Westinghouse Non-Proprietary Class 3

WCAP-14772

AP600 Test Program Overview

Westinghouse Energy Systems

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E. J. Piplica
J. Butler
Engineering

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Approved: Brian McIntyre

Westinghouse Electric Corporation
Business Unit and/or Division
P.O. Box 355
Pittsburgh, PA 15230-0355

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LIST OF ACRONYMS AND ABBREVIATIONS

ADS	automatic depressurization system
CHF	critical heat flux
CMT	core makeup tank
CNRC	Canadian National Research Council
CRDM	control rod drive mechanism
CVS	chemical and volume control system
DAS	data acquisition system
DEG	double-ended guillotine
DNB	departure from nucleate boiling
DOE	U.S. Department of Energy
DVI	direct vessel injection
EMI	electro-magnetic interference
EPRI	Electric Power Research Institute
FID	fixed in-core detector
HX	heat exchanger
IFM	intermediate flow mixer
IRWST	in-containment refueling water storage tank
LCS	lower containment sump
LOCA	loss-of-coolant accident
MSLB	main steamline break
NRC	US Nuclear Regulatory Commission
NSSS	nuclear steam supply system
OSU	Oregon State University
PCS	passive containment cooling system
PORV	power-operated relief valve
PRHR	passive residual heat removal
PWR	pressurized water reactor
PXS	passive core cooling/safety injection system
RCP	reactor coolant pump
RHR	residual heat removal
RNS	normal residual heat removal system
SBLOCA	small-break loss-of-coolant accident
SFWS	startup feedwater system
SG	steam generator
SGTR	steam generator tube rupture
SI	safety injection
SLB	steamline break
SPT	static pressure tap
SSAR	Standard Safety Analysis Report
SSG	simple support grid
STC	Science and Technology Center

1.0 INTRODUCTION

Westinghouse Electric Corporation, in conjunction with the United States Department of Energy (DOE) and the Electric Power Research Institute (EPRI), has developed an advanced light water reactor design known as AP600. AP600 is a 1940 MWt, 600 MWe two-loop pressurized water reactor (PWR) that utilizes passive safety systems.

The AP600 is a new design and, as such, it must conform to the requirements of 10 CFR, Part 52, which states:

> *Certification will be granted only if the performance of each safety feature of the design has been demonstrated through either analysis or the appropriate test programs, experience, or a combination thereof; interdependent effects among the safety features of the design have been found acceptable by analysis, appropriate test programs, experience or a combination thereof; and sufficient data exists on the safety features of the design to assess the analytical tools for safety analysis over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium conditions.*

The purpose of the AP600 Test Program Overview is to identify and summarize the various test programs performed in support of the AP600 design and design certification efforts with the requirements of 10 CFR 50, Part 52.

This report does not strive to supplant the large body of information available on the AP600 test programs. Instead, this report guides the reader to where additional information can be found.

2.0 TEST CLASSIFICATION

Each test performed as part of the AP600 test program was classified according to type. The four types of tests included were:

- Basic research tests
- Engineering tests
- Component separate effects tests
- Integral systems tests

These classifications were determined according to the scope and primary purpose of the individual test. This section summarizes the completed AP600 tests and discusses the important results of those tests. Sources for additional information are identified.

2.1 BASIC RESEARCH TESTS

Basic research tests are experimental in nature and are used to provide engineering guidance or detailed information on specific phenomena to be studied. These tests are also used to determine the feasibility of an engineering concept before proceeding to a larger-scale test or development program. While these tests are not required by the NRC for design certification, they support design certification test and analysis activities. The basic research tests conducted are briefly described in the following sections.

2.1.1 Air-Flow Path Pressure Drop Test

General Description/Purpose

A one-sixth scale replica of a 14-degree section of the passive containment cooling system (PCS) air-flow path was constructed to quantify the air-flow path resistance, determine if aerodynamic improvements were needed, and demonstrate the effectiveness of these improvements (Figure 2-1).

The air-flow path was constructed of heavy plywood and sheet metal and used a blower at the outlet diffuser end to draw air through the model. The air-flow baffle surrounding the vertical sides of containment (downflow inlet/upflow outlet air-flow divider wall) was modeled to reflect the corrugated sheets, reinforcing and support beams, and support posts that maintain separation between the shield wall and hold the baffle and containment. The air-flow above containment modeled the PCS water storage tank support beam flanges, steel radiation shielding plates, wire grill, and chimney structure. The air-flow Reynolds numbers were maintained below the scaled Reynolds number that would correspond to the actual design, throughout testing, to ensure that the measured f(L/D)s were conservative.

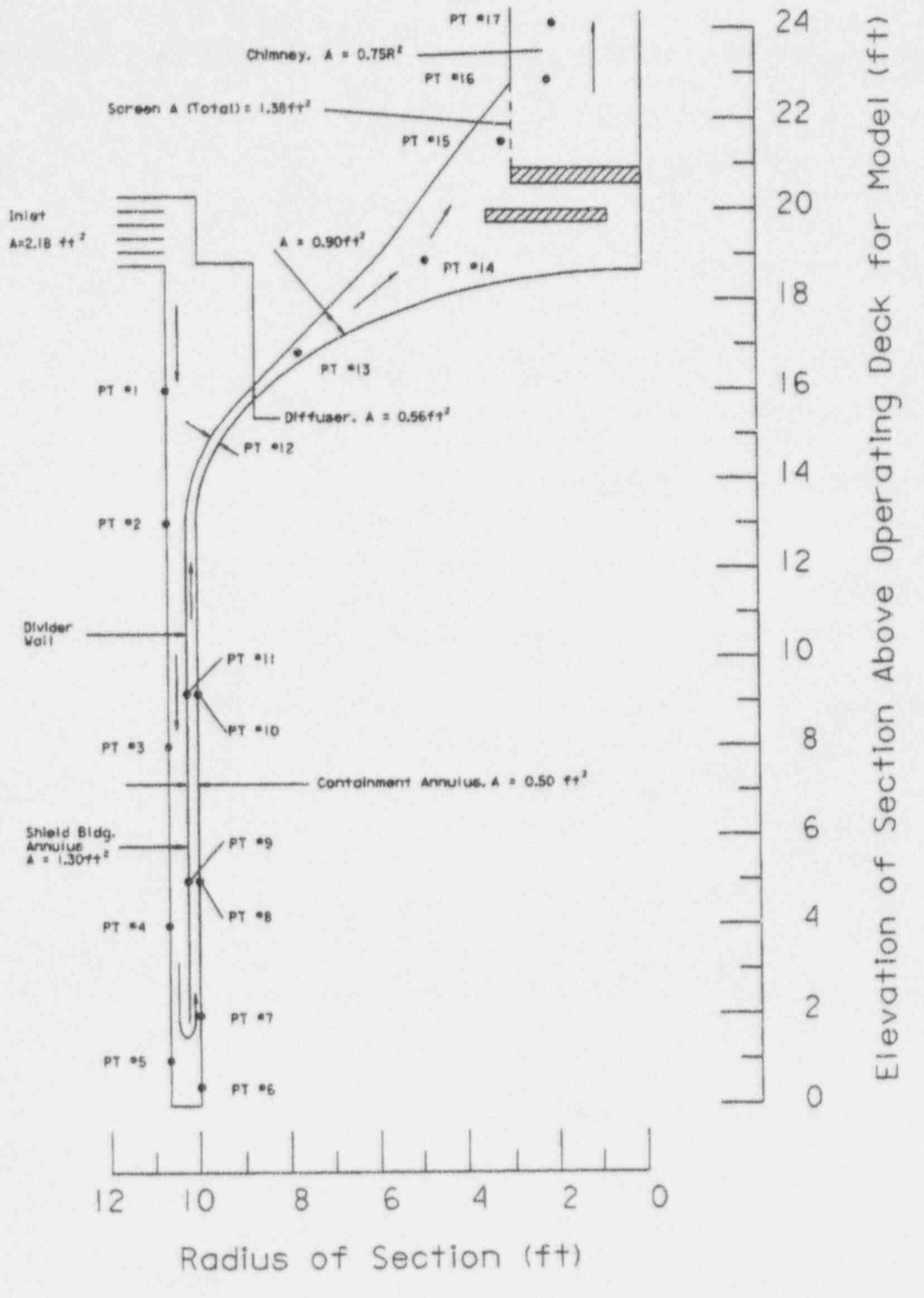

Figure 2-1 Radial Section Showing Air Path Boundaries Through the Test Model

Instrumentation consisted of a series of wall pressure taps located throughout the air-flow path of the model. Each was located in the center of the air-flow path, with care taken to maintain a smooth surface where penetrating the wall. The taps were connected to a pressure transducer via an electrically driven scanning valve. The voltage output of the transducers was measured and recorded at regular intervals by a data actuation system (DAS). Flow velocities were measured using a wedge probe with both wedge side taps connected together.

Test Matrix/Results

The initial test results showed that the turning and inlet flow losses at the 180-degree turn into the bottom of the containment annulus and the losses in the containment annulus were the largest pressure losses. Therefore, several modifications were made:

- A rounded inlet was added at the containment annulus inlet.

- Since the turning radiuses for some streamlines at the annulus inlet would be relatively small, the rounded inlet was constructed using perforated metal to minimize flow separation.

- The air baffle sheet corrugations were made wedge-shaped at the inlet to lessen the tendency to contract the flow.

- The support posts from containment to the baffle were streamlined by adding fairings.

The results of this test showed that the total PCS air cooling path pressure loss coefficient was reduced by 45 percent by adding the streamlining features. This reduced loss coefficient was used in subsequent analyses of PCS performance.

Pressure drop in the air-flow path was quantified for the PCS. This test for the AP600 demonstrated that the pressure coefficients in the air-flow could be estimated, verified, and improved with simple design changes.

Documentation

Additional information on the Air-Flow Path Pressure Drop Test may be found in WCAP-13328, "Tests of Air-Flow Path for Cooling the AP600 Reactor Containment," (Reference 1).

2.1.2 Water Film Formation Test

General Description/Purpose

A survey of coatings that could be used on the AP600 containment was conducted to determine a coating that would provide corrosion protection and could be conducive to establishing a stable water film on the containment exterior surface. After selection of a coating candidate, a simple qualitative test was performed to demonstrate the wettability of the prototypic paint selected for use on the containment outer surface, and to characterize general requirements for forming a water film over a large surface area. The test apparatus consisted of a flat steel plate, 8-foot long in the flow direction and 4-foot wide. The plate was pivoted so that it could simulate nearly horizontal sections of the dome as well as the vertical containment sidewalls.

Test Matrix/Results

Water-flow was supplied to the plate at a single point at the top center edge of the plate and was measured to simulate actual plant-flow conditions. Various flow spreading devices were tried both to induce and observe uniform film behavior, and to judge spreading requirements.

Summarized results of the test are:

- The selected paint readily wetted and rewetted after being dried.
- No rivulet formation was observed on this painted surface even at high point source flow rates and vertical orientation.
- With a point source of water, without additional distribution, most of the flow was in a 12-inch wide path down the 8-foot length.
- Several methods were able to create a water film across the entire width of the plate at various flowrates. Once formed, this water film was stable, did not form into rivulets, and wetted the entire length of the plate surface.

These results, combined with additional observation of film behavior in the tests described in subsections 2.2.3 and 2.3.5, were used to devise appropriate water distribution devices applicable to the actual containment structure.

Documentation

Additional information on the Water Film Formation Test may be found in WCAP-13884, "Water Film Formation on AP600 Reactor Containment Surface," (Reference 2).

2.1.3 PCS Bench Wind Tunnel Test

General Description/Purpose

Bench wind tunnel tests of the PCS were conducted at the Westinghouse Science and Technology Center (STC) using 1/100-scale models of the AP600 shield building, air inlets and outlets, annulus baffle, and containment. These tests were performed to establish the proper location of the air inlets and to confirm that wind will always aid containment cooling air-flow. Two models were used: one consisted of only the shield building and diffuser discharge without inlets and internal flow; the second included the air inlets, air baffle, containment, tank support structure, and a fan to simulate convective air-flow. Pressures were measured at the inlet, building side and top, bottom of inlet annulus, top of containment at the discharge of the air baffle, and in the chimney. Air-flow was measured at the inlet to the containment baffle.

Test Matrix/Results

These tests were run with a uniform wind tunnel air velocity of 85 ft./sec. Test Reynolds numbers for the shield building and chimney were demonstrated to be in the transition region. The models used in this test were 10 inches in diameter and 18 inches in overall height. The model that included the containment and air baffle structures was instrumented with static pressure taps (SPTs) and an air velocity (anemometer) measurement. The instrumentation was located in a common vertical plane, and the model was rotated 360 degrees to obtain the air-pressure profile around the entire structure.

The results from this test showed that when the air inlets are located on the top (roof) of the shield building, a "chimney" effect is created over a significant portion of top of the building (this effect became more pronounced when the wind direction was inclined upward). Air inlets located at the top of the shield building sidewalls provide overall the most positive wind-induced driving pressure versus air exit pressure.

Air-pressure profiles in the shield building across the cooling air baffle to the air exit with external wind were developed. By comparison to a "no-wind" case where all the cooling air-flow was induced by the fan, it was shown that, with the selected air inlet arrangement, the wind will always increase the containment cooling air-flow rate.

Other significant conclusions from this test were:

- Deep beams behind the air inlets (as provided in the PCS water storage tank structure in the original shield building design) significantly increased wind-induced containment air cooling flow.

- Containment air cooling flow was insensitive to wind direction and to a 15-degree downward wind inclination. Cooling flow was increased by a 15-degree upward wind inclination.

Documentation

Additional information on the PCS Bench Wind Tunnel Test may be found in WCAP-14048, "Passive Containment Cooling System Bench Scale Wind Tunnel Test," (Reference 3).

2.2 ENGINEERING TESTS

These tests are primarily performed to obtain specific design information or to verify the design of a particular component. They are also used to provide boundary conditions for analysis of other components or systems, or to determine initial conditions for other separate effect or integral systems tests. Generally, these tests are mechanical in nature.

The engineering tests performed are briefly described below.

2.2.1 Normal Residual Heat Removal (RNS) Suction Nozzle Test

General Description/Purpose

In order to optimize the AP600 hot-leg residual heat removal (RHR) suction nozzle configuration and to eliminate the potential loss of the RHR function during mid-loop operation will not be a concern in the AP600, a series of tests were performed using an existing test facility.

The test model was made of clear plastic material to allow for visual viewing of the water behavior. The model consisted of a simulated reactor vessel with a 1/4.25-scale hot leg and RHR suction pipe. The Froude number was used to scale the test pump flow-rates. A void meter and a strip chart recorder were used to measure the percentage of air entrainment by volume in the pump suction piping continuously. All test runs were recorded on video tape. Two suction nozzle orientations and two potential vortex "breaker" arrangements were tested. For each configuration tested, the critical vortexing water level was measured as a function of both Froude number and loop water level.

Test Matrix/Results

The following configurations were tested:

- A scaled 10-inch RHR pipe in the bottom of the hot leg.
- A "step" nozzle at the bottom of the hot leg and a 10-inch RHR pipe at bottom of the step nozzle. Different diameters (14 to 20 inches) and lengths were investigated for the step nozzle.

These configurations were compared with previous test results obtained with an RHR suction nozzle placed at 45 degrees below the horizontal, the typical configuration on current Westinghouse pressurized water reactors (PWRs).

Among the different nozzle arrangements tested, the optimum arrangement was a step-nozzle. Also, as the hot-leg level was further reduced, vortex formation in the hot leg stopped, as water just spilled into

and filled the large nozzle. Air entrainment during the "spill" mode was small and would not result in unstable pump/system operation.

Documentation

Additional information on the Normal Residual Heat Removal Suction Nozzle Test may be found in APWR-0452-P, "AP600 Vortex Mitigator Development Test for RCS Mid-Loop Operation," (Reference 4).

2.2.2 PCS Wind Tunnel Tests

General Description/Purpose

PCS wind tunnel tests were conducted in boundary layer wind tunnels at the University of Western Ontario and the Canadian National Research Council's (CNRC) wind tunnel in Ottawa, Ontario. The overall objectives of the PCS wind tunnel test were to demonstrate that wind does not adversely affect natural circulation air cooling through the shield building and around the containment shell, and to determine the loads on the air baffle. The test was conducted in four phases (1, 2, 4A, and 4B).

Phases 1 and 2 were conducted with a 1/100-scale model of the AP600 shield building and surrounding site structures, including the cooling tower. The model of the shield building and surrounding structures was placed in the tunnel on a turntable which permitted the entire assembly to be rotated to simulate the full 360 degrees of wind directions. The wind tunnel also allowed extended fetches of coarsely modeled upstream terrain to be placed in front of the building undergoing testing. The wind tunnel flow (about 75 ft./sec.) then developed boundary layer characteristics representative of those found in full scale. For this testing, a boundary layer representative of open-country conditions (ANSI C) was developed.

Phase 1 modeled the site structures and external shield building only. No internal flow passages were provided. The shield building model was instrumented with pressure taps at the inlet locations and in the chimney. The purpose of Phase 1 was to compare the pressure coefficients developed following changes to the shield building and/or site structures with the pressure coefficients developed on the current plant design. Note that the base case is without the cooling tower.

Phase 2 used the model from Phase 1 testing, modified to include a representation of the shield building air-flow path. The shield building model was instrumented with pressure taps inside the inlet plenum and in the chimney. In addition, pressure taps were located throughout the air-flow path to provide for approximate baffle wind loads at several locations. The purpose of Phase 2 was to explore the effects of the flow path on the developed pressure coefficients and to determine wind loads on the air baffle.

Phase 3 was planned to provide an estimate of the amount of effluent that would be recirculated from the chimney of the shield building to the inlets. This phase of testing was cancelled.

Phase 4A was conducted at both the University of Western Ontario and the Canadian National Research Council's (CNRC's) wind tunnel in Ottawa, Ontario, on both the 1/100-scale model and a 1/30-scale model. The primary objectives of the test were to confirm that the detailed Phase 2 results at the University of Western Ontario conservatively represented those expected at full-scale Reynolds numbers, and to obtain better estimates of baffle loads in the presence of a cooling tower. Note that, although the cooling tower represented a blockage in the University of Western Ontario wind tunnel that is normally unacceptable, it introduced conservative errors.

The first portion of Phase 4A was conducted at the University of Western Ontario using the existing 1/100-scale model of the shield building and site-surrounding structures. Additional instrumentation was added to the model to provide useful overall comparison of Reynolds number effects between the tests at the two facilities. For comparative purposes, the model was equipped with a sealing plate at the interior base of the chimney to prevent flow through the interior passages, when desired. Tests were also conducted with the flow path open in a uniform wind field to provide true instantaneous baffle loads for a tornado case.

The Phase 4A tests at CNRC were conducted on a 1/30-scale model of the shield building. The model did not have complete internal passages; however, the chimney was open inside to its base, and a simple inlet manifold was included extending just below the inlets. This was connected to an additional internal volume designed to compensate for the frequency response of the volume of the blocked passages in the 1/100-scale model. Instrumentation on the model was similar to the 1/100-scale model on the exterior and inside the chimney to provide comparative results between the tunnels. A 1/100-scale model of the cooling tower was tested in the CNRC tunnel to provide a cooling tower waste-pressure distribution and wake properties for application in the Phase 4B testing.

The objectives of the Phase 4B tests were to explore variations in site layout and topography to determine whether or when such variations significantly affect the net pressure difference between the inlet and chimney of the AP600 and, by implication, the convected flow and net baffle loads. A small-scale model of the site buildings and local topography was built at a scale of about 1/800. This scale range ensured that both the reactor and cooling tower models were in the same Reynolds number range (subcritical), while remaining a size that allowed the use of straightforward modeling and instrumentation techniques.

Test Matrix/Results

The data from the Phase 1 base case design indicated a significant positive pressure difference between the inlets and the chimney. Changes to the inlets only marginally reduced the pressure difference. Raising and lowering the chimney had little effect. Raising and lowering the turbine building also had little effect. The presence of the natural draft cooling tower significantly increased the turbulence at the shield building, resulting in larger fluctuating differential pressures. However, in all cases, the mean pressure difference remained positive. Removal of the deaerator from the turbine building showed no effect.

The majority of the tests for Phase 2 were conducted at one wind angle with all site structures except the cooling tower. Pressure coefficients were measured across the baffle. Mean pressures from all taps on a particular level were compared to examine the uniformity of the pressures around the baffle. The data indicated that the distributions were fairly uniform, even at the top of the annulus. The presence of the cooling tower increased the pressure fluctuations, but the mean remained about the same.

The Phase 4A tests at CNRC verified that the tests at the University of Western Ontario were independent of Reynolds numbers.

Phase 4B site geography testing conducted at the University of Western Ontario consisted of the following cases:

- A reference case—consisting of the current site layout, including all site buildings and a cooling tower on flat open-country terrain
- A series of other cases—idealized sites based on Diablo Canyon and Trojan and/or Indian Point
- The Diablo Canyon type site addressed speedup due to an escarpment. The Trojan/Indian Point site looked at the effects of a river valley site

Documentation

Additional information on the PCS Wind Tunnel Tests may be found in the following documents:

Phase 1 Wind Tunnel Test

- WCAP-13294, "Phase 1 Wind Tunnel Testing for the Westinghouse AP600 Reactor," (Reference 5)

Phase 2 Wind Tunnel Test

- WCAP-13323, "Phase 2 Wind Tunnel Testing for the Westinghouse AP600 Reactor," (Reference 6)

Phase 4A Wind Tunnel Test

- WCAP-14068, "Phase 4A Wind Tunnel Testing for the Westinghouse AP600 Reactor," (Reference 7)
- WCAP-14169, "Phase 4A Wind Tunnel Testing for the Westinghouse AP600 Reactor, Supplemental Report," (Reference 8)

Phase 4B Wind Tunnel Test

- WCAP-14091, "Phase 4B Wind Tunnel Testing for the Westinghouse AP600 Reactor," (Reference 9)

2.2.3 PCS Water Distribution Tests

General Description/Purpose

The PCS water distribution test was conducted to provide a large-scale demonstration of the capability to distribute water on the steel containment dome outer surface and top of the containment sidewall. The overall objectives of the PCS water distribution test were to quantify the effectiveness of the water distribution over the containment dome and top of the containment sidewall, and to provide data to finalize the design of the AP600 containment water distribution. The results of the tests were used in the safety analysis of the AP600 containment response.

The test was conducted in several phases. Phase 1 utilized a full-scale simulation of the center of the containment dome out to the 10-foot radius. The surface of the model was coated with the prototypic AP600 containment coating. The test was used to evaluate water delivery to the dome. Water distribution measurements were obtained by collecting and measuring flow off the periphery of the model. In addition, the test evaluated the use of a surfactant to promote water film formation.

Phase 2 was conducted on a full-scale 1/8 sector of the containment dome at the Westinghouse Waltz Mill facility located in Madison, Pennsylvania. The Phase 2 test modeled both the AP600 water supply and a distribution system arrangement. The surface of the test model incorporated the maximum allowable weld tolerances between the steel plates and was coated with the prototypic AP600 containment coating to provide similarity to the AP600 plant design. Measurements of the water distribution were obtained by collecting and measuring the flow over defined areas and by selective measurement of film thicknesses using a capacitance probe. In addition, the test evaluated the use of a surfactant to promote water film formation.

Phase 3 was used to confirm the final design of the water distribution system. Measurements of the water distribution were obtained by collecting and measuring the flow over defined areas and by selective measurement of film thicknesses using a capacitance probe. The results of the Phase 3 test were compared with the Phase 2 results to verify the performance of the final water distribution system design.

Test Matrix/Results

Phase 1 tests were conducted over a range of water-flow rates that bracketed the anticipated flows. Tests were also conducted with and without any distribution devices and with imposed surface tilts.

Phase 2 tests were also conducted both with and without prototypic spreading devices at flow rates which simulated the expected water delivery from flow initiation to the 3-day delivery rate. As with the Phase 1 tests, Phase 2 tests showed a more even distribution with increasing flow rate. At high flow rates, water distribution on the dome was greater than 65 percent. At low flow rates, the

coverage decreased to below 40 percent. The test also reaffirmed the need for a water distribution device on the containment dome.

Phase 3 tests were completed and used to verify the performance of the finalized distribution device design. The matrix for Phase 3 testing is provided in Table 2-1.

Documentation

Additional information on the PCS Water Distribution Tests may be found in the following documents:

Phase 1 - Water Distribution Test

- WCAP-13353, "Passive Containment Cooling System Water Distribution Phase 1 Test Data Report," (Reference 10)

Phase 2 - Water Distribution Test

- WCAP-13296, "PCS Water Distribution Test Phase 2 Test Data Report," (Reference 11)

Phase 3 - Water Distribution Test

- WCAP-13960, "PCS Water Distribution Phase 3 Test Data Report," (Reference 12)

Table 2-1 Water Distribution Test, Phase 3		
Test	**Test Number**	**Description**
Weir performance tests	1	Test of weir performance with initial water flow rate
	2	Test of weir performance with 24-hour water flow rate
	3	Test of weir performance with excessive water flow rate
	4	Test of weir performance with 3-day water flow rate
	5	Test of tilted weir performance with initial water flow rate
	6	Test of tilted weir performance with 3-day water flow rate
	7	Test of weir performance with initial water flow rate and plugged drainage holes
	8	Test of weir performance with initial water flow rate and plugged drainage holes
	15	Test of weir performance with initial water flow rate and baffle support plates
	16	Test of weir performance with 3-day water flow rate and baffle support plates
Film thickness tests	9	Test to measure film thickness and flow rate at initial water flow rate
	10	Test to measure film thickness and flow rate at 3-day water flow rate
	11	Test to measure film thickness and flow rate at excessive water flow rate
	12	Test to measure film thickness and flow rate at 24-hour water flow rate
	13	Test to measure film thickness with tilted weir and initial water flow rate
	14	Test to measure film thickness with tilted weir and 3-day water flow rate

2.2.4 Reactor Coolant Pump (RCP) High-Inertia Rotor/Journal and Bearing Tests

General Description/Purpose

An effective way to provide flow during coastdown of a pump during a loss-of-power transient is to add rotational inertia to the pump shaft at a bearing location.

The reference design AP600 canned motor RCP provides a rotating inertia of 5000 lb/ft^2. To achieve this inertia with minimum drag loss, the impeller-end journal contains a 26-inch diameter by 14.5-inch long high-density (depleted uranium alloy) insert. The insert is enclosed in stainless steel for corrosion protection, and the enclosure is hardfaced at the bearing running surfaces for better wear resistance.

The resulting journal diameter is 28 inches, twice the diameter of any previously built water-lubricated RCP bearing. Because of the size and unique construction, manufacturing and testing of the journal and bearing assemblies was undertaken. This engineering test program experimentally confirmed theoretical predictions of the parasitic and bearing losses arising from the "high-inertia" rotor concept applied to canned motor pumps. The test program also verified manufacturability and confirmed the adequacy of the design of both the thrust and journal bearings.

One important objective of this effort was to experimentally confirm the theoretical predictions of the parasitic and bearing losses arising from the high-inertia rotor concept applied to canned motor pumps. Theoretical calculations based on empirical drag laws are not sufficiently accurate to permit a final design to be made without experimental verification. The viability of the high-inertia concept depends on limiting the losses to acceptable values. Additional important objectives included confirming the satisfactory performance of the radial and thrust bearings, and demonstrating the manufacturability and integrity of a full-scale, encapsulated depleted-uranium journal.

In order to measure the losses accurately, a special friction dynamometer was designed, constructed, and put into operation.

Tests of the high inertia RCP were conducted in three phases.

Test Matrix/Results

Phase 1 testing successfully demonstrated the design and construction of a full-scale encapsulated high-inertia journal. Five thousand pounds of depleted-uranium, 2-percent molybdenum alloy were cast, machined, encapsulated in stainless steel, precision-clad with hard-facing (Stellite), and balanced at all speeds up to and including 2000 rpm (13 percent overspeed).

The program was completely successful in demonstrating satisfactory performance under load of one of the largest water-lubricated, high-speed, pivoted-pad journal bearings ever built. The journal,

pivoted-pad radial bearing, thrust bearing, and friction-dynamometer test rig operated smoothly with no significant vibration over the entire speed and load range.

Success was achieved in the accurate measurement of the parasitic drag losses of the complete bearing assembly. These losses were higher than expected. Both radial load and thrust load were shown to have only a minor affect on losses, with speed being the major variable.

The largest contributors to the increase in losses over those originally expected were believed to be the balance cutouts and canopy welds on the journal. Other possible contributors to the losses were identified for investigation in Phase 2.

The first objective in Phase 2 was to measure the losses with smooth-end covers fitted over the canopy weld and balance cutout areas. The second objective was to determine the affect on the losses by removing the flow plugs blocking the ports of a six-hole centrifugal pump in the rotor. The third objective was to determine the affect on losses by increasing the gap between the outboard end of the motor and the bumper plate.

Smooth-end covers were successfully fabricated and fastened to the canopy weld and balance cutout areas of the high-inertia rotor. However, the resultant loss measurements were higher than those obtained previously in Phase 1. Thus, the first try at smoothing these areas was not successful. The Phase 2 tests were successful in determining the effect of removing the flow plugs and increasing the axial gap. Neither of these changes produced a large difference in the measured losses. Removal of the bumper plate reduced the losses by about 9 hp. The most significant finding was that there was no difference in measured losses between the two directions of rotation.

Phase 3 tests were performed to investigate a change in the design and location of the radial bearings in order to reduce the drag losses. The design change removed the radial bearing function from the high-inertia rotor and onto the pump shaft. The objective of the current testing was to measure the losses with the radial bearing pads removed and a cylindrical shroud installed to give an annular space with a radial gap of 0.5 in.

The seven radial bearing pads were removed from the test housing and replaced by a continuous annular space having an average radial clearance of about 0.5 inches. Dynamic analysis predicted that the high-inertia test rotor and shaft would continue to exhibit stable operation. The testing verified the prediction; the test facility remained stable throughout the full-speed range to 1761 rpm. Noncontacting displacement transducers were added to measure the relative radial positions of the rotor and housing. These transducers worked very well to provide information to enable the rotor to be kept well-centered in the housing. The program was completely successful in obtaining a large reduction in power losses with the removal of the radial bearing pads, as predicted prior to testing.

Documentation

Additional information on the RCP High Inertia Rotor/Journal and Bearing Tests may be found in the following documents:

Phase 1 - RCP Rotor Test

- WCAP-12668, Revision 1, "AP600 High Inertia Rotor Testing Phase 1 Test Report," (Reference 13)

Phase 2 - RCP Rotor Test

- WCAP-13319, "AP600 High Inertia Rotor Testing Phase 2 Report," (Reference 14)

Phase 3 - RCP Rotor Test

- WCAP-13758, "High Inertia Rotor Test Phase 3 Report," (Reference 15)

2.2.5 RCP SG Channel Head Air-Flow Test

General Description/Purpose

The air-flow test was performed to identify effects on pump performance due to nonuniform channel head flow distribution, pressure losses of the channel head nozzle dam supports and pump suction nozzle, and possible vortices in the channel head induced by the pump impeller rotation.

The air test facility was constructed as an approximate 1/2-scale mockup of the outlet half of the channel head, two pump suction nozzles, and two pump impellers and diffusers. The channel head tubesheet was constructed from clear plastic to allow smoke flow stream patterns to be seen.

Test Matrix/Results

The results of the test confirmed that no adverse flow condition, anomalies, or vortices in the channel head were induced by the dual impellers.

Documentation

Additional information on the RCP SG Channel Head Air-Flow Test may be found in WCAP-13298, "RCP Air Model Test Report," (Reference 16).

2.2.6 In-Core Instrumentation Electro-Magnetic Interference (EMI) Tests

General Description/Purpose

A test was performed to demonstrate that the system would not be susceptible to EMI from the nearby control rod drive mechanisms (CRDMs). The test was performed by mocking up instrument cables, bringing them into close proximity with an operating CRDM, and measuring the resulting noise induced on simulated flux signals.

Test Matrix/Results

The tests demonstrated that induced currents in the fixed in-core detector (FID) cables were acceptably small compared to the FID signals.

Documentation

Additional information on the In-Core Instrumentation EMI Tests may be found in WCAP-12648, Revision 1, "AP600 In-core Instrumentation System Electromagnetic Interference Test Report," (Reference 17)

2.2.7 Reactor Vessel Air-Flow Visualization Tests

General Description/Purpose

A 1/9-scale model of the AP600 reactor vessel and the four cold legs was constructed at the University of Tennessee. This model was used to visualize the vessel lower plenum to determine if vortices were present and, if so, the effect on them from surrounding features. The model was designed for flow visualization in the lower plenum, so the flow region from the steam generator (SG) outlet through the core support plate was accurately scaled. This included representations of the cold legs, downcomer, lower plenum, and support plate, including the hot-leg segments and the radial support keys in the downcomer and the vortex suppression ring in the lower plenum. Acrylic plastic was used for the cold legs, reactor vessel, and lower plenum, so flow visualization techniques could be employed in these areas. Flow in the model was provided by a blower that exhausted air vertically from the upper plenum region. The flow rate was controlled by a gate valve immediately upstream of the blower. This velocity was measured in each of the four cold legs using low-pressure drop orifices located near the cold leg nozzles.

Test Matrix/Results

These tests confirmed that vortices were effectively eliminated by the design. The absence of adverse effects was confirmed.

Documentation

Additional information on the Reactor Vessel Air-Flow Visualization Tests may be found in WCAP-13351, "Studies of Hydraulic Phenomena in the Reactor Vessel Lower Plenum Region - Test Report," (Reference 18).

2.3 COMPONENT SEPARATE EFFECTS TESTS

General Description/Purpose

Separate effects tests are performed to obtain data for computer code model development of specific thermal-hydraulic phenomena anticipated to occur as a result of the use of an individual component. In these tests, the boundary conditions for the individual component are controlled to provide the range of conditions expected to be experienced by that component. In addition, tests are performed to separate the phenomena of interest in order to investigate the effect of that phenomena.

The following component tests have been completed:

Passive Core Cooling System (PXS):

- Passive residual heat removal (PRHR) heat exchanger (HX) tests (subsection 2.3.1)
- Departure from nucleate boiling (DNB) tests (subsection 2.3.2)
- Automatic depressurization system (ADS) test - Phase A (subsection 2.3.3)
- ADS test - Phase B1 (subsection 2.3.4)
- Core makeup tank (CMT) test (subsection 2.3.5)

PCS:

- PCS heated plate test (subsection 2.3.6)

2.3.1 PRHR HX Test

General Description/Purpose

An experimental program was performed to characterize the thermal performance of the PRHR HX and the mixing behavior of the in-containment refueling water storage tank (IRWST). The experiment used stainless steel tubing material, tube diameter, pitch and vertical length. The tubes were located inside a scaled IRWST. Since the vertical length was preserved, the buoyant-induced flow patterns inside the tank simulated the AP600. The main scaling parameter for the experiment was the pool volume per HX tube so that the heat load characteristics, resulting tank fluid conditions, and induced flow pattern would be similar to those in the AP600.

Test Matrix/Results

The PRHR HX test confirmed the heat transfer characteristics of the PRHR HX and mixing characteristics of the IRWST. These results validated the HX size and configuration.

The test conditions covered a full range of expected flow rates, including forced-convection PRHR cooling (RCPs running) and natural circulation flows by varying the pumped flow through the tubes. The tests also examined different initial primary fluid temperatures over a range from 250° to 650°F using hot pressurized water that flowed downward inside the tubes. The initial tank temperature was either ambient temperature (70°F) or near boiling (212°F). The test data were reduced to obtain the local wall heat flux on the PRHR tubes. Comparisons of the PRHR test data with existing correlations for free convection and boiling were made, and a design correlation for the PRHR HX was developed.

The following conclusions were drawn from the test results:

- A boiling heat flux correlation, similar to recognized correlations, was developed from the PRHR data. Using the PRHR boiling correlation, an overall heat transfer coefficient can be calculated to determine the required surface area and evaluate the PRHR performance during postulated accidents.

- Mixing of the water in the simulated IRWST was very good. Localized boiling did not occur until the entire IRWST water volume was significantly heated. The test demonstrated that the IRWST water will not steam into the AP600 containment for about two hours.

Documentation

Additional information on the PRHR HX test may be found in WCAP-12980, Revision 1, "AP600 Passive Residual Heat Exchanger Test Final Report," (Reference 19).

2.3.2 DNB Tests

General Purpose/Description

While low-flow DNB tests have been performed successfully on other fuel assembly geometries, data accumulated over several years of testing on the current Westinghouse fuel designs have concentrated on the higher flow range associated with operating conditions of conventional, higher-power density cores. The purpose of these tests was to determine the critical heat flux (CHF) performance of the AP600 fuel assembly design, particularly at low-flow conditions. In addition, the effect on CHF of the intermediate flow mixer (IFM) grids at low-flow conditions was measured.

The test objective was to gather CHF data on typical and thimble cell AP600 bundle geometry, covering the range of fluid conditions anticipated during AP600, DNB-related ANS Condition I and II transients. The conditions cover the following ranges:

Pressure:	1500 to 2400 psia
Mass velocity:	0.5 to 3.5 x 10^6 lbm/hr.-ft.^{2}
Inlet temperature:	380° to 620°F

Also, a typical cell test where the AP600 bundle has the IFM grids replaced by simple support grids (SSGs) was run to assess the effect of the IFMs at low-flow conditions.

To perform a series of low-flow tests, two test bundles were constructed. The test bundles consisted of a small 5 by 5 array of rods, which are electrically heated and well-instrumented with thermocouples. The components for the test bundles were shipped to the test site, Columbia University, and assembled just prior to testing.

Test Results/Matrix

Sufficient data were taken to provide a basis for reducing the lower limit on mass velocity by 60 to 70 percent from the current value of 0.9 by 10^6 lb/hr.-ft.^{2} (i.e., to the 3 to 4 fps range).

The results of the DNB tests were used to extend the existing Westinghouse DNB correlation to lower flow rates than previously tested. Other correlations, however, did extend to lower flow rates, and the DNB margin has been shown to exist using these correlations over the lower range of flow rates. Since the AP600 has ample DNB margin, this test did not impact the core or fuel design.

Documentation

Additional information on the DNB tests may be found in WCAP-14371, "AP600 Low Flow Critical Heat Flux Test Data Analysis," (Reference 20).

2.3.3 ADS Test - Phase A

General Description/Purpose

The purpose of these tests was to simulate operation of the ADS, to confirm the capacity of the ADS, and to determine the dynamic effects on the IRWST structure.

The ADS Phase A test was a full-sized simulation of one of the two AP600 depressurization system flow paths from the pressurizer that duplicated or conservatively bounded the operating conditions of the AP600 ADS valves, sparger, and quench tank. A full-sized sparger was tested. The loadings on the sparger and its support were measured, as were temperatures and pressures throughout the test arrangement.

A pressurized, heated water/steam source was used to simulate the water/steam-flow from the AP600 RCS during ADS operation. The flow was piped to a full-sized sparger submerged in a circular rigid quench tank simulating the IRWST. Instrumentation to measure water and steam-flow rate, equipment dynamic loads, IRWST dynamic loads, and sparger/IRWST steam quenching was provided.

The ADS Phase A test arrangement is shown schematically in Figure 2-2. Phase A testing consisted of saturated steam blowdowns, at rates simulating ADS operation, through the submerged sparger. Sparger steam quenching was demonstrated from ambient to fully saturated IRWST water temperatures.

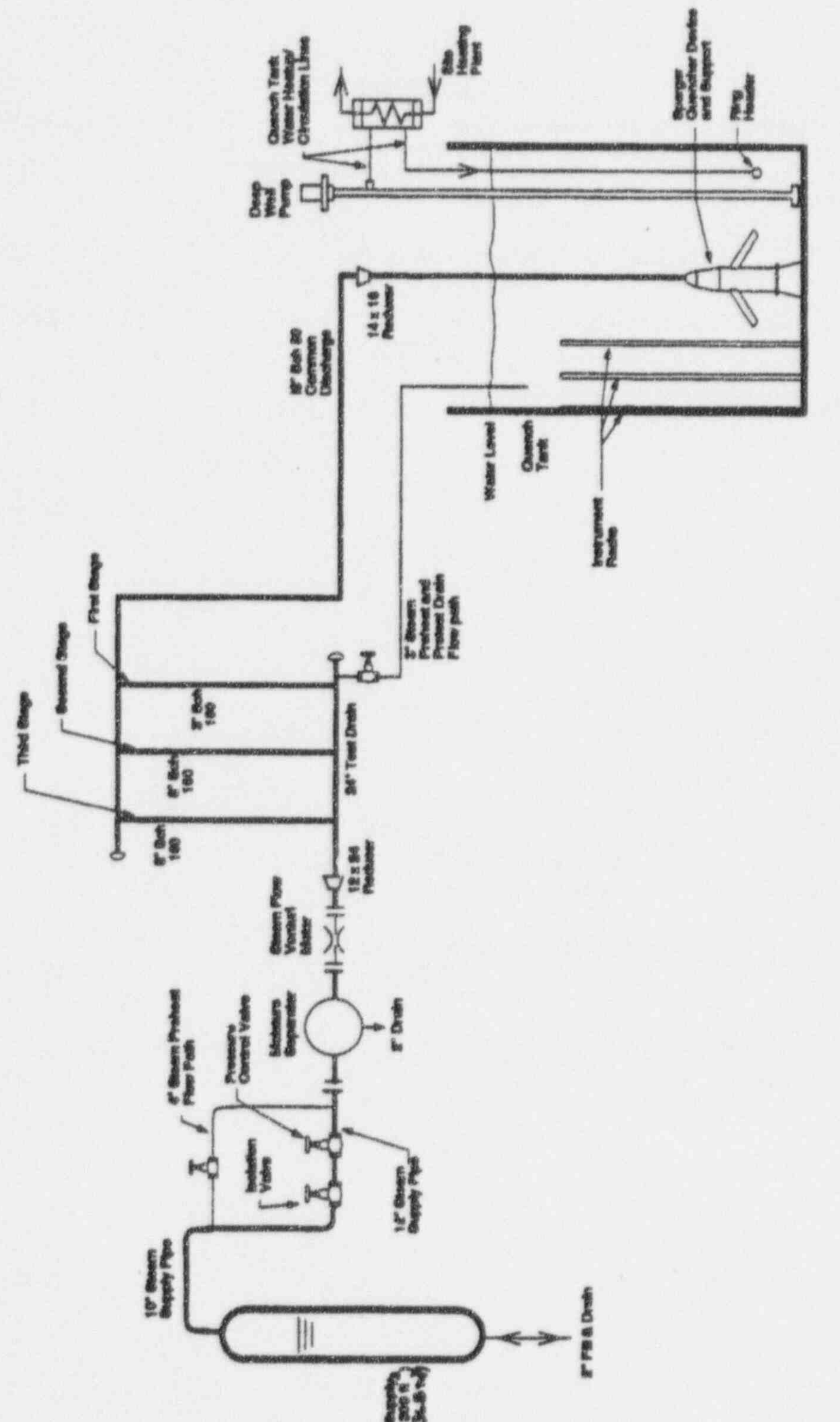

Figure 2-2 ADS Phase A Test Facility

Test Matrix/Results

Phase A v , conducted to provide both the maximum possible blowdown rate, when all three stages of the AP600 ADS were actuated, and to simulate the minimum blowdown rate (end of blowdown) when the pressurizer was essentially depressurized. For these tests, all three piping connections between the test drum and the discharge line were open. These tests were used to select the quench tank water level to be used in all subsequent ADS blowdowns.

Tests were performed to simulate the actuation of the first stage of ADS and blowdown to 500 psig. One test simulated the inadvertent opening of a second- or third-stage ADS valve when the reactor is at operating pressure. Additional tests provided the maximum blowdown rate that will occur in the AP600 when the first- and second-stage ADS valves are open.

Results of the Phase A tests were used to verify the design of the ADS sparger and obtain sufficient information to perform preliminary design of the IRWST. Tests performed with a fully saturated quench tank water showed that loads on the IRWST decrease as water temperature increases.

Documentation

Additional information on the ADS - Phase A tests may be found in the following documents:

Facility Description Report

- WCAP-14149, "VAPORE Facility Description Report, AP600 Automatic Depressurization System, Phase A Test," (Reference 21)

Final Data Report

- WCAP-13891, "AP600 Automatic Depressurization System Phase A Test Data Report," (Reference 22)

2.3.4 ADS Test - Phase B1

General Description/Purpose

The AP600 uses an ADS to depressurize the RCS so that long-term gravity injection is initiated and maintained. The portion of the AP600 ADS tested consisted of two piping flow paths from the top of the pressurizer to a quenching device or sparger submerged in a water-filled portion of the reactor containment structure. Each of these two piping flow paths are made up of a 12-inch pipe from the pressurizer, which connected to three parallel paths (4-, 8-, and 8-inches). These three parallel paths each have one control valve and one isolation valve, and connect to a single 14-inch discharge line to the submerged sparger. The closed control valves are slowly opened sequentially, with the isolation valve open, to provide a staged, controlled depressurization of the RCS from operating conditions of 2250 psia/650°F to saturated conditions at about 25 psia. This staged valve opening limits the maximum mass flow rate through the sparger and also limits the loads imposed on the quench tank which is always maintained at containment pressure.

The ADS Phase B1 test was a full-sized simulation of one of the two AP600 depressurization system flow paths from the pressurizer that duplicated the operating conditions of the AP600 ADS valves, sparger, and quench tank. A full-sized ADS valve piping package was tested. The loadings on the sparger and its support were measured, as were temperatures and pressures throughout the test arrangement.

Phase B1 testing was performed at ENEA's VAPORE test facility in Casaccia, Italy. The test collected sufficient thermal-hydraulic performance data to support the development and verification of analytical models of the ADS used in safety analyses of events for which the ADS is actuated. In addition, it provided the design requirements of the ADS components and obtained sufficient information to establish component design specifications.

Phase B1 testing included the addition of piping to permit the blowdown of either saturated steam or saturated water from the pressurizer, and installation of piping and valves representative of the actual ADS. The ADS Phase B1 test arrangement is shown schematically in Figure 2-3.

ADS Phase B1 test data were used to assess the critical and subsonic flow models for the valves in the ADS, as well as the sparger, when the flow is two-phase. ADS Phase B1 tests supported proper specification of the functional requirements for the valves.

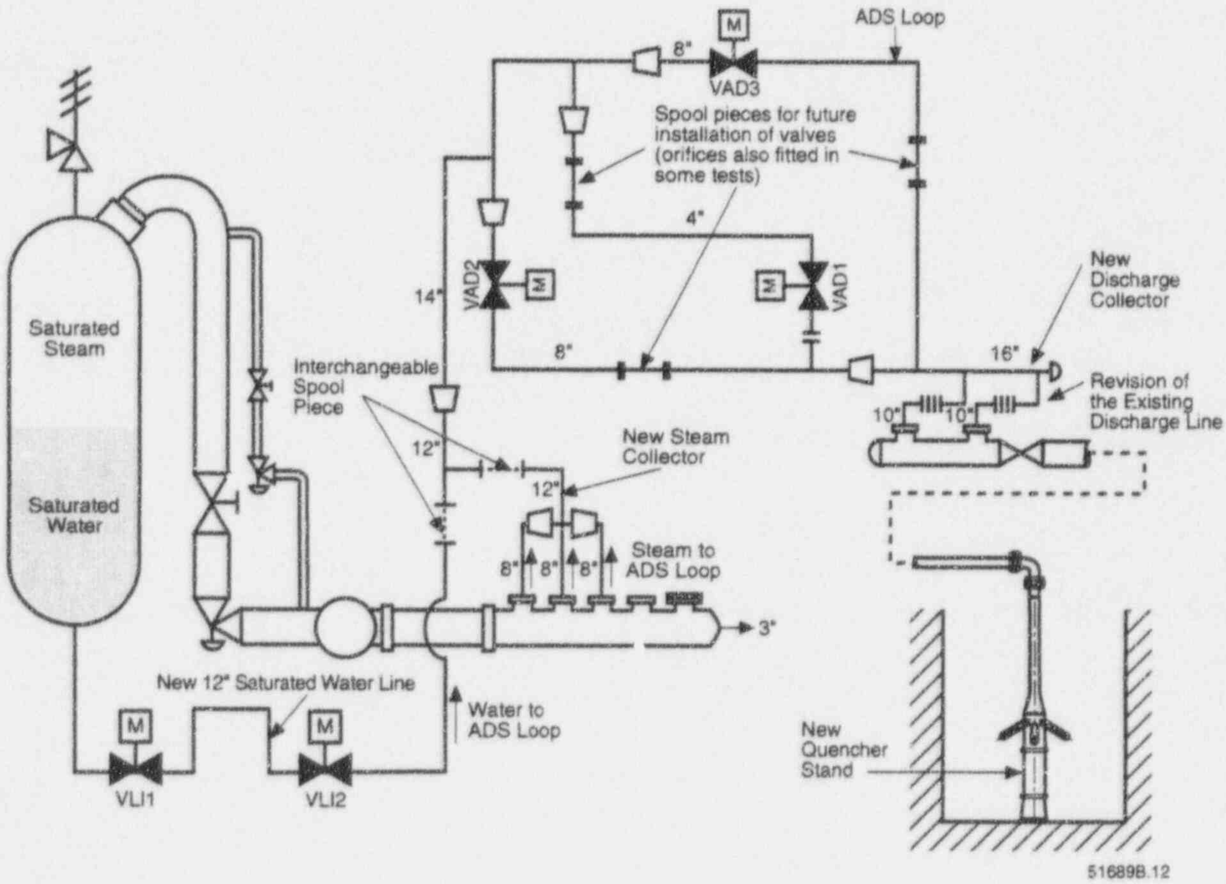

Figure 2-3 ADS Phase B1 Test Facility

Test Matrix/Results

The test matrix is shown in Table 2-2. Tests were run with saturated steam and water, and two-phase fluid at various quantities. The key results and observations for ADS Phase B1 are:

- The sparger operated properly over the full range of ADS flow rates, fluid qualities, and quench tank temperatures.
- ADS quench tank loads resulting from sparger-induced pressure pulses during Phase A are conservative.
- Loads observed for steam and steam/water blowdowns are less than Phase A.
- Pressure drops and flow nodes for water through the piping and valves were obtained, and are similar to those predicted for the AP600.
- No low-flow slugging was exhibited by the sparger.
- Blowdowns into a hot (212°F) quench tank produced small loads.

Documentation

Additional information on the ADS - Phase B1 tests may be found in the following documents:

Facility Description Report

- WCAP-14303, "Facility Description Report, AP600 Automatic Depressurization System Phase B1 Tests," (Reference 23)

Final Data Report

- WCAP-14324, "AP600 Design Certification, ADS Phase B1 Tests, Final Data Report," (Reference 24)

Test Analysis Report

- WCAP-14305, "AP600 Test Program, ADS Phase B1 Test Analysis Report," (Reference 25)

Table 2-2 ADS Phase B1 Test Specification ADS Performance Test Matrix			
Facility Configuration	**Test Run No.**	**ADS Simulation**	**Supply Tank Pressure**
Saturated water blowdowns from bottom of supply tank, no orifices in spool pieces, cold quench tank water	310	Stages 1, 2, and 3 open	High
"	311	Stages 1, 2, and 3 open	Intermediate
"	312	Stages 1, 2, and 3 open	Low
"	330	Stages 1 and 2 open	High
"	331	Stages 1 and 2 open	Intermediate
"	340	Stage 2 open (inadvertent opening)	High
Saturated water blowdowns from bottom of supply tank, orifices installed in spool pieces	250	Stage 2 open (inadvertent opening)	Intermediate
"	210	Stage 1 open	High
"	211	Stage 1 open	High
"	212	Stage 1 open	High
"	220	Stages 1 and 2 open	Intermediate
"	221	Stages 1 and 2 open	High
"	230	Stages 1 and 3 open	Intermediate
"	231	Stages 1 and 3 open	High
"	240	Stages 1, 2, and 3 open	Intermediate
Saturated water blowdowns from bottom of supply tank, orifices installed in spool pieces	241	Stages 1, 2, and 3 open	Low
"	242	Stages 1, 2, and 3 open	Low
Saturated steam blowdowns from top of supply tank, orifices installed in spool pieces	110	Stage 1 open	High
"	120	Stages 1 and 2 open	High
"	130	Stages 1 and 3 open	Intermediate
"	140	Stages 1, 2, and 3 open	High

Table 2-2 ADS Phase B1 Test Specification ADS Performance Test Matrix (Cont.)			
Facility Configuration	**Test Run No.**	**ADS Simulation**	**Supply Tank Pressure**
Saturated water blowdowns from bottom of supply tank, no orifices in spool pieces, quench tank water at 212°F (100°C)	320	Stages 1, 2, and 3 open	High
"	321	Stages 1, 2, and 3 open	Intermediate
"	322	Stages 1, 2, and 3 open	Low
"	350	Stages 1 and 2 open	High
"	351	Stages 1 and 2 open	Intermediate

2.3.5 CMT Test

General Description/Purpose

The AP600 passive safety injection system (PXS) includes two CMTs that are completely full of cold borated water and located above the cold legs of the AP600 RCS. These tanks have a normally open isolation valve on the cold-leg balance line and a normally closed isolation valve on the discharge line. The tanks will drain into the reactor vessel via the discharge line from the bottom of each CMT to the reactor vessel. Water level instrumentation in the CMTs and timers are used to open the ADS valves from the pressurizer. This depressurization system reduces RCS pressure to near atmospheric pressure as the CMTs continue to drain.

The purpose of this test was to simulate CMT operation over a wide range of prototypic pressures and temperatures, to simulate CMT operability, to simulate the operability of a CMT level instrument, and to obtain data to support the development and verification of computer models to be used in safety analyses and licensing of the AP600 design.

The CMT test facility consisted of a CMT tank, a steam/water reservoir, instrumentation, and associated steam supply inlet and water discharge piping and valves (Figure 2-4). A layout comparison between the AP600 CMT and RCS, and the CMT test tank and steam/water reservoir is provided in Figure 2-5. The CMT used in the test was a carbon steel pressure vessel about 2 feet in diameter and 10 feet in overall length. The tank was mounted vertically and elevated so that the height between the bottom of the tank and the steam/water reservoir was equivalent to the initial head for gravity draining available in the plant. The CMT steam supply line from the steam water reservoir to the CMT simulated the cold leg to the CMT balance line. During testing, only one of the two steamlines were open. Steamline 1 had higher resistance than steamline 2 and connected to the top of the steam/water reservoir. Steamline 2 projected into the steam water reservoir and was heat-traced to better simulate the cold-leg balance line. The steam water reservoir was used to provide a source of steam to the CMT and to collect the water discharged from the CMT. Thus, it acted as a simulated RCS for the test facility.

The CMT test was designed to accommodate a device used to reduce steam jetting directly into the tank by mean-pointing a triple-flange connection on the inlet piping. A steam distributor (consisting of a short pipe with a series of holes in the cylindrical section of the pipe and a capped end, attached to a flange) was inserted into the inlet piping to test the effectiveness of the device during the hot preoperational tests.

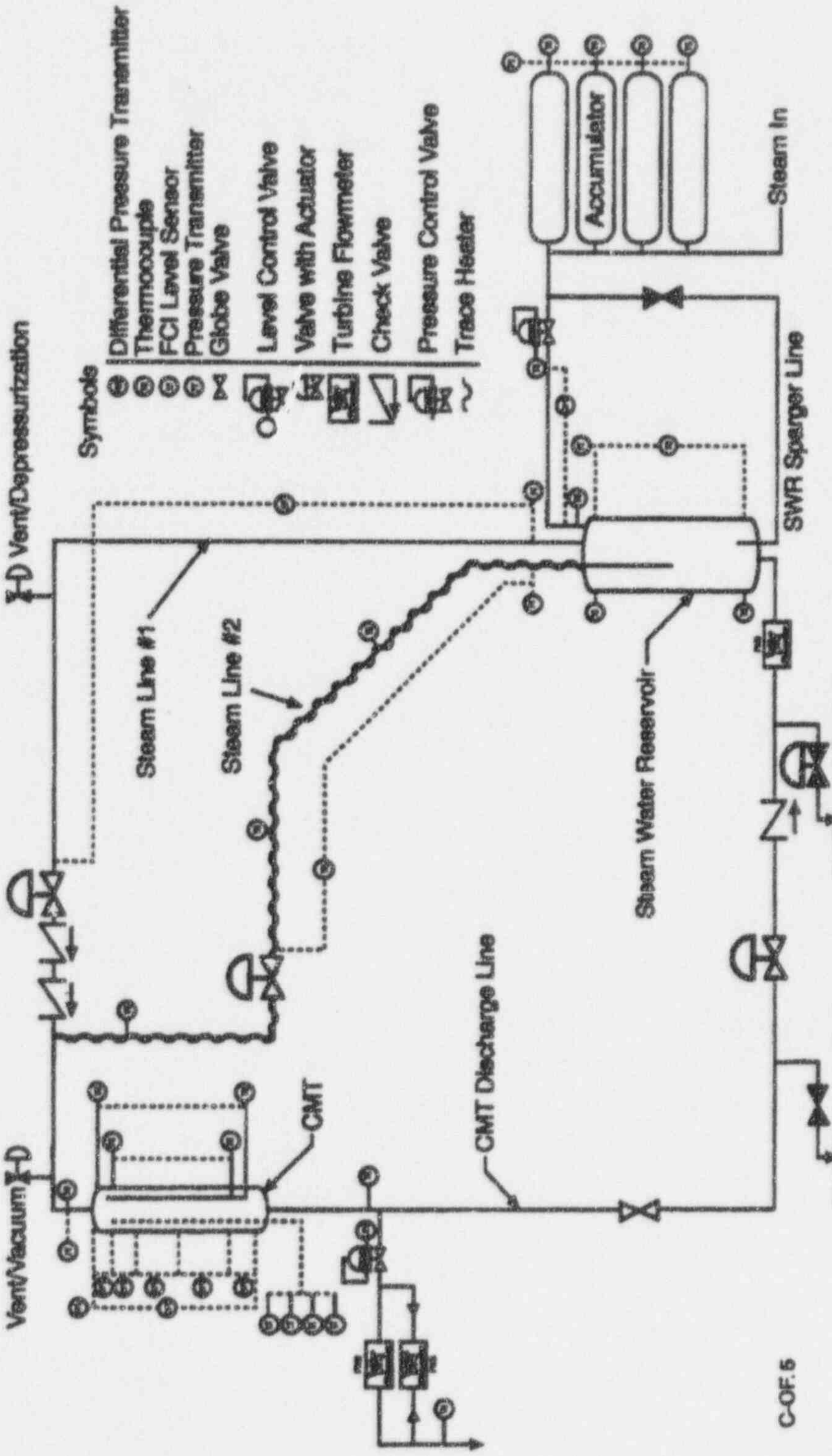

Figure 2-4 **CMT Test Facility Schematic**

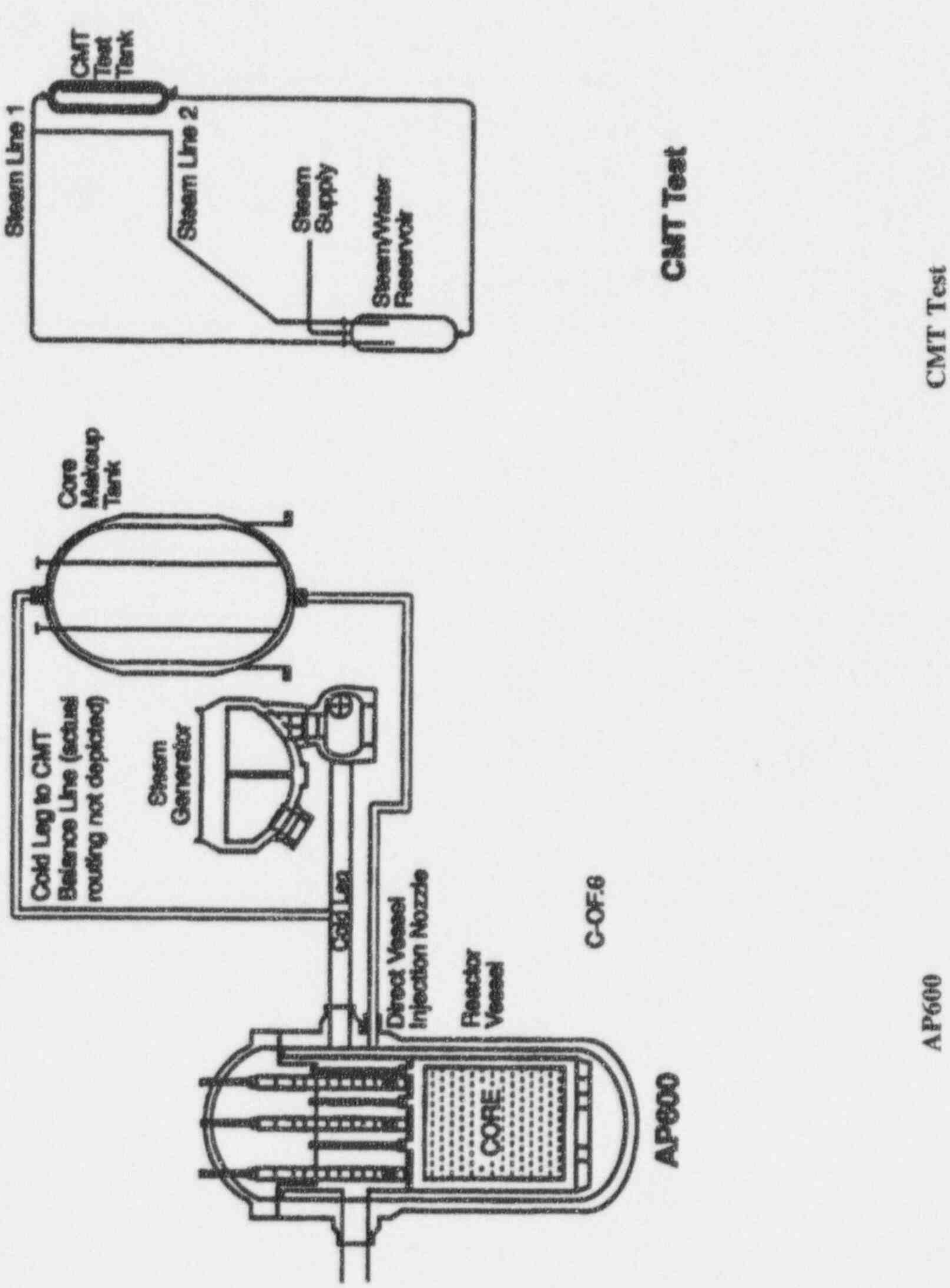

Figure 2-5 AP600 CMT and RCS Layout and CMT Test Tank and Steam/Water Reservoir

The performance of an instrument that may have the characteristics for the desired plant-level instrumentation was obtained for this CMT test program. To test the operation and performance of the CMT level instrumentation that may be used in the actual plant, four pairs of resistance temperature detectors, each pair consisting of one heated resistance temperature detector and one unheated, were located at different elevations on their test tank. The output signals from the four resistance temperature detector pairs were recorded during each matrix test. The data was analyzed and the performance of the instrument characterized and evaluated at the conclusion of the test program to determine overall performance and establish design criteria and specifications for the actual plant-level instrumentation. The CMT test level measurement system data was analyzed to assess the behavior of the CMT differential pressure cells and the response of the CMT level device to a wide range of thermodynamic conditions.

Test Matrix/Results

Shakedown testing of the facility was first completed. This testing was used to establish system volumes, line resistances, valve positions required to establish specific steam injection, and CMT draindown rates.

The matrix tests are provided in Table 2-3.

The objectives of the CMT matrix tests were:

- To simulate CMT conditions and measure the rate of steam condensation on the CMT walls and water surface versus steam pressure and water-drain rate

- To obtain detailed measurements of CMT through-wall temperature profiles, CMT liquid inventory temperature profiles, and condensate drain rates versus steam pressure

- To simulate stable behavior of the CMT water level as the cold water drains and is replaced by steam over a wide range of drain rates and piping resistances binding the prototypic design

- To evaluate the operation of CMT level instrumentation used to actuate the ADS at typical CMT conditions

Table 2-3 Matrix Tests, CMT Test

Test	Test Type	CMT Drain Rate	Steam Supply Pressure(s)	Comments
101	CMT wall condensation with and without noncondensable gases	CMT drain rate based on steam condensation rate and drain capability	10	CMT initially contains no water and is evacuated
102			135	
103			685	
104			1085	
105			2235	
106			10	CMT pressure with air (or N_2) to .236, 1.13, and 2.13 psia, respectively
107				
108				
301	CMT draindown at constant pressure	6	10	Low resistance steam supply line 2 utilized; drain rate controlled by discharge line resistance
302		6	135	
303		6	1085	
304		11	10	
305		11	135	
306		11	1085	
307		16	10	
308		16	135	
309		16	1085	
310		max	10	
311		max	135	
312		max	1085	
317		6	45	
318		11	45	
319		16	45	
320		6	685	
321		11	685	
322		16	685	
323		max	685	

Table 2-3 Matrix Tests, CMT Test (Cont.)

Test	Test Type	CMT Drain Rate	Steam Supply Pressure(s)	Comments
401	CMT draindown during depressurization	6/16 gpm	1085, depressurization to 20	Steam line 2 used
402				
403		Rate controlled by supply line 1 resistance	2235, depressurization to 20	Resistance set for 6/16 gpm drain rate
404				
501	Natural circulation followed by draindown and depressurization	Discharge line resistance set for 6/16 gpm drain rate	1085, depressurization to 20	Natural circulation until 1/5 of CMT heated
502				
503				Natural circulation until 1/2 of CMT heated
504				
505				Natural circulation until CMT fully heated
506				
507		Drain rate to be chosen based on results of tests 501-506	1835, depressurization to 20	1/5 CMT heated
508				1/2 CMT heated
509				CMT fully heated

During CMT hot preoperational testing, the model CMT diffuser was plastically deformed. Through examination and analysis of this CMT diffuser, Westinghouse determined the root cause. During preoperational testing of high-pressure steam injecting into an empty tank, the diffusers were subjected to a high differential pressure in conjection with high temperatures, beyond the system design basis. The diffuser suffered fatigue failure, which is not expected within an AP600 plant operating life. Other diffusers used during more prototypic tests performed without incident.

The key results and observations are:

- The test tank operated over the full range of pressures, temperatures, and flow rates
- Sufficient data were obtained for model development and code validation for recirculation and draindown
- The steam diffuser reduced condensation and limited mixing to about 12 inches below the diffuser, without waterhammer
- Hydraulics of the test were well-predicted by using simple mass and energy equations

Documentation

Additional information on the CMT Test may be found in the following documents:

Scaling Report

- WCAP-13963, Revision 1, "Scaling Logic for the Core Makeup Tank Test," (Reference 26)

Facility Description Report

- WCAP-14132, "AP600 CMT Program - Facility Description Report," (Reference 27)

Final Data Report

- WCAP-14217, "Core Makeup Tank Test Data Report," (Reference 28)

Test Analysis Report

- WCAP-14215, "Core Makeup Tank Test Analysis Report," (Reference 29)
- WCAP-14442, "AP600 Core Makeup Tank Level Instrument Test Data and Evaluation Report," (Reference 30)

2.3.6 PCS Heated Plate Test

General Description/Purpose

In the PCS concept, heat transfer from the outside of the vessel was performed by forced convection heat transfer from the steel containment surface to air (including some radiation to the divider wall) and evaporation of a water film on the wetted outside area of the containment surface above the operating deck elevation. In order to obtain data for the heat and mass transfer processes, and to observe film hydrodynamics including possible formation of dry patches due to surface tension instabilities, experiments were performed on a thick steel plate heated on one side and with an evaporating water film and ducted air-flow on the other side.

T experimental apparatus consisted of a 6-foot long, 2-foot wide, and 1-inch thick steel plate coated with the same coating planned for use on the containment vessel. An air duct was formed over the plate by side walls and a Plexiglas® cover used for flow visualization. A four-speed blower ducted through a set of turning vanes provided air-flow velocities which simulated the full range of both natural draft in the containment cooling duct and flows induced by a high wind. Water preheated in an automatically controlled water heater, was supplied at a metered rate to a simple distributor located at the upper end of the plate.

To simulate the heating of the containment wall that would occur in an actual plant following a postulated accident, the test plate was heated from the back side using a high temperature heat transfer fluid, UCON*500. The heat transfer fluid flowed through copper heating tubes that were soldered into grooves in the back of the plate. The heat transfer fluid was electrically heated in a drum with an automatic temperature control and pumped through a flow meter to the tube inlet manifold. All hot parts, except the front of the plate, were insulated to minimize heat loss.

The plate could be placed in a vertical position to simulate the containment side wall or inclined somewhat from horizontal to simulate the different slopes on the elliptic containment dome. Plate temperatures and heat fluxes were measured at six locations by pairs of thermocouples. In addition, air inlet and outlet temperatures were measured together with duct velocity. An electronic watt meter registered total heater power. Water outlet flow and temperature were also measured. Temperature and power data were recorded on a DAS.

Test Matrix/Results

Experiments were performed with no water on the plate and for a range of water film flow rates simulating the high water-flow on the upper part of containment down to the lower part of containment where the water was nearly completely evaporated at the high heat flux. A series of tests to isolate and observe the effect of air velocity at one representative film-flow were completed. Tests at high air velocities were performed to examine the high wall shear effects for a number of film flow rates. A limited set of tests was performed at 15-degree inclination to horizontal to provide data for the thicker films that flow on the dome. A summary of test conditions is provided in Table 2-4.

The evaporation rate of water from the heated plate was shown to agree with or exceed those expected and confirmed the overall heat transfer capability of the PCS concept. The following conclusions were drawn from the test results:

- Water film evaporation and resultant heat removal agreed with or exceeded expected values.
- Heat transfer from the water film to air was performed by forced convection plus mixing with hotter evaporated water vapor.
- Radiation to the air baffle wall and subsequent heat transfer to the cooling air occurred and accounted for some of the heat transfer.
- Heat transfer from containment to the air with no water film agreed very well with expected values.
- Water film flowing on the coated steel surface was wavy laminar flow not susceptible to instabilities that lead to dry patch formation at any heat flux density or plate surface temperature encountered.
- A water film was easily formed on the coated steel surface even in the vertical orientation. Once formed, the film showed no instability or tendency to form rivulets. This was true at all tested water flow rates.
- The water film was not adversely affected by the countercurrent cooling air-flow up to the maximum air velocity of the test (e.g., no water-film stripping occurred).

Documentation

Additional information on the PCS Heated Plate Test may be found in WCAP-12665, "Test of Heat Transfer and Water Film Evaporation on a Heated Plate Simulating Cooling of the AP600 Reactor Containment," (Reference 31)

Table 2-4 Test Conditions, Test No., and Average Heat Flux (Btu/hr.-ft.^{2})

Water Film Flow Rate lbm/hr./ft. of nominal	Air Velocity (ft./sec.)						
	5.9	12.4	18.8	23.7	28.5	33.2	38.7
	Dry Plate Tests, Vertical Except 15 Degrees from Horizontal						
0		1	2	4	5	6	7
		680	860	930	1040	1100	1210
			3* 420				
	Water Film (Except Partially Dry) on Vertical Plate						
15	8 3120		9 3270				
60		10 3490	11 3640 12 2120				
110	13 3340	14 3610	15 3540 16 3580 17 3490	18 3570	19 3670	20 3670	21 3650
170		22 3520	23 3570 24 2030				
310			25 3560	26 3530			
	Water Film on Plate 15 Degrees from Horizontal						
60			27 3500 2800 1960				
110		29 3580	30 3590 31 2020				
310		32 3510					

2.4 INTEGRAL SYSTEMS TESTS

General Description/Purpose

These tests examined the performance of a complete system through simulation of all interconnecting systems, subsystems, components, and piping to provide thermal-hydraulic data for computer code validation. These data verified that the interaction of the individual components used to model the overall system was correct and that the computer code models predicted the appropriate system response.

PCS:

- Small-scale integral test (subsection 2.4.1)
- Large-scale heat transfer test (subsection 2.4.2)

PXS:

- Full-height, full-pressure integral systems test (subsection 2.4.3)
- Low-pressure, 1/4-height integral systems test (subsection 2.4.4)

2.4.1 PCS Small-Scale Integral Test

General Description/Purpose

This test simulated PCS heat transfer processes occurring on both the inside and outside containment surfaces. The test apparatus included a 3-foot diameter, 24-foot high steel pressure vessel internally heated by steam supplied at various pressures. A transparent wall around the pressure vessel was used to create a 15-in. wide annulus for fan-driven or natural circulation air-flow. In order to simulate a full range of possible air temperatures and humidities, the incoming air was heated by a steam heating coil and humidified with steam. Instrumentation to measure internal steam condensing rates, external water evaporation rates, containment wall inner and outer temperatures, water film and air temperatures, humidities, and air velocities was provided. Speed control of the draft fan at the diffuser section permitted simulation of a full range of air-flow conditions in the air annulus.

Test Matrix/Results

The tests were conducted with varying steam supply flow rates, water film flow rates, inlet air temperatures, and inlet air humidities (Table 2-5). Instrumentation was provided to measure internal steam condensation rates, external water evaporation rates, containment wall inner and outer temperatures, water film temperatures, air temperatures, humidities, and air velocities.

Table 2-5 AP600 PCS Small-Scale Integral Test Matrix						
Test No.	Steam Outlet	Steam/Air Pressure (psig)	Cooling Air Velocity (ft./sec.)	Water Film Flow (gpm)	Cooling Air Temp (°F)	Air Relative Humidity
1	Uniform	10	8	0	Ambient	Ambient
2	Uniform	20	8	0	Ambient	Ambient
3	Uniform	30	16	0	Ambient	Ambient
4	Uniform	40	16	0	Ambient	Ambient
5	Uniform	10	16	2.5	130	Ambient
6	Uniform	30	16	2.5	130	Ambient
7	Uniform	40	16	2.5	130	Ambient
8	Uniform	10	16	2.5	130	95°F wet bulb
9	Uniform	20	16	2.5	130	95°F wet bulb
10	Uniform	30	16	2.5	130	95°F wet bulb
11	Uniform	40	16	2.5	130	95°F wet bulb
12	Uniform	10	8	2.5	130	Ambient
13	Uniform	20	8	2.5	130	Ambient
14	Uniform	20	8	2.5	130	95°F wet bulb
15	Uniform	10	8	1.0	130	Ambient
16	Uniform	20	8	1.0	130	Ambient
17	Uniform	30	16	4.0	130	Ambient
18	Uniform	40	16	4.0	130	Ambient
19	Uniform	10	8	1.0	130	95°F wet bulb
20	Uniform	40	16	4.0	130	95°F wet bulb
21	Uniform	20	16	2.5	130	Ambient

Table 2-5 AP600 PCS Small-Scale Integral Test Matrix (Cont.)

Test No.	Steam Outlet	Steam/Air Pressure (psig)	Cooling Air Velocity (ft./sec.)	Water Film Flow (gpm)	Cooling Air Temp (°F)	Air Relative Humidity
22	Uniform	80	20	0	Ambient	Ambient
23	Bottom inlet	40	16	0	Ambient	Ambient
24	Bottom inlet	10	8	1.0	130	Ambient
25	Bottom inlet	10	8	1.0	130	90°F wet bulb
26	Bottom inlet	40	16	4.0	130	Ambient
27	Bottom inlet	20	16	2.5	130	Ambient
28	Bottom inlet	30	16	4.0	130	Ambient
29	High inlet	10	8	1.0	130	Ambient
30	High inlet	10	8	1.0	130	95°F wet bulb
31	High inlet	20	16	4.0	130	Ambient
32	High inlet	20	16	4.0	130	95°F wet bulb
33	High water	10	8	1.0	130	Ambient
34	High water	10	8	1.0	130	95°F wet bulb
35	High water	40	16	4.0	130	Ambient
36	High water	20	16	2.5	130	Ambient

The following conclusions and observations were drawn from this test:

- The heat removal capability from the external surface of the test vessel for both wetted and dry conditions agreed well with previous heated plate experiments and analytic predictions and supported the AP600 containment analysis.

- The overall heat removal capability from the test vessel with a wetted surface and well-mixed air and steam inside agreed well with analytical predictions.

- The local heat removal rate at the top of the vessel where "cool" water was first applied was significantly higher than the vessel average heat removal rate.

- The water film behavior was stable and predictable, even at evaporating heat fluxes three times higher than likely to be encountered in actual application.

- A uniform water film was easily formed on the coated steel containment surface using simple weirs.

- The water film on the vertical side walls of the coated steel surface of the vessel had no tendency to become less uniform or form rivulets, so that no water film redistribution was required on the vertical walls.

Documentation

Additional information on the PCS Small-Scale Integral Test may be found in WCAP-14134, "Final Test Report for Integral Small-Scale Tests," (Reference 32)

2.4.2 Large-Scale Heat Transfer Test

General Description/Purpose

The large-scale PCS test consisted of a 1/8-scale model of the AP600 containment in which both internal steam/air noncondensible gas conditions and external PCS operation were simulated in order to demonstrate the AP600 PCS heat transfer capability. The purpose of this test was to examine, on a large scale, the natural convection and steam condensation on the interior of the AP600 containment combined with exterior water film evaporation, air cooling heat removal, and water film behavior. The PCS heat transfer test results provided data for the verification of the computer model used to predict the containment response. Also, these test results combined with the PCS smaller-scale integral test provided insight on the ability of the computer model to predict results at two different test scales.

The test facility was located at the Westinghouse Science and Technology Center in Churchill, Pennsylvania. The facility consisted of a 20-foot high by 15-foot diameter pressure vessel with a 7/8-inch wall thickness (Figures 2-6 through 2-8) and the supporting hardware. The larger test vessel made it possible to study in-vessel phenomena such as noncondensable mixing, steam release jetting, condensation, and flow patterns inside containment. The vessel contained air or nitrogen when cold and was supplied with steam for testing. A transparent acrylic cylinder installed around the vessel formed the air-cooling annulus. Air-flow up (and/or water-flow down) the annulus outside the vessel cooled the vessel surface, resulting in condensation of the steam inside the vessel. Superheated steam was throttled to a variable, but controlled, pressure and supplied to the test vessel.

To establish the total heat transfer from the test vessel, measurements were recorded for steam inlet pressure, temperature, and condensate flow and temperature from the vessel. Thermocouples located on both the inner and outer surfaces of the vessel indicated the temperature distribution over the height and circumference of the vessel. Thermocouples placed throughout the inside of the vessel on a movable rake provided a measurement of the vessel bulk steam temperature as a function of position.

An axial fan at the top of the annular shell tested the apparatus at higher air velocities than can be achieved during purely natural convection. The temperature of the cooling air was measured at the entrance of the annular region and on exit of the annulus in the chimney region prior to the fan. The cooling-air velocity was measured in the cooling-air annulus using a hot wire anemometer.

The test facility provided the following critical data for the interpretation of the test performance:

- Containment wall heat flux measurements to provide local heat transfer rates
- Air baffle wall temperatures
- Vessel internal temperatures

- Air/helium concentration measurements

- Instrumentation to measure (to support a heat balance of) the PCS external air and water, and steam and condensate flows and temperatures

Test Matrix/Results

The large-scale PCS test was performed in two phases: baseline tests and confirmatory tests. The baseline tests were conducted to support the June 1992 SSAR submittal. The confirmatory tests were completed in November 1993 and are described in Table 2-6.

Key results and observations for the PCS large-scale heat transfer test are:

- Helium mixed well inside the test vessel; no helium stratification was observed.

- The presence of helium had a negligible effect on heat transfer removal rates.

- Condensation and evaporation mass transfer were the only significant mechanisms for rejecting energy from containment to the PCS.

- Noncondensible distribution and internal velocity were important to the condensation rate.

- Tests simulating loss-of-coolant accidents (LOCAs) show that internal velocities are sufficiently low; free convection dominates; and momentum does not carry from above to below the deck.

- Tests simulating main steamline break (MSLB) events show that internal velocities are significant; mixed convection exists; and momentum is transported from above to below deck (which induces uniform concentrations).

Documentation

Additional information on the Large-Scale Heat Transfer Test may be found in the following documents:

Scaling

- "Scaling Analysis for AP600 Containment Pressure During Design Basis Accidents," (Reference 33)

Table 2-6 Large-Scale, H≥at Transfer Test, Phase 2		
Test	**Test Number**	**Description**
Pre-operational test	Video recording	Videos of water distribution on top of vessel
	Cold annulus velocity	Low temperature annulus startup velocity
	Water distribution	Calibrate water distribution for three different levels of coverage on the vessel
	Condensate system	Check operation of condensate system
	Velocity sensors	Check operation and determine location of velocity meters for future tests
	Cold helium injection	Inject helium into cold vessel and sample to determine helium distribution at selected time intervals following injection
	Delayed water injection	Provide delayed water distribution flow to the surface of hot vessel and video tape performance
Matrix tests	202.3	Constant vessel pressure
	203.3	Constant high vessel pressure
	213.1	Three steam flow levels with reduced water flow and coverage area
	214.1	Constant steam flow, reduced water flow and coverage area, and variable air cooling flow
	216.1	Constant steam flow with reduced water flow over sections of the vessel
	215.1	Constant steam flow, reduced water flow and coverage area, and variable air cooling flow
	212.1	Three steam flow levels with reduced water flow and coverage area; noncondensable gas samples taken
	217.1	Constant steam flow with helium injection; reduced water flow and coverage area
	220.1	Transient blowdown steam flow, reduced water flow and coverage area, noncondensible gas samples taken
	218.1	Constant steam flow with helium injection; reduced water flow and coverage area; each steam flow maintained for about 1 hour and noncondensable measurements taken
	219.1	Constant steam flow with helium injection; reduced water flow and coverage area; each steam flow maintained for about 1 hour and noncondensable measurements taken
	221.1	Transient blowdown steam flow with helium addition sampling; reduced water flow and coverage area

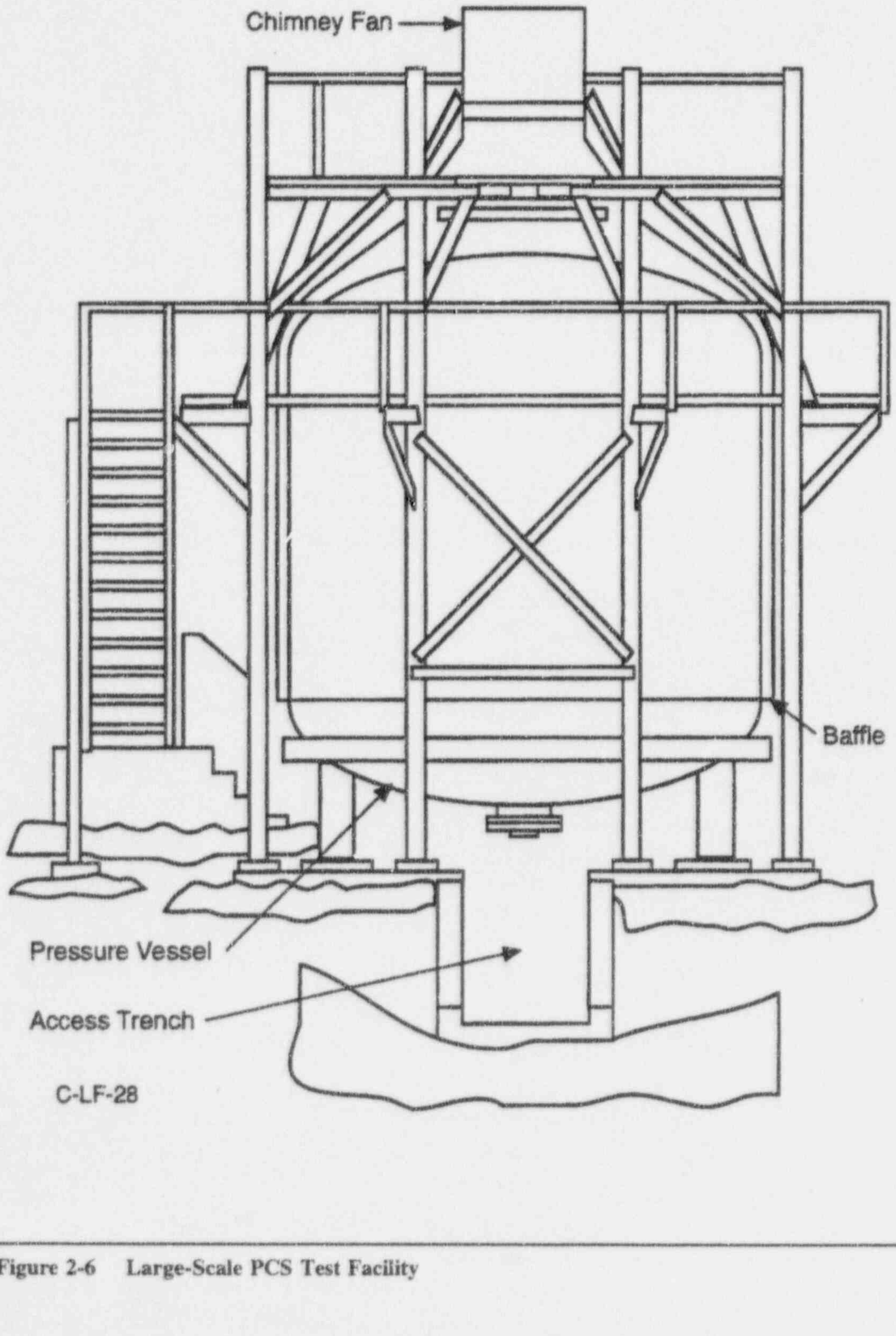

Figure 2-6 Large-Scale PCS Test Facility

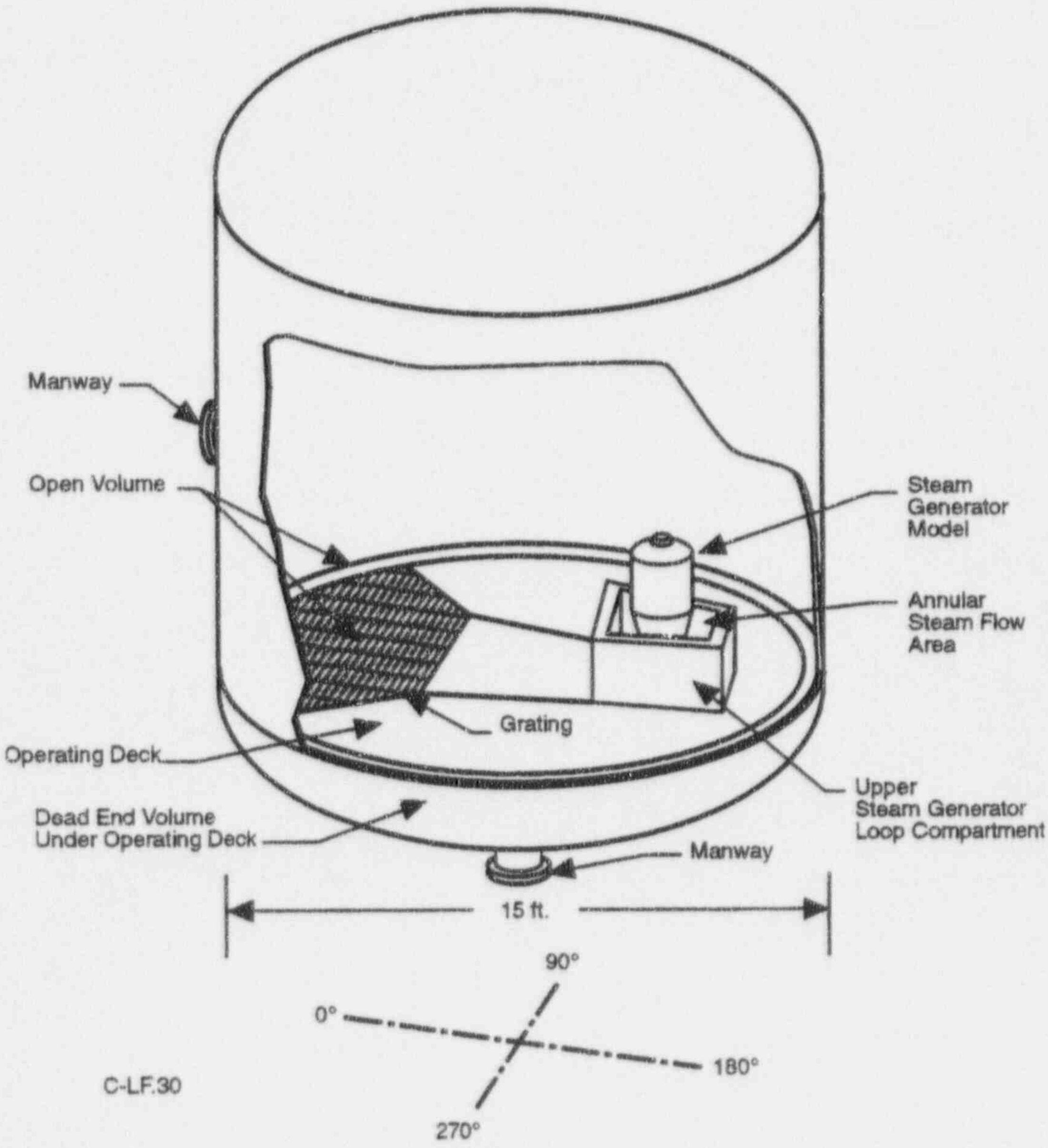

Figure 2-7 Large-Scale PCS Test Facility

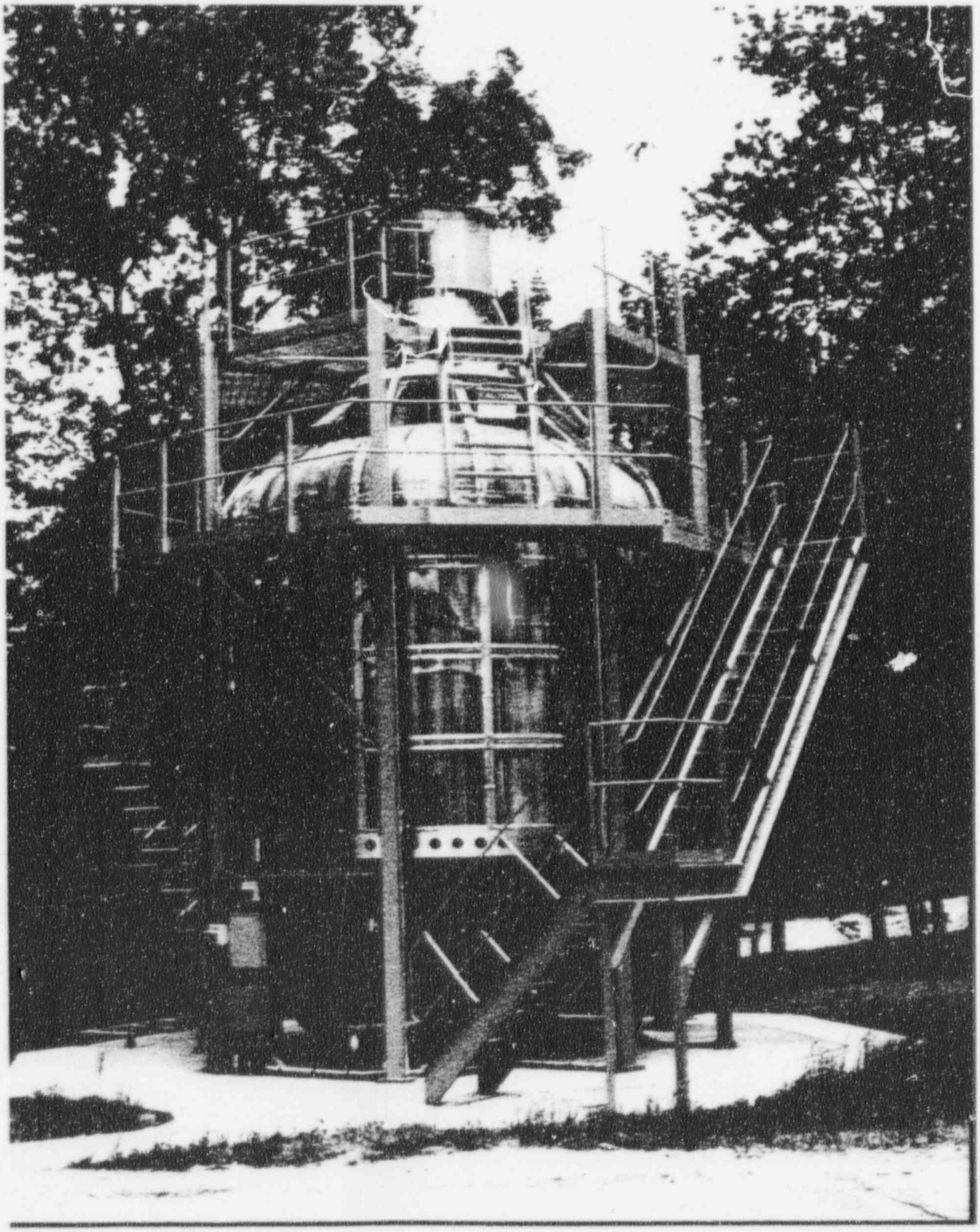

Figure 2-8 Large-Scale PCS Test Facility

Final Data Report

- WCAP-13566, "AP600 1/8th Large Scale Passive Containment Cooling System Heat Transfer Baseline Data Report," (Reference 34)
- WCAP-14135, "Final Test Report for PCS Large Scale Phase 2 and Phase 3 Tests," (Reference 35)

Test Analysis Report

- PCS-T2R-050, "Large Scale Test Data Evaluation," (Reference 36)

2.4.3 Full-Height, Full-Pressure Integral Systems Test (SPES-2)

General Description/Purpose

A full-pressure, full-height integral systems test was performed to provide a simulation of the PXS integrated performance. The existing SPES test facility was configured as a full-height, full-pressure integral test with AP600 features, including two loops with one hot leg and two cold legs per loop, two CMTs, two accumulators, a PRHR HX, an IRWST, and an ADS. The facility included a scaled reactor vessel, SGs, pressurizer, and RCPs. Water was the working fluid, and core power was simulated with electric heater rods.

The test facility was designed to be capable of performing tests representative of a small break LOCA (SBLOCA), steam generator tube rupture (SGTR), and steamline break (SLB) transients. The design certification analysis is being compared to the test results.

The facility simulated the following:

- Primary circuit
- Secondary circuit up to the main steam line isolation valve
- All passive safety systems — CMT, IRWST, PRHR HX, ADS
- Nonsafety nuclear steam supply systems (NSSS) — chemical volume and control system (CVS), RNS, and startup feedwater system (SFWS)

A scaling, design, and verification analysis was performed to delineate the specific design features to be incorporated and modifications to be made to the SPES-1 facility to simulate the AP600 design.

The following general criteria have been applied to the design of the SPES-2 test facility:

- Conservation of thermodynamic conditions (pressure and temperature)
- Power over volume ratio conservation in each component
- Power over mass flow rate conservation
- Fluid transit time preservation
- Heat flux conservation in heat transfer components (core and SG)
- Elevations maintained in lines and components

- Preservation of Froude number in the primary circuit loop piping (hot and cold legs) in order to preserve the slug to stratified flow pattern transition in horizontal piping

The SPES-2 facility consisted of a full simulation of the PXS and the AP600 primary system. The stainless steel test facility used a 97-rod heated rod bundle with a uniform axial power shape and skin heating of the heater rods. The tests were initiated from scaled, full-power conditions. There were 59 heater rod thermocouples distributed over 10 elevations with most located at the top of the bundle to detect the possibility of bundle uncovery. The heater rods were single-ended, connected to a ground bus at the top of the bundle at the upper core plate elevation. All but two rods were designed to have the same power; two heater rods were "hot" rods that had 19 percent higher power.

The primary system, shown in Figure 2-9, included two loops each with two cold legs, one hot leg, an SG, and a single RCP. The cold leg for each loop was divided downstream of the simulated RCP into two separate cold legs, each of which connected into an annular downcomer. The pumps delivered the scaled primary-flow, and the heater rod bundle produced the scaled full-power level so that the AP600 steady-state temperature distribution was simulated. The SGs had a secondary side cooling system that removed heat from the primary loop during simulated full-power operation. Startup feedwater and power-operated relief valve (PORV) heat removal was provided following a simulated plant trip.

The upper portion of the simulated reactor vessel included an annular downcomer region, where the hot and cold legs as well as the SI lines were connected. The annular downcomer was connected to a pipe downcomer below the direct vessel injection (DVI) lines; the pipe downcomer then connected to the vessel lower plenum. In this fashion, the four cold-leg/two hot-leg characteristics of AP600 were preserved, along with the downcomer injection. There were turning devices to direct the SI flow downwater in the annular downcomer as in the AP600.

A full-height, single PRHR HX, constructed in a C-tube design, was located in a simulated IRWST and maintained at atmospheric pressure. The line pressure drop and elevations were preserved, and the heat transfer area was scaled so that the natural circulation behavior of the AP600 PRHR HX was simulated.

The design of the CMTs was developed so that the CMT metal mass was scaled to the AP600 CMT. The CMT design used a thin-walled vessel inside a thicker pressure vessel, with the space between the two vessels pressurized to about 70 bar. In this manner, the amount of steam that condensed on the CMT walls during draindown was preserved. Since the CMTs were full-height and operated at full pressure, the metal mass-to-volume of a single pressure vessel would have been excessive, resulting in very large wall steam condensation effects.

The SPES-2 ADS combined the two sets of AP600 ADS piping off the pressurizer into a single set with the first-, second-, and third-stage valves. An orifice in series with each ADS isolation valve was used to achieve the proper scaled flow area. The three ADS valves shared a common discharge line to

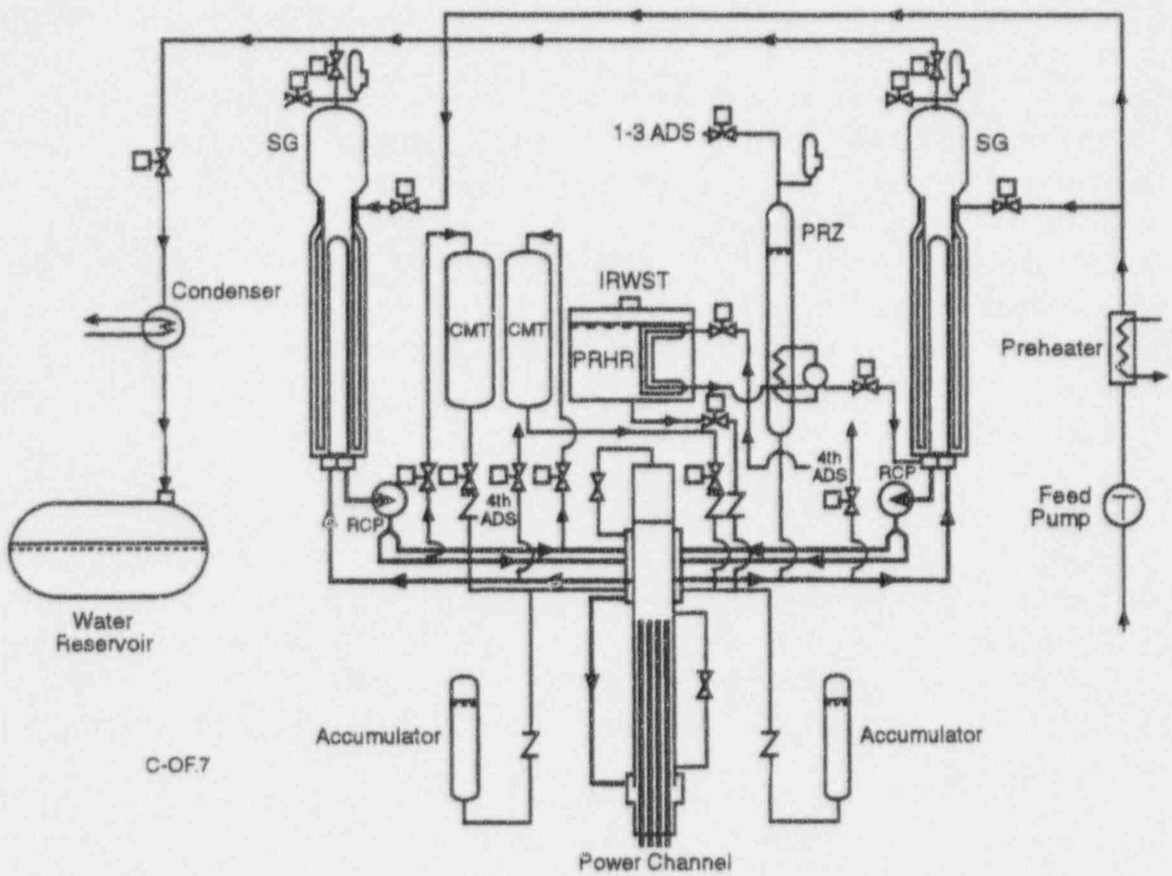

Figure 2-9 SPES-2 Facility Primary System

a condenser and a collection tank that used load cells to measure the mass accumulation. A similar measuring arrangement was also used for the two ADS fourth-stage lines, which were located on the hot legs of the primary system. The SPES-2 tests simulated the AP600 transients up to the time of IRWST injection at low pressure.

Small breaks were simulated using a spool piece that contained a break orifice and quick-opening valve. The break discharge was also condensed and measured by collecting the flow into a catch-tank.

The SPES-2 facility instrumentation was developed to provide transient mass balances on the test facility. There were about 500 channels of instrumentation that monitored the facility, component pressure, temperature, density, and mass inventory. Flows into the simulated reactor system, such as CMT discharge-flow, accumulator-flow, and IRWST-flow, were measured using venturi flow meters. Flows out of the test facility, such as break-flow and ADS-flow, were measured with a turbine meter and condenser/collection tank. The use of condensers allowed accurate integrated mass versus time measurements of the two-phase ADS and break-flow streams. The use of collection tanks following the condensers provided redundancy for the critical measurements of the mass leaving the test system. Differential pressure measurements were arranged as level measurements on all vertical components to measure the rate of mass change in the component. There were also differential pressure measurements between components to measure the frictional pressure drop, both for single- and two-phase flow. The CMTs were instrumented with wall and fluid thermocouples to measure the CMT condensation and heat-up during their operation. The PRHR HX was also instrumented with wall and fluid thermocouples so that the tube wall heat flux could be calculated from the data. There were thermocouples in the simulated IRWST to measure the fluid temperature distribution and assess the amount of mixing that occurred. Rod bundle power was measured accurately to obtain rod heat flux and total power input to the test facility.

Test Matrix/Results

The overall objectives of the AP600 SPES-2 integral system test were:

- To simulate the AP600 thermal-hydraulic phenomena and behavior of the passive safety systems following specified SBLOCAs, SGTRs, and SLBs
- To obtain detailed experimental results for verification of safety analysis computer codes

The SPES-2 test matrix (Table 2-7) examined the AP600 passive safety system response for a range of SBLOCAs at different locations on the primary system, SGTRs with passive and active safety systems, and an MSLB transient.

Key results and observations for the SPES-2 test are:

- The core remained covered following all simulated events, included a double-ended guillotine (DEG) DVI line-break with only passive safety systems operating.

- There was no CMT draindown; therefore, no ADS actuation occurred following the single SGTR with no operator action or nonsafety systems operating.

- Nonsafety system operation had no adverse interaction with passive system operation, and actually added margin to the plant safety response.

- All passive safety systems functioned as expected with no adverse occurrences including CMT recirculation and draindown, PRHR HX heat removal, ADS depressurization, and IRWST gravity draining.

- Timely RNS operation following a LOCA can limit CMT draindown and present ADS fourth-stage actuation.

Documentation

Additional information on the SPES-2 tests may be found in the following documents:

<u>Scaling</u>

- WCAP-13277, Revision 1, "Scaling, Design and Verification of SPES-2, The Italian Experimental of the AP600; Scaling Update," (References 37)

<u>Facility Description</u>

- WCAP-14073, "SPES-2 Facility Description," (Reference 38)

<u>Final Data Report</u>

- WCAP-14309, Revision 1, "AP600 Design Certification Tests, SPES-2 Final Data Report," (Reference 39)

<u>Test Analysis Report</u>

- WCAP-14254, Revision 1, "AP600 Full-Height, Full-Pressure Integral Systems Test: SPES-2 Test Analysis Report," (Reference 40)

Table 2-7	Matrix Tests, Full-Pressure, Full-Height Integral Systems Test (SPES-2)
Test Number	**Description**
3	2-in. cold leg break with nonsafety systems off
1	1-in. cold leg break with nonsafety systems off
4	2-in. cold leg break with nonsafety systems on
5	2-in. DVI line break with nonsafety systems off
6	DEG break of the DVI line with nonsafety systems off
7	2-in. break of cold leg to CMT balance line with nonsafety systems off
8	DEG break of cold leg to CMT balance line with nonsafety systems off
9	Design basis SGTR with nonsafety systems on and operator action to isolate SG
10	Design basis SGTR with nonsafety systems on and no operator action
11	Design basis SGTR with manual ADS actuation
12	Large SLB
13	1-in. cold leg break with three PRHR HX tubes, with non-safety systems off

Table 2-7 Matrix Tests, Full-Pressure, Full-Height Integral Systems Test (SPES-2) (Cont.)

Test Category	Test Number	Description
Cold shakedown tests	C-01	Single-phase flow through the pressurizer surge line, four flow rates
	C-02A,B	Single-phase flow through the pressurizer to CMT balance lines, four flow rates per balance line
	C-03A,B	Single-phase flow through the cold leg to CMT balance lines, four flow rates per balance line
	C-04A,B	CMT draindown using cold leg to CMT balance line
	C-05A,B	CMT gravity draindown using pressurizer to CMT balance line
	C-06A,B	SI accumulator blowdown
	C-07A,B	IRWST gravity draindown, three water levels
	C-08	CVS, RNS, and SFWS pump flow rate verification
	C-09	Operation of primary system with two RCPs running
	C-10A,B	Operation of primary system with one RCP running
Hot shakedown tests	H-01	Facility heated and heat at five constant temperatures
	H-02	Starting from nominal conditions, power will be shut off and SGs isolated
	H-03	Facility operated at normal full-pressure, temperature, and power
	H-04	Facility transitioned from full power operating conditions to hot shutdown/natural circulation mode of operation
	H-05	Low-pressure safety system actuation using the ADS with CMT draindown and accumulator delivery
	H-06	Full-power, full-pressure safety system actuation initiated by the opening of the first stage of the ADS

2.4.4 Low-Pressure, 1/4-Height Integral Systems Test (OSU)

General Description/Purpose

The low-pressure, 1/4-height integral systems test was conducted at the Corvalis campus of OSU. Scaling studies indicated that a scaled low-pressure test facility could be constructed to capture the thermal-hydraulic phenomena of interest for the lower pressure behavior of the AP600.

The OSU test facility is a new facility constructed specifically to investigate the AP600 PXS behavior. The test design accurately modeled the detail of the AP600 geometry including the primary system, pipe routings, and layout for the passive safety systems. The primary system consisted of one hot leg and two cold legs with two active pumps and an active SG for each loop, shown in Figure 2-10. There were two CMTs connected to one primary loop; the pressurizer was connected to the other primary loop, as in the AP600 plant design. Gas-driven accumulators were connected to the DVI lines. The discharge lines from the CMT and one-of-two IRWST and reactor sump lines were connected to each DVI line. The two independent tiers of ADS 1-3 valves were lumped together as a single ADS stage. The two-phase flow from the ADS stages one, two, and three were separated in a swirl-vane separator. The liquid and vapor flows were measured to obtain the total ADS flow rate. The separated flow streams were then recombined and discharged into the IRWST through a sparger. Thus, the mass-flow and energy-flow from the ADS into the IRWST were preserved.

The time period for the simulation included not only IRWST injection, but also draining of the IRWST and lower containment sump (LCS) injection to simulate long-term cooling of the AP600. The duration of this simulation was from several hours to a half day. The time scale for the OSU test facility was about one-half, i.e., phenomena occur at twice the rate of OSU as in the AP600.

To model the long-term cooling aspects of the transient, two-phase flow from the break was separated in a swirl-vane separator, and the liquid and vapor portions of the total flow were measured. The liquid fraction of the flow was discharged to the reactor sump, as in the AP600 plant; the vapor was discharged to the atmosphere; and the equivalent liquid-flow was added to the IRWST and LCS to simulate condensate return from passive containment. A similar approach was used for the fourth-stage ADS valve on the hot leg. Two-phase flow was separated in a swirl-vane separator; the two streams were measured; the liquid phase was discharged into the reactor sump, the vapor-flow was discharged to the atmosphere, and the liquid equivalent was added to the IRWST and LCS. The IRWST and LCS can be pressurized to simulate containment pressurization following a postulated LOCA.

A multi-tube PRHR HX is located in the IRWST. The HX uses the same C-tube design as the AP600 and has two instrumented tubes to obtain wall heat fluxes during tests. There are primary fluid thermocouples, wall thermocouples, and differential pressure drop measurements to determine when the HX begins to drain. The IRWST is also instrumented with strings of fluid thermocouples to

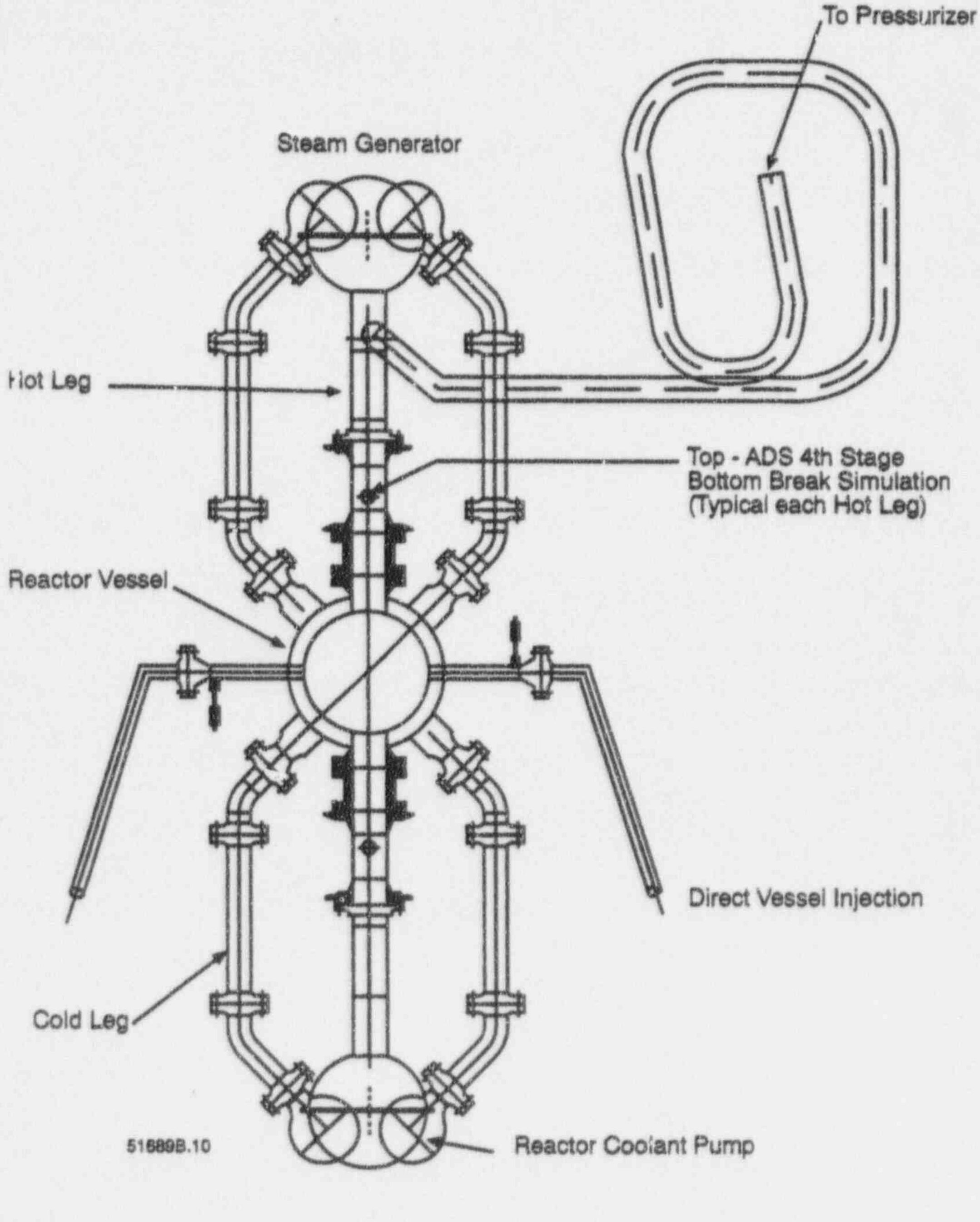

Figure 2-10 OSU Test Facility Primary System Schematic

determine the degree of mixing in the tank and assess the temperature of the coolant delivered to the test vessel.

The reactor vessel for the OSU tests included a 3-foot heated core simulator consisting of forty-eight (48) 1-inch diameter heater rods. The heater rods had a top-skewed power shape. There were wall thermocouples swaged inside the heater rods to measure the heater rod wall temperature. There were also five thermocouple rods in the heater rod bundle, including fluid thermocouples, to measure the axial coolant temperature distribution. The scaled flow area in the core and flow area in the test vessel upper plenum were preserved. There were simulated reactor internals in the upper plenum to preserve the flow area and the correctly scaled fluid volume. The reactor vessel included an annular downcomer into which the four cold legs and the DVI lines were connected. The hot legs penetrated the reactor annulus and connected with the loops. The AP600 reactor vessel neutron reflector was simulated using a ceramic liner to reduce the metal heat release to the coolant.

There was about 1.5 E09 J/hr (540 kW) of electrical power available at the OSU test site, which corresponds to a decay heat of 2 percent of full power in the AP600.

Test Matrix/Results

The OSU experiments examined the passive safety system response for the SBLOCA transition into long-term cooling. A range of SBLOCAs was simulated at different locations on the primary system, such as the cold leg, hot leg, CMT cold-leg pressure balance line, and DVI line. The break orientation (top or bottom of the cold leg) was also studied. Different single failure cases were examined to confirm that the worst situation was used in the AP600 SSAR analysis. Selected tests continued into the long-term cooling, post-accident mode in which passive SI was from the reactor sump as well as the IRWST. A larger-break, post-accident, long-term cooling situation was also simulated. A summary of the test matrix is provided in Table 2-8.

A specific test was performed at the OSU test facility to examine the effects of a higher backpressure on an SBLOCA transient. A sensitivity study was also performed on the effects of containment backpressure, verifying the test assumptions.

The OSU test data was analyzed to determine the long-term cooling behavior of the system. The calculated mass and energy balances from the OSU test facility were used to determine these effects.

The key results and observations for the OSU test are:

- The core remained covered for all design basis transients.
- All passive systems functioned as expected, with no adverse consequences, including CMT recirculation and draindown, PRHR HX heat removal, ADS depressurization, accumulator injection, IRWST gravity draining, and stable long-term sump injection.

Table 2-8	Matrix Tests, Low-Pressure, 1/4-Height, Integral Systems Test (OSU)
Test Number	Description
SB01	2-in. cold-leg break, bottom of pipe, loop A with continuation into long-term cooling mode fail ½ lines in one ADS-4 stage
SB04	2-in. cold-leg break, bottom of pipe, loop A with nonsafety systems on fail ½ lines in one ADS4 stage
SB10	DEG break of cold-leg balance line, horizontal loop, loop A with continuation into LTC fail ½ lines in one ADS-4 stage
SB12	DEG break of DVI line, continuation into LTC, loss of one train of ADS-1 and ADS-3
SB13	2-in. break of DVI line, continuation into LTC fail ½ lines in one ADS-4 stage
LB01	Large cold-leg break, higher decay heat, continuation into LTC fail ½ lines in one ADS-4 stage
SB03	2-in. cold-leg break, top of pipe, loop A fail ½ lines in one ADS-4 stage
SB05	1-in. cold-leg break, bottom of pipe, loop A, with continuation into LTC fail ½ lines in one ADS-4 stage
SB07	2-in. cold-leg small break, bottom of pipe, loop A, fail train of ADS 4-1
SB09	2-in. break on cold-leg balance line, horizontal loop, loop A fail ½ lines in one ADS-4 stage
SB11	DEG break of DVI line with continuation into LTC fail ½ lines in one ADS-4 stage
SB14	Inadvertent ADS stage 1 open, with continuation into LTC fail ½ lines in one ADS-4 stage
SB15	2-in. hot-leg break, bottom of pipe, loop A fail ½ lines in one ADS-4 stage
SB19	SB01 with simulated containment backpressure fail ½ lines in one ADS-4 stage

Additional observations include:

- The CMTs refilled due to condensation effects during long-term recirculation.
- Steam condensation events occurred in the upper downcomer region.
- Thermal stratification occurred in both the hot and cold legs.
- For most tests, regular oscillations occurred during long-term recirculation.

These results are discussed more fully in the final test reports.

Documentation

Additional information on the OSU tests may be found in the following documents:

Scaling

- WCAP-14270, "Westinghouse AP600 Long Term Cooling Test Facility Scaling Report," (Reference 41)

Facility Description Report

- WCAP-14124, "AP600 Low Pressure 1/4 Height Integral Systems Tests - Facility Description Report," (Reference 42)

Final Data Report

- WCAP-14252, "AP600 Low Pressure Integral System Test at OSU: Final Data Report," (Reference 43)

Test Analysis Report

- WCAP-14292, Revision 1, "Low Pressure Integral System Tests at OSU Test Analysis Report," (Reference 44)

- WCAP-14471, "Steam Condensation Events at the OSU AP600 Test Facility," (Reference 45)

3.0 CONCLUSIONS

An integrated test program has been developed and completed for the AP600 design certification process. Four classifications of tests in the program support the engineering design needs as well as the safety analysis needs. Those classifications are basic research tests, engineering tests on components, component separate effects tests, and integral systems tests.

The needs for the tests were derived from an analysis of the design differences of the AP600 design from existing PWR design and the expected thermal-hydraulic phenomena that the AP600 SSAR safety analysis computer codes would have to model and calculate with confidence. The primary objective of the test program was to provide the needed data to develop or modify the existing correlations or models in the safety analysis codes so that these codes could represent the performance of the AP600 passive safety systems.

Each new AP600 system was tested both in a separate effects test which covers the range of application of that component, and in an integral systems test, so that the possibilities of system interaction will be examined. There are two integral systems tests using different scaling rationales that model all the AP600 passive safety injection and core cooling systems.

There are similar basic research, engineering, and separate effects component tests and integral systems tests, at two different scales, which support the development and verification of the AP600 containment safety analysis code. These data, along with the analysis effort, form a comprehensive program that will result in successful licensing and final design certification approval of the AP600 design.

4.0 REFERENCES

1. WCAP-13328, "Tests of Air Flow Path for Cooling the AP600 Reactor Containment"

2. WCAP-13884, "Water Film Formation on AP600 Containment Surface"

3. WCAP-14048, "Passive Containment Cooling System Bench Scale Wind Tunnel Test"

4. APWR-0452-P, "AP600 Vortex Mitigator Development Test for RCS Mid-Loop Operation"

5. WCAP-13294, "Phase 1 Wind Tunnel Testing for the Westinghouse AP600 Reactor"

6. WCAP-13323, "Phase 2 Wind Tunnel Testing for the Westinghouse AP600 Reactor"

7. WCAP-14068, "Phase 4A Wind Tunnel Testing for the Westinghouse AP600 Reactor"

8. WCAP-14169, "Phase 4A Wind Tunnel Testing for the Westinghouse AP600 Reactor, Supplemental Report"

9. WCAP-14091, "Phase 4B Wind Tunnel Testing for the Westinghouse AP600 Reactor"

10. WCAP-13353, "Passive Containment Cooling System Water Distribution Phase 1 Test Data Report"

11. WCAP-13296, "QCS Water Distribution Test Phase 2 Test Data Report"

12. WCAP-13960, "PCS Water Distribution Phase 3 Test Data Report"

13. WCAP-12668, Revision 1, "AP600 High Inertia Rotor Testing Phase 1 Test Report"

14. WCAP-13319, "AP600 High Inertia Rotor Testing Phase 2 Report"

15. WCAP-13758, "High Inertia Rotor Test Phase 3 Report"

16. WCAP-13298, "RCP Air Model Test Report"

17. WCAP-12648, Revision 1, "AP600 In-core Instrumentation System Electromagnetic Interference Test Report"

18. WCAP-13351, "Studies of Hydraulic Phenomena in the Reactor Vessel Lower Plenum Region - Test Report"

19. WCAP-12980, AP600 Passive Residual Heat Exchanger Test Final Report"

20. WCAP-14371, "AP600 Low Flow Critical Heat Flux Test Data Analysis"

21. WCAP-14149, "VAPORE Facility Description Report, AP600 Automatic Depressurization System, Phase A Test"

22. WCAP-13891, "AP600 Automatic Depressurization System Phase A Test Data Report"

23. WCAP-14303, "Facility Description Report, AP600 Automatic Depressurization System Phase B1 Tests"

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25. WCAP-14305, "AP600 Test Program, ADS Phase B1 Test Analysis Report"

26. WCAP-13963, Revision 1, "Scaling Logic for the Core Makeup Tank Test"

27. WCAP-14132, "AP600 CMT Program - Facility Description Report"

28. WCAP-14217, "Core Makeup Tank Test Data Report"

29. WCAP-14215, "Core Makeup Tank Test Analysis Report"

30. WCAP-14442, "AP600 Core Makeup Tank Level Instrument Test Data and Evaluation Report"

31. WCAP-12665, "Test of Heat Transfer and Water Film Evaporation on a Heated Plate Simulating Cooling of the AP600 Reactor Containment"

32. WCAP-14134, "Final Test Report for Integral Small Scale Tests"

33. "Scaling Analysis for AP600 Containment Pressure During Design Basis Accidents," Westinghouse Letter NSD-NRC-96-4790, August 8, 1996

34. WCAP-13566, "AP600 1/8th Large Scale Passive Containment Cooling System Heat Transfer Baseline Data Report"

35. WCAP-14135, "Final Test Report for PCS Large Scale Phase 2 and Phase 3 Tests"

36. PCS-T2R-050, "Large Scale Test Data Evaluation"

37. WCAP-13277, Revision 1 "Scaling, Design, and Verification of SPES-2, The Italian Experimental of the AP600, Scaling Update"

38. WCAP-14073, "SPES-2 Facility Description"

39. WCAP-14309, Revision 1, "AP600 Design Certification Tests, SPES-2 Final Data Report"

40. WCAP-14254, Revision 1, "AP600 Full-Height, Full-Pressure Integral System Tests: SPES-2 Test Analysis Report"

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42. WCAP-14124, "AP600 Low-Pressure, 1/4-Height, Integral Systems Tests - Facility Description Report

43. WCAP-14252, "AP600 Low-Pressure Integral System Test at OSU: Final Data Report"

44. WCAP-14292, Revision 1, "Low-Pressure Integral System Tests at OSU: Test Analysis Report"

45. WCAP-14471, "Steam Condensation Events at the OSU AP600 Test Facility"

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D 2 Rod bundle thermocouple position scheme
D 3 Power channel: pressure vessel
D 4 Power channel: upper riser DPs
D 5 Power channel: upper riser thermocouples
D 6 Power channel: annular downcomer
D 7 Power channel: lower plenum
D 8 Power channel: tubular downcomer
D 9 Power channel: downcomer - upper head bypass
D 10 Pressurizer
D 11 Steam generator A
D 12 Steam generator B
D 13 Steam generator tube bundle
D 14 Core make up tank
D 15 Accumulator A
D 16 Accumulator B

Piping instrumentation

E 1 Hot leg A
E 2 Hot leg B
E 3 Cold leg A
E 4 Cold leg B
E 5 Pump suction A
E 6 Pump suction B
E 7 Surge line
E 8 Main steam line A
E 9 Main steam line B
E 10 Main feedwater A
E 11 Main feedwater B
E 12 Core make up tank injection lines
E 13 Core make up tank CL balance lines
E 14 Core make up tank pressurizer balance lines
E 15 Accumulator injection lines
E 16 IRWST injection lines and DVI
E 17 IRWST and PRHR supply and return lines
E 18 ADS 1, 2, 3 lines
E 19 ADS 4 line
E 20 Start up feedwater line A
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