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LEAKAGE RATE TESTS
ON THE CSE CONTAINMENT VESSEL
WITH HEATED AIR
AND STEAM-AIR ATMOSPHERES

M. E. Witherspoon

December 1970

AEC RESEARCH &
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By

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ABSTRACT

A series of ambient air, hot air and steam-air leakage tests were performed as a part of the Containment Systems Experiment program. Tests at three pressures were performed with room temperature air, heated air, and with saturated steam-air mixtures. Data were taken for calculating integrated vessel leakage rates by the absolute method, and the reference vessel method. Leakage flow rates from individual leakage points were measured in all three atmospheres. Behavior of individual leak points and results of calculations and corrections are described. The vessel leakage rate decreased to less than half the cold air value during the initial heated air test at 170°F and 9 psig. The leakage rate decreased further with higher temperature and with steam-air atmospheres.

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LEAKAGE RATE TESTS ON THE
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INTRODUCTION

The effect of post-accident atmosphere and temperature on the leakage rate of a power reactor containment vessel has been a long-standing question. The leakage rate of such vessels is measured with air at ambient temperature, and no practical means, for determining the containment vessel leakage rate under realistic post-accident conditions is available. The possibility of substantial changes in vessel leakage rate under accident conditions arises from changes in the geometry of leakage paths. For example, thermal expansion, thermal deterioration of elastomeric seal materials, and effect of steam condensate have been suggested as factors which may be significant. In addition, a relatively small change in leak rate for a leak path of fixed geometry will result from the change in physical properties of the atmosphere being leaked. In establishing the leakage rate specification for a reactor containment vessel, it has been common practice to make a correction for the effect of atmosphere composition between accident and test conditions. However, no specific allowance is made for any change in leakage rate due to changed leak path geometry. Thus, while a correlation between the leakage rate of fission product radioactivity under accident conditions and the leakage rate measured under test conditions is what is ultimately desired, the effect of accident conditions on containment vessel leakage rate is an important step in the problem solution.

As part of the Containment Systems Experiment (CSE), containment leakage studies have been carried out on a 30,000 ft³ model containment vessel which has many features representative of power reactor containment systems. The CSE vessel is of welded steel construction, and has a variety of penetrations for access, piping, electrical and instrumentation conductors. An earlier series of leakage rate tests were performed to evaluate the effects of the magnitude of the leakage rate level on the accuracy of leakage rate measurements at different pressures. (1) The studies reported here were conducted to determine the effect of containment atmosphere composition and temperature on vessel leakage rate. Sequential tests at three pressure levels were performed with room temperature air, with heated air, and with saturated steam-air mixtures. Data were taken for calculating integrated vessel leakage rates by both the absolute and reference vessel methods; and leakage flow rates at individual leak points were measured in all tests.

The leakage of fission product species at selected leak paths is being studied as part of the fission product transport task of the CSE program. Results of such studies will be reported separately.

SUMMARY AND CONCLUSIONS

A series of leakage rate tests with ambient temperature air, hot air, and steam-air atmospheres have been performed on the Containment Systems Experiment (CSE) containment vessel. The objective of these tests was to relate the leakage rate of steel containment vessels as measured in a standard air leakage rate test to the leakage rate of the same vessel with post-accident atmospheres.

Base line air leakage rate tests at three nominal pressure levels (9, 23, and 35 psig) were conducted to establish the nominal leakage rate of the vessel

and the leakage at each penetration leak point. The vessel was then retested with heated air and with steam-air atmospheres at the same nominal pressures and three nominal temperatures (175, 225 and 250°F). The intention was to obtain leakage data permitting a direct comparison of the separate effects of temperature and atmosphere on a system of fixed configuration.

Heating of the containment atmosphere to 175°F at 9 psig during the first hot air test had the immediate effect of reducing the leakage flow collected at individual leaks. The lower leakage rate was confirmed by the integrated leakage rate test results as a reduction to about one-third the cold air leakage rate at the same pressure. Higher air temperatures further diminished the leakage flows from the original leakage points and from an additional leak which was intentionally superimposed on the system.

Introduction of steam into the containment atmosphere caused the leakage flow rate at all leak points, including the previously superimposed leaks, to diminish. A pair of deliberately introduced leak points plugged and stopped shortly after they were created. In fact, if the leakage flow rate at superimposed leaks is subtracted, the total leakage flow rate was almost zero (probably $< 0.015\%/day$) during each of the steam-air tests.

Measurements of the integrated leakage rate of the vessel were made successfully by both the absolute and reference vessel methods during the heated air tests. Integrated leakage rate test results were supported by the results derived from the summation of the individual leak flow rates. The agreement was not as good as obtained during the base line air tests; however, it was adequate to confirm that the decrease in leakage rate with temperature was real, and that no new undetected leaks of significance resulted from the higher temperature.

Neither of the integrated leakage rate test methods gave usable results during the tests with steam-air atmospheres. Thus, the further decrease in leakage rate derived from the data on individual leak flows could not be confirmed by other independent measurements. Indirect evidence that no new undetected leak points of significance developed during the steam-air tests was found in the results of the retests with ambient temperature air at the end of the series.

From the results of these tests, the following conclusions are drawn:

- The adjustments made to account for the difference between test and accident atmospheres in establishing the allowable leakage rate for a vessel as now recommended in the AEC Technical Safety Guide are minor in comparison with the very large changes in leakage rate which may result from changes in leak geometry with temperature and atmosphere.
- Although the leakage rate decreased very markedly with temperature and steam-air atmospheres in the current tests, the assumption that this behavior would generally be true is not justified from the limited experience available.
- The results do indicate that a large potential exists for reduced leakage rate under accident conditions. Tests in environmental chambers of the specific penetrations and closures intended for a power reactor plant would seem to be required to support a claim for such a reduction.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

CONTAINMENT VESSEL

The CSE containment vessel is shown schematically in Figure 1 as it was arranged for the heated air and steam-air leakage rate tests. The vessel has

net volume of 30,086 ft³, and is 25 ft in diameter by 67 ft high. The vessel design pressure is 75 psig. Inside the containment vessel are several other compartments. The drywell vessel is 11 ft in diameter and 25 ft high. Each of the four wetwell chambers is 16 ft high, and the four chambers occupy two-thirds of the annulus between the containment vessel and drywell. The access space which occupies the remaining one-third of the annulus provides access to the drywell and also to the bilge area of the containment vessel. The entire vessel, including interior compartments is of welded carbon steel construction. The exterior surfaces of the containment vessel were insulated with a 1 inch fiberglass insulation ($p = 6.0 \text{ lbs/ft}^3$, $k = .026 \text{ BTU/hr ft}^2 \text{ }^\circ\text{F/ft}$). This insulation provided thermal resistance approximately equal to 21 inches of concrete,

AIR CIRCULATION SYSTEM

The vessel was equipped with a fan, motor, and mixing duct to give an air circulation rate of about 5000 cfm. Steam-to-air heat exchanger coils in the duct assembly were provided for heating the air to test conditions. ⁽²⁾ A 2-inch pipe in the bottom of the drywell was used to supply live steam to the vessel when mixtures of steam and air were desired.

As illustrated by the air flow directional arrows in Figure 1, the openings to the interior compartments were arranged to provide air circulation within and through each compartment in order to obtain relatively uniform temperatures within the vessel and to avoid stagnant volumes. Air is discharged by the fan near the top of the main containment volume. The draft tube enhances mixing in this large volume. Air flow is down through the top access opening into each wetwell, through the downcomer pipes into the drywell, out the drywell access door into the access space and down into the bilge to enter the suction pipe to the fan.

INSTRUMENTATION

Thirty thermocouples were distributed in the containment volume. Twenty-three of these thermocouples were distributed in the air space on stainless steel cables and pulleys. Six thermocouples were attached to the surface of the copper reference tubing manifold. A single thermocouple was placed in the exhaust outlet of the fan motor winding, to be used as an indicator of the motor temperature. Six humidity sensors were distributed in containment for the ambient temperature air tests; but only one sensor was left for the hot air tests; and this sensor was destroyed at the beginning of the first **steam-air** test.

The CSE reference vessel is a manifold of 3/4 inch copper tubing which has been helium leak tested to less than 1.4×10^{-6} std cc/sec in fulfillment of allowable leakage criteria of less than 1.4×10^{-5} std cc/sec. This tubing system was installed as shown in Figure 1. A detailed description of the method and criteria for leaktightness of the reference system are described in an earlier report related to the ambient air leakage rate studies on the CSE containment vessel. (1)

Approximately 400 feet of nickel-iron resistance wire was suspended from electrically insulated pulleys as shown in Figure 2. The resistance of this wire was measured with a Muller resistance bridge. Changes in resistance were used to give estimates of changes in average temperature in the containment vessel atmosphere.

Several pressure measurement instruments were used as part of the test equipment. A quartz crystal bourdon tube servomanometer, and an ordinary bourdon tube pressure gage were used to measure total absolute pressure. The nominal accuracy of this and other test devices is summarized in Table 1. A

more detailed analysis of the errors associated with each of these instruments is incorporated in an earlier report. (1)

In addition to the leakage rate testing equipment mentioned above, other thermocouples were attached to the vessel skin on the inside of the containment shell. These thermocouples were used in the process of vessel heating to determine when the vessel itself had reached thermal equilibrium with the vessel atmosphere.

FIGURE 1. Equipment for Hot-Air and Steam-Air Leakage Rate Tests

ALL POINTS OF CONTACT INSULATED
FROM CONTAINMENT SHELL

FIGURE 2. Resistance Wire Routing in Containment Vessel

TABLE I
INSTRUMENTATION

<u>No.</u>	<u>Manufacturer and Item</u>	<u>Type</u>	<u>Range</u>	<u>Accuracy</u>	<u>Sensitivity</u>
	Hewlett-Packard (DYMEC); Digital Voltmeter	Model 2401 A	0-100 MV	$\pm 2 \times 10^{-6}$ volts	$\pm 1 \times 10^{-6}$ volts
	Honeywell; Mueller Resistance Bridge	Model 1551	0-141 Ω	$\pm .002$ ohms	$\pm .0005$ ohms
	Balco Alloy Wire	(see discussion of resistance wire in text)			
{ 2 30	Brown "Elektronik"; contin- uous balance printing recorder	Model Y153X85	0-300 F	1.3 F	$\pm .5$ F
	Thermo-Electric; thermo- couple materials	Chromel-Alumel			
	Texas Instruments, fused quartz pressure gage	Model 141	0-100 psia 0-24 psia	$\pm .008$ psia -	$\pm .0005$ psia
	T.I. Crystal Bourdon tube	No. 2			
	T.I. Crystal Bourdon tube	No. 6			
1	Wallace & Tiernan; Bourdon tube absolute pressure gage	Model FA233-120	0-100 psia	$\pm .1$ psia	$\pm .05$ psia
1	Meriam; mercury column	Model A-324	0-50 in. Hg.	$\pm .01$ in. Hg.	$\pm .01$ in. Hg.
1	Princo; Fortin Barometer	--	0-32 in. Hg.	$\pm .01$ in. Hg.	$\pm .01$ in. Hg.
1	Meriam; Inclined oil manometer	Model B-627	0-2 in. water	$\pm .01$	$\pm .01$
	Hygrodynamics; hygrometer indicator	Model 15-300	0-100% relative humidity	$\pm 2\%$	$\pm 1\%$
	Hygrodynamics; humidity sensing, element	Model H-101			
	Fischer-Porter; flowmeter	Model 1/16-20-6- 5/81	145 - 510 ml/min	3% or 1 minor division	$\pm .05$ full scale
6	RGI, Inc.; flowmeters	Models F 1100 F 1200 F 1400	1 - 260 ml/min 10 - 1900 ml/min 1000 - 36000 ml/min	$\pm 3\%$ or 1 division	$\pm .01$ full scale
1	General Electric; halogen gas detector	Model H-2			9×10^{-5} cc/sec Freon 12
1	Beckman; helium leak detector	Model 14801			2.43×10^{-8} cc/sec helium

PLANNED TEST CONDITIONS AND SEQUENCE

The primary objective of the test series was to determine directly the effect of containment vessel air temperature and atmosphere on the leakage rate of the vessel. Thus, measurements at corresponding pressures and temperatures were desired with different atmospheres.

The starting point for selection of planned test conditions was based on three rather arbitrarily chosen post-accident conditions. On the assumption that a containment vessel atmosphere just before the accident is room temperature air at one atmosphere absolute pressure, and that the post-accident atmosphere is a mixture of the original weight of air plus saturated steam; the total containment vessel pressure is determined by the temperature assumed for the steam air atmosphere.

For the CSE vessel, the maximum temperature for the containment vessel was specified as 250°F based on the known ability of paint on the interior surfaces to withstand several hundred hours exposure without unacceptable deterioration. This temperature corresponds to a 35 psig total pressure for a saturated steam air mixture. The remaining two lower temperature test conditions for the steam-air tests were chosen as 225°F at 23 psig and 175°F at 9 psig.

The same temperatures and pressures selected for the steam-air tests were specified for the heated air atmosphere tests; and the pressures were specified for the room temperature air atmosphere tests.

The experimental design matrix can be summarized concisely in the table below. Test numbers in the body of the table show the corresponding nominal temperature, pressure and atmosphere. Tests in the same column with the air atmosphere were intended to show the effect of temperature alone; and tests in the same row were to show the effect of vessel atmosphere alone.

Test Matrix - Test Numbers Corresponding
to the Different Temperatures, Pressures, and Atmospheres

Temp (°F)	Air Atmosphere			Steam-Air Atmosphere		
	9 psig	23 psig	35 psig	9 psig	23 psig	35 psig
75		2	1, 1A, 10			1
175	4			7		
225					8A, 8B	
250		1	6			9

Table II is a consolidation of temperature and pressure conditions at the beginning and end of each test performed during this series. The first three (Test numbers 1, 2, and 3) were ambient air base line tests. Test numbers 4, 5, and 6 were isothermal hot air tests. The temperature was controlled as closely as possible with the heat exchange system to the condition in the "Nominal Desired Condition" column. Test number 1A was performed after an electrical failure in the fan motor electrical junction box occurred and the vessel personnel access door was opened to allow repair. Beginning with test number 7, live steam was added to the containment atmosphere until the desired test conditions were attained; and then the steam was shut off and the vessel pressure allowed to decay along the saturation line as heat transfer would allow. When the first negative leak value was confirmed after 24 hours of pressure decay, an isothermal test was tried (8A) but the difficulties in controlling the temperature of the bulk volume made leak measurements impossible to get and the vessel was allowed to decay down the saturation curve twice more (8B, 9). Shortly after the end of test number 8, the fan motor failed permanently and the final steam-air test and the ambient air retests were done with no circulation (Test numbers 9, 10A, 10B, 10C). A test chronology in bar chart form is given in Appendix A of this report as an aid in interpreting the sequence of test events.

Table II

SUMMARY OF LEAKAGE RATE TEST CONDITIONS
BASE LINE AIR, HOT AIR, AND STEAM-AIR ATMOSPHERES

<u>Test No.</u>	<u>Atmo-sphere</u>	<u>Nominal Desired Conditions</u>	<u>Beginning Temp. (°F)</u>	<u>Final Temp.</u>	<u>Beginning Press. (psia)</u>	<u>Final Pressure</u>
1	Air	75°F, 49.5 psia (24 hours)	75.3	74.5	48.97	48.60
2	"	75°F, 37.5 (24 hours)	72.4	73.4	38.19	38.08
3	"	75°F, 23.5 (24 hours)	71.4	73.0	23.57	23.56
4	"	175°F, 23.6 (24 hours)	172.6	173.2	23.46	23.45
5	"	225°F, 38.2 (72 hours)	230.1	226.7	38.07	37.78
6	"	250°F, 49.0 (24 hours)	251.3	252.13	49.10	48.96
1A	"	75°F, 49.0 (36 hours)	74.4	76.14	48.88	48.80
7	Steam/Air	175°F, 23.6 (24 hours)	177.4	127.1	23.88	17.63
8A	"	225°F, 38.2 (24 hours)	235.0	228.9	40.16	37.83
8B	"	225°F, 38.2 (24 hours)	225.5	153.25	36.29	19.57
9	"	250°F, 49.0 (24 hours)	255.8	171.2°F	49.8	22.6
10A	Air	75°F, 49.0 (25 hours)	83.4	78.45	49.04	48.10
10B	"	75°F, 49.0 (1.5 hours)	78.45	76.93	48.10	47.89
10C	"	75°F, 49.C (10 hours)	77.25	77.42	47.88	47.71

METHODS OF COLLECTION FOR INDIVIDUAL LEAKS

At each nominal test condition, individual leak points were measured with flowmeters. Each point was measured every 2 hours, or about 12 times per 24 hour test. During the hot air series, the temperature of the discharge of the flowmeters was checked during each test. The results of these checks indicated that the gas passing through the flowmeter ranged from 75F to about 88F in test number 4, from 88F to 96F in test number 5, and from 92 to 98.5 during test number 6. Since the flowmeters were calibrated at room temperature (about 75F) with a positive displacement gas meter, a flow correction ranging from 0 to 4% was possible for individual rotameter readings. However, these corrections were near the measurement accuracy of the flowmeters, and although the corrections were applied to specific data sets in the course of the operations, they were not applied to the averages of readings that appear in Table III.

Collection of the air from the discharge of steam air leakage points was accomplished by two methods illustrated in Figure 3. Smaller leaks were collected by passing the discharge through a tubing filled with a dessicant* and chilled in an ice bath and then on to a flowmeter. The second approach was used for the larger leaks, and involved routing the discharge from the vessel to a chilled glass trap in an ice bath in series with the flowmeter. The temperature of the discharge was measured in these cases also, and found to range from 82 to 84F and was not corrected in the tabulations. In both cases the water collected from the dessicant and the condensate trap was in agreement with the expected collection rate for the flow rate and vessel atmosphere composition, assuming the discharge of the rotameter was at low humidity.

* "DRIERITE" Anhydrous Calcium Sulfate, (CaSO₄), W.A. Hammond Drierite Co.; Xenia, Ohio.

FIGURE 3. Diagram of Collection Apparatus
Steam-Air Leakage

RESULTS AND DISCUSSION

SUMMARY OF TEST RESULTS

Table II summarizes all test results in wt.%/24 hours at the 95% confidence level for the integrated test methods. For the total of collected leaks, the mean is given. The nominal length of all tests was 24 hours, but in test 1A the test period was lengthened in the interest of comparing the result obtained at 24 hours to one obtained by extending the test period an additional 12 hours. Test numbers 10B and 10C were done in 15 and 10 hours, respectively. The purpose of continuing the test 10A was to obtain the leakage rate when an inadvertent leak was eliminated from the system. During the period between test number 9 and test number 10 condensate was drained from the vessel and one of the valves used to drain the vessel condensate was accidentally left open. The magnitude of this leak was not known because the operator closed it as soon as it was located. Consequently, the test period was extended 15 hours to measure the new leakage rate. Finally, a superimposed leakage of .116%/day was added for a system response test. The results of this test were satisfactory and the test series was terminated. The column labeled "Collected Leakage" is the result of collecting the known leakage points, measuring them with flowmeters and converting the sum of these leaks to an equivalent wt.%/day.

In the case of the steam-air tests (7, 8 and 9) the collected leakage is the weight percent of the original air in the vessel.

TABLE III

SUMMARY OF LEAKAGE RATE RESULTS

Test No.	Nominal Test Condition	Collected Leakage Rate	Calc. Abs. Leakage Rate	Calc. Ref. Leakage Rate	Comments
1	Air, Ambient	.41%/day	.471 $\pm$.011%/day	.385 $\pm$.013%/day	
2	Air, Ambient	.37	.417 $\pm$.016	.399 $\pm$.018	
3	Air, Ambient	.23	.226 $\pm$.005	.258 $\pm$.003	
4	Hot Air, 175F	.08	.108 $\pm$.018		Leakage diminished. Reference system out
*5c	Hot Air, 225F	** .48-.20	.268 $\pm$.010	.313 $\pm$.019	
*6	Hot Air, 250F	.17-.10	.147 $\pm$.012	.078 $\pm$.030	
*1A	Air, Ambient	.19	.301 $\pm$.033	.255 $\pm$.008	
*7	Steam-Air 175F	.38-.015	(-)1.20		No reference method observations were possible in steam/air tests
*8A	Steam-Air 225F	.36-.20	(-)1.39		Isothermal steam/air conditions were attempted in Test No. 8A
*8B	Steam-Air 225F	.09-.02	(-)1.90		
*9	Steam-Air 250F	.64-.21	(-)9.6		
*10B	Air, Ambient	.25	.557 $\pm$.0136	.434 $\pm$.0034	
*10C	Air, Ambient	.36	.634 $\pm$.012	.410 $\pm$.112	

*Denotes those tests which include a superimposed leak.

**Collected leakages which have an appreciable range of values are given as the value of leakage at the beginning and end of the test period.

BEHAVIOR OF INDIVIDUAL LEAKS

Table IV gives a consolidation of individual leakage data. The following discussions elaborate on the behavior of the significant leakage points listed.

P-24 is a 16-inch blind flange bulkhead with 96 compression glands, used for the penetration of solid sheathed instrumentation lines. The glands in this penetration are made of teflon and are compressed on short 1/8 and 1/4 inch plugs in those places where an instrument and sheath is not currently installed. At the beginning of the cold air tests, the leakage at this point was 3000, 2370, and 1250 ml/min for test numbers 1, 2 and 3 respectively. Immediately after heat-up for test number 4 (hot air at 175F), the leakage from this point stopped and remained stopped until the vessel was cooled to ambient conditions once again (test number 1A). During test number 1A, the leakage from P-24 was 3450 ml/min. As soon as the vessel was reheated for the steam-air tests, P-24 stopped leaking and did no further leaking until the final ambient air retest (test number 10) when the retest at original pressure revealed it to be leaking more than originally (it increased from 3000 to 4750 ml/min). After all testing was completed, sample glands from the leaking seals were removed and inspected. The glands were found to be deformed considerably; probably as a result of excessive tightening and subsequent "flowing" of the gland under heat and pressure to an abnormal shape. This was a plastic deformation, since the glands retained the inferior shape after cooling was complete.

P-6 was a threaded pipe cap on a carbon steel penetration. At the beginning of the air test series, the leak behaved well in ambient air, but began to diminish during the hot air heating, leaked slightly on the first retest, and none in the final ambient air retest.

P-17 Cap was a loosened straight thread fitting on a 3/8" tubing coming from the vessel. This leakage point diminished during the hot air tests, was found to be leaking slightly during the final steam-air test (number 9) but did not leak in the ambient air retest.

P-17 Gate Valve is a 1/2" gate valve adapted to a 3/8" tubing which penetrated the 2" nozzle at location P-17. This valve, which was normally used for freon injection during pre-run testing, leaked during the ambient air test, diminished during the hot air test series, and finally stopped completely during test number 7. During the isothermal steam-air test (number 8A), the valve was deliberately opened to 355 ml/min as a source of additional leakage, and it decreased to 185 ml/min during the course of the run. During test number 8 it continued to decrease to 20 ml/min. It continued to leak only slightly during test number 9 and subsequent air retests.

N-33 ball valve is a 2" ball valve with a teflon seal and stainless steel internals. It leaked during the ambient air tests, but the leakage began to diminish as soon as heating of the vessel started in test number 4 and finally completely stopped in test number 6. During the final ambient air retest, this point still did not leak and was cracked open slightly to give a superimposed leakage of 2200 ml/min in test number 10C.

N32A drill hole was created at the beginning of test number 5C by drilling a small diameter hole in a 2" blind flange. The hole drilled was .030" in diameter and was partially plugged by driving a piece of grooved wire into the drill hole. The leakage point thus created leaked about 4000 ml/min when completed. The leakage from this source continued to diminish in subsequent tests and plugged completely during the steam-air atmosphere tests. The flange was removed after

the test series was complete, and the hole was found to be plugged with rust, which was evidently generated locally (in the drill hole itself).

N-33 Threaded Cap is a threaded pipe plug on a 3/4" pipe penetrating a flange on which the N-33 ball valve is mounted. During test 5C this cap was loosened slightly for an additional leakage source, with the result that the leak diminished to a useless magnitude. At the beginning of test number 7 a hole was drilled through the threaded cap and a partial plug driven in. This leak was observed to pass rusty water which influenced the observed flow rates. The leak continued to diminish throughout test number 7 and had stopped completely by the beginning of test number 8. The remaining leakage in the tabulation was the result of tampering with the threaded cap in which the hole was drilled. In each case, the leakage established by tampering greatly diminished after exposure to the steam-air atmosphere.

Other leakage points were detected with a freon detector and soap bubbles. P-4, P-7, N-30-D, N-45, SA-1 and P-16 were detected occasionally but were omitted from the tabulation in the interest of brevity. P-16 is a leak through the thermocouple sheath and could not be continuously monitored since a leak check required disconnecting the thermocouples to bag the connectors. Consequently, a measurable leakage rate, probably less than 74 ml/min, could be included in the total for each test. Another leakage point, SA-1 was started when the valve which supplies air to the vessel was disturbed for the air retest. This leak could be eliminated when detected by tightening a valve packing and was eliminated to an insignificant magnitude for all tests except 1A. The other leakage points did not leak rates more than about 5 ml/min and were ignored in the tabulation.

TABLE IV
HISTORIES OF INDIVIDUAL LEAKAGE POINTS

Test Number	Nominal Test Cond. psia, F	P-24	P-6	Cap P-17	P-17 Gate Valve	N-33 Ball Valve	N32A Drill Hole	N-33 THD Cap	N-45	SA-1	P-16	Total Leakage ml/min	Equivalent Leakage** (wt.%/Day)
1	48.9, 74	3000	1865	1270	230	1820	---	---	---	---	---	8185	.408
2	38.2, 72	2370	1380	730	125	1145	---	---	---	---	---	5750	.367
3	23.6, 71	1250	500	85	21	420	---	---	---	---	---	2216	.229
4	23.5, 173	---	420	30	15	330	---	---	---	---	---	795	.083
5a	38.2, 230	---	1275	55	60	400	---	---	---	---	---	1790	.156
5b	38.1, 230	---	1290	4	35	112	---	---	---	---	---	1441	.126
5c	38.1, 230	---	1210-950	---	12	74-54	4000-1230*	200-117*	---	---	---	5496-2363	.481-.207
6	49.1, 250	---	1050-870	---	40	78-54	1380-585	---	---	---	---	2548-1549	.173-.105
1a	48.9, 74	3450	16	8	13	---	32	32	6	100	(74)	3731	.186
7	23.9, 175	---	---	---	---	---	---	2075-80*	---	---	---	2075-80	.380-.014
8a	40.2, 225	---	---	---	355-80*	---	---	1400-1000	---	---	---	1855-1080	.358-.207
8	36.3, 225	---	---	---	56-20	---	---	400-90	---	---	---	456-110	.088-.021
9	49.8, 250	---	---	---	30-11	---	---	3050-1100	---	---	---	2080-1111	.635-.209
10a	49.0, 75	4750	---	---	75	---	---	---	---	---	---	4825	.240
10b	48.1, 75	4750	---	---	74	---	---	---	---	---	---	4825	.245
10c	47.9, 75	4750	---	---	74	2200 *	---	---	---	---	---	7025	.358

*Denotes initiation of superimposed leakage to supplement un ampered leakage.

**Calculations of equivalent leakage made using formulas give: in Appendix B.

Pressure Characteristics of Individual Leaks - Base Line Air Tests

The data gathered in the base line air tests allow the construction of pressure characteristic curves for individual leaks as shown in Figures 4 through 8. In each of these plots, the value of leakage at the higher pressure is used as the basis point for extrapolation to lower pressures using the usual assumptions and formulas suggested for use in upward extrapolations of reduced pressure containment testing. Ideally, leaks of the size measured would be between the two flow regimes shown. Data points above either of the indicated flow regimes would imply that the leakage was closer to flow regimes not shown, namely the molecular flow or orifice flow regimes. Data points below the indicated flow regimes indicate that one or more of the extrapolation assumptions are not holding for the pressure range. These assumptions are as follows;⁽¹⁾

- (a) The leak in containment behaves in accordance with a single mode of flow for the temperature and pressure range.
- (b) All leak geometries (area of flow, leak path length, roughness of passage, etc.) remain constant for the pressure and temperature range of interest.
- (c) The number of leaks in the containment system does not vary with pressure or temperature and is not influenced by the composition of the containment atmosphere (no plugging).
- (d) The conditions within the containment remain constant for the time interval of interest.

For the ambient air tests, at nearly constant temperatures and constant pressure in a given test, assumptions a, b, and c are satisfied. Since the temperature change is small and pressure change is large in the pressure reductions for the tests plotted, a geometry dependence on pressure is the most probable

explanation for the deviation of the individual leakage paths from the closest ideal flow regime. In the case of P-24, N-33 ball valve and P-17 gate valve, some resilient materials in the valve seats and packing could quite possibly relieve the constriction of a leak path and this explanation is offered. In the case of P-17 cap, the large rise in leakage after a change in pressure from 9 to **23** psig is unexplained. It is possible that a blockage was discharged or that the increase in pressure increased the flow area.

FIGURE 4. Comparison of P-24 to Ideal Flow Regimes,
Downward Extrapolations

FIGURE 5. Comparison of P-17 to Ideal Flow Regimes,
Downward Extrapolations

FIGURE 6. Comparison of P-17 Gate Valve to Ideal Flow Regimes,
Downward Extrapolations

FIGURE 7. Comparison of N-33 Ball Valve to Ideal Flow Regimes, Downward Extrapolations

FIGURE 8. Comparison of P-6 to Ideal Flow Regimes,
Downward Extrapolations

BASE LINE AIR LEAKAGE RATE TESTS

The data in the following tables summarizes the results of the ambient temperature air leakage rate tests conducted before, in-between, and after the hot-air and steam-air tests. These tests were conducted for the purpose of establishing the nominal leakage rate of the vessel and the pressure characteristic of both total vessel leakage and the leakage from individual leakage locations.

Absolute Method Calculations

The first tabulation (Table V) is a summary of cumulative absolute method calculations for each air test performed during the series, using either the resistance wire as an average vessel temperature indicator or a volume-weighted temperature average from 23 thermocouples distributed in the vessel air space. As mentioned in the summary of test events, the first three tests were the basic datum tests. Test number 1A was conducted after the hot air series and includes both original and superimposed leakages. Test numbers 10A, B, and C were conducted after the steam-air tests, include original and superimposed leakages, and in test 10A, an open valve. In each test a reference time was chosen to begin the test and an absolute method leakage rate calculation was made each hour using the current hourly data and the reference time data. The result in the column is the absolute leakage rate calculated for the elapsed time period in the left-hand column. These calculations were done during each test as the test progressed and were quite helpful in the diagnosis of test problems (such as the case in test 10A when a small valve was left open after draining condensate from the vessel). The general trend of the data indicates that better results were being obtained using the resistance wire as a temperature averaging device.

The second table (Table VI) consolidates the results of least square fits obtained for the hourly absolute data after the tests were conducted. The procedure used to get these fits was to use the temperature and pressure data to calculate the mass of air in the vessel at each hour, and use the slope of the line through these points and the corresponding confidence interval as an estimate of the change in vessel mass with time. The data available at the end of 8, 16, and 24 hours for each test was fitted for both the mass determinations made with the resistance wire and those made with the thermocouple temperature average. The tabulation verifies trends observed in the cumulative absolute calculations. As time progresses, the interval of 95% confidence and the corresponding absolute error diminish. Error in results using the thermocouple average are generally larger than those made with the wire.

TABLE V
SUMMARY OF CUMULATIVE ABSOLUTE METHOD CALCULATIONS
BASE LINE AIR TESTS AND AMBIENT AIR RETESTS

Elapsed Time	Test #1 35 psig		#2 23 psig		#3 9 psig		#1A 35 psig		#10A 35 psig		#10B 35 psig		#10C 35 psig	
	(W)	(TC)	(W)	(TC)	(W)	(TC)	(W)	(TC)	(W)	(TC)	(W)	(TC)	(W)	(TC)
0														
1	.548	1.937	.093	.363	-.280	1.209	.438	4.030	1.592	2.523	.817	.237	.647	1.584
2	.444	1.742	.585	1.238	-.022	.181	.344	2.430	1.628	1.497	.686	.530	.661	2.266
3	.533	1.668	.373	1.317	.085	.160	.601	1.510	1.353	.972	.439	1.240	.670	1.086
4	.563	1.123	.449	1.020	.108	.465	.530	.889	1.577	1.181	.451	1.152	.645	1.001
5	.479	1.757	.368	.935	.150	.465	.118	.782	1.708	1.055	.462	.809	.648	1.067
6	.394	.408	.333	.791	.172	.735	.170	.887	1.516	.832	.484	.840	.622	.970
7	.495	.687	.336	.830	.129	.419	.159	.946	1.476	1.244	.500	.780	.643	.891
8	.525	.833	.414	.735	.127	.234	.235	.963	1.492	1.322	.495	.495	.547	.865
9	.517	.428	.360	.834	.151	.141	.199	.761	1.507	.569	5	.507	.644	.827
10	.511	.569	.401	.895	.	.161	.212	.709	1.676	1.019	.506	.573	.648	.906
11	.478	.815	.358	.860	.208	.233	.197	.608	1.519	.849	.530	.551		
12	.496	.805	.396	.789	-.365	.166	.352	.658	1.516	.950	.539	.546		
13	.494	.862	.359	.891	.200	.232	.234	---*	1.480	.978	.514	.439		
14	.457	.821	.421	.668	.260	.322	.186	.754	1.488	.861	.538	.430		
15	.495	.834	.424	.442	.182	.224	.268	.774	1.480	1.005	.532	.220		
16	.463	.815	.420	.600	.258	.283	.268	.670	1.462	1.030				
17	.459	.682	.430	.594	2 2	.155	.152	.554	1.459	1.097				
18	.439	.737	.433	.586	.255	.330	.247	.431	1.453	1.150				
19	.457	.674	.417	.545	.229	.278	.336	.555	1.439	1.176				
20	.476	.575	.411	.528	.258	.377	.314	.515	1.444	1.163				
21	.350	.412	.412	.515	.227	.315	.243	.373	1.442	1.067				
22	.458	.533	.417	.511	.247	.403	.324	.361	1.444	1.222				
23	.487	.575	.411	.474	.257	.415	.287	.307	1.495	1.158				
24	.477	.618	.394	.435	.252	.400	.277	.336	1.428	1.175				
25							.282	.366						
26							.320	.442						
27							.299	.334						
28							.303	---*						
29							.294	.383						
30							.277	.317						
31							.326	.378						
32							.315	.363						
33							.325	.368						
34							.307	.370						
35							.293	.341						
36							.289	.345						

(W) - Temperature determined from the resistance wire
(TC) - Temperature determined from the thermocouple average
* - Thermocouple connectors removed for leak check of connector

TABLE VI
SUMMARY OF LEAST SQUARES FITS
BASE LINE AIR TESTS, ABSOLUTE METHOD

<u>Nominal Pressure and Test Number</u>	<u>Elapsed Time</u>	<u>Least Squares Leakage Rate ± 95% Confidence (wt%/day)</u>		<u>Error Expressed as % of Nominal Leakage</u>	
		<u>Wire</u>	<u>Thermocouples</u>	<u>Wire</u>	<u>Thermocouples</u>
35 psig base line air test (Test #1)	8	.478 ± .028	.558 ± .308	5.9	55.2
	16	.472 ± .020	.773 ± .165	4.2	21.3
	24	.471 ± .011	.554 ± .112	2.3	20.2
23 psig base line air test (Test #2)	8	.381 ± .088	1.03 ± .227	23.1	22.0
	16	.415 ± .032	.592 ± .211	7.7	37.3
	24	.417 ± .016	.330 ± .122	3.8	37.0
9 psig base line air test (Test #3)	8	.212 ± .029	.394 ± .301	13.7	76.4
	16	.241 ± .006	.188 ± .106	2.5	56.4
	24	.226 ± .005	.295 ± .065	2.3	22.0
35 psig base line retest (Test #1A)	8	.150 ± .196	.776 ± .555	130.7	71.5
	16	.228 ± .070	.594 ± .157	30.5	26.4
	24	.278 ± .048	.254 ± .129	17.1	50.8
	36	.310 ± .023	.225 ± .0837	7.4	37.2

Reference Method Calculations

The data tabulated in Table VII shows the results of individual reference vessel method leakage observations during the air tests conducted during the test series reported here. The nominal length of all observations is 30 minutes. The number and length of reference observations was varied somewhat during the tests after the basic "Base Line" tests for several reasons. During test number 1A an operator error caused manometer oil to be blown into the tubing system. In the course of replacing the oil, the manometer case was cracked and the apparatus was replaced. In test number 10A, a small amount of water was accumulated in the manometer tubing (from the previous steam tests) and very erratic results were obtained until the line was blown out to clear the water slugs. The observations tabulated are those obtained after the line was cleared. No further trouble was encountered in tests 10B and 10C. These data show the degree of variance in individual observations. The averages of these observations compare favorably with the results obtained from the absolute method determinations and individual collected leakage (review Table III).

Further analysis of the reference method leakage determinations was made using data from the first three Base Line air tests. The procedure for reducing this data to a form for a least squares fit and confidence interval calculation is as follows:

The form to be fitted is $y = a + bx$

where x is the variable with random error. The leakage equation for reference method leakage was given⁽¹⁾ as
$$L \text{ (wt.\%/day)} = K \frac{\Delta(\Delta P)}{P_1 \Delta t}$$

where κ = constant with engineering units

$\Delta(\Delta P)$ = drop in differential pressure from the test reference time

P_1 = total pressure of the vessel at the reference time

$A t$ = elapsed time since the reference time

The quotient $\frac{\Delta P}{P_1}$ was plotted as a function of time, t , so that the slope of the line $\frac{\Delta y}{A t} = \frac{\Delta(\Delta P)}{P_1 \Delta t}$ or $\kappa \frac{\Delta(\Delta P)}{P_1 \Delta t} = L$ (wt.%/day).

The corresponding confidence interval for the slope or leakage obtained was also calculated using a standard method and a simple program developed for that purpose at the CSE.⁽¹⁾ The fits were done for those observations available at the end of 8, 16, and 24 hours with the results shown in Table VIII.

Referring to Table VIII, the format is the same as that for the absolute method confidence interval data. The statistical error of the instrumentation observations is comparable for each of the 35 and 23 psig tests, and unusually good for the 9 psig test. This is explained by the fact that an unusually stable vessel temperature was experienced during this test. It will be noted that the nominal leakage rate values determined at 35 and 23 psig are near the same value, but that the value determined at 23 psig is greater. This does not agree with the absolute method result or collected leakage results and can be explained only by a long term (a few hours) statistical bias in the measurement system. The results serve to illustrate the point that precision in the instrumentation is not sufficient to secure good test results if the measurement system is experiencing a cyclic temperature influence.

TABLE VII

SUMMARY OF REFERENCE METHOD LEAKAGE CALCULATIONS
BASE LINE AIR TESTS

<u>No. of</u> <u>Observations</u>	<u>Test #1</u> <u>35 psig</u>	<u>#2</u> <u>23 psig</u>	<u>#3</u> <u>9 psig</u>	<u>#1A</u> <u>35 psig</u>	<u>#10A</u> <u>35 psig</u>	<u>#10B</u> <u>35 psig</u>	<u>#10C</u> <u>35 psig</u>
1	.329	,733	,578	.250	,644		.577
2	.335	.710	.149	.168	,824	.449	
3	.501	,498	.594	.372	1.074	.410	.541
4	.315	.362	.147	.277	1.074	,354	.505
5	.574	,340	.129	.213	1.074	.431	.505
6	.258	.498	.144	,368	.897	.395	.686
7	.495	.498	,568	,129	.754	,503	.415
8	.283	.476	,152	.275	1.005	.431	.232
9	,460	,249	.220	.157	1.002	,475	.282
10	.460	,476	.323	.431	1.012	.442	.585
11	.283	,436	,235	.266		.486	.487
12	.531	.245	,271	,273		.450	.560
13	,284	,544	,212	,279		.486	.574
14	.461	,272	,238			,480	.582
15	.532	.544	,220			,475	.433
16	.284	.272	,220			,479	.596
17	.425	.531	.220			,508	.290
18	,425	.209	,146			,555	.531
19	,562	,204	.220			.252	.513
20	.193	,454	,403			.504	.615
21	,461	.322	.220			,612	.651
22	.373	,290	,146			.216	.499
23	.227	,454	.110			.576	.514
24	.447	.318	.476			,360	
25	.444	.499	.146			,541	
26	.213	.263	.183			.541	
27	.497	,420	.183			,324	
28	.418	.583	.220			,505	
29	.249	.499	.220			.505	
30	.465	.366	.220			,505	
31	.458	.378	,293			,108	
32	.235	.201	.293			.469	
33	.512	.571	.513				
34	.278	.145	.073				
35	.359	,453	.110				
36	.331	,226	.514				
37	.583	,576	,110				
38	,345	.234	,073				
39	.530	.534	,477				
40	,356	.219	.110				

Continued on following page

Table VII continued

No. of Observations	Test #1 35 psig	#2 23 psig	#3 9 psig	#1A 35 psig	#10A 35 psig	#10B 35 psig	#10C 35 psig	
41	.334	.363	.110					
42	.495	.738	.146					
43	.495	.341	.514					
44	.246	.272	.162					
45	.602	.522	.125					
46	.509	.318	.296					
47		.272	.185					
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>	
Avg	=	.420	.403	.247	.266	.926	.416	.486

TABLE VIII

SUMMARY OF RESULTS, LEAST SQUARES FITS OF REFERENCE DATA

<u>Test Pressure</u>	<u>Elapsed Time (hours)</u>	<u>Nominal Leakage (%/day)</u>	<u>95% Conf. Interval (1.960)</u>	<u>Error Expressed As % of Nominal Leakage (%)</u>
35 psig base line air test (Test #1)	8	.3234 ±	.109	33.7
	16	.3746 ±	.0280	7.5
	24	.3850 ±	.0126	3.3
23 psig base line air test (Test #2)	8	.5107 ±	.131	25.7
	16	.4317 ±	.0327	7.6
	24	.3989 ±	.0182	4.6
9 psig base line air test (Test #3)	8	.2714 ±	.0138	5.1
	16	.2651 ±	.0047	1.8
	24	.2575 ±	.0032	1.2

HEATED AIR LEAKAGE RATE TESTS

Absolute Method Calculations

Table IX has been organized to show the results of absolute leakage rate calculations made during the hot air test series (Tests numbers 4, 5 and 6). In the process of heating the vessel to 175°F it was observed that the collected leakage had diminished to about 40% of its value at the same pressure with cold air. This change was also reflected in the absolute method calculation at the end of 24 hours. The individual leaks had not been tampered with at this point. As the vessel was heated to the next test condition at 225°F, the flows from individual leakage points diminished further (see the tabulation of individual leakage, Table IV). This period of time is that designated as test number 5A in Table IX, where a small positive leakage rate (.023%) was indicated at the end of 22 hours. This leakage rate disagreed with the collected leakage (.09%) and the control chart indicated that the vessel temperature was not yet at equilibrium, so the test was begun again for a second 24-hour test period (5B).

Since the previous sequence of events indicated that further heating of the vessel would result in further flow reduction at the individual leakage points, it was decided to superimpose additional leakage to supplement the .09% collected leakage rate. The final 225°F test, (5C) was conducted after a threaded cap on individual leakage point N-32A was loosened to give an additional leakage of approximately .25%/day. This leak also diminished, but was not further disturbed. All of the leakage points that were active in test number 5C were left undisturbed for test number 6, and by the end of the 24-hour test interval for test number 6, they had all diminished to a level of leakage that could not be measured with the rotameters; or less than 1549 ml/min, which is equivalent to $\sim 0.10\%$ /day.

TABLE IX

SUMMARY OF CUMULATIVE ABSOLUTE METHOD CALCULATIONS, HOT AIR TESTS

Leakage Rates, wt.%/day

Elapsed Time (hours)	Test il4		Test #5A		Test #5B		Test #5C		Test 86	
	W	TC	W	TC	W	TC	W	TC	W	TC
0										
1	.609	2.34	-.805	-.353	.456	-1.64	.400	-.645	.119	-.657
2	.181	1.35	-.269	-.600	.024	-.220	.303	-.307	.119	-.119
3	.175	1.70	-.209	-.407	.087	-.436	.297	-.985	.023	.270
4	.260	1.63	-.258	-.189	.021	.021	.359	+.140	.023	.461
5	.207	1.32	-.171	-.072	.065	-.578	.309	-.055	.066	.261
6	.175	.902	-.129	.345	.054	-.394	.297	.123	.069	.176
7	.124	.747	-.124	-.045	.055	-.044	.304	.235	.026	.191
8	.114	.791	-.107	-.041	.025	-.127	.287	.173	.091	.466
9	.127	.561	-.103	-.011	.050	-.070	.296	.079	.010	.265
10	.136	.530	-.131	.005	.074	-.090	.307	-.049	.111	.324
11	.107	.542	-.065	-.002	.064	.051	.295	.095	.115	.342
12	.087	.560	-.073	.089	.070	.090	.298	.159	.117	.237
13	.085	.482	-.036	.052	.084	-.117	.304	-.015	.154	.092
14	.088	.485	-.041	.148	.065	-.234	.327	.096	.129	.269
15	.110	.461	.033	.013	.074	-.201	.301	.112	.128	.208
16	.093	.283	-.027	.127	.085	.018	.206	.094	.161	.194
17	.096	.325	-.019	-.092	.086	.037	.277	.054	.130	.201
18	.115	.317	-.028	-.164	.090	-.009	.287	.091	.139	.148
19	.109	.277	-.017	-.069	.081	-.175	.286	.110	.131	.100
20	.135	.298	-.006	.016	.087	-.231	.289	.130	.110	.072
21	.139	.224	.010	.068	.095	-.176	.269	.141	.123	.181
22	.138	.149	.023	.044	.090	-.151	.257	-.009	.130	.197
23	.118	.107	.042	-.029	.097	-.259	.271	.028	.129	.232
24	.123	.123	.023	.022	.0902	-.128	.269	.123	.138	.214

(W) Calculations using average temperature determined from the resistance wire
 (TC) Calculations using average temperatures from the thermocouple average

The absolute data cumulative calculations in Table IX reflect the same general trend observed in Table V for the base line air tests. The values of leakage determined with the thermocouple average temperature are more widely scattered than those from the resistance wire. This trend is confirmed by the results of least squares fits of the data from hourly absolute method observations. In Table X the results of least squares fits to these data are shown. The variation in results obtained from each of the two temperature averaging systems is more pronounced in the hot air tests. This can be seen by comparison of the results in Table VI with those of Table X. For a given test at the same pressure, say base line test number 2 and hot air test number 5C, the error expressed in percent of leakage rate in the thermocouple average is usually larger for the hot air test. This is at least partially explained by the fact that the sampling error in temperature measurement becomes greater as the absolute gradient becomes larger. For example, during the base line air tests, temperature changes from the coldest to hottest part of the vessel were about 5°F, and during the hot air series, differences as large as 15°F were observed. It will be observed that the absolute error at a specific time interval, say 24 hours, is remarkably near the same value for both the hot air and the base line air series when the wire is used as a temperature averaging tool. This is evidence that the wire is doing a relatively good job of temperature sampling in the containment vessel.

In summary, the results obtained from the absolute method determinations were satisfying and were in reasonable agreement with the collected and reference method leakage rates (review Table III).

TABLE X
SUMMARY OF LEAST SQUARES FITS
HOT AIR TESTS, ABSOLUTE METHOD

Nominal Test Condition	Elapsed Time	Least Squares Leakage Rate (wt.%/day) $\pm$ 95% Confidence		Error Expressed as % of Nominal Leakage Rate	
		<u>Wire</u>	<u>Thermocouples</u>	<u>Wire</u>	<u>Thermocouple</u>
9 psig, 175F (Test #4)	8	.105 $\pm$.0732	.707 $\pm$.398	69.8	56.3
	16	.0704 $\pm$.0228	.256 $\pm$.154	32.4	60.1
	24	.108 $\pm$.0175	.358 $\pm$.103	28.3	28.8
23 psig, 225B (Test #5A)	8	.0765 $\pm$.0779	.159 $\pm$.296	102	186
	16	.0018 $\pm$.0337	.127 $\pm$.088	546	69.3
	22	.0332 $\pm$.0237	-.024 $\pm$.083	71.3	346
. (Test #5B) "	8	.0204 $\pm$.0525	-.092 $\pm$.332	257	361
	16	.073 $\pm$.0189	-.028 $\pm$.141	25.9	504
	24	.094 $\pm$.0107	-.128 $\pm$.092	11.4	71.9
(Test #5C) "	8	.289 $\pm$.029	.296 $\pm$.361	10.1	122
	16	.288 $\pm$.0102	.147 $\pm$.107	3.53	72.8
	24	.267 $\pm$.010	.114 $\pm$.061	3.79	53.5
35 psig, 250F (Test #6)	8	.0938 $\pm$.0517	.410 $\pm$.245	55.2	59.8
	16	.158 $\pm$.024	.235 $\pm$.098	15.3	41.7
	24	.148 $\pm$.0137	.170 $\pm$.060	9.25	35.3

Reference Method Calculations

Initial efforts to get reference method observations during the first hot-air test failed. During test number 4 the reference vessel manometer liquid surged off scale due to some transient influence on the reference tubing. Later during the same test the manometer was equalized, tried again and was found to be surging less violently, but was still not useful. Absolute method calculations were relied on for the number 4 test leakage rate determinations. However, as the tests progressed to number 5A at 225°F, the reference system began to stabilize. Beginning with the 11th hour of testing, some positive reference method values were obtained; but the general performance of the reference system was oscillatory. Table XI includes a tabulation of two groups of reference method observations obtained during the test 5A. Although individual readings are quite scattered, the averages of these individual observations was a positive number. Two groups of readings, one group at 15 minute intervals and another at 30 minute intervals, were tabulated and averaged with nearly the same result. However, the average leakage rate obtained from these observations (0.09%/day) is in disagreement with the absolute calculation at the end of 24 hours (0.02%/day). During test number 5B, the superimposed leakage from the vessel was increased slightly and two more groups of reference method observations were obtained, at 60 minute and 30 minute observation intervals. Once again the reference method leakage rate determination was greater than the absolute method leakage rate determination for the same interval (.156%/day vs. .09%/day). During test number 5C, 15 minute and 30 minute reference method observations were successfully obtained and the leakage rate obtained from the average of these observations was quite close to that determined by the absolute method (.277%/day vs. .269%/day). Finally, during the test at 259°F (number 6)

an average of 30 minute observations yields a good agreement with the absolute method determination (.148% vs. .158%).

In general, the results obtained from the reference system were largely dependent on the stability of the temperature in the vessel. The air temperature control system was more grossly adjusted during the first hot air test and many of the heat sinks in the vessel were not satisfied. As time progressed and experience with the system allowed better control and more stable temperature gradients in the vessel, the copper reference vessel experienced influences of lesser magnitude, which was reflected in the attenuation of the oscillations observed at the differential pressure manometer. Similar observations were made during ambient temperature air tests reported earlier.⁽¹⁾ The experience in this test series serves to explain the nature of the disturbances observed in the CSE reference system on previous occasions. By increasing the temperature gradients in the vessel more dramatically with the heat exchanger, more significant effects were observed in the reference data. The normal advantage of great sensitivity obtained by using the reference system is offset by its response to non-equilibrium conditions in the vessel air temperature.

In summary, the overall results of the hot air test series were good. Direct comparison of the total vessel leakage rates with those of the baseline tests was not possible because of the major decrease in leakage that occurred when the vessel air atmosphere was heated. Superimposed leakage rates are thus included in the results of the hot air test series. Heating of the vessel air accentuated some phenomena observed in air tests, namely the instability of the reference system during transient temperature excursions, and the sampling error in the thermocouple system.

TABLE XI

SUMMARY OF REFERENCE METHOD LEAKAGE
RATE DETERMINATIONS; HOT AIR TESTS

Test #4 (175 F)	Test #5a (225 F)	At	Test #5b (wt. %/day) (225 F)	At	Test #5c (225 F)	At	Test #6 (250 F)	At
Reference	.418	15	.168	60	.639	15	.088	30
	.354		.118		.274		.088	
System	.463		.068		.182		.370	
Out	-.163		.088		.091	15	.342	
	.082		.184		$\bar{L} = .297$		.195	
	-.019		-.004				.282	
Of	.109		-.086		.502	30	.071	
	-.518		.274	60	.502		-.106	
Order	.106		$\bar{L} = .101$		.502		.388	
	-.055				.456		.176	
	.080		.205	30	.046		-.070	
	.238		.160		.274		.035	
	.125	15	.046		.091		.176	
	$\bar{L} = .094$		-.046		.274		.282	
			.228		.182		.176	
	.091	30	.205		.456		.317	
	.476		.274		.411		.035	
	.205		.205		.182		.211	
	.045		.182		.434		.123	
	-.023		.160		.091		.352	
	.023		.160		.480		-.370	
	.171		.228		.274		1.060	
	.205		-.100	30	.137		-.670	
	-.159		$\bar{L} = .156$		.594		.458	
	.637				.274		.123	
	-.090				.114		-.159	
	.159				.663		.529	
	.200	30			.183		-.459	
	$\bar{L} = .095$				.137		.194	
					.046		.353	
					.548		-.141	
					.366		.212	
					.114		.112	
					.206		.282	30
					.274		$\bar{L} = .148$	
					.229			
					.229			
					.366			
					.329			
					.480			
					-.137			
					.457			
					.091			
					.526			
					.229			
					-.274			
					.457			
					.000			
					.320			
					.274			
					.229	30		
					$\bar{L} = .277$			

STEAM-AIR LEAKAGE RATE TESTS

Shortly after the end of the hot air tests discussed in the previous section, the vessel air circulation fan stopped and it was necessary to cool the vessel by venting the hot air and running cold water through the heat exchanger. The vessel was entered, the fan was repaired, and an air retest at 35 psig (Test number 1A) was conducted to assure the operating staff that the vessel was sealed. The vessel pressure was then dropped to one atmosphere, and steam addition was begun. The vessel atmosphere was heated with the heat exchanger and the live steam jet until thermocouples placed on the inside vessel skin and the vessel atmosphere thermocouples approached the same temperature (within 2°F). When conditions appeared to be approaching an equilibrium, as indicated by a control plot of several key thermocouples, the steam was shut off, condensate in the vessel was drained, and hourly readings were begun to start test number 7. It was observed during the heat-up process that individual leakage point flows had diminished greatly. Two new leaks were created so that some leakage would exist, and permit meaningful leakage rate measurements.

Absolute Method Calculations

The measurements made during the temperature and pressure decay of each test are the same as those made for the previous tests, namely the total pressure of the vessel contents and the average temperature of the bulk air contents. The average temperature of the air was determined using the volume weighted thermocouple average and the resistance wire as usual, although the wire resistance readings were somewhat more difficult to make, due to the steadily falling temperature in the vessel. The average temperature of the vessel atmosphere was used to define the saturation pressure of steam in the vessel,

(obtained from a linear interpolation in the steam tables⁽⁴⁾) which was deducted from the total pressure observed at the pressure gages to give the partial pressure of air in the vessel. Calculations of the weight percent loss of vessel air contents are then made using the Perfect Gas Law. These procedures were executed with the results shown in Table XII. The results obtained in the first steam air test (Test number 7) converged to a negative value which indicated that the vessel had experienced a 1.5% in-leakage of air. The difficulties of getting a good average temperature during the saturated decline of the vessel steam air mixture were suspect; so in the subsequent test (number 8A) an attempt was made to hold the vessel atmosphere temperature at a constant level and see if the leakage would converge to a number near zero (as indicated by the collected leakage). The attempt was unsuccessful and a negative leakage rate was once again recorded at the end of 24 hourly observations.

A second saturated decline was executed in test number 8B with essentially the same result as the first steam-air test (number 7). At the end of test number 8B, the recirculation fan was turned off for a short time to observe the effect on the gradient in the vessel. When a greater gradient began to develop, an unsuccessful attempt to turn the fan back on was made.

Test number 9 was performed with no recirculation fan and, as the cumulative calculations indicate, this mode of operation caused much worse errors in the leakage rate calculations. At the end of 24 hours, the apparent increase in air mass is 9 to 10%.

In summary, it was not possible to make meaningful integrated measurements of the vessel leakage rate with the steam-air atmosphere; and the data based on collected leakage at individual leak points provide the only usable information under the steam-air test conditions.

TABLE XII

SUMMARY OF CUMULATIVE ABSOLUTE METHOD CALCULATIONS;
STEAM AIR TESTS

Leakage Rates, wt. %/day

<u>Elapsed</u> <u>Time</u> <u>(hours)</u>	<u>Test #7</u> <u>(175°F)</u>		<u>Test #8</u> <u>(225°F)</u>		<u>Test #8A</u> <u>(225°F)</u>		<u>Test #9*</u> <u>(250°F)</u>	
0	<u>W</u>	<u>TC</u>	<u>W</u>	<u>TC</u>	<u>W</u>	<u>TC</u>	<u>W</u>	<u>TC</u>
1	-.81	.20	-2.37	-2.62	-7.60	-6.40	-101.3	-98.1
2	-.55	-1.26	-5.90	-6.33	24.24	-26.15	-94.2	-87.3
3	-1.74	.08	-.57	-.61	-6.31	-8.02	-52.4	-50.3
4	-2.54	-2.06	-4.93	-5.25	-3.35	-4.52	-37.8	-36.4
5	-2.06	-1.87	-.52	-.55	-4.97	-6.22	-36.7	-35.4
6	-2.09	-1.68	-1.37	-1.54	-3.04	-4.01	-44.8	-44.1
7	-2.19	-1.75	-4.27	-4.52	-2.38	-3.56	-31.7	-30.9
8	-2.14	-1.75	-3.54	-3.98	-18.91	-17.36	-27.3	-26.4
9	-2.25	-1.64	-.75	-1.00	-3.96	-5.26	-23.3	-22.0
10	-2.38	-1.72	-.86	-.65	-2.34	-3.52	-21.9	-20.6
11	-2.19	-1.97	-.17	-.50	-1.38	-2.59	-20.3	-19.4
12	-2.31	-1.93	-3.44	-3.68	-.08	-1.27	-18.6	-17.5
13	-2.15	-1.62	-2.92	-3.31	-.22	-1.49	-18.5	-17.4
14	-2.22	-1.76	-1.22	-.95	-1.69	-.71	-18.3	-17.3
15	-2.21	-1.73	-.89	-.63	-2.26	-1.34	-18.2	-17.3
16	-2.13	-1.66	-2.00	-1.87	-1.80	-.85	-16.6	-15.6
17	-2.10	-1.66	-.90	-.75	-3.14	-2.42	-15.6	-14.6
18	-1.94	-1.51	-4.77	-4.67	-2.20	-1.33	-14.8	-13.7
19	-1.67	-1.27	-3.04	-2.98	-2.87	-2.13	-14.1	-13.0
20	-1.68	-1.29	-4.25	-4.26	-1.64	-.71	-14.2	-13.2
21	-1.76	-1.24	-2.68	-2.59	-1.93	-1.05	-14.1	-13.2
22	-1.72	-1.24	-2.06	-1.96	-1.58	-.64	-13.4	-12.3
23	-1.61	-1.32	-1.12	-1.00	-1.75	-.87	-12.3	-11.7
24	-1.56	-1.21	-1.39	-1.33	-1.90	-1.06	-9.6	-9.3
25	-1.50	-1.05						

*Test #9 performed with no fan circulation of vessel atmosphere.

(W) Calculations using average temperature determined from the resistance wire.

(TC) Calculations using volume weighted average of thermocouple temperatures.

Corrections for Potential Errors

The apparent increase in vessel air contents may be attributed to any of several error sources during an individual test period.

1. Changes in vessel volume due to temperature and pressure effects on the vessel dimensions.
2. Changes in vessel volume due to accumulation of condensate.
3. Errors in the average temperature measured and used for the determination of steam partial pressure.

Although in ambient air tests insignificant changes in temperature and pressure are usually experienced by the containment shell during the test period, this is not true for the larger temperature and pressure changes experienced in a post-accident atmosphere. Some sample calculations which follow show the influence of changes in test parameters.

Dimensional Changes

The CSE vessel is represented approximately by a cylinder with elipsoidal end caps:

Changes in volume due to temperature change in a volume with dimensions v, ℓ, and h are given by

$$\frac{dv}{dt} = \frac{\partial v}{\partial r} \left(\frac{dr}{dt} \right) + \frac{\partial v}{\partial \ell} \left(\frac{d\ell}{dt} \right) + \frac{\partial v}{\partial h} \left(\frac{dh}{dt} \right) \quad (1)$$

For the CSE geometry $v = \pi r^2 \ell + 2(1/2) \pi r^2 h$

$$\frac{\partial v}{\partial r} = 2\pi r(\ell + h)$$

$$\frac{\partial v}{\partial \ell} = \pi r^2$$

$$\frac{\partial v}{\partial h} = \pi r^2$$

Now the dimensions will be changing by some temperature coefficient of expansion α , related to their original dimension and temperature

$$r = r_o [1 - \alpha(T - T_o)] \text{ and } \frac{\partial r}{\partial t} = -r_o \alpha$$

similarly:

$$\ell = \ell_o [1 - \alpha(T - T_o)]$$

$$h = h_o [1 - \alpha(T - T_o)]$$

So that for the CSE vessel equation (1) becomes

$$\begin{aligned} \frac{dv}{dt} &= -2\pi r_o^2 (\ell_o + h_o) \alpha - \pi r_o^2 \ell_o \alpha - \pi r_o^2 h_o \alpha \\ \frac{dv}{dt} &= -3\pi r_o^2 \alpha (\ell_o + h_o) \end{aligned} \quad (2)$$

For the CSE original dimensions and an α of $7 \times 10^{-6} \text{ } ^\circ\text{F}^{-1}$ this amounts to a fractional volume change of

$$.00205\% \text{ volume change/}^\circ\text{F}$$

A similar calculation can be made for the slight volume change due to the drop in pressure that occurs during the course of a test interval.

$$\frac{dv}{dP} = \frac{\partial v}{\partial r} \left(\frac{dr}{dP} \right) + \frac{\partial v}{\partial \ell} \left(\frac{d\ell}{dP} \right) + \frac{\partial v}{\partial h} \left(\frac{dh}{dP} \right) \quad (3)$$

The dimension change is caused by strain due to pressure loading, and the simplest expression for a thin-walled cylinder is used for this estimate. For hoop stress,

$$\epsilon = \Delta r = \frac{Pr}{Et} \quad \text{where} \quad \begin{array}{l} = \text{strain} \\ t = \text{wall thickness} \\ P = \text{pressure} \\ E = \text{modulus of elasticity} \end{array}$$

For longitudinal stress

$$\epsilon = \Delta \ell = \Delta h = \frac{Pr}{2Et}$$

$$\text{Since } r = r_o + \Delta r = r_o \left(1 - \frac{Pr_o}{Et} \right) \text{ and } \frac{dr}{dP} = \frac{-r_o^2}{Et}$$

$$\ell = \ell_o + \Delta \ell = \ell_o \left(1 - \frac{Pr_o}{2Et} \right) \text{ and } \frac{d\ell}{dP} = \frac{-\ell_o r_o}{2Et}$$

$$h = h_o + \Delta h = h_o \left(1 - \frac{Pr_o}{2Et} \right) \text{ and } \frac{dh}{dP} = \frac{-h_o r_o}{2Et}$$

So equation (3) becomes

$$\frac{dv}{dP} = \frac{5}{2} \frac{\pi r_o^3}{Et} (\ell_o + h_o)$$

where the subscripts o denote the original dimensions at thermal equilibrium. Using the CSE vessel wall thickness of .625 and an $E = 28 \times 10^6$ inches, this correction amounts to a fractional volume change of $\frac{\Delta V}{V} = 8.75^{-4}$ % volume decrease/psi.

Volume Changes Due to Accumulation of Condensate

For a saturated steam-air mixture, the initial mass of water vapor in a well-mixed volume is $M = \frac{V}{v_g} \text{ lbm}$ $v_g = \text{specific volume of water vapor}$

After cooling, some water is in the gas phase and some in the liquid phase as condensate as shown in the mass balance from time 1 to time 2

$$\begin{aligned} 1) \quad M &= \frac{V_1}{v_{g1}} & V_1 &= \text{volume of the gas phase at time 1} \\ & & V_2 &= \text{volume of the gas phase at a later time} \\ 2) \quad M &= \frac{V_2}{v_{g2}} + \frac{V_f}{v_{f2}} & V_f &= \text{volume displaced by the water} \end{aligned}$$

This simplifies under the assumption that $V_1 \approx V_2$ so that

$$V_f = V \left(\frac{1}{v_{g1}} - \frac{1}{v_{g2}} \right)$$

So, depending on the measured temperature of the vessel temperature a correction for volume change can be made.

The corrections dealt with in the previous three paragraphs have been consolidated for the steam-air test series in Table XIII. It can be seen in this table that these corrections do not compensate for the negative values of leakage rate obtained during the CSE test series, but that the corrections are quite significant. Note that in test number 8A only small corrections for temperature and

TABLE XIII

SUMMARY OF CORRECTIONS TO STEAM-AIR TESTS

Test Number	Volume(ft ³) Correction (Temp)	Volume(ft ³) Correction (Pressure)	Calculated Volume(ft ³) Correction (Condensate)	Total ft ³ Correction	Equivalent %/ day Corrections	Calculated Daily Leakage	Corrected Daily Leakage
7	-31 ft ³	-1.84	-6.31	-39.15	.131%	-1.20	-1.07
8A	-3.8 ft ³	-.98	-133*	-137.8	.458%	-1.39	-.93
8B	-44.8 ft ³	-4.94	-18.04	-67.8	.225%	-1.90	-1.68
9	-52.3	-8.0	-31.3	-91.6	.304%	-9.6	-9.3

* By collection of condensate rather than calculation

pressure were necessary, but a rather substantial correction for the condensate accumulated was applied. This was because of the extra steam condensed in the process of maintaining the isothermal vessel conditions.

It is evident that the first three corrections are not the most significant influence on the test results. The prime measurement in the data collection process is that of the temperature, which has an unknown amount of error and is expected to lag the real temperature by an unknown time interval. Figure 10 illustrates the influence of a time lag error on the calculation of the partial pressure of air in containment. At the beginning of the test period t_0 , a relatively steady state was achieved and measurements of total pressure and temperature are thought to be known with small error. The method for calculating the partial pressure of air is to use the temperature measurement as a determiner of the steam partial pressure and using the difference between the steam pressure and the measured total pressure to determine the partial pressure of air. When the saturated decline of the vessel pressure begins, any time lag in the temperature measurement gives an impression of the saturation pressure that is correspondingly lagging in time. However, the total pressure measurement does not lag in time, and is effectively correct at any point in time. The air partial pressure determined with this lag is smaller than real, so additional leakage is indicated.

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APPENDIX A

TEST CHRONOLOGY

Test Chronology
Leakage Test L-4 L-5 Series

APPENDIX B

SENSOR LOCATIONS

Tabulation of Sensor Locations

<u>Thermocouple</u>	<u>Location</u>
1	Top of reference system, in contact with tubing surface
2	15' down from top of ref. system, in contact with tubing surface
3	30' down from top of ref. system, in contact with tubing surface
4	Top of reference tubing (lower section)
5	15' down from top of lower section, in contact with tubing surface
6	30' down from top of lower section, in contact with tubing surface
7	Top of Maypack pulley frame
8	Inside exhaust tube, 1' down from bottom of upper support beam
9	Radius of 8'10" at 45°, el. 26' (against bottom of beam)
10	" " " " 135° " 23'
11	" " " " 225° " 20
12	" " " " 315° " 17
13	" " " " 45° " 14
14	" " " " 135° " 11
15	" " " " 275° " 8
16	" " " " 315° " 5
17	" " " " 45° " 2
18	Attached to the duct work at 285°, el (-) 1'
19	Down wet well at 50° el (-) 13'5" (halfway down)
20	" " " " 90° " (-) 19'5" (2' from floor)
21	" " " " 145° " (-) 13'5" (halfway down)
22	" " " " 200° " (-) 7'5" (2' from top of wet well)
23	Down the manway at 285° (-) 13'5" (halfway down)
24	" " " " 330° (-) 13'5" (halfway down)

- 25 Inside drywell, attached to penetration bell, el = (-) 4.0
- 26 " " center el (-) 12'0"
- 27 Outside center bilge suspended in airspace
- 28 Inside center bilge " " "
- 29 Inside fan intake
- 30 Taped to outlet of fan motor winding exhaust

Humidity Sensors

- H-1 Blower outlet; el. 26'
- H-2 On cable at 315° el. 17'
- H-3 " " " 135° el. 12'
- H-4 Down wetwell at 50° with 19
- H-5 Center of drywell with 26
- H-6 Center of bilge with 28
- H-7 In vicinity of heater coils

- HAYPACK PULLEYS
- + SENSOR SUSPENSION PULLEYS

FIGURE B-1. Pulley Layout, Containment Vessel

APPENDIX C

EQUATIONS AND SAMPLE CALCULATIONS

DEFINITIONS , NOMENCLATURE, AND SAMPLE CALCULATIONS RELATED
TO THE CALCULATION OF LEAKAGE RATES

$$\text{Leakage Rate} = \frac{\text{weight @ } t_1 - \text{weight @ } t_2}{\text{weight @ } t_1} - \frac{\Delta m}{m} \times 100 = \text{wt\%/day}$$

$$\begin{aligned} \text{Steam/air ratio} &= \frac{\text{specific volume steam}}{\text{specific volume air}} = \frac{\text{mole fraction s}}{\text{mole fraction a}} \\ &= \frac{\text{partial pressure s}}{\text{partial pressure a}} \end{aligned}$$

or

$$\frac{v_s}{v_a} = \frac{M_s}{M_a} = \frac{P_s}{P_a}$$

$$P_a V_a = m_a R_a T_a$$

V = volume

v = specific volume

$$P_s V_s = m_s R_s T_s$$

m = mass of air or steam
(m_a , m_s)

M = moles

$$\frac{P_s}{P_a} = \frac{\frac{m_s R_s T_s}{V_s}}{\frac{M_a R_a T_a}{V_a}} = \frac{m_s R_s}{M_a R_a} = \frac{m_s \frac{1545}{18}}{m_a \frac{1545}{29}} = \frac{m_s}{m_a} \quad 1.61$$

$$\frac{P_s}{P_a} = 1.61 \frac{m_s}{m_a} \quad \text{and} \quad \frac{\text{mass steam}}{\text{mass air}} = .622 \frac{P_s}{P_a}$$

mass steam = $.622 \frac{P_s}{P_a} m_a$
mass air = $\frac{1.61 m_s}{}$
absolute humidity = X = $\frac{m_s}{m_a}$

Leakage Rate of Air from A Steam-Air Mixture:

$$L_{\text{air}} = \frac{\text{weight}_{a1} - \text{weight}_{a2}}{\text{weight}_{a1}} = \frac{m_{a1} - m_{a2}}{m_{a1}} \text{ let } m_s = \frac{V_1}{v_{s1}}$$

$$m_{a1} = \frac{1.61 m_s}{P_s/P_a} = 1.61 \frac{P_{a1}}{P_{s1}} \frac{V_1}{v_{s1}};$$

$$\frac{m_{a1} - m_{a2}}{m_{a1}} = 1.61 \frac{P_{a1}}{P_{s1}} \frac{V_1}{v_{s1}} - 1.61 \frac{P_{a2}}{P_{s2}} \frac{V_2}{v_{s2}} = 1 - \frac{P_{a2}}{P_{a1}} \frac{P_{s1}}{P_{s2}} \frac{v_{s1}}{v_{s2}} \frac{V_2}{V_1}$$

$$\frac{1.61 P_{a1} V_1}{P_{s1} v_{s1}}$$

or if P_t = total pressure, $P_a = P_t - P_s$ and the leakage is wt% per day

$$L \text{ wt\%/day} = \frac{2400}{t_1 - t_2} \left[1 - \frac{(P_{t2} - P_{s2}) P_{s1} v_{s1} V_2}{(P_{t1} - P_{s2}) P_{s2} v_{s2} V_1} \right] \quad (1)$$

2. An Alternate Derivation of the Leakage of Air Only

$$\frac{m_{a1} - m_{a2}}{m_{a1}} = \frac{P_{a1} V_1}{R_a T_1} - \frac{P_{a2} V_2}{R_a T_2} = 1 - \frac{P_{a2} T_1 V_2}{P_{a1} T_2 V_1}$$

$$\frac{P_{a1} V_1}{R_a T_1} \quad T = ^\circ R$$

P_a = partial pressure of air, or $P_T - P_s$

For leakage in units of wt%/day

$$L \text{ wt\%/day} = \frac{2400}{t_1 - t_2} \left[1 - \frac{(P_T - P_s)_2 T_1 V_2}{(P_T - P_s)_1 T_2 V_1} \right] \quad (2)$$

Although the two formulas are equivalent, the first depends on data from the steam tables directly, the second uses the perfect gas assumption.

Demonstration of the Equivalence, Eons 1 and 2

$$P_V = mRT$$

$$P_v = n\bar{R}T \quad \bar{R} = \text{universal gas constant}$$

for a given volume, time and gas constituent at 2 times as in the previous equations.

$$\frac{P_{s1} v_{s1}}{P_{s1} v_{s2}} = \frac{nRT_1}{nRT_2} \quad \frac{P_{s1} v_{s1}}{P_{s2} v_{s2}} = \frac{T_1}{T_2}$$

The only two terms in the equations that are different are equivalent, however the method for reduction of data is different in that the Equation (1) inputs are directly from the steam tables and are intrinsically more accurate than the perfect gas assumption. Equation (1) is therefore preferred.

Derivation of General Expression of Measured Outflow as an Equivalent % of Vessel Contents

$$Q = \frac{\text{cc}}{\text{min}} \quad QP = \frac{\text{lbm}}{\text{min}}$$

$$L\%/ \text{day} = \frac{QP \frac{\text{lbm}}{\text{min}} \times 1440 \frac{\text{min}}{\text{day}} \times 100}{\text{lbm in vessel}}$$

$$\text{lbm in vessel; } m_1 = \frac{30,000 \text{ ft}^3 \times 144 \frac{\text{in.}^2}{\text{ft}^2} \rho}{53.3 \frac{\text{lb-ft}}{\text{lbm } ^\circ\text{R}} T ^\circ\text{R}} \quad \rho = \frac{P_2}{RT_2}$$

$$= \frac{30,000 (144)}{53.3} \frac{P}{T}$$

$$m = K \frac{P_1}{T_1} = 8.1(10^4) \frac{P_1}{T_1}$$

$$L(\%/ \text{day}) = \frac{QP(T)}{P(K)} = \frac{Q + \frac{1}{28,300} 1440 \rho}{8.1 (10^4)}$$

$$L(\%)/\text{day} = \frac{QPT}{P} \frac{1.44^{+2} (10^2)}{8.1 (10^4)} \frac{1. (10^2)}{2.83 (10^4)} = 6.26 (10^{-5})$$

$$L(\%/\text{day}) = \frac{QPT}{P} 6.26 \times 10^{-5}$$

Q = flowrate, $\frac{\text{cc}}{\text{min}}$ as obtained from test flowmeters

Flowmeter Corrections

1. Ambient Air Leak Rate Series:

- a. Rotameters are calibrated in cfm at room temperature. The following conversion formula assumes inside temperature and flow temperature were the same for the measurement period

$$L, \text{ wt\%/day} = \frac{\text{atm ft}^3/\text{day leaked}}{\text{atm ft}^3 \text{ in vessel}} = \frac{\frac{\text{ml ft}^3}{\text{min}} \frac{\text{min}}{\text{day}} (K_1)}{30,000 \frac{\text{P}}{14.4} (K_2)}$$

P = 14.4 at Houston

P = 14.4 psia at Hanford

$$L(\%/\text{day}) = \frac{\frac{1}{28320} \frac{1440 \times 100}{1}}{\frac{30,000}{14.4} (P)} = \frac{1440 (14.4(100))}{(28,320)(30,000)} = \frac{.00244}{P} (\text{ml/min})$$

$L\%/\text{day} = \frac{.00244 (\text{ml/min})}{P (\text{psia})}$

2. Hot-Air and Steam/Air Leakrate Series:

(The assumption is that inside and outside are at different temperatures)

$$L(\%/\text{day}) = \frac{\text{mass air leaked/day}}{\text{mass air in the vessel}} \times 100.$$

$$L(\text{wt\%/day}) = \frac{\frac{\text{atm ft}^3}{\text{day}} \cdot \frac{\text{lbm}}{\text{atm ft}^3}}{\frac{P_a V}{RT}} = \frac{1}{\frac{28,320 (1440)(.077)}{P_a (30,000)(144)}} = \frac{1}{\frac{53.35}{T}}$$

$$L = \frac{1440 (53.35) T(R) \times 100 (.077)}{30,000 (28,320) P_a (\text{psia}) (144)} = \frac{T(R)}{206816 \cdot P_a (\text{psia})}$$

$$L(\text{wt\%/day}) = \frac{T(R)}{206816 \cdot P_a (\text{psia})}$$

Estimate of Temperature Lag

An estimate of the temperature lag mentioned in the text can be made using the raw data. For an example, during test #7 the average vessel temperature as estimated by the wire is used to interpolate the partial pressure of water vapor at the beginning and end of the test.

At time 1; $T_1 = 158.56$
 $P_{\text{total}} = 20.855$
 $P_{\text{air}} = 16.274 = P_{a1}$

At time 2; $T_2 = 116.93$
 $P_{\text{total}} = 16.970$
 $P_{\text{air}} = 15.416 = P_{a2} = \text{observed air pressure}$

Based on the collected leakage, we expect the leakage to be near zero since

$$L = \frac{2400}{\Delta t} \left(1 - \frac{P_{a2}}{P_{a1}} \frac{T_1}{T_2} \right)$$

For zero leakage

$$P_{a2} = P_{a1} \frac{T_1}{T_2}$$

For the data points above we would expect:

$$P_{a2} = 16.274 \left(\frac{576.93}{618.56} \right) = 15.156$$

The apparent discrepancy between the expected and observed is

$$E_p = (15.416 - 15.156) = .260 \text{ psia}$$

Referring to the steam tables⁽⁴⁾ in the region from 101 to 162 F

$$\frac{\Delta T}{\Delta P} = \left(\frac{162.25 - 101.76}{4} \right) \frac{^{\circ}\text{F}}{\text{psia}} \left(.26 \text{ psia} \right) = 3.93 ^{\circ}\text{F}$$

This is to say that the apparent pressure discrepancy could be accounted for if the partial pressure of steam were selected with the 3.93 °F temperature error above. In actuality, the temperature error is less than 3.93 °F since an error of this magnitude would also misrepresent the state of the air. For example assume a 3.93 °F error exists in the average temperature;

$$P_{a2} \text{ (real)} = P_{a1} \frac{(576.93 - 3.93)}{618.56}$$

$P_{a2} = 15.075$ which is .081 psia lower than the previously calculated air pressure. These errors are in opposite sense.

Conclusion:

A temperature determination error sufficient to explain the negative leakage value would be about 3.93 °F for test #7.

TABLE 12.
TEMPERATURE OF VESSEL CONTENTS DURING STEAM-AIR TESTS

	Number 7				Number 8				Number 9*			
	(TC)	Δt	(W)	Δt	(TC)	Δt	(W)	Δt	(TC)	Δt	(W)	Δt
0	157.91		158.56		225.50		230.36		255.82		263.02	
1	155.91	-2.00	156.30	-2.26	221.77	-3.73	226.26	-4.10	253.15	-2.67	259.40	-3.82
2	154.19	-0.72	153.91	-2.39	218.48	-3.29	222.18	-4.08	248.01	-5.14	254.00	-5.40
3	152.31	-1.88	151.57	-2.34	214.80	-3.68	218.12	-4.06	244.33	-3.68	249.72	-4.28
4	149.36	-2.95	149.52	-2.05	211.16	-3.64	214.57	-3.55	240.37	-3.96	245.91	-3.81
5	146.85	-2.51	147.25	-2.27	207.89	-3.27	210.85	-3.72	235.85	-4.52	241.11	-4.80
6	145.31	-1.54	145.32	-1.83	204.21	-3.68	207.12	-3.73	230.54	-5.31	236.36	-4.75
7	143.41	-1.50	143.27	-2.05	200.82	-3.39	203.21	-3.91	227.78	-3.26	232.84	-3.52
8	141.30	-2.11	141.15	-2.12	198.22	-2.60	199.66	-3.55	223.22	-4.06	228.29	-4.55
9	139.91	-1.39	139.18	-1.97	194.73	-3.49	196.10	-3.56	220.31	-2.91	223.94	-4.35
10	138.48	-1.43	137.48	-1.70	191.03	-3.70	192.40	-3.70	216.17	-4.14	219.60	-4.34
11	135.72	-2.76	135.74	-1.74	187.87	-3.16	188.81	-3.59	212.63	-3.54	216.78	-2.82
12	134.37	-1.35	133.88	-1.86	184.63	-3.24	185.34	-3.47	209.14	-3.49	212.46	-4.32
13	133.35	-1.02	132.27	-1.61	181.92	-2.71	182.02	-3.32	205.19	-3.95	208.42	-4.04
14	131.48	-1.87	130.54	-1.73	178.12	-3.80	179.01	-3.01	201.43	-3.75	204.51	-3.91
15	130.02	-1.46	128.88	-1.66	175.05	-3.07	175.95	-3.06	197.72	-3.71	200.88	-3.63
16	128.53	-1.49	127.34	-1.54	172.65	-2.40	173.14	-2.81	194.38	-3.34	197.00	-3.88
17	127.11	-1.42	125.92	-1.42	168.99	-3.66	170.31	-2.83	191.12	-3.26	193.25	-3.75
18	125.73	-1.38	124.46	-1.46	167.24	-1.75	167.61	-2.64	188.16	-2.96	189.91	-3.34
19	124.62	-1.11	123.42	-1.04	164.10	-3.14	164.92	-2.69	185.47	-2.69	186.92	-2.99
20	123.30	-1.32	122.00	-1.42	162.68	-1.42	162.31	-2.61	181.85	-3.62	183.50	-3.42
21	122.45	-0.95	120.46	-1.54	160.11	-2.75	159.81	-2.50	178.68	-3.17	180.33	-3.17
22	121.11	-1.34	119.17	-1.29	157.62	-2.49	156.70	-3.11	176.27	-2.41	177.36	-2.97
23	118.99	-2.12	118.03	-1.14	155.69	-1.93	154.89	-1.81	173.70	-2.57	176.74	-0.62
24	118.35	<u>-0.64</u>	116.93	<u>-1.10</u>	153.25	<u>-2.44</u>	152.5	<u>-2.39</u>	171.16	<u>-2.54</u>	175.35	<u>-1.39</u>
At = 1.59 1.73 3.02 3.24 3.53 3.66												

(TC) - Volume weight average, 23 Chromel-Alumel thermocouples.
(W) - Using resistance-temperature characteristic of Balco wire
* - Circulation face out of order

FIGURE C-1. Temperature Versus Time: Saturated Steam-Air Mixtures
(Using a Volume-Weighted Average of 23 Thermocouples)

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