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EXPERIMENTAL DETERMINATION OF THE DRYWELL VOLUME -
1/5 SCALE PRESSURE SUPPRESSION TEST

J. H. Pitts

January 1977

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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SUMMARY

The drywell volume, including space in all ports up to the first flange, was experimentally determined to be 10.01 m^3 (353.4 ft^3) with a uncertainty of $\pm 0.03 \text{ m}^3$ (1.28 ft^3). The method of measurement used a 0.040879 m^3 (1.4434 ft^3) calibrated volume that was initially filled with helium to 36.5 MPa (5290 psia). The calibrated volume was then connected to the drywell and the pressures equalized.

The volumes of the vent pipes, instrumentation ports, and either the steam inlet on nitrogen inlet should be subtracted from the measured drywell volume to obtain the net active drywell volume. The net active drywell volume is 9.87 m^3 (348.6 ft^3) for air tests and 9.85 m^3 (347.9 ft^3) for steam tests.

INTRODUCTION

During a hypothetical Loss of Coolant Accident (LOCA) in a Mark 1, boiling water reactor power plant, air followed by steam is injected from a drywell into a toroidal wetwell half filled with water. Injection of the fluids occurs below the water surface in a vertically downward direction through 0.6 m diameter open ended pipes called downcomers.

A downward load on the toroidal wetwell is induced as the water initially inside the downcomers is forced into the water pool below by fluids from the drywell. The magnitude of this downward load increases for about 1/4 second until just after gas bubbles appear in the water pool below the downcomers. The water surface inside the toroidal wetwell then moves rapidly upward, particularly in the region adjacent to the outside of the downcomers, as water is displaced by the gas bubbles. The gas bubbles overexpand because the flow of gases from the downcomers is not sufficient to counteract the upward displacement rate of the water. The direction of net load on the toroidal wetwell now shifts upward reading a peak of approximately half the magnitude of the maximum downward load at 1/2 second. The vertical load then decreases monotonically to static conditions at about 1 second.

The Lawrence Livermore Laboratory is conducting a 1/5 scale test to verify the predicted loading function and to study the ensuing fluid dynamic phenomena. One of the primary components of the test facility is the drywell. The volume of the drywell in the test apparatus was selected to account for the reduced scale and the fact that less than a full 360° torus is present. The test apparatus includes a 90° sector and a 7-1/2 degree sector of the torus so that with linear scaling laws the ratio of volumes becomes

$$\frac{V_{\text{test apparatus}}}{V_{\text{full scale plant}}} = \left(\frac{1}{5^3}\right) \times \left(\frac{90 + 7.5}{360}\right) = 0.00217$$

The reference full scale plant contains a drywell volume of 4500 m³ (159,000 ft³). The desired drywell volume in the test apparatus is then

$$\begin{aligned} V_{\text{test apparatus}} &= 0.00217 \times 4500 \text{ m}^3 \\ &= 9.75 \text{ m}^3 (345 \text{ ft}^3) \end{aligned}$$

Manufacturing tolerances are such that the drywell volume could be different from the desired value by several per cent. The manufacturer measured the volume to be 9.6 m³ (340 ft³) by an inaccurate water fill method. Because of our need to know the drywell volume accurately, we repeated the measurement using a gas fill method described below.

Method of Volume Measurement

Drywell volume measurement was accomplished by connecting a calibrated volume filled with high pressure helium to the drywell, and opening a valve placed in the connecting line to equalize the pressure. Helium was used rather than any other gas because of convenience. A schematic of the test setup is shown in Figure 1 with initial and final conditions listed in Table 1.

The test was performed on December 14, 1976 between 4 P.M. and 4:30 P.M. Most of the time was spent waiting for the pressures in the calibrated volume and drywell to equalize. We waited about 5 minutes after pressure equalization before we considered the test complete. We then vented the drywell to the atmosphere. During this 5 minute period, the recorded pressures and wall temperatures remained constant. One leak was located on the drywell where the end cap was attached to the drain line, but this leak was less than one liter

SCHEMATIC OF TEST APPARATUS USED
TO CALIBRATE THE DRY WELL VOLUME
PRESSURE SUPPRESSION TEST
FIGURE-1

TABLE 1

Initial and Final Conditions

Drywell Volume Calibration

Pressure Suppression Test

	<u>Calibrated Volume</u>	<u>Drywell</u>
Volume	0.040879 m ³ (1.4434 ft ³)	unknown
<u>Initial Conditions</u>		
Gas	Helium	Air
Pressure	36.5 MPa (5290 psia)	0.1004MPa (14.56 psia)
Wall Temperature	17°C	17°C shady side 24°C sunny side 19°C approximate average
<u>Final Conditions</u>		
Pressure	0.227 MPa (32.9 psia)	0.227 MPa (32.9 psia)
Wall Temperature	7°C	17°C shady side 24°C sunny side 19°C approximate average
<u>Atmospheric</u>		
Pressure		0.1004 MPa (14.56 psia)
Temperature		15°C

per minute and as such was insignificant. We were assured the drywell was essentially leak tight because the recorded pressure remained constant during the 5 minute period after pressure equalization. Even though the effects of any temperature changes would have been small, because the gas equation of state is based on an absolute temperature scale, we observed no change in the drywell wall temperature during the test.

The basis for the method used to calculate the drywell volume is documented in many locations.¹ Although the result is independent of mixing between the air initially in the drywell and the helium initially in the calibrated volume, it is perhaps easier to explain the method by imagining a fictitious membrane between the different gases that prevents mixing. In this fashion, the helium initially in the calibrated volume expands to fill a fraction of the drywell volume. The air initially in the drywell is compressed and in the final state occupies the remaining fraction of the drywell volume. Mathematically this may be written as

$$V_{\text{He}_1} + V_{\text{air}_1} = V_{\text{He}_2} + V_{\text{air}_2} \quad (1)$$

where V is the volume associated with the subscripts. The subscripts He and air represent the type of gas present in the volume, 1 represents the initial state, and 2 represents the final state. V_{He_1} is the calibrated volume (Haskel bottle) and V_{air_1} is drywell volume including space in the ports up to the first flange.

The value of V_{air_2} is determined using the perfect gas relationships

$$PV = mRT \quad (2)$$

where P is absolute pressure, m is mass, R is the gas constant, and T is absolute temperature. The mass and temperature of the air are identical in the initial and final states noted in Table 1 so that

1) For example, see Giedt, W. H., "Thermophysics," Van Nostrand Reinhold, 1971, Chapter 13.

$$V_{air_2} = V_{air_1} \frac{P_1}{P_2} \quad (3)$$

Combining (1) and (3) results in

$$V_{air_1} = \frac{V_{He_2} - V_{He_1}}{(1 - P_1/P_2)} \quad (4)$$

In determining the value of V_{He_2} we must consider compressibility effects associated with deviations from the perfect gas relationship. We used experimentally measured amagot densities² for helium with the relationship

$$V_{He_2} = \frac{\rho_{He_{a1}} V_{He_1}}{\rho_{He_{a2}}} \quad (5)$$

where $\rho_{He_{a1}}$ and $\rho_{He_{a2}}$ are initial and final amagot densities. $\rho_{He_{a1}}$ and $\rho_{He_{a2}}$ were found by interpolating to the appropriate pressure between tabular values and then correcting to a temperature of 17°C between the 0°C and 25°C tabular values. A second temperature correction on V_{He_2} was included to account for the final 7°C temperature value in the calibrated volume using perfect gas relationships. A summary of numerical calculations is shown in Appendix A.

From the value of measured drywell volume we must subtract that space in the vent pipes and either the inlet nitrogen or inlet steam lines to obtain the net active drywell volume. Values of the inactive volume portions of the drywell are also calculated in Appendix A.

Uncertainty Analysis

Uncertainty of the drywell volume is determined by adding the uncertainty

- 2) Amagot density in units of standard cc per cc of volume were determined by L.D. Christensen for various values of pressure up to 140 MPa (20,000 psia) and temperatures of 0, 25, and 50°C. See UCRL-51133, "Helium 3 and Helium 4 Amagot Density at High Pressure," October 5, 1971.

in V_{He2} and V_{air2} . Following the nomenclature of Schenk³ and using equations (5) and (3), we find the relationships of the various standard deviations, s , are

$$\begin{aligned} \left(\frac{s_{V_{He2}}}{V_{He2}} \right)^2 &= \left(\frac{s_{V_{He1}}}{V_{He1}} \right)^2 + \left(\frac{s_{\rho_{He1}}}{\rho_{He1}} \right)^2 + \left(\frac{s_{\rho_{He2}}}{\rho_{He1}} \right)^2 \\ &\approx \left(\frac{s_{V_{He1}}}{V_{He1}} \right)^2 + \left(\frac{s_{p1}}{p1} \right)^2 + \left(\frac{s_{p2}}{p2} \right)^2 \end{aligned} \quad (6)$$

$$\left(\frac{s_{V_{air2}}}{V_{air2}} \right)^2 = \left(\frac{s_{V_{air1}}}{V_{air1}} \right)^2 + \left(\frac{s_{p1}}{p1} \right)^2 + \left(\frac{s_{p2}}{p2} \right)^2 \quad (7)$$

Once the values of the standard deviations, $s_{V_{He2}}$ and $s_{V_{air2}}$, are determined, the standard deviation of the drywell volume is calculated as

$$s_{drywell} = \sqrt{\left(s_{V_{He2}} \right)^2 + \left(s_{V_{air2}} \right)^2} \quad (8)$$

Numerical calculations are given in Appendix A.

Summary and Results

The drywell volume including space in the ports to the first flange was calculated to be 10.01 m^3 (353.4 ft^3) $\pm 0.02 \text{ m}^3$ (1.2 ft^3). The inactive portions of the drywell associated with the space in the vent pipe ports and

3) Schenk, Hilbert Jr., "Theories of Engineering Experimentation," 2nd Edition, McGraw-Hill, (1968), Chapter 3.

either the inlet nitrogen or steam port need to be subtracted to determine the net active drywell volume. This net active drywell volume was found to be 9.87 m^3 (348.6 ft^3) and 9.85 m^3 (347.9 ft^3) for nitrogen and steam tests respectively.

Acknowledgement

This test was performed by personnel of the LLL High Pressure Laboratory under the direction of Lynn Higgins.

APPENDIX A
SUMMARY OF NUMERICAL CALCULATIONS

1) Calculations of $\rho_{\text{He}_{a1}}$ and $\rho_{\text{He}_{a2}}$

(Reference UCRL-51133 and extended tables by L. G. Schmidt, computer run 10.222M06/30).

Amagot densities for Helium - 4

ρ_a	Pressure at 0°C	Pressure at 25°C
2	29.41 psia	32.11 psia
3	44.13	48.17
282	—	5266.
284	—	5310.
304	5284	—
306	5325	—

$$\rho_{a_{5293.6 \text{ psia}, 25^\circ\text{C}}} = 282 + 2 \times \frac{(5293.6 - 5266)}{(5310 - 5266)} = 283.25$$

$$\rho_{a_{5293.6 \text{ psia}, 0^\circ\text{C}}} = 304 + 2 \times \frac{(5293.6 - 5284)}{(5325 - 5284)} = 304.47$$

$$\rho_{\text{He}_{a1}} = \rho_{a_{5293.6 \text{ psia}, 17^\circ\text{C}}} = 304.47 - (304.47 - 283.25) \times \frac{17}{25} = 290.04$$

$$\rho_{a_{32.9 \text{ psia}, 25^\circ\text{C}}} = 2 + \frac{(32.9 - 32.11)}{(42.17 - 32.11)} = 2.0492$$

$$\rho_{a_{32.9 \text{ psia}, 0^\circ\text{C}}} = 2 + \frac{(32.9 - 29.41)}{(44.13 - 29.41)} = 2.2371$$

$$\rho_{\text{He}_{a2}} = \rho_{a32.9 \text{ psia}} = 2.2371 - (2.2371 - 2.0490) \times \frac{17}{25} = 2.1093$$

17°C

$$V_{\text{He}_2} = \frac{290.04}{2.1093} \times 1.4434 \text{ ft}^3 = 198.48 \text{ ft}^3$$

17°C

$$V_{\text{He}_1} - V_{\text{He}_1} = 1.4434 \text{ ft}^3 \times \left(1 - \frac{(7 + 273)}{(17 + 273)} \right) = 0.05 \text{ ft}^3$$

17°C 7°C

$$V_{\text{He}_2} = 198.47 - 0.05 = 198.43 \text{ ft}^3$$

$$V_{\text{drywell}} = V_{\text{air}_1} = \frac{(198.43 - 1.44) \text{ ft}^3}{\left(1 - \frac{14.56 \text{ psia}}{32.9 \text{ psia}} \right)} = 353.4 \text{ ft}^3 (10.01 \text{ m}^3)$$

2) Calculation of port volumes

Vent pipe ports

16.2" Vent pipes (2 each)

$$2 \times 19 \text{ in.} \times \frac{\pi}{4} \times 15^2 \text{ in.}^2 \times \frac{1 \text{ ft}^3}{1728 \text{ in.}^3} = 3.886 \text{ ft}^3$$

5" Vent pipe

$$16.5 \text{ in.} \times \frac{\pi}{4} \times 4.813^2 \text{ in.}^2 \times \frac{1 \text{ ft}^3}{1728 \text{ in.}^3} = 0.174 \text{ ft}^3$$

$$\text{total vent pipe ports} \quad 4.060 \text{ ft}^3$$

(0.115 m³)

Air line port

$$9.5625 \text{ in.} \times \frac{\pi}{4} \times 8.00^2 \text{ in.}^2 \times \frac{1 \text{ ft}^3}{1728 \text{ in.}^3} = 0.278 \text{ ft}^3$$

(0.008 m³)

Steam line

$$9.5625 \text{ in.} \times \pi/4 \times 15.25^2 \text{ in.}^2 \times \frac{1 \text{ ft}^3}{1728 \text{ in.}^3} = 1.011 \text{ ft}^3 \quad (0.028 \text{ m}^3)$$

6" Instrumentation lines (3 ports)

$$3 \times 9.5625 \text{ in.} \times \pi/4 \times 5.875^2 \text{ in.}^2 \times \frac{1 \text{ ft}^3}{1728 \text{ in.}^3} = 0.450 \text{ ft}^3 \quad (0.013 \text{ m}^3)$$

Total inactive drywell volume

Steam tests	$5.521 \text{ ft}^3 \quad (0.156 \text{ m}^3)$
Air tests	$4.788 \text{ ft}^3 \quad (0.136 \text{ m}^3)$

Total active drywell volume

Steam tests	$(353.4-5.5) \text{ ft}^3 = 347.9 \text{ ft}^3 \quad (9.85 \text{ m}^3)$
Air tests	$(353.4-4.8) \text{ ft}^3 = 348.6 \quad (9.87 \text{ m}^3)$

3) Uncertainty Calculations

The minimum divisions on the dials for the 0-50 psi and 0-70 MPa Heise gauges is 0.05 psi and 0.05 MPa. We considered these to be manufacturer's estimates of standard deviation's, under laboratory conditions. Because the test was conducted outdoors, we felt a more reasonable estimate of standard deviations to be 0.1 psi and 0.1 MPa.

The variation between the LLL measured value of the calibrated volume of 40.879 L and the manufacturers value of 40.886 L lead me to the conclusion that the standard deviation of the calibrated volume was about 0.01 L.

Using these values we have

$$\delta_{p_2} = 0.1 \text{ psi}$$

$$\delta_{p_1} = 0.1 \text{ MPa}$$

$$\delta_{V_{He_1}} = 0.01 \text{ l}$$

$$s_{\rho_{He_1}} \approx s_{p_1}$$

$$\delta_{\rho_{He_2}} \approx \delta_{p_2}$$

$$\frac{\delta_{V_{He_2}}}{V_{He_2}} = \sqrt{\left(\frac{0.01}{40.88}\right)^2 + \left(\frac{0.1}{32.9}\right)^2 + \left(\frac{0.1}{36.5}\right)^2}$$

$$= 4.1 \times 10^{-3}$$

$$\delta_{V_{He_2}} = 4.1 \times 10^{-3} \times \left[353.4 \text{ ft}^3 \times \left(1 - \frac{14.56 \text{ psia}}{32.9 \text{ psia}} \right) \right]$$

$$= 0.81 \text{ ft}^3$$

The standard deviation for the final air volume, $S_{V_{air_2}}$, is determined by iteration because the value of $S_{V_{air_1}}/V_{air_1}$ in Equation (7) is initially unknown. The result after iteration is

$$\frac{\delta_{V_{air_2}}}{V_{air_2}} = \sqrt{\left(\frac{1.2}{353.4}\right)^2 + \left(\frac{0.1}{32.9}\right)^2 + \left(\frac{0.1}{36.5}\right)^2}$$

$$= 5.3 \times 10^{-3}$$

$$\delta_{V_{air_2}} = 5 \times 10^3 \times \left[353.4 \text{ ft}^3 \times \frac{14.56 \text{ psia}}{32.9 \text{ psia}} \right]$$

$$= 0.83 \text{ ft}^3$$

$$\delta_{\text{drywell volume}} = \sqrt{(0.81 \text{ ft}^3)^2 + (0.83 \text{ ft}^3)^2}$$

$$= 1.2 \text{ ft}^3$$

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Available from
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U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$: Microfiche \$3.00

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