LIQUID METAL-TO-GAS LEAK DETECTION INSTRUMENTS*

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ABSTRACT

It is desirable for liquid-metal-cooled reactors that small liquid metal-to-gas leaks be reliably detected. Testing has been performed on a number of detection systems to evaluate their sensitivity, response time, and performance characteristics. This testing has been scheduled in three phases. The first phase was aimed at screening out the least suitable detectors and optimizing the performance of the most promising. In the second phase, candidates were tested in a 1500 ft^3 "walk-in" type enclosure in which leaks were simulated on 24-in. and 3-in. piping. In the third phase of testing, selected type detectors were tested in the 1500-ft^3 enclosure with Clinch River Breeder Reactor Plant (CRBRP) pipe insulation configurations and detector tubing configuration with cell gas recirculation simulated. Endurance testing of detection equipment was also performed as part of this effort.

Test results have shown that aerosol-type detectors will reliably detect leaks as small as a few grams per hour when sampling pipe insulation annuli. Sensitivity is improved when the leaking liquid metal temperature is above 500°F. When certain conditions are met, direct aerosol sampling of a cell will provide adequate sensitivity to detect small leaks. Leaks greater than several hundred kg/h can be detected in minutes when annuli or small cell atmospheres are sampled. Aerosol-type detectors appear to be relatively insensitive to typical reactor environmental pollutants.

INTRODUCTION

The use of liquid metals (sodium or a sodium-potassium alloy) as heat transfer fluids in nuclear power plants necessitates a means of detecting leaks of these fluids from pipes and vessels. It is often desirable that even very small leaks, sometimes referred to as "weeping" leaks, be detected in relatively short times. This is especially true for leaks which occur where the pipe or vessel surface is exposed to an air atmosphere because corrosion by sodium reaction products at high temperature can cause the leak size to grow. Larger leaks will increase the clean-up and repair time. For leaks in inerted cells, corrosion proceeds very slowly. However, for the main primary heat transfer piping and components usually contained in inerted cells for loop-type reactors, it is prudent to detect even small leaks, low corrosion rates notwithstanding.

Historically, the approach to leak detection in liquid-metal-cooled reactors has been to attempt to detect only relatively large flowing leaks. The method most commonly used depends upon the electrical conductance of liquid metals and utilizes either probe or cable-type detectors installed below pipe and equipment. The probe-type detector consists of a rigid cable in which the insulated conductors are exposed at one end. This end is installed vertically just underneath a hole provided in the inner sheath of the pipe or vessel insulation. Detection requires that

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the leaking liquid metal flow from the leak site to the insulation sheath, down the sheath to the hole, and onto the exposed conductors, where it causes an electrical short. The cable detector is made up of an assembly of two or more conductors insulated by glass braid or ceramic beads. The cable is mounted horizontally below the pipe or vessel. When a leak occurs, the flowing liquid metal impregnates the insulation, causing the conductors to be shorted. These types of detectors have on occasion detected large leaks but have been shown to be unreliable, particularly for detecting small leaks. Also, false alarms have taken place due to damage during construction or later due to the entrance of moisture.

Because of the need in liquid metal fast breeder reactors (LMFBRs) for sensitive, reliable leak detectors, an extensive development program was started in the early 1970s. The initial phase of this program was the testing of candidate detection systems in a small test chamber. Based on the results of these "screening" tests, the best performing systems were tested in a large "walk-in" enclosure using more prototypical pipe and detector configurations over the range of expected LMFBR environments. These tests are referred to as the "mockup" tests. With the knowledge gained from the mockup tests, a series of verification tests was performed using expected CRBRP detector and pipe insulation configurations and cell gas recirculation rates. Long-term endurance tests were also completed. The results of the mockup and verification tests are presented in this paper.

LEAK DETECTION METHODS TESTED

The "screening" tests evaluated the following type detectors: (1) contact- and cable-type conductivity, (2) aerosol transport, (3) product of combustion, (4) chemical, and (5) gas analysis.

The principle of operation of the conductivity detectors has been described previously. An illustration of the probe-type detector tested is shown in Figure 1a. For these tests, in addition to glass braid insulated cable, a configuration as shown in Figure 1b was tested. This type detector employs metal-sheathed, magnesium-oxide-insulated, two-conductor cable. The sheath is milled out in selected locations to expose the conductors. Leaking liquid metal forms an electrical bridge between the conductors and the sheath at these locations.

Two types of aerosol detectors were tested. These sense the aerosol generated by the reaction of sodium vapor with oxygen in the presence of at least small quantities of moisture. The plugging filter aerosol detector (PFAD), Figure 1c, embodies a differential pressure sensor connected across a filter. Gas from the leak site is drawn through the filter. Upon a liquid metal leak, the sodium aerosol carried by the gas collects on the filter and the pressure drop increases. This pressure drop is then monitored and provides an alarm when it approaches a preset limit. In addition, chemical analysis of the residue on the filter provides confirmation of the liquid metal release.

A second type of aerosol detector, referred to as a sodium ionization detector (SID), Figure 1d, uses a heated filament to ionize particles in the gas that flows through it. The particles are collected by an electrode to provide a measure of ion current. By operation of the filament at the proper temperature, only sodium, or a species with a lower ionization potential, will become charged with the resultant ions collected.

The product of combustion detector tested was a commercially available unit which operates on an ionization principle; invisible or visible combustion products which enter the detector's outer chamber are ionized by a small radiation source and disturb the balance between this chamber and the inner reference chamber. This imbalance generates the output signal.

A pH detector was evaluated during the initial phase of testing. The gas to be sampled for sodium specie was bubbled through water and the resulting change in pH was measured.

Gas analysis refers to the measurement of the oxygen or hydrogen concentration before, during, and after a simulated liquid metal leak.

The first series of tests, the screening tests, demonstrated that the most promising type of detectors from the standpoint of sensitivity and adaptability for reliable LMFBR application were the aerosol types. The hydrogen and smoke detectors showed some promise; conductivity held out some possibility for use in special applications. Therefore, these four detection approaches were selected for the mockup test series.

MOCKUP TESTS

Test Chamber

The test chamber, Figure 2, for the mockup tests consisted of an approximately 1500 ft^3 steel-lined rectangualar enclosure, which could be sealed. For testing in air, moisture could be introduced and the concentration controlled. For nitrogen testing, both moisture content and oxygen content could be controlled. A commercial smoke detector was installed near the enclosure ceiling. Cell atmosphere gas sampling was provided for monitoring for oxygen, hydrogen, and moisture and for collecting sodium on a filter for analysis.

Test Articles

Several test articles were used in the mockup test series. In the first series of tests, the test article consisted of a section of 24-in. stainless steel pipe approximately 10 ft long. Insulation consisted of an inner stainless steel sheath, 5.5 in. of calcium-silicate insulation, and a stainless steel outer sheath. The diameter of the inner insulation sheath was such as to provide a 1-in. annulus between the pipe and the insulation. The pipe section was heated internally and was mounted horizontally as shown in Figure 2. A tube installed in the top of the annulus was connected to one port of a 7-port manifold, the exhaust of which was passed through a SID and PFAD in parallel and thence back into the enclosure using a vacuum pump. The other ports of the manifold were left open to simulate the presence of other sections of pipe sampled by the one SID or PFAD. A gas inlet port was provided at a point underneath the pipe, upstream of the sampling port.

The leak was simulated by loading sodium in a storage tank and controlling the cover gas pressure and the heating rate so that a controlled leak rate could be established through expansion of the sodium. The sodium injection line initially entered above the top of the pipe so that the sodium dripped on the pipe. This was later changed so that the injection line penetrated the pipe from the inside, causing the sodium to flow out through a machined hole in the pipe to more closely simulate an actual leak.

The test article was changed somewhat for the 24-in. pipe natural convection tests. The 24-in. insulated pipe was retained, but as shown in Figure 3, the annulus sampling line was removed and replaced with an upper vent tube. The aerosols generated by the leak were thus transferred only by natural convection to the test enclosure. The cell atmosphere was sampled for aerosol content by externally located PFADs and SIDs as described previously.

The last test series utilized a 3-in. diameter test article designed to simulate auxiliary system piping in an LMFBR. The test module was an 80-in. long stainless steel pipe which was heated by a tubular heater banded to the outside of the pipe. Thermal insulation, 4.5 in. thick, was mounted on stainless steel foil, which was wrapped around the pipe. A stainless steel foil cover surrounded the entire assembly (pipe and insulation). For the last series of 3-in. pipe natural convection tests, the above configuration was changed somewhat to provide a more complete annulus between the pipe and insulation, as shown in Figure 4, for the reasons discussed below.

TEST RESULTS

24-in. Pipe Annulus Sampling

The test conditions for the 24-in. pipe annulus sampling tests are shown in Table I; the results of these tests are given in Table II.

It is seen that by sampling the annulus between the pipe and insulation, very small leaks (0.4 to 100 g/h) can be detected by either SIDs or PFADs. The response time will vary from a few minutes to days, depending on the conditions, particularly liquid metal temperature, with the SID generally responding faster. Calculation of the aerosol concentration in the gas entering the SIDs or PFADs indicates the detection threshold to be approximately 10^{-11}g/cm^3. Test 2 is of interest in understanding the dependence of aerosol generation on temperature. In this test, the sodium temperature was varied from 400 to 700^{o}F. It was seen that at approximately 600^{o}F, a substantial change in aerosol concentration occurred, probably due to the melting of sodium hydroxide (NaOH).

The response of the conductivity-type detectors was not consistent; where leak indication was obtained, it was generally obtained for the larger leak, high-temperature conditions.

24-in. Natural Convection, Cell Sampling

Natural convection tests were run to determine if adequate leak sensitivity could be obtained by sampling cell atmospheres in lieu of annulus sampling or as a backup to annulus sampling. If effective, substantial cost savings would result from elimination of the tubing and manifolds, cell penetrations, etc. Table III gives the test conditions. Results of the test are shown in Table IV. Note that in the 1500-ft^3 enclosure, leaks of 2 g/h or more were detected for all test conditions. This was true even for Test 10 where the vent tubes were deliberately sealed. To apply these data to larger, typical LMFBR cells, it is necessary to take into consideration cell recirculation. Calculations were performed, assuming that the recirculation system removes a fraction of the aerosol from the recirculated gas prior to returning it to the cell. Based on the calculations, liquid metal leaks of 100 g/cm^3 or more into 1-in. annuli can be detected by cell sampling in cells up to 100,000 ft^3. In these calculations, 10^{-11} g/cm^3 is used as the threshold of detection.

3-in. Natural Convection, Cell Sampling

For small auxiliary piping, annulus monitoring, though effective, would be very costly and in many cases not justified by the consequences of a leak. Therefore, all small piping testing was oriented toward verifying the practicality of utilizing cell atmosphere monitoring. The test conditions for these tests are shown in Table V; the results are presented in Table VI. In the first two tests, 16 and 17, the inner insulation sheath was wrapped relatively tightly around the pipe and heaters, providing an irregular annulus, with no space where the sheath contacted the pipe. As seen in Table VI, effective detection did not take place. Calculation of the aerosol concentration in the cell indicated that the levels were below the detection threshold for aerosol detectors. Examination of the test article following these tests revealed that most of the leaked sodium had not reacted and was contained by the inner metal sheath. Accordingly, in Tests 18 through 21, the insulation design was altered to provide a complete annulus around the pipe as shown in Figure 4.

With the modified insulation design, detection was achieved with the SID and PFAD detectors in all cases. Detection times varied from a few minutes to approximately 1 day. Similar results were achieved by the hydrogen detector.

In Test 21, a relatively large leak was simulated (243 x 10^3 g/h). Detection time was a few minutes for both SIDs and PFADs, indicating these detectors respond rapidly to large leaks. Rapid detection was also achieved by the hydrogen detector.

As with the 24-in. pipe natural convection testing, the 1500-ft^3 enclosure data must be converted to expected results for larger cells with recirculating gas flows.

VERIFICATION TESTING

Verification testing of SIDs and PFADs has also been completed. The first mode of testing utilized the 1500-ft^3 enclosure to repeat tests previously performed on 24- and 3-in. piping but with several major changes. First, the atmosphere wihin the enclosure was recirculated at an equivalent rate of 10%/min, simulating typical CRBRP cells. Second, the piping insulation as well as heater and thermocouple and support penetrations were designed to match the planned CRBRP design. Finally, the annulus sampling manifold, including total length of tubing from the pipe to the detectors, was designed to duplicate the present CRBRP design.

The test conditions and results are shown in Table VII. It is seen in Tests 1 through 4, where the detection is based on PFAD monitoring of annuli, detection of the 100 g/h leak took place in less than 7 h over the temperature range of 655 to 1010°F for both nitrogen and air environments. In this temperature range, response in nitrogen was superior to that in air.

For direct cell monitoring where SIDs were employed, the response time was comparable (in some cases faster), with the maximum time being 3.5 h. It must be kept in mind that the response time for direct cell monitoring is a function of cell volume, circulation rate, and greater or lesser opportunity for settling and plate-out. Thus, on many plant cells, direct cell monitoring can be expected to be less effective than annulus monitoring.

The second mode of verification testing is the long-term operation of SIDs and PFADs in an LMFBR-type environment. In previous testing, the various detectors were operated only during the performance period of each test. It is desirable to obtain data on the endurance capability of the detectors and their susceptibility to mal-function due to impurities in the sample gas not related to sodium species.

Accordingly, arrangements were made to install sampling lines in the upper plena of an evaporator and a superheater, part of the steam generation system for EBR-II. These sampling lines are connected to aerosol detectors; SIDs and PFADs which are continuously operated.

Testing was started on April 4, 1977, and was completed in August 1982. The following has been observed.

1) PFAD filter membranes need not be changed more frequently than every 8 weeks to avoid significant DP cell pressure buildup due to the collection of atmospheric dust.

2) The electrical calibration of the PFADs has been extremely constant, and total recalibration and maintenance time has been insignificant.

3) SID maintenance has also been low and has been essentially limited to filament replacement required every 6 to 10 months.

4) Activities of maintenance personnel (cigarette smoke, increased dust generation) were apparent from the SID output trace.

SUMMARY AND CONCLUSIONS

Liquid metal-to-gas leak detection testing has indicated that conductivity type leak detectors (probe and cable) have a usefulness limited to large leaks or leaks in a confined space. Annulus-type aerosol sampling, utilizing either SIDs or PFADs, provides a sensitive method of detecting leaks in both air and nitrogen down to the range of several g/h, with enhanced sensitivity response time when the liquid temperature is above 500°F. Response time will vary depending upon liquid metal temperature, leak rate, etc. Aerosol sampling of cells is an effective method of leak detection for moderate-size cells even with relatively high recirculation rates such as 10%/min. Relatively large leaks (200 kg/h) can be detected by aerosol sampling of annuli or small cells in minutes. Long-term endurance testing has shown both SIDs and PFADs to be relatively insensitive to typical reactor environmental pollutants and otherwise quite reliable.

0001U/nth/emh

TABLE I

MOCKUP LEAK DETECTION TEST CONDITIONS

Test No.	Oxygen	Moisture (vppm)	Temperature (°F)	Sodium Leak Rate (g/h)	Leak Time (h)	Total Sodium Leaked (g)	Remarks
1	1%	1,000	980	100	10	1,000	Forced Convection
2	1%	1,000	400 700	100	10	1,000	Forced Convection
3	21%	30,000	640 920	100	6	600	Forced Convection
4	1%	1,000	980	0.4	250	100	Forced Convection
5	21%	30,000	350 640	2	200	400	Forced Convection
6	21%	30,000	640	2	100	200	Forced Convection
7	1% O_2	1,000	400	100	20	2,000	Forced Convection
8	1% O_2	1,000	500	2	50	100	Forced Convection

TABLE II

MOCKUP LEAK DETECTION TEST RESULTS

Parameter	Test No.							
	1	2	3	4	5	6	7	8
DP (Annulus)	59 min	26 h 54 min	6 h 10 min	6 h 33 min	97 h 52 min	14 h	NR[a]	NR[a]
DP (Cell)	1 h 16 min	26 h 58 min	6 h 8 min	2 h 31 min	47 h 25 min	11 h 25 min	NR[a]	NR[a]
SID (Annulus)	7 min	30 h 38 min	4 h 47 min	3 min	1 min	1 min	13 h	NR
Cable (Annulus)	1 h 10 min	NR	6 h 6 min	NU	104 h 13 min	18 min	NR	NR
Contact (Annulus)	NR	NR	19 h 4 min	NR	NR	NR	8 h 38 min	NR
Hydrogen (Cell)	NU	11 h 4 min	5 hr 32 min	NR	23 h 42 min	20 min	3 h	10 h 45 min
Smoke (Cell)	NU	NU	6 h 4 min	NU	31 h 48 min	NR	NR	39 min

(a) Sodium was found present in filter pads, 130 μg and 110 μg for Test 7 collected in 5 h 22 min; 130 μg and 100 μg for Test 8 collected in 50 h.

NU - Not Used
NR - No Response
DP - Differential Pressure

TABLE III

NATURAL CONVECTION TEST PARAMETERS

Test No.	Oxygen (%)	Moisture (vppm)	Temperature (°F)	Sodium Leak Rate (g/h)	Leak Time (h)	Total Sodium Leak (g)	Pipe Size (in.)
9[a]	1	1,000	980	100	20	350	24
10[a]	1	1,000	980	100	20	625	24
11	1	1,000	980	2	100	175	24
12	1	1,000	640	2	100	200	24
13	21	15,000	900	2	100	175	24
14	21	15,000	640	2	100	180	24
15	21	15,000	400	2	100	155	24

(a) Vent tubes were sealed

TABLE IV

NATURAL CONVECTION TEST RESULTS

Test No.	Differential Pressure Detector Cell		Sodium Ionization Detector		Cable	Contact	H_2
	Floor Area	Ceiling Area	Floor Area	Ceiling Area			
9	3.9 h	3.9 h	0.25 h	0.25 h	0.4 h	NR[a]	2.8 h
10	4.5 h	7.2 h	0.78 h	0.67 h	0.1 h	NR	1.3 h
11	1.0 h	0.7 h	<0.1 h	<0.1 h	<0.1 h	NR	NR
12	12.1 h	12.4 h	1.2 h	NU	NR	NR	NR
13	11.9 h	14.6 h	0.88 h	0.95 h	NR	NR	NR
14	8.0 h	12.9 h	0.025 h	0.016 h	121.1 h	NR	NR
15	53.8 h	44.2 h	0.01 h	0.01 h	NR	NR	NR
11R	<0.5 h	<0.8 h	<1 min	<1 min	NR	NR	NR
13X	23.6 h	25.4 h	15.2 h	15.2 h	15.7 h	NR	0.58 h

(a) NU - Not Used
NR - No Response

TABLE V

SMALL PIPING TEST PARAMETERS

Test No.	Oxygen (%)	Moisture (vppm)	Temperature (°F)	Sodium Leak Rate (g/h)	Leak Time (h)	Total Sodium Leaked (g)	Pipe Size (in.)
16	1	1,000	500	2	100	~200	3
17	21	15,000	650	2	100	~200	3
18	1	1,000	980	100	4.17	~400	3
19	1	1,000	650	100	10	~1,000	3
20	21	15,000	650	100	10	~1,000	3
21	1	1,000	40	243,000	0.033	~8,000	3

TABLE VI

SMALL PIPING TEST RESULTS

Test No.	Differential Pressure Detector Cell		Sodium Ionization Detector		Smoke	Hydrogen
	Floor Area	Ceiling Area	Floor Area	Ceiling Area		
16	NR	NR	116 h	NR(c)	NU(c)	12.7 h
17	NR	NR	NR	NU	NU	NR
18	2.6 h	2.5 h	0.5 h	0.5 h	NR	1.0 h
19	27.4 h(a)	14.0 h	3.2 h	5.7 h	NR	4.0 h
20	25.9 h(a)	17.6 h	0.65 h	0.60 h	NR	0.72 h
21	0.008 h	<0.23 h(b)	0.06 h	0.008 h	<0.03 h	<0.08 h

(a) A bad leak was found on the sampling line of the Differential Pressure (DP) detector which prevented the DP across the filter from rising.

(b) Recorder pen stuck, exact time of response cannot be determined.

(c) NU - Not used
NR - No response

TABLE VII

VERIFICATION TEST, TEST CONDITIONS AND SUMMARY OF RESULTS

Test Number	1	2	3	4	5	6	7	8
ATM	N_2	N_2	Air	Air	N_2	N_2	Air	Air
Detection Time	1.3H	0.6H	7.0H	6.6H	3.5H	1.2H	0.8H	2.0H
Detector	Annulus PFAD	Annulus PFAD	Annulus PFAD	Annulus PFAD	Cell SID	Cell SID	Cell SID	Cell SID
Sodium and Pipe Temperature (^{o}F) Nominal	995	730	936	650	500	650	500	650
Actual Pipe Temperature (^{o}F) (Start/Detect)	1000/1010	735/735	937/951	655/670	510/525	655/655	515/565	655/680

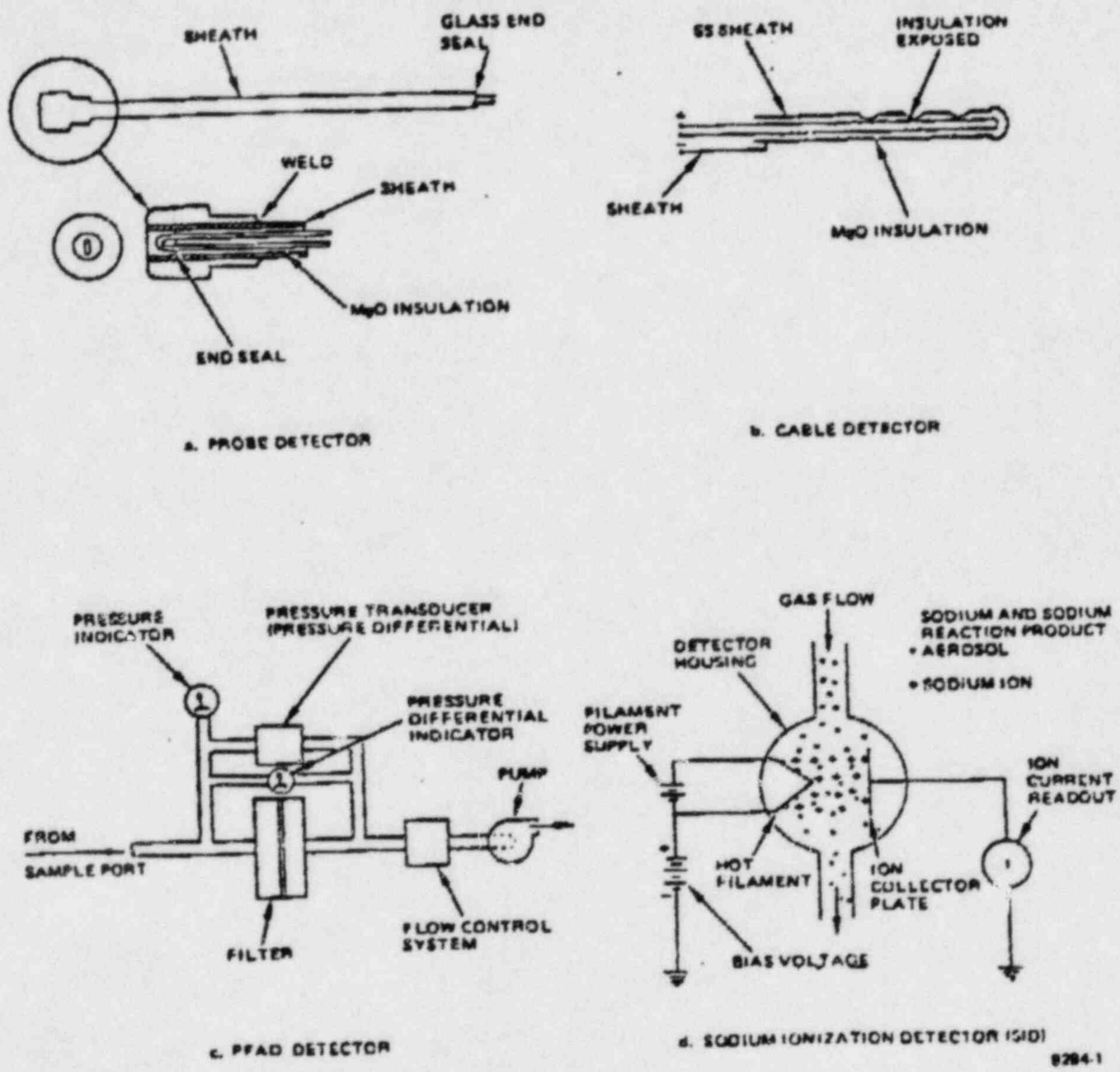


Figure 1. Types of Leak Detectors

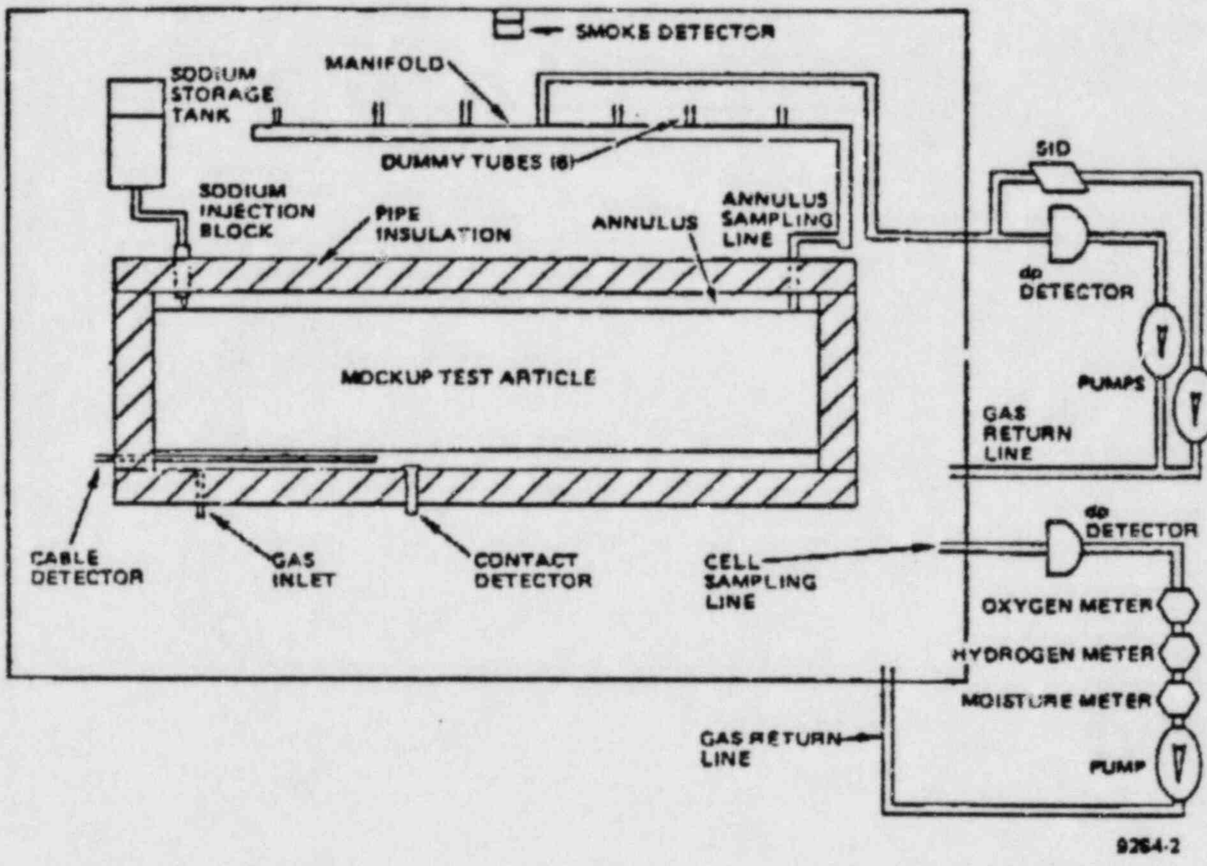


Figure 2. Walk-In Test Chamber

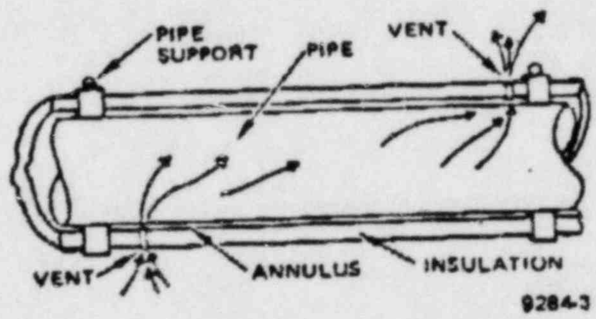
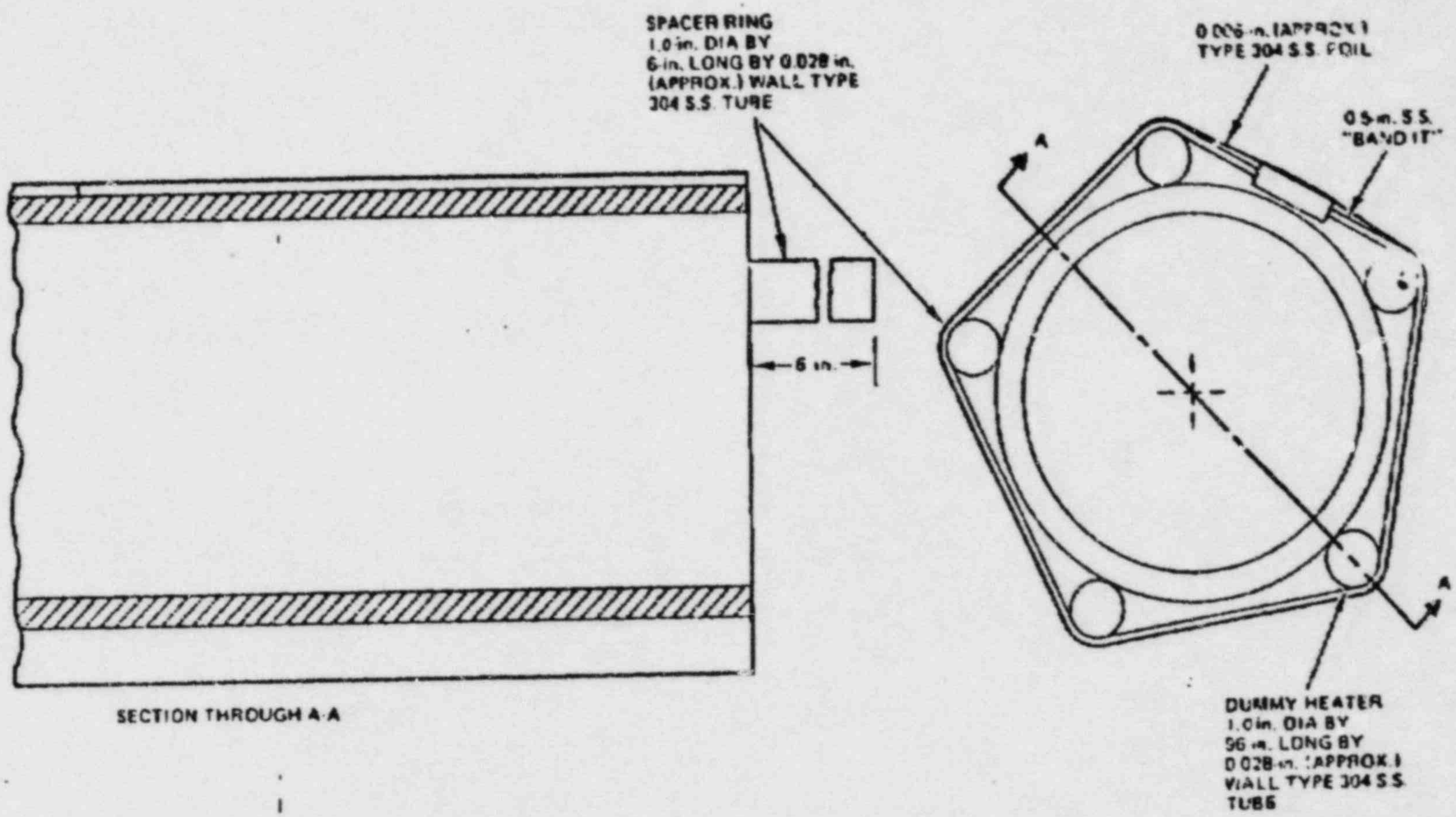


Figure 3. Natural Convection Test Article



NOTE
THE DUMMY HEATER AND 4 SPACER RINGS HELD IN PLACE BY THE BAND SUPPORT THE FOIL. THESE SUPPORTS WERE PLACED AT EACH END, AND AT 2-ft INTERVALS ALONG THE LENGTH

9284-4

Figure 4. Small 3-in. Diameter Pipe with Annulus