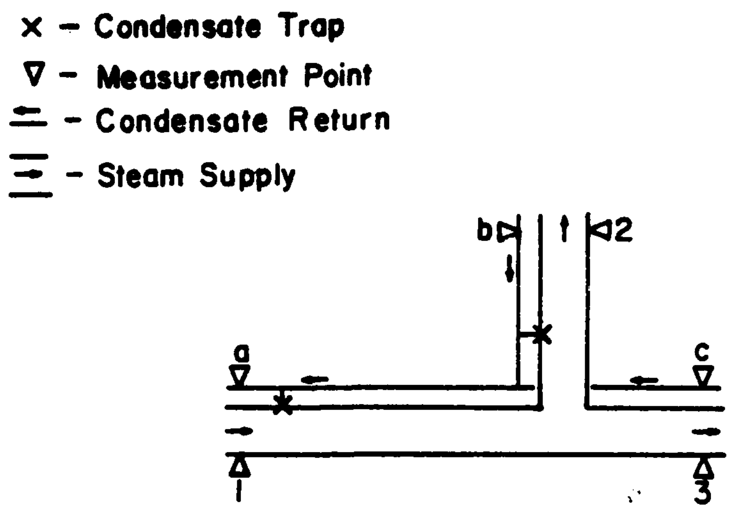

Figure 1. Typical Steam Distribution System

This relation can be simplified if the traps are closed, but this is not always practical in a real system. Since normally less than 1% of the total flow passes from the system through the traps, and since the enthalpy of the condensate is about 20% of the enthalpy of the steam, the total energy loss through the traps is very small (about 0.2%) and can be neglected. If the system contains no steam leaks, then

$$\text{losses} = m_1h_1 - m_2h_2 - m_3h_3.$$

A detailed procedure for measuring the mass flow and enthalpy and calculating the losses is contained in Appendix C. The results of a field test of this method are contained in Appendix A.

IV. CASING FAILURE DETECTION

The technique presented here involves the use of a tracer gas which is introduced into the annular space between the casing and the steam carrier pipe. The gas escapes from the space through a hole or crack in the casing, diffuses through the soil, and is detected at ground level. High concentrations of tracer gas detected at the soil surface result from nearby casing failures.

The prediction of the time needed for the tracer gas to diffuse through the soil and be present at the surface in detectable concentrations is dependent on many variables. The soil type (sand, loam, etc.) and packing density (loose, packed) will certainly affect the diffusion rate of the tracer gas, as will the moisture content (saturated, moist, or dry) of the soil. The burial depth of the steam line in question will affect the diffusion time needed for a detectable concentration of tracer gas to show up at the surface. Lastly, the concentration of the gas introduced into the annulus of the line and the time allowed for the gas to diffuse to the surface will also affect the surface concentration of the gas.

Of the variables mentioned above, only the concentration of gas introduced into the annular space can be readily controlled. Since the use of too low a concentration of tracer gas will result in no leak detection, and the use of too high a concentration will saturate the local area with tracer gas (indicating a leak but not indicating precisely where), the gas concentration must be controlled to yield the most effective results.

The time necessary for the gas to diffuse to the soil surface in a detectable quantity is not independently controllable; it is dependent on the concentration of the gas in the annulus, the size of the leak, and the burial depth. If too short a time is allowed, a detectable concentration of tracer gas will not diffuse to the surface. If too long a time is allowed, area saturation will result, yielding a result similar to using too high a gas concentration. Though the diffusion time cannot be controlled, it can be predicted.

Assuming a suitable concentration of tracer gas had been introduced into the steam line annulus, and that a suitable amount of time has passed for the tracer gas to diffuse to the surface, the gas at the surface must be detected. Two devices are normally used for this purpose: Gas chromatographs and ion-capture devices. The gas chromatograph is the more sensitive of the two, but it is slow, having a response time of around one minute. The ion-capture device is slightly less sensitive, but has a response time of a few seconds (if aspirated). Because of the fast response time, an ion-capture device was chosen for use.

The tracer gas was chosen to be sulfur hexafluoride (SF_6), a highly electronegative, chemically inert, non-photoreactive, non-polluting, colorless, odorless gas. It is slightly heavier than air (desirable in this case), and can be detected by an ion-capture device at concentrations of $1:1x10^9$.

The diffusion of SF_6 through soil could be predicted by finding the solution to Fick's Law:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

where D is a diffusion coefficient, t is time, x, y, and z are space coordinates, and C is the concentration of the diffusing substance at time t and location x, y, z. Although a solution exists, it would not be practical for field use because of its complexity and the uncertainty of the value of the diffusion coefficient D. The solution to Fick's Law for the diffusion of a substance into a semi-infinite medium initially at zero concentration [Ref. 1] contains a single independent variable:

$$x/2\sqrt{Dt}$$

where x is the diffusion distance (in this case the burial depth), D the diffusion coefficient, and t the diffusion time. If the diffusion coefficient (D) is assumed to be constant, then the concentration of tracer gas detected becomes dependent only on the source concentration (C_o) and $x/\sqrt{t}$. Since the burial depth x is fixed, C_o and t can be chosen for convenience. For simplicity and ease of use, the relationship between the surface concentration divided by the source concentration (C/C_o) and $x/\sqrt{t}$ is inferred from the field test data of Lagus and Broce (Figure 2) [Ref. 2].

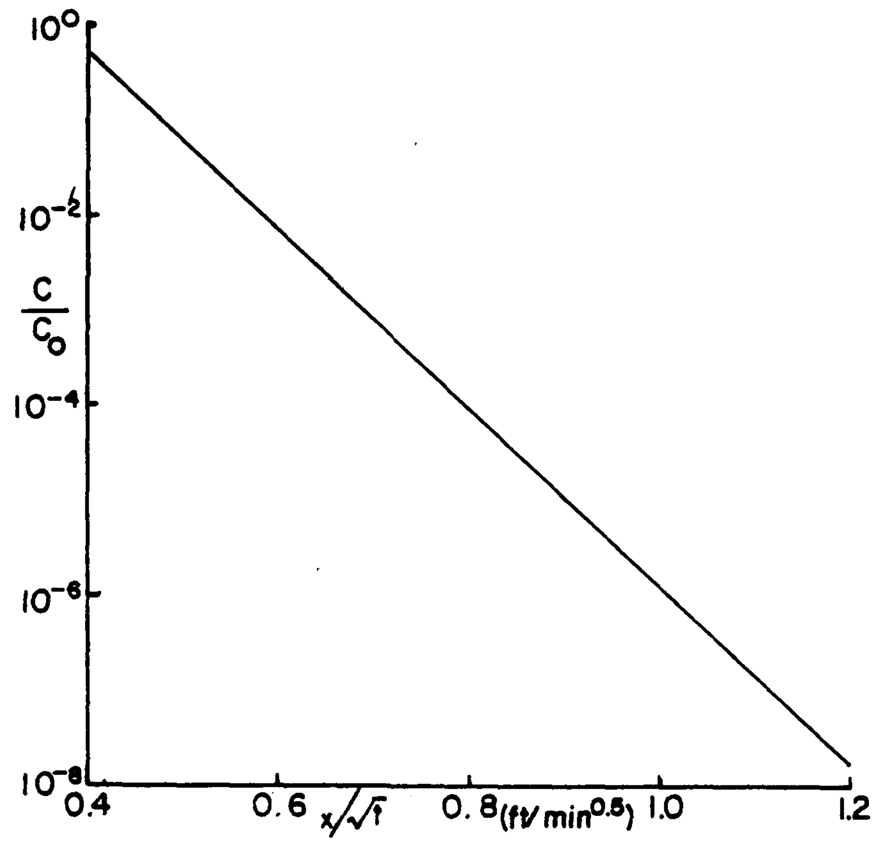

Figure 2. Relationship Between C/C_o and $x/\sqrt{t}$

The procedure is as follows: Fill the annular space between the casing and the carrier pipe with a known concentration (C_o) of tracer gas (SF_6) in air. Knowing the burial depth (x), and the relationship between C/C_o and $x/\sqrt{t}$, pick a suitable C/C_o and search time (t) pair, and predict the surface concentration (C). To reduce the uncertainties involved in the value of the diffusion coefficient search at the surface for concentrations of SF_6 at half the chosen diffusion time, at the chosen diffusion time, and at twice the chosen diffusion time. Any detected surface concentration (C) of the order of that predicted above indicates a casing failure location.

Detailed procedures for this method are contained in Appendix E. The results of a field test of this method are contained in Appendix B.

V. CONCLUSIONS

The techniques described above are simple and do not require a detailed knowledge of thermodynamic, heat transfer, or mass transfer theory. Field tests of these techniques indicate that the results are accurate and reliable for the purposes they were designed for. Although the initial cost of buying the necessary equipment was high, individual test cost is very low. The equipment is portable and may be shipped for use. The tests involve a minimum of preparation, and once the preparations have been made, the equipment can be installed, the tests run, and the instrumentation retrieved within a few hours.

APPENDIX A

FIELD TEST OF HEAT LOSS MEASUREMENT TECHNIQUE

The technique for measuring the heat loss from a steam pipe was tested on a steam line at the Naval Construction Battalion Center, Port Hueneme, CA. The test line was an unbranched 275' long length of 4" Schedule 40 steam pipe, insulated with 2.5" of fiberglass over most of its length, and installed in a dry tunnel.

Mass flow was measured using an Dieterich Standard Corp. FSM-75 Flo-Tap Annubar connected to a water manometer. Enthalpy was measured using a Cal Research, Inc. Ellison's Portable Steam Calorimeter, 900 Series, with a shop made chromel-alumel thermocouple connected to a Fluke digital multimeter.

Since the steam demand at test time was low, the distal end of the line was vented to the atmosphere to produce a mass flow of around 2000 lbs/hr, and the line was allowed to come to thermal equilibrium.

The following data were recorded:

$P_{annubar} = 2.0"H_2O \pm 0.2"H_2O$

$T_{cal\ in} = 130^{\circ}C \pm 0.5^{\circ}C$

$T_{cal\ out} = 113^{\circ}C \pm 0.5^{\circ}C$

The data, when reduced, provided the following information (see Appendix C for calculations):

$m = 1550$ lbm/hr ± 77.5 lbm/hr

$\Delta h = 14.7$ BTU/lbm ± 0.6 BTU/lbm

losses = 22,800 BTU/hr ± 1470 BTU/hr

Expected losses were 23,000 BTU/hr ± 1000 BTU/hr (see Appendix C for calculations).

The field test results agreed well with expected losses. Increased confidence in the accuracy of the results should come with the replacement of the water manometer with a differential pressure transducer, replacement of the shop made thermocouple with a commercially made industrial quality thermocouple, and the use of dedicated digital readouts for both.

APPENDIX B

FIELD TEST OF CASING FAILURE DETECTION TECHNIQUE

The casing failure detection technique was field tested on a "Rik-Wil" direct burial steam line at the Naval Civil Engineering Laboratory, Port Hueneme, CA. The line was 680' long, with one 40' expansion loop. The steam line had a nominal diameter of 4" (4.5" OD), with a casing diameter of 16". The burial depth averaged 2.5'. The line was pressure tested without success, indicating casing failure. Furthermore, infra-red photography studies suggested the presence of high heat losses in the vicinity of the expansion loop.

The void space within the conduit was calculated to be 874 cu. ft. With a 100 CFM air source, the fill time would be 8.75 min. The survey time was estimated at 10 min. An allowed diffusion time was selected as 15 min. $x/\sqrt{t}$ was calculated to be 0.50, with the resulting C/C_o being 0.00276. The source concentration was selected at 1×10^{-4} (this would require a total of 8.74×10^{-2} cu. ft. of SF_6). With this source concentration (C_o) the expected surface concentration (C) was 2.76×10^{-7}. These values were chosen to provide a search concentration at least an order of magnitude higher than the background concentration of fluorinated hydrocarbons in the area.

Sampling holes were made at approximately 4' intervals by driving a 6" length of 3/4" PVC pipe into the ground, and covering it with duct tape to prevent the loss of SF_6 from the hole due to wind. The annular space was filled with the SF_6/air mixture through one vent line, while the vent line on the other end of the line was monitored for the presence of SF_6 with an Ion Track Instruments, Inc. Model 61 Leakmeter II ion capture device. The fill took 21 minutes to complete, much longer than expected. Since the allowed diffusion time had already passed, a new search concentration (C) was calculated using a search time of 21 min. This yielded a search concentration of 2.54×10^{-6}.

The survey was begun at the completion of the fill. Results of the survey are tabulated in Table 1 and portrayed graphically in Figure 3.

The results of the SF_6 field test indicate failed casing around hole nos. 101 and 106. These locations correspond to bends in the expansion loop of the steam line, and confirm the area of the leak suspected from the infra-red photographic study mentioned earlier. One of the leaks (at hole nos. 105-6) is obviously a massive one, since the surface concentration was equal to the concentration of gas introduced into the line annulus. Positive confirmation of the results of this test will come when the line is uncovered (scheduled for a future date).

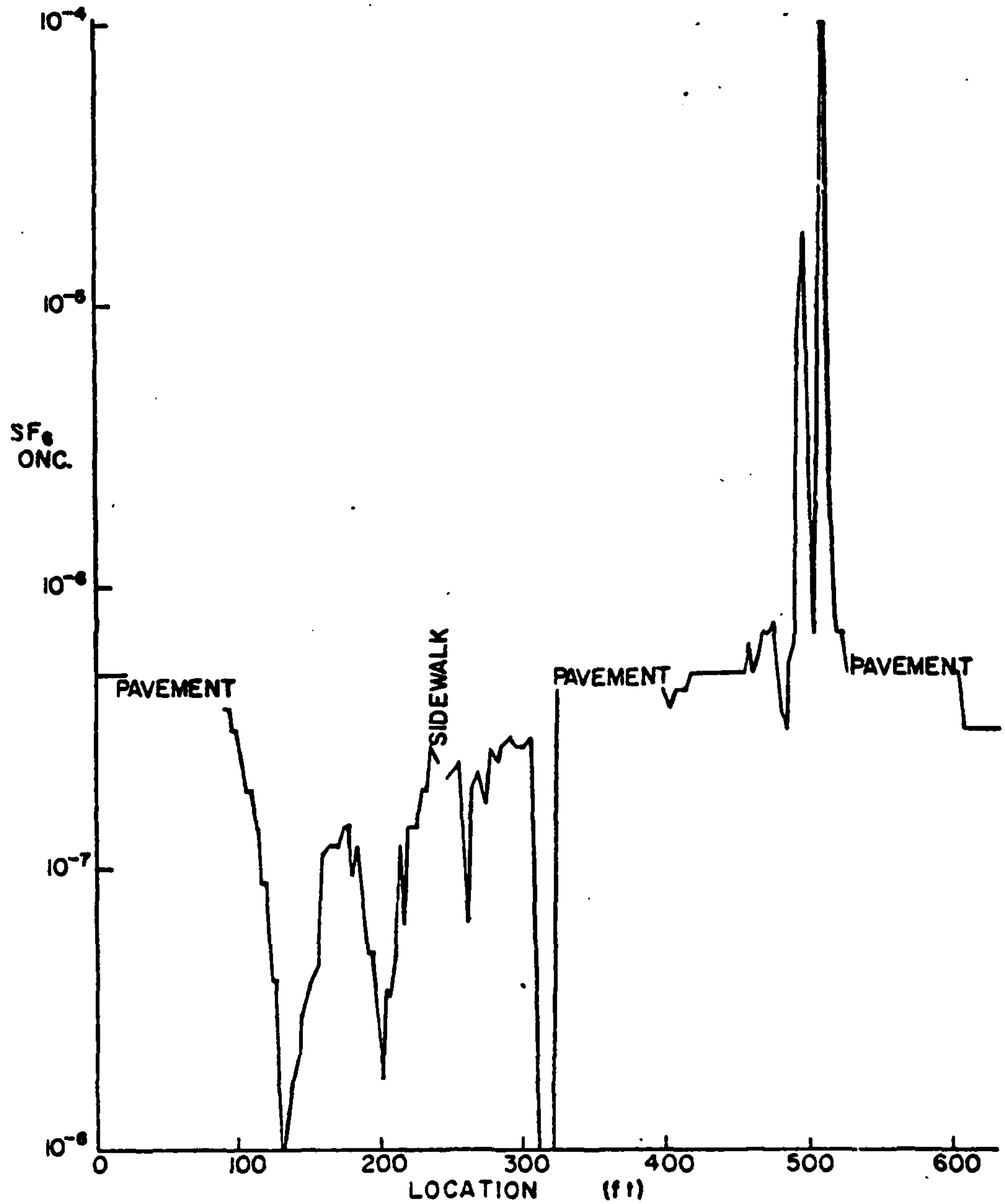

Figure 3. SF_6 Field Test: Location vs. Surface Concentration

Table 1

Results of Casing Failure Field Test

Hole No.	Location	Concentration
1	4	$4.9x10^{-7}$
2	7	$4.9x10^{-7}$
3	12	$4.9x10^{-7}$
4	17	$4.9x10^{-7}$
5	22	$4.9x10^{-7}$
--------PAVEMENT--------		
6	92	$3.7x10^{-7}$
7	95	$3.7x10^{-7}$
8	97	$3.1x10^{-7}$
9	100	$3.1x10^{-7}$
10	104	$2.5x10^{-7}$
11	107	$1.9x10^{-7}$
12	111	$1.9x10^{-7}$
13	115	$1.4x10^{-7}$
14	117	$8.9x10^{-8}$
15	121	$8.9x10^{-8}$
16	124	$4.0x10^{-8}$
17	127	$4.0x10^{-8}$
18	130	$<1.0x10^{-8}$
19	133	$<1.0x10^{-8}$
20	136	$1.4x10^{-8}$
21	139	$1.8x10^{-8}$
22	143	$2.2x10^{-8}$
23	146	$3.1x10^{-8}$
24	150	$3.6x10^{-8}$
25	152	$4.0x10^{-8}$
26	156	$4.5x10^{-8}$
27	159	$6.4x10^{-8}$
28	161	$1.1x10^{-7}$
29	165	$1.2x10^{-7}$
30	168	$1.2x10^{-7}$
31	171	$1.2x10^{-7}$
32	175	$1.4x10^{-7}$
33	178	$1.4x10^{-8}$
34	181	$9.4x10^{-8}$
35	184	$1.2x10^{-7}$
36	188	$7.9x10^{-8}$
37	191	$5.0x10^{-8}$
38	194	$5.0x10^{-8}$
39	197	$3.6x10^{-8}$
40	201	$1.8x10^{-8}$
41	204	$3.6x10^{-8}$
42	207	$3.6x10^{-8}$
43	211	$5.0x10^{-8}$
44	214	$1.2x10^{-7}$
45	217	$6.4x10^{-8}$
46	220	$1.4x10^{-7}$
47	223	$1.4x10^{-7}$
48	226	$1.4x10^{-7}$
49	230	$1.9x10^{-7}$
50	233	$1.9x10^{-7}$
51	236	$2.7x10^{-7}$
52	239	$2.6x10^{-7}$
53	242	$2.4x10^{-7}$
--------SIDEWALK--------		
54	248	$2.1x10^{-7}$
55	252	$2.2x10^{-7}$
56	256	$2.4x10^{-7}$
57	261	$6.4x10^{-8}$
58	266	$1.9x10^{-7}$
59	270	$2.2x10^{-7}$
60	275	$1.7x10^{-7}$
61	279	$2.6x10^{-7}$
62	283	$2.4x10^{-7}$
63	287	$2.7x10^{-7}$
64	292	$2.9x10^{-7}$
65	296	$2.7x10^{-7}$
66	301	$2.7x10^{-7}$
67	306	$2.9x10^{-7}$
68	311	$<1.0x10^{-8}$
69	316	$<1.0x10^{-8}$
70	321	$<1.0x10^{-8}$
71	325	$4.3x10^{-7}$
--------PAVEMENT--------		
72	399	$4.3x10^{-7}$
73	403	$3.7x10^{-7}$
74	407	$4.3x10^{-7}$
75	410	$4.3x10^{-7}$
76	414	$4.3x10^{-7}$
77	418	$4.9x10^{-7}$
78	421	$4.9x10^{-7}$
79	425	$4.9x10^{-7}$
80	429	$4.9x10^{-7}$
81	432	$4.9x10^{-7}$

Table 1

Results of Casing Failure Field Test (Continued)

Hole No.	Location	Concentration	Hole No.	Location	Concentration
82	436	4.9×10^{-7}	102	499	2.4×10^{-6}
83	439	4.9×10^{-7}	103	502	6.8×10^{-7}
84	442	4.9×10^{-7}	104	505	1.9×10^{-6}
85	445	4.9×10^{-7}	105	509	1.0×10^{-4}
86	449	4.9×10^{-7}	106	511	1.0×10^{-4}
87	452	4.9×10^{-7}	107	514	2.4×10^{-6}
88	455	4.9×10^{-7}	108	518	6.8×10^{-7}
89	458	6.2×10^{-7}	109	522	6.8×10^{-7}
90	461	4.9×10^{-7}	110	526	4.9×10^{-7}
91	464	5.5×10^{-7}	---------PAVEMENT---------		
92	467	6.8×10^{-7}	111	599	4.9×10^{-7}
93	470	6.8×10^{-7}	112	603	4.9×10^{-7}
94	474	7.4×10^{-7}	113	607	3.1×10^{-7}
95	477	5.5×10^{-7}	114	611	3.1×10^{-7}
96	480	3.7×10^{-7}	115	614	3.1×10^{-7}
97	484	3.1×10^{-7}	116	617	3.1×10^{-7}
98	486	5.5×10^{-7}	117	621	3.1×10^{-7}
99	489	6.2×10^{-7}	118	624	3.1×10^{-7}
100	492	7.6×10^{-6}	119	627	3.1×10^{-7}
101	496	1.8×10^{-5}	120	631	3.1×10^{-7}

The results of this test show the reliability of the method and its tolerance to variations in procedure. The fill time encountered was much longer than expected, the sampling holes were farther apart than desired, only a single survey was conducted, and the diffusion time was short due to the shallow burial depth. Nevertheless, the results were dramatic and confirmed earlier suspicions.

APPENDIX C

CALCULATIONS

ENTHALPY MEASUREMENT

The throttling calorimeter used for enthalpy measurement isenthalpically expands the steam from line pressure to atmospheric pressure, yielding superheated steam whose enthalpy is defined by temperature and pressure. Since the pressure is known (14.696 psi), only the temperature needs be measured.

Knowing the temperature of the expanded steam inside the calorimeter, the enthalpy of the steam can be found in steam tables, such as those assembled by Keenan and Keyes [Ref. 3], or from the linear approximation (for $T = 212\text{-}360^{o}F$ and $p = 14.696$ psia):

$$h = 1048.5 \text{ BTU/lbm} + 0.4814 \text{ BTU/lbm}\cdot{}^{o}F \times T({}^{o}F)$$

$$h = 1063.9 \text{ BTU/lbm} + 0.8666 \text{ BTU/lbm}\cdot{}^{o}C \times T({}^{o}C)$$

Since we are not as interested in the actual enthalpy of the steam as we are in the change in enthalpy between the two calorimeters, the relations above can be reduced to:

$$\Delta h = 0.4814 \text{ BTU/lbm}\cdot{}^{o}F \times \Delta T(F^{o})$$

$$\Delta h = 0.8666 \text{ BTU/lbm}\cdot{}^{o}C \times \Delta T(C^{o})$$

where ΔT is the difference between the calorimeter temperatures.

For example: For the field test described in Appendix A:

$T_{cal\ in} = 130^oC \pm 0.5^oC$

$T_{cal\ out} = 113^oC \pm 0.5^oC$

$\Delta T = 130^oC - 113^oC = 17^oC \pm 0.7^oC$

$\Delta h = 0.8666$ BTU/lbm$\cdot ^oC \times 17^oC = 14.7$ BTU/lbm $\pm$ 0.6 BTU/lbm

MASS FLOW MEASUREMENT

The relationship between the differential pressure recorded by a pitot-static type mass flow meter and the mass flow rate is found through a form of Bernoulli's Equation:

$$m = C'\sqrt{H}$$

where m is the mass flow rate, H is the differential pressure, C' is a meter coefficient. The meter coefficient is given by

$$C' = (F_{na})(K)(d^2)(F_{ra})(Y_a)(F_m)(F_{aa})(F_1)(\sqrt{p_f})$$

where

F_{na} = units conversion factor

= 358.94 lbm/hr when H is in inches of water

K = meter flow coefficient (characteristic of the meter)

= 0.5528 for the meter used

d = pipe internal diameter

= 4.026 in.

F_{ra} = Reynolds number correction factor (corrects for the change in K with changes in Reynolds number)

= 0.9956

Y_a = flow expansion factor (corrects for velocity changes caused by the presence of the sensing element)

= 0.9956

F_m = manometer factor (corrects for unbalanced fluids in the manometer legs)

= 0.9967

F_{aa} = thermal expansion factor (corrects for pipe area changes due to thermal expansion)

= 1.003

F_1 = location factor (corrects for changes in local gravity due to height above sea level and latitude)

= 0.9998

$_f$ = flow density

= 0.1173 lb/cu.ft.

Substituting these values into the equation for C' yields:

$$C' = 358.94 \times 0.5528 \times 4.026^2 \times 0.9956 \times 0.9997 \times 0.9967 \times 1.003 \times \sqrt{0.1173} = 1096.$$

Then,

$$m = 1096 \sqrt{2}$$

$$= 1550 \text{ lbm/hr} \pm 110 \text{ lbm/hr}$$

TOTAL HEAT LOSS

The total heat loss is found by simply multiplying the mass flow rate by the change in enthalpy:

losses = m x Δh

= 1550 lbm/hr x 14.7 BTU/lbm

= 22,800 BTU/hr ± 1470 BTU/hr

EXPECTED LOSSES

The expected losses for the steam pipe used in the field test were calculated using a resistance model for heat transfer. For the pipe:

4" (nom.) schedule 40 wrought iron pipe

$K = 34.6$ BTU/ft·°F·hr

ID = 4.026"

$L_{insulated} = 255'$

$L_{bare} = 20'$

$T_{inner} = 287°F$.

For the insulation:

2.5" fiberglass insulation

$k = 0.0225$ BTU/ft·°F·hr

$T_{outer} = 80°F$.

The resistance model of heat transfer (found in any heat transfer text such as Ref. 4) states:

$Q = \Delta T/\Sigma R_i$

where Q is the heat transfer rate, ΔT is the difference between the internal and external temperatures, and ΣR_i is the summation of the thermal resistances.

For this case,

$$R = \ln(OD/ID)/2\pi K$$

$$R_{conv} = 1/(h_c + h_r)A$$

where R is the thermal resistance to conductive heat transfer, R_{conv} is the thermal resistance to convective heat transfer, K is the thermal conductivity, ID and OD are the inside and outside diameters of the pipe, $(h_c + h_r)$ is the combined radiative and convective surface heat transfer coefficient, and A is the area through which the heat flows. Then,

$$R_{pipe} = \ln(4.5/4.026)/2 \times \pi \times 34.6$$
$$= 512 \times 10^{-6} \text{ ft} \cdot {}^{o}\text{F} \cdot \text{hr/BTU}$$

$$R_{insul} = \ln(9.5/4.5)/2 \times \pi \times 0.0225$$
$$= 5.29 \text{ ft} \cdot {}^{o}\text{F} \cdot \text{hr/BTU}$$

$$R_{convpipe} = 1/2.76 \times \pi \times (4.5/12)$$
$$= 0.308 \text{ ft} \cdot {}^{o}\text{F} \cdot \text{hr/BTU}$$

$$R_{convins} = 1/1.7 \times \pi \times (9.5/12)$$
$$= 0.237 \text{ ft} \cdot {}^{o}\text{F} \cdot \text{hr/BTU}$$

Substituting these values into the equation for Q,

$$Q_{ins} = (287-80)/(0.237+5.29+0.000512)$$
$$= 37.4 \text{ BTU/ft} \cdot \text{hr} \pm 3.25 \text{ BTU/ft} \cdot \text{hr}$$

$$Q_{bare} = (287-80)/(0.308+0.000512)$$
$$= 671 \text{ BTU/ft} \cdot \text{hr} \pm 16.5 \text{ BTU/ft} \cdot \text{hr}$$

The importance of good insulation can be seen from the above calculations; the loss from the bare pipe is almost 18 times that of the insulated pipe.

The total heat loss of the pipe length is found by:

$$q = L_{bare} \times Q_{bare} + L_{ins} \times Q_{ins}$$

$$= 20 \times 671 + 255 \times 37.4$$

$$= 23{,}000 \text{ BTU/hr} \pm 1000 \text{ BTU/hr}$$

APPENDIX D

FIELD MANUAL FOR HEAT LOSS MEASUREMENTS

This appendix is designed to be used as a field manual for conducting heat loss measurements on steam lines. Although originally applied to buried pressure-testable steam lines, the procedures described below are applicable to any steam line, as long as access to a few feet of bare pipe is available at each end of the line to be tested.

EQUIPMENT

The Annubar (Figure 4) is a pitot-static device for determining the mass flow of the steam within the pipe. It has a sensing element which enters the steam pipe, and two outlets which carry the total and static pressures of the flowing steam.

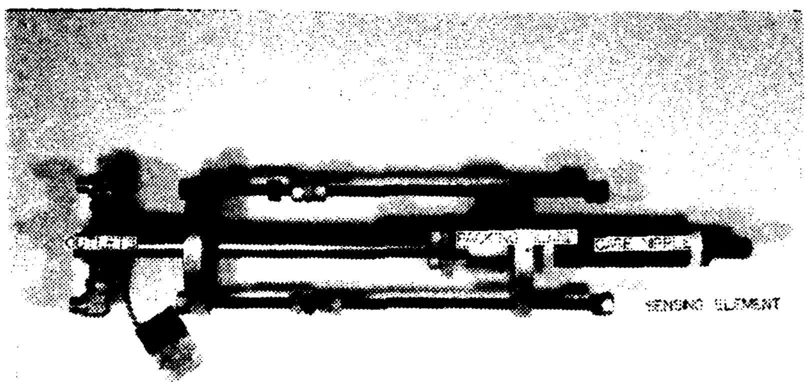

Figure 4. Annubar (Typical)

The calorimeter (Figure 5) expands the steam from the pipe to atmospheric pressure. It contains a port into which a thermocouple can be placed to measure the temperature of the expanded steam. This temperature is used to determine the enthalpy (or heat content) of the steam within the pipe.

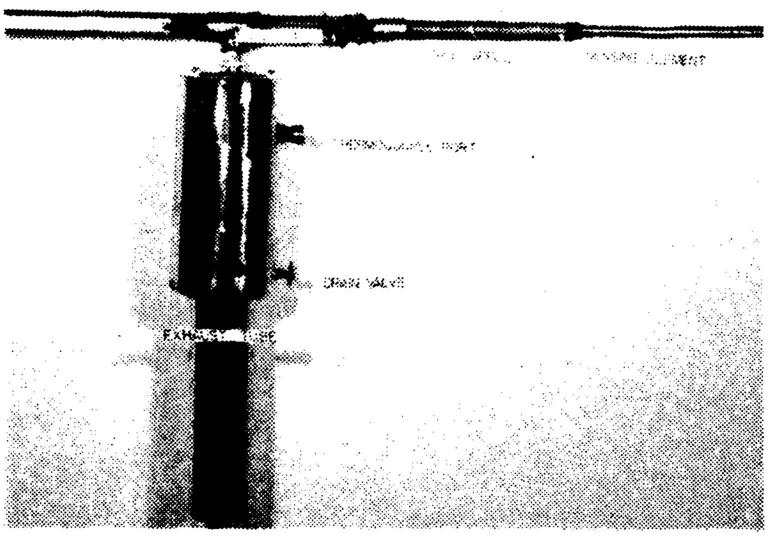

Figure 5. Calorimeter

The differential pressure transducer (Figure 6) converts the pressures from the outlets of the Annubar into an electrical signal, which is converted to inches of water and displayed by the transducer readout. The readout is battery operated and should be charged overnight before use.

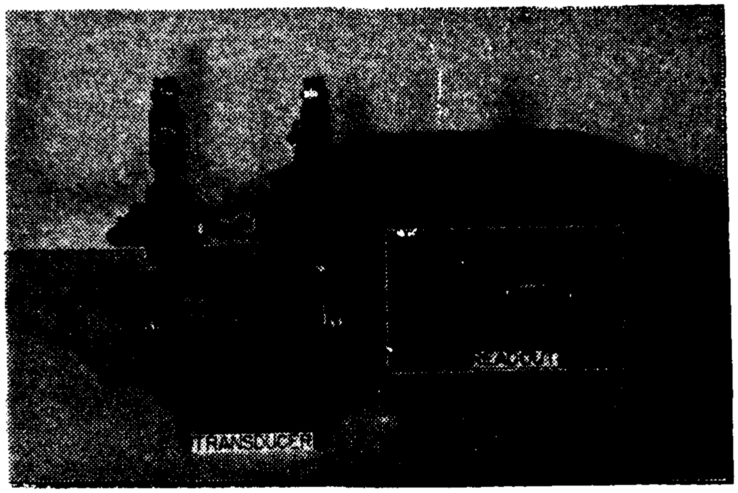

Figure 6. Differential Pressure Transducer and Readout

The thermocouple (Figure 7) is a chromel-alumel temperature sensing element which converts the temperature of the steam within the calorimeter into an electrical signal. The signal is converted back to a temperature and displayed by the thermocouple readout. The readout is battery operated and should be charged overnight before use.

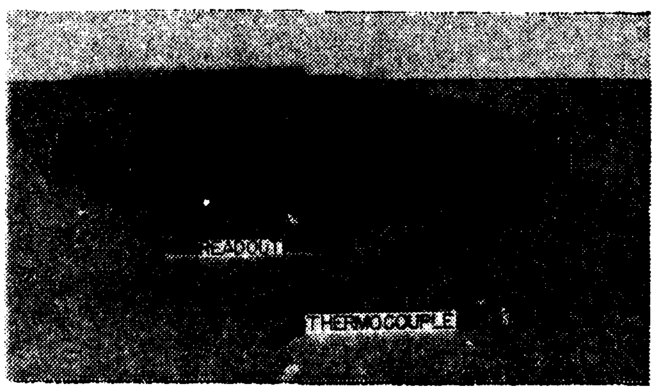

Figure 7. Thermocouple and Readout

The hot-tap machine (Figure 8) is a pressure drilling machine which drills a hole (for the Annubar or the calorimeter) in the steam pipe without requiring depressurization of the line.

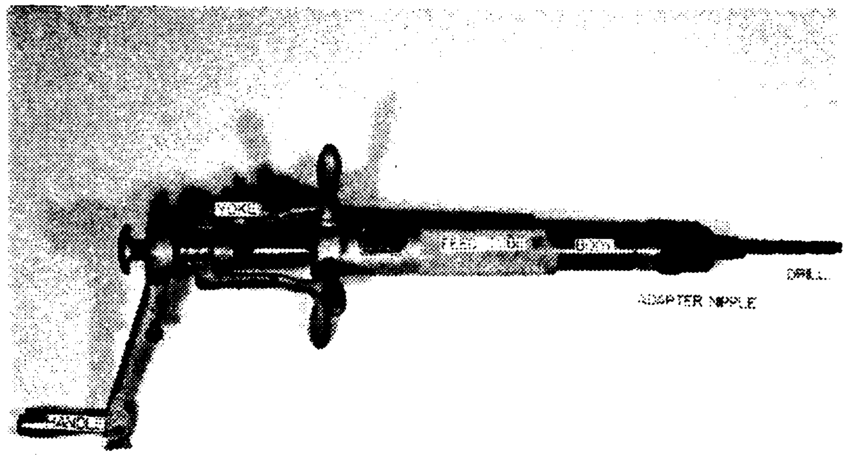

Figure 8. Hot-Tap Machine

PREPARATIONS

First, locate the best possible installation points for the Annubar and the two calorimeters.

If at all possible, the Annubar should be installed in a horizontal position. To do this, about twice the pipe OD plus 2' of clearance is needed. For best performance, a length of straight pipe is desired both upstream and downstream of the Annubar. The necessary straight run values are found in Table 2 and are based on the ID of the pipe.

Table 2

Desired Straight Run Pipe Values for Annubar Installations

Upstream Piping	Upstream Diameters: With Straightening Vanes	Upstream Diameters: Without Straightening Vanes		Downstream Diameters
		In Plane	Out of Plane	
One elbow, tee, etc.	6	7	9	4
Two ells, tees, etc., in same plane	8	9	14	4
Two ells, tees, etc., in different planes	9	19	24	4
Pipe size change or fully open valve	8	8	8	4
Regulating valve (not fully open)	9	24	24	4

NOTES: 1. Use in plane column if Annubar is installed in the same plane as the last upstream bend. Use out of plane column if it is not.

2. Table values are the number of pipe inside diameters of straight pipe desired.

The Annubar may be installed anywhere in the line, but should be installed near a calorimeter (preferably upstream).

If the above conditions can't be met, come as close to them as possible.

The calorimeters need to be installed at the two ends of the pipe segment being tested. They need about the same horizontal clearance as the Annubars (twice the pipe OD plus 2'). The desired locations for calorimeters are, in descending order:

1. Vertical pipe with descending flow,
2. Vertical pipe with ascending flow,
3. Horizontal pipe,
4. Bend in pipe.

The calorimeter's sensing element should be horizontal, if possible. If installed in a vertical pipe, the calorimeter should have the longest possible run of straight pipe upstream of itself. If installed in a horizontal pipe, it should be as close to a disturbance (valve, bend, Annubar, etc.) as possible.

Once the locations are chosen, tack weld a 1-1/4" threaded weld coupling (threadolet) to the pipe for the Annubar, and a 1" coupling for each calorimeter, at the chosen locations. Align the couplings with the centerline of the pipe (use a short pipe screwed into the coupling, if necessary). Once aligned, finish the weld and ean the threads.

Install close nipples and isolation valves (gate valves must be used) to the welded couplings. Valves should be installed fully open with the handles up (valve stem vertical).

HOT-TAPPING THE LINE

1. Remove the machine from its box and ensure that all working parts, especially the threaded feed tube and the boring bar, are well lubricated with the lubricant supplied and free of all dirt and foreign material.
2. Advance the boring bar (center bar) until drilling tools can be attached.
3. For drilling an Annubar hole, attach the 1" drill to the extension bar, and the extension bar to the boring bar. For drilling a calorimeter hole, attach the 5/8" drill directly to the boring bar.
4. Attach the proper size machine adapter nipple to the machine (1-1/4" for Annubar hole, 1" for calorimeter).
5. Coat the drill with cutting grease.
6. Retract the drill as far as possible.
7. Using a close nipple, attach the machine to the valve/nipple/weld coupling assembly on the pipe to be drilled.
8. Open the isolation valve.

9. Advance the boring bar until the drill point contacts the pipe, then retract it a small amount (1/2").

10. Adjust the feed tube (outermost tube) and yoke so that the yoke fits over the collar on the boring bar. Raise the pivot arm on the locking mechanism so that the collar on the boring bar is caught between the yoke and the pivot arm. Secure the pivot arm in place with the screw.

11. Measure and mark the point on the body (threaded tube) that the feed tube will reach when the drilling is complete.

12. Attach the ratchet handle to the boring bar and secure it with the knob.

13. Drill the hole by turning the ratchet handle clockwise while turning the feed tube clockwise a little at a time.

14. When the drilling is complete, use the feed tube to back the boring bar out.

15. Close the isolation valve.

16. Remove the machine.

17. If all drilling is completed, disassemble the machine, clean, lubricate and store. If more holes need to be drilled, change drills and adapter nipples if necessary and repeat the above procedures.

INSTALLING THE ANNUBAR

1. Remove the cage nipple from the Annubar and install it on the isolation valve.
2. Insure the sensing element is fully retracted (Figure 9).

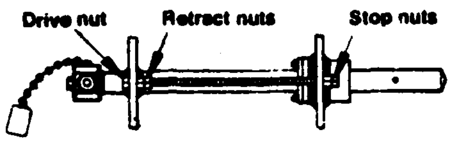

Figure 9. Annubar Mechanism Fully Retracted

3. Install the Annubar on the cage nipple, so that the arrow on the head of the Annubar is pointing downstream.
4. Fill the valve manifold (connected to the pressure transducer) with clean water.
5. Connect the transducer manifold to the Annubar.
6. Insure all three valves on the manifold are closed.
7. Crack open the isolation valve and check for leaks.
8. If there are no leaks, open the isolation valve all the way.
9. Back off the retract nuts about two turns from the flange.
10. Insert the sensing element by turning the drive nuts simultaneously or alternately, two turns at a time to

prevent binding, until the sensing element contacts the opposite side of the pipe (Figure 10).

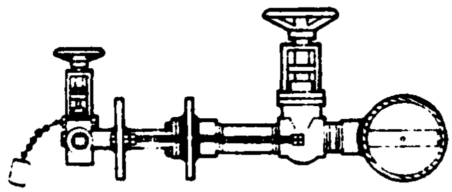

Figure 10. Fully inserted Annubar

11. Inspect for leaks again, and adjust the packing gland if necessary.
12. Connect the pressure transducer to the transducer readout.
13. Turn the transducer readout on and check the zero. Adjust if necessary. Fully open the crossover valve. Fully open the line valves, one at a time.
14. Close the crossover valve and allow the system to reach equilibrium (about 1/2 hour) before taking any readings.

INSTALLING THE CALORIMETER

1. Remove the cage nipple from the sensing element assembly and install it on the isolation valve.
2. Using Table 3, select a throttling plug which will produce a steam flow of around 100 lbs/hr, and install it in the valve body (see Figure 11).

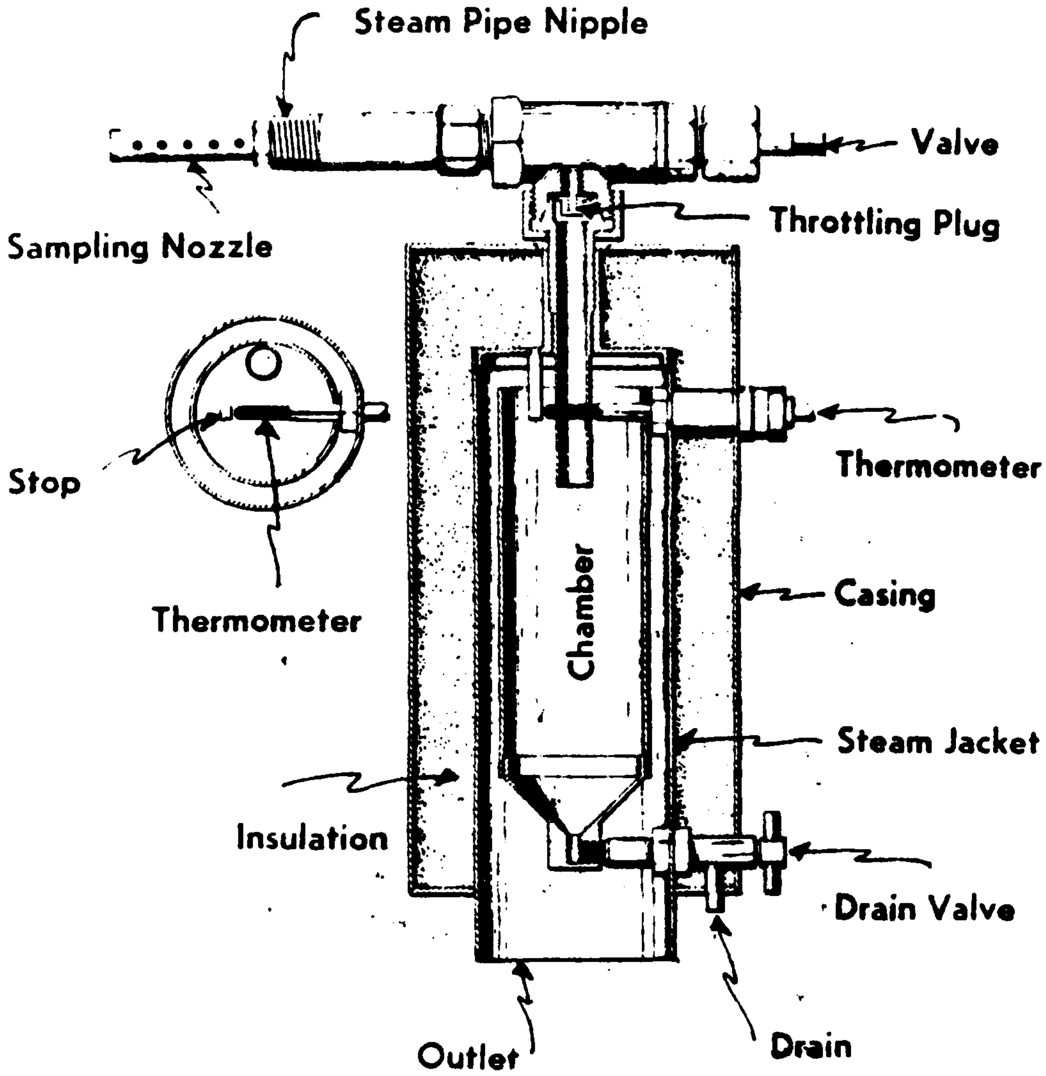

Figure 11. Calorimeter Cross Section

Table 3

Throttling Plug Selection

Absolute Pressure (psia)	Throttling Plug Size (inches)
0-115	5/32
115-140	9/64
140-185	1/8
185-245	7/64
245-460	3/32
Above 460	1/16

3. Install the valve body on the sensing element.
4. Install the sensing element assembly on the cage nipple, so that the holes on the sensing element point upstream.
5. Insure the valve on the valve body is closed, and insert the sensing element into the steam pipe in the same manner as the Annubar was inserted.
6. Install the calorimeter body onto the valve body (hand tight only).
7. Install the exhaust tube on the calorimeter body if room permits.
8. Open the drain valve on the calorimeter.
9. Insert the thermocouple into the calorimeter body until it contacts the stop, then back it out about 1/16" to allow for thermal expansion.
10. Connect the thermocouple lead to the digital readout.
11. Open the calorimeter valve and the drain valve.
12. Allow the calorimeter to warm up for about 10-20 minutes.

DATA RECORDING

After the calorimeters are warmed up, close the drain valves and record the temperatures indicated on the readouts.

After allowing the Annubar to reach equilibrium, record the differential pressure (in inches of water) displayed on the Annubar readout.

Determine the line pressure of the steam distribution system.

DATA REDUCTION

The total losses are the product of the mass flow and enthalpy change of the steam. The mass flow is found by using the slide rule supplied with the Annubar or by the following relation:

$$m = kNd^2\sqrt{\rho P}$$

where

m = the mass flow (in lbs/hr)

k = meter flow coefficient (should be stamped on the Annubar)

N = 358.9 (a conversion factor which gives the result in lbm/hr when the differential pressure is in inches of water)

d = the exact inside diameter of the pipe (in inches)

ρ = the flow density (found in steam tables such as those compiled by Keenan and Keyes) (in lbs/cu. ft.)

P = the differential pressure, in inches of water, indicated by the Annubar.

The enthalpy change is found by the following relation:

$\Delta h = 0.4814\ BTU/lbm \cdot {}^{o}F \times \Delta T\ (F^{o})$

$\Delta h = 0.8666\ BTU/lbm \cdot {}^{o}C \times \Delta T\ (C^{o})$

where

Δh = the enthalpy change

ΔT = the difference between the two calorimeter temperatures.

The losses can now be found from:

losses = $\Delta h\ m$

INTERPRETATION OF RESULTS

The measured losses must be compared to expected losses. Although the expected losses can be calculated from heat transfer theory, the procedure is difficult to generalize and so is beyond the scope of this thesis. The best course to take is to find out, from the manufacturer of the steam line or from the specifications for the steam line, the expected losses per foot of installed line. Multiply this value by the length of the line tested, and compare this value to the measured losses. If the measured losses are more than about 10% greater than the expected losses, an investigation should be made to determine the cause of the losses.

APPENDIX E

FIELD MANUAL FOR CASING FAILURE DETECTION

INTRODUCTION

This appendix is designed to be used as a field manual for conducting a casing failure detection test on "Rik-Wil" or similar types of pressure testable buried conduits consisting of steam/condensate carrier pipes enclosed by a much larger, air-tight, capped and vented casing.

Before the tests described here are conducted, the suspected line should be pressure tested using low pressure air in accordance with the pipe manufacturer's instructions. If the pressure test indicates casing failure, the leaking section should be tested as outlined here to fix the location of the casing failure.

EQUIPMENT

The air manifold (Figure 12) is used to control the flow of air into the Annular space of the conduit. It has a main shut off valve which shuts off all air flow into the manifold. The two controlling valves control the flow of air into each of the two flowmeters. The flowmeters show the volume of air flowing into the conduit. They are read on the metal scales in standard cubic feet per minute (SCFM). They should be read at the widest point of the float (the metal part inside the glass cylinder). The SF_6 port is where the output line from the SF_6 manifold is connected.

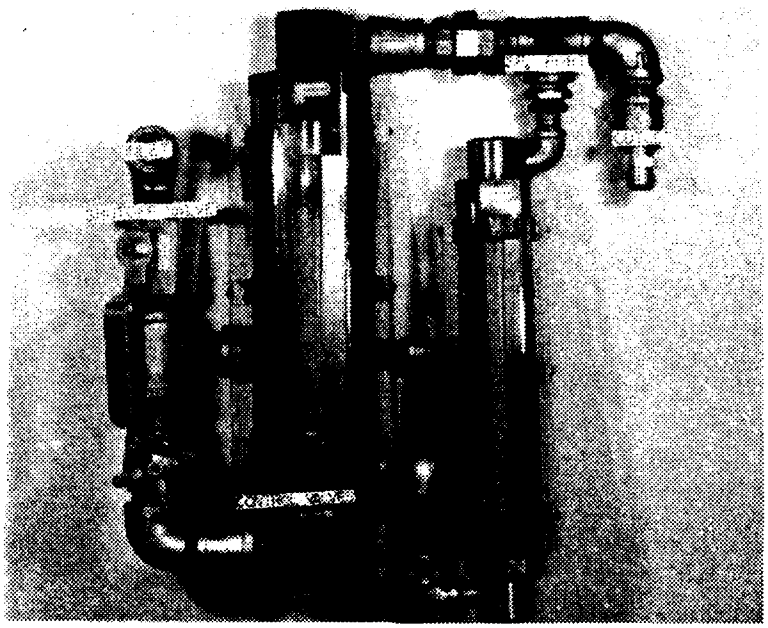

Figure 12. Air Manifold

The SF_6 manifold (Figure 13) controls the flow of SF_6 into the SF_6 port on the air manifold. The scale on the glass flowmeter tubes are read at the widest point of the (ball) floats, in cc/min. The black knobs at the top of each tube are valves which regulate the flow of SF_6 through the flowmeters.

For both manifolds, the total flow is the sum of the flows through each tube (for example, if there is 15 SCFM of flow in the left tube of the air manifold, and 90 SCFM of flow in the right, the total air flow is 105 SCFM).

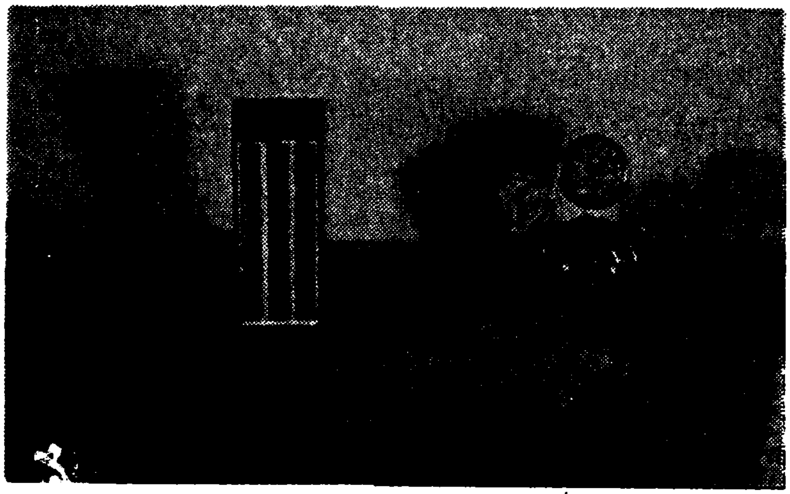

Figure 13. SF_6 Manifold and Pressure Regulator

The pressure regulator (Figure 13) is used to reduce the SF_6 pressure from the high pressure within the SF_6 cylinder to a lower pressure usable by the SF_6 flowmeters. The right dial indicates the cylinder pressure, the left dial the regulated pressure. The small knob controls the flow of SF_6 out of the regulator, and the large knob controls the pressure. The pressure regulator should be set at 20 psi for all tests.

The Ion-Track (Figure 14) is a portable ion-capture device used to search for SF_6 concentrations at ground level. It is battery operated and should be charged overnight before use.

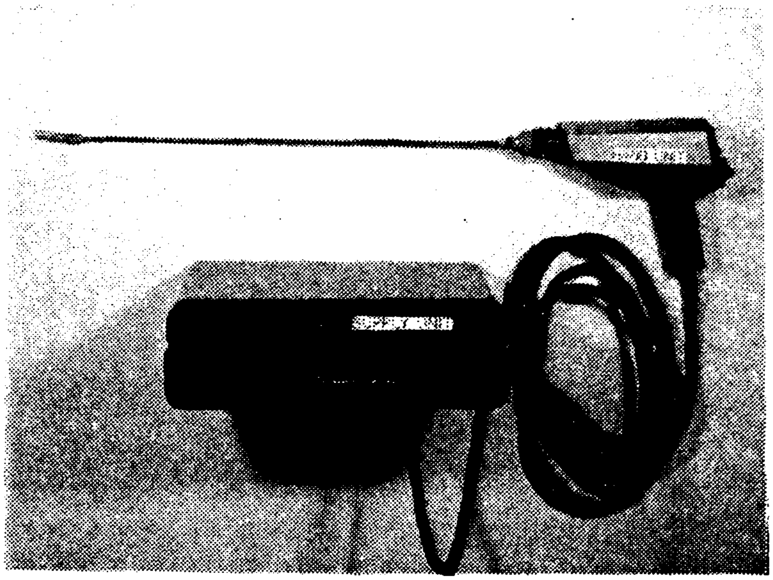

Figure 14. Ion-Track Ion-Capture Device

Other equipment which are needed but not pictured, are an air source capable of delivering around 50-150 SCFM of air, and SF_6, available in high pressure cylinders from major compressed gas suppliers.

PREPARATION

Determine:

1. Path of line
2. Length of line
3. Depth of burial of line (measure to the centerline of the casing). If the burial depth varies, use an average depth

4. Casing diameter

5. Carrier pipe diameter.

Make sampling holes about 1" in diameter and 4-6" deep. They should be made above the centerline of the pipe and spaced at intervals equal to the local burial depth. They may be covered with styrofoam cups, pieces of wood, etc. (covering the holes is desirable if it is windy). Record on a piece of paper the hole number and the location of the hole. A convenient way to make sampling holes in soft soil is to drive 6-8" lengths of 1" PVC pipe into the ground.

Unpack the Ion-Track and screw the sampling nozzle (long tube) onto the hand unit (do not remove the short length of plastic tubing from the nozzle; it is there to protect the tip and keep dirt out of it). Open the top of the supply unit and open the valve on the argon bottle. Replace the cover, and turn the selector switch on the supply unit to "on". Allow it to warm up for about three minutes. It is warmed up when the amber light on the hand unit begins flickering.

Two minutes after the unit is warmed up, press the detector button on the hand unit and check for a meter reading between 5 and 15. Select a scale of 3 and zero the meter. Turn the audio zero and audio volume controls all the way counterclockwise.

Once the Ion-Track is warmed up, time how long it takes to walk the length of the line. At the same time, use the Ion-Track to determine the background concentration of fluorinated hydrocarbons. During this walk, keep the tip of the sampling nozzle a few inches off the ground, and the scale control on a low scale (1 or 3). (Zero the meter each time you switch scales.) Note the highest reading obtained on the meter. Use Table 4 to convert the meter reading to a background concentration. Record this number.

Table 4

Conversion of Ion-Track Meter Readings into SF_6 Concentrations

Meter Reading	Scale					
	1	3	10	30	100	300
5	$2.9x10^{-9}$	$1.0x10^{-8}$	$4.0x10^{-8}$	$1.4x10^{-7}$	$5.5x10^{-7}$	$1.9x10^{-6}$
10	$6.4x10^{-9}$	$2.2x10^{-8}$	$8.9x20^{-8}$	$3.1x10^{-7}$	$1.2x10^{-6}$	$4.2x10^{-6}$
15	$1.0x10^{-8}$	$3.6x10^{-8}$	$1.4x10^{-7}$	$4.9x10^{-7}$	$1.9x10^{-6}$	$6.7x10^{-6}$
20	$1.4x10^{-8}$	$5.0x10^{-8}$	$1.9x10^{-7}$	$6.8x10^{-7}$	$2.7x10^{-6}$	$9.3x10^{-6}$
25	$1.8x10^{-8}$	$6.4x10^{-8}$	$2.5x10^{-7}$	$8.8x10^{-7}$	$3.5x10^{-6}$	$1.2x10^{-5}$
30	$2.2x10^{-8}$	$7.9x10^{-8}$	$3.1x10^{-7}$	$1.1x10^{-6}$	$4.2x10^{-6}$	$1.5x10^{-5}$
35	$2.7x10^{-8}$	$9.4x10^{-8}$	$3.7x10^{-7}$	$1.3x10^{-6}$	$5.1x10^{-6}$	$1.8x10^{-5}$
40	$3.1x10^{-8}$	$1.1x10^{-7}$	$4.3x10^{-7}$	$1.5x10^{-6}$	$5.9x10^{-6}$	$2.1x10^{-5}$
45	$3.6x10^{-8}$	$1.2x10^{-7}$	$4.9x10^{-7}$	$1.7x10^{-6}$	$6.7x10^{-6}$	$2.4x10^{-5}$
50	$4.0x10^{-8}$	$1.4x10^{-7}$	$5.5x10^{-7}$	$1.9x10^{-6}$	$7.6x10^{-6}$	$2.7x10^{-5}$
55	$4.5x10^{-8}$	$1.6x10^{-7}$	$6.2x10^{-7}$	$2.2x10^{-6}$	$8.5x10^{-6}$	$3.0x10^{-5}$
60	$5.0x10^{-8}$	$1.7x10^{-7}$	$6.8x10^{-8}$	$2.4x10^{-6}$	$9.3x10^{-6}$	$3.3x10^{-5}$
65	$5.4x10^{-8}$	$1.9x10^{-7}$	$7.4x10^{-7}$	$2.6x10^{-6}$	$1.0x10^{-5}$	$3.6x10^{-5}$
70	$5.9x10^{-8}$	$2.1x10^{-7}$	$8.1x10^{-7}$	$2.8x10^{-6}$	$1.1x10^{-5}$	$3.9x10^{-5}$
75	$6.4x10^{-8}$	$2.2x10^{-7}$	$8.8x10^{-7}$	$3.1x10^{-6}$	$1.2x10^{-5}$	$4.2x10^{-5}$
80	$6.9x10^{-8}$	$2.4x10^{-7}$	$9.4x10^{-7}$	$3.3x10^{-6}$	$1.3x10^{-5}$	$4.5x10^{-5}$
85	$7.4x10^{-8}$	$2.6x10^{-7}$	$1.0x10^{-6}$	$3.5x10^{-6}$	$1.4x10^{-5}$	$4.8x10^{-5}$
90	$7.9x10^{-8}$	$2.7x10^{-7}$	$1.1x10^{-6}$	$3.8x10^{-6}$	$1.5x10^{-5}$	$5.2x10^{-5}$
95	$8.4x10^{-8}$	$2.9x10^{-7}$	$1.1x10^{-6}$	$4.0x10^{-6}$	$1.6x10^{-5}$	$5.5x10^{-5}$
100	$8.9x10^{-8}$	$3.1x10^{-7}$	$1.2x10^{-6}$	$4.2x10^{-6}$	$1.7x10^{-5}$	$5.8x10^{-5}$

Take the measured time necessary to walk the line and add five seconds for each sampling hole. The result is the search time.

Calculate the space in the annulus of the conduit with the following formula:

$$\text{vol} = \pi/4 \times (d_{casing}{}^2 - d_{pipe}{}^2) \times \text{line length (all measurements in feet)}$$

Estimate the fill time by dividing the void space by the rate of delivery (in CFM) of the air source. (The rate of delivery may be measured with the air manifold).

Pick a diffusion time (t). Use a convenient time (30 min., 1 hour, etc.) that is about 5 times the fill time or the search time, but not greater than 6.25 x the burial depth (x) squared (with t in minutes, x in feet; $t < 6.25x^2$).

Calculate $x/\sqrt{t}$ (x in feet, t in minutes). It should be greater than 0.4. Find the concentration ratio (C/C_o) using Figure 15, Table 5, or the relation

$$C/C_o = 10^{(3.67-9.65(x/\sqrt{t}))}$$

Knowing C/C_o, and knowing that

$$C = C/C_o \times C_o$$

pick a source concentration (C_o), between 1×10^{-6} and 1×10^{-3}, that will produce a survey concentration (C) that can be reliably detected. C should be about an order of magnitude higher than the background concentration determined earlier. Use a C_o as low as possible. If C_o turns out to be high

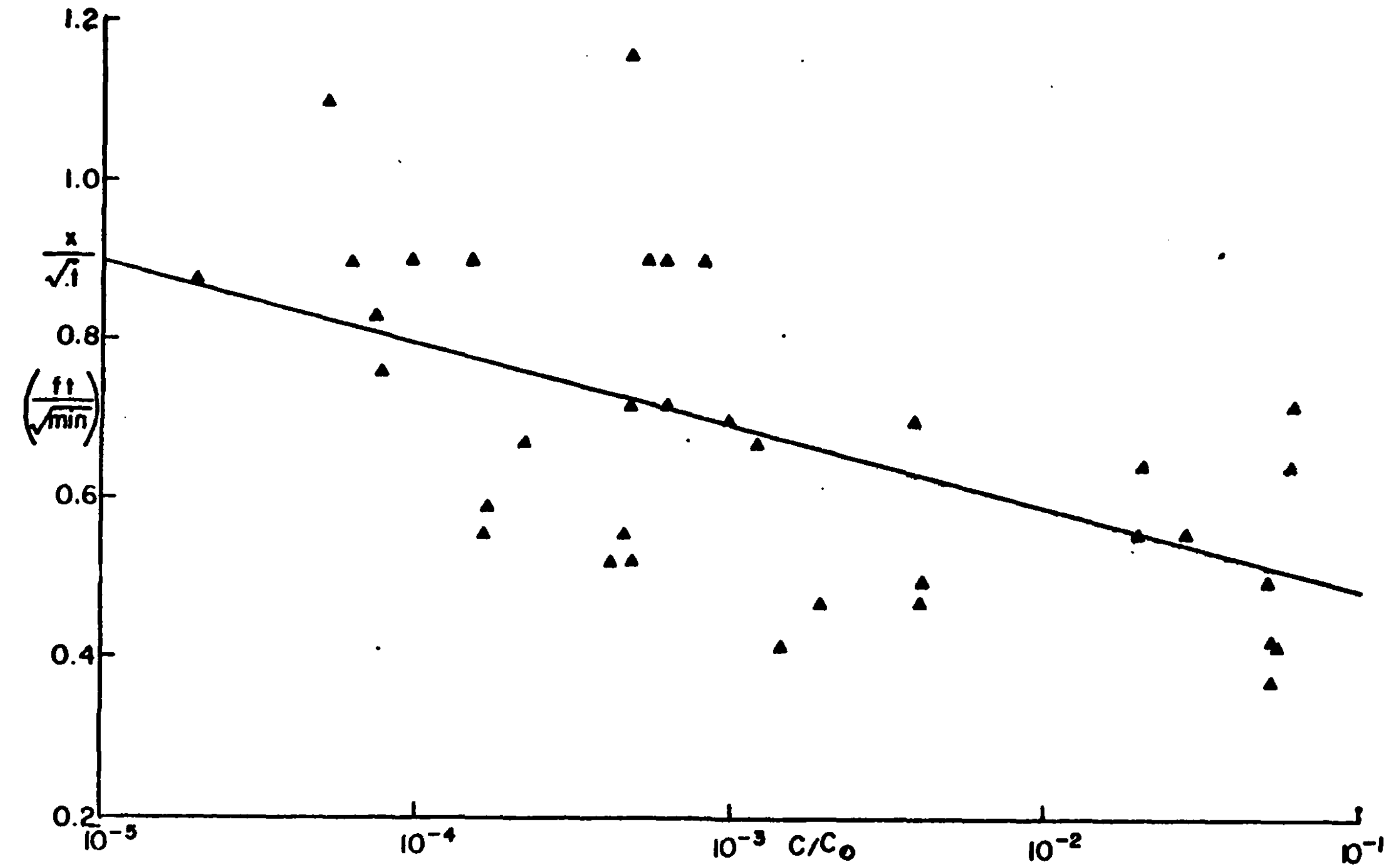

Figure 15. $x/\sqrt{t}$ $(ft/\sqrt{min})$ vs. log (C/C_o)

(above 1×10^{-2}), the diffusion time (t) should be increased and C/C_o recalculated.

Table 5

Relationship Between $x/\sqrt{t}$ and C/C_o

$x/\sqrt{t}$ (ft/$\sqrt{(min)}$)	C/C_o
1.11	10^{-7}
1.00	10^{-6}
0.893	10^{-5}
0.795	10^{-4}
0.691	10^{-3}
0.578	10^{-2}
0.484	10^{-1}

<u>EQUIPMENT SET-UP</u>

1. Connect the air source to the air manifold inlet using one of the 1-1/4" hoses.
2. Connect the air manifold outlet to the conduit vent using the other 1-1/4" hose.
3. Connect the SF_6 manifold outlet (center line) to the SF_6 port on the air manifold using the hose supplied.
4. Install the pressure regulator on the SF_6 cylinder (caution: LH thread).
5. Connect the pressure regulator outlet to the SF_6 manifold inlet using the remaining hose.
6. Position both manifolds so they are vertical and can be easily seen.

TRACER GAS INTRODUCTION

1. Insure that the vent line on the far end of the pipe is open (uncapped).
2. Insure all valves are closed: 3 on the air manifold, 2 on the SF_6 manifold, 1 (small black knob) on the pressure regulator, and 1 on top of the SF_6 cylinder.
3. Turn the large black knob on the pressure regulator counterclockwise until it turns freely.
4. Turn on the air source.
5. Open the air shut-off valve (ball valve on air manifold).
6. Open the air control valves on the air manifold (gate valves) to produce an air flow the same as the air flow used in the preparation calculations (total air flow = sum of flows on both flowmeters as read on metal scales).
7. Use Table 6 to find the SF_6 flowmeter scale reading that will produce the desired source concentration (C_o).
8. From Table 4, find the ion-track scale and meter reading for the selected source concentration (C_o).
9. Slowly open the valve on top of the SF_6 cylinder all the way.
10. Turn the large black knob on the pressure regulator to obtain a pressure of 20 psi on the left dial.

Table 6

SF_6/Air Flowmeter Readings for Given Source Concentrations

Air Rate (SCFM)	SF_6 Source Concentration (C_o)			
	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-4}$	$1x10^{-3}$
5	-	2/-	20/9	-/64
10	-	6/-	32/17	-/116
15	-	9/-	43/25	41+150
20	-	11/-	53/31	-
30	-	14/-	74/43	-
40	1/-	17/7	92/54	-
50	2/-	20/9	-/64	-
60	3/-	22/11	-/75	-
70	4/-	25/13	-/86	-
80	5/-	27/14	-/96	-
90	5/-	30/16	-/106	-
100	6/-	32/17	-/116	-
110	6/-	34/19	-/125	-
120	7/-	37/20	-/137	-
130	8/-	39/22	-/149	-
140	8/-	41/23	17+150	-
150	9/-	43/25	41+150	-
160	9/-	45/26	62+150	-

NOTES:

1. Air rate is the sum of the readings from both metal scales.

2. SF_6 rate is indicated by the numbers under the desired source concentration and across from the obtained air rate.

3. SF_6 rates are given by two numbers. The first number is the reading on the left tube (tube 610A), the second for the right tube (tube 602).

4. A slash (/) indicates the desired rate can be obtained on either tube: 32/17 means use a rate of 32 on the left tube or a rate of 17 on the right tube can be used.

5. A plus (+) means use both tubes: 41+150 means use a rate of 41 on the left tube with a rate of 150 (full scale) on the right tube.

6. Read SF_6 flow rate at the center of the ball float.

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11. Open the outlet valve on the pressure regulator (small black knob) all the way.

12. Open the valves on the SF_6 manifold until the desired SF_6 flow rate is obtained.

13. Record the time.

14. Monitor the vent on the other end of the line with the ion-track detector. When it reads near C_o, the line is full.

15. Close the air shut-off valve.

16. Close the SF_6 cylinder valve (do not dissassemble anything at this time).

17. Cap the open vent line.

SF_6 SEARCH

When half the diffusion time has elapsed (since the fill start time), start the SF_6 surface search. Walk the line, pausing at each hole long enough to get a reading. Insert the probe slightly into the sampling holes, and wait a few seconds for a steady indication. At each hole, record:

1. The hole number

2. The meter reading

3. The meter scale (1, 3, 10, etc.).

Repeat this again when the entire diffusion time has elapsed, and a third time when twice the diffusion time has elapsed.

EQUIPMENT DISASSEMBLY

After ensuring that the air source is secured and the SF_6 cylinder valve is closed, open all other valves to release any pressure in the system. Disassemble the equipment in the reverse order of assembly, clean, and store. Don't forget to turn the argon supply off in the ion-track supply unit.

DATA REDUCTION

Use Table 4 to find the surface concentration (C) from the recorded meter readings, or use the relation:

$$\log(C) = 1.138 \times \log(\text{scale number} \times \text{meter reading}/100) - 7.053$$

Plot the results (location vs. concentration) on log paper.

INTERPRETATION OF RESULTS

Look for SF_6 concentration peaks above or near the expected concentration previously calculated. Some variation in SF_6 concentration is expected along the length of the line, due to background concentrations or spillage, but any leaks should stand out. The relative size of any detected leaks can be estimated from the relative sizes of the peaks and the growth rate of the peaks from search to search.

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