Westinghouse Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

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ATTENTION: MR. T. R. QUAY

SUBJECT: SCALING ROLE IN AP600 PCS DBA ANALYSIS

Dear Mr. Quay:

During the June 22, 1995, meeting between Westinghouse and the Containment Systems and Severe Accident Branch, Westinghouse took an action to provide a discussion on the role of scaling in the AP600 Passive Containment Cooling System (PCS) Design Basis Accident (DBA) analyses. This discussion was requested in light of recent changes to the PCS DBA methodology which incorporates a more traditional bounding approach. The attachment to this letter provides the requested information.

We hope that the attached information provides the needed clarification requested at the June 22, 1995 meeting. Please contact John C. Butler (412-374-5268) if you have any questions concerning this review.

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

/nja

Attachment

cc: T. J. Kenyon, NRC
D. Jackson, NRC
J. Kudrick, NRC
E. Throm, NRC
P. Boehnert, ACRS
N. J. Liparulo, Westinghouse
I. Catton, ACRS

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Role of Scaling for AP600 PCS Design Basis Accidents

1.0 Introduction

A scaling analysis has been conducted by Westinghouse for the AP600 passive containment cooling system (PCS) for design basis accident (DBA) analyses. The scaling analysis utilized guidance provided by the USNRC for severe accident technical resolution[1]. The scaling analysis was applied to two limiting transients: the double-ended cold leg guillotine (DECLG) loss of coolant accident (LOCA) and the main steam line break (MSLB).

The scaling analysis began with a definition of the plant and the accident scenario. All transport processes that could potentially affect the containment pressure were listed and organized into a phenomena identification and ranking table (PIRT) consistent with Reference 1. Control volume equations were written for the containment gas and manipulated to express containment gas pressure as a function of transport processes. The resulting equation, the rate of pressure change (RPC) equation, was normalized to the break steam source, and the relative magnitude of the various transport terms were examined. The normalized transport terms are referred to as "pi", or scaling groups that represent the relative importance of the normalized transport terms, some of which change significantly in importance throughout the various time phases of the transient. The pi group values, as well as test results and other analyses, were used to rank the relative importance of the transport processes in the PIRT[2].

Several separate effects tests (SET) were conducted to experimentally characterize important processes embodied during design basis accidents in AP600. An integral test, referred to as the small scale test (SST), was built and tests were conducted to develop test and analysis techniques. This was followed by a 1/8 scale integral test, referred to as the large scale test (LST). The LST was built to produce data characterizing internal condensation and external evaporation mass transfer in an integral test setting. These tests, as well as other Westinghouse tests, and test results available in the open literature were used to develop and/or validate phenomenological models for:

heat transfer to and through condensing and evaporating liquid films

free and forced convection heat and mass transfer inside and outside containment

wetting and surface coverage of the external liquid film.

The scaling analysis identified the ranges of dimensionless parameters in AP600 that are required to validate the phenomenological models. Other tests (wind tunnel, external flow path ΔP) have been used to develop boundary conditions and hydraulic characteristics. Based on this evaluation of all relevant pheomena, guidelines for developing bounding analysis methods were developed.

A model of the LST was developed with the WGOTHIC computer code to make validation comparisons to the LST steady-state and transient tests. The LST model utilized the most accurate and nominal phenomenological models, initial conditions, and boundary conditions available. The computer model represented the transport phenomena identified as important, as well as many others that are of medium and low importance. Comparisons of code predictions to the test data support code validation, and also confirm that the PIRT and scaling analysis have included the important phenomena.

The LST models, both lumped parameter and distributed parameter, served as a starting point for the PCS DBA evaluation model of AP600. However, the evaluation model is a bounding model, so it is necessary to input bounding initial and boundary conditions, as well as to bias the phenomenological models of the dominant transport processes to provide bounding results.

The large mass of internal heat sinks, the large-scale gas flow that circulates between the above and below deck regions, and the high flow rate steam source during blowdown were not represented in the LST, so their effects were validated in the evaluation model by bounding calculations. The scaling analysis helps with the bounding calculations by providing enough insight into the actual physics to show that bounding modifications can be made to the evaluation model. The application of scaling to the LST showed that the LST well represents the AP600 heat and mass transfer, the dominant transport processes.

Results of AP600 PCS scaling have been provided to the NRC[2] and review comments have been received. Scaling has assisted the determination of bounding models and limits for bounding calculations using the evaluation model. The means by which these are addressed was presented to the NRC[3] in the PCS DBA Road Maps.

The following sections of this document present the major findings of the scaling analysis with references, whether the LST contributes to these findings, and a discussion of how the findings are included in the evaluation model. A summary is presented of how the dominant transport processes and parameters are bounded in the evaluation model.

2.0 Usage of Scaling for AP600 PCS DBA

The scaling analysis has been applied to the two limiting containment pressurization accidents: the double-ended cold leg guillotine LOCA, and the MSLB. The PCS plays a major role in limiting containment pressure following blowdown and reflood in the LOCA, and several important conclusions were drawn from the scaling analysis. The MSLB, in contrast, is almost entirely a blowdown transient that terminates prior to the PCS becoming effective. Consequently, the MSLB conclusions drawn from scaling are similar to those for the LOCA blowdown.

The following conclusions were reached from scaling the rate of pressure change (RPC) equation, above-deck momentum, PCS air flow path momentum, and energy transfer resistance. Conclusions are first discussed for the LOCA, followed by conclusions for the MSLB.

2.1 Scaling Conclusions for LOCA

2.1.1 Effect of Mass and Energy Transfer on Containment Pressure

Containment pressure scaling has shown that condensation and evaporation mass transfer are the dominant transport processes that effect pressure, by an order of magnitude. Therefore, other effects are second order, including the subcooled heat capacity of the external coolant.

Scaling has shown the major energy sinks are the atmosphere and internal heat sinks during blowdown, the internal heat sinks during reflood, internal heat sinks and PCS evaporation at the second peak, and the external PCS evaporation after the second peak. Processes outside the external shell have no effect on blowdown pressures.

The application of scaling to the LST showed that condensation and evaporation mass transfer are the dominant transport processes that affect pressure, and that the dimensionless groups that characterize mass transfer in the LST adequately represent AP600. The major LST energy sinks are the atmosphere during blowdown, and the external PCS evaporation post-blowdown. The ratio of subcooled heat capacity to evaporative heat removal in the LST ranges from less than to greater than that in AP600.

Inclusion in Evaluation Model:

The LST and other relevant mass transfer test results are used to validate the condensation and evaporation mass transfer models[4]. The correlations are biased to bound valid data points, and the biased models are included in the evaluation model. Additional transport processes identified as second-order are also included in the evaluation model, including liquid enthalpy transport, radiation, and convection. The effect of these processes are bounded in the evaluation model as described in Section 3.0.

The evaluation model includes a detailed, yet conservative list and distribution of the internal heat sinks and shell, as well as both the major and second-order energy removal mechanisms.

2.1.2 Containment Momentum

Containment momentum scaling has shown that during blowdown, the jet greatly dominates buoyancy effects, so forced convection heat and mass transfer are expected to dominate, with minimal concentration gradients within the above-deck volume. After blowdown, buoyancy dominates forced convection, so heat and mass transfer are well characterized by free convection models.

Momentum scaling inside the LST shows that when free convection dominates internal heat transfer, the free convection heat and mass transfer correlation selected for AP600 predicted the LST results with acceptable accuracy[4]. The tests that operated with such high jet source velocities that forced convection dominated internal transport processes showed that measured internal heat and mass transfer rates significantly exceeded those predicted by free convection correlations.

Inclusion in Evaluation Model:

Free convection is used for heat and mass transfer to the shell throughout the transient. This produces lower transfer rates than the actual process of forced convection during blowdown, and the biased correlation produces bounded transport rates after blowdown. The Uchida correlation is used for internal heat sinks throughout the transient, consistent with accepted Standard Review Plan methodology.

The effect of air/steam concentration on the mass transfer to the shell is bounded:

- For short term LOCA and MSLB by minimizing steam access to lower internal heat sinks, and

- For long term LOCA by using well-mixed conditions to conservatively bound PCS mass transfer.

2.1.3 PCS Air Flow Path

PCS air flow path scaling[2] showed that the air flow path can be modeled by simply equating drag forces and buoyant forces. The drag forces can be represented by a constant loss coefficient, and the buoyant forces can be calculated for the downcomer, riser, and chimney. The PCS air flow path momentum equation was scaled, and the pi groups showed that the magnitude of the downcomer buoyant force is less than 1/10 of the total buoyant force, and acts in a direction opposite to the direction of circulation. Because the downcomer force is such a small fraction of the total buoyant force, the downcomer has little or no effect on the PCS circulation. In addition, buoyancy in the downcomer is driven by heatup of the baffle, and shield, each of which successively lags the shell temperature rise in time. Thus the downcomer buoyancy develops more slowly (is phase shifted in time) as containment heats up and the PCS air flow starts up, so there is no potential for thermally induced instabilities to impact flow startup.

Although the PCS air flow path circulation starts up by free convection, heat and mass transfer are predominantly forced convection when the shell outside temperature is more than a few degrees F above the ambient temperature[5].

Models of the air circulation in the LST, SST, Siegel and Norris, and Hugot tests[4] have verified that the riser circulation can be accurately modeled with a simple one-dimensional model that equates the buoyant and drag forces.

Inclusion in Evaluation Model:

> The loss coefficient, and the distribution of its component parts, based on the 1/6 scale, 14° sector model test conducted at Westinghouse STC[6] are included in the evaluation model. The heat transfer to the downcomer, and the heat and mass transfer to the riser and chimney are included in the determination of the buoyant force, using a one-dimensional coupled solution for the mass, momentum, and energy equations.
>
> Sensitivity studies have shown the containment pressure is not sensitive to variations in the loss coefficient.

2.1.4 Energy Transfer Resistance

Scaling the energy transport resistance between the containment gas and riser of AP600 showed that condensation and evaporation resistance fractions are both significant. Since both are significant, both must be considered in the modeling.

Specific tests conducted on the LST facility were examined in which the internal temperature and steam pressure were similar to those in AP600. Measurements from the inside to the outside of the LST showed that the inside resistance was nearly identical to that in AP600, as was the outside resistance, but with approximately 1/2 the wall resistance due to the thinner LST shell. Variations of the LST internal air/steam concentrations demonstrated the sensitivity of condensation mass transfer to concentration, and its effect on containment pressure. Variations in the magnitude of internal momentum showed the effect of jet velocity on the condensation mass transfer rate. Variations of the external velocity demonstrated the sensitivity of evaporation mass transfer to riser air velocity and its effect on containment pressure[7].

Inclusion in Evaluation Model:

The phenomenological models for condensation and evaporation mass transfer accurately predict the local test measurements from inside to outside containment, and hence the series resistances, when the correct values of air/steam concentration and velocity are known. After validating the models against local test data, the models were biased to bound the data for both condensation and evaporation mass transfer.

Modeling inside containment has conservatively selected free convection heat and mass transfer, to eliminate any uncertainty due to internal velocity. Air/steam concentrations are bounded in the evaluation model.

Outside containment a forced convection model is used that is conservative at PCS air flow path startup, and is biased to bound all the test data at wall temperatures more than a few degrees hotter than the environment air. Sensitivity studies have shown that containment pressure is not sensitive to the external air velocity.

2.2 Scaling Conclusions for MSLB

The MSLB blowdown lasts approximately 400 seconds, compared to the 27 second LOCA blowdown. Throughout blowdown, the mass and energy release rates are more than an order of magnitude greater than the energy removal rate from the shell due to evaporation, convection, and radiation. Consequently, external energy removal processes can be neglected in the scaling analysis. Furthermore, once the blowdown stops, the mass and energy inputs effectively stop and the pressure drops rapidly due to internal heat sinks and the external heat removal processes. Thus, there are no phases that require consideration beyond blowdown as there are in a LOCA.

2.2.1 Containment Momentum

Containment momentum scaling has shown that during blowdown, the jet greatly dominates buoyancy effects, so forced convection heat and mass transfer are expected to dominate, with minimal concentration gradients within the above-deck volume.

Momentum scaling inside the LST shows that the highest jet velocities achieved in the tests produced Froude numbers equal to the lowest Froude numbers during the AP600 MSLB. The test results showed the mass transfer was dominated by forced convection, with transfer rates greater than those predicted by free convection. Data for jets with either horizontal or vertical orientation produced the same well-mixed above deck region, and forced convection dominated mass transfer. The higher Froude numbers in AP600 will produce even higher forced convection heat transfer than measured in the LST.

Inclusion in Evaluation Model:

Free convection is used for heat and mass transfer to the shell throughout the transient. This produces lower transfer rates than the actual process of forced convection during blowdown. The Uchida correlation is used for internal heat sinks throughout the transient, consistent with accepted Standard Review Plan methodology.

The effect of air/steam concentration on the mass transfer to the shell and internal heat sinks is bounded by using a minimum flow area through the operating deck, thus limiting steam access to the lower heat sinks which dominates the pressure drop during reflood.

2.2.2 Energy Transfer Resistance

Scaling the energy transfer resistance between the containment gas and the internal heat sinks and shell of AP600 showed that the condensation coefficient is the dominant resistance, and that the forced convection gas velocity and air/steam concentrations are parameters of major importance in determining the condensation rate.

Measurements on the LST showed that the air/steam concentrations were ranged appropriately to simulate conditions in AP600. Measurements also showed that the effect of jet velocity is not easily related to the local forced convection dominated mass transfer coefficient inside containment, so forced convection will have to be conservatively bounded, rather than modeled directly.

Inclusion in Evaluation Model:

The evaluation model uses free convection heat and mass transfer on the shell throughout the MSLB transient to conservatively bound the transfer rates. The actual transfer rates were shown by the scaling and LST to be significantly higher than those predicted with a free convection model.

Air/steam concentrations are bounded in the evaluation model.

2.2.3 Effect of Mass and Energy Transfer on Containment Pressure

Containment pressure scaling has shown that condensation mass transfer is the dominant transport process that affects pressure, by an order of magnitude. The major energy sinks are the atmosphere, internal heat sinks, and containment shell. The shell and internal heat sinks are more effective during the MSLB than for the LOCA due to the longer MSLB blowdown period.

The LST showed that free convection condensation bounds the actual mass transfer rate.

Inclusion in Evaluation Model:

The heat and mass transfer correlation is conservatively bounded by the free convection models for the inside of the shell. The Uchida correlation is used, consistent with the SRP, for internal heat sinks.

The evaluation model includes conservative values for the gas volumes, solid heat sinks, and shell, as well as second-order convection and radiation heat transfer on the inside. Although shown to be a minor effect on pressure, the outside of the shell includes a bounded evaporative mass transfer correlation and convection and radiation heat transfer.

3.0 Usage of Scaling to Develop Rationale for Bounding Approach

The scaling analysis shows that condensation on the shell and internal heat sinks, and evaporation from the shell are the dominant transport processes for containment heat removal and containment pressurization. A bounding approach was developed[3] such that:

The condensation and evaporation mass transfer correlations are each biased to bound appropriate test data,

The input parameters to the mass transfer correlations (velocity, concentrations, and wetted coverage) are bounded, and

The effect of internal circulation from the source to the above and below-deck heat sinks and heat removal paths are bounded.

In conclusion, the scaling groups were used to identify the dominant transport processes, the LST and other tests provided validation for phenomenological models of the dominant transport processes, and the phenomenological models and inputs to the evaluation model were conservatively biased to produce a bounding evaluation model.

4.0 References

1. NUREG/CR-5809, "An integrated Structure and Scaling Methodology for Severe Accident Issue Resolution", November 1991, U.S. NRC.

2. D. R. Spencer, "Scaling Analysis for AP600 Passive Containment Cooling System", October 1994, Westinghouse Electric Corporation, WCAP-14190.

3. Letter N. J. Liparulo (Westinghouse) to R. W. Borchardt (USNRC),"AP600 PCS DBA Road Maps", NTD-NRC-95-4545 August 31, 1995.

4. R. P. Ofstun, "Experimental Basis for the AP600 Containment Vessel Heat and Mass Transfer Correlations", WCAP-14326, March 31, 1995, Westinghouse Electric Corporation.

5. Letter, N. J. Liparulo (Westinghouse) to R. W. Borchardt (USNRC), "Supporting Information for the Use of Forced Convection in the AP600 PCS Annulus", February 16, 1995, NTD-NRC-95-4397.

6. W. A. Stewart, A. T. Pieczynski, "Tests of Air Flow Path for Cooling the AP600 Reactor Containment", WCAP-13328, Westinghouse Electric Corporation.

7. R. P. Ofstun and D. R. Spencer, "Large-Scale Test Data Evaluation", May 1995, PCS-T2R-050, Westinghouse Electric Corporation.