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An Analytical Method for
Mass Spectrometer Leak Detection

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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Printed in the United States of America. Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

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Report written: June 1968

Report distributed: March 21, 1969

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Norman G. Wilson

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AN ANALYTICAL METHOD FOR MASS SPECTROMETER LEAK DETECTION

by

Claude R. Winkelman and Norman G. Wilson

ABSTRACT

A method is presented for using a mass spectrometer leak detector analytically for large systems. The method consists of calibrating the mass spectrometer, measuring the response time of the system being checked for leaks, and then utilizing these results in the system tests. The method has been used to measure leaks in two large (360 and 600 liters) heat exchangers of complex internal geometry. The response times of these vessels were 18 and 24 min, respectively, and the minimum detectable leak was about 4.6×10^{-10} std-cc/sec for each vessel.

INTRODUCTION

A method of helium mass spectrometer leak detection has been developed by which mass spectrometers can be used to their fullest capability. This method is necessary for the measurement of compound leaks, leaks smaller than 10^{-8} std-cc/sec, and leaks in vessels having a large volume. Thus, the method is particularly applicable to large reactor sodium containment equipment and other equipment requiring high reliability. By isolating sections of the device being tested and applying the method to each section, the location of a leak can easily be determined.

Several quantities characteristic of the detector and the entire system to be tested must be determined and then applied to the interpretation of the leak detector output, thus eliminating the effects of outgassing and similar phenomena which may be confused with leaks.

TEST METHOD

First, the mass spectrometer is calibrated and the response time of the system is determined. After the system outgassing load has dropped to an acceptable level, the device being tested is flooded with helium and the output is read on the mass spectrometer. This output is interpreted with the aid of the calibration. Calibration consists of determining the sensitivity, stability, background,

and minimum detectable leak of the leak detector and the sensitivity of the system. The response time of the system must be known for reliable measurement of leakage; it must be checked experimentally, although it can be calculated from the volume of the system and the pumping speed of the leak detector.

Detector Sensitivity

Detector sensitivity is determined with either a calibrated leak or a standard leak. The calibrated leak is constructed of metal with an aperture to which tracer gas of known pressure and concentration may be applied. The standard leak is composed of a sealed glass or metal container with a known concentration of tracer gas at a known pressure and a quartz frit or capillary leak. Methods¹ have been developed by which these leaks can be calibrated to a few percent accuracy. With the standard leak, any leak detector sensitive to the tracer gas may be calibrated. Calibrated leaks are used less frequently because they are much less reliable than standard leaks.

Sensitivity is generally stated in terms of pressure-volume units of gas per unit time per unit of instrument indication, e.g., std-cc/sec-scale division. It is the number of cubic centimeters of the test gas at standard conditions (STP) that will pass through the leak in one second for

each scale division on the leak detector. Leak detectors of current manufacture commonly have sensitivities to helium of 1×10^{-10} to 1×10^{-12} std-cc/sec-scale div. The unit of scale division is not universally standardized. Some testing organizations define a scale division as 2% of full scale, while others define the scale division as 1% of full scale. In this report, a scale division will be defined as 1% of full scale.

Stability

Stability describes the random variation in signal level (or zero) caused by such things as electronic noise and mechanical vibration. In order to specify this characteristic properly, one must arbitrarily choose a signal-to-noise ratio at which he will interpret the indication of the leak detector. If the instrument is very stable and not subject to random indication, one can fairly say that he can see one scale division reliably. Generally, however, there is a slight random variation in the indicator at maximum sensitivity; 1% noise is considered reasonable.

Background

Background is a real signal originating within the instrument system from residual tracer gas or contamination in the mass spectrometer or its plumbing, or from its electronics. It may be either a stable or an exponentially varying signal. If it varies slowly or is steady, it can be electronically zeroed or subtracted from a calibration signal in order to normalize the signal. Because background often varies rapidly and cannot be assumed to be constant, it must be included in the arbitrary multiplier which determines the smallest signal to which the leak detector will reliably respond (see minimum detectable leak calculation).

Minimum Detectable Leak

Although a leak detector may have very high sensitivity, it does not necessarily follow that a leak of the same size can be detected.

The minimum detectable leak (MDL) can be calculated from the leak detector sensitivity, background, and noise with the aid of the standard leak. Consider the following example: If the indication

produced by a standard leak of 2×10^{-8} std-cc/sec on a leak detector is 1000 div, then the leak detector sensitivity, neglecting the background, is

$$\frac{2 \times 10^{-8}}{1000} = 2 \times 10^{-11} \text{ std-cc/sec-scale div.}$$

If the background is stable at 5 div, then the net signal for the standard leak is 995 div, and the leak detector sensitivity, including background, is

$$\frac{2 \times 10^{-8}}{995} = \approx 2 \times 10^{-11} \text{ std-cc/sec-scale div.}$$

If the noise in the system is 1 div, then the required signal for reliable indication is

$$\begin{aligned} \text{MDL} &= 2 \times (\text{noise}) \times (\text{leak detector sensitivity including background}) \\ &= 2(1 \text{ div})(2 \times 10^{-11} \text{ std-cc/sec-div}) \\ &= 4 \times 10^{-11} \text{ std-cc/sec.} \end{aligned}$$

We have arbitrarily selected a factor of twice the random noise fluctuations as a multiplier of the apparent leak detector sensitivity to specify the minimum detectable leak.

Had the 5-div background (Bg) been random, the total noise would have been

$$1 \text{ div noise} + 5 \text{ div Bg} = 6 \text{ div total noise,}$$

and the MDL would be 2.4×10^{-10} std-cc/sec.

Response Time

The response time is defined as the time necessary to obtain 63% of maximum indication from a standard leak attached to the system to be tested. It relates a time interval to the pressure drop in a constant-volume system and the effective pumping speed in the system of the leak detector and its connecting hoses. It can be shown that²

$$T_{63} = \frac{V}{S_{\text{eff}}}, \quad (1)$$

where

$$\begin{aligned} T_{63} &= \text{response time,} \\ V &= \text{volume of the device being tested, and} \\ S_{\text{eff}} &= \text{effective pumping speed at the test volume.} \end{aligned}$$

This equation holds for any system.

Pumping speed, S_{pump} , is the rate at which the leak detector pumps a given gas at its entrance port. The pumping speed varies for each type of

gas, as a result of the characteristics of the leak detector pumps and of the difference in the molecular weights of the various gases. The unit of pumping speed is volume per time, e.g., liters/sec. It is important to realize that the pumping speed does not give the number of moles or grams of gas that the pumps of the leak detector will transfer, but rather the volume of gas. Pumping speed provides an estimate of the response time, and, therefore, is useful in planning testing procedures.

The resistance to gas flow in the connecting piping must also be considered in any test setup. The effect of piping on the test appears as reduced pumping speeds and a resulting increase in system response time. Piping conductance is directly analogous to electrical conductance and is expressed in liters/sec. Piping conductance, C_{pipe} , can be calculated or measured and is combined with pumping speed, S_{pump} , to give the effective system pumping speed:

$$S_{\text{eff}} = \frac{C_{\text{pipe}} S_{\text{pump}}}{C_{\text{pipe}} + S_{\text{pump}}} \quad (2)$$

Although the response time can be calculated from Eqs. 1 and 2, it should be determined experimentally for the system. A standard leak is attached to the system and allowed to come to equilibrium. The system must include all components that will be included in the actual test system and must be at the same environmental conditions as the actual test system. The maximum indication observed with the standard leak attached to the system is called the calibration factor. The same standard leak must be used for determining the calibration factor and the response time. The response time is 63% of the time needed for the leak to produce the calibration factor. It can then be assumed that any leak will reach 63% of its maximum indication in this time.

System Sensitivity

The system sensitivity is analogous to the detector sensitivity, but it is determined with the standard leak attached to the test system. If all hardware is clean and no background has been added, the two terms are identical in value. The rate

with which the signal will appear on the leak detector, however, will always be less than when the sensitivity of the leak detector alone was established.

In order to measure the full system sensitivity, it is necessary to extend each measurement over at least $3T_{63}$. For any time, t , the effective system sensitivity, SS_{eff} , is related to the system sensitivity, SS , by

$$SS_{\text{eff}} = \frac{SS}{1 - e^{-t/T_{63}}} \quad (3)$$

System Outgassing Load

The system outgassing load is evaluated by valving the pumps out of the test setup and measuring the rise in pressure during a given time. This rise in pressure provides a measure of the condition of the setup and will also show up gross leaks rapidly, although the leak location is not easily determined in this manner. Outgassing loads should be minimized, since they contribute noise to the leak detector.

Leak Testing

The leak detector vacuum system is connected to the device to be tested for leaks, the device is evacuated, and the external surfaces of the device are flooded with the tracer gas. Helium is generally used for this purpose because of its high diffusion rate, inertness, safety, low concentration in the atmosphere, small atomic radius, and ease of detection. Some other tracer gases in common use are Freon, methane, and argon. The mass spectrometer is adjusted to detect the tracer gas being used.

It is important that the tracer concentration be as close to 100% as possible, so that any leak detected can be related to the system sensitivity. On many occasions, an auxiliary pumping system must be used in parallel with the leak detector pumping system to handle the gases present in the test device due to the system volume and response time, outgassing, or leaks. If it is necessary to operate the auxiliary pumps during leak testing, the system sensitivity and minimum detectable leak must

be determined with these pumps operating. The use of auxiliary pumps during testing always reduces the system sensitivity, since some tracer gas will be bypassed by the auxiliary pumps.

Environmental control may be important in the testing of large, complicated systems, particularly where long response times are encountered. Tracer gases must be applied to allow for gravitational flow effects, drafts, and assessment of average air concentration of the tracer gas. Gas from an area under probe may drift to a leak in another region. The average concentration of the tracer gas in air contributes to the background which must be considered in determining system sensitivities and minimum detectable leaks.

Leakage, if present, is observed on the mass spectrometer. Measurements should be made at the proper times indicated by the previously determined system response time, and noise and background corrections must be applied. The quantities discussed in the preceding sections must be determined for each run; they cannot be assumed to be constant. When a leak is found, sections of the device being tested should be isolated, and the procedure repeated for each section until all leakage is accounted for. All measurements should be reproducible.

EXAMPLE

Two stainless-steel, shell-and-tube, sodium-to-sodium heat exchangers (5 MW, 360 liters; and 15 MW, 600 liters) for the coolant in a reactor system were checked by this method. As far as possible, these tests conformed to military standards³ and American Vacuum Society standards.⁴

Shell Tests

The equipment used in these tests was arranged as shown in Fig. 1. The sequence of test operations was as follows:

The shell was pumped until, with the roughing pumps out of the system, the system outgassing load had decreased to a point where the leak detector could be operated at $<0.2 \mu$ pressure (as determined by the leak detector cold cathode gauge) for the time required to complete a response-time measurement. This pressure was the maximum desirable for

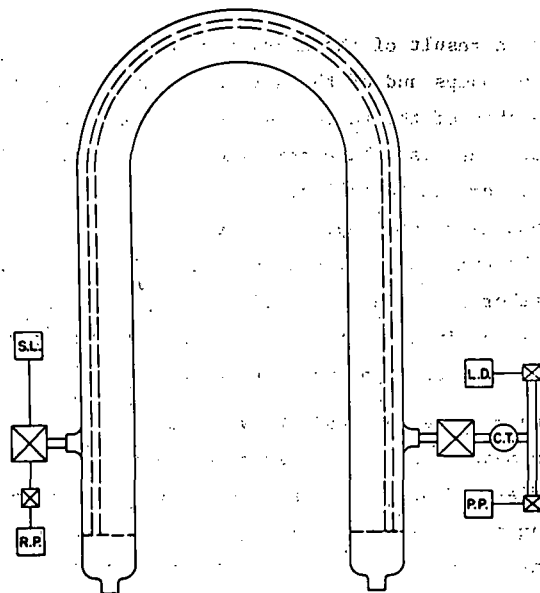


Fig. 1. Equipment for shell tests. S.L. = standard leak (CEC type 141430); R.P. = roughing pump (Welch 1400 and Kinney KC-46); L.D. = leak detector (CEC type 24-120A); P.P. = Phillips gauge (Dresser type DCG-101); C.T. = cold trap (CEC type 24-004A); valves were Veeco brass-block type; the thermocouple gauge was Veeco type TG-6; hoses were metal and gum rubber; and the hood was a plastic sheet.

the tests; the actual leak detector pressure was less than 0.01μ . Pressure rise determinations were made overnight (5:00 p.m.-8:00 a.m.). The system background for both heat exchangers was less than 5 div.

Calibration factors and system response times were then determined. Both quantities can be measured in the same sequence of readings from the mass spectrometer. Tables I and II give typical measurements for the two heat exchangers. After 60 min, the response was stable. Note that the response time is the time required to reach 63% of maximum indication, not 63% of the time, since the response is not linear, as is shown in Figs. 2 and 3. Leakage observed at T_{63} was extrapolated to 100% to give the total leakage. The system response times for the 5-MW and 15-MW heat exchangers were 18 and 24 min, respectively.

A hood was constructed of 0.012-in. sheet plastic, which was weighted with lead bricks and taped to the concrete floor. A vent valve in the hood allowed trapped air to be purged. The hood was filled to a slightly positive pressure with continuous purging, so that the concentration of helium would be as close to 100% as possible.

TABLE I

SHELL RESPONSE TIME FOR 5-MW HEAT EXCHANGER

Time (min)	Response (div)	Time (min)	Response (div)
0		12	1200
1	185	13	1260
2	315	14	1350
3	435	15	1400
4		16	1460
5	660	17	1500
6	750	18	1575
7	840	19	1620
8	930	20	1670
9	1000	30	2000
10	1075	45	2250
11	1150	60	2490

Test Conditions

Leak detector sensitivity: 2.3×10^{-10} std-cc/sec
 Minimum detectable leak: 4.6×10^{-10} " "
 System calibration factor: $2490 \text{ div} = 5.75 \times 10^{-7}$ std-cc/sec

System background: 5 div
 Leak detector background: 1 div
 T_{63} : 18 min

Base runs were then initiated, and the total leakage was measured. The average of the total leakage tests on the shell of the 5-MW heat exchanger was 4.6×10^{-8} std-cc/sec (Table III).

Sections of the shell of the 5-MW heat exchanger were isolated (Fig. 4), and a leak was located on a side cap weld of the shell inlet connection. The average leak in the cap weld was 3.8×10^{-8} std-cc/sec (Table IV), leaving 8×10^{-9} std-cc/sec to be accounted for. Further isolation tests

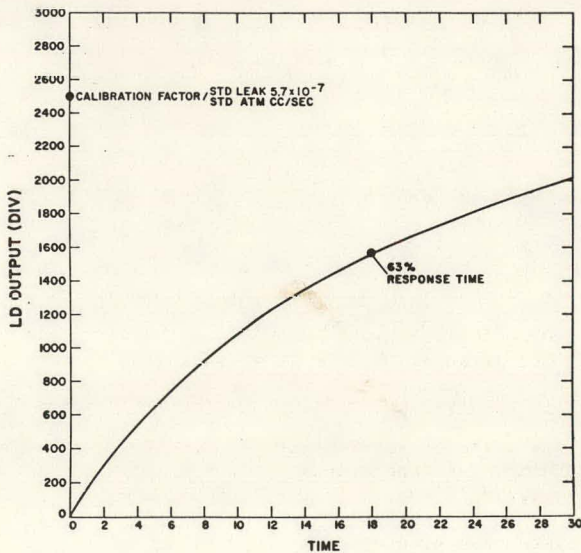


Fig. 2. Shell response time for 5-MW heat exchanger.

TABLE II

SHELL RESPONSE TIME FOR 15-MW HEAT EXCHANGER

Time (min)	Response (div)	Time (min)	Response (div)
0		17	1300
1	115	18	1350
2	220	19	1400
3	325	20	1450
4	420	21	1490
5	510	22	1540
6	600	23	1590
7	690	24	1650
8	775	25	1675
9	830	26	1690
10	910	27	1750
11	990	28	1785
12	1050	29	1830
13	1100	30	1890
14	1150	45	2150
15	1200	60	2620
16	1250		

Test Conditions

Leak detector sensitivity: 2.4×10^{-10} std-cc/sec
 Minimum detectable leak: 4.8×10^{-10} " "
 System calibration factor: $2620 \text{ div} = 6.3 \times 10^{-7}$ std-cc/sec

System background: 5 div
 Leak detector background: 0 div
 T_{63} : 23 min

indicated no additional leaks, and it was concluded that the residual leak was probably not under the hood.

All external plumbing and instrumentation was leak checked periodically throughout the test procedure. Also, the leak detector was back diffusion checked; that is, the outlet of the mechanical pump

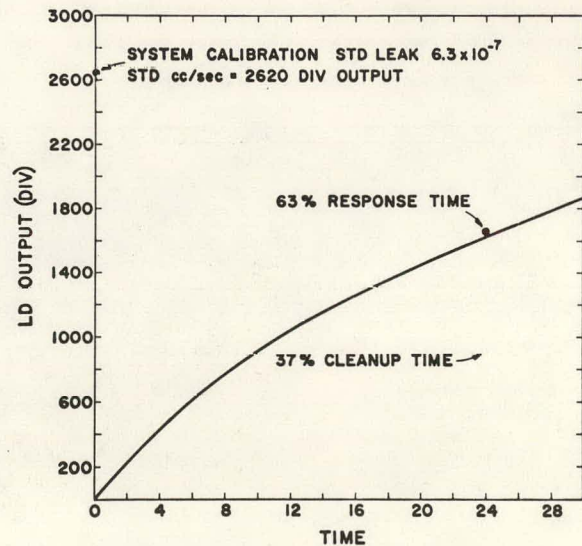


Fig. 3. Shell response time for 15-MW heat exchanger.

TABLE III

TOTAL SHELL TEST OF 5-MW HEAT EXCHANGER

Time (min)	Output (div)		
	Run 1	Run 2	Run 3
1	3	3	3
5	45	30	35
10	60	75	80
15	90	91	95
18	123	134	133

Net output (10^{-8} std-cc/sec)
2.7 3.01 2.99

Average: 2.92×10^{-8} std-cc/sec

Total leakage: 4.6×10^{-8} std-cc/sec

Test Conditions

Leak detector sensitivity: 2.3×10^{-10} std-cc/sec
Minimum detectable leak: 4.6×10^{-10} " "
System calibration factor: 2500 div = 5.75×10^{-7}
std-cc/sec

System background: 3 div

Leak detector background: 0 div

T_{63} : 18 min

was exposed to an atmosphere of pure helium. This procedure gave an average "leak rate" of 2.15×10^{-8} std-cc/sec (Table V).

Although the "leak rate" was larger than that unaccounted for, it was obtained by exposing the leak detector and pumps to nearly 100% helium. The 8×10^{-9} std-cc/sec value was obtained while the leak detector was exposed to the room atmosphere at a position close enough to the test hood so that a 10 to 30% helium concentration would be reasonable. With these considerations, this accounted for the difference in leak rates.

Three runs were then made with the leaking cap weld and the leak detector exhaust isolated. On these three runs, no leaks were detected in the



Fig. 4. 5-MW heat exchanger with sections isolated by polyethylene sheeting.

TABLE IV

CAP WELD TEST OF 5-MW HEAT EXCHANGER

Time (min)	Output (div)		
	Run 1	Run 2	Run 3
1	3	3	3
5	30	28	25
10	85	90	75
15	98	100	90
18	112.5	112	100

Net output (10^{-8} std-cc/sec)
2.51 2.50 2.23

Average: 2.41×10^{-8} std-cc/sec

Total leakage: 3.8×10^{-8} std-cc/sec

Test Conditions

Leak detector sensitivity: 2.3×10^{-10} std-cc/sec
Minimum detectable leak: 4.6×10^{-10} " "
System calibration factor: 2500 div = 5.75×10^{-7}
std-cc/sec

System background: 3 div

Leak detector background: 0 div

T_{63} : 18 min

5-MW heat exchanger shell proper. The shell was sealed off at less than 0.01μ pressure preparatory to back filling for the tube test.

The average of the total leakage tests on the shell of the 15-MW heat exchanger was 3.7×10^{-8} std-cc/sec (Table VI).

Sections of the shell were isolated, and a leak was located in the girth weld of the return bend of the shell inlet leg. The average of the leakage measurements for the girth weld was 5.9×10^{-8}

TABLE V

LEAK DETECTOR VACUUM SYSTEM TEST

Time (min)	Output (div)		
	Run 1	Run 2	Run 3
1	0	0	0
5	30	28	31
10	48	50	45
15	60	52	54
20	67	55	55

Net output (10^{-8} std-cc/sec)
1.54 1.26 1.26

Average: 1.35×10^{-8} std-cc/sec

Total leakage: 2.15×10^{-8} std-cc/sec

Test Conditions

Leak detector sensitivity: 2.3×10^{-10} std-cc/sec
Minimum detectable leak: 4.6×10^{-10} " "
System calibration factor: 2500 div = 5.75×10^{-7}
std-cc/sec

System background: 3 div

Leak detector background: 0 div

TABLE VI
INTEGRATED SHELL BACKGROUND RUN
15-MW HEAT EXCHANGER

Time (min)	Output (div)	
	Run 1	Run 2
1	0	0
5	1.5	1
10	3.5	3.0
15	4.0	4.5
20	4.5	4.75
25	5	5
30	5	5
45	5	5
60	5	5
120	5	5

Test Conditions

Leak detector sensitivity: 2.4×10^{-10} std-cc/sec
 Minimum detectable leak: 4.8×10^{-10} " "
 System calibration factor: $2620 \text{ div} = 6.3 \times 10^{-7}$ std-cc/sec
 Leak detector background: 0 div

std-cc/sec (Table VII), which accounted for the total leakage determined. The location of the leak in the girth weld was isolated to an area of 8 sq in. of the weld.

TABLE VII
INTEGRATED SHELL TEST OF 15-MW HEAT EXCHANGER

Time (min)	Output (div)		
	Run 1	Run 2	Run 3
1	5	5	5
5	5	5	5
10	5	6	7.5
15	15	18	20
20	35.5	31	40
25	63	66	65
30	84	85	87
35	104	102	107
40	138	132	144
45	158	150	167
50	158	150	173
55	158	151	174
60	158	150	173
70	158	152	173
75	157	150	174
80	158	150	173

Net output (10^{-8} std-cc/sec)
 3.68 3.49 4.04

Average: 3.73×10^{-8} std-cc/sec
 Total leakage: 5.9×10^{-8} std-cc/sec

Test Conditions

Leak detector sensitivity: 2.4×10^{-10} std-cc/sec
 Minimum detectable leak: 4.8×10^{-10} " "
 System calibration factor: $2620 \text{ div} = 6.3 \times 10^{-7}$ std-cc/sec
 System background: 5 div
 Leak detector background: 0 div
 T₆₃: 24 min

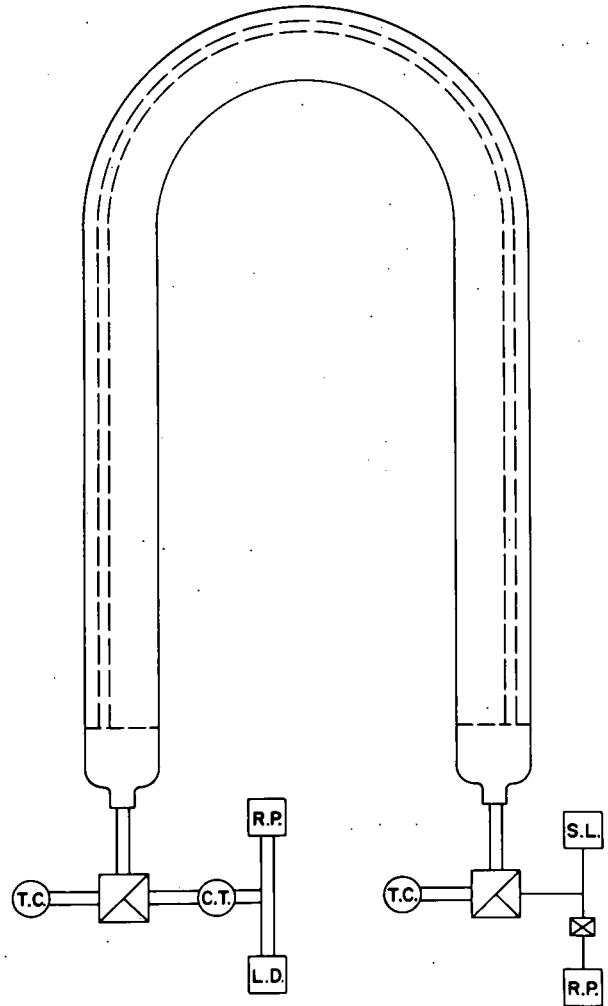


Fig. 5. Equipment for tube test; symbols are the same as in Fig. 1.

Tube Tests

The equipment setup for leak testing the tubes within the heat exchangers is shown in Fig. 5.

The heat exchanger tubes were pumped until the leak detector could be operated, with the roughing pump out of the system, at $\leq 0.2 \mu$ pressure (as determined by the leak detector cold cathode gauge) for a time constant measurement. Pressure rise determinations were made overnight (5:00 p.m.-8:00 a.m.). System backgrounds for these tests were less than 5 div, and the leak detector pressure was less than 0.01μ .

The experimental value for the 5-MW heat exchanger tube system response time is 10 min (Table VIII, Fig. 6). The 5-MW heat exchanger shell was back-filled with helium from a pressure of 25μ to a

TABLE VIII

TUBE RESPONSE TIME FOR 5-MW HEAT EXCHANGER

Time (min)	Response (div)	Time (min)	Response (div)
0		8	1650
1	350	9	1800
2	600	10	1890
3	820	11	2100
4	1050	30	2800
5	1250	45	2900
6	1400	60	3006
7	1550		

Test Conditions

Leak detector sensitivity: 1.9×10^{-10} std-cc/sec
 Minimum detectable leak: 3.8×10^{-10} " "
 System calibration factor: 3000 div = 5.75×10^{-7} std-cc/sec

System background: 5 div
 Leak detector background: 0 div
 T_{63} : 10 min

pressure of 1 atm. Gas was pumped from the tubes and sampled. All three runs indicated leakage of less than the minimum detectable leak of the leak detector (3.8×10^{-10} std-cc/sec).

Leak tests of the 15-MW heat exchanger tubes were conducted similarly, and leakage was found to be less than the minimum detectable leak.

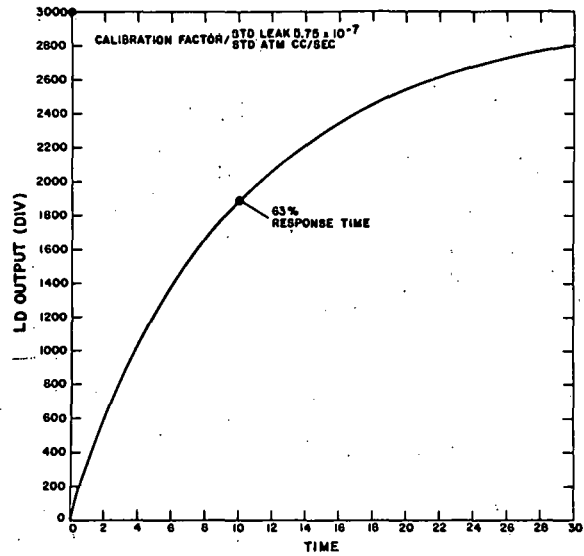


Fig. 6. Tube response time for 5-MW heat exchanger.

REFERENCES

1. M. K. Laufer; "Leak Detectors and Their Calibration," SC-DC-64-349, Sandia Corporation (1964).
2. D. J. Santeler, D. H. Holkeboer, D. W. Jones, F. Pagano, "Vacuum Technology and Space Simulation," NASA SP-15, National Aeronautics and Space Administration (1966), p. 286.
3. "Military Standard Nondestructive Testing Requirements for Metals," MIL-STD-271A (SHIPS), Department of the Navy (1959).
4. C. H. Bachman, Chairman of the Standard Committee of the American Vacuum Society, private communication (1963).