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SUMMARY

The expressions for leakage used in the absolute- and reference-system methods are derived, discussed, and compared. It is concluded that no direct temperature measurements are required in the reference method. An error analysis is also performed that indicates the reference method to be the more accurate.

In the most recent leak-rate tests of the Plum Brook Reactor Facility an unusual method of measuring the vessel average air temperature was used. A 550-foot length of nickel wire was distributed about the vessel interior and employed as a resistance thermometer. Additional sets of temperature measurements were obtained by means of thermocouples, a platinum resistance thermometer, and a closed system of pressurized copper tubing that functions as a gas thermometer (reference system). Results were calculated from all sets of temperature measurements and compared.

The principal findings of this investigation are as follows:

(1) The reference-method results had significantly less scatter than the absolute-method results. This substantiated the conclusion of an analytical comparison of the error in the two methods.

(2) The accuracy of the leak-rate results obtained by the reference method substantiated the analytical conclusion that direct temperature measurements are not necessary when the reference method is employed.

(3) Measuring the vessel average air temperature by employing a length of nickel wire as a resistance thermometer is both feasible and accurate, as indicated by the accuracy of the leak-rate results obtained.

(4) The greatly increased temperature sampling afforded by a 550-foot length of nickel wire did not appreciably reduce the scatter of absolute-method results.

INTRODUCTION

In testing reactor containment vessels for leakage, the two most commonly employed methods are the absolute-temperature - pressure method and the reference-system method. In the absolute method, the leakage from the pressurized vessel is calculated from direct measurements of the vessel absolute pressure and average absolute air temperature. In the reference method, leakage is indicated by the pressure differential in a manometer, one leg of which is connected to a leak-tight pressurized system of tubing placed about the vessel interior, while the other leg is opened to the pressurized, but leaking, containment vessel.

In either of the foregoing cases the allowable vessel leakage is normally so small that testing time must be of the order of days before the leak rate may be established with sufficient certainty. The choice of a testing method is governed by factors of accuracy, reliability, complexity, and perhaps other factors dependent on conditions within the vessel being tested. It appears that one method has not yet been established as being superior to another because (1) the foregoing factors have not been evaluated with sufficient clarity, (2) the advantages and disadvantages of both methods are mixed, and (3) the relative merits of each method may be dependent on the test conditions existing at a particular reactor site.

In the first attempt to compare the two methods experimentally (described in ref. 1) the reference system could not be made sufficiently leak tight; hence, no results were available to compare with the absolute-method results. This occurrence emphasizes the greatest shortcoming of the reference method, the possibility that it may leak, particularly during a test. It was also judged that the reference method was inherently less accurate since a theoretical analysis indicated that four direct temperature measurements are required

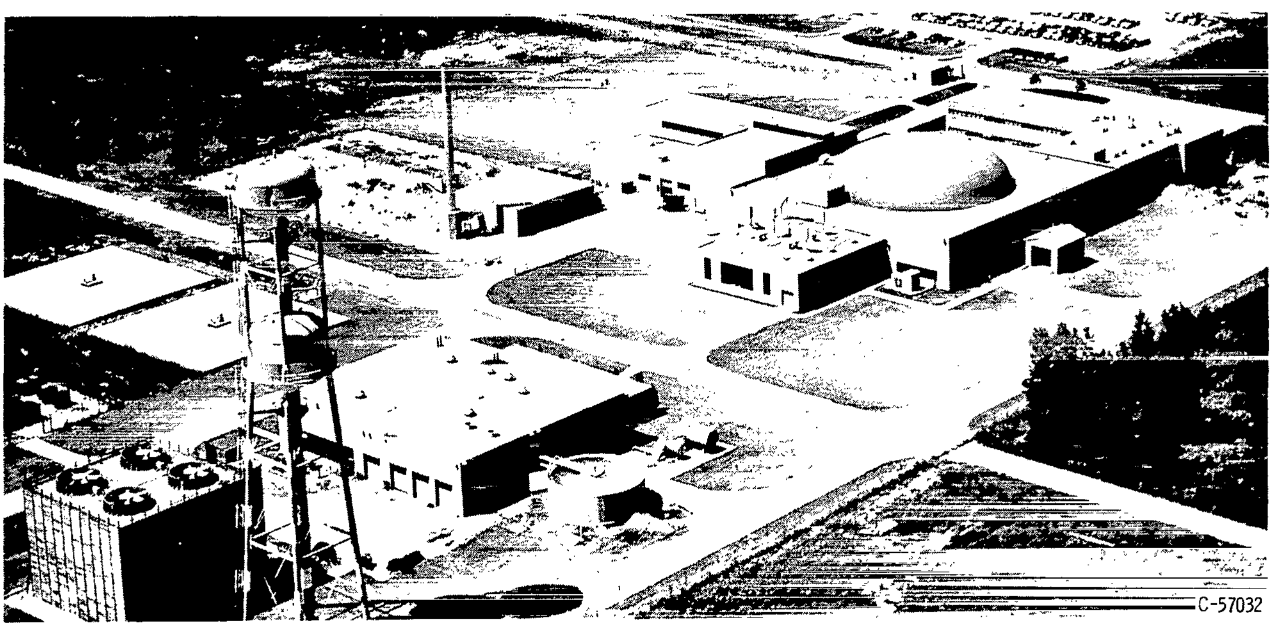

Figure 1. - NASA Plum Brook Reactor.

as compared with only two in the absolute method. In addition, the reference system was judged to be more complex, apparently because of the necessity of making measurements of air temperature within the reference system.

In later tests at the Plum Brook Reactor Facility (PBRF, fig. 1) the two methods were compared experimentally and also investigated analytically (refs. 2 and 3). In three separate tests the reference-method results were observed to have significantly less scatter than the absolute-method results. While the reference method has the advantage of providing line sampling (contrasted to the point sampling of thermocouples) of the atmosphere, it was also found to involve considerable pretest time to ensure its leak tightness. It was determined analytically that with a sufficiently small-diameter reference system thermal time-lag effects are insignificant. Partly because of this condition, it was concluded that it is not necessary to make direct temperature measurements of the vessel atmosphere and the air within the reference system. This is at variance, however, with the final expression for leakage derived in reference 4, which indicates that, even though the containment-vessel and reference-system air temperatures may be assumed equal, it is still necessary to make direct temperature measurements of the vessel atmosphere. If the latter conditions must be fulfilled, it would be pointless to employ a reference system; if direct temperature measurements are made, one is already employing the absolute method. Hence, one of the purposes of this paper is to establish whether or not any direct temperature measurements are required in the reference method. In addition, the comparative accuracy of the two methods will be investigated analytically and compared with the experimental results.

A second purpose of this paper is to present results of recent leak-rate tests of the PBRF containment vessel in which, as in references 2 and 3, the absolute and reference methods were employed simultaneously. In this latest test an effort was made to combine the best features of the two methods (line sampling, reliability, accuracy, and simplicity) by distributing a 550-foot length of nickel wire throughout the vessel interior and employing it as a resistance thermometer. This method of temperature measurement was employed in tests of the BR-2 reactor in Belgium (ref. 5) in which the resistance changes of a copper wire were measured. As noted in reference 1, a possible objection to this method is that calibration of the wire as a resistance thermometer would be nullified by the unavoidable resistance changes (resulting from kinks and bends) that occur in installing the wire. In a leak-rate test, however, temperature changes are of prime significance rather than temperature level. Such errors, which are fixed, or systematic errors, are of little importance; hence, this method was also employed in these tests. The results of these tests will be presented and discussed.

SYMBOLS

L result

P pressure

ΔP difference in pressure between containment vessel and reference system

ΔP_h difference in containment-vessel water-vapor pressure between first measurement and any later measurement, $P_{h,2} - P_{h,1}$

R gas constant

$\mathcal{R}$ resistance

T temperature

V volume

W weight of air

α temperature coefficient of resistivity

τ time

φ variable

ω uncertainty interval

Subscripts:

ABS absolute method

h water vapor

ind indicated or measured value

L result

n number of independent variables

P pressure

ΔP difference in pressure between containment vessel and reference system

ΔP_h difference in containment-vessel water-vapor pressure between first measurement and any later measurement, $P_{h,2} - P_{h,1}$

REF reference system

r reference-system properties

s indications of any system of temperature sensors

T temperature

v containment-vessel properties

0 time at which pressurization is completed and reference system is isolated from containment vessel

1 time of first measurements

2 time of any later measurements

ANALYSIS

Expressions for Leakage

In the absolute method, where a perfect gas is assumed and the equation of state is employed, the weight of air within the pressurized vessel at the initiation of the test is

$$W_{v,1} = \frac{P_{v,1}V_{v,1}}{RT_{v,1}} \tag{1}$$

At any later time, the weight of air is

$$W_{v,2} = \frac{P_{v,2}V_{v,2}}{RT_{v,2}} \tag{2}$$

If a constant vessel volume is assumed, the fractional loss of contained air from equations (1) and (2) is

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{T_{v,1}}{T_{v,2}} \tag{3}$$

In an actual test a system of temperature sensors is required to measure $T_{v,1}$ and $T_{v,2}$. Generally the measured average temperature will not be identical to the true average temperature because of instrument inaccuracies, personal error, and inadequate sampling. Hence, when a distinction between the indicated and actual average temperature is made, the indicated leakage is

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{T_{s,1}}{T_{s,2}} \tag{4}$$

The actual fractional weight loss may be obtained from equation (4) by multiplying both $T_{s,1}$ and $T_{s,2}$ by appropriate temperature ratios as follows:

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{T_{s,1}}{T_{s,2}} \frac{T_{v,1}}{T_{s,1}} \frac{T_{s,2}}{T_{v,2}} \tag{5}$$

Equation (5) is seen to be identical to equation (3). In an actual test T_v is not known but is estimated by T_s, and hence equation (5), the exact expression for leakage, is not usable. To put equation (5) in a usable form, two temperature ratios must be neglected; the result is equation (4), which is the indicated expression for leakage. The foregoing distinction between indicated and actual quantities is made primarily for a later discussion and comparison of the absolute and reference methods.

In the reference method, the vessel and the reference system are considered to have been brought to the testing pressure. The reference system is then closed at time τ_0, and the required periodic measurements are begun. Since a period of time has elapsed between closing the reference system and taking the first set of readings, the difference in the pressures of the reference system and the containment vessel is

$$P_{r,1} - P_{v,1} = \frac{W_{r,1}R_{r,1}T_{r,1}}{V_{r,1}} - \frac{W_{v,1}R_{v,1}T_{v,1}}{V_{v,1}} = \Delta P_1 \tag{6}$$

At any later time,

$$P_{r,2} - P_{v,2} = \frac{W_{r,2}R_{r,2}T_{r,2}}{V_{r,2}} - \frac{W_{v,2}R_{v,2}T_{v,2}}{V_{v,2}} = \Delta P_2 \tag{7}$$

It is assumed that

(1) The gas constant R remains the same throughout the test and is the same in both the reference system and the containment vessel.

(2) The density of air within the reference system is constant.

(3) The reference-system and containment-vessel volumes are constant.

Then solving for the weight of air in the vessel at both times results in

$$W_{v,1} = \frac{V_v}{T_{v,1}}\left(\frac{W_r}{V_r} T_{r,1} - \frac{\Delta P_1}{R}\right) \tag{8}$$

$$W_{v,2} = \frac{V_v}{T_{v,2}}\left(\frac{W_r}{V_r} T_{r,2} - \frac{\Delta P_2}{R}\right) \tag{9}$$

From equations (8) and (9) it can be determined that

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{W_r V_v}{V_r W_{v,1}}\left(\frac{T_{r,1}}{T_{v,1}} - \frac{T_{r,2}}{T_{v,2}}\right) + \frac{V_v}{RW_{v,1}}\left(\frac{\Delta P_2}{T_{v,2}} - \frac{\Delta P_1}{T_{v,1}}\right) \tag{10}$$

Using the equation of state to modify equation (10) produces the final expression for the percent loss as given in reference 2:

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{P_{r,1}}{P_{v,1}}\left(1 - \frac{T_{v,1}}{T_{r,1}}\frac{T_{r,2}}{T_{v,2}}\right) + \frac{1}{P_{v,1}}\left(\frac{T_{v,1}}{T_{v,2}}\Delta P_2 - \Delta P_1\right) \tag{11}$$

If it is assumed that the reference-system air temperature is equal to the vessel air temperature at all times, that is, $T_{r,1} = T_{v,1}$ and $T_{r,2} = T_{v,2}$, equation (11) becomes

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{1}{P_{v,1}}\left(\frac{T_{v,1}}{T_{v,2}} \Delta P_2 - \Delta P_1\right) \tag{12}$$

(This equation is contained in the proposed American Nuclear Society standard for containment-vessel leakage-rate testing that uses the reference-system method.) Equation (12) indicates that direct temperature measurements of the vessel air temperature must be made throughout the test. If this is true, however, it would be pointless to use the reference method since direct temperature measurements permit calculation of the leakage by the absolute method. (The reference method was originally proposed (ref. 6) as offering the advantage of eliminating direct temperature measurements.) Without making any additional assumptions, however, equation (11) may be rearranged into a physically more meaningful form that indicates there is no necessity for making direct temperature measurements.

Letting the first set of terms on the right side of equation (11) equal A and factoring $T_{v,1}$ from the second set of brackets yield

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = A + \frac{T_{v,1}}{P_{v,1}}\left(\frac{\Delta P_2}{T_{v,2}} - \frac{\Delta P_1}{T_{v,1}}\right) \tag{13}$$

Using the perfect gas law to replace $T_{v,1}/P_{v,1}$ and multiplying both sides by $W_{v,1}$ yield

$$W_{v,1} - W_{v,2} = W_{v,1} A + \Delta P_2 \frac{V}{RT_{v,2}} - \Delta P_1 \frac{V}{RT_{v,1}}$$

$$W_{v,1} - W_{v,2} = W_{v,1} A + \Delta P_2 \frac{W_{v,2}}{P_{v,2}} - \Delta P_1 \frac{W_{v,1}}{P_{v,1}} \tag{14}$$

from which

$$W_{v,1}\left(1 - A + \frac{\Delta P_1}{P_{v,1}}\right) = W_{v,2}\left(1 + \frac{\Delta P_2}{P_{v,2}}\right)$$

and

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{P_{v,1} + \Delta P_1 - P_{v,1} A}{P_{v,2} + P_2}$$

Substituting for A yields

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{P_{v,1} + \Delta P_1 - P_{r,1} + P_{r,1} \frac{T_{v,1}}{T_{r,1}} \frac{T_{r,2}}{T_{v,2}}}{P_{v,2} + \Delta P_2}$$

but by definition, $\Delta P_1 = P_{r,1} - P_{v,1}$, and so

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{P_{r,1} \frac{T_{v,1}}{T_{r,1}} \frac{T_{r,2}}{T_{v,2}}}{P_{v,2} + \Delta P_2}$$

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{P_{v,1} + \Delta P_1}{P_{v,2} + \Delta P_2} \frac{T_{v,1}}{T_{r,1}} \frac{T_{r,2}}{T_{v,2}} \tag{15}$$

From this equation it would still seem that temperature measurements must be made; however, as in equation (5) a distinction between the indicated and actual temperatures (implicit in eqs. (6) and (7)) has also been made here. Furthermore, from the perfect gas law it may be shown that

$$\frac{P_{v,1} + \Delta P_1}{P_{v,2} + \Delta P_2} = \frac{T_{r,1}}{T_{r,2}}$$

If this is substituted into equation (15) and compared with equation (5), the two equations are seen to be equivalent; the only difference is that equation (5) applies to any system of temperature sensors, whereas equation (15) applies to a particular type of temperature sensor, a reference system, which may be thought of as a gas thermometer. If the thermal time-lag effects in the reference system are negligible, the necessity for measuring the air temperature within the reference system is comparable to measuring the mercury temperature in a mercury thermometer. It has been shown in reference 2 that for a small-diameter copper reference system (~2 in.) thermal time-lag errors may be assumed negligible for temperature transients characteristic of tests of this type.

In practice it is not possible to use equation (15) because the true average vessel temperature T_v is not determinable because of sampling limitations alone. Hence, the two temperature ratios must be neglected, and the indicated values of temperature $P_v + \Delta P$ are used to determine an indicated value of the fractional weight loss according to the expression

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{P_{v,1} + \Delta P_1}{P_{v,2} + \Delta P_2} \tag{16}$$

Lest neglecting these temperature ratios be viewed as a fundamental shortcoming of the reference method, it should be noted that two temperature ratios must likewise be neglected in the absolute method (see eqs. (4) and (5)); in both instances these ratios result from distinguishing between the indicated and actual temperatures.

It should be pointed out that, if there is a fundamental inaccuracy in equation (16) arising from the omission of any direct temperature measurements, this inaccuracy should be evident in a test where (1) the results so obtained are compared with those obtained by the absolute method (which is commonly regarded as a reliable method owing to the conventional measuring techniques it employs), and (2) a known leak rate is employed to establish the accuracy of the absolute-method results. Both of these conditions have been fulfilled in two of the PBRF tests. The results of these tests are presented and discussed later.

Error Analysis

The final expressions for leakage, with corrections for changes in water-vapor pressure in the vessel atmosphere (see ref. 2), for the absolute and reference methods are, respectively,

$$\frac{W_1 - W_2}{W_1} = 1 - \frac{P_2 - \Delta P_h}{P_1} \frac{T_1}{T_2} \tag{17}$$

and

$$\frac{W_1 - W_2}{W_1} = 1 - \frac{P_2 - \Delta P_h}{P_1} \frac{P_1 + \Delta P_1}{P_2 + \Delta P_2} \tag{18}$$

where the subscript v has been dropped since all quantities refer to the containment vessel. In a leak-rate test the trend of data with time is of prime significance; hence, random errors rather than fixed errors are of primary concern. An error in the quantities measured at the beginning of the test (T_1, P_1, and ΔP_1) is a fixed error and therefore does not influence the scatter of results appearing throughout the test.

In order to estimate the error propagated into the final result $(W_1 - W_2)/W_1$ because of errors in measuring the pressure, temperature, and water-vapor-pressure variables, the second-power equation is used, which is

$$\omega_L = \left[\left(\frac{\partial L}{\partial \varphi_1} \omega_1\right)^2 + \left(\frac{\partial L}{\partial \varphi_2} \omega_2\right)^2 + \ . \ . \ . + \left(\frac{\partial L}{\partial \varphi_n} \omega_n\right)^2\right]^{1/2} \tag{19}$$

where ω_L is the uncertainty interval of the result, L is the result and is a linear function of n independent variables, each of which is normally distributed, and $\omega_1, \omega_2, . . ., \omega_n$ are the uncertainty intervals for the variables $\varphi_1, \varphi_2, . . ., \varphi_n$ (ref. 7).

Before employing equation (19), equations (17) and (18) are solved for $[(W_{v,1} - W_{v,2})/W_{v,1}] - 1$. Treating P_1, T_1, and ΔP_1 as constants, equation (19) is then applied to these rearranged forms of equations (17) and (18). The resulting expressions are nondimensionalized by dividing by the respective expressions for $[W_{v,1} - W_{v,2})/W_{v,1}] - 1$. The error in each method is then given by the following equations:

$$\left(\frac{\omega_L}{L}\right)_{ABS} = \left[\left(\frac{\omega_{T_2}}{T_2}\right)^2 + \left(\frac{\omega_{\Delta P_h}}{P_2 - \Delta P_h}\right)^2 + \left(\frac{\omega_{P_2}}{P_2 - \Delta P_h}\right)^2\right]^{1/2} \tag{20}$$

$$\left(\frac{\omega_L}{L}\right)_{REF} = \left[\left(\frac{\omega_{\Delta P_2}}{P_2 + \Delta P_2}\right)^2 + \left(\frac{\omega_{\Delta P_h}}{P_2 - \Delta P_h}\right)^2 + \left(\frac{\Delta P_h + \Delta P_2}{(P_2 - \Delta P_h)(P_2 + \Delta P_2)}\,\omega_{P_2}\right)^2\right]^{1/2} \tag{21}$$

where

$$L = \frac{W_1 - W_2}{W_1} - 1$$

Since only the relative magnitude of error is desired, it is assumed for simplicity that $T_1 = T_2$ and $P_1 = P_2$. Also, in an actual test $\Delta P_h \ll P \gg \Delta P$. In addition, in equation (21) the error due to P_2 is seen to be negligibly small in comparison with all other error terms in both equations (21) and (20). Equations (20) and (21) then become

$$\left(\frac{\omega_L}{L}\right)_{ABS} \approx \frac{1}{P}\left[\left(\frac{P}{T}\,\omega_T\right)^2 + \left(\omega_{\Delta P_h}\right)^2 + \left(\omega_P\right)^2\right]^{1/2} \tag{22}$$

$$\left(\frac{\omega_L}{L}\right)_{REF} \approx \frac{1}{P}\left[(\omega_{\Delta P})^2 + (\omega_{\Delta P_h})^2\right]^{1/2} \tag{23}$$

It is seen by comparing the error in the two methods that both are subject to the same error of water-vapor-pressure measurements. Equation (21) indicates, however, that a negligibly small error is introduced in the reference method by inaccuracies in absolute-pressure measurements. Contrasting to this, in the absolute method, absolute-pressure inaccuracies are propagated into the result.

In the reference method, temperature-measurement inaccuracies are reflected in the error in the pressure differential ΔP. Hence, in estimating the error in ΔP it is not only necessary to take into account the precision and accuracy of the inclined manometer, but also the ability of the reference system to sense the vessel average air temperature, and the systems freedom from thermal time-lag errors.

In comparing the total error in each method, even if it is assumed that a system of thermocouples measures the average temperature with the same accuracy as a reference system, the absolute method is seen to be less accurate since it contains an additional error arising from the absolute-pressure measurement. Hence, in a test where both methods are employed simultaneously and essentially the same volume is sampled by the temperature sensors, the scatter of data should be greater for the absolute method.

The foregoing contradicts the conclusions reached in references 1 and 4 where the reference method is judged less accurate because (1) two temperature ratios must be neglected, and (2) even if measurements are made to evaluate these temperature ratios, the reference method has additional temperature errors arising from two temperature measurements that do not appear in the absolute method. With regard to (1), it is concluded in the previous section that these temperature ratios may be neglected without affecting the validity of results. By neglecting these ratios it was found in the Error Analysis of this section that the reference method should yield results having less scatter of data than that obtainable by the absolute method. Hence, the experimental results presented in the following section should be of value in resolving this conflict.

APPARATUS

The apparatus employed in these tests is essentially the same as that described in reference 2. The only additional piece of apparatus employed in these tests was a 550-foot length of 0.025-inch-diameter commercially pure bare nickel wire placed about the interior of the vessel as shown in figure 2.

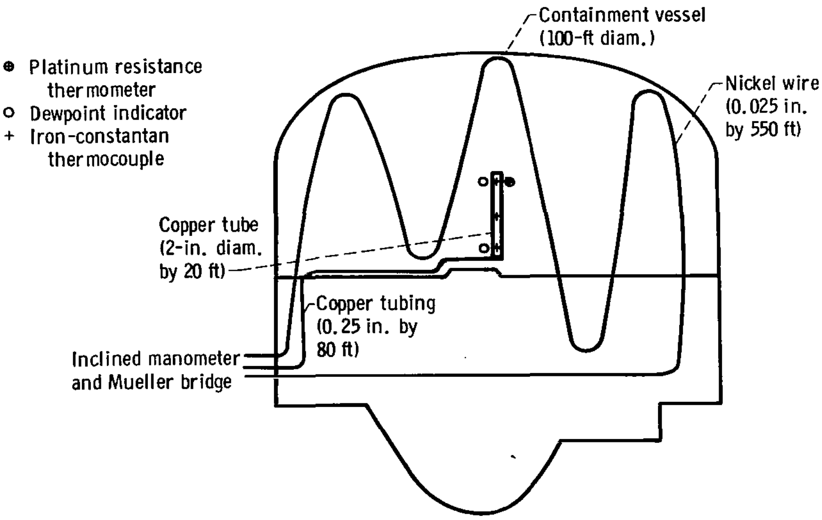

Figure 2. - Location of instruments.

Resistance changes were related to temperature changes by the temperature coefficient of resistivity α that was obtained by measuring the change in resistance of a 10-foot section of wire from the same spool over the range from 67° to 84° F. From these data α was calculated to be 2.60×10^{-3} ohm per °F ohm. It was not necessary to calibrate the entire 550-foot length as a resistance thermometer since in these tests temperature changes are of prime significance rather than temperature level. Since the entire length was not calibrated, the initial temperature of the wire was taken to be the same as that indicated by the platinum resistance thermometer (71.823° F). Actually, since changes are of primary significance, the initial temperature could have been any convenient value close to room temperature. For the present test the nickel-wire temperature was calculated using the expression

$$T_2 = \frac{\mathcal{R}_2 - \mathcal{R}_1}{\alpha \mathcal{R}_1} + 531.823 \tag{24}$$

The reference system employed consisted of a 20-foot length of 2-inch-diameter copper tubing located vertically at the vessel centerline, which was connected by means of an 80-foot length of 1/4-inch copper tubing to an inclined manometer located immediately outside the containment vessel (fig. 2).

The remainder of the apparatus employed is as follows:

(1) One calibrated precision platinum resistance thermometer located at the vessel centerline

(2) Three iron-constantan thermocouples soldered to the outer surface of the reference system

(3) One inclined water manometer for measuring the pressure differential between the containment vessel and the 2-inch-diameter reference systems (least division, 0.01 in.); the inclined manometer was filled with a fluid that had a saturated vapor pressure of 0.00005 inch of water at 77° F to eliminate the necessity of making vapor-pressure corrections in the reference system

(4) One 10-foot water manometer for measuring the pressure differential between the containment vessel and the atmosphere (least division, 0.1 in.)

(5) One standard precision mercury barometer (least division, 0.01 in.)

(6) One gas flowmeter for metering a controlled leak (range, 0 to 165 cu ft/hr; least division, 0.1 cu ft)

(7) Two dewpoint indicators for measuring the partial pressure of water vapor in the vessel atmosphere (least count, ~0.1° F dewpoint temperature)

(8) One potentiometer for dewpoint and thermocouple measurements (least division, 0.001 mv)

(9) One Mueller bridge for measurements with platinum- and nickel-wire-resistance-thermometers (least division, 0.0001 ohm)

PROCEDURE

All PBRF leak-rate tests are accelerated; that is, the vessel overpressure is 4 pounds per square inch gage rather than the 0.3-pound-per-square-inch-gage pressure calculated for the maximum credible accident. For a complete description of the test procedure, the reader is referred to reference 2. It is sufficient to say here that hourly measurements were begun after the vessel had been pressurized and equilibrium conditions were judged to exist. These measurements continued for a period of 68 hours. The quantities measured were the vessel absolute pressure and air temperature, vessel water-vapor pressure, and pressure differential between the reference system and containment vessel atmosphere. During the last 25 hours of the test, air was bled from the vessel through a gas flowmeter at a rate roughly equal to the allowable. This served to establish the accuracy of the measuring systems by comparing the change in trend of the data with the magnitude of the metered leak introduced.

RESULTS AND DISCUSSION

The leak-rate results for this test were obtained by both the absolute and the reference methods. In the absolute method the fractional weight loss was calculated by using equation (17). Three sets of values were obtained by using

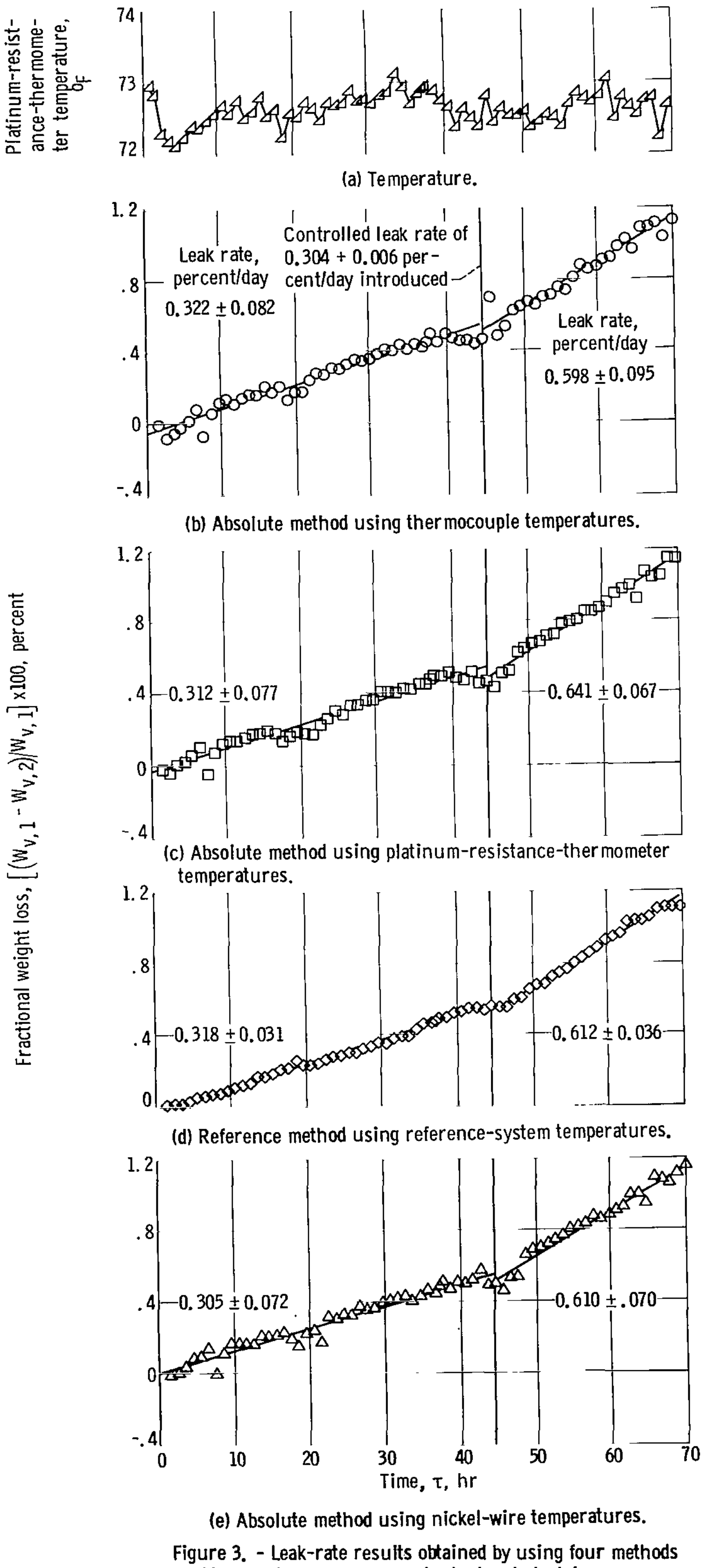

Figure 3. - Leak-rate results obtained by using four methods of temperature measurement. Leak-rate test 4.

the temperatures indicated by the thermocouples, the platinum resistance thermometer, and the nickel-wire thermometer. In the reference method the fractional weight loss was calculated from equation (18), which contains no terms for direct temperature measurements. The same absolute-pressure and vapor-pressure measurements were used for all of the foregoing cases; hence, the only difference among the sets of leakage results lies in the different sources of the temperature-measurement values.

For each set of results the leak rate was obtained by fitting a straight line to the data points by the method of least squares. The limits of error are taken as twice the standard deviation about the least squares fit.

The leak-rate results are shown in figure 3. It is readily seen that the reference-method results have less scatter than the absolute-method results. This is consistent with the results of all past PBRF tests (see figs. 4 to 6). Hence these test results substantiate the conclusion arrived at analytically in the section Error Analysis, wherein the reference method is predicted to be of greater accuracy.

It is seen that the results obtained from all four sets of temperature measurement (fig. 3) are in substantial agreement for both portions of the test period. The controlled leak rate introduced was 0.304±0.006 percent per day; hence, the accuracy of each of the sets of indications is evident. By examining the results of past PBRF tests (figs. 4 to 6), it is seen that corresponding sets of results from each

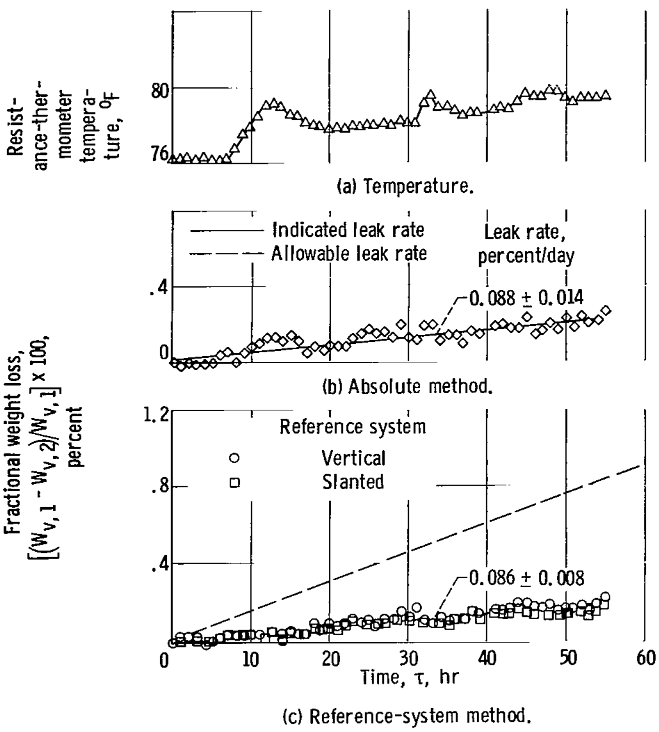

Figure 4. - Leak-rate results obtained by using two methods of temperature measurement. Leak-rate test 1.

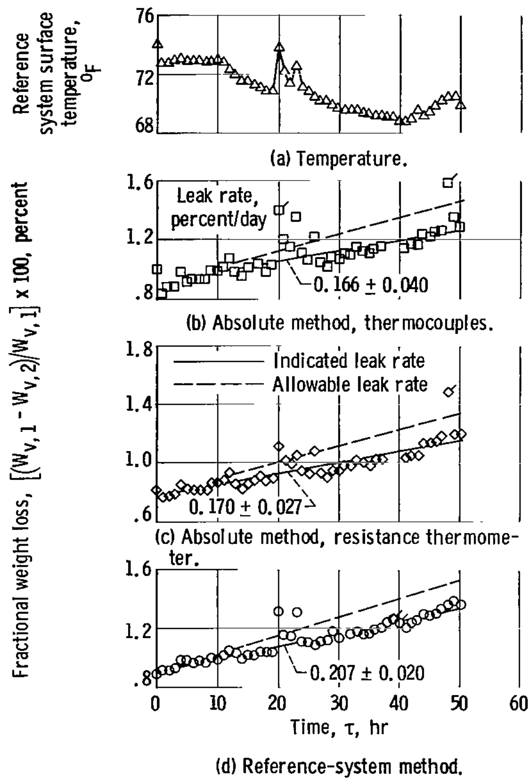

Figure 5. - Leak-rate results obtained by using three methods of temperature measurements. Leak-rate test 2.

method are in reasonably good agreement. In figure 6, where a known leak rate was introduced (0.226±0.004 percent/day), it is seen that both measuring methods are accurate within the limits of error. It should be noted that in all of these tests the reference-method results were calculated by using equation (18), which contains no direct temperature measurements. Hence, the accuracy and agreement of the foregoing results substantiate the conclusion arrived at in the section Expressions for Leakage; that is, direct temperature measurements are not necessary in the reference method.

The results of figure 3 are also seen to indicate the accuracy and feasibility of employing a long length of nickel wire as a resistance thermometer to measure the vessel average air temperature. It was anticipated that, because of the vastly increased spatial sampling afforded by the nickel wire, the scatter of results would be diminished to the same magnitude as that of the reference-method results. The fact that this was not accomplished is believed to have two causes. The first is that evidently nearly ideal test conditions exist at PBRF because of the thorough mixing of the vessel air and the very mild fluctuations of the average air temperature. An indication of the uniformity of the temperature field is obtained by comparing the nickel-wire and platinum-resistance-thermometer results in figure 3. The scatter of results is virtually the same even though the platinum thermometer measured the tempera-

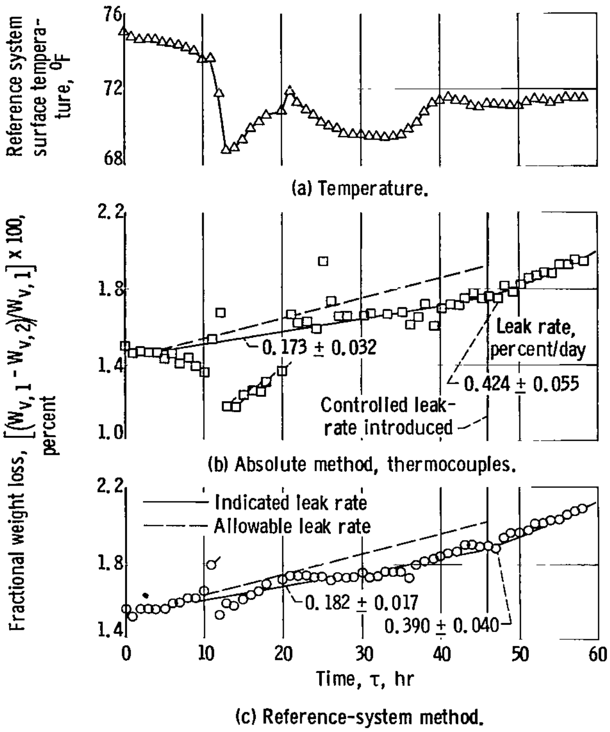

Figure 6. - Leak-rate results obtained by using two methods of temperature measurement. Leak-rate test 3.

ture only at a single point, which is in contrast to the continuous spatial averaging of the nickel wire.

The mild changes in temperature level are indicated by the resistance-thermometer changes shown in figure 3. It should be added that, even though the maximum change in temperature over the entire test period was only about one degree, accurate measurement of these small changes in temperature level must still be made. Neglecting even the small changes in this test would result in a significant change in slope of the fractional weight loss results and would also result in increased scatter. The present test results indicate that for PBRF conditions little or no decrease in scatter of results is gained by vastly increased sampling. At other reactor sites, where spatial or diurnal temperature variations may be more pronounced, a decrease in scatter of results appears likely.

The second reason for the difference in scatter between the two methods is that in the absolute method pressure-measurement errors are propagated into the results, whereas the reference method is virtually insensitive to these errors (see eqs. (20) to (23)). Consequently, for PBRF tests, it appears that the only way to reduce the scatter of absolute-method results is to improve the accuracy of the absolute-pressure measurements. Presently, the absolute pressure is obtained by adding the readings of a 10-foot water manometer, readable to 0.05 inch of water, and a mercury barometer, readable to 0.01 inch of mercury but probably giving readings reproducible to about ±0.02 to 0.03 inch of mercury. A direct means of improving the reproducibility of the barometric readings is simply to employ another instrument capable of greater precision and accuracy. Another possible method would be to eliminate the barometric-pressure measurements entirely by terminating the 10-foot vessel gage pressure manometer, which is normally open to a varying ambient pressure, into a closed artificial atmosphere, whose temperature may be maintained constant to ±0.005° F by using the methods described, for example, in reference 8. In effect, this would control the atmospheric pressure to ±0.004 inch of water and virtually eliminate the barometric-pressure-measurement error since the barometric pressure is now essentially constant. The design problems involved in arranging such an apparatus are not all readily evident, however, and perhaps (for tests conducted at higher pressure especially) it would be simpler to employ a very precise barometer or absolute manometer.

Besides the relative scatter of results, additional factors of significance in comparing the absolute and reference methods are their relative complexity and reliability, both of which may significantly influence the total time expenditure. In previous PBRF tests it was found that the absolute method offered greater overall simplicity principally because of the considerable amount of pretest time required to ensure the leak tightness of the reference-system tubing, valves, and manometer connections. In the present test this was again found to be true.

In regard to the use of the nickel wire, the installation and preparation time was only a fraction of that required in the reference method. In terms of relative reliability, the principal shortcoming of the reference method, the possibility that it may leak, is always present, whereas no comparable inherent catastrophic shortcoming is involved in using the nickel-wire thermometer.

One of the advantages of a reference system is the continuous spatial sampling it affords as contrasted with the point sampling obtained from a system of thermocouples. In addition, the sampling is automatic in that a single pressure differential reflects the average temperature (in addition to vessel leakage), whereas in the absolute method a number of thermocouple measurements must first be obtained, usually by manual means, and then averaged. If a nickel wire is used, however, these advantages no longer exist. In this case the averaging is also automatic and obtainable by a single reading. Also, the spatial sampling obtainable by a nickel wire is not only continuous but can be much more thorough because of its flexibility and ease of installation.

SUMMARY OF RESULTS

It is believed that the most significant results of this comparison of absolute- and reference-system methods of measuring containment-vessel leakage rates are the following:

1. It is not necessary to make direct temperature measurements of the containment-vessel atmosphere when the reference method is employed.

2. Since the accuracy of the reference-method results has been indicated by comparison with absolute-method results in four Plum Brook Reactor Facility tests and by use of a known leak rate in two of those tests, the analytical conclusion in item 1 has been experimentally substantiated.

3. The results of an error analysis show that the reference method is a more accurate means of measurement than the absolute method because the reference method is relatively insensitive to error in absolute-pressure measurements.

4. The results of this test and all past tests at the Plum Brook Reactor Facility show that there is significantly less scatter in the reference-method results, which substantiates the analytical conclusion stated in item 3.

5. Measuring the vessel average air temperature by employing a length of nickel wire as a resistance thermometer is both feasible and accurate as indi-

cated by the accuracy of the leak-rate results obtained.

6. The greatly increased temperature sampling afforded by a 550-foot length of nickel wire did not appreciably reduce the scatter of absolute-method results.

7. In all Plum Brook Reactor Facility tests the absolute method proved to have greater overall simplicity than the reference method.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 23, 1964

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