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AIR LEAKAGE RATE STUDIES
ON THE C. S. E. CONTAINMENT VESSEL

September 1969

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AIR LEAKAGE RATE STUDIES
ON THE C.S.E. CONTAINMENT VESSEL

by

M. E. Witherspoon and G. J. Rogers

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Physics and Engineering Division

September 1969

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ABSTRACT

A series of air leakage rate tests were performed as part of the Containment Systems Experiment program. The 30,700 ft³ model containment vessel was tested at three nominal leakage rates and several pressures at each leakage rate. Leakage rate determinations were made using the Perfect Gas Law, the reference vessel method, and by collection of leakage through individual leakage paths. Error analyses, pressure characteristics of leakage rates, results of extrapolations, statistical analyses, comparisons of observed and predicted errors, and general observations are described.

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AIR LEAKAGE RATE STUDIES
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INTRODUCTION

The Containment Systems Experiment (CSE) is a multiple purpose nuclear safety research and development program assigned the overall purpose of investigating the behavior of power reactor containment systems and related engineered safety features under accident conditions such as loss of coolant and fuel meltdown. The overall CSE program includes studies on containment leakage, fission product transport, and coolant blowdown. A general objective in all phases of the program is to obtain experimental data in large scale experiments in order to verify or develop mathematical models which permit confident analysis of the consequences of major reactor accidents. The experimental facilities for the CSE program include a 30,000 ft³ containment vessel possessing many features representative of power reactor containment vessels. The CSE vessel is of welded steel construction, has several interior compartments, and is equipped with numerous penetrations for piping, electrical, and instrumentation conductors, and with personnel and equipment access openings.

A basic objective of the leakage rate experiments is to relate the leakage of fission product activity after an incident to the results of air leakage rate tests on the containment vessel. The test series discussed in this report was conducted to examine the ability to make meaningful and accurate air leakage rate measurements as a function of test pressure and leakage rate levels. Information gathered on the rates of ambient temperature air leakage from a containment vessel will

be compared to the results of heated air and steam-air leakage tests to be conducted later and described in a separate report.

The leakage rate test results and related analyses reported herein provide information useful for conducting leakage rate tests and periodic retests of reactor containment vessels, and for the analysis of the results of such tests.

SUMMARY AND CONCLUSIONS

SUMMARY

Ambient temperature air leakage tests were performed on the CSE containment vessel at three nominal leakage rate levels (1.0, 0.5, and 0.1 %/day), and at several pressures at each leakage level. The purpose of the investigation was to examine the ability to conduct meaningful leakage rate tests as a function of pressure and nominal leakage level for a range of conditions applicable to both PWR and BWR containment vessel leakage rate testing.

Results of the tests indicated generally good agreement between redundant methods of testing and comparable performance from the "absolute" and the "reference vessel" methods. The major cause of inaccuracy and uncertainty in both methods was due to inadequate measurements of temperature changes during containment system temperature excursions induced by changing external conditions. The results of tests conducted at leakage levels less than 0.1% were very uncertain. Collection of leakage at individual leaks was used to provide an independent check of the integrated leakage rate test methods.

The pressure characteristic of total vessel leakage and of several individual leakage points was near the laminar flow regime. Upward extrapolations of leakage using test pressures above 10 psig gave results comparing favorably with test data gathered at the extrapolation pressures. It was observed that most individual leakage points did not give repeatable results in retests at nearly the same pressure.

Error analyses applied to test instrumentation indicated the equipment to be adequate for measurement of the leakage in terms of sensitivity criteria. The error analysis points out the relative unimportance of random sensitivity error in temperature measurements compared to error associated

with location of temperature sensors. Sample calculations showed that comparable results were obtained when as few as 7 out of 19 sensors available were used to calculate average temperature. The current method for volume weighting the vessel temperature can introduce a systematic error, and the leakage rate calculated by the practice of averaging successive results is not the best available estimate of the true leakage rate. Least squares analysis with confidence intervals is the best technique for analysis of results. This method is applied to both reference and absolute method calculations and the error from the confidence interval is compared with "best estimates" of predicted leakage. The error in results ranges to as much as 20 times the error predicted with a standard error propagation equation. The usual error analysis, while unable to account for dynamic error influences or to adequately predict the outcome of proposed tests, is useful in checking instrumentation for adequate sensitivity.

CONCLUSIONS

The following conclusions drawn from the data collected and experience gained during the CSE leakage rate studies are believed by the authors to be generally applicable to power reactor containment leakage rate testing.

- Least squares analysis with confidence intervals is technically superior to other methods of test data analysis, particularly when the data are scattered. The practicality and technical superiority of the confidence interval approach as a means of assessing the reliability of test results recommends this method. Relatively simple methods providing basic statistical integrity can be applied to data obtained from standard testing procedures. The approach is useful as a basis for comparison of the results of tests performed at different times or on different vessels. Establishment of confidence interval specifications before a test would be desirable. Given the specification, the test engineers could quantitatively assess the worth of results, significance of test duration, and the influence of individual test conditions on results.
- The equivalence of the absolute and reference methods of testing is confirmed. All general results were found to be comparable, and the two methods will give comparable results when corresponding care in the selection of the instrument combinations required for each is taken.
- Good test results were obtained by using a relatively cheap nickel alloy wire as an indicator of change in temperature. A few calibrated sensors are necessary to set the nominal temperature of the wire, and temperature changes are then determined from resistance measurements of the wire. The conclusion is that the problem of expense related to installation of large numbers of sensors in

large containment volumes could be alleviated by using fewer high accuracy sensors and nickel-iron wire, whose sensitivity can be used with good results.

- Individual leakage point flows were successfully collected and correlated to calculated leakage rates. An allowance for the uncollected fraction of leakage must be made, depending on the pressure and nominal leakage level. As much as 95% of the calculated leakage was collected at 60 psig with a nominal 1.0%/day leakage rate, but less than 50% of the calculated leakage was collected at 30 psig when the nominal leakage level was less than 0.1%/day. It is considered impossible to guarantee that the relationship between individual leakage points and the integrated test results will be maintained over an extended period of time. Although the general results of CSE test were not affected, some individual leakage points failed to display repeatable leakage characteristics when repressurized to the same nominal pressure level in repeat tests. Resilient seals and spring loaded valve seats were found to be particularly unreliable in this respect.
- Extrapolation of test results to higher pressures was within 25% error when the leakage rate level at high pressure was on the order of 0.5 to 1.0%/day and the test pressure was not less than 10 psig. Attempts to extrapolate results of tests in which the high pressure leakage rate was about 0.1%/day produced greater errors because of the great uncertainty of results in low pressure, low leakage rate level tests.
- Results obtained from reference and absolute observations during the 60 psig nominal 0.1% test series disagree as much as 100% for the same 24-hr period. Results obtained from either the absolute or reference method disagree as much as 50% with results obtained with the same method in other

24-hr periods. The major influence on test results is that of changing temperature gradients in the vessel during the test period. General observations made during the test series lead to the conclusion that measured test variables during tests (on the order of 0.1%/day) are externally affected to the extent that errors on the order of 100% might be expected. Although the CSE containment vessel was protected from diurnal cycles, the skin was not insulated in the first group of air tests. Better results might reasonably be expected with an insulated vessel. In the case of reactor containment structures, better results could be expected from more adequately insulated vessels.

- The error in leakage rate test results is dependent on both total pressure and nominal leakage rate level. Error analysis and test experience confirm the adequacy of commercially available testing equipment for good test results in terms of sensitivity criteria. The difficulty of adequately estimating average air temperature in the vessel remains as the greatest single factor affecting test results. The effects of changing spatial temperature gradients and the inability of instruments and the reference tubing system to respond to small changes in temperature as they occur are responsible for the most influential errors in the testing procedure. Error analyses and observations indicate that placement of sensors is more important than their absolute number, and that tests can be performed at higher leakage rate levels with a few, well placed sensors.
- No encouragement is offered for the development of sound techniques for predicting the results or likely results of a forthcoming test. Objective analysis of the error due to temperature measurement requires knowledge of the

gradient and the assumption that the gradient does not change with time. Analyses of the cyclic behavior of the gradient requires a lengthy test period (4 cycles or 4 days in the case of diurnal cycles) and relatively minor changes in the pattern of the cycle. Errors in measurement of the pattern due to the slow response of the temperature measurement system can further complicate the analysis.

There are several interesting conclusions related to the CSE test experience that, while not generally applicable to all reactor containment tests, could be significant in some specific test situations.

- The influence of fan motor heat on containment temperature observed during some tests at CSE was found to be significant. The potential for this influence although realized in larger containments, depends on the specific insulation and recirculation system of each plant. Further testing is required to establish the maximum allowable motor wattage in the contained volume.
- Radioactive tracer gases can be used in steam-air mixtures to estimate the total gas mixture flow from an individual leakage point. A good gamma analysis capability and some special collection apparatus is required for the analysis of the leak discharge. Since the total gas phase must be collected in the course of collecting the radioactive gas, a direct measurement is possible.

EXPERIMENTAL EQUIPMENT AND PROCEDURESCSE CONTAINMENT LEAKAGE STUDIESObjectives

The basic objective of the leakage testing studies is to relate the leakage of fission product activity after an accident to the results of leakage rate tests performed with ambient temperature air. The following specific objectives will be achieved during the containment leakage program:

- Measure air leakage rates on the CSE containment vessel to identify and characterize individual leak points and to determine the overall leakage rate as a function of pressure.
- Assess the practical importance of factors affecting the sensitivity and accuracy of leakage rate measurements as, for example, the errors resulting from inadequate sampling of containment temperature and humidity, the variation of leakage rate as a function of time, and the influence of uncontrolled factors, including natural vessel temperature cycles.
- Determine the relations between leakage rates of steam-air-fission product mixtures and that of air through representative containment vessel leakage paths.

This report covers experiments and analyses directed to the first two specific objectives listed. A separate report, in preparation, covers a series of leakage rate tests with heated air and steam-air containment atmospheres and compares the results with cold air test results for the same vessel configuration. The leakage of fission products is being studied as a part of fission product transport experiments in the CSE containment vessel.

Leakage Rate Test Conditions

The experiment was designed with the intent of setting nominal leakage rates at 60 psig and depressurizing the vessel in several pressure steps with a leakage rate test performed at each pressure step. Each test was to have at least a 3-day duration so that the nominal leakage rate could be established with greater certainty than that given by a single day's testing. The following tabulation constitutes the basic test series performed in December 1966 to February 1967.

TABLE 1. *Test Conditions - First Series*

Nominal Leakage Rate at 60 psig (wt%/day)	Test Pressure Levels, psig						
	60*	30	10				
1.0%	60*	30	10				
0.5%	60	30	15	10	5	1	
0.1%	60	45	30	15*	10	5	1

**Hourly observations around the clock.*

Although all of the tests could not be conducted on a 24-hr data collection basis because of limitations in manpower, two tests (shown with asterisk) were selected to be conducted with round-the-clock observations. Each of the other tests was conducted by making frequent periodic instrument observations during the test period, although not necessarily at 1-hr intervals throughout the 24-hr test period.

In addition to these 24-hr data collected in the basic series, additional 24-hr tests in preparation for hot air and steam air tests in April, 1968 were conducted. The nominal leakage and pressures for the second series of tests were at conditions shown in the following tabulation.

<u>Leakage Rate (wt%/day)</u>	<u>Test Pressure Levels, psig</u>		
0.5%	35	23	9
0.3%	35		

Certain changes in the system made for the second series are described in the following sections.

DESCRIPTION OF CSE CONTAINMENT VESSEL

The containment vessel for the Containment Systems Experiment is located in a concrete structure originally used as a chemical processing plant at the Hanford Project. Figure 1 shows the physical arrangement of the vessel within this structure. The vessel itself is 25 ft in diameter, 66 ft 8 in. high, has a gross volume of 30,700 ft³ and is designed for 75 psig internal pressure. The containment vessel is intended for use in both the fission product transport and coolant blowdown experiments being carried out by the CSE program. The internal compartmentation to provide a drywell and four wetwell chambers resulted from the requirements of the coolant blowdown program. However, the subdivision into several volumes additional to the main volume above the deck level provided a system more nearly representative of actual reactor containment vessels. The vessel was fabricated from carbon steel in accordance with Section VIII of the ASME Pressure Vessel Code. All interior surfaces were painted with a modified phenolic paint (Phenoline 302*), while the exterior remained unpainted.

The vessel was uninsulated for the first series of tests. A 1-in. thick layer of glass fiber insulation in sheet form was applied to the exterior surfaces before the second test

*Product of the Carboline Co., St. Louis, Mo.

Neg 38010-1

FIGURE 1. Containment Systems Experiment

series was started. This insulation was equivalent in thermal resistance to about 21 in. of concrete.

Test instrumentation for the leakage tests was located in the control room (Figure 1) immediately opposite penetrations in the vessel shell provided for the sensing apparatus. Individual temperature and humidity sensors and the resistance wire used as a temperature sensor were distributed in the vessel airspace with small pulleys and ropes attached to the upper vessel level, as illustrated in Figure 2. The distribution of the nickel-iron resistance wire is shown in Figure 3. The resistance wire was carefully insulated from contact with the shell and distributed to avoid kinking or coldworking it. These steps were necessary to retain the resistance characteristics of the material.

A fan, shown in Figure 2, was placed for the purpose of mixing containment air drawn from the wetwells and the access compartment. Fan flow rate was 2200 and 4500 scfm in the first and second test series, respectively. A plywood orifice 20 in. in diameter was placed in the drywell door to obtain flow resistance for the air drawn from the access compartment similar to that of the wetwells designed for 20-in. penetrations. The fan was supplied with a motor suitable for circulating the compressed vessel air at approximately 5 atmospheres.

The reference system is shown in Figure 2 also. This manifold, of 3/4-in. diam hard drawn 0.035-in. thick wall tubing, was leak tested in sections before installation in the vessel and again after assembly. Details of this testing are included in the instrumentation description section of this report.

Containment Vessel Penetrations

The penetrations were provided for the functional needs of the varied experiments planned for the CSE program. A high

FIGURE 2. Sketch of C.S.E. Containment Vessel with Leak Test Equipment Installed

*All Points of Contact Insulated from Containment Shell

FIGURE 3. Resistance Wire Routing in Containment Vessel

integrity containment was a criteria of design. Consequently, the penetration design was similar to those used on power reactor containment structures although no attempt was made to adopt the specific penetration designs of a particular power reactor containment vessel.

Figures 4 and 5 show the CSE containment vessel penetration panels. Many other penetrations of piping, at various levels on the vessel, include 1/2 to 12-in. sizes of stainless and carbon steel piping equipped with several types of fittings and valves. The penetrations and seal types fall into the following categories:

- Compression fittings with Teflon glands, used in multiple penetration configurations as shown in the pictures.
- Multipin electrical fittings, bulkhead type with O-ring seals between the fitting and mounting flange.
- Potted or resin filled chambers around cables and individual wires.
- Tubing plugs and unions with compression type fittings (metal-to-metal seals).
- Block valve seals; steel-to-rubber seat and steel-to-steel seats.
- Valve stem packings, Teflon and standard packing materials.
- Needle-and-seat solenoid valves, with stainless steel sealing parts.
- Butterfly valves with ethylene propylene-coated blades and ethylene propylene seats.
- Standard NPT threaded pipe fittings.
- Welded couplings and flanges.
- Blind flanges with double O-rings.

A double seal philosophy has served as the general construction guide for penetrations on the containment. Most penetrations have chambers between the seals that are tapped for collection of leakage past the primary seal. In cases such as valve packing

FIGURE 4. P-24, A Multiple Conax Penetration
P-25, A Potted Multi-Cable Penetration

Neg 43781-22

Neg 0671512-11

FIGURE 5. A View of the Major Penetration Panel from the Inside of the Containment Shell

where this is impossible, bags taped around the seal provide the second bulkhead for leak collection.

The CSE vessel penetrations, although not designed to represent those of any specific power reactor containment, are similar in number and type to those used in current reactor designs. The CSE vessel is fitted with a personnel access door, manholes, an equipment access hatch, and bellows seals on high temperature piping. Some examples of penetration number and type for two power reactors and for the CSE are given below:

TABLE 2. *Comparison of Penetrations: CSE, PWR, and BWR Power Plants*

<u>Plant</u>	<u>Piping 2 to 28-in. Diameter</u>	<u>Piping Less Than 2-in. Diameter</u>	<u>Electrical And Instrument Penetrations*</u>
Kuwaunee (PWR) Zion, Illinois	42	12	80
Quad Cities (BWR) Cordova, Illinois	48	370 (Includes Control Rod Drive Inlets and Outlets)	141
Containment Systems Experiment Battelle-Northwest	25	86	200

**Some multiconductor routings counted as single penetrations.*

TEST EQUIPMENT AND INSTRUMENTS

Reference Vessel

The reference vessel was fabricated from 3/4-in. hard drawn copper tubing and 3/4-in. solder couplings. Silver solder was used to join tubing and fittings into a manifold of four parallel tubes. The tubing system was shop tested

for leakage in two major sections, placed in the vessel, and tested further. The use of silver solder and braces on the tubing sections strengthened the system mechanically and thus reduced the possibility of breaking the pre-tested joints during installation. Copper tubing external to the vessel was a combination of 3/8 and 1/4-in. soft drawn copper tubing with silver solder joints. Packless vacuum valves were used on the reference manometer board, and the board itself was tested as a separate unit, and joined to the vessel tubing. External reference system lines were insulated with adhesive refrigeration insulation to reduce the influence of temperature changes on this small fraction of reference system volume.

Internal pressurization of the reference vessel and sniffing at the joints, or pumping down the vessel to a high vacuum with the leak detector and applying helium to the joints are two possible methods of helium leak testing. The latter method is the more sensitive, but is difficult to perform on large volumes unless good, high volume vacuum pumps are available. Either method is acceptable if a helium standard is available to verify the sensitivity of the testing system. The vacuum method was chosen for our reference vessel system leak testing.

Reference Vessel Allowable Leakage

Limiting leakage rate in the reference volume can be developed by examining the size of the proposed reference system and the containment leakage rates to be measured. The CSE reference system volume is $2.48 \times 10^4 \text{ cm}^3$. In order to obtain useful measurements of containment vessel leakage rates ($\sim 0.1\%$ /day of contents), the reference vessel leakage should not exceed 1% of 0.1% of its contents per day, or 1×10^{-5} of its contents/day, or

$$\left(\frac{1 \times 10^{-5}}{\text{day}} \right) \left(\frac{1 \text{ day}}{0.864 \times 10^5 \text{ sec}} \right) = 1.2 \times 10^{-10} \text{ sec}^{-1}$$

At 5 atmospheres, the allowable leakage would then be

$$\frac{(1.1 \times 10^{-10})}{\text{sec}} (5 \text{ atm}) (2.48 \times 10^4 \text{ cm}^3) = 1.36 \times 10^{-5} \frac{\text{atm-cm}^3}{\text{sec}}$$

Assuming the vessel to be pressurized with a test gas and the leaking gas diluted 100 parts to 1 at the leak detector sensor, it would then be necessary to detect 1.36×10^{-7} std cm^3/sec of the test gas. From this analysis, a helium leak detector with a sensitivity greater than $1.36 \times 10^{-7} \text{ cm}^3/\text{sec}$ would be satisfactory for the proof testing of this reference system. The instrument used had a sensitivity of $2.43 \times 10^{-8} \text{ cm}^3/\text{sec}$.

Reference volumes for reactor containment vessel testing would normally involve larger volumes of reference tubing, since more routing would be required to sample the larger volumes. It would then be feasible to test systems 10 times the volume of the CSE tubing with a leak detector on the order of 1×10^{-6} std cm^3/sec . Some halogen detectors and most helium detectors can fulfill this testing requirement.

INSTRUMENTATION

Table 3 summarizes information on sensors and complementary readout equipment used for the measurement of temperature, pressure, humidity, and leakage flow rate. The equipment used to locate leaks is also included.

The accuracies listed here are those certified by the vendors or those verified locally by use of calibration standards traceable to primary standards of the National Bureau of Standards. The sensitivities listed are determined by the ability of an operator to discern a least division on a scale. In some cases, a digital readout is available and the sensitivity is the smallest order digit.

TABLE 3. Leakage Rate Test Instrumentation

No.	Manufacturer and Item	Type	Range	Accuracy	Sensitivity
{ 24	Rosemount Engineering Co.; Platinum Sensor	Model 118 LD	0-50 °F	±0.1 °F	±0.05 °F
	Rosemount Engineering Co.; Resistance Bridge	Model 400 A			
	Rosemount Engineering Co.; Power Supply	Model 410 A			
	Hewlett-Packard (DYMEC); Digital Voltmeter	Model 2401 A	0-100 mV	±2 × 10 ⁻⁶ V	±1 × 10 ⁻⁶ V
{ 1	Honeywell; Mueller Resistance Bridge	Model 1551	0-141 Ω	±0.002 Ω	±0.0005 Ω
{ 1	Balco Alloy Wire*				
{ 2	Brown "Elektronik"; continuous balance printing recorder	Model Y153X85	0-300 °F	1.3 °F	±0.5 °F
{ 30	Thermo-Electric; thermo-couple materials	Chromel-Alumel			
{ 1	Texas Instruments, fused quartz pressure gage	Model 141			
{ 1	T.I. Crystal Bourdon tube	No. 2	0-100 psia	±0.008 psia	±0.0005 psia
{ 1	T.I. Crystal Bourdon tube	No. 6	0-24 psia		
1	Wallace and Tiernan; Bourdon tube absolute	Model FA233-120	0-100 psia	±0.1 psia	±0.05 psia
1	Meriam; mercury column	Model A-324	0-50 in. Hg	±0.01 in. Hg	±0.01 in. Hg
1	Princo; Fortin Barometer	---	0-32 in. Hg	±0.01 in. Hg	±0.01 in. Hg
1	Meriam, inclined oil manometer	Model B-627	0-2 in. water	±0.01 in. Hg	±0.01
{ 1	Hygrodynamics; hygrometer indicator	Model 15-3001	0-100% relative humidity	±2%	±1%
{ 7	Hygrodynamics; humidity sensing, elements	Model H-101			
1	Fischer-Porter; flowmeter	Model 1/16-20-6 5/81	145 - 510 ml/min	3% or 1 minor division	±0.05 full scale
3	RGI Inc.; flowmeters	Models F 1100	1 - 260 ml/min	±3% or 1 division	±0.01 full scale
		F 1200	10 - 1900 ml/min		
		F 1400	1000 - 36000 ml/min		
1	ACE Glass Inc.; flowmeter	Model 1A-15-1	1 - 100 ml/min	±3% or 1 division	±0.02 full scale
1	General Electric; halogen gas detector	Model H-2			9 × 10 ⁻⁵ cm ³ /sec Freon 12
1	Beckman; helium leak detector	Model 14801			2.43 × 10 ⁻⁸ cm ³ /sec helium

*See discussion of resistance wire in text.

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Temperature Measurements

Platinum RTD System.

The platinum resistance temperature detector (RTD) system was the primary temperature measurement standard for the first series of leakage rate tests. The system consisted of 24 RTD sensors with matched bridges such that a zero to 25 mV signal is sensed for a range of temperature from 50 to 100 °F. The calibration of these sensors was verified at the BNW Standards Laboratory using a platinum secondary traceable to the National Bureau of Standards. The accuracy of the standard was ± 0.01 °F (10 times that of the Rosemounts). All RTD's were found to be within the manufacturer's claim with one exception, which was returned and replaced. A digital voltmeter was used to read the RTD millivoltage to 0.02 mV accuracy. The combination of these devices gives a system sensitivity of 0.05 °F. Nineteen of these sensors were used in the vessel airspace to provide a weighted average temperature for use in the absolute method of leakage calculation. Four RTD's were taped in thermal contact with the reference tubing to monitor temperature on the outside tubing skin. Sensor locations are tabulated in Appendix E, and approximate locations are indicated on Figure 2.

Resistance Wire

A long nickel-iron alloy wire also was used successfully as a temperature averaging resistance temperature detector. The layout of this wire is shown in Figure 3, and temperatures measured with this device are compared in Appendix E with a volume weighted temperature average using 19 RTD's. The resistance characteristics of this wire were verified by obtaining a temperature-resistance calibration for a 10-ft piece against the same platinum standard used for the platinum RTD's. The following characteristics were determined for the wire:

$$\alpha = \text{coefficient of thermal resistivity} = 2.33 \times 10^{-3} \frac{\Omega}{\Omega-\text{°F}}$$

$$R = \text{nominal resistance at } 75 \text{ °F} = 0.19308 \Omega/\text{ft}$$

The wire, installed as shown in Figure 3, had a nominal resistance of 80.0 Ω . The length of wire in the vessel was 80.0/0.01938 = 414 ft and the resistance change expected for a degree Fahrenheit change was

$$80 \Omega (2.33 \times 10^{-3} \frac{\Omega}{\Omega-\text{°F}}) = 0.1864 \Omega/\text{°F}$$

The manufacturer's data for the Mueller bridge lists the accuracy of the system at 0.02% of the setting. The accuracy of the nominal 80 Ω resistance wire reading is then 0.02% $\times$ 80 $\pm$ 0.0016 Ω = 0.002 Ω . The temperature sensitivity of this system using the Mueller bridge was about $\frac{0.002}{0.1864} \approx 0.01 \text{ °F}$.

Thermocouples and Recorder System

The chromel-alumel thermocouple system was calibrated using a constant temperature bath and a reference thermocouple obtained from the BNW Standards Laboratory. The nominal accuracy of the recorder-thermocouple system was found to be approximately 1.6% at 84 °F, and the nominal sensitivity was 1/2 of one minor scale division or 0.5 °F. The thermocouples chosen were found to deviate very little from each other in signal level (about 0.25% at 84 °F). All thermocouples were fabricated from the same lot of wire.

Pressure Measurement

The Texas Instrument crystal bourdon tube precision pressure gage was also checked by the BNW Standards Lab against a dead weight tester and the nominal accuracy was found to be ± 0.0014 psia. Temperature fluctuations in the instrument case due to a thermostat controlled heater increased the uncertainty to ± 0.008 psia.

The Wallace and Tiernan absolute pressure gage was found to agree closely with the mercury columns and the Texas Instruments pressure device, and the manufacturer's specifications were verified by the CSE operating staff.

Mercury columns from the manometer and barometer were used for a redundant pressure measurement. A source of error in these devices is the variation of the height of the mercury column with a change in the temperature of the mercury. The error $\frac{\Delta L}{L}$ for mercury⁽¹⁾ for a temperature fluctuation of 5 °F is $\frac{0.48928 - 0.48904}{0.48928} = 0.05\%$. The temperature measured at the manometers was found to be quite stable, varying less than 5 °F, and this correction was neglected. Similarly, the gage oil used in the inclined manometer has a correction of $\frac{0.004}{1.668} = 0.24\% = 0.004$ in. of water for a 5 °F change. This correction is below the sensitivity of the manometer and was neglected. A mercury thermometer in the manometer case indicated a stable temperature throughout the testing interval.

Humidity Measurement

The humidity system was provided with several correction curves. The meter humidity reading was corrected to a calibration humidity. The sensor also served as a temperature sensor on one scale, and the temperature was taken for a current temperature versus calibration temperature correction. A resistor causing the sensor to represent 50% relative humidity was used to adjust the meter for different lengths of cable between each sensor. The pressure equivalent of a 10% relative humidity change at 75 °F could be calculated for error estimate purposes.

$$\text{Relative Humidity} = \frac{\text{vapor-pressure of water in air at any temperature}}{\text{saturation pressure of water at the same temperature}}$$

Assuming the relative humidity to change from 70% to 60% at a constant temperature of 75 °F (by an error of measurement) and the vapor pressure of water at 75 °F = 0.875 in. Hg,

$$\begin{array}{rcl} 0.875 \times 0.70 & = & 0.6125 \\ 0.875 \times 0.60 & = & 0.5250 \\ \hline \text{change} & = & 0.0875 \text{ in. Hg, or } 0.043 \text{ psi.} \end{array}$$

In actuality, the manufacturer's specification is $\pm 2\%$ RH, so a $\pm 2\%$ RH error at 75 °F gives a pressure error of ± 0.0086 psia.

Flowmeters

Each of the CSE rotameters used for collection of individual leakage was calibrated from a set of standard rotameters supplied by the BNW Standards Laboratory. The small rotameters (0 to 100 ml/min) were also checked using a graduated cylinder and soap bubble technique and with a positive displacement wet-test meter. These calibrations were verified before test series began, and again about halfway through the series in the second week of January. One of the rotameters in the 0-3 cfm range was found to be off calibration and was cleaned and recalibrated. The data collected with this rotameter were corrected.

Leak Detection

Halogen Gas Detector

The sensitivity of this instrument was confirmed with a calculation based on the halogen gas dilution in the CSE containment shell during the first leak test. This instrument is provided with a 0.5 ounce per year Freon-12 standard, and the sensitivity can be checked continually. The sensitivity figure in Table 3 is that given by the manufacturer and was confirmed by the CSE operating staff with a standard leak.

Helium Leak Detector

The Beckman Model 145, used for testing the reference system, was continually adjusted to give 100% response when exposed to helium leak of $2.43 \times 10^{-8} \text{ cm}^3/\text{sec}$. Sensitivity to an air leak is slightly greater than this number since a helium-air dilution usually occurs. The operation of this device will not be discussed here. Helium systems and high vacuum equipment are furnished

with operational suggestions from the manufacturers, and the procedure at CSE was to follow these instructions with little deviation.

TEST PROCEDURES

Establishing the Nominal Leakage Rate

As stated earlier, the tests were performed at several pressure levels for each nominal leakage rate level. The approach used to establish the nominal leakage rate was to adjust the leak flow rate at one or more naturally occurring leak points with the vessel at a pressure of 60 psig. This adjustment, made at valves in piping systems, is described more fully in the section titled "Behavior of Individual Leak Points". Once this nominal leakage rate level was established, the tests at each pressure level were performed without disturbing any leak point with the single exception of the air line valves used to bleed air from the vessel to reduce pressure to the next test level.

Instrument Readings

Hourly observations of test instruments were made using a standard data sheet. Readings were taken in a consistent order as given on the data sheet from top to bottom (refer to Appendix B, OP 7.4.8) with the exception of the resistance wire reading, which was taken last. The total time required to read and record all instruments was approximately 10 min, and a consistent order was used to minimize the variation between hour-to-hour reading intervals for each sensor.

The inclined manometer reading was recorded on the data sheet and transcribed to the data reduction sheet (OP 7.4.5, Appendix B) for calculation of hourly or half-hourly leakage rates. In those cases where reference method readings were taken more frequently than were the absolute method readings, the inclined manometer and the current pressures were recorded

directly on the reference method reduction sheet (OP 7.4.5). No corrections to readings were necessary except for humidity as covered in an earlier section "Description of Test Equipment".

Individual Leaks

Individual leak points were measured with flowmeters at each nominal pressure level. Each leak point was measured at least twice each day. Since the total pressure of the containment system was relatively stable, these individual measurements were taken twice each day for each individual leakage point, usually between hourly instrument readings, rather than at prescribed times. The data sheet for these observations is also included in Appendix B (OP 7.4.4).

Calculations

The data sheets and associated calculation sheets (Appendix B) show the stepwise procedure for calculating leakage rates from the raw data. Customary equations are used and are included in Appendix C with nomenclature. Running calculations of results were carried out during the tests by the Engineering Technicians by a desk calculator. Results were checked by a second person at a later time. By the time of the second test series, simple computer programs had been prepared for the small digital computer available at CSE, and the checking of results was carried out on this machine. The programs for calculation of leakage rate by the conventional equations as well as by linear regression analysis are included in Appendix D.

RESULTS AND DISCUSSIONS

ERROR ANALYSIS OF LEAKAGE RATE TESTING

Since leakage tests are very often performed at the limit of instrument capability, the analysis of errors in the measurements of the test variables is important. Although these tests are often classified as field tests, they must be performed using the same approach as for a precise laboratory test. It is helpful to begin the analysis with a classification of errors and definitions of the classifications:⁽²⁾

Systematic Errors - consistent inaccuracies due to the assumptions and approximations applied to all the observations. These may be assumptions and approximations in theory, imperfections in the design of the apparatus, or the use of auxiliary quantities or constants in the observations.

Personal Errors and Bias - Those errors associated with the judgment of different observers, usually on scales and cross hairs.

Mistakes - Arithmetic, sign reversal, transposition of figures.

Assignable Causes - Uncontrolled variables which may or may not be taken into account.

Random Errors - Also uncontrolled variables, but successive observations of these variables form a random sequence.

In leakage rate testing, the systematic errors intrinsic to the perfect gas assumptions are accepted for practical testing considerations. Some systematic errors are associated with instrumentation such as the pressure gage. For example, the nominal absolute accuracy of the instrument becomes a systematic error after the first reading. A systematic error also present in the volume weighting procedure will be discussed on subsequent pages.

Personal errors and mistakes are minimized with techniques, but these errors cannot be treated in a general manner. Control of this error source during leakage tests is usually accomplished by using well organized data sheets, and by having calculations checked by a second individual.

Random errors and assignable causes are the sources of error the engineer can isolate and deal with in the practical test situation. When test results are uncertain, the influence of random errors can be isolated from the total error, and the remaining influence will be that due to changing spatial temperature gradients, adverse humidity change, or instrumentation malfunction. A judgment will be required as to whether errors due to external influences constitute grounds for rejecting the results and continuing or repeating the test.

Treatment of Random Errors

The methods for treatment of random errors have been developed with elementary statistical theories based on the assumption that the errors occur in a normal distribution. The applicability of the normal law is acceptable if there are several sources of uncertainty (4 or more) each with binomially distributed error, such as the case for a group of instruments which read $\pm$ values from the true value.⁽²⁾ A "second power error propagation law" has been derived and was applied by Kline and McClintock⁽³⁾ with good results to several cases of other than normal error distribution. Leakage rate tests fall into the category of "single sample experiments", or instrument data not recorded enough times at each time interval to determine the variance of the measurement. The experimenter must either use the vendor's value for variance or a value he believes to be true within the bounds of some stated probability. The variance so chosen replaces the variance normally determined by multiple measurement, and the equation retains the same form as for a multiple measurement of a constant quantity.

Using the equation $L = \frac{2400}{\Delta t} \left(1 - \frac{P_2 T_1}{P_1 T_2} \right)$ for leakage rate in units of "% of original weight per 24 hr", ignore for the moment the time interval between the two readings of P and T.

The outleakage is a fractional weight loss $\frac{W_1 - W_2}{W_1} = 1 - \frac{W_2}{W_1}$.

To evaluate the propagation of errors in measuring P and T into the leakage, let $\frac{W_2}{W_1} = K$; then leakage = $1 - \frac{W_2}{W_1} = 1 - K$ and the error in the fractional leakage is the error in K.

Use the symbol ϵ for uncertainty, with a subscript to indicate the term to which it applies.

$$\epsilon \frac{W_1 - W_2}{W_1} = \epsilon \frac{W_2}{W_1} = \epsilon K$$

$$\text{Now } \frac{W_2}{W_1} = K = \frac{P_2 T_1}{P_1 T_2} \quad (1)$$

The second power law of propagation of errors may be utilized to approximate the uncertainty interval for a result which is a linear function of several variables, each of which is assumed to be normally distributed, and whose individual uncertainty intervals are assumed known with the same odds as will be taken for the uncertainty interval of the result. ⁽³⁾

$$\epsilon K = \left[\left(\frac{\partial K}{\partial P_2} \epsilon_{P_2} \right)^2 + \left(\frac{\partial K}{\partial P_1} \epsilon_{P_1} \right)^2 + \left(\frac{\partial K}{\partial T_1} \epsilon_{T_1} \right)^2 + \left(\frac{\partial K}{\partial T_2} \epsilon_{T_2} \right)^2 \right]^{1/2} \quad (2)$$

$$\epsilon K = \left[\left(\frac{T_1}{P_1 T_2} \epsilon_{P_2} \right)^2 + \left(\frac{P_2 T_1}{T_2} \epsilon_{P_1} \right)^2 + \left(\frac{P_2}{P_1 T_2} \epsilon_{T_1} \right)^2 + \left(\frac{P_2 T_1}{P_1} \epsilon_{T_2} \right)^2 \right]^{1/2} \quad (3)$$

Equation (3) is more easily evaluated by dividing by Equation (1).

$$\frac{\epsilon K}{K} = \left[\left(\frac{\epsilon_{P_2}}{P_2} \right)^2 + \left(\frac{\epsilon_{P_1}}{P_1} \right)^2 + \left(\frac{\epsilon_{T_1}}{T_1} \right)^2 + \left(\frac{\epsilon_{T_2}}{T_2} \right)^2 \right]^{1/2} \quad (4)$$

This equation gives the relative error in each source constituent. The equation seems reasonable because the uncertainties are best deduced from the precision of the gage used for the experiment. For example, if the least division on the pressure gage is 0.01 psi, the experimenter will assign $\epsilon_P = 0.01$ psia if he is confident that the same gage reading would be obtained, say 19 out of 20 times within one minor division when the same pressure was read (95% confidence). Returning to Equation (4), if changes in pressure and temperature are small compared to the magnitude of P and T,

$$\frac{\epsilon_K}{K} = [2(\frac{\epsilon_P}{P})^2 + 2(\frac{\epsilon_T}{T})^2]^{1/2}$$

The factor 2 is a natural result of the fact that two pressure and two temperature measurements are made for each test period.

It can be shown that the error in time has a small influence on the result of the calculation compared to the errors in pressure and temperature. Using the same nomenclature as before:

$$L = \frac{1}{\Delta t} (1 - \frac{P_2}{P_1} \frac{T_1}{T_2})$$

$$\text{Let } Q = 1 - \frac{P_2}{P_1} \frac{T_1}{T_2}, \quad R = \frac{P_2}{P_1} \frac{T_1}{T_2}$$

$$\frac{\epsilon_L^2}{L^2} = \frac{\epsilon_t^2}{t^2} + \frac{\epsilon_Q^2}{Q^2}$$

$$R = \frac{P_2}{P_1} \frac{T_1}{T_2}; \quad \frac{\partial R}{\partial P_2} = \frac{T_1}{P_1 T_2}; \quad \frac{\partial R}{\partial T_1} = \frac{P_2}{P_1 T_2}; \quad \frac{\partial R}{\partial P_1} = \frac{P_2}{P_1^2 T_2}; \quad \frac{\partial R}{\partial T_2} = \frac{P_2}{P_1 T_2^2}$$

$$\text{if } P_1 \approx P_2 \text{ and } T_1 \approx T_2$$

$$\frac{\epsilon_R^2}{R^2} = 2 \frac{\epsilon_P^2}{P^2} + 2 \frac{\epsilon_T^2}{T^2}$$

$$\epsilon_Q^2 = \epsilon_R^2 = R^2 \left(2 \frac{\epsilon_P^2}{P^2} + 2 \frac{\epsilon_T^2}{T^2} \right); \quad \frac{\epsilon_L^2}{L^2} = \frac{\epsilon_t^2}{t^2} + \frac{R^2}{Q^2} \left(2 \frac{\epsilon_P^2}{P^2} + 2 \frac{\epsilon_T^2}{T^2} \right)$$

$$\frac{\epsilon_L^2}{L^2} = \frac{\epsilon_t^2}{t^2} + \frac{\left(\frac{P_2}{P_1} \frac{T_1}{T_2} \right)}{\left(1 - \frac{P_2}{P_1} \frac{T_1}{T_2} \right)} \left(\frac{\epsilon_P^2}{P^2} + \frac{\epsilon_T^2}{T^2} \right)$$

For tests on the order of 1.0%,

$$\frac{\epsilon_L^2}{L^2} = (1) \frac{\epsilon_t^2}{t^2} + \left(\frac{1}{10^{-4}} \right) \left(\frac{2\epsilon_P^2}{P^2} + \frac{2\epsilon_T^2}{T^2} \right), \text{ and}$$

the coefficient of the pressure and temperature error term is 10^4 bigger than that of the time.

Eliminating the influence of the time error in the absolute formula, the problem becomes one of selecting the best estimate of error for the pressure gage, and the best estimate for the volume weighted temperature average as obtained from multiple sensors.

Error in a Volume Weighted Average

The sensors used for temperature measurements in leakage rate tests are usually multiplied by a factor representing a fractional volume in the vicinity of the sensor. In a strict sense, the mass in a fractional volume of the vessel is estimated with the temperature in that volume or, in other words, the mass in the vessel is estimated with a summation of volumes which is an approximation of the integral⁽⁴⁾

$$M = \frac{PV}{R} \int_V \frac{d(v/V)}{T(v)}$$

The $d(v/V)$ differential denotes integration with respect to fractional volume. The summation approximating this integral is

$$\hat{M} = \frac{PV}{R} \sum_{j=1}^k \frac{f_j}{T_j}$$

where T_j is the individual temperature sensor, and f_j is the volume fraction represented by an individual sensor. The object of this analysis is to point out the fact that a volume weighted average should be formed as the

$$\sum \frac{f_j}{T_j} \text{ and not } \frac{1}{\sum f_j T_j}$$

As an example, the volume weighted average for the temperatures read on 4/18/68 at 1330 hours is

$$\bar{T} = \sum T_j \times f_j = 74.54 \text{ } ^\circ\text{F} = 534.54 \text{ } ^\circ\text{R}$$

$$\text{and } \frac{1}{\bar{T}} = 0.001871$$

$$\text{but } \sum \frac{f_j}{T_j} = 0.001886$$

Note that the first number is 0.8% lower than the second.

The influence of this approximation will enter as a constant if the spatial gradient does not change significantly and the volume factors are nearly equal. As a constant error, it will be eliminated on differencing operations. Temperature changes computed both ways will, for example, give nearly the same result as the difference between results obtained by computing the $\sum \frac{f_j}{T_j}$. However, it can be eliminated completely as a source of error if the average is formed properly. The common method for volume weighting containment volumes is an incorrect one.

A simplified version of the formula for error in a mass measurement where

$$r = \frac{\epsilon_p}{p} \text{ and } q = \frac{\epsilon_T}{T}$$

is developed by Nicholson⁽⁴⁾ as

$$\epsilon_M = M \left[r^2 + q^2 \frac{\sum_{j=1}^k \left(\frac{f_j}{T} \right)^2}{\left(\sum_{j=1}^k \frac{f_j}{T} \right)^2} \right]^{1/2}$$

where f_j = volume fraction represented by each temperature sensor. This simplifies under the assumption that the range of the temperatures is small compared to their average;

$$\epsilon_M = M \left[r^2 + q^2 \sum_{j=1}^k f_j^2 \right]^{1/2}$$

As the number of sensors increases and the fractions decrease, the random error term in the temperature would tend to be eliminated. However, there is error in the volume weighted average other than the random error. The error associated with improper or inadequate selection of temperature sampling locations must be dealt with. This error, based on the test engineer's knowledge of the gradient in the vessel, can only be estimated. The error in volume sampling should not exceed the worst error in a single segment. As an example, assume that the temperature gradient in a vessel with 20 volume segment is 10 °F.

If the gradient is linear from top to bottom of the vessel, the maximum sampling error due to location of the sensor is 0.5 °F.

$$T_{avg} = \sum_{j=1}^{20} f_j (T_j \pm 0.5)$$

$$T_{avg} = \sum_{j=1}^{20} \frac{T_j}{20} \pm \frac{20(0.5)}{20} = \sum_{j=1}^{20} \frac{T_j}{20} \pm 0.5 \text{ } ^\circ\text{F}$$

and the average error can be no worse than 0.5 °F.

In cases of complicated gradients, further segmentation of the vessel and volume weighted averages of the error will allow a rough estimate of sampling error possibilities. An example of this approach appears in subsequent calculations for sampling error in the CSE vessel. Now, the question is how this estimate may be combined with the random error. Unfortunately, the sampling error term is not a "most probable" error but a conservative estimate. As an engineering expedient, the two can be combined in an RMS "error boundary".⁽⁴⁾

$$\epsilon_{\bar{T}} = \left(q^2 \sum_{j=1}^k f_j^2 + B^2 \right)^{1/2}$$

where B = sampling error or bias term estimated from the gradient. It can readily be seen now that the error in temperature is predominantly due to the bias term or the sampling error. If the volume factors are on the order of 0.05 (twenty sensors), the gradient between sensors is 0.5 °F, the sensitivity of the individual sensors is 0.1 °F, and

$$\epsilon_{\bar{T}} = \left[(0.1)^2 (0.05)^2 + (0.5)^2 \right]^{1/2}$$

$$\epsilon_{\bar{T}} = \left[25 \times 10^{-6} + 25 \times 10^{-2} \right]^{1/2}$$

Thus, the potential error of 0.5 °F in the volumeweight average due to misplacement of the sensors or a changing spatial gradient swamps the error due to random sensitivity errors. The practical

implication is that placement of the sensor is much more important than the actual number of sensors used.

Estimates of Errors for CSE Instrumentation

Errors in Pressure

- First, the nominal absolute accuracy of the gage from comparison with a NBS standard is 0.025% of full scale. For a 60 psig or approximately 75 psia test, 75 psi $(0.025 \times 10^{-2}) = 0.01875$ psia. It should be understood that the nominal absolute accuracy of the instrument becomes a systematic error after the first reading at the test pressure. After the test begins, the changes in the gage reading are determined by its sensitivity only.
- The finest division on the scale is 0.0001 psia.
- Temperature cycling error due to a thermostat controlled heater in the quartz tube case = 0.008 psia.
- The humidity instrument can be read $\pm 1\%$ relative humidity. At a nominal test temperature of 75 °F, the vapor pressure of water is 0.043 psi. ($1\% \times 0.043 = \pm 0.00043$ psi). The device has corrections which can also introduce a 1% relative humidity error and another ± 0.00043 psi. Combining the last three random errors in a single pressure reading with the second power law;

$$\frac{\epsilon_P}{P} = \left[\left(\frac{0.0001}{75} \right)^2 + \left(\frac{0.008}{75} \right)^2 + \left(\frac{0.00086}{75} \right)^2 \right]^{1/2}$$

$$\frac{\epsilon_P}{P} = 1.03 \times 10^{-4}; \quad \epsilon_P = .0077 \text{ psia}$$

It is evident from the magnitudes of the contributors that the thermostat cycling error swamps the random sensitivity errors from the other sources.

Errors in Temperature

A value for sampling error in all leak test cases cannot be easily chosen. An arbitrary but reasonable value of 0.5 °F was chosen in the sample analysis. Some test data for a sample test may be used to check the reasonableness of this value as an arbitrary assumption. From the sample data in Table 20 it can be seen that changes in gradient of 4.5 °F occur between the boundaries of the wetwell chambers and lower vessel and the first volume sample in upper containment. The volume segment for lower containment amounts to about 45% of the total containment volume, and nine sensors are used in the region. If the gradient in this area were linear with vessel height and the sensors were spaced from top to bottom of the volume evenly, the maximum gradient between sensors would be $\frac{4.5}{9} = 0.5$ °F. The gradient in the volume above this region (55% of the volume) is about 0.32 °F with 10 sensors, so the gradient is about 0.03 °F. A weighted average of 0.25 °F for these two estimates is the maximum possible error in the volume weighted average. Combining the ϵ_P and ϵ_T errors in the relative error expression

$$\frac{\epsilon_L}{L} = \left[2 \left(\frac{0.008}{75} \frac{\text{psia}}{\text{psia}} \right)^2 + 2 \left(\frac{0.25}{530} \frac{^\circ\text{R}}{^\circ\text{R}} \right)^2 \right]^{1/2}$$

$$\frac{\epsilon_L}{L} = 3.39 \times 10^{-4} = 0.034\% \text{ at the } 75 \text{ psia test pressure.}$$

So the error in a leakage of 0.01 or 1% is

$$\epsilon_L = 1.0 (0.034\%)$$

$$L = 1.0 \pm 0.034\%/\text{day}$$

The relative pressure error increases as the test pressure is reduced and, assuming at the extreme a 1 psi test, the error is

$$\frac{\epsilon_L}{L} = \left[2 \left(\frac{0.008}{15.7} \right)^2 + \left(\frac{0.25}{530} \right) \right]^{1/2}$$

$$\frac{\epsilon_L}{L} = 4.44 \times 10^{-4} = 0.044\%$$

Thus, it becomes evident that the total error in testing due to instrument sensitivity alone changes little in the pressure range of interest.

Errors in the Reference Method

Values for reference leakage are determined from calculations using the form

$$L \text{ (\%/day)} = \frac{1}{t_2 - t_1} \frac{\Delta P_1 - \Delta P_2}{P_1} = \frac{1}{\Delta t} \frac{\Delta \Delta P}{P_1}$$

where ΔP_1 and ΔP_2 are the pressure readings from a differential pressure device at times 1 and 2, and P_1 is the absolute pressure of the containment vessel at time 1. Applying the same equation as in the absolute analysis;

$$\frac{\epsilon_L}{L} = \left[2 \left(\frac{\epsilon_{\Delta t}}{\Delta t} \right)^2 + 2 \left(\frac{\epsilon_{\Delta \Delta P}}{\Delta \Delta P} \right)^2 + 2 \left(\frac{\epsilon_{P_1}}{P_1} \right)^2 \right]^{1/2}$$

It can be shown that the dominating error influence in the reference calculation is the random error in the differential pressure change. The relative error in time can easily be less than 1 min per day with a wall clock. For the test at 75 psia, the total pressure measurement is within 0.025% (from NBS calibration). If the vessel is leaking 0.1%/day, the ΔP is $0.001 \times 75 \text{ psia} \times 27.68 \frac{\text{in H}_2\text{O}}{\text{psi}} = 2.08 \text{ in H}_2\text{O/day}$.

$$\begin{aligned} \frac{\epsilon_L}{L} &= \left[2 \left(\frac{1}{1440} \right)^2 + 2 \left(\frac{0.01}{2.08} \right)^2 + 2 \left(0.00025 \right)^2 \right]^{1/2} \\ &= 0.0068 \end{aligned}$$

This says that the calculated leakage error should be no more than 6.8% of 0.1% with most of this error in the manometer reading.

The results of these error analysis calculations indicate the relative importance of the various variables measured in leakage rate tests. The calculated percentage accuracies indicate adequate instrument sensitivity and only small error in determinations made from their output. It should be understood that all of these considerations were based on an assumption of static measurement of the variables. Further analysis indicates these estimates to be useful as indicators of the relative importance of the instrument measurements, but do not account for the bulk of error in leakage rate tests. Consequently, calculations using these formulas would not provide a basis for predicting the results of tests.

VARIATION OF LEAKAGE RATE WITH PRESSURE

Comparisons of Results - Different Test Methods

The tabulations and discussions in this and the following sections present summaries and consolidate data collected with the equipment, methods, and procedures described in the previous section. Other data collected in the test series supplement the data presented here. The data omitted are for irregular time intervals, and do not lend themselves to straightforward reduction by all methods, particularly by those methods employed in the statistical section. These data are consistent with the trend of data presented in support of the conclusions stated in this report. Any or all of the raw data used to form these summaries, and other supplemental leakage calculations for various time intervals throughout the test series are available to technical personnel from the authors upon request.

Copies of the completed data and calculation sheets from one of the individual tests are included in Appendix E for purposes of illustration.

Referring to Table 4, the determinations of leakage rate by four methods are tabulated in four columns. The "Reference Method" column is the result of an average of individual leakage determinations made by reading the inclined manometer several times during each of the nominal 24-hr periods indicated in the "Date-Time" column. The two "Absolute" columns are the result of perfect gas law calculations of the leakage using the crystal bourdon tube pressure device and two separate temperature averaging systems consisting of the volume weighted average temperature determined from 19 platinum RTD's, and the average temperature as determined from the resistance characteristic of the nickel alloy wire. The "Collected Leakage" column is the result of summing the individual leakage point flow rates and converting the sum to an equivalent loss of weight in percentage per day. Test periods shown in the "Absolute Test Duration" column are sometimes longer than 24 hr, since observations were made at the beginning and end of weekends and year-end holidays.

The 1.0%/day Series

The summary of data is shown in Table 4. Twenty-four hour test periods for several days at each pressure provided data for comparisons of results at the same nominal leakage rate and pressure. These data indicate good agreement between the testing methods, and that a large fraction of the leakage was collected. Many of the discrepancies appearing in this tabulation could have been adjusted to some extent by calculation of leakage for 24-hr periods differing from the 1300 to 1300 hours period. This approach was avoided in the interest of consistency and clarity. While detailed juggling of

TABLE 4. Summary: 1.0%/day Nominal Leakage Rate Test Results

<u>Date - Time</u>		<u>Nominal Pressure psig</u>	<u>Reference Method</u>	<u>Absolute (RTDs)</u>	<u>Absolute (Ni Wire)</u>	<u>Collected Leakage</u>	<u>Absolute Test Duration, hr</u>
12-7	1300	60	1.03	1.14	1.08	0.98	24.0
12-8	1300	60	0.98	1.09	1.05	0.94	24.0
12-9	.300	60	0.97	1.07	1.12	0.86	24.0
12-10	1600	30	0.62	0.63	0.87	0.56	24.5
12-12	1300	30	0.74	0.70	0.72	0.52	45.0
12-13	1300	30	0.59	0.65	0.66	0.63	24.0
12-14	1300	10	0.26*	0.34	--	0.28	21.5
12-15	1300	10	0.26*	0.29	0.30	0.28	24.0
12-16	1300	10	0.28	0.28	0.30	0.28	24.0
12-19	1300	10	0.23	0.48	0.48	0.28	72.0
12-20	1300	10	0.39	0.53	0.41	0.28	24.0
12-22	1300	10	0.29	0.32	0.22	0.28	24.0
12-27	0745	10	0.28	0.37	0.41	0.28	114.75
12-28	1300	10	0.32	0.41	0.66	0.28	24.0
12-29	1300	10	0.33	0.43	0.26	0.28	24.0
12-30	1300	10	0.34	0.31	0.47	0.28	24.0

* See footnote on Table 5.

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individual test data will improve the comparisons of some periods, the general trend of the data would not change significantly.

The collected leakage was composed of a single large leak representing approximately 90% of the total leakage, and five smaller leaks accounting for the remaining 10% of the collected total. The difference between the collected leakage and calculated leakage ranged between 0.05% and 0.21% at 60 psig. Some small fraction of this difference was accounted for by known leaks not of a measurable magnitude. The remaining fraction was neither detected nor collected, and escaped either through one of the containment vessel's 300 odd sample lines, piping penetrations, and instrumentation lines, or was accumulated in the piping complex. The results of the 1.0% series confirmed the equivalence of the reference and absolute method, and indicated proper operation of test instrumentation because of the agreement with collected leakage. The rather small day to day variation in results appears to indicate no difficulty in obtaining reliable results at this leakage level with instrumentation of the sensitivity used.

The 0.5%/day Series

The data is summarized in Table 5. The collected leakage is composed of a single large leak comprising 80% of the total, while the same five smaller leaks, as in the 1.0%/day tests, comprise the remaining 20%.

During the period 1-12 to 1-16, 1967, leakage determinations were unusually variable due to changes in weather and in the building temperature control system which caused corresponding changes of about 2 °F in the volume weighted average temperature. The scatter due to external influences was isolated from the drop in test pressure since the results of a later test at

TABLE 5. Summary: 0.5%/day Nominal Leakage Rate Test Results

<u>Date - Time</u>		<u>Nominal Pressure, psig</u>	<u>Reference Method</u>	<u>Absolute (RTDs)</u>	<u>Absolute (Ni Wire)</u>	<u>Collected Leakage</u>	<u>Absolute Test Duration, hr</u>
1-6	1300	60	0.48	0.51	0.96*	0.35	21.5
1-7	1610	60	0.43	0.56	0.69*	0.34	27.2
1-8	1610	60	0.43	0.47	0.38	0.34	24.0
1-9	1300	60	0.45	0.48	0.44	0.33	21.0
1-11	0800	30	0.23	0.42	0.35	0.23	24.0
1-11	1300	30	0.33	0.47	0.49	0.23	24.0
1-12	1300	30	0.33	0.37	0.32	0.24	24.0
1-13	1530	15	0.13	0.27	0.25	0.21	24.0
1-14	1600	15	0.42	0.18	0.17	0.21	24.5
1-15	1600	15	0.39	0.27	0.32	0.21	24.0
1-16	1300	15	0.21	0.50	0.51	0.20	21.0
1-17	1300	10	0.26	0.23	0.23	0.18	21.5
1-18	1330	10	0.22	0.24	0.25	0.18	24.5
1-19	1300	10	0.27	0.30	0.30	0.19	23.5
1-20	1300	10	0.52**	0.47**	0.46**	0.38**	24.0
1-21	1600	5	0.18	0.20	0.19	0.13	25.5
1-22	1600	5	0.15	0.17	0.18	0.13	23.0
1-23	1600	5	0.19	0.15	0.16	0.13	21.0
1-24	1300	1	0.04	0.07	0.08	0.07	21.5
1-25	1300	1	0.06	0.07	0.08	0.07	24.0
1-26	1300	1	0.06	(-)0.28	(-)0.28	0.06	24.0

*Mueller bridge contacts dirty--corrected, 1-8.

**Additional superimposed leak equivalent to 0.19%/day
opened between 1300 on 1-19 and 1300 on 1-20.

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stable vessel temperature and at still lower pressures (10 psig), were much less scattered.

From the period 1-19 to 1-20, additional leakage equivalent to 0.19%/day was superimposed on the nominal leakage to verify that all instruments and the reference system were still in good order. The indicated increase in leakage rate ranged from 0.16% for the absolute method with nickel wire, to 0.25% for the reference method.

In these tests, about 70% of the leakage indicated by absolute or reference method results was captured and collected. On the last day of testing (1-26 at 1300 hr), a negative leakage was indicated at very low pressures. This value, since it was independent of both temperature systems for the absolute method, was thought to have been caused by a slight reading error or a malfunction in the pressure device.

The general results of the 0.5% series indicate that the measurement systems will give meaningful determinations at a nominal rate similar to that required for BWR plants. The data scatter during the 15 psig test in this series illustrated the serious influence of external temperature changes on calculated rates.

The 0.1%/day Series

During the first 24-hr period at 60 psig (1-29 to 1-30), the leakage rate of the vessel was indicated to be between 0.05 and 0.17%/day and the test series was begun. Radioactive ^{133}Xe gas was in the vessel for the purpose of checking a method for determining the flow rate of known individual leaks. Several samples of the vessel air additional to the leakage through natural leakage points were drawn through special sample tubes. These samples were added to the total of collected leakage and automatically accounted for in the leakage calculations.

In addition to the data collected on a day shift basis in this series, a 24-hr round-the-clock observation was made during the 15 psig test for the dates 2-10 to 2-11 at 0800 hr. The results of 24-hr tests are presented together in a subsequent section of this report. The results of the xenon testing are also discussed later.

The results of this series, shown in Table 6, illustrate the increasing uncertainty of the test results with lower and lower leakage rates. The results at 30 psig and above seem reasonably consistent although scattered, whereas those at 15 psig and below are so badly scattered and inconsistent as to be of little value. In these tests, the temperature variations of the containment vessel airspace are considered to be responsible for this scatter.

The Second Test Series, Base Line Air Tests

In addition to the original test series summarized in Tables 4, 5, and 6, air tests were conducted to establish a base line or datum for hot-air and steam-air tests. All of these tests were conducted on a 24-hr basis with hourly data readings. Hot-air and steam-air tests were performed but will not be discussed in this report. The retest, at 35 psig following the steam and air tests, is included in the results summary for these tests (Table 7). Before this test series, insulation had been applied to the containment vessel exterior. In addition, the precision RTD temperature sensors were removed and replaced by a thermocouple system suitable for the heated air and steam-air tests. Circulation of the containment vessel atmosphere for these tests was discontinued after it was discovered that fan work was heating the containment air at about 1 °F/hr.

TABLE 6. Summary: 0.1%/day Nominal Leakage Rate Test Results

Date - Time	Nominal Pressure, psig	Reference Method	Absolute (RTDs) %	Absolute (Balco wire) %	Collected Leakage %	Absolute Test Duration, hr
1-30 1300	60	0.13	0.17	0.05	0.054*	24.0
2-1 1300	60	0.14	0.27	0.14	0.054	24.0
2-2 1300	60	0.10	0.32	0.22	0.04	24.0
2-3 1530	45	0.11	0.19	0.11	0.06*	24.0
2-4 1600	45	0.09	0.14	0.18	0.04	27.0
2-5 1600	45	0.16	0.14	0.19	0.04	24.0
2-6 1300	45	0.13	0.11	0.25	0.05*	21.0
2-7 1530	30	0.11	0.11	0.25	0.04	24.0
2-8 1300	30	0.15	0.10	0.15	0.05*	24.0
2-9 1300	30	0.11	0.12	--	0.03	24.0
2-11 1600	15	0.09	0.08	0.06	0.03	24.0
2-12 1600	15	0.12	0.12	0.10	0.03	24.0
2-13 1600	15	0.07	0.07	0.08	0.03	24.0
2-14 1300	15	0.06	0.02	0.02	0.03	21.0
2-15 1600	10	0.022	0.049	0.180	0.051**	24.0
2-16 1300	10	0.087	0.024	0.110	0.051	24.0
2-17 1300	10	0.026	0.043	0.021	0.051	24.0
2-18 1600	5	--	0.04	0.05	0.036**	24.0
2-19 1600	5	--	0.006	(-)0.0004	0.036	24.0
2-20 1300	5	0.004	0.157	0.042	0.036	15.0
2-21 1300	5	0.013	(-)0.072	0.041	0.036	24.0
2-22 1600	1	(-)0.007	0.036	0.030	0.003	24.0
2-23 1300	1	0.008	0.020	0.024	0.003	24.0
2-24 1300	1	0.032	(-)0.019	(-)0.014	0.003	24.0
2-25 1600	30†	0.024	0.035	(-)0.08	0.032	24.0
2-26 1600	30	0.099	0.105	0.016	0.030	24.0
2-27 1600	30	--	0.049	0.183	0.030	15.6

*Xenon leak test samples are included in these data. Equivalent leakage rate was 0.014%/day on 1-30 and 2-1, 0.017%/day on 2-3 and 2-8, and 0.01%/day on 2-6.

**See text under "Behavior of Individual Leaks".

†Vessel was repressurized to test effect of pressurization versus depressurization on individual leaks.

TABLE 7. *Summary: Base Line Air Leakage Rate Tests*

<u>Test No.</u>	<u>Nominal Pressure, psig</u>	<u>Reference Method</u>	<u>Absolute Method (Wire)</u>	<u>Absolute Method (Thermo-couples)</u>	<u>Collected Leakage</u>
1	35	0.408	0.477	0.618	0.402
2	23	0.393	0.394	0.435	0.349
3	9	0.259	0.252	0.400	0.252
1a	35	0.266	0.289	0.336	0.182

Test results showed close agreement between test methods and with collected leakage except for the retest (No. 1A) in which only about 70% of the indicated leakage was collected.

In summary, the test results have shown absolute and reference testing techniques to be closely comparable. Absolute method tests based on either the average of individual thermocouples or a long average temperature sensing resistance wire are shown. Results from the thermocouple system are not in as close agreement as were results between the RTDs and the wire from previous tests. The total leakage collected and measured at individual leaks corresponded reasonably well with the results of integrated leakage rate tests. In most of the CSE tests, an amount of leakage equivalent to an absolute value of about 0.1%/day was not collected or accounted for in the leakage measured at individual leak points. Thus, whereas about 90% of the total leakage was accounted for at individual leaks for the 1.0%/day leakage rate tests, only about 30% was accounted for on the 0.1%/day tests. This degree of agreement, together with the superimposed leak sensitivity test carried out in the 0.5%/day series is concluded to assure ability of the customary integrated leakage rate testing methods to provide realistic estimates of the actual vessel leakage rate. The choice of method for application to a specific plant is dependent upon

individual factors, and results from the CSE tests do not support a technical basis for preferring one technique over others insofar as the basic capability of the methods are concerned.

One question these tests attempted to answer was whether there is a sensitivity limit or a lowest leakage rate level that can be meaningfully measured. This point cannot be properly assessed without defining some confidence level acceptable for the boundaries within which a measured result will probably lie. These topics are covered at some length in the section on Statistical Treatment of Leakage Rate Test Data. In general, however, from the tests summarized in Table 6, one would suspect that, while a 0.1%/day leakage rate would appear measurable with some confidence, rates below this might be questioned unless very stable conditions existed in the containment vessel and the test instrumentation was of the highest sensitivity.

Extrapolation of Leakage Rate Test Results to Other Pressures

Leakage Flow Regime

Formulas for five possible flow regimes have been reduced to a form showing the pressure dependence and combining all unknown constant factors in the flow equations.⁽⁵⁾

The possibilities are:

1. Molecular flow; $L_r = K_m (1 - \frac{1}{P})$
2. Laminar (viscous) flow; $L_r = K_L (P - \frac{1}{P})$
3. Turbulent flow, rough passage; $L_r = K_{tr} (1 - \frac{1}{P^2})^{1/2}$
4. Turbulent flow, smooth passage; $L_r = K_{tr} (1 - \frac{1}{P^2})^{4/7} P^{1/7}$
5. Compressible flow through orifice leaks;

$$P < 1.9 \text{ atm}; \quad L_r = K_o \frac{1}{P^{.715}} (1 - \frac{1}{P^{.286}})^{1/2}$$

$$P \geq 1.9 \text{ atm}; \quad L_r = .259 K_o$$

L_r = leakage rate, weight % per day

P = absolute pressure in atmospheres

K = leak constant (viscosity, geometry, roughness)

A nondimensional graphical representation of the results of extrapolation using these formulas is shown in Figure 6. It is assumed in this Figure that one is testing at a pressure of 10 psig and wishes to extrapolate the results of the test to higher pressure, as would be the case in a retest of a power reactor. There is a 15 psig data point for each of the 0.1 and 0.5% tests (see Table 1) and a 30 psig and 60 psig data point for all three test series. Although the 0.1% series and 1.0% series tend toward the laminar regime in this figure, it can only be said at this point that the laminar flow regime is not too conservative an estimate of leakage at higher pressures. During the 0.5% series, the leakage characteristic of the vessel seems to be dominated by a turbulent leak contributor, and in the 0.1% and 1.0% series, by contributors with laminar characteristics.

The molecular flow regime is usually ignored because of the enormous number of very tiny leaks required to make a significant contribution to the total leakage rate.⁽⁵⁾ Orifice flow seems improbable because of the special geometric situation that must develop before sonic decompression of the vessel gas can occur, and before the leakage can enter the sonic flow regime. The three remaining possible flow regimes were then applied to the test data and results are shown in Figures 7, 8, and 9.

These plots were constructed by taking the measured leakage rate at 60 psig and applying the preceding equations for laminar and turbulent flow. The constant factor, K , is determined at the first pressure level and used in subsequent calculations at

FIGURE 6. Upward Extrapolation Results of Several Flow Regimes

lower pressures. These calculations are then used to plot the flow regime lines. The turbulent regime lines appear on the left of the laminar flow regime since this extrapolation is directed to lower rather than to higher pressures.

Figures 7, 8, and 9 are plots of CSE vessel leakage rates as a function of pressure compared to ideal lines of extrapolation based on the laminar and turbulent extrapolation formulas for the 1.0, 0.5, and 0.1%/day tests. Since the total leakage seems to be a combination of laminar and turbulent flows, the large leaks comprising 90% and 80% of the collected leakage in the 1.0% and 0.5% tests are obviously in the same flow regimes (total leakage is essentially a plot of their performance with pressure). The remainder is accounted for in the plots of major individual leak behavior shown in Figures 10-14. Note that P-23 (Figures 13 and 14) was plotted for two leakage level test series with different results.

Comparison of Extrapolated and Observed Leakage Rates

Figures 7 through 9 show graphically that an extrapolation formula reasonably approximating the vessel leakage characteristic as a function of pressure can be selected. However, the formula selected would usually be applied to tests at lower pressures with the intent of predicting the leakage at higher pressures. Table 8 is the result obtained when test data from all pressures less than 60 psig are extrapolated by means of the laminar extrapolation formula to 60 psig. The leakage rate as determined with the reference method L_e/L_{t60} is an indicator of how well the extrapolated leakage rate compares with the leakage rate determined by testing at 60 psig. For example, if the measured 0.33% leakage rate at 30 psig in the 0.5% series is extrapolated to 60 psig, the resulting value is 0.59%/day compared to 0.48% determined by testing. The ratio of 1.23 denotes the prediction of 23% more leakage than is measured.

FIGURE 7. C.S.E. Containment Leakage Rates 1.0% Test Series

FIGURE 8. Total Leakage versus Pressure, 0.5% Test Series

FIGURE 9. Comparison of Laminar and Turbulent Flow Regimes with Experimental Data, 0.1% Series.

FIGURE 10. N39-DOV - Leakage Past the Seat of a Diaphragm Operated Valve

FIGURE 11. N32-D1 Leakage Past an O-Ring

FIGURE 12. N32-D2, Leakage Past an O-Ring

FIGURE 13. P-23, a Penetration with Multiple Conax Fittings

FIGURE 14. P-23; A Penetration with Multiple Conax
(Plotted here for the 0.5% Test Series)

TABLE 8. *Comparison of Extrapolated and Observed Leakage Rates (Laminar Extrapolation)*

<u>Test Pressure, psig</u>	<u>Leak Rate Reference Method (L_t) (%/day)</u>	<u>Extrapolation To ~ 60 psig (L_e) (%/day)</u>	<u>Ratio, L_e/L_{t60}</u>
For the 1.0%/day series:			
~ 60 psig	1.03	--	1.00
~ 30 psig	0.55	1.02	1.01
~ 10 psig	0.28	1.30	1.26
For the 0.5%/day series:			
~ 60 psig	0.48	--	1.00
~ 30 psig	0.33	0.59	1.23
~ 10 psig	0.22	1.03	2.15
~ 5 psig	0.15	1.29	2.69
~ 1 psig	0.06	2.14	4.46
For the 0.1%/day series:			
~ 60 psig	0.14	--	1.00
~ 30 psig	0.11	0.17	1.21
~ 15 psig	0.060	0.20	1.43
~ 10 psig	0.026	0.12	0.86
~ 5 psig	0.013	0.11	0.79
~ 1 psig	0.008	0.33	2.36

For the 1.0%/day tests, upward extrapolation gives rather good results. The extrapolation of the 10 psig test result, conservative by 26%, would be expected because the variation of leakage rate with pressure is quite close to the laminar flow regime, as shown in Figure 5. The upward extrapolations of the 30 psig data in the 0.5 and 0.1%/day test series are conservative by less than 25% but extrapolation results from lower pressures are quite poor and not necessarily conservative.

The current technical guideline draft for containment leakage rate testing⁽⁶⁾ proposes that retests of vessel leakage rate be conducted at not less than 50% of maximum accident pressure. The present results would lend some support to this arbitrarily chosen retest pressure if the laminar flow regime extrapolation were to be used without any data at lower test pressures. In practice, however, it must be obvious that these CSE vessel results will not necessarily be true for any other reactor containment vessel. Thus, the appropriate extrapolation formula and the validity of extrapolation to accident pressure of the leakage rate found at lower pressures should be based on actual test results for a specific containment system.

Behavior of Individual Leaks

During pressurization of the vessel in preparation for the test series at 1.0%/day, freon gas was injected into the vessel. Approximately 7 lb of freon was included in the vessel contents at 60 psig. A portable freon leak detector was used to check all potential leakage locations. Locations of several leaks too insignificant to indicate on the smallest flowmeter were detected. Because the smallest flowmeter allows measurement of flows on the order of $5 \text{ std cm}^3/\text{min}$, these leaks were thought to be less than $5 \text{ cm}^3/\text{min}$, or less than 0.0002%/day at 60 psig and therefore negligible. These leaks, therefore, were reported as DNM (detected but not measurable). Five of the

check points in the double seal taps and the locations covered with plastic bags were found to be leaking sufficiently to permit measurement with rotameters. One other leakage source was located on a wetwell drain line which provides a secondary barrier for several leak sources. This leak was contained with a second valve in the system, and could be tapped from a 1/2-in. detection stub and valve for a source of superimposed leakage. Table 9 presents the location, type, and history of each leakage location during all the test series. Units for the collected leakage are $\text{std cm}^3/\text{min}$. The status of each leak at each of the three nominal test pressures for the 1.0%/day series is also shown. The "drain line set leakage" is the tap on leakage escaping through one or more sources into a common header. This leak was the source of 91% of the total leakage in this test series. The five other leakage points were undisturbed natural leak points. The remaining leakage was enough to give a nominal 0.1%/day leakage if the drain line tap was closed. Three of the measurable leaks were past resilient materials consisting of either Teflon glands in the compression fittings or the O-rings in flanged nozzles (P-23, N-32-D-1, N-32-D-2). Two leaks were past the seats (stainless steel) of diaphragm operated valves. The drain line was set and left undisturbed.

Leakage at the same locations was again found (Table 10) and an additional point (SA-1 MV) added to the list represented leakage past the seat of a 2 in. manual gate valve used to lower the pressure for each test step. With this location leaking, the drain line was shut off and a calculated leakage of about 0.5%/day was obtained. The valve reseated when the vessel was depressurized to 30 psig, and it then became necessary to return to the drain line for a source of leakage. The method for determining the equivalent leakage from the drain line was to reduce the $8600 \text{ cm}^3/\text{min}$ leak using the ratio of the leakages from the same source at the same pressures on the previous test. The

TABLE 9. *History of Individual Leakage Points; 60 psig, 1.0% Test Series*

<u>Location and Type</u>	<u>Designation</u>	<u>60 psig (cm³/min)</u>	<u>30 psig</u>	<u>10 psig</u>
18-in. Gasketed Flange with bag	N-1	(a)	(b)	(b)
6-in. Gasketed Flange bagged relief valve	N-1-3	(a)	(b)	(b)
10-in. Blind Flange with multiple conax	P-23	2020	1050	350
12-in. Blind Flange with multiple conax	P-24	(a)	(b)	(c)
16-in. Blind Flange with multipin connectors	P-25	(a)	(c)	(c)
2-in. O-ring Flange	N-32-D-1	232	75	12
2-in. O-ring Flange	N-32-D-2	172	26	3
2-in. O-ring Flange	N-39-1	(a)		
Valve seat, diaphragm operated valve	N-39-DOV	229	67	10
Valve seat, diaphragm operated valve	N-44-DOV	32	(c)	(c)
Manual valve, past seat	SA-1-MV	(b)	(c)	(c)
Manual valve, past packing	N-30-C	(b)	(c)	(c)
Past seat of 1/2-in. manual valve on wetwell drain	Drain line	27,600	10,500	2540

- a. Detectable but not measurable.*
b. None detected.
c. No further check.

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TABLE 10. History of Individual Leakage Points

Location and Type	Designation	cm ³ /min					
		60 psig	30 psig	15 psig	10 psig	5 psig	1 psig
18-in. Gasketed Flange with bag	N-1	(a)	(c)	(c)	(c)	(c)	(c)
6-in. Gasketed Flange bagged relief valve	N-1-3	(a)	(c)	(c)	(c)	(b)	(c)
10-in. Blind Flange with multiple conax	P-23	1620	920	285	285	163	62
12-in. Blind Flange with multiple conax	P-24	(a)	(c)	(c)	(c)	(c)	(c)
16-in. Blind Flange with multipin connectors	P-25	(a)	(c)	(c)	(c)	(b)	(c)
2-in. O-ring Flange	N-32-D-1	131	32	16	18	3	DNM
2-in. O-ring Flange	N-32-D-2	90	20	5	5	(a)	(c)
2-in. O-ring Flange	N-39-1	(a)	(c)	(c)	(c)	(c)	ND
Valve seat, diaphragm operated valve	N-39-DOV	195	67	27	30	15	1
Valve seat, diaphragm operated valve	N-44-DOV	36	2	(a)	(c)	(c)	(c)
Manual valve, past seat	SA-1-MV	8600	40	30	2000	8	(a)
Manual valve, past packing	N-30-C	(a)	(c)	(c)	(c)	(c)	(c)
Past seat of 1/2-in. manual valve on wetwell drain	Drain line	Closed off	3400	2150	1480	848	420
Total Equivalent wt%/day		0.34%	0.23%	0.21%	0.19%	0.13%	0.07%

a. Detectable but not measurable.
 b. None detected.
 c. No further check.

result was set in the drain line ($3400 \text{ cm}^3/\text{min}$) and left undisturbed for the remainder of the test series.

Leakage at 60 psig, during 1% = $27,600 \text{ cm}^3/\text{min}$

Leakage at 30 psig, during 1% = $10,500 \text{ cm}^3/\text{min}$

Leakage at 60 psig, during 0.5% = $8,600 \text{ cm}^3/\text{min}$

$$\frac{\text{Leakage to be set at 30 psig during 0.5\%}}{8600} = \frac{10,500}{27,600}$$

Leakage to be set = $3270 \text{ cm}^3/\text{min}$

The SA-1-MV continued to leak slightly at 30 and 15 psig and was used as a source of superimposed leakage at 10 psig.

The drain line set leakage and the SA-1-MV (Table 11) were completely closed to reduce the total leakage rate to a calculated value of 0.1%/day or less. At 10 psig during this series, the SA-1-MV again did not seat well and contributed about half of the leakage at this point.

A review of all three tables reveals the fact that most of the individual leakage points (and particularly those with resilient seats) did not repeat the same values of leakage in retests at the same pressures. In general, most of these diminished, possibly because of better seating of the seal materials after cycling. One exception to the general trend was N-32-D-2, a small leak past the inner O-ring on a 2-in. flange. This leak increased leakage on the third 60 psig cycle. The two valves with steel-to-steel seats (N39 DOV and N-44 DOV) repeated well on the first two tests and diminished on the third cycle. The third cycle was approximately 1 psi lower in pressure than the first two tests. The valves involved are spring loaded in the closed position, and it is considered possible that a threshold of pressure must be reached before leaking begins.

TABLE 11. History of Individual Leakage Points; 60 psig, 0.1% Test Series

Location and Type	Designation	60 psig	45 psig	30 psig	15 psig	10 psig	5 psig	1 psig
18-in. Gasketed Flange with bag	N-1	(a)	(c)	(c)	(c)	(c)	(c)	(c)
6-in. Gasketed Flange bagged relief valve	N-1-3	(a)	(c)	(c)	(c)	(c)	(c)	(c)
10-in. Blind Flange with multiple conax	P-23	890	640	500	305	240	130	20
12-in. Blind Flange with multiple conax	P-24	(a)	(c)	(c)	(c)	(c)	(c)	(c)
16-in. Blind Flange with multipin connectors	P-25	(a)	(c)	(c)	(c)	(c)	(c)	(c)
2-in. O-ring Flange	N-32-D-1	223	140	50	(a)	(c)	(c)	(c)
2-in. O-ring Flange	N-32-D-2	190	119	66	19	15	13	(c)
2-in. O-ring Flange	N-39-1	(a)	(c)	(c)	(c)	(c)	(c)	(c)
Valve Seat, diaphragm operated valve	N-39-DOV	92	41	42	16	4	2	(c)
Valve Seat, diaphragm operated valve	N-44-DOV	(a)	5	(a)	(c)	(c)	(c)	(c)
Manual Valve, past seat	SA-1-MV	(b)	90	28	25	268	148	(c)
Manual Valve, past packing	N-30-C	(a)	(c)	(c)	(c)	(c)	(c)	(c)
Past seat of 1/2-in. manual valve on wetwell drain	Drain line	(b)	(c)	(c)	(c)	(c)	(c)	(c)

a. Detectable but not measurable.
b. None detected.
c. No further check.

STATISTICAL TREATMENT OF LEAKAGE RATE TEST DATACumulative Calculations Of Leakage Rate

Leakage rate tests result in periodic data (usually hourly) from which the rate is calculated for each successive data period. If a cumulative average is formed from the individual calculated rates, the fluctuations of the individual period results will tend to be suppressed. As time progresses and more samples are included in the running average, one can expect it to converge on the final average leakage rate. The same result can be obtained by calculating the average leakage rate based on data at the start of the test and that taken at the most recent time, and continuing this calculation at each new data collection time. The stability of this sequence of progressive average leakage rates should give a useful indication of whether the test is progressing satisfactorily and, in particular, whether the planned test duration will be satisfactory.

Results calculated in this way are shown in Table 12 for tests at several pressures and leakage rates. All the leakage rates were calculated from absolute method data.

For the 60 psig, 1.0%/day test, the values after the first hour were all within 10% of the final average for the 24 hr test. Future results of similar stability would strengthen confidence in the obtained values and could be used to justify a shorter test duration.

The other test tabulations show more variable results. The continued large fluctuation of the running average in the 15 psig, 0.03%/day test in particular would limit confidence in that test result and further extension of the test duration would serve no apparent purpose. For the 35 psig, 0.35%/day test, unstable temperature conditions were observed at the beginning of the test, and the test duration was therefore

*TABLE 12. Cumulative Calculations of
Leakage Rate, Absolute Method*

Differential Time, hr	60 psig 1.0%	35 psig 0.5%	23 psig 0.4%	9 psig 0.3%	15 psig 0.03%	35 psig 0.35%
1	0.882	0.548	0.093	-0.280	0.413	4.030
2	1.018	0.444	0.585	-0.022	0.601	2.430
3	1.098	0.533	0.373	0.085	0.438	1.513
4	1.097	0.563	0.449	0.108	0.384	0.889
5	0.98	0.479	0.368	0.150	0.313	0.782
6	1.062	0.394	0.333	0.172	0.216	0.887
7	1.128	0.495	0.336	0.129	0.155	0.946
8	1.033	0.525	0.414	0.127	0.152	0.963
9	1.095	0.517	0.360	0.151	0.128	0.761
10	1.107	0.511	0.401	0.192	0.106	0.709
11	1.069	0.478	0.358	0.208	0.048	0.608
12	1.068	0.496	0.396	0.365	0.065	0.658
13	1.096	0.494	0.359	0.200	0.074	--
14	1.078	0.457	0.421	0.260	0.061	0.754
15	1.091	0.495	0.424	0.182	0.063	0.774
16	1.060	0.463	0.420	0.258	-0.013	0.670
17	1.081	0.459	0.430	0.221	-0.011	0.554
18	1.078	0.439	0.433	0.255	0.018	0.431
19	1.081	0.457	0.417	0.229	0.012	0.555
20	1.081	0.476	0.411	0.258	-0.007	0.515
21	1.086	0.350	0.412	0.227	0.020	0.373
22	1.078	0.458	0.417	0.247	0.055	0.361
23	1.088	0.487	0.411	0.257	0.020	0.307
24	1.062	0.477	0.394	0.252	0.032	0.336
25						0.366
26						0.442
27						0.334
28						--
29						0.383
30						0.317
31						0.378
32						0.363
33						0.368
34						0.370
35						0.341
36						0.345

extended to 36 hr. In retrospect, the average leakage rates after 36 hr and after 24 hr do not appear to differ greatly. However, the stability of the running average at the later times permits more confidence in the test result.

Confidence Interval Analysis

One of the usual requirements for performing a leakage rate test is a 24-hr minimum test period with hourly or more frequent observations. "The average of at least 24 consecutive hourly determinations shall be used in establishing the percent leakage during a 24-hr period".⁽⁷⁾ One of the arguments for a 24-hr test is to enable the gathering of leakage rate data samples sufficient to justify a tolerable confidence in the leakage rate reported. No requirement has been established for a quantitative measure of what constitutes acceptable or tolerable confidence in the test result. Elementary statistical techniques can be applied to leakage rate test results to formulate a measure of the confidence applying to the result found. The technique used is to calculate the confidence interval for the mean leakage rate. The hourly leakage rate determinations may be treated as samples of the leakage rate of the vessel. The average or mean, $\bar{x}$, of the individual samples is an estimate of the true value of the vessel leakage rate, and the standard deviation of the samples, σ_s , is a measure of the sample dispersion about the mean. The standard deviation of the mean, $\sigma_{\bar{x}}$, is a measure of the variation of $\bar{x}$ from the true leakage rate of the vessel. The value of $\sigma_{\bar{x}}$ is

$$\sigma_{\bar{x}} = \frac{\sigma_s}{\sqrt{N}}$$

where N is the number of samples.

This relation is the basis for considering the true value to be better estimated by obtaining larger numbers of samples.

If we assume satisfaction with a specific confidence placing the true value within a known error band, we can calculate the width of the error band on either side of $\bar{x}$ by multiplying $\sigma_{\bar{x}}$ by a factor depending on the confidence level desired. For example, the 95% confidence interval is $1.96 \sigma_{\bar{x}}$ on both sides of $\bar{x}$.

In any given leakage rate test situation, the standard deviation of the samples is affected by the sensitivity of the test instruments, and perhaps more importantly by dynamic changes in vessel temperature gradients during the test. Thus, the σ_s can only be evaluated as the data becomes available. The value of $\sigma_{\bar{x}}$ also depends upon the duration of the test (number of samples), and may serve as a useful indication of whether further extension of the test duration would be effective in reducing the width of the error band. The following tabulations of CSE test results are arranged so that the error in the estimated average for progressive numbers of samples (and therefore longer intervals) can be seen.

The four tabulations (Tables 13-16) are cumulative averages and confidence intervals for tests at 1.0% at 60 psig, 0.4% at 35 psig, 0.31% at 10 psig, and 0.03% at 15 psig. Table 13 shows the reduction of error for 40 nominal one-hour reference method determinations. Table 14 shows the reduction in error for 47 nominal 30-min observations. Table 15 lists nominal 2-hr observations taken for several days. Table 16 shows 30-min samples taken in a single 24-hr interval.

In the 60 psig 1.0% test (Table 13), the average leakage rate is established after 8 samples to within a 2.89% error band. The error band remains small for later times. Hence, this test result might be considered satisfactory after less than a 24-hr test. Similarly, the results of the following test (Table 14) indicate the average as determined after 4 or 8 hr

TABLE 13. *Confidence Interval Analysis;
60 psig, 1.0%/day Test Data,
Reference Method*

<u>x = L%/day</u>	<u>No. Samples</u>	<u>$\bar{x}$</u>	<u>$\sigma_{\bar{x}}$</u>	<u>$1.96\sigma_{\bar{x}}$</u>	<u>95% Confidence Error Band (% of $\bar{x}$)</u>
0.99					
1.03					
1.07					
1.07					
1.04					
0.94					
1.05					
1.06	8	1.03	0.0152	0.0298	2.89
1.07					
1.03					
0.97					
0.90					
0.97					
0.93					
0.89					
1.08	16	1.01	0.0159	0.0311	3.09
0.92					
0.95					
0.96					
0.77					
0.88					
0.91					
1.08					
1.20	24	0.99	0.0187	0.0366	3.70
1.22					
1.05					
0.93					
0.92					
0.95					
0.87					
0.87					
0.93	32	0.98	0.0148	0.0290	2.96
0.95					
0.84					
0.88					
0.94					
0.88					
0.92					
0.96					
0.93	40	0.97	0.0146	0.0287	2.95

TABLE 14. *Confidence Interval Analysis;
35 psig, 0.4%/day Test Data,
Reference Method*

$x = \text{L\%/day}$	No. Samples	$\bar{x}$	$\sigma_{\bar{x}}$	$1.96 \sigma_{\bar{x}}$	95% Confidence Error Band (% of $\bar{x}$)
0.392	8	0.386	0.0135	0.0266	6.90
0.335					
0.501					
0.315					
0.574					
0.258					
0.495					
0.283					
0.460	16	0.399	0.0124	0.0243	6.09
0.460					
0.283					
0.531					
0.284					
0.461					
0.532					
0.284					
0.425	24	0.403	0.0114	0.0223	5.53
0.425					
0.425					
0.425					
0.562					
0.193					
0.461					
0.373					
0.227	32	0.395	0.0118	0.0231	5.85
0.447					
0.444					
0.213					
0.497					
0.418					
0.249					
0.465					
0.485	40	0.393	0.0120	0.0236	6.00
0.235					
0.512					
0.278					
0.359					
0.331					
0.583					
0.345					
0.530	47	0.402	0.0125	0.0246	6.12
0.356					
0.334					
0.495					
0.246					
0.602					
0.509					

TABLE 15. *Confidence Interval Analysis;
10 psig, 0.31%/day Test Data,
Reference Method*

$x = L\%/day$	No. Samples	$\bar{x}$	$\sigma_{\bar{x}}$	$1.96 \sigma_{\bar{x}}$	95% Confidence Error Band (% of $\bar{x}$)
0.19					
0.32					
0.21					
0.24	4	0.24	0.0204	0.0400	16.7
0.27					
0.29					
0.31	7	0.261	0.0188	0.0370	14.1
0.28					
0.25					
0.37					
0.11	11	0.258	0.0207	0.0406	15.7
0.20					
0.41					
0.46					
0.31					
0.40					
0.28					
0.27	18	0.288	0.0203	0.0397	13.8
0.27					
0.35					
0.31					
0.34					
0.20					
0.31	24	0.29	0.016	0.0314	10.8
0.33					
0.34					
0.31					
0.32					
0.36					
0.32					
0.52					
0.34					
0.30					
0.33					
0.37					
0.22	36	0.31	0.013	0.025	8.06

TABLE 16. Confidence Interval Analysis;
15 psig, 0.1%/day Test Data
Reference Method

$x = L\%/day$	No. Samples	$\bar{x}$	$\sigma_{\bar{x}}$	$1.96 \sigma_{\bar{x}}$	95% Confidence Error Band (% of $\bar{x}$)
-0.12	8	-0.0225	0.0252	0.0494	220
0.06					
0.00					
-0.06					
0.00					
-0.12					
0.06					
0.00					
-0.06	16	-0.0075	0.0202	0.0395	527
0.00					
0.12					
0.06					
-0.12					
0.00					
0.12					
-0.06					
-0.08	24	0.034	0.0261	0.051	150
0.47					
0.12					
0.03					
0.06					
0.24					
0.06					
0.03					
0.09	32	0.037	0.021	0.042	112
0.06					
0.00					
0.15					
0.17					
0.03					
0.03					
-0.15					
-0.06	40	0.02	0.023	0.045	225
0.00					
-0.06					
-0.12					
-0.05					
-0.06					
-0.12					
0.06					
0.06	48	0.0212	0.0154	0.030	151
0.00					
0.00					
0.06					
0.00					
0.00					
0.00					
0.06					

(eight or 16 samples) to compare favorably with results for the 24-hr period. The test at 10 psig, 0.31% (Table 15) shows somewhat larger error (15.7%) after 11 samples and some further reduction in error band width until the test ends after 36 samples.

Finally, a very low leakage level test (Table 16) gives negative leakage values at 4 and 8 hr (8 and 16 samples), and great uncertainty after 24 hr (48 samples). Obviously, further testing will not greatly improve estimates of the true leakage rate. However, if the specified maximum allowable leakage rate of the containment vessel during such a test were, say, 0.1%/day one could predict with 95% confidence a true leakage rate of between 0.02%/day $\pm 150\%$, or between zero and 0.05%/day and, hence, a rate within the specification.

These examples illustrate the value of confidence interval analysis in obtaining a quantitative measure of data validity. The technique is simple to use and could be employed during leakage rate tests to facilitate sound decisions on such topics as whether to extend the test duration in hopes of further reducing the error band width.

Linear Regression Analysis

The preceding sections have shown the utility of leakage data averages in test analysis. However, averages of this type formed from successive data have a serious technical deficiency. Each successive pair of instrument readings is used to calculate a leakage rate for the period by a differencing operation in which every value except the first and last is used twice and cancels out. The procedure then gives the same numerical result for the average or mean value obtainable from only the first and last points. Since the first and last points cannot be shown to be any better

statistically than the others, the mean is not the best available estimate for the vessel leakage rate.

The foregoing can be simply illustrated as follows. The reference method calculation is used as an example, but the same reasoning applies to the absolute method calculation. Each leakage rate calculation performed for the reference method consists of two differential pressure readings which determine the fraction of the pressure loss to total pressures, P .

$$L_j = K \frac{\Delta P_j - \Delta P_{j-1}}{P}$$

where K = constant containing engineering units and time conversion to 24-hr leakage rate.

If P is essentially constant over a short testing interval, then

$$L_j = K' (\Delta P_j - \Delta P_{j-1})$$

If the sum of individual observations is formed for an average, there results

$$\bar{L} = \frac{\sum L_j}{N} = \frac{K'}{N} \sum_{j=1}^n (\Delta P_j - \Delta P_{j-1})$$

or

$$\bar{L} = \frac{K'}{N} \left\{ (\Delta P_1 - \Delta P_0) + (\Delta P_2 - \Delta P_1) \dots + (\Delta P_{n-1} - \Delta P_{n-2}) + (\Delta P_n - \Delta P_{n-1}) \right\}$$

$$\bar{L} = \frac{K}{N} \left\{ \Delta P_n - \Delta P_0 \right\}$$

which is the equivalent of having read only the first and last differential pressures and divided by the total number of samples (time conversion being included in the constant).

This deficiency can be avoided by the use of linear regression analysis, as proposed and practiced in at least

one leakage rate test of a reactor containment vessel.⁽⁸⁾ The best estimate of the leakage rate is a line through all the data points minimizing the sum of squares of deviations of each observed point from the line. This line is the "least squares" line. The following sketch illustrates the application of the least squares line and the mean of individual results to the same scattered data points for a reference method leakage rate test. Note that the choice of the first and last data point can significantly affect the mean leakage rate when scattered data is used.

In order to permit application of the least squares analysis, the leakage rate test data taken at each reading time is converted to a quantity other than percentage weight loss per day. Cumulative weight loss, total contained weight, or cumulative pressure drop can be used as a variable with time. The problem becomes one of fitting a straight line to a set of n points whose y coordinates are known to have random errors

due to instrumentation sensitivities, and possibly others of a random nature. Each of these points is assumed to have the same degree of reliability as any other in terms of an absolute value. The slope of the line gives the leakage rate. The function to be fitted is of the form

$$y_i = a + b x_i$$

If the sum of the squares of the deviations are formed and the conditions for a minimum solved for a and b, there results

$$b = \frac{\overline{xy} - \bar{x}\bar{y}}{(\bar{x})^2 - \bar{x}^2}$$

$$a = \bar{y} - b \bar{x}$$

where y is the observed value, $\bar{x}$ denotes the average value of x, $\overline{xy}$ is the average of the products xy, and so on.

The confidence intervals for the slope of a line can be determined so that an estimate of the reliability of the leakage rate indicated by this slope can be obtained. The following tabulations of data summarize the results obtained when several tests were treated with the least squares method for progressive intervals of test duration (8, 16, and 24 hr). As in any statistical estimate, the accuracy of the test should improve as the number of samples (hourly readings) increase. The nature of the calculations involved in these curve fits is tedious and repetitive. Consequently, computer programs are usually used to do the arithmetic. A copy of the program used for these results and an example of input are included in Appendix D of this report.

The results in Table 17 show that surprisingly good confidence intervals can be obtained with 24 data points in all cases except the 15 psig 0.1% test. Examination of the raw data used for the absolute calculations in this test show a

TABLE 17. *Least Squares Fits of Absolute Data*

<u>Test</u>	<u>Elapsed Time, hr</u>	<u>Nominal Leakage Rate, %/day</u>	<u>95% Conf. Interval, %/day</u>	<u>Error, %</u>
60 psig, 1.0% 24 hr Test	8	1.073	±0.077	7.2
	16	1.083	±0.023	2.1
	24	1.083	±0.0115	1.1
35 psig, 0.5% Base Line Air Test	8	0.478	±0.028	5.9
	16	0.472	±0.020	4.2
	24	0.471	±0.011	2.3
23 psig Base Line Air Test	8	0.381	±0.088	23.1
	16	0.415	±0.032	7.7
	24	0.417	±0.016	3.8
9 psig Base Line Air Test	8	0.212	±0.029	13.7
	16	0.241	±0.006	2.5
	24	0.226	±0.005	2.3
35 psig Base Line Retest	8	0.150	±0.196	130.7
	16	0.228	±0.070	30.5
	24	0.278	±0.048	17.1
	36	0.310	±0.023	7.4
15 psig, 0.1% Test Series	8	-1.266	±0.733	58.0
	16	-0.614	±0.241	39.3
	24	-0.342	±0.1476	43.2

steady rise in pressure and a rise in temperature. The measured value of temperature increase is obviously lagging the actual value since an increase in mass rather than a decrease is indicated. A least squares analysis performed on reference method data for the 15 psig 0.1% test would determine the leakage rate by the line slope. More confidence is accorded in the closeness of this slope to the average leakage rate, assuming a normal distribution of data scatter. The slope of the pressure drop line best fitting the entire 24-hr group of data is found to be 0.011 ± 0.003 in. of water/hr, which is 0.033 ± 0.009 wt%/day or $0.033 \pm 27\%$ error at the 95% confidence level. This level expresses a 95% confidence that the true leakage rate is within 27% of 0.033 wt%/day. The data in Table 16, without minimized deviations, denotes a 95% confidence that the true leakage rate is within 150% of 0.022 wt%/day. The short dashed line in Figure 15 shows the slope of this line, and the least squares line for 24-hr test duration is also plotted.

As a final exercise, a least squares line for the first 15 hr of reference determinations is shown in Figure 15. The leakage rate by this slope is 0.06 ± 0.015 wt%/day, or about three times the leakage rate computed at the end of 24 hr. The total time needed to establish the leakage rate accurately appears to be longer than 24 hr. Perhaps several rates computed in multiples of 24-hr periods are needed to properly sample the leakage rate throughout diurnal cycles or any other influencing temperature cycle.

The influence of repetitive diurnal cycles or any cycles or any cyclic influences can be statistically accounted for with time series analyses. Nicholson⁽⁴⁾ discusses the assumptions and restrictions on such an analysis with regard to correcting the correlations of varying water vapor pressure with time. The major practical restrictions are that the tests must be lengthy (a minimum of 4 cycles or 4 days), and include only

FIGURE 15. A Linear Regression Line Fitted to Scattered Reference Data

minor changes in the pattern of the temporal cycle from day to day relative to the amplitude. These restrictions make the method impractical for most testing situations. Further analysis of dynamic cycles is beyond the scope of this report.

COMPARISON OF OBSERVED AND PREDICTED ERRORS

Absolute Method

Discussions in previous sections indicated that it is possible to estimate the error in the absolute method and reference method calculations from the errors in the measurements of the variables placed in the equation. It was also shown that the results of experiments can be treated in such a way that estimates of the reliability of the results or the error at some level of confidence can be approximated. The analysis used for estimate of instrument error is actually derived on the assumption of static measurement conditions. Application of this formula to a leakage rate test condition ignores the error in the measurement of the true value of a quantity experiencing a slight change, a considerable shortcoming in tests where only slight changes are expected in the measured variable. The response of the temperature measurement system is thought to contribute considerable error of this sort and, as a result, test errors often exceed expectations by much more than the predicted error. The data in Table 18 have been arranged to allow the error observed in results of six example tests to be compared to the error that would be predicted by using the available techniques and estimates described in this report. The measurements collected after 24 hr of testing give a value for the slope of the regression line and a corresponding error at the 95% confidence level. This error is compared to the error predicted by using the Kline and McClintock formula, and by assuming the ϵ_p to be 1.03×10^{-4} and the total error in the volume weighted average temperature to be either 0.5 °R or 1.0 °F. These conservative estimates are combined in a formula

TABLE 18. Comparison of Observed and Predicted Errors; Absolute Method Tests

Test Pressure And Leakage Level	Elapsed Time, hr	Observed Leakage Rate, %/day	95% Confidence Interval, %/day	% Error From Confidence Interval	% Error Predicted 0.5 Temp Error	Ratio: Observed to Predicted 0.5 °F Error	% Error Predicted (1.0 Temp Error)	Ratio: Observed to Predicted (1 °F Error)
60 psig, 1.0% test	24	1.082	0.0115	1.1	0.094	11.7	0.187	5.9
35 psig, 0.5%	24	0.471	0.011	2.3	0.095	24.2	0.188	12.2
23 psig, 0.4%	24	0.417	0.016	3.8	0.096	39.6	0.189	20.1
9 psig, 0.2%	24	0.226	0.005	2.3	0.100	23.0	0.191	12.0
35 psig, 0.3%	36	0.310	0.023	7.4	0.095	77.9	0.188	39.4
15 psig, 0.03%*	24	-0.342	0.148	43.2	0.098	440.8	0.190	227.4

*Leakage level is based on collected leakage for the test period because of the great uncertainty in the calculated leakage value.

to give the most probable error for the combination of estimates. Referring to Table 18, data from the 60 psig 1.0% test had a confidence interval of 0.005%/day absolute error, or 0.462% expressed as a percentage error. The percentage error predicted assuming that the spatial gradient and random error give a combined error of 0.5 °R is 0.094%. Assuming the combined temperature error is 1.0 °R, the error is 0.187%. The ratio of observed to predicted error for the latter case is $\frac{1.1}{0.187} = 5.9$. The data from the first five examples tabulated show error bands from 6 to 40 times that predicted. The remaining example is an illustration of an inadequate test. The data gathered in this testing period are such that a line fitted to the data would result in a negative leakage rate. Nonetheless, the statistical analysis leads to a reasonable estimate of the error at the 95% confidence level. However, collected leakage for the same period, the equivalent of 0.03%/day, merely serves as a reminder that statistical analysis is no guarantee of correctness. Negative leakage rates such as these are calculated frequently at low leakage rates when a rise in the bulk air temperature is felt first by the pressure sensor and later by the temperature averaging system. The practical implication of these results is that errors of an order of magnitude greater than those predicted are not only possible but even to be expected in tests of low leakage rates. Although predicted error remains relatively constant for the pressures between 9 and 60 psig, the error observed in results has a definite leakage rate dependence.

Reference Method

Table 19 has been constructed to allow comparison of the error predicted to the error observed in reference method observations. The procedure for construction of the predicted error column is to calculate and assume the error expected for a single half-hour observation to be known with 95% confidence.

TABLE 19. *Comparison of Predicted and Observed Errors - Reference Method Tests*

<u>Test Number</u>	<u>Elapsed Time, hr</u>	<u>Nominal Leakage, %/day</u>	<u>95% Confidence Interval, %/day</u>	<u>Equivalent Observed Error, %</u>	<u>Predicted Error, %</u>	<u>Ratio of Observed to Predicted</u>
35 psig, Base line air tests	8	0.3234 ±	0.109	33.7	1.12	30.1
	10	0.3746 ±	0.028	7.5	0.795	9.4
	24	0.3850 ±	0.013	3.4	0.65	5.2
23 psig, Base line air tests	8	0.5107 ±	0.131	25.7	2.02	12.7
	16	0.4317 ±	0.033	7.6	1.43	5.3
	24	0.3989 ±	0.018	4.5	1.17	3.8
9 psig, Base line air tests	8	0.2714 ±	0.014	5.2	5.05	1.03
	16	0.2651 ±	0.0047	1.8	3.58	0.50
	24	0.2575 ±	0.0032	1.2	2.92	0.41

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The error in an average of multiple readings is the error in a single reading divided by the square root of the number of observations used in the average. Note that there is no way to factor in an allowance for the bias due to failure of the reference volume to perfectly sample the containment temperature.

$$\epsilon_N = \frac{\epsilon_i}{\sqrt{N}}$$

ϵ_i = 95% confidence error in a single reading

ϵ_N = 95% confidence error in multiple readings

$$\epsilon_i = \frac{\epsilon_L}{L} = \left[\left(\frac{\epsilon_{\Delta\Delta P}}{\Delta P} \right)^2 + \left(\frac{\epsilon_t}{t} \right)^2 + \left(\frac{\epsilon_P}{P} \right)^2 \right]^{1/2}$$

The results of reference method tests in the base line air series were good. The raw data indicate that very little external influence was felt on the vessel during the test periods shown in this tabulation. As a result, the error in calculated leakage by the least squares method for the 9 psig was less than the predicted error. The explanation for this result is that an exceptionally stable test period was experienced. The results of the two previous tests were slightly more scattered and are considered more representative of the types of error experienced in reference method tests.

OTHER RESULTS AND OBSERVATIONS

Air Temperature Sampling

The results of the error analysis indicated the influence of the number of sensors involved in a weighted temperature average to be small compared to the importance of sampling error or sensor location. It is difficult to generalize on the number of sensors adequate for all specific reactor systems, since the influence of the size of the sampled area (volume factor) and the gradient within the compartment must be considered. However, since the CSE experiment employed a rather

high density of temperature sensors (1 sensor per 1600 ft³ of air) some of these considerations can be illustrated with temperature data collected during the leak test series. Table 20 shows individual sensors as the source of the 30 psig, 1.0% test series temperature data used to calculate the leakage by the absolute method, rather than the volume weighted temperature average. It is obvious from these data that good and bad sampling points do exist. Those compartments relatively insulated or poorly serviced by the air circulation system, do not adequately represent the rest of the contained air. However, those areas open and well circulated, such as the upper containment area at CSE, are fairly consistent in temperature, and multiple sensors are superfluous.

This point is further illustrated by calculation of data using either advantageous or disadvantageous locations for sensors. Calculated leakage from two groups of six sensors each will be compared to leakage calculated using all of the sensors. All combinations are volume weighted.

Sensor No.	Location	Comments
1	Top of containment vessel	} Advantageous locations, good sampling, all compartments sampled, 2 sensors in upper vessel.
26	Center of upper containment	
2	Center of Drywell	
4	Wetwell	
5	Center of accessway	
11	Bilge	
1	Top or containment	} Poor sampling, insulated chambers, great distances between sensors.
4	Wetwell	
14	Wetwell	
18	Wetwell	
28	Wetwell	
11	Bilge	

The following tabulation (Table 21) shows calculations made at several test pressures in the 0.5% test series. The data are for 24-hr periods.

TABLE 20. Absolute Calculations Using
Individual Temperature Sensors

Point No. Location	Temperature 12/14/67 at 1300, °F	Temperature 12/15/67 at 1300, °F	Leakage Calculated Individual Sensor=Li, %/day	Li/L	Error, %
1. Containment	73.16	71.70	0.245	0.85	15
3.	73.14	71.64	0.238	0.82	18
7.	72.84	71.56	0.279	0.96	4
8.	72.98	71.60	0.260	0.90	10
9.	73.06	71.50	0.226	0.78	22
13.	73.22	71.82	0.256	0.88	12
15.	73.08	71.54	0.230	0.79	21
17.	73.08	71.64	0.249	0.86	14
25.	73.08	71.60	0.241	0.83	17
26.	73.10	71.60	0.236	0.82	18
29.	72.96	71.46	0.238	0.82	18
2. Drywell	70.98	70.15	0.363	1.25	25
5. Access way	70.11	69.41	0.387	1.33	33
4. Wetwell	68.40	67.94	0.432	1.49	49
14. Wetwell	72.00	70.66	0.267	0.92	8
18. Wetwell	71.22	70.56	0.301	1.03	3
28. Wetwell	68.42	67.49	0.249	0.86	14
11. Bilge	67.47	67.11	0.450	1.55	55
30. Bilge	67.65	67.15	0.430	1.48	48
Volume weighted average	= 71.67	70.47	0.290	1.00	

TABLE 21. *Leakage Calculations Using Advantageous and Disadvantageous Sensor Locations*

<u>Date - Time</u>		<u>L</u>	<u>La</u>	<u>Ld</u>	<u>La/L</u>	<u>Ld/L</u>	<u>Comment</u>
1/7	1610	0.56	0.56	0.59	1.0	1.05	60 psig
1/8	1610	0.47	0.47	0.49	1.0	1.04	
1/9	1300	0.48	0.53	0.45	1.1	0.94	
1/11	1300	0.42	0.48	0.51	1.14	1.21	30 psig
1/15	1600	0.39	0.28	0.13	0.72	0.33	15 psig
1/16	1300	0.21	0.39	0.69	1.85	3.28	
1/17	1300	0.26	0.25	0.23	0.96	0.88	10 psig
1/18	1300	0.22	0.25	0.26	1.14	1.18	
1/19	1300	0.27	0.30	0.31	1.10	1.15	

L = Leakage calculated using all 19 sensors available.

La = Leakage calculated using only 6 sensors at good air sampling locations.

Ld = Leakage calculated using only 6 sensors at poor air sampling locations.

The implication of these calculations is that comparable results could have been obtained with fewer, reasonably located sensors. Sensors poorly located and weighted in such a way that substantial portions of the containment area are not sampled will yield poorer results, but not as drastically different as one might first expect.

Influence of Fans on Containment Atmosphere

One of the procedures frequently followed in containment testing is that of running the circulation fans in the vessel to create forced circulation. The purpose of this procedure is to dissipate temperature gradients within the vessel. Tests on the CSE vessel have been performed with no circulation and, on separate occasions, with a 2200 cfm and a 5000 cfm circulation system. Before any fan systems were installed, a 4 to 5 °F temperature difference was noted between the top and bottom of the vessel. A greater section of the vessel was at a homogeneous temperature after installation of the 2200 cfm system, but the maximum temperature from top to bottom of the vessel was still 4 to 6 °F. Later, a 5000 cfm system with a mixing duct was installed for the base line air tests. During the shakedown test, this circulation system was found to be heating up the vessel at a rate of almost 1 °F per hr. The data from the reference system during this period was useless because of the influences of the changing temperature.

The experience brings to light the possibility of fan work and fan motor heat influencing the contained atmosphere in larger systems and suggests that gains from circulation in some systems can be offset by the influence of motor heat and fan work. A practical solution for this problem is to operate fans during pressurization of the vessel and for a period of time afterward until temperature sensors indicate a relatively uniform temperature distribution. The fans would then be turned off and the test begun.

MISCELLANEOUS

In addition to the observations reported on pressure and leakage level for the formal test series, several interesting insights on matters of practical importance were gained from experiences during the test series. The following discussions relate to these experiences and their implications.

Correction for Temperature Lags Between Vessel
Airspace and the Reference Chamber

The difference in temperature between the vessel airspace and the reference chamber can be incorporated in a reference method equation developed⁽⁸⁾ and rearranged⁽⁹⁾ to the form

$$\frac{W_1 - W_2}{W_1} = \frac{\Delta T}{T_2} - \frac{\Delta T'}{T_1'} + \frac{T}{P_1 T_2} \Delta P \quad (1)$$

where $W_{1,2}$ = weights of vessel air at times 1, 2, respectively

$T_{1,2}$ = temperature of vessel air at times 1, 2 respectively

$T'_{1,2}$ = temperature of reference vessel at times 1, 2
respectively

ΔP = pressure difference between reference vessel
and containment

In an attempt to use this correction, four of the 0.1 °F platinum RDT's were attached in thermal contact with the reference vessel. The difference between the vessel volume weighted average air and the average of the RTD's on the reference tubing were to estimate the temperatures required in the formula. The result, as the following example calculations indicate was unsuccessful.

Applying the correction to a 24-hr reference observation during the 15 psig, 0.02% test, the following information is available:

2-10-67 at 0800 $\Delta P = 0.41$; $T = 533.61$; $T' = 533.80$

2-11-67 at 0800 $\Delta P = 0.58$; $T = 532.62$; $T' = 532.54$

$\Delta t = 24$ hr; $\Delta \Delta P = 0.17$; $\Delta T = 0.99$; $\Delta T' = 1.26$

$P' = 29.7$ psia

So, using Equation (1)

$$\frac{W_1 - W_2}{W_1} = \frac{0.99}{532.62} - \frac{1.26}{532.54} + \left(\frac{533.61}{532.62} \right) \frac{0.17}{(29.7)} \frac{(100)}{(27.68)} = \underline{\underline{0.029\%/day}}$$

Uncorrected

0.0207%/day

Corrected

-0.029%/day

Continuing with other attempts to correct hourly data at the same leakage level:

Uncorrected

0800

0900 - 0.029

1000 - 0.029

1100 - 0.058

1200 + 0.029

1300 - 0.029

1400 + 0.087

1500 - 0.058

1600 - 0.044

Corrected

-0.036

-0.009

-0.065

+0.035

-0.023

+0.087

-0.058

-0.051

Xenon Leak Rate Measurements

An alternate method of individual leak rate measurement was used in the nominal 0.1%/day test series. Radioactive xenon (^{133}Xe) was injected into the CSE containment vessel. After uniform concentration was attained, xenon escaping through individual leak points was caught on refrigerated charcoal traps which were then analyzed for gamma activity. The results of this analysis, calculated as leak rate in cm^3/min ,

were compared with values obtained by flowmeter. The method was evaluated for possible later use during tests with steam and air containment atmosphere leakage rate tests.

Method of Xenon Release and Sampling

Approximately 1.1 curies of ^{133}Xe were added to the CSE vessel during pressurization for the 0.1 test series. Stable xenon was first allowed to equilibrate with the ^{133}Xe in a 7.3-liter tank. The tank was pressurized to 48.7 psig with nitrogen and allowed to mix by diffusion. Aliquots were taken in a calibrated volume (8.6 cm^3) at known pressures, transferred to xenon traps, and used to check the CSE gamma counting system calibration. The balance of the xenon was transferred to the CSE vessel with a nitrogen purge just prior to the pressurization of the vessel.

Sampling the xenon concentration in the vessel atmosphere was accomplished for five sample locations in the vessel. Penetrations were used to transmit aerosol sampling to a laboratory near the counting apparatus. Uniform concentrations were found to exist a few hours after the injection. Figure 16 shows the measured concentrations during the 12-day test period.

The five measurable leaks were sampled by putting the activated charcoal-filled xenon traps on the outlets of flowmeters used at each point. A glass bead trap removed moisture from the gas to prevent plugging of the charcoal. Both the traps and glass beads were kept at dry ice temperatures. The leak rate was calculated by dividing the collected xenon activity by the sampling duration and by the average xenon concentration in the vessel. Table 22 summarizes the leak rates found by xenon collection and those measured by flowmeter. Collection duration, depending on the leak rate expected, varied from 90 to 360 min.

This method is not generally applicable to power reactor systems because of the special equipment requirements. However, the method would be practical for steam leakage measurements to be conducted at CSE, where sampling and counting facilities used in conjunction with fission product transport studies are readily available.

FIGURE 16. Measured Xenon Concentrations During 12-Day Test

TABLE 22. Leak Rate Measurements by ^{133}Xe Collection

Date 1967	CV Pressure, psig	Leak Rate, cm^3/min									
		39 DOV		32 D1		32 D2		P-23		N 44 DOV	
		T	M	T	M	T	M	T	M	T	M
1-30	60	118	80	295	175	190	137	830	828	14	17
2-1	60	63	129	230	214	192	171	880	846	--	18
2-3	46	41	76	116	125	119	113	640	565*	5	0
2-6	46	52	84	140	107	115	122	640	680	5	4.7
2-7	32	42	54	50	86	66	53	500	670	--	5.9
Average Ratio	M/T	1.5		1.02		0.88		1.05		1.1	

T = Flow measured with rotameter

M = Flow measured with ^{133}Xe collection on charcoal and gamma counting.

*Xe collected without flowmeter in sample train.

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APPENDIX A
CALENDAR OF TEST EVENTS
CSE LEAKAGE RATE TESTS

APPENDIX A

CALENDAR OF TEST EVENTSCSE LEAKAGE RATE TESTS

Date	Comment
December 1966	
6	Began official series L-2 at 1300. 62.95 psig, ~1.0%/day.
7	Began at 0800 to record data for two days every hour on the hour until 12-9-66 @1300.
9	Reduced pressure to 31.6 psig @1530 p.m. 1% test series was continued.
13	Reduced pressure at 1445 p.m. to 10.4 psig. 1% test was continued.
20	Exhausted vessel to end the 10 psig, 1% run #1. Left exhausting over night.
21	Repressurized to 10 psig nominal @ 1130. Continued testing during Christmas holidays for the second run at 10 psig during 1.0% test series.
January 1967	
3	Exhausted vessel by 1145. End of 10 psig, 1% series.
4	Refilled vessel to 63 psig and began 63 psig, 0.5% test series at 1300 hours.
9	Reduced pressure, began 32 psig, 0.5% test series at 1300 hours.
12	Reduced pressure to 15.5 psig and began 15.5 psig, 0.5% test series. Contacts on Mueller bridge found to be dirty. Removed and repaired.
16	End of 15.5 psig, 0.5% test @ 1300. Began 10.3 psig test @1530 hours.
19	End of 10.3 psig test @1530. Opened ~ 0.19%/day leak for instrument sensitivity test.
20	End of sensitivity test @1300. Started 5.4 psig test @1530.
23	End of 5.4 psig test @1300. Started 1 psig test @1530.
26	End of 1.0 psig test and the 0.5% test series @1300.
27	Repressurized to 62.5 psig. Leakage still set @0.5%

Date	Comment
January 29	Power failure on the weekend.
30	Extra leak due to 3/8-in. line removed by construction. Began 0.1% test at 1300 hours. A xenon sample was also drawn, and 21.6 scf were removed from vessel.
February 1967	
1	Continued 62 psig, 0.1% testing. Changed precision pressure gage capsule to 0-100 psia range. Withdrew 22 scf @1355 hours during xenon tests.
2	End of 62 psig, 0.1% test @1300. Began psig testing.
3	Xenon sampling test performed. Withdrew 20 scf from vessel.
6	End of 46 psig testing in 0.1% test series. Began 31.4 psig test @1530. Xenon sampling again conducted. 12 scf withdrawn from vessel.
7	Xenon sample again conducted. Withdrew 20 scf.
9	End of 31 psig testing @1300. Depressurized to 15.4 psig by 1530.
10	Began 24-hr observation test @0800. This data gathered during 0.1%/day test series at 15 psig. The nominal leakage rate was about 0.02%/day.
11	End of 24-hr test @0800.
14	Depressurized to ~10 psig @1600. Changed precision pressure gage capsule to 0-25 psia range.
17	Depressurized to ~5 psig @1600. 10 psig testing completed.
21	Depressurized to ~1 psig. 5 psig testing completed.
24	1 psig testing completed. The vessel was then repressurized to 30 psig for a repeat of test on 2-6-9.
27	30 psig repeat test completed.

Note: Began Dec. 6, 1966 @1300 hours.

Ended Feb. 27, 1967 @0800 hours.

Test duration was 82 days and 19 hours.

APPENDIX B
SAMPLE DATA

APPENDIX B

SAMPLE DATA

The data given in this appendix are provided as a sample of the data reduction involved in the leakage tests described in this report. Referring to Page B-2, raw data are tabulated on data sheet at the time noted and in the order top to bottom. Data from these sheets are transposed and reduced (see Pages B-3 and B-4), first by volume weighting the temperature sensors, then correcting and volume-weighting of the humidity data (using 2 supplementary correction charts and a water vapor versus temperature plot). Finally, the correction to the pressure readings is done and the results used in an absolute leakage calculation (see page B-5).

Data for the reference vessel leakage calculation are recorded directly on the sheet shown in page B-6. The total pressure in column (5) is recorded from the Texas Instrument pressure device and a correction factor applied to the reading. This is the explanation for two readings appearing in each block in column (5). The top reading is the pressure, and the bottom reading is the raw gage reading. When a single number is recorded, it is the converted pressure.

Individual leakages are recorded on a sheet carried on a clipboard by the leak checker (Page B-7). The raw rotameter reading is recorded, and the corresponding flowrate for that rotameter reading is obtained later, and the sum of all individual leakages converted to the equivalent weight percent leakage per day.

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OPERATING PROCEDURE

LEAKAGE TEST DATA SHEET

INSTRUMENT READINGS

Date	Time	12-6-66	12-7-66	12-7-66	12-7	12-7	12-7
		1300	0800	0900	1000	1100	1200
Barometer Reading		28.61	28.86	28.88	29.90	28.89	28.87
Mercury Manometer		—	—	—	—	—	—
Manometer Temperature		—	—	—	—	—	—
Absolute Press. Gage		77.15	76.42	76.38	76.35	76.32	76.32
Texas Inst. Gage		78.322	77.579	77.545	77.510	77.484	77.460
Inclined Manometer		.815	—	—	—	—	—
Static Pressure		64	63	63	62	63	63
Controlled Bleed Rate		—	—	—	—	—	—
Ni Wire Resistance		80.058	79.939	79.980	79.925	79.970	79.999

Switch No.	Sensor	Humidity / Temperature					
1	1927	100 71	99 70	99 70	100 70	100 70	100 70
2	1930	92.5 72	84.5 73	84 73	83 72.5	82 73	82 73
3	1924	86 74	62.5 76	62.5 76	62 76	61.5 76	62 76
4	1923	93 73	84 74	83.5 73	83 73	82 73	84 74
5	1928	>100 72	>100 71	>100 72	>100 70	>100 70	>100 70
6	1929	>100 68	>100 68	>100 68	>100 68	>100 68	>100 68
7	1926	>100 76	>100 75	>100 74	>100 74	>100 73	>100 73

Switch No.	Bridge	Rosemount RTD					
001	811	11.14	11.95	11.94	11.95	11.99	12.02
002	812	9.36	8.41	8.39	8.38	8.37	8.37
003	813	10.34	10.41	10.42	10.48	10.55	10.59
004	814	8.27	7.77	7.76	7.75	7.78	7.80
005	815	8.47	7.84	7.82	7.83	7.87	7.87
006	816	11.21	12.11	12.03	12.07	12.14	12.19
007	817	10.52	10.60	10.64	10.68	10.74	10.76
008	818	11.22	12.12	12.10	12.11	12.17	12.21
009	819	9.90	9.69	9.69	9.72	9.81	9.85
011	801	8.32	7.72	7.68	7.68	7.69	7.71
012	802	10.54	10.62	10.64	10.68	10.76	10.79
013	803	9.87	9.78	9.71	9.71	9.98	9.95
014	804	8.51	7.82	7.79	7.79	7.71	7.82
015	805	10.10	10.13	10.13	10.18	10.23	10.31
016	806	8.87	7.94	7.91	7.90	7.99	7.88
017	807	10.61	11.38	11.37	11.37	11.40	11.41
018	808	8.47	7.82	7.80	7.80	7.82	7.83
020	810	10.07	9.99	9.99	10.00	10.11	10.12
025	795	10.46	10.57	10.57	10.65	10.72	10.72
026	796	10.41	10.51	10.52	10.57	10.64	10.68
027	797	8.44	7.82	7.81	7.81	7.79	7.86
028	798	8.15	7.63	7.62	7.64	7.69	7.70
029	799	9.67	9.49	9.50	9.52	9.67	9.64
030	800	8.09	7.68	7.68	7.66	7.69	7.70
Initial		UIC	UIC	UIC	UIC	UIC	UIC

RTD 545 → 68.85
68.67 68.58 68.57 68.61 68.73 68.59
68.50 68.40 68.37 68.47

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OPERATING PROCEDURE

LEAKAGE TEST DATA SHEET

Test No. 6.2

TEMPERATURE-PRESSURE-HUMIDITY-CORRECTION

(Rosemount)

Switch	RTD	Bridge	Location	Millivolts	Volume Factor	Vi (X) mVi
001	892	811	Beam, all the way		.0476	
002	893	812	Dry-well		.0745	
003	894	813	Dry-well 12' up		.0476	
004	896	814	Wet-well 145°		.0343	
005	897	815	Access way 8' down		.0807	
006	898	816	Top Ref. tubing		---	
007	899	817	Beam 9' down		.0476	
008	978	818	Upper dome		.0667	
009	979	819	Dry-well 3' up		.0475	
011	882	801	Bilge		.0487	
012	883	802	Beam 12' down on Ref.		---	
013	884	803	Dry-well 6' up		.0475	
014	885	804	Wet-well 90°		.0343	
015	886	805	Dry-well 9' up		.0475	
016	887	806	Read & omit		---	
017	888	807	Beam 6' down		.0476	
018	889	808	Wet-well 200°		.0343	
020	891	810	6' up Ref. tubing		---	
025	961	795	Beam 3' down		.0476	
026	962	796	Beam 12' down		.0476	
027	963	797	Access Ref. tubing		---	
028	964	798	Wet-well 50°		.0343	
029	965	799	Dry-well 2 1/2'		.1150	
030	966	800	Bilge		.0489	

Date 12-7-66 Time 0900 From (OP 7.4.8) Sum 68.57
 Initial (From Graph T-2 Converted Avg. Temp.)

Initial Ni Wire Resistance 77.980 Ni Wire Avg. Temp. 63.7

(1) Hum. Sensor Switch-No.	(2) Hum. Ind. Read	(3) Temp. Ind. Read °F	(4) % R H (2) From H-1	(5) Hum. (3) Corr. From H-2	(6) Corr % R H (4)+(5)	(7) Pw Sat. (3) From H-3	(8) Pw (6)X(7) 100	(9) Volume Factor	(10) Vi Pwi (8)X(9)
1 - 1927	99	70	94	+ 1.50	95.5	.74	.7067	.1371	.0968
2 - 1930	84	73	86	+ 1.05	87.05	.82	.7139	.2033	.1451
3 - 1924	62.5	76	76	+ .60	76.60	.905	.6932	.2033	.1409
4 - 1923	83.5	73	85.5	+ 1.05	86.55	.82	.7097	.2034	.1444
5 - 1928	100	70	94	+ 1.50	95.5	.74	.7067	.0745	.0526
6 - 1929	100	68	94	+ 1.80	95.8	.69	.6610	.0977	.0646
7 - 1926	100	74	94	+ .90	94.9	.845	.8019	.0807	.0647

Date 12-7-66 Time 0900 From (OP 7.4.8) Sum = Pressure Correction For
 Initial Humidity in Mercury Abs. .7091

From (OP 7.4.8)	Units	Reading
Manometer Temperature	°F	73
(1) Absolute Pressure (Gage)	Psia	76.38
(2) Mercury Manometer	in. Hg (70F)	---
(3) Barometer Reading	in. Hg (70F)	---
(4) Absolute Pressure (2)+(3)	in. Hg (70F)	---
(5) Correction for Humidity	in. Hg (70F)	.7091
(6) Corrected Abs. Press. (4)-(5)	in. Hg (70F)	---
(7) Texas Inst. Gage (77.545)	Corr. Psia	76.276
Initial <u> </u>		

X 2.044 156.1207 in. Hg
 (5) .7091 in. Hg
 (1)-(5) 155.4116 in. Hg
 X 2.044 155.9081 in. Hg
 (5) .7091 in. Hg
 (7)-(5) 155.1990 in. Hg

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OPERATING PROCEDURE

LEAKAGE TEST DATA SHEET

Test No. L-2

TEMPERATURE-PRESSURE-HUMIDITY-CORRECTION

(Rosemount)

Switch	RTD	Bridge	Location	Millivolts	Volume Factor	Vi (X) mVi
001	892	811	Beam, all the way		.0476	
002	893	812	Dry-well		.0745	
003	894	813	Dry-well 12' up		.0476	
004	896	814	Wet-well 145°		.0343	
005	897	815	Access way 8' down		.0807	
006	898	816	Top Ref. tubing		---	
007	899	817	Beam 9' down		.0476	
008	978	818	Upper dome		.0667	
009	979	819	Dry-well 3' up		.0475	
011	882	801	Bilge		.0489	
012	883	802	Beam 12' down on Ref.		---	
013	884	803	Dry-well 6' up		.0475	
014	885	804	Wet-well 90°		.0343	
015	886	805	Dry-well 9' up		.0475	
016	887	806	Read & omit		---	
017	888	807	Beam 6' down		.0476	
018	889	808	Wet-well 200°		.0343	
020	891	810	6' up Ref. tubing		---	
025	961	795	Beam 3' down		.0476	
026	962	796	Beam 12' down		.0476	
027	963	797	Access Ref. tubing		---	
028	964	798	Wet-well 50°		.0343	
029	965	799	Dry-well 2 1/2'		.1150	
030	966	800	Bilge		.0489	

Date 12-7-66 Time 0800 From (OP 7.4.8)Initial 68.58 (From Graph T-2 Converted Avg. Temp.) SumInitial 77.930 Ni Wire Resistance 77.930 Ni Wire Avg. Temp. = 68.58

(1) Hum. Sensor Switch-No.	(2) Hum. Ind. Read	(3) Temp. Ind. Read °F	(4) % R H (2) From H-1	(5) Hum. (3) Corr. From H-2	(6) Corr. % R H (4)+(5)	(7) Pw Sat. (3) From H-3	(8) Pw (6)X(7) 100	(9) Volume Factor	(10) Vi Pwi (8)X(9)
1 - 1927	99	70	94	+1.5	95.5	.74	.7667	.1371	.0939
2 - 1930	84.5	73	86	+1.05	87.05	.82	.7138	.2033	.1451
3 - 1924	62.5	76	76	+1.65	76.65	.955	.6932	.2033	.1409
4 - 1923	84	74	86	+1.90	86.90	.845	.7343	.2034	.1482
5 - 1928	100	71	94	+1.35	95.35	.765	.7290	.0745	.0544
6 - 1929	100	68	94	+1.80	95.8	.69	.6610	.0977	.0544
7 - 1926	100	75	94	+1.75	94.75	.875	.8291	.0807	.0669

Date 12-7-66 Time 0800 From (OP 7.4.8) Sum =Initial 46 Humidity in Mercury Abs. .7181

From (OP 7.4.8)	Units	Reading
Manometer Temperature	°F	73
(1) Absolute Pressure (Gage)	Psia	76.42
(2) Mercury Manometer	in. Hg (70F)	---
(3) Barometer Reading	in. Hg (70F)	---
(4) Absolute Pressure (2)+(3)	in. Hg (70F)	---
(5) Correction for Humidity	in. Hg (70F)	.7121
(6) Corrected Abs. Press. (4)-(5)	in. Hg (70F)	---
(7) Texas Inst. Gage (77.579)	Corr. Psia	76.3093
Initial <u>46</u>		

X 2.044 156.2025 in. Hg
 (5) .7181 in. Hg
 (1)-(5) 155.4844 in. Hg

X 2.044 155.9772 in. Hg
 (5) .7181 in. Hg
 (7)-(5) 155.2591 in. Hg

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LEAKAGE TEST DATA SHEET

LEAKAGE RATE CALCULATION - ABSOLUTE METHOD

Test number L-2 Date 12-7-66 Time 1930 Initial FPD

Date 12-7-66 Date 12-7-66
 From (t_1) 0800 To (t_2) 0900 $\Delta t =$ 1 hours.

T_1 68.58 T_2 68.57

$T'_1 = 460 + (T_1) =$ 528.58

$T'_2 = 460 + (T_2) =$ 528.57

$$\frac{T'_1}{T'_2} = \underline{1.000019}$$

P_2 155.4116 P_1 155.4244 $\frac{P_2}{P_1} =$.999532

$$\frac{T'_1}{T'_2} \times \frac{P_2}{P_1} = \frac{1.000000}{.999551} = \underline{(0.000449)}$$

$$L = \frac{2400}{\Delta t} \times (0.000449) = \underline{1.08} \text{ \%/day}$$

Set Leakage %

Nomenclature:

t_1 = First date and time	From OP 7.4.3
t_2 = Final date and time	From OP 7.4.3
Δt = Number of hours	From (t_1) to (t_2)
T_1 = First corr. avg. temp. ($^{\circ}\text{F}$)	From OP 7.4.3 @ time (t_1)
T_2 = Final Corr. avg. temp. ($^{\circ}\text{F}$)	From OP 7.4.3 @ time (t_2)
T'_1 = First average temp. ($^{\circ}\text{R}$)	
T'_2 = Final average temp. ($^{\circ}\text{R}$)	
P_1 = First corr. avg. press. (Abs)	From OP 7.4.3 @ time (t_1)
P_2 = Final corr. avg. press. (Abs)	From OP 7.4.3 @ time (t_2)
L = Leakage rate.	

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OPERATING PROCEDURELEAKAGE TEST DATA SHEETLEAKAGE RATE CALCULATION - REFERENCE SYSTEM METHODTest Number 21, P1Vessel Pressure 60 psia

	(1)	(2)	(3)	(4)	(5)	(6)	
Date	Time (Hour)	Δt (Min)	ΔP (in.w.c.)	$\Delta \Delta P$ (in.w.c.)	P' (psia)	L (%/day)	Initial
12-7-66	0812	—	.07		76.82 77.570	—	M.E.W.
	0914	62	.95	.91	76.36 77.534	.99	M.E.W.
	1016	62	1.89	.94	76.32	1.03	
	1017	—	.04	—	76.32	—	M.E.W.
	1117	60	1.01	.95	76.32	1.07	M.E.W.
	1204	47	1.75	.74	76.32	1.07	M.E.W.
	1205	61	.05	—	76.30	—	M.E.W.
	1310	65	1.05	1.00	76.25 77.410	1.049	WR
	1311	—	.05	—	76.25	—	
	1530	139	1.96	1.91	76.16 77.228	.94	M.E.W.
	1531		.05		76.18 77.245	—	
	1631	60	.970	.92	76.12 77.211	1.05	R1
	1731	60	1.905	.935	76.11 77.245	1.06	R1

Calculation of L:

$$L = \frac{5.2 \times 10^3 \Delta P}{P' \Delta t}$$

Nomenclature:

- (1) Clock time.
- (2) Difference between successive lines of column (1) in minutes.
- (3) Scale reading of the inclined manometer, inches water column.
- (4) Difference between successive lines of column (3).
- (5) Reading of the absolute pressure gage, psia.
- (6) L = Leakage rate - %/day.

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LEAKAGE TEST DATA SHEET

Test Number

FLOW RATE AT INDIVIDUAL LEAKS

Date	12-8-66	12-8-66	12-9-66
Time	0930	1815	0130
Vessel Pressure	61	61	61
Initial	WR	882.	1405

[illegible]

APPENDIX C
EQUATIONS AND NOMENCLATURE

APPENDIX C

EQUATIONS AND NOMENCLATURELeak Rate Formulas Based on the Perfect Gas Law :

$$PV = \omega RT \text{ or } \omega = \frac{PV}{RT} = K \frac{P}{T}$$

where

$$K = \frac{V}{R}$$

P = Absolute Pressure

T = Absolute Temperature

t = Time

Weight Loss with Time; at Times 1 and 2 as a Fraction of the Weight at Time 1

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{\omega_1 - \omega_2}{\omega_1}$$

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{\frac{P_1}{T_1} - \frac{P_2}{T_2}}{\frac{P_1}{T_1}} \cdot \frac{1}{\Delta t}$$

and

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{1}{\Delta t} \left(1 - \frac{T_1}{T_2} \frac{P_2}{P_1} \right)$$

The Form for the Absolute Method.

Percent Weight Lost in 24 Hours = L%

$$L\% = \frac{24 \times 100}{t(\text{hours})} \left(1 - \frac{T_1}{T_2} \frac{P_2}{P_1} \right)$$

Reference Method:

Weight Loss Fraction;

$$\frac{\Delta \omega}{\omega} = \frac{\omega_1 - \omega_2}{\omega_1} = 1 - \frac{P_2}{P_1} \frac{T_1}{T_2}$$

Assuming the Reference Vessel Follows the Temperature of Vessel Contents:

$$P_{R_1} V_R = \omega R T_1 \quad P_{R_1} = \text{Pressure of Reference Vessel at Time 1}$$

$$P_{R_2} V_R = \omega R T_2 \quad V_R = \text{Volume of the Reference Vessel}$$

and

$$\frac{P_{R_1}}{P_{R_2}} \frac{V}{R} = \frac{\omega R T_1}{\omega R T_2} ; \frac{P_{R_1}}{P_{R_2}} = \frac{T_1}{T_2}$$

If ΔP is the Difference Between the Pressure of the Containment and Reference Vessels;

or

$$\begin{aligned} \Delta P &= P_R - P_C \\ P_R &= P_C + \Delta P \end{aligned}$$

and

$$\begin{aligned} P_{C_1} &= P_1 \\ P_{C_2} &= P_2 \end{aligned}$$

then

$$\frac{T_1}{T_2} = \frac{P_{R_1}}{P_{R_2}} = \frac{P_1 + \Delta P_1}{P_2 + \Delta P_2}$$

$$\frac{\Delta \omega}{\omega} = \frac{\omega_1 - \omega_2}{\omega_1} = 1 - \frac{P_2}{P_1} \left(\frac{P_1 + \Delta P_1}{P_2 + \Delta P_2} \right)$$

Fractional Weight Loss with Time:

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{1}{\Delta t} \left[1 - \frac{P_2}{P_1} \left(\frac{P_1 + \Delta P_1}{P_2 + \Delta P_2} \right) \right]$$

Reference Method - Continued

Completing the Square:

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{1}{\Delta t} \left[1 - \frac{P_2}{P_1} \left\{ \frac{P_1}{P_2} + \frac{\Delta P_1}{P_2} - \frac{\Delta P_2}{P_2} \frac{P_1}{P_2} \right\} \right]$$

For Short Test Periods

$$P_2 \cong P_1 \text{ and } \frac{P_2}{P_1} \cong 1; \frac{P_1}{P_2} \cong 1$$

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{1}{\Delta t} \left[1 - 1 + \frac{\Delta P_1 - \Delta P_2}{P_1} \right]$$

$$\frac{\Delta \omega}{\omega} \cdot \frac{1}{\Delta t} = \frac{1}{\Delta t} \frac{\Delta (\Delta P)}{P_1}$$

This is the CSE Form with Engineering Units:

$$L(\%)/\text{day} = \frac{1}{\Delta t} \frac{\Delta (\Delta P)}{P_1 (\text{psi})} (\text{in. H}_2\text{O}) \cdot 1.44 \times 10^3 / \text{day} \frac{1}{27.68} (100)$$

$$L = \frac{5.2 \times 10^3 \Delta \Delta P (\text{in H}_2\text{O})}{\Delta t(\text{min}) P(\text{psi})}$$

Extrapolation Formulas

$$(1) \quad L_r = \omega_r \cdot \frac{R_a T_a}{P_a V}$$

where

L_r = Leakage Rate for a 24-Hour Period

$\omega_r = \omega_0 - \omega_1$ = Weight of Air Escaping in a 24 hr. Period.

P_a = Absolute Pressure of Containment Air

T_a = Temperature of the Air

R_a = Gas Constant for Air

An Extrapolation Factor is Expressed as a Dimensionless Ratio of Leakage Rates at two Conditions of Interest

L_E = Leakage Rate at Extrapolated Conditions

L_t = Leakage Rate at Test Conditions

Therefore the Factor of Extrapolation is Expressed Conviently as:

$$\frac{L_E}{L_t}$$

The Possibilities for Flow with Pressure have been Reduced to a Form with all Factors Except Pressure in a Single Constant K^{15}

(a) Molecular Flow

$$L_r = K_m \left[1 - \frac{1}{\bar{P}_a} \right]$$

where $\bar{P}_a$ = Upstream Absolute Pressure at the Leak

(b) Laminar Flow

$$L_r = K_L \left[\bar{P}_a - \frac{1}{\bar{P}_a} \right]$$

(c) Turbulent Flow, Rough Passage

$$L_r = K_{tr} \left[1 - \frac{1}{\bar{P}_a^2} \right]^{1/2}$$

(d) Turbulent Flow, Smooth Passage

$$L_r = K_{ts} \left[1 - \frac{1}{\bar{P}_a^2} \right]^{4/7} \bar{P}_a^{1/7}$$

(e) Compressible Flow Through Orifice Leaks

$$\begin{aligned} \bar{P}_a < 1.9 \text{ atm} \quad L_r &= K_0 \frac{1}{\bar{P}_a^{0.715}} \left[1 - \frac{1}{\bar{P}_a^{0.286}} \right]^{1/2} \\ \bar{P}_a \geq 1.9 \text{ atm} \quad L_r &= 0.259 K_0 \end{aligned}$$

Substitution of any of These Cases into Formula (1) Results in an Extrapolation Formula Suitable for a Single Flow Regime. For and Example, Laminar:

$$\frac{L_E}{L_t} = \frac{\left(1 - \frac{1}{\bar{P}_2} \right)}{\left(1 - \frac{1}{\bar{P}_t} \right)} = \frac{\left(1 - \frac{1}{\bar{P}_E} \right)}{\left(1 - \frac{1}{\bar{P}_t} \right)}$$

Regression Relations (1), (2), (3)

$$\bar{X} = \frac{\sum X_i}{N}$$

$$\bar{Y} = \frac{\sum Y_i}{N}$$

$$Y' = \text{Regression Line} = a + bX$$

where

$$b = \frac{n \sum X_i Y_i - \sum X_i \sum Y_i}{n \sum X_i^2 - (\sum X_i)^2}$$

$$a = \bar{Y} - b\bar{X}$$

Variance of Regression is Given by:

$$S_{YX}^2 = \frac{\sum Y_i^2 - a \sum Y_i - b \sum X_i Y_i}{N-2}$$

$$S_X^2 = \frac{\sum X_i^2 - \frac{(\sum X_i)^2}{N}}{N-1} ; S_Y^2 = \frac{\sum Y_i^2 - \frac{(\sum Y_i)^2}{N}}{N}$$

Confidence Interval for the Slope b

$$b \pm t_{\alpha/2} \frac{S_{YX}}{\sqrt{N}}$$

Where t = Small Sample Distribution Factor

$$100(1 - \alpha) = \text{Confidence Interval}$$

$$\text{i.e. for 95\%, } \alpha = 0.05$$

- (1) Hirsch, Werner F. Introduction to Modern Statistics MacMillian Company New York, N.Y. 1956 4th Edition pp. 247-275
- (2) Hoel, Paul G. Introduction to Mathematical Statistics, John Wiley & Sons Inc. New York, N.Y. 2nd Edition pp. 229-231
- (3) Busch, J.S. and Hautala, H.W. Experimental Gas Cooled Reactor, Containment Shell Leak Rate Test Kaiser Engineers, Oakland, California

For Individual Leakage:

A convenient volumetric flow rate unit is $\frac{\text{atm. cm}^3}{\text{sec}}$ and making the appropriate substitutions for units;

$$q \frac{\text{atm. cm}^3}{\text{sec}} = 3.28 (L\%/day) V (K \text{ ft}^3) \bar{P} (\text{atm. abs.})$$

Conversely, %/day leakage equivalent to a given $\frac{\text{cm}^3}{\text{sec}}$ leak is:

$$L(\%/day) = \frac{3 \cdot q \left(\frac{\text{atm. cm}^3}{\text{sec}} \right)}{10 V (K \text{ ft}^3) \bar{P} (\text{atm. abs.})}$$

other volumetric flow rate units are:

$$1 \text{ atm} \frac{\text{cm}^3}{\text{sec}} = 0.127 \frac{\text{scf}}{\text{hr}} = 3.05 \frac{\text{scf}}{\text{day}}$$

2000-2001

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APPENDIX D
DATA REDUCTION PROGRAMS

APPENDIX D

DATA REDUCTION PROGRAMS

LEASTS

The program LEAST is used to get the least squares data fit for data once it has been collected and reduced. The program requires a data card for each data pair, usually the lbm in the vessel and elapsed time referenced to the start of the test. The slope of the regression line is obtained from standard linear regression formula. The confidence interval for the slope is calculated using the formula

$$b - \beta = \frac{t}{\sqrt{\frac{(m - 2) \sum (x_i - \bar{x})^2}{(Y_i - y')^2}}}$$

$b - \beta$ is the difference between the estimated slope and the population slope.

t = students t distribution factor for small numbers of samples (the z factors in the program are a tabulation of these factors).

x_i, Y_i = individual data points.

y' = y 's calculated using the estimated slope and intercept.

Pages D-2 to D-4 give a listing of the program and a sample output obtained.

Two other programs were used during the course of the tests for the purpose of reducing data. These two programs were written for the PDP-7, a small digital computer in the vicinity of the leak test equipment.

The first program (TEMROU) accepts the typed in signals for each RTD in millivoltage and responds with the volume-weighted temperature average after substitution into the second order calibration function(Pages D-6 and D-7). The second (REFF)

accepts the differential pressure, total pressure, and elapsed time, and responds with the calculated reference method leakage (Page D-8).

C...PROGRAM LEAST

C*****THIS PROGRAM FITS DATA TO A CURVE OF THE FORM $Y=A+BX$

C*****TO USE THIS PROGRAM THE FIRST DATA CARD MUST CONTAIN THE NUMBER

C*****OF DATA PAIRS (FORMAT I4)

C*****THE OTHER DATA CARDS MUST CONTAIN THE X Y PAIRS WITH X PUNCHED IN

C*****THE FIRST 20 COLUMNS AND Y IN THE SECOND TWENTY.

C*****THIS PROGRAM WILL ACCEPT ANY NUMBER OF SETS OF DATA, AS LONG AS

C*****THE FIRST CARD IN EACH SET CONTAINS THE EXACT NUMBER OF DATA PAIRS.

C*****THIS PROGRAM WILL GIVE THE CONSTANTS A AND B ALONG WITH THE

C*****CONFIDENCE INTERVAL.

```

1  FORMAT(I4,10A6)
4  FORMAT(1X,3H1= ,E20.8,/1X,3HM= ,E20.8,/1X,4HSX= ,E20.8,/1X,4HSY= ,
    1E20.8,/1X,5HSX2= ,E20.8,/1X,5HSY2= ,E20.8,/1X,5HSXY= ,E20.8/
    11X,4HCI= E20.8//)
5  FORMAT(1H , 10X,1HX,20X,1HY,20X,4HF(X))
6  FORMAT(1H ,3E20.8)
7  FORMAT(2F20.8)
100 FORMAT(1H1,10A6)
    DIMENSION YOFX(50)
    DIMENSION Z(35)
    DIMENSION X(50),Y(50)
20  READ(5,1)N,ANAME
    DO 10 I=1,N
        READ(5,7)X(I),Y(I)
10  CONTINUE
    AN=N
    YB=0.0
    XB=0.0
    XX=0.0
    SXY=0.0
    SX=0.0
    SY=0.0
    SX2=0.0
    SY2=0.0
    DO 3 J=1,N
        XB=XB+X(J)
        SXY=SXY+X(J)*Y(J)
        SX=SX+X(J)
        SY=SY+Y(J)
3  SX2=SX2+(X(J))**2
    SY2=SY2+(Y(J))**2
    XB=XB/AN
    SXI2=(SX)**2
    A=(SY*SX2-SXY*SX)/(AN*SX2-SXI2)
    B=(AN*SXY-SX*SY)/(AN*SX2-SXI2)
    DO 31 I=1,N
        XX=(X(I)-XB)**2+XX
        YOFX(I)=A+B*X(I)
        YB=YB+(Y(I)-YOFX(I))**2.0

```

```

31 CONTINUE
  T=((AN-2.0)*(XX)/(YB))**0.5
  Z( 1)=0.0
  Z(02)=0.0000
  Z(03)=12.706
  Z(04)=4.3030
  Z(05)=3.182
  Z(06)=2.7760
  Z(07)=2.5710

  Z(08)=2.4470
  Z(09)=2.3650
  Z(10)=2.3060
  Z(11)=2.2620
  Z(12)=2.2280
  Z(13)=2.2010
  Z(14)=2.1790
  Z(15)=2.1600
  Z(16)=2.1450
  Z(17)=2.1310
  Z(18)=2.1200
  Z(19)=2.1100
  Z(20)=2.1010
  Z(21)=2.0930
  Z(22)=2.0860
  Z(23)=2.0800
  Z(24)=2.0740
  Z(25)=2.0690
  Z(26)=2.0640
  Z(27)=2.0600
  Z(28)=2.0560
  Z(29)=2.0520
  Z(30)=2.0480
  Z(31)=2.0450
  Z(32)=1.9600
  M=N
  IF (M.GE.32) M=32
  CI=Z(M)/T
  WRITE(6,100) ANAME
  WRITE(6,5)
  DO 12 I=1,N
12 WRITE(6,6)X(I),Y(I),YOFX(I)
  WRITE(6,4) A,B,SX,SY,SX2,SY2,SXY,CI
  GO TO 20
END

```

60 PS

	X	Y	F(X)
	-.00000000	.11674740+05	.11675252+05
	.10000000+01	.11670760+05	.11669985+05
	.20000000+01	.11664800+05	.11664718+05
	.30000000+01	.11658840+05	.11659451+05
	.40000001+01	.11653670+05	.11654184+05
	.50000000+01	.11650890+05	.11648917+05
	.60000000+01	.11643730+05	.11643649+05
	.70000000+01	.11636580+05	.11638382+05
	.80000000+01	.11634590+05	.11633115+05
	.90000000+01	.11627040+05	.11627848+05
	.10000000+02	.11623070+05	.11622581+05
	.11000000+02	.11617500+05	.11617313+05
	.12000000+02	.11612330+05	.11612046+05
	.13000000+02	.11605580+05	.11606779+05
	.14000000+02	.11601600+05	.11601512+05
	.15000000+02	.11595240+05	.11596245+05
	.16000000+02	.11592460+05	.11590977+05
	.17000000+02	.11585310+05	.11585710+05
	.18000000+02	.11580540+05	.11580443+05
	.19000000+02	.11574970+05	.11575176+05
	.20000000+02	.11569800+05	.11569909+05
	.21000000+02	.11563840+05	.11564641+05
	.22000000+02	.11559470+05	.11559374+05
	.23000000+02	.11553110+05	.11554107+05
	.24000000+02	.11550720+05	.11548840+05
I=	.11675252+05	INTERCEPT	
M=	-.52671999+01	SLOPE	
SX=	.30000000+03	SUM OF X	
SY=	.29030117+06	SUM OF Y	
SX2=	.49000000+04	SUM OF X ²	
SY2=	.00000000	SUM OF Y ²	
SXY=	.34767666+07	SUM OF XY	
CI=	.55988550-01	CONFIDENCE INTERVAL FOR THE SLOPE	

$$L = \frac{\Delta M}{\Delta t} = 5.2671 \frac{\text{lbm}}{\text{hour}}$$

$$L\%/day = \frac{5.2672(24)}{11674.47} \pm \frac{0.05599(24)}{11674.47}$$

$$= 1.6827 \pm 0.0115\%/day$$

TEMROU -

A Program to Convert Platinum RTD Signals to Volume
Weighted Temperature

```

/VOL. WTD. TEMP. ROUTINE 11/18/66
DIMENSIONXMV(19),VFAC(19),TOTAL(19),V2(19)
26      N=0
        FAC=0.0
        J=0
        VFAC(1)=.0476
        VFAC(2)=.0745
        VFAC(3)=.0476
        VFAC(4)=.0343
        VFAC(5)=.0807
        VFAC(6)=.0476
        VFAC(7)=.0667
        VFAC(8)=.0475
        VFAC(9)=.0484
        VFAC(10)=.0475
        VFAC(11)=.0343
        VFAC(12)=.0475
        VFAC(13)=.0476
        VFAC(14)=.0343
        VFAC(15)=.0476
        VFAC(16)=.0476
        VFAC(17)=.0343
        VFAC(18)=.1150
        VFAC(19)=.0489
        WRITE2,1
        WRITE2,6
        WRITE2,7
        READ1,8,N
        IF(N-19)28,27,40
28      WRITE2,9
        DO10I=1,N
        READ1,11,FAC
        V2(I)=FAC
10      CONTINUE
        GOTO20
27      DO 20L=1,19
        V2(L)=VFAC(L)
20      CONTINUE
        WRITE2,2
        READ1,3,(XMV(I),I=1,N)
        TOTAL=0.
        I=0

```

```
30      I=I+1
      E=(.002564*XMV(I)+2)
      F=(1.93589*XMV(I)+50.)
      G=(E+F)*V2(I)
      TOTAL=TOTAL+G
      IF(I-N)30,35,40
35      WRITE2,5,TOTAL
      WRITE 2,50
      READ2,45,M
      IF(1-M)26,20,26
1      FORMAT(30HVOL. WTD. TEMP. M.E.W. 5-16-66)
2      FORMAT(31HTYPE IN RAW MV, LF CR AFTER EA.)
3      FORMAT(F6.2)
4      FORMAT(5HERROR)
5      FORMAT(6HTEMP.=,F8.2)
6      FORMAT(13HLETS GO AGAIN)
7      FORMAT(16HHOW MANY POINTS )
8      FORMAT(I3)
9      FORMAT(28HLESS THAN 19, LIST NEW VFACS)
11     FORMAT(F6.4)
40     WRITE2,4
45     FORMAT(I2)
50     FORMAT(16HSAVE VFAC-TYPE 7)
      GOTO26
      END
```

REFERENCE CALCULATION ROUTINE

```

1000    WRITE 2,1
        WRITE 2,2
        READ 1,3, XTM
        WRITE 2,4
        READ 1,3, YDP
        WRITE 2,5
        READ 1,3, ZNP
        XLEAK=(5.2E3*YDP)/(ZNP*XTM)
        WRITE 2,6,XLEAK
        WRITE 2,7
        GO TO 1000
1       FORMAT (31HREF. CALCULATION-M.E.W. 6-28-66/)
2       FORMAT (24HTYPE IN TIME IN MINUTES/)
3       FORMAT (F10.6)
4       FORMAT (35HTYPE IN DELTA DELTA P IN IN. WATER/)
5       FORMAT (34HTYPE IN NOMINAL ABSOLUTE P IN PSI/)
6       FORMAT (25HLEAKAGE BY WT. % PER DAY=,F10.5)
7       FORMAT (19HWANT TO DO ANOTHER)
        END

```

REF. CALCULATION-M.E.W. 6-28-66

```

TYPE IN TIME IN MINUTES/
30.
TYPE IN DELTA DELTA P IN IN. WATER/
.05
TYPE IN NOMINAL ABSOLUTE P IN PSI/
49.335
LEAKAGE BY WT. PER DAY= .17566
WANT TO DO ANOTHER
TYPE IN TIME IN MINUTES/
60.
TYPE IN DELTA DELTA P IN IN. WATER/
..05
TYPE IN NOMINAL ABSOLUTE P IN PSI/
49.335
LEAKAGE BY WT. PER DAY= .08783
WANT TO DO ANOTHER
TYPE IN TIME IN MINUTES/

```

APPENDIX E

LOCATIONS OF SENSORS, PENETRATIONS AND
NOZZLES IN C.S.E. CONTAINMENT VESSEL

FIGURE E-1. Top Section View Containment Vessel

TABULATION OF SENSOR LOCATIONSHumidity Sensors

Serial No.	Location	Elevation, ±ft*	Containment Air Volume Represented, %
1) 001924	On support above pulley #66	+ 34.0	20.33
2) 001930	On pulley #58	+ 9.0**	20.33
3) 001923	On pulley #64,	+ 17.5	20.34
4) 001927	Down wetwell at 90°	- 13.5†	13.71
5) 001926	Down manway at 275°	- 13.5	8.07
6) 001929	Center of bilge	- 24.0	9.77
7) 001928	Center of drywell	- 16.5	7.45
			<u>100.00%</u>

Distribution of Resistance Wire

	Volume Representations		Length of wire, ft	V/L
	%	ft ³		
Containment above elevation (-) 5'5", Excluding drywell	66.7	20,500	248	82.8
Containment below elevation (-) 5'5", Excluding drywell	18.9	5,800	88	66.0
Wetwells	14.4	4,400	78	56.4

*See Figure 2 for elevation reference.

**Above fan outlet.

†Halfway down.

TABULATION OF SENSOR LOCATIONS

RTD's

Serial No.	Location	Elevation, ±ft	Containment Air Volume Represented, %
1) 964	Down wetwell at 50°	- 19.5	3.43
2) 885	Down wetwell at 90°	- 13.5	3.43
3) 896	Down wetwell at 145°	- 13.5	3.43
4) 889	Down wetwell at 200°	- 7.5	3.43
5) 963	Down manway at 275° (taped to ref. tubing)	- 13.5	--
6) 897	Down manway at 330°	- 13.5	8.07
7) 882	Center of bilge	- 24.0	4.89
8) 966	Bilge, at 50°, outside drywell skirt	- 24.0	4.89
9) 893	Center of drywell	- 11.5	7.45
*10) 887	Center of drywell	- 21.0	0.00
11) 978	On support above pulley #66	+ 34.0	6.67
12) 898	Taped to top of reference tubing	+ 34.0	--
13) 892	On pulley #55	+ 26.5	4.76
14) 961	On pulley #62	+ 23.5	4.76
15) 888	On pulley #60	+ 20.5	4.76
16) 899	On pulley #58	+ 17.5	4.76
17) 962	On pulley #64	+ 14.5	4.76
18) 894	On pulley #53	+ 12.0	4.76
19) 886	On pulley #51	+ 9.0	4.75
20) 884	On pulley #57	± 6.0	4.75
21) 979	On pulley #55	+ 3.0	4.75
22) 965	On pulley #53	- 2.5	11.50
23) 883	Taped to reference tubing	+ 0.715	--
24) 891	Taped to reference tubing	+ 6.0	--
			100.00%

*Not used in airspace temperature average.

BNWL-1028

BNW - CSE221-T OP 12.3.1
Revised 7/19/66
Page 1 of 2OPERATING PROCEDUREPENETRATION PANEL NOZZLESContainment Vessel

Number	Size	Drywell Routing	Print Number	Function
P-1	1-1/4" Sch. 80	P-20B	H-2-32773	1/4" Electrode for simulator heater
P-2	"	"	"	" " " " "
P-3	"	--	H-2-32772	Control cable for 6 solenoid valves and lights
P-4	"	P-20B	H-2-32773	1/4" Electrode for simulator heater
P-5	"	P-20B	"	" " " " "
P-6	"	--	H-2-32772	Control cable for solenoid valve and light and CVT-1, CVT-2
P-7	"	P-15B	H-2-33162	Conductivity probes
P-8	"	P-14B	H-2-33164	1" tu. transducer cooling inlet
P-9	"	P-20B	H-2-33162	TE 3-1, 3-2, 3-3 and 15 spares Deutsch connectors
P-10	"	P-13B	H-2-33164	1" tu. transducer cooling outlet
P-11	1-1/4" Sch. 40	P-12B	"	1" tu. N ₂ to dump
P-12	"	--	"	1" tu. 150# air replacement
P-13	"	P-11B	H-2-32604	1" tu. N ₂ to simulator K
P-14	"	--	"	Water hose bib V-1
P-15 P-16	2" Sch. 80 "	P-6B	H-2-32626 H-2-32604	1/2" tu. N ₂ to RD simulator E
P-17 P-18	2-1/2" Sch. 40 "	P-20B	H-2-33164	Control cable for 3 solenoid valves, lights and vent (2) sensing lines (2) wet sample lines
P-23 P-24	10" Sch. 40 "	P-27B P-24B	H-2-33161 H-2-33162	SS instrument sheaths " " "
P-25	"	--	"	Deutsch connectors

PENETRATION PANEL NOZZLESDrywell Vessel

Number	Size	Routing	Print Number	Function
P-6B	1-1/4" Sch. 80		H-2-32626 H-2-32604	Same as P-15
P-7B	"			
P-11B	1-1/4" Sch. 40		H-2-32604	Same as P-13
P-12B	"		H-2-33164	Same as P-11
P-13B	"		"	Same as P-10
P-14B	"		"	Same as P-8
P-15B	2" Sch. 80		H-2-33162	Same as P-7
P-16B	"	N-45	H-2-33171	Aerosol electrical (7)
P-19B	2-1/2" Sch. 40		H-2-32602	Simulator relief to V-1
P-20B	"		H-2-33164	P-1, 2, 4, 5 P-9, P-17
P-24B	10" to 12" Sch. 40	P-24	H-2-33161	SS instrument sheaths
P-27B	10" Sch. 40	P-23	"	" " "

BNW - CSEOPERATING PROCEDURE

221-T OP 12.3
 Revised 7/19/66
 Page 1 of 3

NOZZLE SCHEDULE

Number	Vessel	Function	Size	Location	Elevation	Routing
1	Cont.	Vent-in	18"	70°	27'	
2	"		12"	285°	7' 8"	
3	"	Equip. Access	96"	0°	3'	
4	"	Person Access	36"	315°	2' 6"	
6	"		8"	241°	-8' 3"	
7	"	Steam-Air, Aerosol, Electrical	12"	270°	-9' 10"	D-W, #27
9	"	SG-Vent	8"	8°	-6' 4"	
10	"	Vent-out	12"	285°	-17' 3"	D-W, #23
11	"	Vent-out	18"	256°	-19' 3"	
12	"	Drain	4"	270°	Bot.	
13	W-W A	Rupture Disc	10"	5°	-7' 9"	
16	W-W A	Access	36"	41°	-4' 6"	
17	D-W	Vent-in	12"	Center	Top	
18	D-W		20"	305°	-4'	
19	D-W C	Air Samples	20"	125°	-4'	Cont. #46
20	D-W	Access	36"	305°	-12' 11"	
21 A	D-W	Blowdown	24"	35°	-8'	
21 B	D-W	Blowdown	24"	95°	-8'	
21 C	D-W	Blowdown	24"	155°	-8'	
21 D	D-W	Blowdown	24"	215°	-8'	
22	D-W		4"	270°	-4'	
23	D-W	Vent-out	12"	285°	-17' 3"	Cont. #10

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NOZZLE SCHEDULE

Number	Vessel	Function	Size	Location	Elevation	Routing
24 A	D-W		24"	35°	-17'	
24 B	D-W		24"	95°	-17'	
24 C	D-W		24"	155°	-17'	
24 D	D-W		24"	215°	-17'	
25	D-W	Drain	4"	Center	Bot.	Cont. #44
26	W-W D	Vent	10"	245°	-6'	
27	D-W	Aerosol-jet	4"	270°	-7'	Cont. #7 "O" Sim.
28	D-W	Steam-Air	4"	270°	-13'	
30 A	W-W	Drain	2"	10°	-22'	
30 B	W-W	Drain	2"	70°	-22'	
30 C	W-W	Drain	2"	130°	-22'	
30 D	W-W	Drain	2"	190°	-22'	
32 A	W-W	Recirc. & Proc.	2"	55°	-13'	
32 B	W-W	" "	2"	115°	-13'	
32 C	W-W	" "	2"	175°	-13'	
32 D	W-W	" "	2"	235°	-13'	
33	Cont.	Leak Test	10"	135°	4' 6"	Outer Flange Only Blanked Inside
34	Cont.	Leak Test	10"	145°	4' 6"	Outer Flange
			2"	145°	4' 6"	Inner Opening
36	W-W B	Access	36"	88°	-4' 6"	
37	W-W C	Access	36"	146°	-4' 6"	
38	W-W D	Access	36"	206°	-4' 6"	

BNW - CSE
OPERATING PROCEDURE

221-T OP 12.3
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NOZZLE SCHEDULE

Number	Vessel	Function	Size	Location	Elevation	Routing
39	Cont.	Rec. & Spray	6"	280°	27'	
40	Cont.	Loop Out	6"	266°	-20'	D-W #42
41	Cont.	Loop In	6"	260°	-26'	D-W #43
42	D-W	Loop Out	6"	264°	-17' 3"	Cont. #40 "S", "O", "Q", Sim.
43	D-W	Loop In	6"	305°	-21' 9"	Cont. #41 "N"-Sim.
44	Cont.	DW Drain	2"	250°	-23' 4"	D-W #25
45	Cont.	Aerosol Electrical (22)	10"	245°	20'	
46	Cont.	Air Samples (18)	10"	245°	-2' 3"	
47	Cont.	Air Samples (8) Electrical (4)	10"	248°	-10'	
48	D-W A	Vent	12"	12°	-6' 9"	
49 B	W-W B	Air Circ.	16"	65°	-7' 7"	
49 C	W-W C	" "	16"	125°	-7' 7"	
49 D	W-W D	" "	16"	186°	-7' 7"	
50 B	W-W B	Water Circ.	10"	65°	-20' 7"	
50 C	W-W C	" "	10"	125°	-20' 7"	
50 D	W-W D	" "	10"	185°	-20' 7"	

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