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SEMISCALE PRESSURE SUPPRESSION SYSTEM PERFORMANCE DURING THE ISOTHERMAL BLOWDOWN TEST SERIES

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MASTER

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SEMISCALE PRESSURE SUPPRESSION SYSTEM PERFORMANCE
DURING THE ISOTHERMAL BLOWDOWN TEST SERIES

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by

R. A. Livingston

AEROJET NUCLEAR COMPANY

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ABSTRACT

Test results relating to the performance of the pressure suppression system used for the semiscale isothermal blowdown test series are analyzed. The semiscale test system is a nonnuclear, subscale representation of a four-loop pressurized water reactor, and is used for blowdown tests pertinent to water reactor safety analysis. The pressure suppression system in the subject test series provides modeled PWR containment pressure response for the blowdown experiments which simulate loss-of-coolant accident conditions.

SUMMARY

The Semiscale Blowdown and Emergency Core Cooling (ECC) Project is being conducted by Aerojet Nuclear Company for the U. S. Atomic Energy Commission to understand and develop methods to quantify the behavior of pressurized water reactors under postulated loss-of-coolant accident (LOCA) conditions. The semiscale test system is a small scale, electrically heated representation of LOFT, which in turn is intended to be a representation of a pressurized water nuclear system for a 1000-MW power station. A pressure suppression system (PSS) is used during semiscale loss-of-coolant experiments to simulate the containment pressure of a PWR and to condense and retain the blowdown effluent. The pressure suppression system used in the 1-1/2-loop semiscale isothermal blowdown test series is a system comprised of piping and a vessel, partially filled with water. The performance of that system is the subject of this report.

The semiscale PSS performed satisfactorily during the subject test series in that it both retained the blowdown effluent and provided an environment during the blowdown experiments that simulated the predicted pressure response of a PWR containment during a loss-of-coolant accident. The PSS pressure response varied between experiments in this test series because different methods of pressure response control were tried. The most successful method of pressure control involved preheating the water pool in the PSS vessel and partially prepressurizing the PSS with air. By this means the energy added to the PSS water by the blowdown effluent resulted in an increase in vapor pressure, thereby producing the desired PSS pressure at the end of blowdown of the semiscale primary system. The results from the tests which utilized this self-pressurizing method involving preheated PSS water and prepressurization with air indicate that the peak PSS pressure can be predicted on the basis of a mass and energy balance within limitations imposed by thermal stratification within the PSS water pool.

Another method of PSS pressure response control used in the test series involved pressurizing the PSS using steam from an external source simultaneously with primary system blowdown. This method produced erratic PSS pressure response due to inability of the simple pressurizing steam flow control apparatus to adjust for the different conditions existing between pretest checkout and blowdown experiments.

The semiscale PSS has a water spray nozzle assembly installed in the top of the PSS vessel. The purpose of the spray was to reduce the PSS pressure during the postblowdown period through condensation of water vapor in the gas region of the partially water filled vessel. The spray did not effect the intended pressure reduction in the two tests in which it was used.

The pressure suppression system performance obtained in this test series is coupled to the particular factors associated with these tests which include system component configuration, PSS fluid conditions, and coupling with the primary system. Extrapolation

of these test results to a pressure suppression system that differs in those respects should be based on careful evaluation of the system effects on the thermodynamic and hydraulic phenomena that represent PSS performance.

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SEMISCALE PRESSURE SUPPRESSION SYSTEM PERFORMANCE

DURING THE ISOTHERMAL BLOWDOWN TEST SERIES

I. INTRODUCTION

The Semiscale Blowdown and Emergency Core Cooling (ECC) Project is part of the U. S. Atomic Energy Commission research and development effort being carried out to understand and develop methods to quantify the transient performance of pressurized water reactors and their associated protective systems following a postulated pipe rupture in one of the primary coolant loops. The contribution of the semiscale program to the overall effort in this area is experimental data for the development and verification of analytical models.

The semiscale test system is designed to provide coupled thermal and hydraulic system response data from experiments simulating a loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR). In the semiscale system, specifically the 1-1/2-loop isothermal system, three of the coolant loops in a four-loop PWR are represented by a single loop containing a modeled steam generator and coolant circulation pump. The fourth PWR loop, the broken loop during a postulated LOCA, is represented by a broken loop which contains rupture disc assemblies in the cold-leg pipe to represent a double-ended, offset shear of that pipe. The broken loop contains steam generator and pump simulators to represent the flow resistance of those components in the PWR broken loop. The semiscale test system components represent the components comprising a four-loop PWR in the volume ratio of 1:1500. The representation of the PWR vessel contains electrically heated rods representing nuclear fuel elements, but in the 1-1/2-loop semiscale isothermal test series no temperature differential was developed across the core volume. The fluid discharged from the semiscale primary system during blowdown experiments is directed to a pressure suppression system designed to simulate the pressure response of a PWR dry containment building during a loss-of-coolant accident.

A PSS pressure response that is typical of that shown in Figure 1 is required to model the environment in a PWR primary system during the phase of decompression when the break flow becomes unchoked, and system back pressure (that is, containment pressure) begins to influence the hydraulic and thermodynamic phenomena occurring in the primary system. Important factors during the core reflood phase of the experiments are the resistance to steam flow through the reactor core and the broken loop hot-leg circuit, and the countercurrent flow phenomena that are expected to occur in the vessel downcomer annulus as emergency core coolant flows down the hot vessel walls, producing steam in the process. Since both of these phenomena are affected by the density of the steam associated with them, and steam density is a strong function of pressure, the PSS

Fig. 1 Predicted PWR containment pressure response.

pressure must correctly model PWR containment pressure in the period following unchoking of the break flow. Therefore, the emphasis on pressure response modeling was placed on achieving a PSS pressure response that accurately modeled PWR containment pressure from the time just before blowdown ends through the following core reflood period.

The semiscale pressure suppression system (PSS) used in the isothermal tests consisted of piping and a vessel that was partially filled with water. The piping was arranged to discharge the blowdown effluent beneath the surface of the water in the PSS vessel whereby the steam fraction was condensed. The pressure suppression system interfaced with the primary system at the broken loop burst diaphragm assemblies and, therefore, was not part of the primary system pressure boundary.

The semiscale PSS is functionally a model of the LOFT^[1] PSS. Providing data for design evaluation of the LOFT PSS was one of the objectives of the semiscale isothermal test series. The primary function of the PSS during blowdown tests of both the semiscale and LOFT systems is to provide simulation of the pressure response predicted to occur in a pressurized water reactor containment building during an LOCA resulting from a large pipe break.

Since containment of potentially radioactive blowdown effluent is an important PSS function in the LOFT experiments which will utilize a nuclear core in the reactor, LOFT-PSS design requirements are that the blowdown effluent be reliably condensed and retained in the PSS without any pressure disturbances that could cause flow through the relief valve to the atmosphere in the containment building.

The scope of this report is an analysis of the semiscale PSS performance observed during the isothermal test series in terms of the performance objectives which were:

- (1) PWR containment pressure response modeling
- (2) Complete and reliable condensation of the blowdown flow.

The analysis performed includes an examination of phenomena governing the semiscale PSS behavior and a comparison of the measured pressure response with the calculated pressure response computed by the CONTEMPT containment analysis code^[2]. Test results related to the performance of a water spray system designed to reduce PSS pressure through condensation in the PSS gas region and measured values of the PSS component displacements resulting from blowdown loads are also discussed. A comparison is made between the PSS design parameters and operating conditions proven successful in the semiscale isothermal test series and those used in larger scale suppression system tests performed by a reactor vendor in support of containment system design.

II. TEST SYSTEM DESCRIPTION

The semiscale pressure suppression system interfaces with the semiscale primary system at two burst diaphragm assemblies installed in the broken loop of the primary system. The two burst diaphragms represent the flow path resulting from a postulated double ended, offset shear rupture in the cold leg of a PWR coolant loop. Figure 2 depicts the semiscale system configuration used for the isothermal test series. Following is a description of the components and subsystems that comprise the semiscale pressure suppression system. A more detailed description of the overall semiscale test system is given in Reference 3.

1. BASIC PSS CONFIGURATION

The principal components of the semiscale PSS are a vertically mounted cylindrical vessel with an internal, centrally located downcomer pipe designed to discharge the blowdown effluent beneath the surface of the water pool partially filling the PSS vessel. The downcomer pipe is connected to the primary system blowdown nozzles by way of a single large-diameter header pipe. Figures 3 and 4 show the internal features and give principal dimensions of the semiscale PSS components. (Measurement designations and locations, also shown in Figure 3, are discussed in Section II-3.) The design basis of the PSS is that the discharge of the blowdown effluent beneath the PSS vessel water pool surface produces condensation of the steam phase and entrapment of the water phase. The PSS vessel gas region together with the header provides a modeled representation of the region in a PWR containment in communication with the postulated pipe break area. In the semiscale PSS, three 1-1/2-inch swing check valves are provided in the vessel downcomer above the water level to prevent water from being drawn back into the primary system from the PSS vessel water pool following primary system blowdown. An external pump circulates the PSS water at 30 gpm to promote temperature uniformity.

2. PSS GAS REGION SPRAY SYSTEM

The semiscale PSS has a water spray nozzle assembly installed in the upper region of the vessel. The spray configuration used in the semiscale isothermal test series consisted of four equally spaced spray nozzles having a 105-degree hollow cone pattern. The nozzles were mounted on a pipe extending down about 30 inches from the top of the vessel and were directed upward 45 degrees from the vertical axis. The PSS vessel gas region water spray system was intended to be used for pressure reduction in the postblowdown period of the experiment to cancel the pressure increase caused by nitrogen flow from the simulated ECC supply accumulators after their water supply was exhausted.

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Fig. 2 1-1/2-loop semiscale isothermal system.

Fig. 3 Semiscale pressure suppression system vessel.

Fig. 4 Schematic of semiscale pressure suppression system.

3. INSTRUMENTATION

The semiscale PSS was instrumented to obtain the data required for basic performance evaluation. Since the semiscale isothermal series tests were integrated system tests primarily concerned with primary system blowdown and simulated ECC behavior, the emphasis on measurements was placed on the primary system rather than on the PSS parameters.

The test instrumentation associated with the PSS during the subject test series provided for the measurements shown in Figure 3 and listed in Table I. Additional information regarding the instrumentation used may be found in References 3 through 8.

TABLE I

PRESSURE SUPPRESSION SYSTEM INSTRUMENTATION FOR
SEMISCALE ISOTHERMAL TEST SERIES

<u>Measurement Identification</u>	<u>Location</u>
<u>Pressure</u>	
P-53	Broken loop cold leg upstream of PSS header, vessel side of break
P-77	Broken loop cold leg upstream of PSS header, pump side of break
P-80	Straight section of pressure suppression header between elbows
P-81	Pressure suppression header
P-89	Upper (vapor) region of pressure suppression vessel
<u>Differential Pressure</u>	
DP-81-83	Suppression header to downcomer entrance at header "Y"
DP-81-85	Suppression header to downcomer discharge end in vessel
DP-81-89	Suppression header to suppression vessel vapor region
DP-83-85	Across suppression downcomer
DP-83-89	Suppression system downcomer entrance to suppression vessel vapor region
DP-85-89	Suppression vessel water region at downcomer exit to vapor region
<u>Fluid Temperature</u>	
TF-83	Pressure suppression header near downcomer entrance
TF-86-1	Pressure suppression vessel, 3 in. from inner wall, 62.5 in. from bottom of vessel
TF-86-2	Pressure suppression vessel, 3 in. from inner wall, 47.5 in. from bottom of vessel
TF-86-3	Pressure suppression vessel, 3 in. from inner wall, 32.5 in. from bottom of vessel
TF-86-4	Pressure suppression vessel, 3 in. from inner wall, 17.25 in. from bottom of vessel
RB-86-6	Pressure suppression vessel, 3 in. from inner wall, 10 in. from bottom of vessel

TABLE I (Contd.)

<u>Measurement Identification</u>	<u>Location</u>
<u>Fluid Temperature (contd.)</u>	
TF-88	Suppression vessel vapor region, 2 in. from inner wall, 10 in. from top of vessel
<u>Metal Temperature</u>	
TM-83	Outer surface of suppression header near connection to downcomer
TM-PSH-EL	Outer surface of suppression header near first elbow
<u>Flow (Drag Disc)</u>	
FD-83	Suppression header near entrance to downcomer
<u>Flow (Turbine Flow Meter)</u>	
FT-PSS	Pressure suppression spray system water
<u>Liquid Level</u>	
LL-PSS	In suppression vessel

III. TEST CONDITIONS AND PROCEDURES

The initial fluid conditions and operating procedures applied to the semiscale pressure suppression system were established to provide a PSS pressure response that would approximate the predicted PWR containment pressure response during an LOCA. Additionally, the PSS conditions were established to satisfy the objective of complete blowdown fluid condensation in the PSS water pool. Complete condensation was desired in order to preclude an unpredictable pressure increase that would interfere with the primary objective of controlled PSS pressure response.

1. TEST CONDITIONS

The PSS functional characteristics of condensing the steam phase of the blowdown effluent and providing a simulation of predicted PWR containment pressure response are related to the following PSS conditions:

- (1) Initial volume of water in the PSS vessel
- (2) Initial water temperature in the PSS vessel
- (3) Initial air pressure in the PSS
- (4) Depth of downcomer submergence beneath the water surface of the PSS vessel
- (5) Water spray introduced into the PSS vapor-gas region.

The particular values of these parameters are tabulated in Table II for tests comprising the isothermal blowdown series.

2. DISCUSSION AND BASIS OF PROCEDURES

Two methods of PSS pressure response control were used during the isothermal test series: a self-pressurization method utilizing blowdown heat addition and prepressurization with air and a method employing an external steam supply. As indicated in Table II, the self-pressurization method was used for the majority of the tests.

The self-pressurization method utilized heat addition to the PSS water pool from the blowdown flow as a source of PSS pressurization. The PSS was partially prepressurized with air as required to augment the pressure rise obtained by heat addition to the water pool. In

TABLE II

PRESSURE SUPPRESSION SYSTEM INITIAL CONDITIONS

Test	Method of Pressure Control	Initial Water Volume (ft ³)	Initial Water Temperature (°F)	Initial Pressure (psig) [a]	Water Spray Flow (gpm)	Downcomer Submergence (in.)
1001	Self-pressurization	29.5	199	13.5	None	11
1002	Self-pressurization	29.5	192	12.9	1.24	11
1003	Self-pressurization	45	141	0	Unknown	34
1004	Self-pressurization	30	190	16.5	None	11
1006	Self-pressurization	30	190	16.5	4.3	11
1008	Self-pressurization	30	230	12.3	None	11
1009	External steam source	30	150	1.2	[b]	11
1010	Self-pressurization	30	218	16.0	None	11
1011	External steam source	30	70	4.0	[b]	11

[a] Atmospheric pressure = 12.3 psia.

[b] Unsteady behavior of PSS pressurizing system precluded meaningful spray effectiveness tests.

In addition, the PSS water pool was preheated to take advantage of the higher value of vapor pressure increase with temperature that exists at higher than ambient temperatures ($\partial P_v / \partial T = 0.03$ psi/ $^{\circ}$ F at 100 $^{\circ}$ F and 0.60 psi/ $^{\circ}$ F at 230 $^{\circ}$ F). PSS conditions for this method were based on producing air and water vapor partial pressures in the PSS vessel at the end of primary system blowdown that together would equal the predicted PWR containment pressure at that time [52 psig at 30 sec (Figure 1)].

The maximum extent to which PSS pressure rise during blowdown was extracted from vapor pressure increase was limited by the subcooling required of the PSS water pool to effect complete condensation of the steam fraction of the blowdown fluid. The pool subcooling ($T_{SAT} - T_{PSS-BULK}$) is the minimum temperature differential that produces heat transfer between the pool water and the blowdown steam jet, where T_{SAT} is the saturation temperature at PSS pressure and $T_{PSS-BULK}$ is the average water temperature in the PSS pool. The heat transfer required to produce complete condensation of the steam jet is shown by the following equation:

$$hA (T_{STEAM} - T_{PSS}) = \dot{m}_{STEAM} h_{fg} \quad (1)$$

where

- h = coefficient of heat transfer between the steam and the PSS water
- A = interfacial area between the steam jet and the pool water
- T_{STEAM} = steam temperature [a]
- T_{PSS} = temperature of water in PSS pool in the vicinity of the steam jet
- $\dot{m}_{STEAM}$ = blowdown steam flow
- h_{fg} = latent heat of steam vaporization.

Three of the variables in Equation (1) (h , A , and T_{PSS}) are difficult to define accurately by analytical methods; therefore, the semiscale isothermal experiments were conducted with several values of bulk pool subcooling ($T_{SAT} - T_{PSS-BULK}$) and the effectiveness of steam condensation was assessed by the PSS pressure response, which would indicate the escape of uncondensed steam from the PSS pool.

[a] The measured temperature of the blowdown effluent entering the PSS downcomer was greater than equilibrium saturation temperature at the prevailing pressure.

A simple heat balance indicated that to obtain the desired pressure rise of 52 psig during blowdown solely through pool vapor pressure increase, the PSS pool volume would have had to have been on the order of the primary system volume. Because of hydrodynamic agitation of the water pool, such a small PSS pool volume may have been inadequate to effect reliable and complete condensation of the blowdown flow. The water pool vapor pressure increase was, therefore, supplemented by prepressurization with air to the extent computed to be necessary to produce the desired total pressure at the end of blowdown commensurate with the PSS pool being at least 24°F subcooled at that time.

The method of PSS pressure control utilizing blowdown heat addition and prepressurization with air has several less than ideal characteristics. One undesirable inherent characteristic of the method is the atypical PSS pressure rise at the start of blowdown due to the displacement into the vessel of noncondensable gas (air in this case) from the PSS header. However, break flow is choked at this time and unaffected by the atypical pressure rise; therefore, the atypicality is of no significance. A more important undesirable characteristic of this method of pressure modeling is the unpredictable influence of simulated ECC water carryover to the PSS during the blowdown. Since PSS pressure rise is dependent on energy transfer from the primary system, the unpredictability of ECC bypass during blowdown creates a corresponding unpredictability in the temperature rise and vapor pressure increase in the PSS vessel. Although significant, the variability introduced by ECC bypass is not a large percentage of the PSS pressure rise. This effect is discussed in the following data analysis section of this report.

The method of PSS pressure response control using an external steam source was used only for two tests (Tests 1009 and 1011). The basis for use of this method was to decouple PSS pressure response from the primary system blowdown variables and to preclude the undesirable characteristics of the prepressurization method. This PSS pressurization scheme used an external steam source to first purge the air from the PSS; then at the time the break was produced, an on-off valve was opened to admit a larger flow of steam into the PSS vessel. For Test 1011 the circuit also had a pressure regulator installed. The external steam supply circuit flow resistance was experimentally set by trial and error pressurizations of the PSS without any primary system blowdown effluent.

IV. ANALYSIS AND DISCUSSION OF TEST RESULTS

The principal PSS performance requirements in the semiscale isothermal tests were to model predicted PWR LOCA containment pressure response and effect complete condensation of the steam fraction of the blowdown effluent during blowdown experiments. An evaluation of the factors affecting PSS pressure control and blowdown condensation as observed in the subject tests is presented in this section. The measured pressure response is compared with the response computed by the CONTEMPT computer code^[2]. Other topics discussed include the effectiveness of water spray in the PSS gas region, the deflection of PSS components, and PSS gas composition. The PSS design parameters and test conditions utilized in the semiscale isothermal tests are also compared to those proven successful through large-scale tests associated with BWR containment design studies.

1. CONDENSATION OF BLOWDOWN EFFLUENT

The PSS vessel gas region volume is such that the admission of uncondensed steam from the blowdown effluent would result in the predicted pressure increase shown in Figure 5.

The requirement that the PSS effectively condense the steam phase of the blowdown effluent was fulfilled as demonstrated by the measured PSS pressure response shown in Figures 6 through 14^[a]. Significant pressure fluctuations, which would accompany the release of uncondensed steam in the PSS vessel gas region, are absent from the response. The principal suppression system parameters that affect blowdown condensation are the combined geometry of the downcomer and water pool and the amount of PSS pool water subcooling existing during the blowdown. As shown in Table III, temperature measurements in the PSS water pool indicated significant spatial temperature variations both prior to and following blowdown. The measured minimum pool subcooling occurred during Test 1008 and was 24°F at the end of the blowdown period. However, the PSS pool water temperature immediately adjacent to the downcomer exit was probably higher than the measured temperature of the water near the vessel wall. The measured subcooling and PSS pressure at the end of blowdown together with pertinent PSS variables and initial conditions are shown in Table IV for the isothermal test series.

[a] The figures show pressure in psi gauge. Atmospheric pressure at the test location is 12.3 psia.

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Fig. 5 Predicted semiscale system pressure at end of blowdown versus suppression system steam condensation.

Fig. 6 Pressure suppression vessel pressure, Test 1001.

Fig. 7 Pressure suppression vessel pressure, Test 1002.

Fig. 8 Pressure suppression vessel pressure, Test 1003.

Fig. 9 Pressure suppression vessel pressure, Test 1004.

Fig. 10 Pressure suppression vessel pressure, Test 1006.

Fig. 11 Pressure suppression vessel pressure, Test 1008.

Fig. 12 Pressure suppression vessel pressure, Test 1009.

Fig. 13 Pressure suppression vessel pressure, Test 1010.

Fig. 14 Pressure suppression vessel pressure, Test 1011.

TABLE III

TEMPERATURES IN PRESSURE SUPPRESSION SYSTEM VESSEL

Location	Time (sec)	Temperature (°F)								
		Semiscale Isothermal Test								
		1001	1002	1003	1004	1006	1008	1009	1010	1011
TF-88	-1	191	169	141	181	172	180	199	173	88
Gas region,	30	250	231	201	230	220	225	269	232	280
top of vessel	60	245	220	180	225	212	219	262	227	280
TF-86-3	-1	190	190	150 ^[a]	192	190	198	153	190	85
Water region,	30	250	233	189 ^[a]	248	240	243	210	250	160
32.5-in. level	60		231	188 ^[a]	242	240	249	222	253	152
TF-86-4	-1	[b]	192	[b]	192	187	[b]	[b]	[b]	[b]
Water region,	30	[b]	227	[b]	220	219	[b]	[b]	[b]	[b]
17.25-in. level	60	[b]	226	[b]	220	220	[b]	[b]	[b]	[b]
RB-86-6	-1	206	196	132	232	193	228	163	220	73
Water region, 10	30	240	220	192	262	221	263	210	258	155
in. from bottom	60	240	220	190	260	218	265	210	256	178
of vessel										

[a] TF-86-1, 62.5-in. level.

[b] Not measured.

TABLE IV

PRESSURE SUPPRESSION SYSTEM CONDITIONS AND RESULTS

Test	Initial Water Volume (ft ³)	Initial Water Temperature (°F)	Initial Pressure ^[a] (psig)	Pressure at end of Blowdown (psig)	Temperature of PSS Water Pool at End of Blowdown (°F)	Water Spray Flow (gpm)	Pool Subcooling at End of Blowdown (°F)	Downcomer Submergence (in.)
1001	29.5	199	13.5	48	240	None	51	11
1002	29.5	192	12.9	46	224	1.24	65	11
1003	45	141	0	23	193	Unknown	84	34
1004	30	190	16.5	50	234	None	61	11
1006	30	190	16.5	48	227	4.3	70	11
1008	30	230	12.3	43	263	None	24	11
1009	30	150	1.2	35	205	[b]	72	11
1010	30	218	16.0	53	258	None	40	11
1011	30	70	4.0	53	165	[b]	133	11

[a] Atmospheric pressure = 12.3 psia.

[b] Unsteady behavior of PSS pressurizing system precluded meaningful spray effectiveness tests.

2. PWR CONTAINMENT PRESSURE RESPONSE MODELING

The most representative pressure modeling of the predicted PWR containment pressure response to a large break loss-of-coolant accident was achieved during Test 1010 (Figure 13). The measured PSS and predicted PWR containment pressures are shown in Figure 15. In this test and Tests 1001, 1002, 1003, 1004, 1006, and 1008, the PSS pressure response was controlled by initially heating the PSS water pool and prepressurizing the PSS with air to produce the desired pressure at the end of the blowdown experiment. As shown in Table V, calculations of the air and water vapor partial pressures for three representative tests (Tests 1001, 1004, and 1010)^[a] at the measured temperatures indicate that the peak PSS pressure occurring at about 30 seconds after the start of the blowdown experiments is within 1 psi of the sum of the pressure components. This result indicates that evaporation from the PSS water pool during blowdown produced a saturated air-vapor mixture in the gas region above the pool surface, with the vapor pressure corresponding to the temperature near the water surface. The accuracy of predictions of PSS pressure response due to air compression plus vapor pressure increase using this result is limited by the accuracy with which the PSS pool surface temperature can be predicted. The PSS pressure response is coupled to pool surface temperature response through the 0.6 psi/°F vapor pressure relationship existing at 230°F. As indicated in Table III, temperature nonuniformity of up to 42°F was measured in the PSS water pool at the end of blowdown. For example, comparison of the measured pool temperature (250°F close to the surface and 260°F close to the bottom) with the average value computed for Test 1010 due to energy addition (266°F without wall heat transfer) reveals an error of 16°F.

In the tests utilizing the method of pressure response control discussed in the foregoing and also having simulated ECC injection during blowdown, the PSS pressure reached a maximum earlier in the experiment (Figures 9, 10, and 11). In addition, the pressure decline after the maximum was reached was more pronounced in the tests with ECC injection than those without ECC injection, probably because of steam condensation in the primary system and PSS header which causes flow of some of the air-vapor mixture from the PSS vessel gas region through the vacuum breaker valves provided for that purpose. The momentum flux (drag disc) measurement in the broken loop piping indicates erratic, near zero flow in the period when the PSS pressure is rapidly decreasing in the tests with ECC injection, whereas a steady outward flow is maintained in the same period (25 to 35 seconds after rupture) in tests without ECC injection.

The prepressurization with air required to achieve the desired pressure at the end of blowdown produces a higher than typical PSS pressure during the first 12 seconds of the blowdown experiment (Figure 15). This higher pressure cannot affect primary system blowdown because the blowdown flow rate is controlled by the choked flow at the break area in the primary system and is unresponsive to downstream pressure until the primary

[a] Tests 1001 and 1010 had no ECC injection; Test 1004 had ECC injection.

Fig. 15 Comparison of measured PSS pressure response with predicted PWR containment pressure response.

system pressure drops to about 150 psig, after which the break flow becomes unchoked. For the large break experiments under consideration, break flow unchoking probably occurred at 22 to 25 seconds after break initiation, depending on ECC effects on blowdown rate.

A feature of the PSS pressure response that is inherent to the PSS concept, but not typical of PWR dry containment pressure response, is the transient pressure spike associated with displacement of the plug of water initially residing in the PSS downcomer, which is commonly referred to as the vent clearing spike. The magnitude of the vent clearing pressure spike is coupled to the mass and geometry of the water plug in the downcomer pipe (which changes with downcomer diameter and depth of submergence) and the compressibility and damping characteristics of the gas initially in the PSS header. In Tests 1001 and 1002 the measured peak pressure attributed to vent clearing was 50 psig, as shown in Figures 16 and 17. A calculation of the transient pressure response associated with the initiation of blowdown flow into the PSS would ideally include the acoustic effects at area changes, as

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Fig. 17 Pressure at entrance to PSS header, Test 1002.

well as fluid inertia effects among which vent clearing is the most significant. Due to the complexity of such an analysis, a simple calculational model of the problem is not attainable. An analysis of the vent clearing pressure response was made using the CONTEMPT computer code that was developed to analyze reactor containment pressure response to postulated loss-of-coolant accidents. The following are the calculated and measured vent clearing pressure spikes for Tests 1001 and 1002, and the calculated vent clearing spike for Test 1003:

<u>Test</u>	<u>Pressure (psig)</u>	
	<u>Measured</u>	<u>Calculated</u>
1001	50	34
1002	50	34
1003	not measured	38

Two tests in the isothermal blowdown series (Tests 1009 and 1011) utilized an external steam pressurization source in an attempt to uncouple the PSS pressure transient from the blowdown flow and the effects of ECC injection. The plotted pressure measurement for Test 1009 (Figure 12) indicates a pressure rise that is more rapid than desired, followed by a rate of decline that is also more rapid than desired. The reason for the poor pressure response behavior was the inadequacy of the steam flow control circuit. The flow circuit used for Test 1009 to admit PSS pressurization steam from the external source consisted of a fixed resistance and a simple on-off valve that was opened simultaneously with blowdown initiation. The circuit resistance was determined by preblowdown trial pressurizations of the PSS vessel. When the blowdown test was run, the blowdown flow filled the PSS header which was previously filled by the pressurizing steam during the trial system pressurization tests. The steam flow from the external source, therefore, pressurized the smaller volume more rapidly than desired as the pressure response in Figure 12 illustrated. PSS pressurization from an external steam source was also used for Test 1011; however, a pressure regulator was added to the steam supply circuit. The pressure response measured during Test 1011 is shown in Figure 14. As during Test 1009, the air was purged from the PSS header prior to the test, and as during Test 1009 the pressure rise starting simultaneously with system blowdown was more rapid than desired for the same reason as discussed for Test 1009. The addition of a pressure regulator in the PSS pressurizing steam circuit resulted in the much improved pressure modeling during the postblowdown period; however, the regulator flow capacity was somewhat too small to compensate for the condensation occurring immediately after the fixed resistance pressurizing circuit valve was closed (at 15 seconds in Figure 14). For this reason, the pressurizing circuit valve was momentarily reopened at 20 seconds to raise the PSS pressure to the desired 53 psi after which the regulated steam flow was adequate to maintain system pressure. The pressurizing steam flow rate was not measured in these tests due to the unavailability of appropriate instrumentation.

3. COMPARISON OF TEST RESULTS WITH CONTEMPT CODE PREDICTION OF PSS PRESSURE RESPONSE

The CONTEMPT computer code^[2] is a calculational model developed to predict the pressure and temperature response within reactor plant containments to a postulated LOCA. The semiscale isothermal test system geometry and fluid conditions were input to the CONTEMPT code through use of the pressure suppression containment option which provides for calculation of the containment dry well pressure during vent clearing. Figure 18 compares the PSS vessel pressure response computed by the CONTEMPT code with the measured pressure for Test 1010. The discrepancy illustrated in Figure 18 is primarily attributable to the lack of provision in CONTEMPT for calculating evaporation from the PSS water pool and the attendant vapor pressure increase in the gas region above the pool. Since the vapor pressure increases about 0.6 psi/°F of temperature increase (at 250°F), a relatively large error is introduced into the calculation by the effect of water pool temperature increase due to blowdown heat addition being neglected. The CONTEMPT code is being modified to include evaporation and condensation effects in pressure suppression containment analysis.

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5. DEFLECTION OF PRESSURE SUPPRESSION SYSTEM COMPONENTS

The effect of blowdown-imposed loading on the PSS structure was monitored through displacement measurements on the PSS header and vessel. The measured displacements are listed in Table VI. The position of the PSS header at the first elbow was monitored to detect motion in the horizontal plane, parallel to the inlet pipes. The position of the PSS vessel was monitored to detect vertical motion of the bottom head of the vessel.

TABLE VI

DISPLACEMENT OF PRESSURE SUPPRESSION SYSTEM HEADER AND VESSEL

Test	Displacement (in.)			
	Header		Vessel ^[b]	
	Initial	At 40 Sec	Initial Oscillation	At 40 Sec
1001	0.13	0.09	0.013 0.005	0.02
1002	0.03	0.025	0.025 -0.020	0.017
1003	-0.30	-0.22	0.08 -0.17	0.02
1004	0.10	0.07	+0.010	0.02
1006	0.22	0.16	0.025 -0.020	0.055
1008	0.17	0.10	0.015	0.035
1009	0.07	0.03	0.013 -0.020	0.022
1010	0.20	0.16	+0.010	0.040
1011	0.14	0.09	0.013 -0.066	0.032

[a] Positive values indicate that motion at first elbow parallel to inlet pipes is toward the break nozzle and negative values indicate that motion at elbow is away from the break nozzle.

[b] Positive values indicate that vertical displacement at bottom of tank is upward and negative values indicate vertical displacement is downward.

The loads imposed on PSS components during the blowdown experiments were not measured and cannot be obtained from the displacement measurements. Blowdown loads are coupled to the geometry of the flow path; hence semiscale PSS load data do not apply to different suppression system component designs and are, therefore, not reported or analyzed further. The principal, but qualitative, conclusion that can be drawn from the displacement data with regard to blowdown loads is that the loads on the PSS header were substantial relative to the rigidity of the support structure, whereas the deflections of the PSS vessel were less severe.

6. MODELING OF PWR CONTAINMENT GAS COMPOSITION

The predicted gas composition in a PWR dry containment following a postulated large break LOCA is 36% air and 64% water vapor by mass^[9]. The semiscale suppression system conditions used for Test 1010 resulted in a calculated gas composition of 65% air, 35% water vapor by mass. The PSS vessel gas composition can affect postblowdown ECCS performance because of the difference between condensable and noncondensable gas behavior in the primary system if PSS gas is drawn back into the primary system due to condensation. Semiscale experiments differ from a PWR LOCA in this respect because the PSS header contains only water vapor in the break region, hence modeling the PWR containment gross gas composition at the break is inherently impossible. If ECCS condensation produces inward flow through the break nozzles that is sufficiently extensive to exhaust the PSS header volume, the gas mixture in the PSS vessel approximately simulates the PWR containment gas mixture composition. More accurate modeling of the PWR gas composition could have been achieved at the expense of reduced PSS pool subcooling.

7. COMPARISON OF SEMISCALE PSS TEST CONDITIONS WITH THOSE DERIVED FROM LARGE SCALE TESTS

A series of pressure suppression tests was performed by the Pacific Gas and Electric Company and the General Electric Company at the Moss Landing facilities in support of the Humboldt Bay and Bodega Bay plant pressure suppression containment designs. A report on the results of these tests^[9] included a list of recommended suppression system parameters based on duplication of key design parameters used in the Moss Landing tests that were successful with respect to effective condensation. Reference 9 states that the design parameters proven satisfactory in the referenced tests do not represent the only conditions under which satisfactory blowdown fluid condensation can be achieved in a pressure suppression containment. Rather, the listed conditions represent the parameter values proven successful with regard to condensation during the Moss Landing tests, which if duplicated ensure the applicability of those test results to a pressure suppression system design. The recommended list of parameters is reproduced here together with the values of those parameters occurring during the semiscale isothermal blowdown test series.

- (1) The downcomer diameter should be no greater than 24 inches. (The semiscale PSS downcomer diameter was 8 inches.)
- (2) The downcomer exit should discharge downward and be submerged in the pool water by at least three feet. (The semiscale PSS downcomer submergence was 33 inches for Test 1003 and about 11 inches for the other tests.)
- (3) The clearance between the downcomer exit and the pool bottom should be no less than 6 feet nor more than 12 feet. (The clearance was 3 feet for the semiscale tests.)
- (4) The downcomer spacing should not be less than 3.6 feet from centerline to centerline. (The semiscale PSS had a single 8-inch-diameter downcomer centered in a 40-inch-diameter vessel.)
- (5) The average pool temperature should not exceed 170°F at the end of reactor vessel blowdown. (The semiscale PSS pool temperature ranged from 160 to 263°F at the end of vessel blowdown.)
- (6) The ratio of design break area to vent total flow area shall not exceed 0.05. (This ratio was 0.0135 in the semiscale system.)

The preceding comparisons show that the semiscale tests proved that satisfactory steam condensation can be achieved in the PSS with less downcomer submergence and higher pool water temperatures than were investigated in the Moss Landing tests. This result suggests that downcomer submergence limitations may be related to downcomer diameter and that subcooling rather than absolute temperature governs the condensation process.

V. CONCLUSIONS

The basic design concept of the semiscale PSS was verified as being capable of fulfilling the functional requirements during the isothermal blowdown test series. The condensation and retention of the blowdown effluent in the PSS vessel water pool were reliably accomplished for all the blowdown tests in the series under a variety of initial PSS conditions. Since the semiscale PSS is a functional model of the LOFT PSS, the blowdown fluid condensation and retention capability of the LOFT PSS is probably satisfactory, but the detailed verification of the LOFT design is beyond the scope of this report. The successful condensation of blowdown effluent realized during the isothermal test series under a variety of initial PSS conditions extends the range of experimentally verified PSS design parameters beyond those proven by the Moss Landing tests. The degree to which the PSS pressure response modeled the predicted PWR containment pressure response varied as was expected, because the PSS parameters were experimentally varied from test to test to obtain definition of the system interactions. As a result of the experimentation, a set of PSS parameters was defined that produced a predictable and a fairly accurate PSS pressure model of the predicted PWR containment pressure response (Figure 15 and Table IV). This desired response was achieved through use of a simple PSS pressurization method involving preheating the PSS water pool to 180°F and prepressurizing the air to 16 psig. Although the PSS pressure is untypically high during the first 13 seconds of blowdown, it does not affect primary system blowdown because the blowdown flow is choked at the break area and unresponsive to PSS back pressure during this initial time interval.

An alternate method of PSS pressure control used in the isothermal test series involving an external steam source for pressurization of the PSS simultaneous with, but independent of, the primary system blowdown provided less satisfactory pressure response modeling.

The simple flow control devices used to provide transient pressurization of the PSS during blowdown proved inadequate to decouple PSS pressure from the blowdown flow. Although this concept potentially offers uncoupled PSS pressure modeling control, a more sophisticated pressurizing steam flow control device is required to implement the concept than was used for the semiscale isothermal tests.

VI. REFERENCES

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APPENDIX A

PRESSURE SUPPRESSION SYSTEM DATA FROM THE SEMISCALE

ISOTHERMAL TEST SERIES

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APPENDIX A

PRESSURE SUPPRESSION SYSTEM DATA FROM THE SEMISCALE

ISOTHERMAL TEST SERIES

Figures A-1 through -50 of this appendix provide the isothermal blowdown data pertinent to the pressure suppression system behavior.

Fig. A-1 Fluid temperatures in pressure suppression system -- Test 1001.

Fig. A-2 Fluid temperatures in pressure suppression system -- Test 1002.

Fig. A-3 Fluid temperatures in pressure suppression system -- Test 1003.

Fig. A-4 Fluid density in pressure suppression header -- Test 1001.

Fig. A-5 Fluid density in pressure suppression header -- Test 1002.

Fig. A-6 Fluid density in pressure suppression header -- Test 1003.

Fig. A-7 Pressure in pressure suppression system -- Test 1001.

Fig. A-8 Pressure in pressure suppression system -- Test 1002.

Fig. A-9 Pressure in pressure suppression system -- Test 1003 (P-80, P-83).

Fig. A-10 Pressure in pressure suppression system -- Test 1003 (P-77, P-89).

Fig. A-11 Differential pressure between pressure suppression header and pressure suppression tank downcomer entrance -- Tests 1001, 1002, and 1003.

Fig. A-12 Differential pressure between pressure suppression tank downcomer entrance and exit -- Tests 1001, 1002, and 1003.

Fig. A-13 Differential pressure between pressure suppression tank downcomer entrance and pressure suppression tank vapor chamber -- Tests 1001, 1002, and 1003.

Fig. A-14 Differential pressure between pressure suppression tank downcomer exit and pressure suppression tank vapor chamber -- Tests 1002 and 1003.

Fig. A-15 Liquid level in pressure suppression tank -- Test 1001.

Fig. A-16 Displacement of pressure suppression header -- Test 1001.

Fig. A-17 Displacement of pressure suppression header -- Test 1002.

Fig. A-18 Displacement of pressure suppression header -- Test 1003.

Fig. A-19 Fluid temperatures in pressure suppression system -- Test 1004.

Fig. A-20 Fluid temperatures in pressure suppression system -- Test 1006.

Fig. A-21 Fluid density in pressure suppression header -- Tests 1004 and 1006.

Fig. A-22 Pressure in pressure suppression system -- Test 1004.

Fig. A-23 Pressure in pressure suppression system -- Test 1006.

Fig. A-24 Differential pressure between vessel upper plenum and pressure suppression tank vapor chamber -- Tests 1004 and 1006.

Fig. A-25 Differential pressure between pressure suppression header and pressure suppression tank vapor chamber -- Tests 1004 and 1006.

Fig. A-26 Differential pressure between pressure suppression header and pressure suppression tank downcomer entrance -- Tests 1004 and 1006.

Fig. A-27 Liquid level in pressure suppression tank -- Tests 1004 and 1006.

Fig. A-28 Fluid temperatures in pressure suppression system -- Test 1008.

Fig. A-29 Fluid temperatures in pressure suppression system -- Test 1010.

Fig. A-30 Fluid density in pressure suppression header -- Test 1010.

Fig. A-31 Pressure in pressure suppression system -- Test 1008.

Fig. A-32 Pressure in pressure suppression system -- Test 1010.

Fig. A-33 Differential pressure between vessel upper plenum and pressure suppression tank vapor chamber -- Tests 1008 and 1010.

Fig. A-34 Differential pressure between pressure suppression header and pressure suppression tank vapor chamber -- Tests 1008 and 1010.

Fig. A-35 Differential pressure between pressure suppression header and pressure suppression tank downcomer entrance -- Tests 1008 and 1010.

Fig. A-36 Liquid level in pressure suppression tank -- Tests 1008 and 1010.

Fig. A-37 Fluid temperatures in pressure suppression system -- Test 1009.

Fig. A-38 Pressure in pressure suppression system -- Test 1009.

Fig. A-39 Differential pressure between vessel upper plenum and pressure suppression tank vapor chamber -- Test 1009.

Fig. A-40 Differential pressure between pressure suppression header and pressure suppression tank vapor chamber -- Test 1009.

Fig. A-41 Differential pressure between pressure suppression header and pressure suppression tank downcomer entrance -- Test 1009.

Fig. A-42 Liquid level in pressure suppression tank -- Test 1009.

Fig. A-43 Displacement of pressure suppression system -- Test 1009.

Fig. A-44 Fluid temperatures in pressure suppression system -- Test 1011.

Fig. A-45 Pressure in pressure suppression system -- Test 1011.

Fig. A-46 Differential pressure between vessel upper plenum and pressure suppression tank vapor chamber -- Test 1011.

Fig. A-47 Differential pressure between pressure suppression header and pressure suppression tank vapor chamber -- Test 1011.

Fig. A-48 Differential pressure between pressure suppression header and pressure suppression tank downcomer entrance -- Test 1011.

Fig. A-49 Liquid level in pressure suppression tank -- Test 1011.

Fig. A-50 Displacement of pressure suppression system -- Test 1011.