21. TESTING AND COMPUTER CODE EVALUATION

21.1 Introduction

The AP1000 standard design is a two-loop, pressurized-water reactor (PWR) with an electric output of approximately 1,117 MWe. As such, the AP1000 is a passive plant design that represents an evolution from the AP600 design, which has an electric output of approximately 600 MWe and was the first passive, advanced light-water reactor (ALWR) design reviewed by the U.S. Nuclear Regulatory Commission (NRC). These advanced plant designs differ from conventional PWRs in that they use passive safety systems to provide the means to cool the reactor core following an accident. Unlike conventional active safety systems, these passive safety systems use only natural forces, requiring no continuously operating, electrically [alternating current (ac)] powered, mechanical components (such as pumps).

In the context of the AP600 and AP1000 passive plant designs, the natural forces include gravity, natural circulation, compressed gas, and stored mechanical energy. Also included in the definition of “passive” systems are components that may use electrical power supplied by batteries [direct current (dc)] to change state; however, if called upon to function, these components change state only once (i.e., a valve can change from “closed” to “open,” but remains open thereafter). Check valves, which use no power and open or close according to the differential pressure across the valve, are also included in the passive systems.

The AP1000 design maintains the same plant and system configurations, arrangement, and layout as the AP600 design. The major differences between the AP1000 design and the AP600 design, as summarized in Table 21-1 of this report, are increased AP1000 thermal power and increased capacities of the major components of the AP1000 to accommodate the increased thermal output. The applicant asserts that the AP1000 design represents an incremental change to the AP600 design, and that the AP600 test program and the computer codes used for the analyses of the AP600 design-basis events also apply to the AP1000 design.

During the AP1000 pre-application review, the applicant submitted the following topical reports to support its assertions that the AP600 design-basis analysis codes are applicable to the AP1000 design, and that the test data obtained from the AP600 test program are also sufficient for the AP1000 design:

- WCAP-15612, “AP1000 Plant Description & Analysis Report,” describes the AP1000 design, compares it with the AP600 design, and provides a partial, preliminary AP1000 safety analysis and margin assessment.

- WCAP-15613, “AP1000 PIRT and Scaling Assessment,” presents (1) the AP1000 phenomena identification and ranking tables (PIRTs) for large- and small-break loss-of-coolant accidents (LOCAs), long-term cooling (LTC), non-LOCA transients, and the containment response; (2) an overview of the AP600 test program; and (3) scaling assessments of important separate-effects, integral-effects, and containment tests.

- WCAP-15644, “AP1000 Code Applicability Report,” documents the applicant’s assessment of the safety analysis codes that were developed and approved for the AP600 design certification to determine their applicability for use in the AP1000 design.

> Specifically, those safety analysis codes are (1) LOFTRAN for non-LOCA transients and steam generator (SG) tube rupture analyses, (2) NOTRUMP for small-break LOCA (SBLOCA) analyses, (3) WCOBRA/TRAC for large-break LOCA (LBLOCA) and LTC analyses, and (4) WGOTHIC for containment analyses.

At the time the DSER was issued, the staff's evaluation documented in this chapter concentrated on the differences between the AP1000 and the AP600 design. In evaluating the AP1000 design, as set forth in the DSER, the staff relied on the AP600 testing and computer codes, which the staff found to be acceptable for the AP600 design, as documented in Chapter 21 of NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," September 1998. This chapter contained references to NUREG-1512, which provided the basis for accepting the AP600 testing and computer codes. The staff stated that it would remove these references from the FSER and replace the references with the basis for its conclusion that the testing and computer codes are acceptable for the AP1000. This was Open Item 21.1-1 in the DSER.

The AP1000 testing and computer codes are founded on those used for the AP600 design analysis. In evaluating the AP1000 testing and computer codes, the NRC staff first evaluated the applicability of the AP600 test program and computer codes to the AP1000. In so doing, the staff considered both the similarities and differences in the thermal-hydraulic (T-H) phenomena that might be experienced in operation of the AP1000 and AP600, and responses to transients and accidents. The review and evaluation process included identifying important phenomena during various transients and accidents, and conducting a scaling assessment of test facilities and an evaluation of computer codes to assess their adequacy with respect to the important phenomena. This process resulted in the identification of deficiencies in the AP600 test programs for application to the AP1000 design. The NRC then asked the applicant to acquire additional test data related to these phenomena (specifically, liquid entrainment in the upper plenum, hot-legs, and stage 4 of the automatic depressurization system) to verify the applicability of the codes to the AP1000 design.

Where the AP600 test program and computer codes are directly applicable to the AP1000 design, the staff's review and evaluation for the AP600 design certification remain valid for the AP1000 design certification. In Chapter 21 of NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," the NRC staff described in detail its evaluation of the AP600 test program and computer codes for application to the AP600 design. Similarly, this chapter describes the staff's evaluation of the AP1000 test programs and computer codes, including an evaluation of the applicability of the AP600 test program and computer codes to the AP1000. Because of code deficiencies identified through assessment against the additional test data acquired to support the AP1000 code assessment, additional sensitivity studies and supplemental calculations on the small-break LOCA evaluation model were performed for the AP1000 design.

The staff has now completed its review of the testing and computer codes used for the design certification of the AP1000 and the results of that review are set forth in this chapter. Therefore, Open Item 21.1-1 is resolved. In the remaining sections of this chapter, the staff describes the information submitted in connection with the AP600 application that also supports the AP1000 application. As set forth below, the staff has evaluated whether that information applies to the AP1000 design and has also evaluated all AP1000 issues not otherwise addressed.

21.1.1 Passive Emergency Injection Systems

The AP1000's emergency core cooling (ECC) injection systems include the following:

- two core makeup tanks (CMTs), which initially inject cold, borated water into the reactor coolant system (RCS), and can operate either in a natural-circulation-driven recirculatory mode or by gravity drain

- two accumulators, pressurized by compressed nitrogen gas, which also inject cold, borated water into the RCS if RCS pressure is less than 4.8 MPa (700 psig)

- one in-containment refueling water storage tank (IRWST), which provides borated water by gravity drain to the RCS

The accumulators are isolated from the RCS during normal operation by means of check valves in their injection lines that are held shut by RCS pressure. The CMTs are prevented from injecting into the RCS during normal operations by fail-open air-operated valves in the CMT discharge lines which open on an actuation signal. The IRWST is isolated from the RCS by a check valve and squib valve in series in each IRWST discharge line.

21.1.2 Ultimate Heat Sink

The ultimate heat sink for core decay heat in the AP1000 is provided by the passive containment cooling system (PCS), which condenses steam released into containment on the inside surface of the steel containment shell. The steam can result from efflux from an RCS breach or a steamline break, or from boiling in the IRWST as a result of long-term passive residual heat removal (PRHR) operation. The condensate returns to the IRWST or to the containment sump and may be recirculated from either to the RCS if necessary.

21.1.3 Passive Residual Heat Removal System

The PRHR system cools the core in the event that heat removal via the steam generators is not available. The PRHR system, which can operate up to full RCS pressure, contains one heat exchanger (HX) tube bundle submerged in the IRWST. Water flows by natural circulation from one hot-leg through the HX and returns to one of the steam generator cold-leg channel heads. This system can also function with the reactor coolant pumps (RCPs) operating.

21.1.4 Automatic Depressurization System

The automatic depressurization system (ADS) consists of two independent sets of depressurization valves, arranged in four stages. The first three stages of each set are connected to the RCS at the top of the pressurizer and exhaust through pipes and a sparger into the IRWST where steam contained in the effluent is condensed. The fourth stage is connected to the hot-leg (one bank per hot-leg) and exhausts directly to the containment. The first stage of the ADS is actuated when the liquid volume of either of the CMTs reaches 67.5 percent full; timers are also actuated, which then control the opening of the second and third ADS stages. The fourth stage opens when either of the CMTs reaches 20 percent full.

Operation of the ADS is crucial to the performance of the passive safety injection systems. While the CMTs are connected directly to RCS cold-legs and operate at full RCS pressure, the gas pressure of the accumulators is approximately 4.8 MPa (700 psig), and the IRWST is at containment pressure and cannot drain into the RCS until the RCS pressure is reduced to less than approximately 0.1 MPa (14 psi) above containment pressure.

21.1.5 Unique Characteristics of the Passive Design

All active systems in the AP1000, such as the pumped normal residual heat removal system (RNS), the startup feedwater system, and the chemical and volume control system (CVCS), and including the diesel generators that provide onsite ac power, are classified as non-safety-related components. Thus, the AP1000 represents a significant departure from both the current generation of operating reactors and the "evolutionary" light-water reactors (LWRs) in its dependence on passive safety systems (as did its predecessor, the AP600 design).

Although passive systems may be conceptually simpler than conventional active systems, they are potentially more susceptible to system interactions that can upset the balance of forces on which passive safety systems depend for operation. In addition, with the exception of compressed-gas-driven accumulators, the industry has very little experience with these types of safety systems. The unique characteristics of these types of systems are explicitly recognized in the regulations governing the evaluation of standard plant designs. Specifically, in Title 10, Section 52.47(b)(2)(i)(A), of the Code of Federal Regulations [10 CFR 52.47(b)(2)(i)(A)], the NRC states that three requirements, among others, must be met for a standard design that differs significantly from those designs that are evolutionary changes from LWR designs of plants which have been licensed and in commercial operation before the effective date of 10 CFR Part 52, "Early Site Permits; Standard Design Certification; and Combined Licenses for Nuclear Power Plants," or a standard design that "utilizes simplified, inherent, passive, or other innovative means to accomplish its safety functions." These three requirements are:

(1) The performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof.

(2) Interdependent effects among the safety features of the design have been found acceptable by analysis, appropriate test programs, experience, or a combination thereof.

(3) Sufficient data exist on the safety features of the design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.

Pursuant to these requirements, a passive plant vendor must develop and perform design certification test programs of scope sufficient to cover the range of conditions described in Item 3 above. This includes both separate-effects and integral-systems experiments to provide data to assess the computer codes used to analyze plant behavior during such conditions.

To satisfy the requirements of 10 CFR 52.47(b)(2)(i)(A), the applicant developed test programs to investigate the behavior of the passive reactor and containment safety systems, including both component and phenomenological (separate-effects) tests and integral-systems tests. In this chapter, the NRC staff evaluates the capability of the AP1000 test programs, which include the test programs performed for the AP600, to satisfy these regulatory requirements.

For systems-related testing, the staff requested that the applicant submit, as a minimum, the following material for each test program:

- a test specification, describing the test facility, test objectives, and test matrix

- for those facilities testing scaled systems or components, a scaling report, demonstrating that the test facility met appropriate geometric and T-H similarity criteria, and that the data would cover a parametric phenomenological range comparable to that expected in the AP1000 plant

- one or more report(s) containing a record of data from all tests in the facility, an uncertainty/error evaluation of the test data, and analyses of selected tests (as approved by the NRC staff) demonstrating an understanding of the sequence of events and key phenomena influencing system (or component) behavior

The next section describes the major issues pertaining to passive safety system performance, which the applicant needed to address in the design certification testing programs. It then presents an overview of each test program, followed by a summary of the NRC's activities in reviewing each test program. The remainder of this chapter is devoted to individual evaluations of each program, a description and review of the applicant's code validation program, and the staff's determination regarding the compliance of the design certification test programs with the regulatory requirements previously described.

21.2 Issues of Concern

The safety systems in the AP1000 design represent the same plant safety system design concepts that the staff reviewed for the AP600 plant. Because they differ from the safety systems of operating plants, numerous questions and issues arose with regard to the performance of these unique components and systems. These issues ranged from relatively straightforward phenomenological questions to complex, system-related concerns. The staff identified the major issues related to each safety system during its AP600 design certification review, as described in NUREG-1512, Section 21.2, "Issues of Concern." The applicant resolved these issues through the AP600 test program, as discussed below. However, additional issues arose during the AP1000 review. These additional issues primarily relate to the increased scale and power density of the AP1000 systems compared to the AP600 systems that the staff reviewed and approved.

21.2.1 Core Makeup Tanks

The AP1000 has two CMTs, each with a volume of about 71 m^3 (2500 ft^3), which are initially filled completely with cold, borated water. The top of each tank is connected by means of a pressure balance line (PBL) to an RCS cold-leg; this connection maintains the tanks at RCS pressure. A discharge line connects the bottom of each tank to a direct vessel injection (DVI) line, which provides ECC flow to the vessel downcomer. In many transients and accidents, after the CMT discharge line isolation valves open, the CMTs begin to recirculate, with the cold, borated water flowing into the RCS being replaced by RCS water flowing up through the PBLs. When either RCS pressure or inventory is reduced to the point at which vapor is introduced into the PBLs, the recirculatory loop is broken and the CMTs begin to drain into the RCS. Specific issues related to CMT operation include the following:

- recirculation and gravity drain behavior, including condensation during draining
- thermal stratification in the CMTs
- effects of system depressurization on heated CMT behavior

The T-H response of the CMTs also affects the ADS. The first stage of the ADS is actuated when the water level in either of the two CMTs reaches a level corresponding to 67.5-percent volume, the subsequent two stages then actuate on timers, and the fourth stage actuates again on level, corresponding to 20-percent volume.

21.2.2 Automatic Depressurization System

The ADS comprises four stages of depressurization valves. The first three stages are connected to a piping network off the top of the pressurizer; the fourth stage is connected to the RCS hot-leg. There are two complete networks connected to the pressurizer and one fourth-stage assembly on each hot-leg. Each of the first three stages consists of two valves in series, an “isolation” valve, which opens first, and a “control” valve, which opens shortly thereafter. Effluent from the RCS travels through the pressurizer, exhausts into a pipe, and flows into the IRWST through a sparger.

Each fourth-stage assembly contains four valves, which are arranged in two parallel flow paths, each path with two valves in series. The two valves in series are again designated as “isolation” and “control.” Effluent from the fourth stage of ADS exhausts directly into the containment.

The following issues are important to ADS operation:

- ADS valve performance and reliability (discussed in Section 19.1.8.13 of this report)

- critical flow through the various components of the ADS network (valves, pipes, spargers), including transition from critical to subcritical flow

- the effects of condensation in the IRWST on ADS system performance, including mechanical and thermal loading on the IRWST and submerged mechanical components such as pipes, spargers, and HXs
- the severity of IRWST vibration due to ADS system performance (discussed in Section 3.8.3.3.1 of this report)

21.2.3 Passive Residual Heat Removal System

The main component of the PRHR system is the HX, comprising a C-shaped bundle of several hundred tubes. The bundle is completely submerged in the IRWST. The PRHR system can cool the RCS either by forced or natural circulation in the event of a complete loss of feedwater (main and startup) to the steam generators. The HX bundle is designed to remove about 2 percent of AP1000 full power using natural circulation, and about twice that amount using forced convection. Heat transfer on the inside (primary side) of the tubes is initially single-phase (liquid) convection, although during some accidents, steam may also enter the tubes after some time; heat transfer on the outside (IRWST side) of the tubes is either single-phase natural convection (liquid) or boiling, depending on the temperatures of the primary and IRWST sides. The main issues related to PRHR system operation follow:

- natural convection heat transfer in the tube bundle
- heat transfer on the IRWST side of the tubes, especially in two-phase flow, where critical heat flux and vapor blanketing of the tubes may be of concern

21.2.4 Interdependency of Systems

In addition to component and safety system performance on a system-by-system basis, there are systems interactions that must also be considered in the AP1000 design. The safety systems in the AP1000 design are highly interdependent in their influence on plant response. For instance, it is expected that during a small-break, loss-of-coolant accident (SBLOCA), a low pressurizer level or pressure signal will generate a safety injection (“S”) signal. CMT and PRHR discharge valves then open. The rate at which the RCS is cooled by the CMT and PRHR influences the depressurization rate, CMT recirculation and draining, and possibly accumulator injection. CMT level then actuates the ADS, which proceeds to reduce plant pressure to near containment pressure, ultimately allowing IRWST injection; the plant then makes a transition into long-term recirculatory behavior that also involves the PCS. Interactions may also occur if operators actuate non-safety-related active systems to attempt to cope with accidents. The close coupling between AP1000 safety systems and the multiple flow paths that can develop, especially with the small pressure differentials characteristic of natural circulation flows, makes the AP1000 a complex system to analyze. Consequently, it is necessary to understand integral-systems response over the entire pressure range of the AP1000 design, and to have data from such experiments of integral-system test on a system-wide basis, as well as component and phenomenological models developed from separate-effects tests. In some cases, behavior of the AP1000 design may parallel that of the AP600 design. In those situations where the ranges of the AP600 testing were directly applicable to AP1000 assessment, previous testing was considered for the AP1000 evaluation.

21.2.5 Application of Existing Models and Correlations

There are also issues related to the application of existing models and correlations to the operating, transient, and accident conditions that can exist in the AP1000. These issues are discussed in the following sections.

21.2.5.1 Departure From Nucleate Boiling

A specific area of interest involves models for the departure from nucleate boiling (DNB). Most DNB correlations are developed for limited ranges of T-H and geometric parameters, and the AP1000 DNB calculations cannot apply the correlations for conditions beyond those ranges.

The AP1000 core design uses fuel assemblies similar to the 17x17 robust fuel assemblies (RFAs) and 17x17 XL RFAs, which were developed from NRC-approved Westinghouse fuel designs, such as VANTAGE 5, VANTAGE 5 Hybrid, and the VANTAGE+ fuel design. All these designs have substantial design and operating experience associated with them. The DNB prediction for the RFA is done with the existing WRB-2M critical heat flux correlation. The WRB-2M correlation, described in WCAP-15025-P-A, “Modified WRB-2 Correlation, WRB-2M, for Predicting Critical Heat Flux in 17x17 Rod Bundles with Modified LPD Mixing Vane Grids,” was developed from Westinghouse rod bundle test data, which include 14-foot heated length, 17x17 fuel equipped with 0.95 cm (0.374 inch) outside diameter (O.D.) fuel rods, and modified low pressure drop (LPD) structural mixing vane grids, with or without modified intermediate flow mixer grids. In a letter from T. Essig (USNRC) to H. Sepp (Westinghouse), “Acceptance for Referencing of Licensing Topical Report WCAP-15025-P, ‘Modified WRB-2 Correlation, WRB-2M, for Predicting Critical Heat Flux in 17x17 Rod Bundles with Modified LPD Mixing Vane Grids,’ TAC No. MA1074,” December 1, 1998, the NRC staff has approved the WRB-2M correlation for predicting critical heat flux (CHF) in the modified 17x17 Vantage 5H fuel with or without modified intermediate flow mixer grids within specified applicability ranges of various parameters, including pressure, local mass velocity, local quality, heated length, grid spacing, and equivalent hydraulic and heated diameters.

Section 4.4.2.2 of this report describes the AP1000 DNB calculation. The WRB-2M is used for the analysis of the AP1000 RFA fuel within its ranges of applicability. The local mass velocity does not fall below the lower limit of the WRB-2M local mass velocity range of applicability for any of the AP1000 design-basis transients. Therefore, the existing Westinghouse rod bundle CHF test data adequately addresses the need for the DNB tests, and no additional DNB test is necessary for the AP1000.

21.2.5.2 Shutdown Operations

Since the test program focused on events occurring in conjunction with power operations, no testing was performed to deal specifically with the issue of shutdown events to validate the analysis codes for shutdown conditions. However, based on the following discussions, the staff concluded that no additional testing was needed specifically for shutdown conditions.

The AP1000 shutdown evaluation is described in AP1000 Design Control Document (DCD) Tier 2, Appendix 19E, “Shutdown Evaluation.” The non-LOCA transient code LOFTRAN-AP is not needed for AP1000 safety analyses during shutdown conditions because either (1) accidents that are normally analyzed (such as turbine trip or loss of feedwater) are not possible, or (2) the system response was bounded by full-power scenarios. The WCOBRA/TRAC and NOTRUMP codes, respectively, are used to analyze LOCA and loss of RNS cooling during shutdown conditions. However, the important phenomena associated with the AP1000 system response to these events are included in the AP1000 PIRTs described in WCAP-15613. The gravity drain phenomenon that is important for SBLOCA events remains important during shutdown. The existing test program used for validation of NOTRUMP and WCOBRA/TRAC has included all of the phenomena that are important to the analysis of the accidents that begin during shutdown. Accordingly, the staff concludes that the applicant’s test program adequately addresses the phenomena expected during shutdown conditions.

21.2.6 Summary

Each of the major areas described above has been addressed by testing in one or more experimental facilities, with the objectives of resolving the key issues and complying with the requirements of 10 CFR 52.47(b)(2)(i)(A). In Section 21.3 of this report, the staff describes each of the major AP1000 test programs.

21.3 Overview of Westinghouse Testing Programs

As summarized in Table 21-1 of this report, the major differences between the AP1000 and the AP600 plant designs are an increased thermal power (approximately 3,400 megawatt thermal (MWt) versus 1,933 MWt, respectively) and increased capacities of the major components of the AP1000 to accommodate the increased thermal output. In particular, the AP1000 reactor system has a taller reactor core with a longer active fuel length, more fuel assemblies, and higher power density; a larger pressurizer; larger SGs with more tubes and larger heat transfer areas; and larger canned RCPs with higher head, capacity, and inertia. In addition to a taller containment with a larger free volume, the capability of the AP1000 passive safety systems is increased with a larger CMT diameter; a larger IRWST and larger injection line diameters; a larger PRHR system with more tubes and longer tube length in the HX, and larger inlet and outlet line diameter; and larger valve and flow path diameters for Stage 4 of the ADS. Given these differences, the applicant asserted that the AP1000 design represents an incremental change to the AP600 design, because it maintains and preserves the design configuration and arrangement, key design features, and performance characteristics of the AP600 design. Consequently, the applicant concluded that the computer codes used for safety analyses of the AP600 design-basis events can be applied to the AP1000 design, and the AP600 test program is sufficient for the AP1000 design.

For the AP600 design certification, the applicant developed a design certification test program utilizing both separate-effects and integral-systems facilities to investigate the behavior of the

AP600 passive safety systems and to develop a database for the validation of the computer codes used to perform the transient and accident analyses. The test programs can be broadly characterized as programs that are related to reactor systems, programs that are related to containment systems, and component testing. The test program to investigate the behavior of the passive core cooling systems include (1) the separate-effects tests on the PRHR HX, ADS, and CMT; and (2) the integral system tests performed at the Advanced Plant Experiment (APEX) facility and the Simulatore per Esperienze di Sicurezza (SPES) facility. As described in Section 21.5 of this report, the staff evaluated the adequacy of each of the AP600 test programs for the AP1000 design, and concluded that additional test data were needed to address liquid entrainment in the upper plenum and hot-leg. As a result, the applicant added the APEX-1000 integral test program to the AP1000 test program.

Each test program is described briefly in this section. Except for the APEX-1000 integral test program, which is developed specifically for the AP1000, all test programs originally developed for the AP600 design are described in Section 21.3, “Overview of Westinghouse Testing Programs,” of NUREG-1512. For completeness, all test programs are described again here. Since most of the tests were performed at scaled test facilities, scaling analyses were performed to demonstrate the acceptability of the test data base. The staff’s detailed evaluation of each program is given in Section 21.5 of this report.

21.3.1 Core Makeup Tank Test Program

The CMT test program was a separate-effects test program developed to characterize the CMT over the range of T-H (pressure, temperature, flow) conditions that it will experience in the plant. Important phenomena studied included thermal stratification in the CMT and the effects of recirculation, draining, and plant depressurization on CMT behavior. Tests were performed at the facility located at the applicant’s Waltz Mill site in Pennsylvania. The test article was approximately 3.3 m (10 ft) in height and 0.49 m (1.6 ft) in diameter. Compared to the actual AP600 and AP1000 component, the test article was one-half of the height, and 1/7.77 and 1/8.69, respectively, of the diameters of the AP600 and AP1000 designs. The reactor vessel was simulated by a steam/water reservoir (SWR). The CMT test article was connected to the SWR by a pipe simulating the cold-leg/CMT PBL, which came directly off the SWR, and by a drain line, simulating the DVI line. The RCS cold-leg was not represented in this facility. A steam distributor of a design similar to that of the AP600/AP1000 CMT was installed in the upper head of the test article at the PBL nozzle.

The CMT test facility was capable of operating up to approximately 17.2 MPa (2500 psia) and 364 °C (688 °F). Data acquisition was accomplished using a personal computer (PC)-based data acquisition system (PC-DAS). The facility was equipped with the following instrumentation:

- thermocouples, including those to obtain detailed spacial measurements of CMT fluid and wall temperatures
- pressure transducers, including differential pressure transducers to measure CMT level

- flowmeters

The CMT test program began with cold preoperational tests in May 1993. The program proceeded though several series of tests. The “100” series investigated condensation of steam on the CMT walls, with and without the effects of noncondensable gases. The “300” series looked at mixing, condensation behavior, and CMT draining when steam was injected into cold water, such as might occur during a large SBLOCA or LBLOCA (i.e., no recirculation to heat the CMT water. The “400” test series was similar to the “300" series, but the system was depressurized gradually during the tests to assess the effect of changing pressure on the draining behavior. The final “500” series of tests included a period of recirculation between the SWR and the CMT to establish a desired temperature profile in the CMT. After the recirculation period, the SWR water level was reduced to allow steam to flow to the CMT, and the CMT was depressurized and drained. This series most closely represented conditions in the CMT expected during non-LOCA transients (CMT recirculation) and most SBLOCAs (recirculation, followed by draindown and depressurization). The test program was completed in September 1994.

WCAP-14217, “Core Makeup Tank Test Data Report,” and WCAP-14215, “AP600 Core Makeup Tank Test analysis,” respectively, provided the CMT test program final data report and test analysis report. The scaling of the CMT tests for the AP600 design were documented in WCAP-13963, Revision 1, “Scaling Logic for the Core Makeup Tank Test.” In topical report WCAP-15613, the applicant provided its evaluation to justify that the AP600 CMT test program is applicable to the AP1000 design.

The staff evaluated the CMT test program during the AP600 design certification review, as described in Chapter 21 of NUREG-1512. For the AP1000 design certification, the staff also evaluated its applicability to the AP1000 design. Based on the staff evaluation discussed in Section 21.5.2 of this report, the staff concluded that the CMT tests are valid for the AP1000 code validation.

21.3.2 Automatic Depressurization System Test Program

The ADS test program consisted of separate-effects tests performed at the facility called “VAPORE,” located at Central Research Establishment of Italian Energy Agency ENEA (Ente per le Nuove Technologie, l’Energia e l’Ambiente, the Italian Energy Agency) at Casaccia, Italy. It has a full-size configuration of the AP600/AP1000 ADS stages 1, 2, and 3 (ADS-1/2/3) piping network, exhaust pipe, and sparger. The tests consisted of two phases with somewhat different objectives. Phase A tests were performed for the ADS-1/2/3 with steam flow through a sparger into a larger water-filled tank to investigate the capacity of the ADS sparger in the IRWST and determine the dynamic effects on the IRWST structure. Parameters of interest are as follows:

- sparger flow and pressure drop
- tank T-H and structural response, including condensation, thermal stratification, and condensation-induced pressure loads on the tank walls

The second part, Phase B1, was a test of the T-H behavior of the ADS piping network that extends from the pressurizer into the IRWST. The test objective was focused only on the T-H behavior of the ADS valves, piping, and sparger. The main parameter of interest was the flow from the pressurizer to the simulated IRWST with various combinations of ADS stages open, including choking at various locations through the valve/piping/sparger network. The major T-H variable for these tests was the quality of the fluid entering the ADS network. Steam-only blowdowns were performed using a discharge line from the top of the steam-water supply tank. This discharge line contained a separator to remove entrained liquid. A discharge line was also provided from the bottom of the supply tank to obtain two-phase mixtures through the ADS network. A control valve in the bottom discharge line from the supply tank was adjusted to allow the flow to be varied from saturated liquid conditions to two-phase flow over a range of qualities. In addition, a series of tests was performed with cold water flowing through the valve/piping network to aid in determining the hydraulic characteristics of the valve/piping/sparger system under single-phase, non-choked conditions.

For Phase A, the actual test article was only the sparger, installed in the large water quench tank. Saturated steam was supplied to the sparger from a large supply tank.

The test facility was modified extensively for Phase B1. The supply tank, the large water quench tank, and the sparger were retained, and a piping network representing one complete group of ADS valves (stages 1, 2, and 3, with two valves in series per stage) was added. One ADS valve in each stage was represented by an actual valve. The other valve in each stage was represented by a spool piece containing an orifice to simulate the throat area and loss characteristics of various potential valve designs. Exhaust piping led from the ADS piping network to the same quench tank and sparger assembly used in Phase A. The ADS piping, the valves and simulated valves, and the sparger were full-size components, and could operate up to full AP600/AP1000 pressure. The facility was equipped with the following instrumentation:

- flowmeters
- pressure transducers
- thermocouples, including rakes in the simulated IRWST to measure stratification

Instrumentation to measure pressure loads and tank response in the IRWST were included. Data acquisition was accomplished using a computer-controlled PC-DAS.

The ADS test program is described in WCAP-13342 (“AP600 Automatic Depressurization System Test”) and the Phase A facility configuration is described in WCAP-14149 (“VAPORE Facility Description Report, AP600 Automatic Depressurization System Phase A Test”). The Phase B1 facility is described WCAP-14303, “Facility Description Report AP600 ADS Phase B1 Tests.”

Because the VAPORE facility incorporated full-scale components, a formal scaling report was not necessary for this test program. The Phase A program and selected test data are described in WCAP-13891 (“AP600 Automatic Depressurization System Phase A Test Data Report”).

Phase B1 of the ADS test program was documented in the final data report WCAP-14234, "LOFTRAN & LOFTTR2 AP600 Code Applicability Document," and the test analysis was documented in the final analysis report WCAP-14305, Revision 3, "AP600 Test Program ADS Phase B1 Test Analysis Report." The staff evaluated the ADS test program during the AP600 design certification review. For the AP1000 design certification, the staff also evaluated its applicability to the AP1000 design. Section 21.5.3 of this report discusses details of the staff's evaluation. Based on its evaluation, the staff concluded that tests performed to investigate ADS-1/2/3 valve performance for the AP600 design, which included a wide range of actuation pressures and flow qualities, are appropriate to represent conditions in the AP1000 standard plant design.

The applicant did not perform ADS-4 separate-effects testing for the AP600 design. The applicant stated that ADS-4 was treated/sized conservatively and tested as part of the integral-effects tests, and the applicant took the same approach for the AP1000 standard plant design. Sections 21.5.7.2 and 21.5.7.4 of this report discuss the staff's evaluation of the ADS-4 testing.

21.3.3 Passive Residual Heat Removal Heat Exchanger Test Program

The PRHR HX separate effect tests were performed at the applicant's Science and Technology Center near Pittsburgh before the staff began its review of the AP600 design certification testing. The objective of the PRHR test program was to generate data on heat transfer to be used in the design and characterization of the AP600 PRHR HX. The test article consisted of three vertical (straight) type 304 stainless steel tubes, approximately 5.49 m (18 ft) in length, with an outer diameter of 19.0 mm (0.75 in.) and wall thickness of 1.69 mm (0.0665 in.). The tubes were placed in a water tank approximately 1.2 m (4 ft) in diameter and 9.8 m (32 ft) tall, with a nominal water depth inside the tank of 7.3 m (24 ft) (this depth was varied as a test parameter). The tubes were placed in a straight line near a wall of the tank, with a center-to-center spacing of 38.1 mm (1.5 in.). A baffle was placed near the tubes, almost at the same height as the tank to limit natural convection flow around the tubes.

The PRHR facility could operate with primary (tube side) conditions up to full AP600/AP1000 pressure and temperature; the tank-side conditions were initially ambient, since the tank was not inside a building. However, the tank temperature could be varied by operating the HX tubes before the test to establish desired initial conditions. The facility was instrumented primarily with thermocouples to measure local temperatures and to determine heat transfer coefficients. Flow to each tube could also be measured.

WCAP-12980, Revision 3, "AP600 Passive Residual Heat Removal Heat Exchanger Test Final Report," described the PRHR test program, including full descriptions of the test facility, instrumentation, data collection procedures, and test matrices, as well as selected data. Since the HX tubes were nominally full length, no scaling report was submitted on this test facility.

The staff evaluated the PRHR test program during the AP600 design certification review, as described in Chapter 21 of NUREG-1512. The staff's evaluation focused on the applicability of the three-tube test data to a full-size HX and on the applicability of the straight-tube PRHR HX test data to the C-tube configuration. In order to gain additional confidence in the ability of the applicant's PRHR heat transfer model to calculate actual C-tube performance data, the staff provided selected data from the NRC's confirmatory test program in the Rig of Safety Assessment/Large-Scale Test Facility (ROSA/LSTF) loop, which employs a simulated C-tube PRHR HX of prototypic bundle dimensions (with approximately 1/30 the number of HX tubes) immersed in a tank of water simulating the IRWST. The data provided to the applicant included the PRHR HX inlet flow and inlet temperature, and the IRWST temperature profile, for two ROSA tests at several times in each test. The staff then asked the applicant to use this information to perform a "blind" calculation of the PRHR HX outlet temperature and tube temperatures at several locations along the length of the HX. The staff reviewed the applicant's calculations, and found that the applicant's correlation predicted tube and outlet temperatures within a few degrees of the data at all times and locations. Consequently, the staff concluded that the PRHR HX model does an adequate job of predicting PRHR HX tube and outlet temperatures, and that the applicant had demonstrated the adequacy of the straight-tube-based correlations for analysis of the C-tube PRHR HX.

As discussed in Section 21.5.4 of this report, the staff's evaluation of the effect of increasing the horizontal length of the AP1000 PRHR HX on the overall heat transfer has concluded that no additional PRHR separate-effects testing is needed for the AP1000.

21.3.4 Oregon State University/Advanced Plant Experiment (APEX-600) Test Program

The APEX-600 test program was a major integral test program conducted by the applicant for AP600 design certification. Tests were performed at a facility located on the Oregon State University (OSU) campus in Corvallis, Oregon. The objective of the test program was to obtain integral-systems data for the validation of computer codes used for AP600 safety analyses. Particular emphasis was placed on low-pressure and long-term cooling behavior in design-basis SBLOCAs.

APEX-600 was a low-pressure, one-quarter-height representation of the AP600 design, including the RCS and related components and all safety systems in direct communication with the primary system. Although containment cooling systems were not represented, the containment sump was simulated by two tanks. The "primary" sump tank simulated containment sump volumes from which fluid could be recirculated back to the RCS during the long-term cooling phase of a LOCA, and was connected to DVI lines. The "secondary" sump tank simulated volumes in the AP600 containment from which fluid could not be recirculated back to the RCS; fluid that entered the secondary sump was unrecoverable for long-term cooling, as would be the case in the AP600 plant. The volume scale of the facility was 1/192. The layout of the facility was similar to the AP600 design, with two cold-legs and one hot-leg per loop and vertically mounted reactor coolant pumps with no loop seals. In addition to the safety injection systems (CMTs, accumulators, and IRWST) and the four-stage ADS, the PRHR HX was simulated by a scaled HX bundle in the IRWST. The facility was instrumented with over 700 thermocouples, flowmeters, pressure transducers, and void detectors. Data were collected using three linked PCS that could record data and display real-time plots of selected channels.

WCAP-14124 (“AP600 Low Pressure Integral Systems Test at Oregon State University — Facility Description Report”) and WCAP-13234, Revision 1 (“Long-Term Cooling Test”), respectively, documented the facility design and test program specifications. An extensive scaling analysis was performed for the APEX-600 facility and documented in WCAP-14270, Revision 1 (“Low Pressure Systems Test Facility Scaling Report,” August 1997).

Tests were performed in 1994. Most of the test runs in the APEX-600 facility simulated design-basis accidents (DBAs) for the AP600, primarily SBLOCAs of various sizes and at different locations in the RCS. All of the tests included an extended period after the loop was fully depressurized to investigate integral system T-H behavior during injection from the IRWST, transition from IRWST to sump injection, and long-term recirculatory cooling from the simulated sump. The two major variables affecting system behavior were break size and location. Break size varied from (scaled) 12.7 mm (0.5 in.) to approximately 203 mm (8 in.). Break locations tested included the cold-leg, hot-leg, CMT pressure balance line, and DVI line. Other effects studied included interactions with non-safety-related systems and the effect of elevated containment pressure, which was simulated by increasing the pressure of the IRWST and sump tanks.

The staff evaluated the OSU APEX-600 test program during the AP600 design certification review, as described in Chapter 21 of NUREG-1512. For the AP1000 design certification, the staff also evaluated the applicability of the APEX-600 test program to the AP1000 design. As described in Section 21.5.7 of this report, the staff determined that the APEX-600 facility is generally appropriately scaled for the AP1000 design, and is acceptable for the AP1000 code validation for the periods of the IRWST injection/drain phase and the IRWST/sump injection phase of a transient. However, the staff also found that the APEX-600 test data were inadequate for use in the AP1000 code validation in the areas of liquid entrainment in the upper plenum and hot-legs, and core liquid level swell, and that additional test data were needed for the AP1000. As a result, the applicant added the APEX-1000 integral test program, which is described in Section 21.3.6 of this report.

21.3.5 SPES-2 High-Pressure, Full-Height Integral-Systems Test Program

The SPES-2 test program was the second integral-systems test program performed for design certification of the AP600. The objective of this test program was similar to that of the OSU APEX-600 program (i.e., acquisition of integral-systems data for the validation of computer codes used to perform AP600 safety analyses). Unlike the APEX-600 facility, however, SPES-2 could operate at pressures and temperatures up to prototypic AP600/AP1000 values and was approximately full vertical scale. Because of this unique capability, tests in SPES-2 focused primarily on integral system behavior in the period from accident initiation (at prototypic pressure and temperature and scaled full power) to the establishment of stable injection from the IRWST. The test matrix included a range of SBLOCAs from scaled 25 mm (1 in.) cold-leg breaks to double-ended guillotine breaks of a DVI line and a CMT balance line. In addition, non-LOCA transients were simulated in SPES-2, including single steam generator tube ruptures (SGTRs) and a main steamline break. Other parameters tested included interactions with non-safety-related systems (cold-leg SBLOCA and SGTR) and inadvertent actuation of the ADS during an SGTR event. Tests were performed at the facility located at the Societa' Informazioni Esperienze Termoidrauliche (SIET) laboratories in Piacenza, Italy, in 1994.

SPES-2 was a full-height representation of the AP600 design. The volume scale was approximately 1/395. However, SPES was not designed from the beginning as an AP600 test facility. Rather, SPES-2 was a modification of the existing SPES-1 facility, which represented a 1/427-volume-scale of a Westinghouse three-loop PWR. As a result, some distortions and atypicalities existed in SPES-2 compared to the AP600/AP1000 design. The most significant of these were as follows:

- SPES-2 had only one pump per loop, rather than the two pumps per loop of the AP600 and AP1000, so that outlet flow from (or through) the pump had to be split between the two cold-legs.

- SPES-2 had an external piped downcomer, rather than an annular downcomer. The design was modified, however, so that there was an annular section at the top of the simulated reactor vessel, which then fed into the piped downcomer below the elevation of the DVI lines.

- SPES-2 had a much larger surface-area-to-volume ratio than the AP600. This caused distortions in two ways. In the initial stages of a transient, high heat losses occurred. This was compensated by increasing the rod bundle power during the period from accident initiation to the beginning of ADS blowdown. In the later stages of a transient, the effect was reversed, and excessive heat input to the system occurred from the structure. To relieve the excess steam resulting from this effect, the vent area of the simulated ADS-4 valves in SPES-2 was significantly larger than its nominal scaled (1/395) value, to achieve a depressurization rate calculated to be approximately the same as in the AP600 design.

All AP600/AP1000 safety systems were represented, including CMTs, accumulators, IRWST injection, four-stage ADS, and the PRHR system, in which the PRHR HX was simulated by three C-tubes in the IRWST tank. (For most tests, only one of the three C-tubes was used.) Sump recirculation was not simulated in the SPES-2 loop. The facility contained over 300 instruments, including thermocouples, flowmeters, pressure transducers, and void instrumentation. Data were collected using a computer-controlled PC-DAS.

The SPES-2 test program was documented in several reports, including WCAP-13277 ("Scaling, Design, and Verification of SPES-2, the Italian Experimental Facility Simulator of the AP600 Plant"); WCAP-13277, Revision 1 ("Scaling, Design, and Verification of SPES-2, the Italian Experimental [sic] of the AP600; Scaling Update"); WCAP-14053 ("AP600 FHFP Integral Systems Test Specification"); and WCAP-14073 ("SPES-2 Facility Description").

Cold preoperational testing in the SPES-2 facility began in May 1993; matrix testing began in February 1994 and was completed in November 1994. The final data report and the test analysis report for the SPES-2 program are contained in WCAP-14309, Revision 1, "AP600 Design Certification Program SPES-2 Tests Final Data Report," and WCAP-14254, "AP600 SPES-2 Test Analysis Report," respectively. Pre-test predictions of the SPES-2 tests were also performed by Ansaldo for the applicant. However, these predictions were performed with the RELAP5/MOD3 computer code, rather than with any of the codes that the applicant qualified for design certification analyses.

The staff evaluated the SPES-2 test program during the AP600 design certification review, as described in Chapter 21 of NUREG-1512. For the AP1000 design certification, the staff evaluated the applicability of the SPES-2 test program to the AP1000 design. Section 21.5.7 of this report describes the staff's scaling assessment, which concludes that code validation on the basis of the SPES facility is acceptable for the AP1000 design for a small-break LOCA in the subcooled blowdown phase, intermediate ADS-1/2/3 blowdown phase, and the high-pressure phase of ADS-4 blowdown.

21.3.6 OSU APEX-1000 Test Program

The OSU APEX-600 integral system test facility was designed and used to assess the passive safety systems for the AP600 design. As described in Section 21.3.4 of this report, the staff found that the APEX-600 test data were inadequate for use in the AP1000 code validation in the areas of liquid entrainment in the upper plenum, hot-legs, and ADS-4 piping, and that additional test data were needed for the AP1000. To address performance specific to the AP1000 design, the APEX-600 facility underwent significant modifications in 2002 to more accurately represent the AP1000 design and was renamed the APEX-1000 Test Facility. Like APEX-600, the APEX-1000 is a low-pressure, 1/4-height representation of the AP1000 design. The applicant submitted two topical reports describing the APEX-1000 facility and the basis for its scaling. The details of the APEX-1000 test facility, including the modifications from the original OSU APEX facility, are described in the report OSU-APEX-03002, "OSU APEX-1000 Test Facility Description Report." Topical report OSU-APEX-03001, "Scaling Assessment for the Design of the OSU APEX-1000 Test Facility," describes the scaling analysis performed to guide the OSU APEX-1000 test facility modifications.

The facility modifications include an increase in the maximum core power, a larger pressurizer and reduced surge line diameter, and larger CMTs. The ADS Stage 4 was replaced with appropriate sized valves and piping, and the line resistances between the CMT and vessel, and through the PRHR were likewise reduced consistent with the AP1000 design. Table 21.3.6-1 summarizes changes made to the APEX facility for AP1000.

Table 21.3.6-1 Modifications to APEX for AP1000 Test Program

Component	**Modifications to APEX-600**
Reactor Power	Increase core power by 67 percent (to nearly 1 MW).
Pressurizer	Increase pressurizer volume. Reduce pressurizer surge line diameter.
SG Heat Transfer Area	No change required for testing.

Component	Modifications to APEX-600
RCP Flow	No change required for testing.
CMTs	Increase CMT volumes by 25 percent. Reduce line resistance by 64 percent.
Accumulators	No change required for testing.
IRWST	Increase initial IRWST level for testing.
ADS Stages 1-3	No change required for testing.
ADS Stage 4	Increase ADS-4 flow area by 76 percent. Reduce line resistance to 28 percent of original.
PRHR	Increase PRHR flow capacity by 74 percent. No change in heat transfer area.
Containment	Increase sump curb height.

Not all components in APEX were modified even though corresponding changes were made to the plant design from AP600 to AP1000. For example, the AP1000 steam generators, with 11477 m^2 (123,538 ft^2) of heat transfer area, are substantially larger than the AP600 steam generators, with 6984.5 m^2 (75,180 ft^2). No changes were made to the APEX steam generators, since the tube volume is small compared to the volume of the rest of the primary system and the generators are oversized for the decay power involved in testing. That is, the existing APEX steam generators have more heat transfer area than is necessary to remove decay heat. An increase in the pump capacity was not necessary because the pumps are tripped at the start of each transient, and their main contribution thereafter is their resistance, which was preserved. Therefore, it was neither important nor necessary to modify these components for AP1000 testing in either case.

The upper core plate and upper plenum of APEX were redesigned in order to improve the modeling of upper plenum entrainment and core plate flooding, and to account for differences between the AP600 and AP1000 designs. In the AP1000, in order to accommodate the higher core power, twelve additional fuel assemblies were added to the AP600 core design. These assemblies were positioned at the outer edge of the core, with some of the new assemblies placed just below the two hot-leg nozzles. In the APEX-1000, additional holes were place in the upper core plate to capture the localized jetting of steam flow at these locations. The upper core plate design utilized a hole pattern so that drainage from the upper plenum to the core was preserved.

Since there were numerous changes made to APEX-600 in development of the APEX- AP1000 facility, scaling analyses were conducted by both the applicant and the staff to ensure that the appropriate modifications were made, and that the APEX-1000 facility was a reasonable representation of the full scale prototype. Special emphasis was placed on scaling upper plenum entrainment, since this had been identified as a nonconservative distortion in the APEX-AP600 facility for application to AP1000 design.

Testing in the APEX-1000 facility began in 2003, with several integral experiments sponsored by the U.S. Department of Energy to investigate performance of AP1000 passive safety systems at DBA conditions. The NRC also conducted confirmatory tests on T-H processes for which data from the APEX-600 series of tests were not adequate.

The APEX-1000 integral test series performed for simulation of the DBAs includes simulations of (1) two tests of a double-ended guillotine break of the DVI line (DEDVI) with a single failure of one ADS-4 valve on the nonpressurizer side before and after modifications to the ADS-4 piping and valves, respectively, (2) a DEDVI break with failure of one ADS-4 valve on the pressurizer side, and (3) two tests of a 2-inch cold-leg break with a single failure of one ADS-4 valve at 2.65 MPa (370 psig) and 0.96 MPa (125 psig), respectively. The test results are documented in test summary reports OSU-AP1000-01, OSU-AP1000-02, OSU-AP1000-03, OSU-AP1000-04, and OSU-AP1000-05, respectively. The applicant also uses the DEDVI break test runs (test runs DBA-02 and DBA-03) to benchmark the NOTRUMP computer code, which is the code used for SBLOCA design-basis analyses. This is documented in Appendix E in WCAP-15644-P, Revision 2.

Section 21.5.8 of this report describes the staff evaluation of the APEX-1000 test program.

21.3.7 Wind Tunnel Test Program

One of the principal design objectives for the PCS was that the external wind conditions should not resist the buoyant airflow in the annular region between the containment vessel and the baffle wall. Counterflow in this region could diminish the natural convective cooling, which constitutes a portion of the total heat removal from the postaccident containment atmosphere. The containment can be characterized as either wind-neutral, wind-positive, or wind-negative, depending on whether external winds have no effect, assist, or hinder buoyant flow in the annulus. To better understand the effects of adverse weather conditions, severe terrain, adjacent structures, and building design variations on the airflow within the annulus, the applicant conducted a series of wind tunnel tests on scale models of the AP600 containment.

The wind tunnel tests consisted of four phases, 1, 2, 4A, and 4B (there were no Phase 3 tests), each with the following objectives:

- Phase 1—Determine the effect of external winds and external structures on the flow around the containment and in the annulus, and determine any modifications to the design necessary for better wind neutrality.

- Phase 2—Determine the flow-induced loads on the baffle wall separating the shield building and the containment building, and investigate the effects of a cooling tower and various chimney designs on flow within the annulus.

- Phase 4A—Study the sensitivity of the tests to the wind tunnel Reynolds (Re) number, to further examine the effects of a hyperbolic cooling tower on flow in the annulus, and examine the effects of a tornado velocity profile on flow in the annulus.

- Phase 4B—Examine the effects of severe terrain on flow in the annulus and on baffle wall loading.

The final data for all test phases can be found in WCAP-13294-P, "Phase I Wind Tunnel Testing for the Westinghouse AP600 Reactor"; WCAP-13323-P, "Phase II Wind Tunnel Testing for the Westinghouse AP600 Reactor"; WCAP-14068-P, "Phase IVA Wind Tunnel Testing for the Westinghouse AP600 Reactor"; and WCAP-14091, "Phase IVB Wind Tunnel Testing for the Westinghouse AP600 Reactor." PCS-T2C-059, "Analysis of AP600 Wind Tunnel Testing for PCS Heat Removal," includes an analysis of the test data.

21.3.7.1 Test Models—Phases 1 and 2

The Phase 1 tests used 1:96.67 scale models of the containment shield building and its surrounding structures, including the turbine building and a hyperbolic cooling tower. The complete model assembly was located on a turntable which simulated different wind directions. The height of the turbine building was adjustable.

The Phase 2 tests used the same models as those used in Phase 1, with the exception of the following two modifications:

(4) The modeling of the flowpath between the shield building and the containment vessel included the baffle wall.

(5) A second chimney design, in addition to the Phase 1 design, was investigated.

For both the Phase 1 and Phase 2 tests, the flow in the wind tunnel represented a turbulent boundary layer and corresponded to American National Standards Institute (ANSI) A58.1, "Minimum Design Loads for Buildings and Other Structures," exposure category C, as documented in WCAP-13323-P. This exposure category is typical of open terrain with scattered obstructions generally less than 9.14 m (30 ft) in height, and includes terrains such as flat regions, open country regions, and grasslands (American National Standard A58.1-1982, pp. 12-16).

21.3.7.2 Test Matrix—Phases 1 and 2

Phase 1 tests were conducted to determine the optimal inlet vent configuration for a wind-positive or wind-neutral design, and to investigate the effects of the turbine building, cooling tower, and chimney height on flow in the annulus. The tests also examined the effects of a chimney cap and deaerator. To characterize the flow, the applicant measured the pressure at selected circumferential locations at the inlet to the annulus and at the outlet of the chimney, and calculated a pressure difference. The test reports express this pressure difference, which represents the driving force for wind-induced flow, as a dimensionless pressure coefficient.

In the Phase 2 tests, the applicant determined the baffle wall loads by measuring the differential pressure across the baffle. As in the Phase 1 tests, the applicant determined the inlet-minus-chimney pressure difference. They also performed flow visualization studies to determine the flow characteristics in the annulus.

The Phase 1 test report presented data in the form of pressure coefficients for various inlet vent configurations, adjacent building configurations, and wind directions. Data presented from the Phase 2 tests consisted of plots of pressure coefficients versus wind direction for various chimney/top configurations. Note that for all test phases, wind angles of attack varied from 0° to 360°. Table 21.3-1 of this report provides a summary of the test matrix.

Table 21.3-1 Wind Tunnel Test Phases 1 and 2 Matrix

Test Configuration	Phase 1	Phase 2
Turbine building elevation varied	Yes	No
Effect of cooling tower tested	Yes	Yes
Chimney height varied	Yes	No
Chimney cap and deaerator tested	Yes	No
Different chimney designs tested	No	Yes
Inlet-chimney ΔP measured	Yes	Yes
Baffle ΔP measured	No	Yes

21.3.7.3 Test Models—Phases 4A and 4B

The Phase 4A tests were comprised of three subtests which addressed tornado wind loading, the effects of a cooling tower, and the sensitivity of Phase 1 and Phase 2 test results to the wind tunnel Reynolds number. Each subtest included various combinations of models and wind tunnels.

Tornado Wind Loadings—Phase 4A

The Phase 4A tests to study tornado wind loadings used the same 1:96.67 model as that used in the Phase 1 and Phase 2 tests. The tests were performed at the University of Western Ontario (UWO) boundary layer wind tunnel. Modifications to the model used in the Phase 1 tests involved the addition of circumferential rings of pressure taps at the following locations:

- the exterior of the main building at two-thirds the height of the inlets
- the main building exterior just below the inlets
- directly inside the inlet manifold
- half-way up the exterior of the chimney
- the top of the containment annulus

Effects of the Cooling Tower—Phase 4A

The same 1:96.67 model was used to investigate the effects of the cooling tower. However, these tests were conducted in the National Research Council of Canada's 9.14 m x 9.14 m (30 ft x 30 ft) wind tunnel in Ottawa, Canada.

Effects of High Reynolds Number—Phase 4A

A 1:30 scale model was chosen to achieve the highest Reynolds number possible. This allowed the applicant to study the effects of a high Reynolds number on the results. The model was not capable of being rotated and did not include internal flowpaths. The tests were performed at the National Research Council of Canada's 9.14 m x 9.14 m (30 ft x 30 ft) wind tunnel in Ottawa, Canada.

Effect of Severe Terrain—Phase 4B

The Phase 4B tests investigated the effect of severe terrain on baffle wall loads. These tests used a 1:800 scale model of the containment and surrounding buildings. This scaling allowed a large area of terrain to be included in the proximity of the plant. The complete assembly was placed on a turntable and could be rotated to investigate the effects of different wind azimuths.

As in the Phase 1 and Phase 2 tests, both wind tunnels used a scaled boundary layer wind profile corresponding to ANSI A58.1 exposure category C.

21.3.7.4 Test Matrix—Phase 4A

The tests conducted at the UWO facility represent the most complete set of data from all of the Phase 4A tests. Data taken from the Phase 4A tests conducted at the National Research Council of Canada's facility were primarily obtained to address concerns with the UWO data regarding Reynolds number scaling, and to determine if any adjustments to Phase 1 and Phase 2 tests were necessary.

Data collected in all of the Phase 4A tests included air inlet and outlet pressure measurements and the pressure difference across the baffle wall. For the Phase 4A, 1:96.67 scale tests at UWO, data were taken for a full range of wind speeds and azimuths, including those representative of tornado conditions, to determine the design-basis loading of the baffle wall. The Phase 4A, 1:30 scale tests were conducted over a range of wind speeds, up to the maximum attainable in the wind tunnel. Table 21.3-2 of this report summarizes the Phase 4A test matrix.

Table 21.3-2 Wind Tunnel Test Phase 4A Matrix

Configuration/ Effect Modeled	**Phase 4A 1:96.67, National Research Council**	**Phase 4A 1:96.67, Univ. of Western Ontario**	**Phase 4A 1:30, National Research Council**
Surroundings	Yes	Yes	No
Cooling tower	Yes	No	No
Chimney	Opened/closed/ roughened/smooth	Closed/smooth/ roughened	Closed/smooth/ roughened
No. of azimuths	2	Full 360°	1
No. of speeds	3	1	6
Tornado	No	Yes	No

21.3.7.5 Test Matrix—Phase 4B

The Phase 4B tests measured pressures around the throat and in the wake of the cooling tower to determine the effects of severe terrain on flow in the annulus and around the containment building. The applicant also measured wind speeds in the wake of the cooling tower. The wake characteristics taken during the Phase 4A tests were later used to determine the placement of the cooling tower for the Phase 4B tests.

Tests were performed using the following configurations:

- the base case, which consisted of a complete AP600 plant model and one cooling tower
- the base case with two cooling towers
- the base case with a nearby escarpment
- the base case with an escarpment and mountain backdrop
- a river valley with a mountain backdrop, another mountain on the other side of the shield building, and with a filled-in escarpment
- a river valley with two cooling towers

21.3.7.6 Scaling Validation Tests

WCAP-12394, "SPNOVA-A Multi-Dimensional Static and Transient Computer Program for PWR Core Analysis," presents the results of validation tests which show that the aerodynamics in the range from the model to full scale were not significantly affected by the Reynolds number. The Reynolds number affects where flow separation will occur, thereby affecting the pressure on the structure. These tests were necessary because achieving strict dynamic similarity between the model and the AP600 necessitated wind tunnel speeds at which compressible flow phenomena become important, adding considerable complexity to the problem of modeling the flow around the model. To remove the necessity of matching the Reynolds number, the flow separation points in the full and model scales were matched by roughening the model surface. The applicant wished to show that the pressure variation versus wind speed was considerably less for a roughened model surface than for a smooth model surface and, therefore, there were few Reynolds-number-induced effects in the roughened model. The amount of surface roughening was found by determining a relative roughness for the model based on knowledge of the full-scale Reynolds number.

Results from the tests of the smooth and roughened models showed that the pressure varied 10–30 percent less with wind speed for the roughened model, with fluctuations in pressure of less than 12 percent. The test report interpreted this result as an indication that the effects of the Reynolds number were significant for a smooth model. Consequently, roughening was necessary to minimize these effects. The applicant further concluded that only chimney roughening was necessary. Any residual effects, as a result of the Reynolds number, would amount to a maximum of 20 percent of the pressure fluctuations.

WCAP-13323-P outlines the applicant’s approach to scaling the wind tunnel test data to the full-scale AP600. This approach used dynamic pressures scaled to the height of the AP600 inlet vents to determine design loads for a number of design wind speed cases. The report also provided sample calculations. In addition, the report addressed the following wind cases:

- fastest mile wind speed in ANSI exposure category C
- fastest mile wind speed in ANSI exposure category D (less gusty than exposure category C)
- probable maximum hurricane speed
- tornado speeds

The applicant modeled flow losses in the model annulus by matching, at various points in the flowpath, loss coefficients in the model with losses representative of the AP600. Because no full-scale test data were available to determine the AP600 loss coefficients, the applicant used coefficients determined from tests conducted with a 1/6-scale, 14° sector model.

21.3.7.7 Assessment of Wind Tunnel Test Program to the AP1000

The important features of the PCS design in the AP1000 ARE identical to the PCS design in the AP600. These features include the air inlets near the top of the containment structure and the baffle region, including the turning vane. Only the height of the containment has changed. Therefore, the staff considers these test to be applicable to the AP1000 and the insights and data used to develop WGOTHIC models remain acceptable.

21.3.8 Large-Scale Passive Containment Cooling System Test Program

The PCS Large-Scale Test (LST) Program investigated anticipated T-H phenomena in a large-scale facility. WCAP-14135, Revision 1, “Final Data Report for PCS Large-Scale Tests, Phase 2 and Phase 3,” Revision 1, issued April 1997, states the following:

> The purpose of the passive containment cooling system (PCS) heat transfer test was to examine anticipated T-H phenomena on a large scale: the interior natural convection and steam condensation, the exterior water film evaporation, air cooling heat removal, and water film behavior. This experiment is designed to induce similar containment dome heat transfer processes and circulation/stratification patterns inside containment as in the AP600; however it is not meant to simulate specific AP600 accident scenarios. The large scale test data is used to validate the WGOTHIC computer code, which will be used to analyze the AP600 containment.

21.3.8.1 Test Objectives

The LSTs were conducted in three phases with the following objectives:

- Phase 1—These baseline tests were performed at constant pressure conditions to investigate the effect of different levels of water coverage, various external airflow rates, and the presence of internal structures on containment heat removal.

- Phase 2—These tests were conducted to validate heat and mass transfer correlations over a range of prototypical internal conditions. The tests also examined transient heat transfer, the distribution of noncondensable gases, and the effect of noncondensable gases on heat transfer.

- Phase 3—These tests examined the effects of break location and noncondensable concentration on mixing in the vessel and on overall heat removal. These tests were to aid in the overall understanding of the containment cooling phenomena.

The applicant has completed all planned phases of the LST Program and submitted test data reports. WCAP-13566, “AP600 1/8th Large-Scale Passive Containment Cooling System Heat Transfer Baseline Data Report,” issued October 1992, documents the baseline tests. WCAP-14135, “Final Data Report for PCS Large-Scale Tests, Phase 2 and 3,” issued July 1994, documents the Phase 2 and Phase 3 tests. These reports contained primarily test data, and did not provide any evaluation or interpretation of the test results. The applicant, in letter NTD-NRC-95-4463, dated May 15, 1995, submitted “AP600 Testing Program Report: Large-Scale Test Data Evaluation (PCS-T2R-050),” which evaluated and interpreted the test results.

Testing and Computer Code Evaluation

The applicant's evaluation of the large-scale PCS test data yielded the following information and conclusions:

- Evaporation was the primary mode of heat removal from the outside of the vessel (approximately 75 percent of the total), followed by sensible heating of the subcooled liquid film (approximately 17 percent of the total). The remainder of the heat was transferred to the environment by convection and radiation.

- The heat removal rate was proportional to the film area in the quadrant-coverage cases, but had a weak dependence on the coverage area in the striped-coverage cases. For the same film coverage area, striped coverage provided better heat removal than quadrant coverage.

- The heat removal rate appears to be more strongly dependent on ambient air temperature than on initial liquid film temperature.

- The heat removal rate has a relatively weak dependence on annulus air velocity, which indicates that the resistance to heat transfer on the inside of the vessel is greater than on the outside, for the conditions tested.

- For all of the wetted, large-scale tests (except the horizontal, high-velocity steam jet injection case), the highest heat fluxes occurred near the top of the dome at the elevation at which the external film was applied. Although the dome represents about 30 percent of the heat transfer surface area, approximately 40 percent of the total heat removal occurred on the dome and 60 percent on the cylindrical sidewalls.

- Injection of low-velocity steam resulted in relatively good mixing above the injection location, but stratification occurred below this location, causing air to be concentrated below the operating deck. The heat removal flux (or rate per unit area) increased as the axial steam concentration gradient was increased (by raising the injection location).

- Injection of high-velocity steam resulted in a well-mixed vessel (both above and below the operating deck).

- Injection of a light, noncondensable gas did not degrade the condensation heat transfer or affect the overall heat removal. The gas did not stratify (collect at the top of the vessel), but was well mixed above the injection location, and was eventually well mixed throughout the entire vessel.

21.3.8.2 <u>Test Facility</u>

The LST facility was located at the Westinghouse Science and Technology Center in Churchill, Pennsylvania. The vessel used in all test phases was a 1/8-linear-scale version of the actual AP600 containment vessel. It was constructed of steel, with a height of approximately 6.09 m (20 ft), a diameter of 4.57 m (15 ft), and a shell-wall thickness of 2.2 cm (0.875 in.).

A transparent plexiglass shell surrounded the containment vessel to form a 7.6 cm (3 in.) annular cooling air flowpath. Air enters the annulus at an elevation near the simulated operating deck level. An axial fan was mounted at the exit of the annulus to establish prototypic airflow velocity in the riser. For the Phase 2 and Phase 3 tests, the axial fan speed was set to a predetermined value to establish an airflow rate in the LST riser section typical of that expected in the prototypical AP600. The LST did not model the downcomer portion of the AP600 PCS. Section 21.5.10 of this report discusses the lack of a downcomer region.

Water was applied to the external surface of the containment vessel by a water distribution system consisting of four independently controlled sectors of inverted J-tubes. The system delivered water to the containment dome at two radial locations. The flow rate was adjustable to allow investigation of water film striping effects. The delivery system geometry used in the LST differed from that used in the prototypical plant design. In addition, the plant delivery system is gravity feed while the LST water delivery system was tied to the municipal water system. The LST water delivery system tended to provide a fluctuating flow rate for most tests. A predetermined valve position was set at the start of a test, based on unheated surface tests and the target water coverage condition was set prior to the test run as specified in the test matrix. Of the 13 priority tests (analyzed with WGOTHIC in WCAP-14382, "WGOTHIC Code Description and Validation," issued May 1995), only 6 (including 2 dry tests which started with a dry surface instead of the target water coverage) achieved the target water coverage condition of 75 percent. In all but one of the remaining tests, the actual coverage was higher. In one test, the coverage was well below the target condition.

Superheated steam was supplied at a controlled pressure to the steam generator compartment below the operating deck of the interior of the test vessel. A flow distributor was used to provide low-velocity steam at a height scaled to that of the actual AP600 operating deck. In some tests, the steamflow was too low to be measured with the existing instrumentation. In these cases, post test analysis of the condensation collection data determined the steam boundary condition for use in the WGOTHIC analyses of these tests. The blind test (LST test 220.1) was one such case.

Gutters mounted around the inner circumference of the vessel collected condensed steam from the inner surface of the test vessel dome and sidewall. The condensate drained into a handling system that measured the mass of the liquid collected. In addition, there were four other condensate collection points. The five collection points included the following:

(1) inside surface sidewall condensate discharge system
(2) polar crane girder condensate discharge system
(3) rainfall condensate discharge system
(4) inside vessel condensate discharge system (below deck)
(5) steam generator compartment condensate discharge system

Certain LST Phase 1 (baseline) tests included internal partitions to model open, closed, and steam generator volumes below the operating deck.

Vertical communication existed between these open volumes and the area above the operating deck, while the closed areas consisted of dead-end spaces with one entrance and no exit. The off-center steam generator compartment, into which steam was injected, communicated vertically with the test vessel volume above the operating deck. However, unlike the prototypical AP600 configuration, this compartment did not communicate with other compartments below the operating deck. Therefore, it is difficult to directly assess global natural circulation and below-deck behavior in the prototypical AP600 on the basis of the LST tests. The applicant addressed this distortion in WCAP-14845, Revision 3, "Scaling Analysis for AP600 Containment Pressure During Design-Basis Accidents," issued March 1998, and it is further discussed in Section 21.6.5.5 of this report.

To study the effect of hydrogen generation and distribution in the Phase 2 and Phase 3 tests, helium was injected into the vessel through a port in the steam-supply line near the bottom of the vessel. Instrumentation was supplied to monitor and measure the parameters of interest. Table 21.3-3 of this report provides an instrumentation summary.

Table 21.3-3 Large-Scale Test (LST) Facility Instrumentation

Parameter Measured	**Instrument**
Steamflow	Vortex shedding flow meter, variable orifice flow meter, rate of condensate collection
Steam inlet pressure	Pressure transducer
System pressure	Pressure transducer
Wind speed/direction	Anemometer/weather vane
Cooling water flow (on- and off-shell)	Magnetic flow meter
Annulus differential pressure	Pressure transducer
Internal velocity	Pacer and Höntzsch anemometers
Internal fluid temperatures	Thermocouple rake
Vessel wall temperatures	Thermocouples
Gas sampling	Sample tube and sample bomb
Annulus wall temperatures	Thermocouples
Annulus airflow and temperature (inlet/outlet)	Anemometers and radiation shielded thermocouples

21.3.8.3 Modeling of Internal Heat Sinks

Heat sinks in the containment consist of equipment and structural materials, and can be divided into short-term sinks, with relatively small time constants, and long-term sinks, with a relatively slow response to thermal transients and larger time constants. The modeling of internal heat sinks in the Phase 1 (baseline) tests consisted of the steel superstructure which supports the subcompartment partitions and operating deck grating. The Phase 2 and Phase 3 tests included these subcompartment partitions. They also used 0.975-cm- (0.375-in.-) thick aluminum plates installed in the open and dead-end compartments to more realistically simulate the short-term heat absorption of the AP600 equipment and structures. Since this region (below the operating deck) in the AP1000 is similar in design and contains similar heat structures, the short-term heat sinks in the LST were also representative of the AP1000 design. The modeling of long-term heat sinks in the LST was accomplished by removing portions of the insulation surrounding the open and dead-end volume compartments near the bottom of the vessel. This was done to study the effects of the heat sinks on the distribution of noncondensable gases within the vessel.

21.3.8.4 Test Matrix

Table 21.3-4 of this report summarizes the tests and target conditions covered by the test matrix. Sixteen Phase 1 (baseline) steady-state tests were performed at three constant pressures of 170, 308, and 377 kPa (10, 30, and 40 psig). The effects of water coverage, external airflow, and internal structures on heat removal were investigated.

Table 21.3-4 Large-Scale Tests and Target Conditions

Test Configuration	**Phase 1**	**Phase 2**	**Phase 3**
Number of tests	16	24	10
Internals modeled	Partially	Yes	Yes
Steam pressure varied	Yes	Yes	Yes
Steamflow rate varied	No	Yes (includes modeling of transients)	Yes (includes modeling of transients)
Annulus airflow varied	Yes	No	No
Helium added	No	Yes	No
Water coverage varied	Yes (75% to full)	Yes (50% to full)	No (75%)
Blowdown modeled	No	Yes	Yes (steam discharge point varied)
Effect of noncondensable gases	No	Yes	Yes (amount of air varied)

Twenty-four Phase 2 tests included both steady-state and transient investigations, and spanned a range of operating parameters (noncondensable gas concentration, steamflow, and steam pressure) sufficient to validate the ability of WGOTHIC to predict the containment temperature and pressure response to a DBA. External water flow rates were intended to represent those expected for the AP600. The airflow in the annulus was not varied.

Ten Phase 3 tests studied the effects of rapid pressurization, steam discharge location, and initial vessel air pressure on condensation mass transfer. Tests conducted at pressurized and evacuated initial conditions studied the effect of noncondensable gases.

21.3.8.5 Scaling

The applicant performed a number of experiments to obtain data to qualify the WGOTHIC computer program for performing containment design calculations. The most significant test for the WGOTHIC computer program validation was the LST, which was the only integral systems test of the PCS. Section 21.6.5.5 of this report presents the scaling analysis and the staff's evaluation.

There was a concern regarding whether the LST program included test conditions sufficient to simulate the phenomena identified in the phenomena identification and ranking table (PIRT) and whether it covered a range of parameters representative of design-basis events. The tests and facility also had a large number of nonprototypical features that could distort the data and affect scale-up of the tests to prototypical size, including the following:

- PCS flow established before start of transient (except test 219, which had low heat flux)

- fluctuating PCS flow rate, requiring additional consideration in evaluating and understanding some test results, because of the variability in water pressure to the sprays hooked up to the facility's municipal water supply

- different water distribution system on shell dome (inverted J-tubes in the LST versus water distribution bucket and weirs in the prototypical plant)

- relatively high heat removal via sensible heat addition (raising subcooled liquid to saturation as opposed to evaporation)

- lack of internal heat sinks and nonprototypical internal flowpaths (steam generator subcompartment isolation from remainder of below-deck regions)

- shorter test vessel [6.1 m (20 ft)] than the height dictated by the 1/8-linear-scale used for the LST facility

- differing distribution of free volume below the operating deck in the test vessel from that in the prototypical plant:

AP600	LST
19 percent by open volumes	21 percent by open volumes
73 percent by dead-end volumes	70 percent by dead-end volumes
8 percent by steam generator subcompartment	9 percent by steam generator subcompartment

- annulus riser too narrow, lack of a downcomer, and forced airflow
- vessel shell too thick

WCAP-14845 documents the LST scaling analysis. WCAP-14812, Revision 2, "Accident Specification and Phenomena Evaluation for the AP600 Passive Containment Cooling System," issued April 1998, documents the containment PIRT.

In support of the AP1000 design, the applicant provided an evaluation of the differences in scaling and the PIRT between the AP600 and the AP1000 in WCAP-15613, "AP1000 PIRT and Scaling Assessment," issued February 2001. This evaluation demonstrated that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena.

Section 21.6.5.5 of this report presents the staff's review of the LST scaling analysis and the containment PIRT, their relationship to the development of the bounding analysis (the evaluation model), and their use to support design certification.

21.3.8.6 Assessment of LST Test Program to the AP1000

Westinghouse used the AP600 scaling study to support the AP1000 review. However, the staff and Westinghouse agreed during the AP600 review that the LST was not properly scaled for transient situations. The LST is only valid for steady-state conditions. Under such conditions, the LST does support the mass and heat transfer correlations used in the WGOTHIC code for the AP600 and AP1000 designs. Therefore, the staff considers these test to be applicable to the AP1000 and the insights and data used to develop WGOTHIC models remain acceptable.

21.3.9 Water Distribution Testing Program

21.3.9.1 Introduction

The water distribution tests investigated the effectiveness of the PCS to deliver a uniform water film to the outer surface of the containment vessel. The tests were performed on both a 1/8 sector of a full-scale AP600 containment dome with a shortened sidewall and on a cap representing a section of the full-scale containment. The facility was located at Westinghouse's Waltz Mill facility in Madison, Pennsylvania. Data gathered from the tests helped to determine water coverage fractions used as input to the WGOTHIC code. Testing was conducted in three phases, each with the following objectives:

- Phase 1—Determine the effectiveness of the water distribution system in delivering water to the containment dome.

- Phase 2—Investigate the ability of the weir system to provide a uniform flow distribution over the containment dome and sidewall.

- Phase 3—Continue the Phase 2 tests to determine the flow off the bottom and sides of the model, and determine the water film thickness.

The water distribution tests have been completed. The test data are included in WCAP-13353, “Passive Containment Cooling System Water Distribution, Phase 1 Test Data Report”; WCAP-13296, “PCS Water Distribution Test Phase II Report”; and WCAP-13960, “PCS Water Distribution Phase 3 Test Data Report.”

The applicant included its evaluation of the test data in PCS-GSR-003, “A Method for Determining Film Flow Coverage for the AP600 Passive Containment Cooling System,” and NSD-NRC-96-4646, “Conservatism in Modeling of the PCS Film in the DBA Evaluation Model and Comparison of the Range of Film Parameters in the PCS Test Data with AP600.”

21.3.9.2 Test Models

The Phase 1 test model consisted of a full-scale, 6.1-m (20-ft)-diameter circumferential section, or cap, of the containment dome, which was fabricated from steel. The complete model assembly was capable of being tilted horizontally to investigate the effect this had on the surface film distribution.

The model for both the Phase 2 and Phase 3 tests was a full-scale, 1/8 sector of the containment dome attached to a 1/16 sector of the sidewall, which was fabricated from steel. However, while the scale of the sidewall was the same as that of an actual AP600, the full height of the sidewall was not modeled. The height of the sidewall in the model was 3.048 m (10 ft), whereas the height of an actual AP600 sidewall is 25.29 m (83 ft). The AP1000 sidewall is about 7.77 m (25.5 ft) longer than that of the AP600.

Certain welds on the surfaces were made using worst-case welding tolerances to represent surface irregularities which would likely be present in an actual structure. Attempts were made to enhance water coverage by adding surfactants to the water and scoring the surface, but these efforts were unsuccessful. However, a commercially available inorganic zinc paint was used to coat the surface of the model to enhance its wettability.

For all test phases, the water distribution system consisted of a distribution bucket attached to the top of the dome. The distribution bucket had equally spaced slots cut around its perimeter to regulate water flow onto the containment dome. Adjustable weirs were installed on the surface of the dome at two radial locations to promote water distribution over the vessel surface. Water runoff from the dome and sidewall was collected using a system of gutters located around the lower circumference of the test structure. The gutters drained into individual buckets, thereby allowing the volume of water in each bucket to be measured and used to determine the azimuthal distribution of water on the model surface. For each test, water flow rates ranged from 26.1 L/min to 832.8 L/min (6.9 gpm to 220 gpm). The data reports indicate that all tests were run with water at near-ambient temperature.

21.3.9.3 Test Matrix

Table 21.3-5 of this report summarizes the tests performed in Phases 1–3. As indicated in Table 21.3-5 of this report, the Phase 1 tests investigated the effects of tilting the containment model on water distribution and the azimuthal water distribution over the dome. The Phase 2 tests investigated the performance of various weir and distribution bucket designs and measured the water film thickness and width. The Phase 3 tests were similar to those conducted in Phase 2. However, the Phase 3 tests also modeled the PCS baffle wall structural supports and investigated the effect of tilting the distribution weirs on film coverage.

The staff noted that none of the tests in Phases 1, 2, or 3 were conducted with a heated dome or sidewall. A heated surface would likely affect water coverage differently than an unheated surface. Before commencement of the test program, the staff alerted the applicant to its concern regarding the use of an unheated surface. Section 21.5.11 of this report discusses the applicability of water coverage data taken from an unheated surface.

Table 21.3-5 Summary of Phases 1 through 3 Water Distribution Tests

Effects Investigated	**Phase 1**	**Phase 2**	**Phase 3**
Model/weir tilt	Model	No	Weir
Heated surface	No	No	No
Surfactant in water	Yes	No	No
Worst-case surface welds modeled	No	Yes	Yes
Baffle wall supports modeled	No	No	Yes
Water film thickness/width measurements	No	Yes	Yes
Water runoff measurements	Yes	Yes	Yes

21.3.9.4 Assessment of Water Distribution Test Program to the AP1000

The water distribution system in the AP1000 is nearly identical to the water distribution system in the AP600. The distribution system and the containment upper dome region are identical. The AP1000 flow capacity is larger to accommodate the increase in the plant power, and to improve the plant risk profile there is a third flow path to provide water from the water storage tank. In addition, there is a forth stand pipe in the water storage tank to improve the flow rate match to the decay heat resulting in an improved utilization of the water. None of these

AP1000 features changes the phenomena studied by the test program Therefore, the staff considers these tests to be applicable to the AP1000 and the insights and data used to develop WGOTHIC models remain acceptable.

21.4 Overview of NRC Activities on the Test Programs

During the AP600 design certification review, the NRC staff performed a comprehensive review of each Westinghouse design certification test program. The review activities were carried out by several different branches within the Office of Nuclear Reactor Regulation, with support from the Office of Nuclear Regulatory Research. These activities included observing selected tests at many AP600 test facilities, and auditing the applicant's performance of a broad range of issues related to the following:

- test facility design, instrumentation, and scaling
- test data and analyses
- quality assurance (QA)

Section 21.4, "Overview of NRC Activities," of NUREG-1512 describes the staff's activities for each AP600 test program (i.e., CMT, ADS, PRHR HX, OSU/APEX-600, and SPES-2 test programs). Section 21.7, "Quality Assurance Inspections," of NUREG-1512 provides a comprehensive summary of the quality assurance inspections. On the basis of the staff's observations of these tests, as documented in test observations reports, the staff concluded that the applicant's design certification test programs were performed in a competent, professional manner, with due consideration for meeting test specifications and acceptance criteria. The staff believed that the test programs provided useful data for evaluating the AP600 passive safety system performance; however, the staff performed a detailed review of the test results to reach a final judgment on the adequacy of the vendor's test programs. As discussed in Sections 21.5.2 through 21.5.7 of this report, the staff, based on its evaluation, concludes that the AP600 testing is also applicable to AP1000 design certification.

For the AP1000 design certification, the staff monitored the testing program conducted at OSU and performed an independent assessment of the scaling of the APEX-1000 test facility for applicability to the full scale AP1000 design. The overall test program included experiments that were designed to investigate performance of the passive safety systems and provide information on liquid entrainment processes. The staff performed an independent evaluation of APEX-1000 test results, and used the experimental data to determine adequacy of the NOTRUMP code modeling of entrainment.

Because code analysis and results from prior APEX-600 tests indicated that the DEDVI represented the most challenging SBLOCA scenario for core uncovery, a large proportion of the APEX-1000 test matrix examined that particular transient. The applicant conducted design-basis tests to provide data for code assessment. In additional, the design-basis tests examined the effect of ADS4 valve failure location, showing that failure of an ADS4 valve on the nonpressurizer side of the facility resulted in less margin to core uncovery.

The staff evaluation of the APEX-1000 test program is discussed in Section 21.5.8 of this report.

21.4.1 Wind Tunnel Test Programs

The staff witnessed portions of the applicant's Phase 4A and Phase 4B tests at the National Research Council of Canada's boundary layer wind tunnel in Ottawa, Canada, and at UWO in London, Canada. The staff's activities included a complete facility tour, which allowed closeup examination of the models and the wind tunnels, observation of confirmatory testing conducted before installing the actual test model, and observation of a test performed to characterize the flow past the cooling tower. Overall, competent personnel practicing sound experimental procedures conducted the tests.

21.4.2 Large-Scale PCS Test Program

The staff witnessed Phase 2 test 220.1, "Transient Blowdown Steam Flow, Reduced Water Flow and Coverage Area, Noncondensable Gas Samples Taken," and test 221.1, "Transient Blowdown Test with Helium Addition." The staff performed a top-level check of the facility QA, testing performance, and test results. While only a fraction of the tests in the complete program were witnessed, the staff expects that the general observations made of the viewed tests were representative of the other tests in the program, and that they were generally indicative of the complete program.

Section 21.7, "Quality Assurance Inspections," of this report includes the results of the staff's QA review of the AP1000 testing activities.

21.4.2.1 Phase 2 Test 220.1

The staff discussed the test objectives, instrumentation, and operational problems with the test supervisor. The objectives were clearly defined, the crew was well versed in its duties, and, because this was a later test in a long series, most testing problems were resolved. Transitional points where problems were likely to arise were discussed, and the staff watched carefully during these periods to ensure that any problems were properly handled. A step-by-step procedure, including test prerequisites and instructions, target test parameters, the necessary instrumentation, and gas sample data sheets, guided the test. The operators were knowledgeable as to the facility layout and the location of instruments and controls.

Before running test 220.1, the Westinghouse crew had practiced with the steam boiler and was well versed in its operating idiosyncrasies. However, problems with the boiler almost invalidated the test. The test procedures called for three rounds of data measurements; however, after the second round was completed, the boiler shut down on low feedwater flow and testing ceased. In examining the first two rounds of measurements, it was found that the pressure readings were within 0.69 kPa (0.1 psi) of each other at each sampling point. Normally, a 2.07–2.76 kPa (0.3–0.4 psi) discrepancy would be considered acceptable for readings that were supposed to be the same. Therefore, the Westinghouse test engineers determined that a third round of data measurements was not necessary.

During the test, condensate was collected at five different locations and was removed through a manifold under the vessel. The rate of condensate collection provided a check on the steamflow rate measurement during steady-state operation.

A total of 315 chromel-alumel thermocouples measured temperatures. The Westinghouse testing laboratory batch-sample calibrated these devices. Multiple thermocouples were provided at various locations to provide data to determine through-wall vessel heat flux and to measure internal and external atmospheric temperatures. Only one thermocouple was provided to measure incoming steam temperature. Five steam pipe thermocouples provided a check of steam temperature under steady-state conditions. Containment atmosphere gas sample lines were provided at four locations and extended into the bulk fluid of the vessel. The gas sample data were collected to assess the ability of computer programs to predict steam stratification and noncondensable gas concentrations within the vessel. The staff observed one sample being taken. A valve was opened, allowing vessel atmosphere to flow through a heated collection line into a heated collection bottle. The staff expressed concern as to the uniform temperature of the collection apparatus. Nonuniform temperatures might cause condensation within the sample bottles, distorting the measurement. No sample lines were routed to the dead-end compartments within the test vessel where noncondensable levels were expected to be the highest.

WCAP-14135, Revision 1, discusses the gas sampling apparatus. The procedures used to collect a sample included heating the tube to 205 °C (400 °F) (although the internal temperature might be 18 °C (65 °F) warmer). The probe tube inside the containment was also heated; its temperature could be as high as 167 °C (300 °F) above the air and steam temperature. This procedure avoids any measurement problems resulting from steam condensing in the sampling system by maintaining the gas sample apparatus temperature higher than the 150 °C (300 °F) to 175 °C (350 °F) containment atmosphere temperature.

The applicant followed the instrument manufacturers' calibrations and instructions concerning periodic recalibrations. As appropriate instrument readings were zeroed following each test. Instrument errors were provided along with the data to the analyst. Recalibration of steamflow instrumentation was necessary after the installation of the high-capacity steam source.

WCAP-14135, Revision 1, discusses the steamflow measurements for test 220.1. A comparison of condensate and vortex meters suggested that the vortex meter consistently indicated a 15–20 percent lower flow rate than was expected on the basis of the collected condensate over the steady-state period. The vortex meter was operating at the lower end of its operational range during the steady-state period. During the low-flow, steady-state portion of the test, the discrepancy noted was about 1.9 percent of full scale, but about 15 percent lower than the recorded condensate readings. (The meter accuracy was quoted as 1 percent of full scale, with the range extending from 2.68 to 0.20 kg/sec (5.9 to 0.45 lb/sec) at the meter's test operating conditions.) To compensate for this difference, the Westinghouse test engineering group recommended that 15 percent should be added to the steamflow rate for all times greater than 10.9 hours. Post-test calibration showed no discrepancies in performance of the flow meter, although the calibration was limited to the lower 15 percent of its span.

Test 220.1 was particularly important because it was the only PCS blind test. A blind test is a test in which data are withheld from the test analysts. The analysts predict the test's outcome only on the basis of the expected test conditions. The analysis is then compared to the actual test data. In the case of test 220.1, the Westinghouse analysts had only the test boundary conditions (inlet steam flow rate and temperature; steamline pressure and temperature; air annulus exit velocity and pressure drop; the PCS water flow rate and temperature; and wind speed, wind direction, and ambient temperature) to use in predicting the resulting parameters (internal pressures, temperatures, air-steam flow rates, and noncondensable concentrations) based on the WGOTHIC computer program. WCAP-14135, Revision 1, provided the boundary data. The applicant provided the blind test boundary conditions used for the WGOTHIC analysis to the NRC staff in letter NTD-NRC-95-4422, "Mass and Energy Tables for AP600 Large Scale Containment Test 220.1," dated March 27, 1995, and included the 15 percent increase in the steamflow, as recommended by the Westinghouse test engineering group.

After the pre-test calculation was performed, the Westinghouse analysis group obtained the post-test data from the Westinghouse test engineering group. The post-test condensation rate data showed that the average steamflow used in the pre-test prediction was too low, and that significant dips in the pre-test steamflows, taken from the vortex meter, were in error. The applicant modified the mass and energy release rates for the blind test evaluation, and provided the new boundary conditions to the staff in letter NTD-NRC-95-4456, "Revised Mass and Energy Tables for the AP600 Large-Scale Containment Test 220.1." WCAP-14382, "WGOTHIC Code Description and Validation," issued May 1995, provided the analyses of blind test 220.1, based on the revised steamflow.

After a review of the test analysis results presented in WCAP-14382 and the problems associated with the low steamflow, it was apparent that a third test would not have provided any additional data to improve the boundary data set for use in the WGOTHIC analyses. The steam inlet flow was too low to be measured adequately by the available instrumentation for the steady-state portion of the test, and the boundary conditions used in the analyses would still contain uncertainty and the need to rely on the analysis of the post-test condensation collection data to determine the steam flow boundary conditions. Therefore, the data from test 220.1 were determined to be acceptable for the blind test evaluation.

21.4.2.2 Phase 2 Test 221.1

This test was important because it was the first time that all significant parameters were incorporated into a single test. As with previous staff observations, the staff discussed the test objectives, instrumentation, and operational problems with the test supervisor. The objectives were clearly defined, the test crew was well versed in its duties, and most problems were resolved. The written test procedures and prerequisites were correctly followed by the test personnel. Facility instrumentation seemed satisfactory, with the exception that only five anemometers were available to measure the flow of the internal atmosphere of the containment vessel. Section 21.5.10 of this report more fully discusses the staff's concerns associated with the PCS testing program.

21.4.3 Water Distribution Test Program

The staff witnessed three of the Phase 3 water distribution tests. These particular tests were chosen because they spanned the range of design flow rates for the PCS. The staff's activities included a prebriefing with the test supervisor to review the test objectives, identify any operational problems, and discuss the instrumentation. Because this was a later test in a long series, most operational and equipment problems were resolved. The staff observed that test personnel were well versed in their duties, and that the test operators appeared very knowledgeable about the facility layout and the location of instruments and controls.

In general, the instrumentation appeared sufficient for the purposes of the experiment. A particularly difficult measurement was that of the film thickness using a capacitance probe. Because the film was not uniform in thickness, its surface on the sidewall exhibited wavy laminar flow. The staff noted that the measurements were probably inadequate to accurately characterize the film flow because of the nonuniformity of the film and the relatively small number of readings taken. The staff further noted that the model contained several representations of welds and surface defects, as discussed in WCAP-13290, “Passive Containment Cooling System Water Distribution Test Specification,” that could affect the film coverage.

The staff concludes that the water distribution tests were performed by competent personnel following clear, complete procedures. Section 21.5.11 of this report discusses the issues regarding the validity of the test data and the nonprototypical features of the model.

21.5 Evaluation of Vendor Testing Programs

As discussed in Sections 21.1 and 21.3 of this report, with the exception of the APEX-1000 test facility, the AP1000 test program is founded on the AP600 test program that was utilized for the validation of the computer codes used for safety analyses of the AP600 design-basis events.

WCAP-14727, Revision 2, “AP600 Scaling and PIRT Closure Report,” is an overall “closure” document, which integrates the applicant's test results for the AP600 design, demonstrating that the test data cover an appropriate T-H range, address the pertinent phenomena identified in the AP600 PIRTs, and are consistent with assumptions made in deriving the scaling parameters used to design the test facilities and develop the test matrices. The NRC staff performed a comprehensive, thorough review and evaluation of the AP600 test programs during the AP600 design certification review, and determined that the AP600 test programs provide a sufficient data to assess the analytical codes used for the safety analyses of the design-basis transients and accidents for the AP600 design, per the requirements of 10 CFR 52.47(b)(2)(i)(A), as set forth in NUREG-1512.

In support of its assertion that the AP600 test program is sufficient to meet the test requirements for a design certification application for the AP1000 standard plant design, the applicant submitted topical report WCAP-15613. The staff review of the AP1000 test programs is based upon the foundation of the previous review of the AP600 test programs, where applicable to the AP1000 design. The staff review efforts focused on (1) whether these test programs are applicable to the AP1000, (2) whether they cover important T-H phenomena identified in the AP1000 design, (3) whether additional tests are necessary for the AP1000 design, and (4) whether these additional tests are scaled appropriately and cover appropriate ranges.

The following sections describe (1) the staff's evaluation of the AP1000 PIRTs; (2) the staff's evaluation of various AP600 test programs, including a brief discussion of the staff evaluation during the AP600 review, and its applicability to the AP1000 design; (3) the scaling assessment of the AP600 test facilities to the AP1000 design with respect to the important phenomena; and (4) an evaluation of the APEX-1000 test program. The staff notes that the staff review of the AP600 test programs was described in detail in Section 21.5.5, "Oregon State University/Advanced Plant Experiment Test Program," of NUREG-1512, from which the staff extracts an evaluation summary to be included in the following sections.

21.5.1 Phenomena Identification and Ranking Tables

Section 2 of WCAP-15613 contains separate PIRTs for LBLOCAs, SBLOCAs, and non-LOCA transients for the AP1000 design, with comparisons to the AP600 PIRTs. The PIRTs provide a means to identify and classify, in terms of importance, the T-H phenomena expected to occur in transients and accidents that must be included in the analytical models, and for which data must, therefore, be available to evaluate those analytical models. The NRC staff evaluated the AP600 PIRTs during the AP600 design certification review, and found that they captured the important phenomena, processes, and components of the AP600 design.

The staff notes that, in general, the AP1000 PIRTs are very similar to those of the AP600 design, with only minor changes (mostly in the importance ranking of certain phenomena). In addition, although the applicant developed a separate LTC PIRT for the AP600 design, it merged the LTC PIRT into the SBLOCA PIRT for the AP1000 design. This is because the sump injection for LTC is also the final phase of the SBLOCA recovery transient. In the combined SBLOCA PIRT, the phenomena that were ranked higher in the LTC PIRT than in the SBLOCA PIRT remain higher. Also, because of the higher steam flow rate expected to result from increased core power in the AP1000 design, hot-leg entrainment during the ADS-4 blowdown, IRWST injection, and the sump injection phase is increased to a "high" importance ranking from "medium" in the AP600 as is the ADS-4 two-phase pressure drop during the IRWST injection phase. The entrainment/de-entrainment in the upper head and upper plenum region is also increased from "medium" to "high" ranking. In addition, some phenomena ranked as "low" importance for the AP600 design are changed to "medium" importance in the AP1000 PIRT. The applicant stated that the AP1000 PIRTs were reviewed by a group of nuclear industry experts, and some of the changes reflect their suggestions.

The AP1000 LBLOCA PIRT places a slightly higher importance ranking than the AP600 LBLOCA PIRT on the reflood heat transfer and the entrainment/de-entrainment due to the higher power density of the AP1000 design. The AP1000 non-LOCA transients PIRT assigns a "medium" importance ranking, compared to "N/A" ranking in the AP600 PIRT, for the CMT gravity draining injection and vapor condensation rate phenomena, which occur during the steamline break and feedwater line break events, respectively. This increased importance ranking is appropriate based on consideration of the RCS of the AP1000 design, which has a decreased pressurizer volume-to-power ratio and an increased SG secondary volume, which could be more sensitive to shrink and swell events. During the RCS cooldown, if the RCS pressure decreases enough to cause the CMT to switch from recirculation to injection, the gravity injection and vapor condensation rate phenomena may become important. Overall, based on the above, the staff concludes that the AP600 and AP1000 PIRTs for LBLOCA, SGTR, and non-LOCA transients are very similar, and no new “high” ranked phenomena are expected. The minor changes in “low” and “medium” ranked processes are considered appropriate.

For the reasons set forth below, the staff also finds that the AP1000 SBLOCA PIRT appropriately ranks the important phenomena. The staff requested that the applicant evaluate a potential for a condensation-induced water hammer (CIWH) in the DVI line, which could occur when cold CMT or accumulator water contacts a low-velocity, stratified steam-water mixture in the DVI line during the early part of the ADS-1/2/3 blowdown in an SBLOCA. In its response, the applicant stated that CIWH potential in the AP1000 DVI line is small, as substantiated by the following considerations:

- A comprehensive water hammer assessment performed by the applicant for the AP600 design concluded that water hammer potential for the DVI piping is small, given the criteria described in NUREG/CR-6519, “Screening Reactor Steam/Water Piping Systems for Water Hammer,” September 1997, for piping configurations and T-H conditions that can result in water hammer induced by steam bubble collapse.

- Water hammer evaluations for the tests performed at the APEX and SPES facilities found no evidence of significant CIWH events in the DVI lines. There was some evidence of CIWH in the vessel downcomer at the APEX facility during recovery following simulated SBLOCAs when the accumulator injection flow rate was high. However, given the water slug velocity in the downcomer calculated by the RELAP5 code, the applicant estimated that the peak pressure in the AP600 reactor is less than 1.03 MPa (150 psi), which is significantly less than the 2.76 MPa (400 psid) differential for which the affected reactor vessel components are designed.

Because the AP1000 and the AP600 DVI piping and T-H conditions during recovery from design-basis events are almost identical, the applicant concluded that the CIWH potential is small, with no need to add the CIWH to the SBLOCA PIRT for the AP1000 standard plant design. The staff also concludes that the CIWH is not a high-ranking phenomenon, given that the DVI line is expected to be full at the initiation of the ADS-1/2/3 blowdown, which would reduce the probability of CIWH at a time when it would be the most severe.

The staff also evaluated a need to increase the ranking of pressurizer phenomena during the ADS blowdown period. Since the AP1000 ADS-1/2/3 valve size is the same as in the AP600 design, velocities during ADS-1/2/3 blowdown are expected to be similar to those in an AP600 plant. Accordingly, the staff concludes that the AP1000 ranking of these processes is acceptable.

In summary, the staff finds that the AP1000 PIRTs (with the changes from the AP600 PIRTs described above), reflect the changes associated with the AP1000 design characteristics of higher core power density and steam flow rate. The high-importance phenomena in the AP1000 PIRTs are covered by the various separate-effects and integral-systems test programs data.

21.5.2 Core Makeup Tank Test Program

The staff evaluated the applicant's CMT test program during the AP600 design certification review. As described in Section 21.5.1, "Core Makeup Tank Test Program," of NUREG-1512, the staff reviewed the design, instrumentation, and scaling of the test facility, and the test matrix. The staff determined that the final design of the test facility provided an adequate representation of the key features of the RCS and connecting piping that would affect CMT performance, such as the relative elevations of the steam-water reservoir (representing the reactor vessel) and the test article (representing the CMT) and the resistances of the pressure balance line and CMT drain line. The test article was sufficiently large to provide data representative of actual CMT performance. The staff noted that the aspect ratio of the test article provided a largely one-dimensional representation of CMT T-H behavior. The staff also found that the number, type, and location of the facility instrumentation was adequate to provide data on CMT temperatures, pressures, and flows during the tests.

The staff reviewed the CMT scaling report WCAP-13963, Revision 1, and found the following:

- The applicant demonstrated that the heat transfer between the fluid and the CMT wall during the recirculation phase would be adequately represented in the test article over a similar range of T-H conditions.

- The applicant showed that the recirculation and draining rate of the CMT was sufficiently slow during events of interest to make its behavior largely one-dimensional, thus permitting the use of a one-dimensional scaling approach. The effects of multi-dimensional T-H phenomena on conclusions drawn from a one-dimensional scaling analysis were, therefore, determined to be relatively minor.

- The approach for scaling the steam diffuser in the CMT provided an adequate means of representing steam condensation phenomena near the diffuser.

- While the transition from the recirculation mode to the draining mode of operation was not represented in a prototypic manner, the process for doing this was sufficiently rapid as to preserve the key T-H phenomena of interest, particularly the temperature profile in the tank.

- T-H parameters important to condensation phenomena were adequately represented.

- The separate-effects data developed in this test program would be used in conjunction with and augmented by data on CMT performance acquired in the two integral-systems tests programs.

The staff reviewed the final test matrix, and determined that the testing program would permit acquisition of data over most of the operating range of the CMT in the AP600, with respect to temperature, pressure, and flow, and would address the “important” phenomena, as determined from the AP600 PIRT. The design and operation of the facility did not permit acquisition of data at very low pressures. However, this was judged to be acceptable, since both of the integral test facilities would operate down to those pressures and would provide additional data for code validation in that range.

The staff’s overall assessment of the CMT test program was that the data acquired during the test program and verified to meet the applicant’s acceptance criteria are valid and applicable for use to validate computer models for the AP600. The staff concluded that the CMT test program has fulfilled its objectives to provide a separate-effects database to assess AP600 analytical models, per the requirements of 10 CFR 52.47(b)(2)(i)(A).

Applicability of CMT Tests to AP1000

The AP1000 CMTs have larger volumes (diameters) and drain rates because of reduced piping resistance than do the AP600 CMTs. As described in WCAP-13963, Revision 1, key dimensionless Pi group parameters to scale CMT circulation and heat transfer include the Richardson number and the Friction number. In this case, the scaling assessment described in WCAP-15613 shows that the ratio of the Richardson number to the Friction number for the AP1000 CMT remains acceptably close to those in the test matrix. The applicant also showed that other CMT scaling groups (e.g., the Stanton number, the liquid heat source ratio, and the heat source ratio) that are affected by the larger CMT diameter and drain rate also remain reasonably scaled for the AP1000. Therefore, the CMT tests are considered to be acceptable for the AP1000 design as they were for the AP600 design. The staff, therefore, concludes that the CMT tests performed for the AP600 remain valid for the AP1000 code validation.

21.5.3 Automatic Depressurization System Test Program

The staff evaluated the applicant’s ADS test program during the AP600 design certification review. Section 21.5.2, “Automatic Depressurization System Test Program,” of NUREG-1512 describes in detail the staff evaluation of the ADS test program. The staff’s original review of the ADS test program in the VAPORE facility focused primarily on the Phase B1 facility design, instrumentation, and test matrix. Scaling was not a significant issue because of the full-size configuration of the ADS piping network, exhaust pipe, and sparger. The staff determined that the facility design and instrumentation were generally acceptable, but the staff noted that only one of the two ADS valves in each stage would actually be installed in the facility for these tests, with the second valve represented by nozzles and/or orifices designed to give flow area (in choked flow) and flow resistance (in unchoked flow) similar to those of a prototypic valve. The applicant submitted a “road map,” describing the specific relationship between the design certification test program and the qualification of the actual valves (qualification, in this context, refers to demonstration of a valve’s capability to meet its design performance criteria). The staff concluded that the “road map” adequately discussed the range of data acquired during the Phase B1 test program, how the data from the design certification test program are used to validate code models for prediction of ADS performance, and how these models are used to analyze the results of follow-on testing outside of design certification and to thereby establish performance criteria for the AP600 ADS valves. The staff further concluded that the design certification test program test matrix provided adequate coverage of T-H conditions as indicated in the “road map,” and addressed the “important” phenomena related to ADS performance identified in the AP600 PIRT and, therefore, was acceptable.

Because of the importance of the information contained in the ADS “road map” in establishing a process for ensuring that the actual ADS valves in the plant function as designed, consistent with performance specifications determined from the design certification test program and reflected in design-basis analyses performed for the plant, the ADS “road map” was incorporated into the AP600 Standard Safety Analysis Report (SSAR) and inspections, tests, analyses, and acceptance criteria (ITAAC). AP600 SSAR Section 5.4.6.3, “Design Verification,” summarizes the ADS valve qualification process to meet the ADS safety-related design functions described in the “road map, and provides cross-reference to various sections in the AP600 DCD Tier 2 information regarding ADS valve qualification. AP600 DCD Tier 1, Section 2.1.2, describes the functional design of the ADS valves, and the ITAAC specifies the qualification tests and acceptance criteria for the ADS valves to ensure that each ADS valve was appropriately qualified and that the valve performance is bounded by qualification tests.

WCAP-14305 provided the ADS test analysis and justification as to why the range of T-H conditions covered by the ADS test program, and the data acquired therefrom, comprise an adequate basis for validation of code models for ADS performance analysis. The staff’s review concluded that the applicant had demonstrated that the test conditions provided sufficient coverage of the operating conditions expected in the AP600, and that the assumptions made in analyzing the data were reasonable. Consequently, the staff concluded that the ADS test program was adequate to provide the basis for validating computer code models of ADS performance and, therefore, was acceptable for the AP600 design.

Applicability of ADS Test Program to AP1000

The ADS-1/2/3 system for the AP1000 standard plant design is identical to that of the AP600 design. During the RCS blowdown the flow through the ADS-1/2/3 is expected to be choked. Simulations have revealed that upstream pressures in the AP1000 are very similar to those in the AP600 design. T-H conditions affecting ADS-1/2/3 performance will be close to those in the AP600 design. Consequently, tests performed to investigate ADS-1/2/3 valve performance for the AP600 design, which included a wide range of actuation pressures and flow qualities, are considered appropriate to represent conditions in the AP1000 standard plant design. Therefore, the staff concludes that the ADS test program for the AP600 design also applies to the AP1000 design. The staff also notes that the same ADS qualification process and criteria described in AP600 SSAR Section 5.4.6.3 and Tier 1 ITAAC are described in the corresponding sections of AP1000 DCD Tier 2 information and Tier 1 ITAAC.

21.5.4 Passive Residual Heat Removal Heat Exchanger Test Program

The staff evaluated the applicant’s PRHR HX test program during the AP600 design certification review. Section 21.5.3, “Passive Residual Heat Removal Heat Exchanger Test Program,” of NUREG-1512 describes in detail the staff review of the PRHR HX test program. The configuration of the PRHR HX test program, consisting of three straight vertical tubes, is different from the PRHR HX design for the AP600 or AP1000, which has a vertical C-shaped tube bundle with several hundred tubes. The staff’s evaluation of the test program focused on the applicability of the three-tube test data to the design of the standard plant PRHR HX.

Results from selected integral tests and preliminary NRC analyses showed that the behavior of the PRHR system has a significant, possibly dominant, effect on RCS behavior over a wide range of DBAs. Therefore, the capability to predict this behavior is an important aspect of the plant safety analyses for passive safety systems. The differences between the test facility configuration and the standard design affect both primary (tube side) and secondary (tank side) heat transfer. Of specific concern was flow distribution and behavior in the tubes and two-phase flow behavior in the IRWST, especially within the tube bundle. High heat transfer rates could cause violent boiling on the outer surface of the tube, resulting in vapor blanketing of some portion of the HX surface and drastic reduction in heat transfer. However, this concern was resolved as the applicant analyzed the PRHR HX performance and concluded that it is unlikely that vapor blanketing would occur on the PRHR HX tubes, and that if it did occur, such behavior would be limited to a very short length near the inlet of the tube bundle, leaving sufficient heat transfer area to meet its design performance requirements. In addition, the staff noted that vapor blanketing was not observed on the simulated PRHR HXs in the applicant’s OSU/APEX and SPES-2 integral test facilities. The staff also studied the NRC’s confirmatory test program in the ROSA/LSTF loop at the Japan Atomic Energy Research Institute. The ROSA/LSTF test facility included a scaled C-tube PRHR HX of prototypic tube dimensions and spacing, but with a reduced number of tubes in the HX bundle. The HX was submerged in a large tank of water, simulating the IRWST. Vapor blanketing was not observed in the tests simulating a station blackout (SBO) and a 12.7-mm (0.5-in.) SBLOCA.

WCAP-12980 provided the analysis of the data from the PRHR test program. The staff requested that the applicant justify the use of the straight-tube data by performing confirmatory analyses of data from a C-tube HX. The staff provided the applicant with data from two tests from the confirmatory test program in the ROSA/LSTF. The tests included a simulated SBO and a simulated 12.7-mm (0.5-in.) SBLOCA. For both of these tests, the fluid entering the PRHR HX remained a single phase liquid for an extended period. Data provided to the applicant included the HX inlet flow and temperature and the temperature profile of the IRWST tank. The applicant used its PRHR analysis model, developed from the straight-tube tests, to calculate the PRHR HX outlet temperature and tube wall temperatures at three locations along the length of the tubes. These calculations were performed at five discrete times over the course of the SBO test and at three times over the course of the SBLOCA test.

The applicant provided its calculated results by letter to the NRC dated September 18, 1997. Calculated temperatures were on the basis of an equivalent single HX tube and an average IRWST temperature. The staff reviewed the calculated HX outlet and tube wall temperatures.

The applicant's results predicted the ROSA/LSTF data quite well, with calculated temperatures within a few degrees of measured temperatures. Some of the disagreement between the data and the applicant's calculations were attributed to the way the staff averaged the ROSA/LSTF data (averaging the data from three instrumented tubes to get an equivalent single tube temperature). The staff performed confirmatory calculations, using the applicant's heat transfer correlations, for the same tests and times as the applicant, and the results were consistent with the applicant's results. In addition, improved agreement between the data and calculated results was observed when the IRWST model was modified to explicitly represent the temperature stratification in the tank, as compared to a single average tank temperature. The staff concluded that the remaining discrepancies between the data and the applicant's calculations were largely attributable to IRWST modeling and not to the performance of the correlations themselves. On the basis of the staff's analysis and the review of the applicant's results, the staff concluded that the straight-tube-based heat transfer model did an adequate job of predicting C-tube HX performance. Thus, the staff concluded that the PRHR HX test program met its objectives and fulfilled the regulatory requirements of 10 CFR 52.47(b)(2)(i)(A) with respect to the AP600.

Applicability of PRHR Heat Transfer Tests to AP1000

The AP1000 PRHR maintains the same "C-tube" HX, tube diameter, spacing, and pitch ratio of the AP600 PRHR. To accommodate the higher core power, however, the AP1000 PRHR line resistances are reduced to increase the natural circulation flow, and the PRHR HX heat transfer area is increased by about 22 percent by adding tubes to the top and bottom of the tube sheet and adding length to the horizontal sections. Thus, a higher proportion of the heat transfer is expected to occur by crossflow through the horizontal section in the AP1000 design than in the AP600 design.

During the AP600 review, a concern was raised regarding the potential for a drastic reduction in heat transfer caused by vapor blanketing attributable to violent boiling on the outer tube surface in the top horizontal tube region of the PRHR HX. This concern was resolved on the basis of the applicant's analyses of the margin of the PRHR HX heat flux to the critical heat flux limit, and the fact that vapor blanketing was not observed in the APEX, SPES, and ROSA integral-effects test facilities. Section 4.1.1.3.2 of WCAP-15613 provides an evaluation of the AP1000 PRHR, using various heat transfer correlations on the inside and outside of the PRHR tubes to determine the heat flux on the outside of the tubes and margin to the critical heat flux limit. The results show that the expected operating conditions for the AP1000 PRHR result in external tube heat flux values that are far below the critical heat flux limits, and are bracketed by forced flow test data from the AP600 integral-effects tests.

The applicant, therefore, concluded that heat transfer correlations that were developed from the AP600 test data remain valid for the AP1000 PRHR. On the basis of its evaluation of the effect of increasing the horizontal length on the overall heat transfer, the staff has concluded that no additional testing is necessary at the applicant's separate-effects test facility. Acceptability of the applicant's codes to predict PRHR heat transfer is based on the use of an acceptable HX heat transfer correlation, which was verified with integral-effects test data. In Section 21.6.1 of this report, the staff discusses the PRHR HX heat transfer correlation in the LOFTRAN code, which is verified with the data from the ROSA and SPES facilities.

21.5.5 Oregon State University/Advanced Plant Experiment (APEX-600) Test Program

The staff evaluated the OSU/APEX-600 test facility during the AP600 design certification review. Section 21.5.5, “Oregon State University/Advanced Plant Experiment Test Program,” of NUREG-1512 describes in detail the staff evaluation of the OSU APEX test program. In addition to the applicant’s design certification testing, the NRC conducted a confirmatory testing program in the OSU/APEX-600 facility. Insights from those confirmatory tests that bear upon integral system behavior in general, and facility response in particular, had been factored into the test program review.

Staff review of the facility design, instrumentation, test matrix, and scaling of the OSU/APEX-600 facility developed with the test program. As originally conceived, the facility was to be a low-pressure [approximately 345 kPa (50 psia)] loop to investigate the last part of the plant depressurization and long-term cooling behavior in SBLOCA events. The applicant and OSU gradually changed the design to increase the maximum pressure to about 2.7 MPa (400 psia), which improved scaling and allowed a wider range of test conditions to be explored. The staff determined that the final design was acceptable. Essentially, the entire primary system was represented, including all safety-related systems, in a geometry very similar to the actual plant design. While the containment itself was not simulated, the two sump tanks provided a scaled representation of the volumes into which flow from the break and ADS-4 discharge, and condensate from the PCS would drain and recirculate to the RCS. The facility was extensively instrumented to provide temperature, pressure, flow, and void fraction data throughout the system. The test matrix focused on SBLOCAs because (1) LOCAs are the only events to cause the ADS to actuate and to progress to long-term cooling within the design basis; and (2) LBLOCA response in the AP600 was calculated to be similar in many ways to conventional designs, and the applicant asserted that important phenomena in LBLOCAs related to long-term cooling would be similar to SBLOCA behavior. The staff agreed with the applicant’s approach, found this reasoning acceptable, and determined that the OSU/APEX-600 test matrix provided adequate coverage of break size and location to address important system-related phenomena identified in the AP600 PIRT.

WCAP-14252, “AP600 Low-Pressure Integral System Test at Oregon State University Final Data Report,” and WCAP-14292, Revision 1, “AP600 Low-Pressure Integral System Test at Oregon State University Test Analysis Report,” respectively, described the test data and test analyses for the OSU/APEX-600 test program. However, the staff raised the following technical concerns related to these two reports:

- A check valve was installed improperly in the facility. This error permitted flow between the two DVI lines, which was not quantified.

- Potential scaling distortions related to the break size and simulated ADS valve sizes were identified.

- Several types of oscillations, during various phases of the tests, were noted during the applicant’s program. Further investigation of these phenomena indicated that some may be related to specific aspects of the facility's design, and that others could be representative of AP600 phenomena.

- A higher-than-expected break flow was measured in Test SB5.

The applicant responded to these issues in Appendix A of WCAP-14727, Revision 2, "AP600 Scaling and PIRT Closure Report." WCAP-14272, Revision 2, described the applicant's scaling assessment of the OSU/APEX-600 facility. The staff reviewed and determined that the scaling analysis for the APEX facility appropriately reflected consideration of key AP600 T-H phenomena. The check valve issue and the scaling of the break and ADS valves were handled as potential distortions.

The oscillations identified during tests were determined to occur for several reasons. In some cases, such as oscillations related to CMT draining during the long-term cooling phase, the behavior was determined to be specific to the OSU/APEX-600 loop and was related to CMT refill during the test. CMT refill was able to occur because of the reduced height of the test facility and is not expected to occur in the actual plant. The impact of this distortion was considered to be relatively minor.

Other oscillations occurred because of the interaction between various volumes of water in the facility at different periods of the transient. The staff believed that these oscillations could potentially occur in the actual plant. However, the oscillations are self-limiting, and cease when the mixture level in the reactor vessel drops below the top of the hot-leg. This level still provides a large margin to uncovering the core; thus, the staff concluded that oscillations do not represent a safety concern in the actual plant.

The reason for the anomalous break flow in Test SB5 could not be determined. The amount of excess flow was consistent with a leak around the orifice used to simulate the SBLOCA for this test. Since the break flow was measured directly, far downstream of the orifice, determination of the conditions for the test was not dependent on trying to model directly the flow through the orifice. Thus, rather than the nominal conditions for the test (simulated 25.4 mm (1 in.) break), the actual flow was closer to that expected for a 50.8 mm (2 in.) break. The data were still applicable for code validation, and the staff determined that the coverage of test matrix was adequate despite the anomaly. Thus, the staff found the applicant's responses to be acceptable to resolve the key issues raised. In addition, while the staff's confirmatory test program provided substantial additional data from the OSU/APEX-600 test facility, and contributed to the staff's understanding of potential actual plant integral system behavior in design-basis events, the staff did not identify any significant phenomena to call into question the adequacy or applicability of the design certification test program at OSU.

<u>Applicability of OSU/APEX-600 Test Program to AP1000</u>

In Section 21.5.7 of this report, the staff performed a scaling analysis of the integral effect test programs to evaluate the applicability of the APEX-600 test program to the AP1000 design.

21.5.6 SPES-2 High-Pressure, Full-Height Integral Systems Test Program

The staff evaluated the applicant's SPES-2 test program during the AP600 design certification review. Section 21.5.6, "SPES-2 High-Pressure, Full-Height Integral Systems Test Program," of NUREG-1512 describes in detail the staff evaluation of the SPES-2 test program. Early staff review of the SPES-2 program focused on test facility modifications (since SPES was an existing facility), instrumentation, scaling, and the test matrix. As discussed in Section 21.3.5 of this report, SPES-2 included several distortions that arose either as a result of its 1/395 scaling ratio to the AP600 plant (e.g., heat loss, metal heat addition) or the necessity of modifying an already-existing facility (e.g., external downcomer, one pump per loop). The staff reviewed the impact of these distortions. The major design distortions were found to be acceptable. In the case of the downcomer, the addition of an annular section to accommodate the cold-legs and DVI lines was found to adequately characterize flow behavior within the context of the one-dimensional system representation provided by the SPES-2 facility. The single pump per loop, rather than the two pumps in the actual plant, was considered to be a relatively minor distortion, since the safety system response in the types of events simulated in SPES-2 included tripping the reactor coolant pumps early in the accident, coincident with CMT actuation. The resistance to natural circulation flow through the actual plant piping and two pumps was represented in SPES-2, and the elevation of the cold-legs with reference to the steam generators was maintained.

Because the SPES-2 facility was full-height and operated at full pressure and scaled full power conditions, the scaling analysis was a relatively simple comparison of the configuration (piping and key elevations), component flow areas, and pressure losses in SPES-2 to the plant design. Except for those distortions identified above, the facility compared well to the plant. Innovative designs were employed to minimize distortions where possible. For example, the SPES-2 CMTs were full-pressure and full-height, but were about 1/20 the diameter of the AP600 components. This can cause a distortion in the structural heat content, which could affect CMT draining behavior. To minimize the distortion, the SPES-2 CMTs were designed with thin walls. Since these tanks could not withstand differential pressures up to full RCS pressure, they were placed inside larger vessels that were pressurized with air to maintain acceptable stresses in the tank walls. As the loop (and CMTs) depressurized during a test, air was exhausted from the vessels to maintain acceptable structural conditions. The staff found the scaling approach and modified facility design acceptable.

The staff reviewed the test matrix and determined that it covered an adequate range of SBLOCA sizes and locations; the simulation of the SGTR and main steamline break events was also found to be adequate. The staff also determined that the test program would address many "important" items related to integral system behavior as identified in the AP600 PIRT, especially at elevated system pressures and temperatures outside the range of conditions covered in the OSU/APEX-600 tests. All of the tests represented "design-basis" accident scenarios (including a single active failure), with the exception of one SGTR test, and one SBLOCA test that included the use of (simulated) non-safety systems to assess potential adverse systems interactions. The testing procedure for all SBLOCA tests was to consider the test as concluded when stable IRWST injection was established (i.e., there was no attempt to represent long-term cooling, as was the case in the OSU/APEX-600 tests). The only exception was the test with non-safety systems simulated, which was not predicted to fully depressurize; use of the simulated RNS system as a low-pressure injection system prevented the CMTs from draining to the ADS-4 level setpoint. For the non-LOCA tests (SGTRs and main steamline break), the criterion for test termination was for the system to be stabilized at elevated pressures, since within the design basis, these events were not predicted to result in ADS actuation.

The applicant's program was guided in part by pre-test predictions performed by Ansaldo Company. As discussed in Section 21.3.5 of this report, the staff did not formally review those pre-test predictions, since they were performed using RELAP5/MOD3. The NRC used the RELAP5 code to perform audit calculations of both test facility experiments and AP600 accidents and transients. However, it is not one of the codes being used by the applicant for AP600 design certification analyses, and the pre-test predictions are thus, to some extent, irrelevant as far as review of the AP600 testing and analysis programs.

The onsite observations by the staff and Agenzia Nazionale per la Protezione dell' Ambiente (ANPA), together with the examination of preliminary ("quick-look") test reports, indicated that the facility appeared to operate predictably. The tests simulating design-basis SBLOCAs ended with the facility fully depressurized and with the core covered and cooled using IRWST injection. The SBLOCA test that included use of non-safety systems also proceeded as expected, with injection from the IRWST using the RNS pumps allowing the system to stabilize at a slightly elevated pressure. For the non-LOCA transients, the system stabilized at elevated pressures with no ADS actuation. CMT injection in the recirculation mode was successful in adding coolant inventory without reducing CMT levels to the ADS-1 setpoint. No core heatup was observed during any of the tests. Oscillations were observed during several of the tests, and were especially persistent during the SGTR tests. However, the reactor vessel liquid levels were well above the top of the simulated core. Responding to the staff requests, the applicant provided plausible explanations for the observed phenomena, relating them to density-wave oscillations that ceased when the steam generators drained. Since in a LOCA this would occur well before any possibility of uncovering the core, the behavior did not raise safety concerns. In the SGTR test, the steam generators did not drain for an extended period, causing the oscillations to persist. However, this did not affect the ability of the CMTs to recirculate and stabilize the system pressure and temperature without ADS actuation. The applicant's response adequately resolved the staff's concerns.

The primary issues to be addressed by the SPES-2 tests were related to integral systems behavior, especially at elevated pressures beyond those covered in the OSU/APEX-600 experiments. Examples of these issues were as follows:

- system response and systems interactions in the early stages of DBAs, including transition from CMT recirculation to CMT draining, accumulator injection, and effects of early stages of depressurization

- for non-LOCA transients, ability of the system to come to a stable condition at elevated pressures

Testing and Computer Code Evaluation

WCAP-14727, Revision 2, "AP600 Scaling and PIRT Closure Report," addressed issues related to distortions from identified sources (e.g., excess power to compensate for heat losses) and "validation" of those aspects of the AP600 PIRT relevant to the SPES-2 tests. The major technical issue not related to distortions was the oscillatory behavior, which was acceptably resolved as discussed above. The staff concluded that the SPES-2 test program accomplished its objectives and that the applicant developed a database that addressed the issues raised by the staff. Also, as with the APEX-600 test program, insights gained from NRC-sponsored AP600 confirmatory testing in both the ROSA facility and the OSU/APEX-600 facility were considered in the SPES-2 evaluation. Therefore, on the basis of its review of the test program reports and the applicant's responses to the staff's requests for additional information (RAIs), the staff determined that the SPES-2 testing program was acceptable and met the requirements of 10 CFR 52.47(b)(2)(i)(A).

Applicability of SPES-2 Test Program to AP1000

In Section 21.5.7 of this report, the staff performed a scaling analysis of the integral effects test program to evaluate the applicability of the SPES-2 test program to the AP1000 design.

21.5.7 Scaling Analysis for Application of AP600 Integral Effects Tests to AP1000

The AP600 integral-effects tests from the APEX-600 and SPES facilities provide experimental data. The applicant simulated the tests and used the data for the AP600 code validation and design certification. The staff evaluated the applicability of these integral-effects tests to the AP1000 code validation and design certification through both top-down and bottom-up scaling analyses, as described in the following subsections.

21.5.7.1 Westinghouse Scaling Analysis

Section 4 of WCAP-15613 documents the applicant's scaling evaluation to demonstrate the applicability of the AP600 test program database to the AP1000 safety analysis code validation. Specifically, that scaling evaluation provides a quantitative means to evaluate whether important AP1000 phenomena are preserved in the test facilities that were originally scaled for the AP600 plant design.

As in the AP600 scaling evaluation of the passive core cooling system test facilities, the top-down system-level scaling analysis of the integral-effects tests is based on the SBLOCA transients. This is because an SBLOCA transient includes broad ranges of T-H behavior, and all of the safety features of the passive core cooling systems (PXS) are employed during the transient. In an SBLOCA, the RCS depressurizes during initial blowdown through the break. As the safeguard ("S") signal actuates the passive safety system, the RCPs trip quickly, and the RCS passes into natural circulation. In the early stage, the RCS experiences single-phase natural circulation, with the SGs providing the dominant heat sink. This is followed by a later phase when the PRHR becomes the dominant heat sink after the SGs have drained. As the primary system drains, it passes into two-phase natural circulation, in which a mixture exists in the cold and hot-legs; the CMT cold-leg pressure balance line is either two-phase or steam, and the CMTs are draining. There is boiling in the core and a two-phase mixture leaves the core and flows into the hot-legs. Steam or a two-phase mixture enters the PRHR with single-phase water leaving.

Similar behavior occurs in the CMTs, in which a two-phase mixture or steam enters the cold-leg balance line and liquid flows from the CMT to the vessel in the DVI line. As the CMT drains to a level of 67.5 percent, ADS-1 is actuated, followed by ADS-2/3, resulting in RCS depressurization by venting the steam from the pressurizer to the IRWST. The accumulators also inject borated water into the RCS as it depressurizes below the accumulator pressure.

During the ADS-1/2/3 blowdown phase, a portion of the system (such as the DVI line, vessel downcomer, and lower plenum) remains single-phase. The remainder of the system is two-phase, including the core, upper plenum, hot legs, pressurizer, and pressurizer surge line, which now fills in response to the activation of ADS-1/2/3. As the CMT drains to 20 percent, ADS-4 is actuated, and its blowdown further depressurizes the RCS to enable IRWST injection.

The ADS-4 blowdown transition to the inception of IRWST injection is considered critical in the AP1000 passive plant design because it is in this period that minimum inventory in the reactor vessel is expected to occur. During the IRWST injection, the RCS is an open system with the IRWST feeding the reactor vessel by gravity injection, which flows through the DVI line into the downcomer, then up and around the downcomer and out the break to the sump, or down the downcomer into the core and out the ADS-4 valves on the hot legs to the containment.

As the IRWST drains, containment sump injection (or recirculation) is initiated. The sump injection period is similar to the IRWST injection, with the exception that the system is now a closed loop with the primary system coupled to the containment, which provides for LTC.

The applicant divided the SBLOCA transient into the following six phases:

(1) initial blowdown
(2) natural circulation
(3) ADS-1/2/3 depressurization
(4) ADS-4 to IRWST transition
(5) IRWST injection
(6) sump injection

One major difference in this breakdown of the transient phases from that of the AP600 design is the addition of the ADS-4 to IRWST transition. This phase was added to facilitate its study for the AP1000 review. This is the most important phase in a SBLOCA, as the minimum mixture level in the reactor vessel is expected to occur during this period. As in the AP600 scaling analysis, the applicant's AP1000 scaling analysis does not consider the initial blowdown phase because it is a relatively short period common to both current operating plants and the advanced passive plant design, and does not involve passive safety system components.

For the top-down scaling analysis, system-level conservation equations are written to address the important processes and parameters that are involved in each specific phase. The equations are combined in a form which identifies the physical processes and key parameters of interest, such as reactor vessel inventory, pressure, quality, or void fraction. The variables in the combined equations are non-dimensionalized using reference values appropriate for the specific period of the transient, and the resulting dimensional coefficients in the equations are then normalized using the coefficient of the dominant process. The end result yields dimensionless Pi groups. The test facility/plant scaling ratios of these Pi groups are then calculated and compared to the acceptance criteria to determine if the test facility is sufficiently scaled to the full-scale plant.

For the natural circulation phase, two-phase natural circulation with PRHR providing heat removal is analyzed by combining the steady-state mass, momentum, and energy equations into a core exit quality scaling ratio expression in terms of the dominant influences (such as PRHR gravity head, PRHR flow path hydraulic resistance, and core decay power). The scaling ratios of core exit quality between the test facility and the AP1000 design indicate that the SPES facility with a scaling ratio of 0.71 is sufficiently scaled for the AP1000 design, whereas the APEX-600 facility with a scaling ratio of 5.0 is not well-scaled for the natural circulation phase for the AP1000.

For the ADS-1/2/3 blowdown depressurization phase, the scaling analysis is performed with the rate of pressure change equation for the ADS depressurization process. The analysis produces the scaling ratios of two Pi groups; one group is the ratio of core steam generated by the decay heat to RCS steam volume, and the other is the ratio of the steam venting through ADS-1/2/3 to the RCS steam volume. The resulting scaling ratios of these two Pi groups show that the SPES facility having scaling ratios of 0.77 and 1.26 respectively for these two Pi groups is sufficiently scaled to the AP1000 design; however, the APEX-600 facility has distortion in the ratio of ADS-1/2/3 steam venting to the RCS steam volume with a scaling ratio of 5.58.

The top-down scaling analysis of the ADS-4 to IRWST transition phase considers the CMT injection dominating subphase, the IRWST-injection dominating subphase, and the ADS-4 depressurization phase. For the CMT-injection and the IRWST-injection dominating subphases, the scaling analyses are derived from the transient equations of the reactor vessel inventory. For the ADS-4 blowdown, the scaling analysis is derived from the rate of RCS pressure change. The scaling analyses of these subphases generate seven Pi groups. The facility/plant scaling ratios of these Pi groups (with scaling ratios between 0.5 and 2) showed that the APEX-600 and SPES facilities are sufficiently scaled to the AP1000 design, when the ADS-4 flow is critical. When the ADS-4 flow is subcritical, the SPES facility (with an ADS-4 vent/RCS steam volume Pi group ratio well over 2) is distorted as a result of the oversized ADS-4 vent paths.

The applicant also performed a scaling analysis applicable to the NRC-sponsored test NRC-25, which was performed at the APEX-600 facility. This test included a series of 10 “core uncovery tests,” in which the RCS was drained to the hot-leg level and the IRWST was pressurized to simulate AP600 IRWST gravity injection. The ADS-4 vents were used to depressurize the system. The top-down analysis of the IRWST injection, where the two-phase resistance dominates, derived a Pi group for the equilibrium quality. The scaling ratio (1.55) of this Pi group indicates that the APEX facility is sufficiently scaled for the AP1000 standard plant design.

The scaling analyses of the IRWST and sump injection phases are performed to determine the core exit quality, which impacts the thermodynamic state, two-phase flow regime, and pressure drop. By combining the conservation of mass, momentum, and energy, an expression is developed for the core exit quality. Expressions are then derived for the core exit quality scaling ratio, which contain a density ratio, a gravity head to resistance ratio, and a core power to enthalpy ratio. The scaling ratios show that the core exit quality of the APEX-600 facility (scaling ratio of 1.24) is sufficiently scaled to the AP1000 design; however, the SPES facility (with a scaling ratio well below 0.5) is not well-scaled to the design, as it did not simulate sump injection.

It should be noted that the top-down scaling approach used in the AP1000 review is not the same approach used in licensing the AP600 design, as documented in WCAP-14727. Unlike the AP600 design, the AP1000 top-down scaling approach combines the mass, momentum, and energy equations into a single expression for the parameter of interest and significantly reduces the number of scaling groups.

To complement the applicant's top-down scaling analysis for the AP1000 standard plant design, the staff requested (RAIs P55, P56, P57, and P58) that the applicant provide the AP1000 numerical values of those Pi groups listed for the AP600 design in Tables 3.2-8 through 3.2-12 of WCAP-14727, Revision 2, which were derived directly from the separate momentum and energy equations. Assessments of these Pi groups would provide consistency with that accepted for the AP600 design. In response to the staff's RAIs, the applicant provided the numerical values of these Pi groups for the two-phase natural circulation, ADS blowdown, and IRWST and sump injection phases. For each Pi group in a transient phase, the applicant provided the Pi value for the SPES and APEX-600 facilities and the AP600 and AP1000 plants, as well as the facility-to-AP1000 scaling ratios.

For the majority of the Pi groups, the scaling ratios between the facility and the AP1000 design are within the acceptance criteria. For certain Pi groups, the scaling ratios are outside of the acceptance criteria, indicating scaling distortion; however, some of the distorted Pi groups are insignificant as indicated by their small Pi values relative to other more dominating terms. These insignificant Pi groups include the inertia-to-buoyancy ratio, the phase change momentum flux-to-buoyancy ratio for the natural circulation phase, the single-phase pressure compliance-to-core power ratio, the two-phase mechanical compliance-to-core power ratio for the ADS blowdown phase, and the inertia and momentum flux terms for the IRWST and sump injection phases.

For the IRWST injection phase, the scaling ratios of the Pi group of the resistance-to-buoyancy ratio for the SPES and APEX-600 facilities are outside of the acceptance criteria. The applicant states that the formulation of this scaling group was derived from the AP600 program on the basis of the single-phase contribution to resistance of the DVI and ADS paths, which significantly understates the two-phase resistance associated with the ADS flow path. Therefore, the scaling of this phase was reformulated for the AP1000 to account for the two-phase resistance associated with the ADS flow path in WCAP-15613. The results show that the APEX-600 facility is well-scaled to the AP1000 design, while the SPES facility shows distorted scaling. Therefore, the staff concludes that data from the SPES facility are not appropriate for code validation for the AP1000 IRWST injection phase.

In the ADS blowdown phase, the scaling ratios (provided in the applicant's response to RAI P56) showed that the SPES facility has slight distortions for the Pi groups of the boiling heat to core power ratio and the single-phase mechanical compliance-to-core power ratio. Since the scaling ratios of these two Pi groups are just slightly outside the applicant's acceptance criteria, this does not preclude the use of SPES facility for code validation. However, the scaling analysis also showed that the APEX-600 facility has distortion in the sensible heat-to-core power Pi group. Therefore, the staff has determined that AP1000 code validation using the APEX-600 facility is not acceptable during the ADS blowdown phase.

To supplement the top-down system-level scaling analyses, the applicant performed the bottom-up scaling analyses for the important local processes or phenomena (during various phases of the transient) that are not captured in the top-down scaling analysis. For the natural circulation phase, the bottom-up scaling analyses are performed for the flow patterns and phase separation at the cold-leg T-junction at the CMT balance line. The cold-leg flow pattern is analyzed on the basis of the Taitel-Dukler horizontal flow regime transition map (AIChE Journal, Vol. 22, No. 1, pp. 47-55, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," January 1976), and the facility/plant scaling ratio of the Froude number is calculated. The resulting scaling ratios show that the APEX-600 and SPES facilities are sufficiently scaled to both the AP600 and the AP1000 designs. The scaling analysis of phase separation at the cold-leg-CMT balance line junction is performed on the basis of the correlation developed by Seeger, et al. (Int. J. Multiple Flow, Vol. 12, No. 4, pp. 575-585, "Two-phase Flow in a T-Junction with a Horizontal Inlet, Part I: Phase Separation," 1986), for a top vertical branch in a non-stratified upstream flow regime, which correlated the quality ratio to the mass flux ratio of the branch and the main pipes. The facility/plant scaling ratio of the balance line-cold-leg quality ratio shows that the APEX-600 and SPES facilities are sufficiently scaled to the AP1000 design.

During the initial stage of the ADS-1/2/3 blowdown when only steam is vented, the applicant states that the APEX-600 facility surge line length-to-diameter ratio and surge line layout are preserved relative to the AP600 standard plant design to preserve the surge line pressure drop. Because those values are unchanged in the AP1000 design, the surge line pressure drop should also be preserved for that design. However, in the later stages of ADS-1/2/3 depressurization, a two-phase mixture flows through the surge line into the pressurizer.

The applicant stated that the principal investigator found that the APEX-600 facility was probably distorted for some flow patterns (such as the slug-annular flow regime transition) with respect to the AP600 design. Therefore, the applicant anticipates (and the staff agrees) that some distortion may also exist with respect to the AP1000 design. In addition, the length-to-diameter ratio of the SPES facility is not scaled, and the flow pattern transition scaling analysis was not performed. The applicant contended that although there may be some distortion of flow regime in the surge line of the SPES and APEX-600 facilities, it should only affect the later stages of the ADS depressurization when a two-phase mixture is discharged.

For the ADS-4 to IRWST transition phase, the bottom-up scaling analysis considered hot leg flow pattern, liquid entrainment from the hot leg into the ADS-4, and countercurrent flow in the surge line during pressurizer draining. Like the cold-leg flow pattern, the hot-leg flow regime transition from stratified to non-stratified flow is an important phenomenon as it influences pressure drop and entrainment in the ADS-4 flow path. Taitel-Dukler's general flow regime map for the horizontal two-phase flow is used to predict flow regime transitions. A scaling ratio expression between the test facility and plant is derived on the basis of preserving the modified Froude number used in the Taitel-Dukler flow regime map and pressure similitude. The scaling ratios show that the APEX-600 and SPES facilities are sufficiently scaled to the AP1000 design.

The scaling analysis for ADS-4 entrainment is performed for the onset of liquid entrainment on the basis of the following correlation of the onset of liquid entrainment for a vertical offtake with stratified flow in the main pipe using an expression of the following form:

$$Fr_g = \frac{U_g}{\sqrt{\frac{gd\Delta\rho}{\rho_g}}} = C_1\left(\frac{h_b}{d}\right)^{C_2}$$

where Fr is the Froude number, U_g is the superficial velocity of steam, g is gravitational acceleration, ρ_g is the density of steam, $\Delta\rho$ is density difference, d is the off-take pipe diameter, and h_b is the distance from the top of the pipe to the stratified level. The coefficients C_1 and C_2 are functions of the orientation and geometry of the offtake, with C_1 ranging from 0.35 to 5.7 and C_2 ranging from 1.5 to 2.5.

A scaling ratio relation for the entrainment onset is derived assuming pressure similitude. The APEX-600/AP1000 scaling ratio for entrainment onset is calculated to be 0.69, which indicates that the APEX-600 facility is sufficiently scaled; however, the SPES facility has distortion with a scaling ratio of 0.14. Therefore, tests from the SPES facility are not appropriate for AP1000 code validation regarding ADS-4 liquid entrainment.

The scaling analysis for countercurrent flow in the surge line and pressurizer draining is performed on the basis of the Kutateladze flooding relation. The applicant examined the scaling of the Kutateladze number during this transition phase with the pressurizer draining. For scaling purposes, because the pressurizer is poorly vented as the ADS-1/2/3 path is plugged by a column of water above the sparger in the IRWST during this phase of a transient, the mode of pressurizer draining can be described as an equal volume replacement process so that the superficial velocities of liquid and steam in the Kutateladze number are equal. With this assumption, the scaling relationship simply states that the superficial velocity (and hence the Kutateladze number) is preserved in the test facilities and the AP1000 plant as pressure similitude exists.

For the IRWST injection phase, the bottom-up scaling analysis is performed for the reactor core void fraction on the basis of the Yeh correlation (Nuclear Engineering and Design 60, pp. 413-429, "Mass Effluence During FLECHT Forced Reflood Experiments," 1980). By preserving the void fraction between the test facility and the plant, the scaling ratio of the Pi group for the core exit void fraction is derived. The scaling ratio of the Pi group shows that the APEX-600 facility is sufficiently scaled to the AP1000 design.

21.5.7.2 NRC Independent Top-Down Scaling Assessment

The staff performed an independent scaling assessment to determine whether the AP600 test program also applies to the AP1000 standard plant design. The staff's review and assessment of scaling did not address containment phenomena and was limited to those affecting the AP1000 primary system. The review and assessment of the applicability of test programs to the AP1000 design considered both the primary and containment systems. (The assessment of the containment system is addressed in Section 21.6.5 of this report.)

During its assessment, the NRC staff performed both top-down system-level and bottom-up process scaling evaluations of the SPES, ROSA, and APEX-600 facilities for applicability to the AP1000 code validation and confirmation of safety margin. In general, at least one facility is well-scaled for the AP1000 standard plant design during the early, high-pressure blowdown periods, and later after sump injection occurs. However, the transition from ADS-1/2/3 blowdown to IRWST injection shows distortions that raise significant concerns. The staff's scaling evaluation follows the methodology developed by Idaho National Engineering Laboratory (INEL) (INEL-96/0040, "Top-Down Scaling Analysis Methodology for AP600 Integral Tests," May 1997) to evaluate scaling for the AP600 standard plant design. The independent scaling analysis considered five separate periods:

(1) subcooled blowdown
(2) intermediate (ADS-1/2/3 venting)
(3) ADS-4 blowdown
(4) IRWST injection
(5) sump injection

The intermediate and IRWST injection periods were also divided into subphases to examine additional system processes. The following paragraphs discuss the staff's conclusions regarding these scaling evaluations beginning with a summary of the top-down scaling analysis.

Subcooled Blowdown Phase

The subcooled blowdown phase is initiated by the break, and ends just after the pressurizer drains. Differences in core power and pressurizer volume between the AP1000 and the AP600 designs affect some scaling groups. However, no significant distortions were found by comparing the AP1000 Pi groups to those of the SPES and ROSA facilities. Therefore, code validation on the basis of the SPES facility is acceptable.

Intermediate (ADS-1/2/3) Blowdown Phase

The intermediate blowdown phase is considered to be composed of three subphases. Subphase I begins with pressurizer draining and extends to when the hot legs, upper head, and SG reach saturation pressure. Subphase II extends from the end of Subphase I to the initiation of net inflows to the RCS from the accumulators or CMTs. Subphase III extends from the initiation of accumulator injection or CMT draining to the opening of ADS-4. During the intermediate periods, the ADS-1/2/3 system actuates, the PRHR becomes active, and the CMTs begin to drain, as follows.

- Intermediate Subphase I—For this period, the staff finds that the most important Pi group for the AP1000 design agrees well with that for the SPES facility (indeed, it agrees with that for the SPES facility better than that for the AP600 design). (There may, however, be some distortion in comparisons of Pi groups with minor importance.) Therefore, code validation on the basis of the SPES facility data is acceptable.

- Intermediate Subphase II—In general, scaling groups for this period are in good agreement between the SPES facility and the AP1000 design. No significant, nonconservative distortions exist and, thus, the SPES facility is adequate for code validation. With regard to PRHR performance, the AP1000 design exhibited better agreement with the ROSA Pi groups than with the SPES Pi groups. Thus, conclusions regarding simulation of PRHR heat transfer have higher confidence if based on tests of the ROSA facility rather than the SPES facility. Nonetheless, the Pi group values are close enough that overall code validation on the basis of the SPES facility data is considered acceptable.

- Intermediate Subphase III—The Pi groups for this period show good agreement between the SPES facility and the AP1000 design. Differences between scaling groups for AP1000 and the SPES facility are either small or conservative. Therefore, code validation on the basis of the SPES facility is acceptable.

ADS-4 Blowdown Phase

The staff's top-down scaling analysis shows that there may be distortions during the ADS-4 blowdown period. Early in this period when the system pressure is high, the flow is critical. Assuming critical flow, the SPES and ROSA facilities are appropriately scaled for the AP1000 standard plant design conditions during ADS-4 blowdown. The APEX-600 facility however, was found to have non-conservative distortions. The analysis considered a 2.54-cm (1-in.) cold-leg break and a DEDVI, and found that the SPES facility is appropriate in both scenarios, but the APEX-600 facility is not appropriate (by contrast, for the AP600 standard plant design, this approach found that the APEX-600 facility is acceptable, but the SPES facility had conservative distortions). Eventually, the system pressure decreases and the ADS-4 flow becomes noncritical. Assuming noncritical flow from the system, the APEX-600 facility becomes appropriately scaled for the AP1000 design based on scaling groups defined in the INEL scaling methodology. On that basis, code validation using the SPES facility is considered acceptable during the high-pressure phase of the ADS-4 blowdown, but the APEX-600 facility is not considered acceptable until late in the period when the IRWST transition is about to occur.

This conclusion conflicts with the applicant's scaling analysis and the conclusion that the APEX-600 facility is appropriately scaled while flow is critical in the ADS-4 to IRWST transition period. The scaling methodology in WCAP-15613 defines dimensionless groups and calculates values showing that the SPES and APEX-600 facilities are correctly scaled. The response to RAI P56 (issued on August 22, 2001 during the AP1000 pre-application review), however, lists "single-loop" scaling groups for the ADS blowdown phase. The applicant cited both the SPES and APEX facilities as having distortions, yet these facilities are considered by the applicant to be acceptable for code validation. The staff concludes, however, that code accuracy and validation in the ADS-4 transition period should be based on the SPES facility simulation. The staff further discusses this issue in Section 21.5.7.4 of this report.

IRWST Injection/Drain Phase

Results of the top-down scaling analysis show that the APEX-600 facility is appropriately scaled for the AP1000 standard plant design. Therefore, code validation on the basis of that facility is acceptable.

IRWST/Sump Injection Phase

Results of the top-down scaling analysis show that the APEX-600 facility is appropriately scaled for the AP1000 standard plant design. Therefore, code validation on the basis of that facility is acceptable.

21.5.7.3 NRC Independent Bottom-Up Scaling Assessment

Conclusions from the staff's independent bottom-up scaling analysis are as follows:

- Froude number comparisons indicate that the SPES facility appropriately scales both the hot and cold-leg flow regimes for the high-pressure periods in the AP1000, and the APEX-600 facility appropriately scales these regimes for the low-pressure periods of the SBLOCA and LTC.

- The experimental data in the integral-effects tests are not considered sufficient to validate code models for entrainment and carryover for the AP1000 standard plant design.

- Entrainment in the hot-leg and carryover into the branch lines leading to the ADS will occur to a greater extent in the AP1000 design than in the AP600 design or APEX-600. Because of higher steam velocity during ADS-4 blowdown in the AP1000 plant, and because the applicant was basing its scaling evaluation on a correlation that may not be applicable to the AP1000 geometry, the applicant did not demonstrate that the existing data are sufficient to validate hot-leg entrainment models for the AP1000 design.

- Specifically, the AP1000 hot-leg-to-branch line diameter ratio is significantly larger than the ratio used in developing the entrainment onset correlation. Alternative evaluation and scaling of entrainment onset leads to the conclusion that entrainment is more prevalent and will occur at lower hot-leg water levels in the AP1000 design than in the tests.

- None of the AP600 integral-effects tests appropriately scale the facilities entrainment from the pool of water in the upper plenum above the upper core plate for the AP1000 standard plant design. The staff's evaluation of entrainment from the upper plenum pool shows that the rate of entrainment in the AP1000 design will be significantly higher than shown in the integral-effects tests.

In Section 21.5.7.4 of this report, the staff further discusses the liquid entrainment issue related to the last two findings above.

21.5.7.4 Scaling Assessment Findings Regarding AP600 Test Program

Given the evaluation discussed above, the staff finds that the AP600 test program is generally applicable for code validation of the AP1000 standard plant design. However, the staff also found in the DSER that additional validation was necessary for the liquid entrainment phenomena. The ADS-4 blowdown period to the inception of IRWST injection is important in the AP1000 passive plant design because it is during this period that minimum inventory in the reactor vessel is expected to occur. Compared to the AP600 standard plant design, the AP1000 design has 76 percent higher core power and, therefore, higher steam flow in the upper plenum, hot leg, and ADS discharge during the ADS-4 blowdown. Although the AP1000 hot-leg diameter remains the same 78.7 cm (31 in.) as in the AP600 design, the diameters of the ADS-4 valves and the off-take pipe from the hot leg are increased from 25.4 and 30.5 cm (10 and 12 in.) to 35.6 and 45.7 cm (14 and 18 in.), respectively. The higher steam flow and larger ADS-4 diameter will affect liquid entrainment through the ADS-4 discharge.

As described in Section 21.5.7.2 of this report, the NRC staff's top-down scaling analysis revealed that, during the early phase of the ADS-4 blowdown when the flow is critical, the APEX-600 facility has a nonconservative distortion. The staff, therefore, asked the applicant to justify its basis for the acceptability of the AP600 code validation for the AP1000 design, or determine whether additional AP1000 testing was necessary for code validation of the ADS-4 blowdown. In its response, the applicant stated that it did not agree with the staff's conclusion that the APEX-600 facility is not suitably scaled for the ADS-4 blowdown phase, and additional hot-leg entrainment data for ADS-4 blowdown was not needed for AP1000 code validation. Even though it was expected that higher liquid entrainment may occur in the AP1000 design than in the AP600 design during the ADS-4 blowdown, the applicant contended that this does not render the AP600 code validation unacceptable for the AP1000 during the ADS-IRWST transition phase. Moreover, the applicant contended that the APEX-600 test facility showed significant entrainment during the ADS-4 blowdown phase. The staff did not agree with this finding.

The applicant's scaling assessment for the ADS-IRWST transition phase included both top-down and bottom-up analyses. The overall top-down scaling analysis generated several Pi groups. The test facility/plant scaling ratios of these Pi groups showed that the APEX-600 and SPES facilities were sufficiently scaled to the AP1000 design for choked ADS-4 flow and with respect to core power. When ADS-4 flow is subsonic, the SPES facility is distorted as a result of its oversized ADS-4 vent paths. As discussed in Section 21.5.7.2 of this report, the staff's top-down scaling analysis showed that when the ADS-4 flow is choked, the SPES facility is appropriately scaled for the AP1000 design, but the APEX-600 facility is distorted.

Although the applicant's bottom-up scaling analysis of entrainment onset concluded that the APEX-600 facility is well-scaled for the AP1000 standard plant design, the staff found, as described in the DSER, that the applicant's analysis contained several shortcomings.

Testing and Computer Code Evaluation

- The applicant's scaling analysis was based on an entrainment onset correlation in which the applicability to the AP1000 geometry has not been confirmed. This correlation was derived from experimental data with a small branch line to main pipe diameter ratio (d/D), which may not be appropriate for the AP1000 design because it has a large d/D ratio.

- Existing correlations are based on tests performed with small offtake diameter more than 10 times smaller than the main pipe diameter, as summarized by Ardron and Bryce, 1990. In the AP1000 design, the ADS-4 branch pipe diameter to hot-leg d/D is large and is considerably larger than that in any supporting test data.

- The general entrainment onset correlation does not account for the effect of viscosity and liquid surface tension, which may affect liquid entrainment. Correlations that account for these parameters suggest that significant entrainment will occur for the AP1000 design, but will not occur in the tests the applicant has used for code validation.

The staff, therefore, did not agree with the applicant's approach for scaling hot-leg phase separation, and did not agree that the test data that the applicant used in experiments to validate its codes adequately represent the process as it would occur in the AP1000 design. In particular, the applicant had not demonstrated that its codes appropriately account for the high rates of hot-leg entrainment observed in OSU's ATLATS facility (RAI 440.151), or that the codes have the ability to model all of the flow patterns that may occur in the AP1000 hot-leg (RAI 440.155).

The staff, however, performed audit calculations and sensitivity studies using RELAP5. These studies showed that the impact of poorly modeling hot-leg phase separation has only a small effect on the minimum vessel inventory for the AP1000 DEDVI. The staff sensitivity studies took into account hot-leg phase separation from the ATLATS facility at OSU. The staff calculations suggest that precise modeling of hot-leg phase separation is not a safety-significant issue in AP1000, and that the core remains covered even under the conservative assumption of zero phase separation in the hot-leg. As discussed in Section 21.6.2 of this report, the applicant also demonstrated that its codes show the same sensitivity and that the conclusion that hot-leg phase separation is not safety significant applies to other small-break scenarios.

Based on its scaling evaluation, the staff also concluded that upper plenum pool entrainment was an issue for the AP1000 design. Experiments in the APEX-600 facility as well as in simulations of the AP600 design showed that the double-ended guillotine break of one of the DVI lines and a 25.4-cm (10-in.) cold-leg break could lead to the minimum vessel inventory or core uncovery. Entrainment of liquid from the upper plenum will be significant, and will be more important in the AP1000 design than in the AP600 design. The NRC staff conducted a bottom-up scaling evaluation of upper plenum entrainment. Pool entrainment is a complex process that is highly dependent on the gas velocity bubbling through the pool, and the height to which droplets and other entrained liquid must be elevated to exit the vessel. The AP1000 core power is 76 percent higher than in the AP600 design, but the upper plenum design is nearly identical. The entrainment is often defined as the ratio of the droplet upward mass flux to the gas mass flux:

$$E_{fg} = \frac{\rho_f J_{fe}}{\rho_g J_g}$$

Where ρ_f and ρ_g are liquid and gas phase densities, J_g is the gas superficial velocity, and J_{fe} is the entrained phase superficial velocity.

Expressions for E_{fg} show the following functional dependence:

$$E_{fg} \propto (J_g)^n$$

The exponent n is generally 3 or higher. Assuming pressure similitude and preserving the dimensionless height ratio, the AP1000 upper plenum pool entrainment can be expected to be at least 1.76 to 5.45 times as large as that in the AP600 design. Consideration of experimental tests scaled to the AP600 design power levels leads to the conclusion that the AP1000 upper plenum entrainment is significantly higher than entrainment in the integral-effects tests.

To address upper plenum entrainment, the staff issued several RAIs (including 440.162, 440.169, 440.170, 440.171, and 440.172) requesting the applicant to provide additional supporting information on its modeling approach for upper plenum entrainment, and to provide justification that the correlations in its codes were validated by appropriate experimental data. New information provided by the applicant in response to these RAIs 440.164 and 440.171 to resolve the upper plenum entrainment issue raised new concerns on core modeling and the calculation of level swell. (The staff notes that these RAIs were based on the staff review of the applicant's topical report WCAP-15833, "WCOBRA/TRAC AP1000 ADS-4/IRWST Phase Modeling," December 2002, which describes a special version of the WCOBRA/TRAC code, called "WCOBRA/TRAC-AP." The original intent of WCAP-15833 was to support validation of the NOTRUMP code for the AP1000 SBLOCA analysis. Subsequent to submitting this report, the applicant applied alternate means of validating NOTRUMP, primarily comparison to test data. In WCAP-15644, Revisions 1 and 2, the applicant deleted the WCOBRA/TRAC-AP supplemental calculation as part of SBLOCA analysis. In its letter of March 10, 2004, the applicant stated that it is not relying on WCAP-15833 to support the AP1000 Design Certification review, as this report is no longer referenced in the AP1000 DCD. Therefore, WCAP-15833 and WCOBRA/TRAC-AP are no longer relevant to the AP1000 design. However, many of the RAIs, even though related to WCAP-15833, are applicable to analysis codes such as NOTRUMP in general.)

With regard to upper plenum entrainment scaling, the staff found in the DSER that none of the AP600 integral-effects test facilities are sufficiently well-scaled to provide an acceptable database to validate T-H codes for the high rates of liquid entrainment that are expected to occur in the AP1000 design during ADS-4 and IRWST injection periods of an SBLOCA. The staff did not agree with the applicant's assertion that it had provided adequate scaling evaluation for the AP1000 upper plenum entrainment phenomena.

The applicant had also not demonstrated that the existing AP600 integral-effects tests provide data over the range of conditions necessary to validate entrainment models in the codes that the applicant intended to use. The staff concluded that the applicant must either obtain entrainment test data applicable to the AP1000 steam flow rates for code validation, or provide proper justification for the entrainment models to be used for the AP1000 applications.

Therefore, in the AP1000 draft safety evaluation report (DSER), the staff identified three issues related to three important processes during a SBLOCA needing further study. Specifically, those issues were (1) phase separation in the hot leg, (2) upper plenum pool entrainment, and (3) level swell in the core. The following discussion summarizes each of these issues.

Hot-Leg Phase Separation

Hot-leg phase separation refers to the T-H processes that occur near the ADS-4 branch line connection that act to entrain liquid in the hot leg and carry that liquid over into the ADS-4 system. As discussed above, the staff concluded that this process was not well scaled in the tests used to validate AP1000 safety analysis codes, and that the higher steam velocities in the AP1000 design would result in much higher liquid carry over into the ADS-4 than in the AP600 design. This could cause a relatively large two-phase pressure drop in the AP1000 design and delay the start of IRWST injection.

Correlations currently used in the T-H codes, and used to scale the hot-leg phase separation process for AP1000 design assume that the flow pattern is horizontal-stratified. However, recent experimental information obtained from the ATLATS facility at OSU showed that the hot-leg flow pattern is not horizontal-stratified when most entrainment occurs. Rather, an oscillating slug of liquid forms between the branch line and SG inlet plenum and slug behavior dominates the entrainment process.

The applicant’s submittals and responses to RAIs concerning hot-leg phase separation were not sufficient to demonstrate that the codes used in AP1000 safety analysis model the hot-leg phase separation process correctly. However, the sensitivity studies by the NRC staff to investigate the effect of modeling this process on important AP1000 transients indicated the effect to be relatively small. Therefore, in the DSER, the staff identified Open Item 21.5-1, which requested the applicant to confirm the sensitivity studies performed by the staff using the code(s) the applicant intends to use to model SBLOCAs in AP1000. The staff expected that the confirmatory analyses would range hot-leg entrainment consistent with ATLATS data and show that the uncertainty in modeling hot-leg phase separation does not represent a significant safety issue in AP1000. The resolution of Open Item 21.5-1 is discussed in Section 21.6.2 of this report.

Upper Plenum Pool Entrainment

Upper plenum pool entrainment refers to the T-H processes that carry liquid out of the upper plenum and into the hot leg, where it is likely to be swept into the ADS-4 piping. The process is of importance in transients such as a DEDVI or an inadvertent ADS actuation. In these transients, core uncovery and cladding heat up are prevented by the liquid level above the top of the active fuel. With the higher power and steam production in AP1000 design, carry over from the vessel may increase and lead to core uncovery.

As discussed earlier in this section, the staff, based on its examination of scaling and test data, concluded that scaled entrainment rates in the upper plenums of the tests used to assess T-H codes for AP600 design were too low to be used for that purpose in AP1000 design. The applicant originally attempted to validate NOTRUMP for the ADS-4/IRWST injection transition period by using WCOBRA/TRAC-AP described in WCAP-15833. In order to justify the models, correlations, and methods to predict upper plenum entrainment in the AP1000 design, the staff requested the applicant to provide additional information. The staff requested additional information (RAIs 440.149 through 440.180) regarding WCAP-15833. Some of the RAIs (e.g., RAIs 440.151 through 440.157) are related to scaling of upper plenum and hot-leg entrainment processes, and on the models used by the applicant to predict processes within the upper plenum and hot-leg during a SBLOCA. The applicant responded to the RAIs by the submittal of WCAP-15833, Revision 2, and by the responses to several RAIs. However, as described earlier in this section, the applicant revised its SBLOCA analysis model in that WCOBRA/TRAC will no longer be used for supplemental calculation for the transition phase from ADS-4 actuation to the IRWST transition phase. Therefore, WCAP-15833 is no longer relevant for the AP1000 SBLOCA analysis. In the AP1000 DSER, the staff identified Confirmatory Item 21.5-1, which the applicant committed to update WCAP-15833 to include the final RAI responses. Since WCAP-15833 is no longer relevant to AP1000 SBLOCA analysis, the staff concludes that Confirmatory Item 21.5-1 is resolved.

In the AP1000 DSER, the staff stated that the applicant’s submittals did not provide sufficient justification that the models and correlations in NOTRUMP or WCOBRA/TRAC had been adequately assessed to cover the ranges expected to occur in the upper plenum of the AP1000 design. While correlations existed to model the upper plenum entrainment phenomenon, the issue that remained was adequacy of the database. Existing correlations were based on relatively small diameter vessels, low gas flow rates, and for some data, air-water as opposed to steam-water. Because of the small vessel size in these data, conditions were essentially one-dimensional. Flow in the upper plenum of the AP1000 design is expected to be nonuniform and three-dimensional. Thus, a suitable database for assessing entrainment correlations in the upper plenum had not been established. Given the lack of well scaled experimental data on upper plenum entrainment phenomena and the importance of predicting this process in the AP1000 SBLOCA transients, the staff recommended that new experimental data be obtained to support the use of the upper plenum entrainment models in the AP1000 design. This data was requested by the NRC staff in letter, “AP1000 Request for Data to Resolve Liquid Entrainment Request for Additional Information,” dated March 18, 2003, from J. Lyons. Subsequently, the applicant provided test data from the APEX-1000 test facility at OSU to address the liquid entrainment issue. The staff evaluation of APEX-1000 test program discussed in Section 21.6.2 of this report. The upper plenum pool entrainment issue was identified as DSER Open Item 21.5-2. The resolution of Open Item 21.5-2 is described in Section 21.6.2 of this report.

Core Level Swell

Level swell refers to the effect of T-H processes such as two-phase interfacial drag, interfacial area generation and flow pattern transitions that cause a two-phase mixture level to exceed the collapsed water level in the core. In the AP1000 design, prediction of level swell is important in demonstrating that cladding does not undergo a significant heat up during SBLOCAs.

Testing and Computer Code Evaluation

In the AP1000 DSER, the staff stated that information supplied by the applicant as part of the response to RAIs 440.164 and 440.171 suggested that level swell may not be adequately predicted for the AP1000 design and that the codes may not be predicting cladding heatup because of insufficient core nodalization and inadequate correlations used in predicting the level swell.

At a meeting of the NRC's Advisory Committee on Reactor Safeguards (ACRS), Subcommittee on Thermal/Hydraulics, on March 19 and 20, 2003, the subcommittee raised concerns on the high void fractions within the core calculated by NOTRUMP, WCOBRA/TRAC-AP, and RELAP5 during recovery from SBLOCA. The applicant responded that it had also predicted high void fractions in correlating test data. The subcommittee requested that the applicant provide additional justification that the AP1000 design will remain covered as predicted by the codes by comparing the collapsed liquid levels predicted by the codes to that measured in tests. This was identified as Open Item 21.5-3. The resolution of Open Item 21.5-3 is discussed in Section 21.6.2 of this report as part of the NOTRUMP code review.

21.5.8 APEX-1000 Test Program

The APEX-1000 integral test facility, located at OSU, is a reduced pressure, one-quarter-height representation of the AP1000 design. As described in Section 21.3.6 of this report, APEX-1000 developed from the OSU APEX-600 facility with modifications specifically for the AP1000 design. The staff evaluation of the APEX test program focused on the APEX-1000 facility scaling and test matrix to address issues specific to the AP1000 design.

In topical report OSU-APEX-03001, "Scaling Assessment for the Design of the OSU APEX-1000 Test Facility," the applicant documents its scaling analysis for APEX-1000. The staff's evaluation includes the review of the applicant's scaling analysis and an independent assessment of the APEX-1000 facility.

Westinghouse Scaling Evaluation

The applicant's scaling analysis performed to guide the APEX-1000 facility modifications is described in topical report OSU-APEX-03001. The basis for the APEX-1000 scaling analysis is the AP600 scaling analysis, which was documented in WCAP-14270. The scaling expressions developed in WCAP-14270 for the APEX- AP600 facility are an application of the Hierarchical Two-Tiered Scaling (H2TS) methodology for design and construction of an experimental test facility. Similarity criteria are derived from governing equations of mass, momentum, and energy for the system for each operational period of a SBLOCA transient.

The methodology and scaling parameters developed for the AP600 design are considered applicable to the AP1000 design. This is because the PIRT developed for the AP600 is nearly the same as that for the AP1000 design. Only entrainment processes in the hot legs and upper plenum were considered to have higher importance in the AP1000 design than in the AP600 design. Discussion on the AP1000 PIRT, and staff conclusions regarding phenomena in the PIRT, is in Section 21.5.1 of this report. These processes were given special treatment in the APEX-1000 scaling evaluation as a result.

In addition, the AP1000 design is geometrically similar to the AP600 design. No additional flow circulation paths were introduced into the design, and a one-to-one correspondence of primary loop components remained. Therefore, the conservation equations are the same for both the AP600 and AP1000 designs, and the same Pi groups are obtained.

Of particular importance in the APEX-1000 scaling report is the scaling of upper plenum entrainment. The upper plenum was treated as a separate and distinct region and a top-down and bottom-up two-tiered process was applied. The top-down scaling of the upper plenum used the conservation of liquid mass, and considered inventory sources and losses including entrainment and de-entrainment. The scaling groups derived were then used to preserve the upper plenum overall drain rate.

The bottom-up scaling analysis considered pool entrainment, de-entrainment on guide tubes, and countercurrent flow limiting (CCFL) at the upper core plate. New scaling criteria were derived for each of these processes and were used to determine the upper plenum hydraulic diameter, upper plenum metal structure pitch to diameter ratio, and upper core plate hole pattern.

In addition, the scaling analysis included an evaluation of AP1000 and APEX-1000 upper plenum pool entrainment as a function of water level in the upper plenum in order to assess potential distortions. The applicant concluded that the APEX-1000 upper plenum was well-scaled for entrainment to a depth of approximately 18.9 cm below the bottom of the hot-leg. For lower water levels (when the level was below the midpoint of the upper plenum), the applicant concluded that the APEX-1000 facility was conservatively scaled. This is partly due to the one-quarter height scaling employed in the APEX-1000 facility. In APEX-1000, the entrainment regime for low upper plenum water levels is what Ishii and Kataoka (Kataoka, I., and Ishii, M., "Mechanistic Modeling and Correlations for Pool Entrainment Phenomenon," NUREG/CR-3304, 1983) describe as the momentum-controlled regime, whereas for the full scale AP1000 upper plenum the regime becomes the deposition-controlled regime. Since entrainment rates in the momentum controlled regime are four to six times greater than the rates in the deposition controlled regime for a given gas flux, the AP1000 upper plenum will entrain less water to the hot leg than would APEX-1000 assuming the Kataoka-Ishii correlations are correct. The staff performed an independent analysis of the APEX-1000 test data, and has determined that the Kataoka-Ishii correlations are reasonably representative of the upper plenum entrainment process, and are adequate for scaling purposes.

<u>NRC Independent Scaling Assessment</u>

The staff performed an independent scaling assessment to determine whether the APEX-1000 test facility was adequate for the AP1000 plant design. While the applicant's scaling analysis, which concluded that APEX-1000 was adequately scaled for the AP1000 design, was performed using a reasonable and established scaling rationale and the initial top-down scaling analysis for APEX-600 showed few distortions, the staff was concerned that the modifications may introduce new distortions. Therefore, the NRC staff repeated both top-down system-level and bottom-up process scaling evaluations of the APEX-1000 facility for those periods of a SBLOCA for which the APEX-1000 data were to be used.

Testing and Computer Code Evaluation

As in the independent scaling analysis performed for the APEX-600 facility, the staff applied the scaling methodology developed by INEL (INEL-96/0040, “Top-Down Scaling Analysis Methodology for AP600 Integral Tests,” May 1997).

As described previously, the staff scaling analysis divided a small LOCA transient into five separate periods for evaluation:

(1) subcooled blowdown
(2) intermediate (ADS-1/2/3 venting)
(3) ADS-4 blowdown
(4) IRWST injection
(5) sump injection

Both the staff and the applicant concluded that during the initial phases of a SBLOCA, T-H conditions in the AP1000 design were adequately represented by tests that had been conducted for the AP600 design in the SPES facility. As discussed in Section 21.5.7.2 of this report, the staff further determined that data from the ROSA facility were also adequate for AP1000 analysis during the initial, high pressure periods. Therefore, it was not necessary to evaluate the APEX-1000 modifications for the subcooled blowdown or intermediate (ADS-1/2/3 venting) periods.

The top-down scaling methodology described in INEL-96/0040 was applied to the ADS-4 blowdown and IRWST injection periods. The independent, top-down scaling evaluation for these periods showed the APEX-1000 facility to be adequately scaled for the full scale AP1000 plant (with the exception of downcomer volume, which is discussed later). From this, the staff concludes that the overall, system-wide T-H response of the APEX-1000 facility is representative of the full scale AP1000 prototype. This conclusion is valid for periods of a SBLOCA that include the ADS4 blowdown and transition to stable IRWST injection.

However, the staff identified downcomer volume as a non-conservative distortion in both the APEX-600 and APEX-1000 facilities. The downcomer volume is oversized in the APEX-AP1000 facility, and thus stores excess inventory. This distortion is important when the downcomer inventory is necessary to supply coolant to the core during periods in which passive safety injection from the CMT to the vessel does not occur. This occurred in APEX-1000 design-basis test DBA-02. The staff does not believe, however, that this distortion prohibits the use of APEX-1000 data for code assessment and model development. The extra mass from the oversized downcomer is expected to increase the inner vessel water level by less than 12.7 cm (5 in.) during the boil off period. This amount is not expected to significantly disrupt the overall transient, although it may delay or prevent cladding heatup in tests where the two-phase level drops below the bottom of the upper core plate.

Top-down scaling of the sump recirculation period for APEX-1000 was not reconsidered, since data from APEX-1000 tests for the sump recirculation period was not used in assessment of either the NOTRUMP or WCOBRA/TRAC codes.

The staff also re-evaluated bottom-up scaling in APEX-1000 for several processes affected by modifications made to APEX-1000.

The pressurizer surge line in APEX was modified based on the pressurizer surge line scaling analysis developed by the NRC (D. Bessette and M. di Marzo, “Transition from Depressurization to Long-Term Cooling in AP600 Scaled Integral Test Facilities,” Nucl. Eng. and Design, 188, pp. 331–344, 1999.). In the original (APEX-600) pressurizer surge line scaling, the surge line was sized to preserve the two-phase flow regime transitions. Using the NRC approach, pressurizer draining behavior is preserved. Because drainage from the pressurizer to the hot legs, and the potential for that water to contribute to the two-phase resistance in the associated ADS-4 branch line is important, the staff concludes that this type of scaling approach is appropriate for APEX-1000.

Upper plenum liquid entrainment is adequately scaled in the APEX-1000 facility. The processes of upper plenum entrainment and de-entrainment were accounted for in scaling parameters developed in Section 7 of topical report OSU- APEX-03001, “Scaling Assessment for the Design of the OSU APEX-1000 Test Facility.” Correlations used in the “bottom-up” scaling for upper plenum entrainment were those originally suggested by Katoaka and Ishii (NUREG/CR-3304) as being reasonably representative of the upper plenum entrainment process. This conclusion is supported by experimental data obtained from tests (test runs DBA-02 and DBA-03) conducted in the APEX-1000 facility.

Hot-leg entrainment in the APEX-600 facility was not found to be adequately scaled during the pre-design certification phase of the review. The main difficulty in scaling this process was the lack of an appropriate correlation for phase separation at an upward oriented branch line in a geometry similar to that in the AP600 or AP1000 design. The staff evaluation of hot-leg entrainment using models developed from ATLATS test data shows that the APEX-1000 is adequately scaled for the AP1000 design. It must be recognized however, that ATLATS showed the fluid dynamic behavior near the branch line to be complex and of a highly oscillatory nature. Modeling of these processes is subject to large uncertainty.

APEX-1000 Test Matrix

The applicant performed several integral experiments in the APEX-1000 facility to investigate performance of AP1000 passive safety systems at DBA conditions. The APEX-1000 integral test series performed for simulation of the DBAs includes two tests simulating a DEDVI break with a single failure of one of the ADS-4 valve on the non-pressurizer side, a DEDVI break with failure of one ADS-4 valve on the pressurizer side, and two tests simulating a 5.08-cm (2-in.) cold-leg break with a single failure of one ADS-4 valve. The test results are documented in test summary reports OSU-AP1000-01, OSU-AP1000-02, OSU- AP1000-03, OSU-AP1000-04, and OSU-AP1000-05 respectively. The applicant also used the DEDVI break test runs (test runs DBA-02 and DBA-03) to benchmark the NOTRUMP computer code, which is the code used for SBLOCA design-basis analyses. This is documented in Appendix E in WCAP-15644-P, Revision 2.

Test run DBA-01 simulates a double-ended guillotine break of DVI line #1 (DEDVI break) with three out of the four ADS-4 valves available and one ADS-4 on the non-pressurizer side failed closed. Test run DBA-02 is identical to DBA-01 except that it was performed after the modification of ADS-4 piping and valves. Test run DBA-03 is identical to Test run DBA-02 except that the failed closed ADS-4 valve is on the pressurizer side instead. Test runs DBA-04 and DBA-05 simulate a 5.08-cm (2-in.) cold-leg break with a single failure of one ADS-4 valve and an initial condition of 370 psig (2.65 mPa) and 125 psig (0.96 mPa), respectively. In addition, the NRC staff also conducted several confirmatory, beyond-design-basis tests of its own in order to gain a better understanding of performance of the ADS-4 system during a LOCA transient and to investigate robustness of the passive safety systems. One beyond-DBA test run of particular interest is NRC-AP1000-05, which is a DEDVI break with two of the four ADS-4 valves available and both ADS-4 valves on the non-pressurizer side failed closed. Although test run NRC-AP1000-05, having failure of two ADS-4 valves, is a beyond-DBA, the test provides additional insights into the robustness of the AP1000 passive safety systems. The staff also used data from the beyond-design-basis test in which core uncovery occurred to evaluate correlations for upper plenum pool entrainment and scaling of the APEX-1000 upper plenum. Correlations used in the “bottom-up” scaling for upper plenum entrainment were found to be reasonably representative of the process and thus acceptable for scaling.

The staff evaluation of the APEX-1000 test results concluded that the applicant’s tests at the APEX-1000 facility yield useful insights and provide data for the benchmarking of analysis codes and evaluation methodology. Therefore, the APEX-1000 test program is acceptable. The following summarizes the insights from the APEX-1000 DBA tests and the staff’s beyond-DBA tests:

- The APEX-1000 tests confirm significant entrainment and carryover of water to the ADS-4 system during and after ADS-4 actuation. Flow quality in the ADS-4 is low ($x < 0.5$) when the water level in the vessel is above the bottom of the hot leg. Carryover to the ADS-4 can also be significant, as indicated by flow quality remaining below 1.0, after the vessel level decreases below the bottom of the hot leg. When the upper plenum collapsed level is low, a significant water level in the hot legs can still persist. This suggests that the processes of entrainment and flow dynamics within the hot leg remain important to carryover to the ADS-4 even when the water level in the vessel decreases well below the bottom of the hot leg. As a result, as discussed in Section 21.6.2 of this report, the staff requested the applicant to perform bounding calculations for the DEDVI line breaks by maximizing entrainment, assuming homogeneous flow in the upper plenum and hot-leg regions as a part of the SBLOCA evaluation model.

- No core uncovery or cladding heatup was observed in the APEX-1000 design-basis tests, although the tests do indicate less margin to uncovery and heat up than in corresponding APEX-600 tests. A one-to-one comparison of corresponding tests showed lower vessel water levels and a delay in the IRWST injection time for APEX-1000, suggesting less margin to core uncovery and cladding heatup in the AP1000 design when compared to AP600 design.

- Comparisons of test runs DBA-02 and DBA-03 show that failure of ADS-4 valves on the nonpressurizer side of the system results in a greater delay in IRWST injection than failure of ADS-4 valves on the pressurizer side of the plant. Because failure of an ADS-4 valve on the nonpressurizer loop resulted in less margin to core uncovery in the APEX-1000 tests, the staff concludes that the SBLOCA calculations should assume a single failure of the ADS-4 at that location.

- Failure of the two of four ADS-4 valves produced a core uncovery and cladding heatup (NRC-AP1000-05 and NRC-AP1000-06). This suggests that the full scale AP1000 plant would also experience a deep uncovery if two ADS-4 valves were to fail. This insight is considered in the staff's review of the success criteria for probabilistic risk assessment (PRA) in Chapter 19 of this report.

- The design-basis test run DBA-02 showed that there can be a significant period of time for which the vessel does not receive passive safety injection in a DEDVI line break with a single ADS-4 valve failure on the non-pressurizer side. During this period, core cooling was maintained by boil off of the existing vessel inventory. Because the downcomer is oversized in the APEX-1000 facility, the absence of core uncovery and a prolonged period of cladding heatup in the full scale AP1000 plant might be inferred. This gap in passive safety injection would be reduced or eliminated if containment back pressure is considered. Distortions in 1/4 height versus full height scales may also affect this result.

- The design-basis tests demonstrated that water levels in the inner vessel remain high; near the bottom of the hot legs, or above. This indicates that mixture level swell in the core region is not a critical concern for the AP1000 DBA scenarios, minimizing the concern of uncertainties in the prediction of level swell.

21.5.9 Wind Tunnel Test Programs

21.5.9.1 Phase 1

As indicated in WCAP-13294, pressure measurements taken during Phase 1 indicated that for many of the test cases, a net positive pressure difference existed, with substantial fluctuations, between the inlets and the chimney. Experimentation determined that adjusting the inlet vent configuration could reduce this difference somewhat. The pressure difference was relatively insensitive to the height of the chimney and the adjacent turbine building, but installation of the chimney cap resulted in noticeably smaller mean pressure differences. However, there were still substantial fluctuations. The presence of the cooling tower increased the fluctuating component of the pressure difference for those tests in which it was upstream of containment.

21.5.9.2 Phase 2

The main results of the Phase 2 tests, documented in WCAP-13323-P, indicated that for one chimney design, nonuniformities in flow existed around the building circumference and as far as two-thirds of the way down the shield building annulus. However, very little annular flow was observed for the other chimney design tested. The peak pressure differences between the inlets and chimneys occurred for 1–5 seconds, and the cooling tower caused a significant increase in the fluctuations of the measurements.

21.5.9.3 Phase 4A

As indicated in WCAP-14068-P, test data showed that at higher wind-tunnel flows, the test results became insensitive to the Reynolds number. To account for differences in the results taken in the range between the Reynolds number used for the main UWO tests and the Reynolds number above which the results do not change, the mean and peak baffle wall and inlet-minus-chimney pressure coefficients for the Phase 2 tests were adjusted by a factor determined from the Phase 4A test data. The data also indicated that the presence of a cooling tower resulted in substantially lower mean loads, but larger peak loads on the baffle. However, the effect of the cooling tower was not considered large enough to warrant any adjustment to the Phase 1 and Phase 2 data.

Baffle loading under simulated tornado conditions was lower than that under normal conditions because of a reduction in the unsteady component of the pressure difference across the baffle. The tornado loads were also enveloped by the hurricane-induced loads determined in the Phase 2 tests. The applicant concluded that the hurricane-induced loads were conservative for determining baffle wall loading under tornado conditions.

21.5.9.4 Phase 4B

As indicated in WCAP-14091, for most configurations of the Phase 4B tests, the largest peak inlet-minus-chimney pressure varied little from the base case. In the case of a river valley with a cooling tower, the inlet-minus-chimney pressure difference increased by a factor of 1.14 over the base case for a small range of wind angles. WCAP-14091 concluded that the baffle loads determined from the base case were bounding, with the exception of the case of the river valley with two cooling towers.

The report also stated that mountains or an extra cooling tower reduced the inlet-minus-chimney pressure difference for those wind directions with the mountains or cooling towers upstream of the plant. In all such cases, the mean difference remained positive.

The most negative fluctuation in the inlet-minus-chimney pressure difference occurred for certain incoming wind angles in the case of a river valley terrain with one cooling tower. In this case, the pressure difference was negative 68 percent of the time versus 4.5 percent of the time in the base case. The applicant's letter PCS-T2C-059, "Analysis of AP600 Wind Tunnel Testing for PCCS Heat Removal," dated May 1995, indicated that the addition of a second cooling tower had little effect on the fluctuations or pressure difference.

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), pressure fluctuations on the outside of a structure can be caused by other upwind structures and terrain irregularities. Such fluctuations generally have time periods from 1 to several seconds. The magnitude and direction of the differential pressure across openings in a structure (the downcomer and annulus) can depend on the configuration and size of the openings (ASHRAE Handbook, 1985 Fundamentals, pages 14.5–14.10).

In document PCS-TAC-059, "Analysis of AP600 Wind Tunnel Testing for PCS Heat Removal," the applicant analyzed the effect of oscillating inlet-minus-chimney pressure differences on the

AP600 containment LOCA response. This analysis reasoned that the time constant which characterizes the vessel shell response to heat transfer in the annulus, and the time constant which characterizes the shell heat capacity relative to its conductivity (255 and 69 seconds, respectively), were both longer than the period of pressure fluctuations observed in the wind tunnel tests (several seconds for the period of pressure fluctuations, as indicated in W letter PCS-T2C-059). The stated period of the pressure fluctuations were on the order of those cited in the ASHRAE Handbook (see above paragraph). The applicant concluded from these observations that the response of the containment shell and the temperature on the inside surface of the vessel would be relatively unaffected by external pressure fluctuations.

For cases involving lower wind speeds, corresponding to lower frequency pressure oscillations, the inlet-minus-chimney pressure differences were correspondingly much lower. The applicant concluded that such pressure differences would not have a significant impact on PCS heat removal because lower pressure differences result in reduced forced flow in the annulus.

The analysis also included an investigation of the effect of pressure oscillations applied to the chimney of the AP600 WGOTHIC model. The input data came from the river valley with one cooling tower test configuration, which contained the highest percentage of negative inlet-minus-chimney pressure differences (on a time basis) of all the test cases. The containment pressure response to a LOCA was calculated with WGOTHIC for various external wind speeds, most of which used a forced-convection heat transfer correlation in the annulus. This was considered conservative because, as stated in letter PCS-T2C-059, it would tend to underpredict heat transfer when flow in the annulus reversed and the velocity in the annulus temporarily passed through zero because of pressure oscillations.

The analysis indicated that oscillating inlet-minus-chimney pressure differences slightly increased heat removal from the containment, thereby slightly decreasing the calculated pressure. For wind profiles representative of different terrains, such as open country terrain, the report indicated that the mean pressure difference was above zero and, therefore, would tend to enhance forced-convection heat transfer. The applicant concluded from these studies that a conservative calculation of the containment response to a LOCA or main steamline break (MSLB) should include the assumption of no imposed wind conditions.

The staff reviewed the applicant's methodology for assessing the wind-neutrality of the AP600 containment. Based on the above, the staff agreed with the applicant's conclusion that it is conservative to assume no imposed wind conditions for the containment analysis, and the staff found it acceptable to use this methodology in WGOTHIC design-basis analyses.

In WCAP-15613, "AP1000 PIRT and Scaling Assessment," issued February 2001, the applicant provided an assessment of the AP1000 design changes as they relate to the use of the wind tunnel tests. The AP1000 air inlets are located in the same place as those of the AP600 relative to the chimney. The diameter of the containment shield building is the same. The height of the AP1000 containment/shield building is greater than that of the AP600. This should have a beneficial effect by moving the inlets further above any surrounding buildings. The staff agrees with this assessment, as well as the applicant's conclusion that it is conservative to assume no imposed wind conditions for the AP1000 containment analysis. Accordingly, the staff finds the applicant's decision to use this methodology in the WGOTHIC design-basis analyses to be acceptable.

21.5.10 PCS Test Program

Noncondensables, Mixing, and Stratification

During LST test 220.1, the staff noted that there were only four gas sampling ports for measuring and sampling the internal vessel atmosphere for noncondensable gas concentrations. The samples were taken at a location approximately 15.2 cm (6 in.) from the vessel wall. These experiments did not yield data that could be used to validate and verify the detailed three-dimensional (3-D) spatial distribution of noncondensable gases, as calculated by computer programs such as COBRA-NC or COMMIX. Only coarse axial, integral results were available (e.g., a grab sample, noncondensable concentration in and near the vessel dome versus near and below the operating deck). Furthermore, the bomb sampling technique for sorting out the ratios of steam concentration to those of air and helium was subject to its own experimental uncertainties. In the test specification, WCAP-13267, "Test Specification: Large-Scale Containment Cooling Test," and PCS-T1P-002, Revision 1, issued December 1991, the applicant described a 4-percent uncertainty band in the air-steam ratio devices. An evaluation of the sampling error was provided in WCAP-14135, Revision 1, issued April 1997. The reported error in the measurement of the partial pressure of air was ±7.10 kPa (1.03 psi).

In August 1995, the applicant informed the staff that the DBA evaluation model (EM) would be based on a conservative assessment of mixing and stratification. In NSD-NRC-96-4763, dated July 1, 1996, the applicant submitted a report entitled "Assessment of Mixing and Stratification Effects on AP600 Containment."

In keeping with the DBA approach, mixing and stratification were treated in a conservative manner. The use of the LST data to support the EM was presented in the scaling report, WCAP-14845. In support of the AP1000 design, WCAP-15613 provides an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena.

Section 21.6.5 of this report presents the staff's review of the relationship of the LST scaling analysis and the containment PIRT to the development of the bounding analysis (the EM), as well as their use to support design certification.

The treatment of mixing (circulation) and stratification to support the EM is presented in Section 9 of WCAP-14407, Revision 3, "WGOTHIC Application to AP600," issued April 1998, and in Section 9 of WCAP-15846, "WGOTHIC Application to AP600 and AP1000." Section 21.6.5 of this report presents the staff's review of these documents.

PCS Water Coverage Flow Rate

The staff also observed that the 50-percent water coverage specified for the first few hours of test 220.1 was only a target. A 90- to 95-percent coverage was more representative of what test 220.1 actually achieved, on average. Even this number is somewhat misleading, because during the test, large portions of the exterior dried out from time to time. Therefore, the water coverage probably ranged between 40 and 100 percent. This was partially because of what was occurring inside containment, and partially as a result of the variability in water pressure to the inverted J-tubes hooked up to the facility's municipal water supply. Additionally, a technician made water striping measurements with a ruler during the steady-state end portion of the run. The staff was concerned with the uncertainty of experimental results. For example, the test results state only that the test was run with 95-percent striping.

During the May 1995 QA audit of the LST facility (NRC Inspection No. 99900404/95-01), the staff discussed water coverage with the Westinghouse test engineering group. Test 219.1 was discussed during the audit. As with other tests, the staff noted that the water flow rate was not constant.

The water distribution flow control valve was set to a predetermined position (for test 219.1, this was 10 percent of full flow for a target coverage of 50 percent) at the start of a test using a data table developed early in the test program relating the valve position to observed striping. This table was developed for the water coverage fraction specified in the test target data matrix. No changes to the valve position were made during a test to compensate for any change in the water coverage flow rate. The test procedures and specifications did not address variations in the water coverage flow rate as a potential problem.

The Westinghouse test engineering group stated that Westinghouse's Containment and Radiological Analysis Group acknowledged the disposition of test deviations such as this and others, including, for example, the lowering of the steamflow from 0.09 kg/sec (0.2 lb/sec) to 0.05 kg/sec (0.12 lb/sec) for test 219.1. As noted in the audit, the disposition of test deviations between the Westinghouse test engineering group and the Westinghouse analysis group were to be reviewed during a future inspection.

During NRC Inspection No. 999900404/97-02, held from November 17–21, 1997, the test acceptance criteria were discussed with appropriate Westinghouse staff. The following four test acceptance criteria were established for the LST:

(1) Data on forcing functions available (i.e., steamflow rate, fan speed, water flow rates, and inlet temperature of steam, water, and air). Strict adherence to the specific absolute pressures and flow rates was not necessary, but values were to be nearly constant as defined in the test matrix.

(2) Data on response variables available (i.e., condensate flow rates; excess water flow rates; air, water, and steam outlet temperatures; vessel pressure; 80 percent of the vessel and fluid temperature instrumentation; and vessel water coverage measurements).

(3) Unplanned excursions were to be evaluated on a case-by-case basis. Failures that may result in faulty data outputs were not acceptable.

(4) The vessel pressure was to be maintained within specified pressure limits during the constant pressure portions.

Variations in the PCS water coverage flow rate were not considered in the development of the test acceptance criteria. The important criterion was the target coverage area, as specified in the test matrix. Even then, the acceptance criteria did not specify strict adherence to the target value. Instead, they specified only that a nearly constant value could be determined for a test. The test acceptance criteria were followed for the specific steamflow rate in test 219.1.

The Zuber-Staub model is used for establishing water coverage for use in the WGOTHIC computer program. Section 7 of WCAP-14407, Revision 3, "WGOTHIC Application to AP600," issued April 1998, and Section 7 of WCAP-15846, "WGOTHIC Application to AP600 and AP1000," issued April 2002, describe the water coverage model used in the WGOTHIC EM. Section 21.6.5 of this report presents the staff's review of these documents and the water coverage model.

Internal Velocities

The staff expressed concern with the instrumentation provided in the LST to measure the velocity of the internal atmosphere of the containment vessel. This instrumentation included the following:

- three anemometers—Pacer, Model APT 275 Vane, 0 to 2419 m/min (7935 ft/min)
- two anemometers—Höntzsch Instruments, 0 to 914 m/min (3000 ft/min)

The three Pacer models failed during testing. The applicant explained that they had generally measured the same range of values, 152 cm/sec (5 ft/sec) to 244 cm/sec (8 ft/sec). The Höntzsch meters failed during the high-capacity blowdown testing. Because the internal velocity is important to the condensation of steam on the containment wall, the staff believed that more measurements would be needed to quantify the mixed-convective flow field.

The NRC performed a QA review for the LST in May 1995 (see NRC Inspection No. 99900404/95-01, letter from R.M. Gallo (NRC) to N.J. Liparulo (WEC), dated August 8, 1995). During this review, the staff determined that the Westinghouse analysis group's judgment on internal velocities (i.e., the measurements obtained indicate local bulk velocity along the vessel wall) were useful, although not necessary, in the validation of WGOTHIC. It was also known that the instrumentation might not survive the test conditions.

In August 1995, the applicant informed the staff that the DBA EM would no longer be based on the use of the mixed-convection correlation. Rather, the analysis was based on a bounding, conservative approach and the use of free-convection correlations for the mass and heat transfer on the vessel interior wall. A multiplier, based on the experimental database, was to be applied to the correlations to ensure that the correlation bounds the data (letter

NTD-NRC-95-4570, “Bases for AP600 PCS Mass Transfer Correlation Biases,” dated September 28, 1995).

Since the August 1995 change in the DBA EM, the need to accurately predict the interior velocities for validation of the WGOTHIC computer program was no longer a concern. However, it was still a concern that the LST provided sufficient information to assist in the development of a conservative, bounding analysis. WCAP-14845, Revision 3, documents the scaling analysis. WCAP-14812, Revision 2, documents the PIRT.

In support of the AP1000 design, WCAP-15613 provides an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena.

Section 21.6.5 of this report presents the staff’s review of the relationship of the LST scaling analysis and the containment PIRT to the development of the bounding analysis (the EM), as well as their use to support the design certification.

Condensate Formation Inside Containment

Another area of staff concern was related to the measurement of the condensate forming within the containment vessel. Condensate was collected from (1) a girder, (2) inside the vessel sidewall, (3) rain (collected on a lower horizontal plane), (4) inside the vessel (below deck), and (5) a simulated steam generator section. While these five regions were intended to be measured individually, their flows were combined into two measuring tanks, thus losing the identification of their sources. The measurement of condensate forming within the containment vessel needs be considered when addressing the capability of the WGOTHIC computer program to predict containment performance.

The LST final data report, WCAP-14135, summarized the condensation collection and data. (WCAP-14135 was revised in April 1997; however, the summary of the condensation collection data did not change.) Condensation collection for the Phase 2 tests directed the condensate from the regions below the simulated operating deck to one collection system, and the remaining condensate from the three locations above the simulated operating deck went to a second collection system. Phase 3 tests 222.1, 222.2, 222.3, and 222.4 were used to obtain additional insights into the condensation. The condensate discharges were realigned during various steady-state portions of the tests. In test 222.1, it was found that about 3 to 4 percent of the condensate was from the combined rainfall and regions below the operating deck. The remainder was evenly divided between the dome and vessel sidewall. During the final collection period, in test 222.2, 61 percent of the condensate collected was from the dome. In the last two steady-state portions of test 222.3, 56 to 58 percent of the condensate was generated on the sidewalls. In test 222.3, erratic steamflow led to a difference of 18 to 26 percent between the condensate and the average steamflow measurements made during the first three periods of this test. Finally, in test 222.4, the Westinghouse test engineering group provided a caution on the use of the condensate distribution data. During two collection periods, the mismatch between the steamflow and the condensate flow indicated 18 percent more condensate flow than steamflow.

In WCAP-14382, "WGOTHIC Code Description and Validation," issued May 1995, a comparison of the total measured to the predicted condensate flow rate was provided for the priority tests analyzed with the distributed parameter model. No data comparisons were provided for the individual measurements for test 222.4, the only Phase 3 test which isolated the condensate flows. The LST data report, WCAP-14135, assessed the overall data quality and provided a rough comparison of the system heat balance, as evaluated using the following three methods:

(1) condensate mass flow rate
(2) external heat loss (water, air, and radiant)
(3) heat flux across the vessel wall

This comparison suggested that the condensate mass flow rate method overestimated the heat removal when compared to the other two methods. In its letter dated August 29, 1997 (NSD-NRC-97-5299), the applicant addressed this apparent overestimation. The referenced heat balances were only prepared to provide a comparison of the test data. Review of the data in Table 3.3-1 of WCAP-14135 indicated that the estimate of the heat balance from the condensate was lower than the estimates from the other calculational methods. Each calculation was based on the following assumptions and simplifications:

- Condensate—This calculation relied on the accuracy of the condensate measurements and assumed a negligible heat loss between the vessel and the measurement location of the condensate temperature. The calculation also assumed that there was no holdup of condensate within the vessel. This appeared to be the most accurate of the heat balances.

- External Heat Loss—This calculation relied on the accuracy of the water flow on and off the vessel. The uniformity of the water and air temperature, the exit air velocity measurement, and the estimate of heat loss through the baffle assembly were all simplifications used in obtaining the estimate from this heat balance.

- Heat Flux—This calculation assumed that the water coverage was constant from the top of the vessel to the bottom outside gutter. It applied the minimum and maximum temperatures assumed over an entire area, centered at the thermocouple elevations, to the estimated wet and dry areas, respectively.

Numerous attempts were made during the course of testing to measure rainfall within the test vessel, in addition to the events detailed in the test report. In no case was any rainfall measured, and conditions only resulted in a backup of condensate within the vessel at high steamflows because of the relative capacity of each system.

The heat balance was performed to assess the overall quality of the LST. The condensate measurement-based heat balance was used as the reference for the comparison of the various methods, and was judged by the applicant as the best measure. No appreciable rainfall was identified during any test. The heat balance analyses were only used to judge the overall performance of the test.

Air Annulus Instrumentation

Lack of adequate instrumentation in the annular region was a concern. Initial results obtained by the staff using the CONTAIN computer program show that evaporation from the exterior liquid film controlled the performance of test 212.1. The lack of adequate instrumentation in the LST annular region made it difficult to evaluate the evaporation rate from the containment shell.

WCAP-14382 provides a comparison of the measured to the predicted external excess flow rates for the priority tests analyzed with the distributed parameter model. The external excess water was collected in an external gutter mounted on the LST vessel and measured with a flow meter. No uncertainty bands were provided on the plots for the measured values. The fluctuating PCS water flow rate is seen in the data, adding a level of complexity to the interpretation of these data.

In NTD-NRC-95-4463, the applicant submitted “AP600 Testing Program Report: Large-Scale Test Data Evaluation (PCS-T2R-050).” The applicant’s evaluation of the large-scale PCS test data concluded that evaporation was the primary mode of heat removal from the outside of the vessel (approximately 75 percent of the total), followed by sensible heating of the subcooled liquid film (approximately 17 percent of the total). The remainder of the heat was transferred to the environment by convection and radiation.

Air Annulus Design

It was also noted that the LST model did not include a downcomer region and used a chimney-installed fan to create the circulation in the annular region, both of which were nonprototypical of the AP600. WCAP-14845, Revision 3, documented the scaling analysis. This report addressed distortions and nonprototypical features of the LST. WCAP-14812, Revision 2, documents the PIRT. This report addressed the development of the EM, including the treatment of distortions and nonprototypical features of the LST.

In support of the AP1000 design, WCAP-15613 provides an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena.

Section 21.6.5 of this report presents the staff’s review of the relationship of the LST scaling analysis and the containment PIRT to the development of the bounding analysis (the EM), as well as their use to support design certification.

Internal Heat Sinks

Section 21.6.5 of this report discusses the modeling of the long- and short-term heat sinks, flowpaths, and internal volumes in containment, especially in relation to their representation in

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Section 21.6.5 of this report presents the staff's review of the relationship of the LST scaling analysis and the containment PIRT to the development of the bounding analysis (the EM), as well as their use to support design certification.

21.5.11 Water Distribution Test Program

Measurements of water striping (distinct strips of water flow) were made during steady-state conditions (approximately 10 minutes after initiation of flow) by measuring the width of the dry and the wet patches on the test model with a ruler. The applicant only counted an area as wet if active flow could be seen, and considered damp areas dry because they most likely would be if the shell were heated.

The method of measurement and the assumptions made concerning wet and damp areas could result in significant uncertainty in the experimental results. Because the water distribution test data served to validate the coverage model used as input to WGOTHIC, uncertainty in the coverage model could result in errors in WGOTHIC predictions of DBA containment response. The limited PCS flow model considers the changing wetted area coverage as the PCS flow rate decreases over time. Section 21.6.5 of this report discusses the use of the water distribution test data in the development of the water coverage model (a part of the limited PCS flow model) employed by WGOTHIC for licensing analyses in support of design certification.

These tests were conducted with an unheated surface. Under actual DBA conditions, the vessel shell is heated because of the energy release from the accident, possibly resulting in different coverage fractions. While the LST employed a heated surface, the fact that the tests were not full scale and that considerable fluctuations were present in the water supply both tend to question the credibility of the data.

In PCS-GSR-003, the applicant provided a model for determining coverage values to be used in the WGOTHIC analysis. The model, developed by Zuber and Staub, included terms which account for the film momentum, surface tension, thermocapillary effects, film potential energy, and static pressure (added by the applicant). The applicant's adaptation of the model attempted to mechanistically predict the onset of flow instability, a phenomenon which could result in redistribution of the water film on the surface. To apply the model, the applicant introduced an arbitrary parameter, referred to as the reference stability margin R_{ref}, to determine the onset of flow instability and to account for surface irregularities. The model was applied to four water distribution tests and all of the LST tests to yield a value of R_{ref} that predicted the test results. To determine coverage fractions for input to WGOTHIC, the applicant used expected initial PCS flow rates and shell heat flux values obtained from WGOTHIC as input to the coverage model.

According to the model predictions, the applicant concluded that the coverage fraction input to the WGOTHIC model should be higher in the dome region and lower on the sidewall. Letter NTD-NRC-94-4286, "Supplemental Information on AP600 PCS Film Flow Coverage Methodology," dated August 31, 1994, addressed questions that were raised about the model, and forwarded the results of sensitivity studies which showed that coverage can be reduced by a factor of 2 without reaching the design pressure, if the value of R_{ref} is appropriately adjusted.

The staff was interested in understanding if and how the baffle wall standoffs were treated in the coverage model. They may have a destabilizing effect on the film flow and may change the reference stability margin, R_{ref}. The staff was also interested in understanding whether the degree of conservatism present in the coverage fractions included a reduction in PCS flow to account for the possibility of the weirs becoming clogged with debris, a situation which could be postulated to occur during the course of plant operation. Both the water distribution test and the LST modeled baffle standoffs. Therefore, the applicant concluded that the basis for the limited PCS flow model accounted for the effects of the baffle standoffs. The applicant further concluded that the design, in combination with an appropriate surveillance program as part of the inservice inspection program, minimizes the possibility of weir clogging. Periodic inspections of the PCS airflow path from the shield building annulus inlet to the exit ensure that it is unobstructed, the baffle plates are properly installed, and the upper annulus safety-related drains are unobstructed. As specified in Technical Specification (TS) 3.6.6, these inspections are performed every 24 months. The limited PCS flow model, as discussed in Section 21.6.5 of this report, includes a conservative value for R_{ref} and for the PCS flow credited as compared to the actual available flow.

Section 21.6.5 of this report discusses the current licensing model, including the limited PCS flow model, and the use of the water distribution test, the LST, and other test data. The limited PCS flow model considers the changing coverage fractions as the PCS water flow rate is decreased over time. The development of the limited PCS flow model considers the LST, as well as other heated, separate-effects experiments, in evaluating the expected film behavior.

21.5.12 Compliance With 10 CFR 52.47(b)(2)

The three requirements for design certification testing and analysis programs, as stated in the Introduction to this chapter, can be summarized as demonstration of

(1) performance of each safety feature
(2) acceptability of effects of systems interactions and
(3) existence of an adequate database for code validation

For the reactor systems, the applicant has completed a test and analysis program to address each of these requirements. Separate-effects tests address the performance of AP1000 safety systems, including CMTs, ADS, and PRHR. Integral systems tests also produce data on performance of these safety systems, with the addition of both accumulator (compressed-gas-driven) injection and gravity-drain safety injection from the CMTs and IRWST. The integral systems tests also produced data on the effects of systems interactions. Demonstration of the existence of an adequate database for code validation was the objective of the code qualification effort and has been verified by the staff's conclusions regarding the acceptability of the code qualification effort.

Compliance of the containment systems testing program with the requirements of 10 CFR 52.47(b)(2) are addressed in Section 21.6.5.3.3 of this report.

On the basis of the specific evaluations provided in the various sections of Chapter 21 of this report, the staff has concluded that the individual test programs and the code qualification program are acceptable with respect to the AP1000 design. Accordingly, for test facility designs, instrumentation, scaling, and test matrices in the applicant's testing and analysis programs, the staff concludes that the requirements of 10 CFR 52.47(b)(2) have been met.

21.6 Assessment of Analysis Codes

The applicant has specified three reactor system computer codes and one containment system computer code for use in performing AP1000 design-basis safety analyses. The codes are as follows:

- LOFTRAN/LOFTTR2, for non-LOCA transients, such as SGTRs and MSLBs
- NOTRUMP, for small-break LOCAs
- WCOBRA/TRAC, for large-break LOCAs
- WCOBRA/TRAC, for long-term cooling analysis
- WGOTHIC, for containment systems performance analysis

These safety analysis codes were used for the AP600 design-basis analyses and were validated with the test data from the AP600 test program. Chapter 21 of NUREG-1512 describes the staff's evaluation of the validation of these codes for the AP600 design.

WCAP-15644, Revision 2, documents the applicant's assessment of these codes to determine their applicability and use for the AP1000 design. The staff evaluated the applicability of these codes to the AP1000 and identified three open items in the DSER relating to the test program and NOTRUMP code review at the time the DSER was issued:

(1) DSER Open Item 21.5-1 requested that the applicant perform sensitivity studies using the code the applicant intends to use to model small-break LOCAs in the AP1000 (i.e., NOTRUMP) to demonstrate that the uncertainty in modeling hot-leg phase separation does not represent a significant safety issue in the AP1000. The staff notes that Open Item 21.5-1 was also inadvertently identified in the DSER as Confirmatory Item 21.7-1 as the applicant had agreed to provide the requested sensitivity analyses. Therefore, Open Item 21.5-1 and Confirmatory Item 21.7-1 refer to the same item.

(2) DSER Open Item 21.5-2 recommended that, given the lack of well scaled experimental data on upper plenum entrainment phenomena and the importance of predicting this process in an advanced plant SBLOCA transient, the applicant obtain new experimental data to support the use of the upper plenum entrainment models in the AP1000.

(3) DSER Open Item 21.5-3 requested that the applicant provide additional justification that the AP1000 will remain covered as predicted by the codes by comparing the collapsed liquid levels predicted by the codes to that measured in tests.

In the following sections, the staff provides its assessment of each computer code used for the AP1000 design-basis analyses, including the closure of the above open items identified in the DSER.

21.6.1 LOFTRAN/LOFTTR2 Computer Code for non-LOCA Transients

LOFTRAN simulates a multi-loop reactor system by modeling the reactor core and vessel, hot- and cold-leg piping, SG tube and shell sides, pressurizer, and RCPs, with up to four coolant loops. The pressurizer model includes the effects of pressurizer heaters, spray, operation, and relief and safety valve operation. The reactor core model employs a lumped fuel heat transfer model with point neutron kinetics and includes the reactivity effects of variations in moderator density, fuel temperature (Doppler), boron concentration, and control rod insertion and withdrawal. The secondary side of the model uses a homogenous, saturated mixture for thermal transients and a water level correlation for indication and control. Safety injection systems including the accumulators are modeled. Flow reversal in the reactor coolant loops is allowed except in the loop with the pressurizer, where flow reversal is not allowed. The LOFTRAN T-H model is best suited for use in transients in which the primary coolant system remains subcooled. LOFTRAN may be used for an MSLB analysis where two phase conditions occur in the upper reactor vessel head, since the upper head is a hydraulically stagnant region which receives only a small fraction of the main coolant flow. For accident conditions when the extent of voiding extends beyond the pressurizer and the upper head, the use of LOFTRAN would not be appropriate without additional justification.

LOFTRAN does not have a detailed core heat transfer model. An overall fuel rod to coolant heat transfer coefficient is utilized which is a parabolic fit to values specified by the user. Input values either maximize or minimize core heat transfer depending on the conservative direction for the transient of interest. The inputs are obtained from the limiting values predicted using detailed Westinghouse fuel rod design codes. For evaluations where accurate knowledge of core heat transfer or fuel temperature is important, physical conditions are transferred from LOFTRAN to more detailed thermal/hydraulic codes such as THINC, FACTRAN, or VIPRE.

The NRC staff found LOFTRAN (WCAP-7907-P-A, “LOFTRAN Code Description,” issued April 1984) to be acceptable for analysis of transients and accidents at operating plants as presented in Chapter 15 of the plant safety analysis reports. Chapter 15 safety analysis is discussed in NUREG-0800, “Standard Review Plan.” This approval did not extend to LOCA or SGTR analysis.

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In order to model an SGTR, the applicant modified the LOFTRAN code to include an enhanced SG secondary-side model, a tube rupture break flow model, and improvements to allow simulation of operator actions. This version of the code is sometimes referred to as LOFTTR2. The SGTR version of LOFTRAN was reviewed and approved by the NRC staff and is discussed in Westinghouse Topical Reports WCAP-10698-P-A, “SGTR Analysis Methodology to Determine the Margin to Steam Generator Overfill,” issued August 1985; WCAP-10698-P-A, “Evaluation of Offsite Radiation Doses for a Steam Generator Tube Rupture Accident,” Supplement 1, issued March 1986; and WCAP-11002, “Evaluation of Steam Generator Overfill Due to a Steam Generator Tube Rupture Accident,” issued February 1986.

21.6.1.1 Application of LOFTRAN to Passive Plants

Additional modifications were made to LOFTRAN to model the AP600. These are described in Westinghouse Topical Reports WCAP-14234, “LOFTRAN & LOFTTR2 AP600 Code Applicability Document,” Revision 1, issued June 1997, and WCAP-14307, “AP600 LOFTRAN-AP and LOFTTR2-AP Final Verification and Validation Report,” Revision 1, issued August 1997. The applicant modified the LOFTRAN code by adding the capability to model the following additional components, which are part of the AP600 and AP1000 designs but are not present in operating plants:

- ADS
- CMT
- PRHR HX
- IRWST

As part of the AP600 review the staff evaluated the ability of LOFTRAN to predict the performance of these components during transients and accidents without exceeding the capabilities of the code. This review included the constitutive equations, the ability of the code to predict test results, stand-alone simulations of the passive components, and comparison of code predictions with data from the SPES-2 test loop in which the action of all the passive components was modeled in the simulation of an MSLB. The LOFTRAN code was found to provide a reasonable and conservative simulation of the test data. After reviewing the LOFTRAN code for the AP600 application, the staff concluded that LOFTRAN had been modified to include the necessary models for the AP600 plant features and the behavior expected during non-LOCA transients and, therefore, is applicable to the AP600 reactor design. Table 21-2 of this report lists the transients and accidents for which LOFTRAN has been approved, considering possible failure in the AP600 passive safeguard systems.

WCAP-15612 and WCAP-15644 describe the use of the LOFTRAN code for the AP1000 design-basis transient and accident evaluations. WCAP-15612 contains a general description of the AP1000 standard plant design and preliminary analyses of a subset of the transients and accidents listed in Table 21-2 of this report. The subset was selected by the applicant to illustrate performance of the AP1000 passive safety features and plant differences between the AP600 and the AP1000 designs. WCAP-15644 presented additional details and justifications for use of the LOFTRAN code for AP1000 analyses. WCAP-15613 gives a revised PIRT for the AP1000 transients and accidents, with a scaling assessment of the tests used to qualify the LOFTRAN code.

Since the AP1000 is similar in design to the AP600, the applicant believes modifications made to the code to model the AP600 will also address the AP1000. The differences in size between the two designs can be accounted for in the code inputs. The fuel, pressurizer, and SGs for the two passive plant designs will be similar to those used in operating plants. Unlike operating plants where the hot- and cold-leg nozzles are at the same elevation on the reactor vessel, for the AP600 and the AP1000, the hot and cold-leg nozzles are at different elevations. The elevation difference is accounted for by modifications within LOFTRAN. The RCPs for the passive plants are of a canned rotor design with their own characteristics for developed head and torque as functions of flow rate and impeller speed. The mass of the pump flywheel was increased for the AP1000 to provide for a longer flow coastdown should an RCP inadvertently trip during operation. The pump characteristics are accounted for by inputting the proper information from the pump manufacturer. Since full pump characteristics can be input into LOFTRAN, the code is able to model the RCPs of the AP1000 when properly described in the input.

Operating Westinghouse plants have a single cold-leg and RCP per coolant loop, whereas the AP600 and the AP1000 have two cold-legs and two RCPs per loop. LOFTRAN is capable of evaluating the dual cold-leg loop arrangement so long as the two cold-legs in a loop have the same behavior so that they can be lumped together. For conditions when the two cold-legs do not behave the same, such as for a tripped RCP or locked rotor/sheared RCP shaft, the applicant inputs the net cold-leg flow as a function of time. The net cold-leg flow rate is calculated by external methods. The applicant presented the asymmetrical cold-leg methodology to the NRC staff for review as part of the review of LOFTRAN for the AP600. The staff determined that the external flow calculation methodology appropriately modeled the phenomena, and concluded that the methodology was acceptable for the AP600. The applicant used this same methodology of calculating asymmetric cold-leg flow rates outside of the LOFTRAN code for analyses for the AP1000. The methodology remains acceptable for the AP1000 since no new phenomena associated with pump coastdown are expected for the AP1000.

The applicant did not analyze events that would cause the ADS to open using LOFTRAN with the exception of inadvertent opening of a single valve. The scope of this analysis is limited to the initial few seconds so that core heat transfer can be evaluated. The analysis is terminated before significant steam voiding can occur in the reactor system.

Similarly the applicant does not analyze conditions for which two phase voiding will occur in the CMTs. The CMTs actuate during transients analyzed by LOFTRAN but steam formation in the CMT inlet lines does not occur so that the CMTs will not drain in LOFTRAN analyses. Actuation of the CMTs creates a circulation path so that the cooler borated water from the CMTs mixes with the reactor coolant. This provides for additional core cooling and boron addition to shut down the core even before the CMTs begin to drain.

Of the events listed in Table 21-2 of this report, steam voiding in the reactor system and CMT draining would be most likely following an MSLB. This is because the accompanying reduction in steam pressure would cause a rapid increase in the rate of heat removal from the reactor system. The CMTs would begin to drain if steam were to form in the pressure balance lines connected to the cold-legs. Although LOFTRAN can not adequately simulate CMT draining, the code is capable of determining if saturated conditions occur in the reactor system such that steam formation in the CMT pressure balance lines might begin to occur. The beginning of steam formation is the limit for reliable use of LOFTRAN. The NRC staff questioned if this limit might be exceeded following an MSLB at an AP1000 reactor.

The SGs for the AP1000 are significantly larger than those of the AP600 and have the potential for more pressure reduction in the reactor system than do those of the AP600. Thus, voiding might be produced within the AP1000 following an MSLB while none was predicted for the AP600. Flow restrictions in the SG nozzles are the same for the AP600 and the AP1000 so the rate of reactor system pressure reduction would be approximately the same. The NRC staff's concern of the ability of LOFTRAN to adequately model an MSLB for the AP1000 was resolved by submission of analyses by the applicant using LOFTRAN demonstrating that following an MSLB the reactor coolant loops would remain subcooled so that CMT draining would not occur. These analyses are described in DCD Tier 2, Section 15.1.5. Therefore, the NRC staff concludes that LOFTRAN is acceptable for use in MSLB analyses for the AP1000 design.

The PRHR HX provides a passive means of decay heat removal that can be effective at all reactor system pressures. As for the AP600, the PRHR HX for the AP1000 is located within the IRWST and transfers heat from the RCS to the IRWST for conditions when the normal means to remove reactor heat might be lost. For both designs, the PRHR HX tube bundle is C-shaped and makes a single pass within the IRWST. The IRWST is described as one lumped parameter region in LOFTRAN. Local heating of the IRWST water in the vicinity of the PRHR HX is not included in the analysis. The applicant demonstrated that the PRHR HX models in LOFTRAN were adequate for the AP600 by modifying the code so that the code predications compared well with the results from scale model tests.

The PRHR HX for the AP1000 standard plant design is essentially the same design as for the AP600. The heat transfer area has been increased by 22 percent and the flow resistance in the inlet and outlet piping has been decreased so that the design heat flow rate is increased by 72 percent. The average heat flux in the PRHR HX for the AP1000 is expected to be 41 percent higher than for the AP600. The applicant calculates heat transfer through the PRHR HX in LOFTRAN using standard convective heat transfer correlations for the water flowing on the inside of the PRHR HX tubes. These correlations were found to be valid for a wide range of test conditions including those expected for the AP1000.

On the secondary side of the PRHR HX, the most significant mode of heat transfer will be nucleate boiling. The applicant had previously found standard nucleate boiling correlations to over predict the heat flow from the PRHR test facility in Westinghouse Topical Report WCAP-12980, "AP600 Passive Residual Heat Removal Heat Exchanger Final Report," Revision 3, issued April 1997. The nucleate boiling heat transfer correlation used in LOFTRAN was modified to provide a best fit to the data. Further verification for the derived nucleate boiling correlation was obtained by correlation of PRHR HX data from the ROSA facility and the SPES facility experiments that were performed for the AP600. Based on the similarity of the AP1000 PRHR HX to the AP600 PRHR HX and scaling studies of the test configuration for the AP1000, as discussed in Section 21.3.3 of this report, the NRC staff concludes that the PRHR HX model in LOFTRAN will be valid for the AP1000. Individual analysis for the non-LOCA transients evaluated by LOFTRAN are performed taking into account the uncertainty in PRHR heat transfer. The uncertainties were determined from the scatter in the test data and are included so as to be most conservative for the transient analyzed.

21.6.1.2 LOFTRAN Code Conclusions

Based on the foregoing considerations, the NRC staff concludes that the applicant's use of LOFTRAN as described in WCAP-15612, WCAP-15613, and WCAP-15644 is acceptable for licensing calculations of the AP1000 subject to the following limitation:

- The transients and accidents that the applicant proposes to analyze with LOFTRAN are listed in Table 21-2 of this report, and the staff review of the applicant's use of LOFTRAN was limited to this set. Use of the code for other analytical purposes will call for additional justification.

Following its review of the DCD, the staff concludes that Table 21-2 of this report encompasses the analyses that the applicant has performed for the AP1000 design and, therefore, use of LOFTRAN is acceptable for AP1000.

21.6.2 NOTRUMP Computer Code for Small-Break LOCAs

NOTRUMP was first submitted for NRC review in November 1982. The code was developed to better address the T-H aspects of a postulated SBLOCA, which had become an issue following the accident at Three Mile Island. Following a review by the NRC staff, NOTRUMP was found to be acceptable for the analysis of SBLOCA events for Westinghouse reactor designs (WCAP-10079-P-A, "NOTRUMP A Nodal Transient Small-Break and General Network Code," issued August 1985). For NOTRUMP evaluations, an SBLOCA is considered to be a rupture in the RCS pressure boundary with a total cross-sectional area less than 0.09 m^2 (1.0 ft^2) for which the normal charging system flow is not sufficient to maintain pressurizer level and pressure. The NRC staff has also approved the use of NOTRUMP for SBLOCA evaluation for plants designed by Combustion Engineering (WCAP-10054-P-A, "Addendum to the Westinghouse Small-Break ECCS Evaluation Model Using the NOTRUMP Code for the Combustion Engineering NSSS," Addendum 1, issued March 1987).

NOTRUMP models one-dimensional thermal hydraulics using control volumes interconnected by flow paths (links). The spacial and time dependent solution is governed by the integral forms of the conservation equations in the control volumes and flow links. The thermal hydraulic model accounts for nonequilibrium conditions and applies drift flux models for calculating relative velocities between the steam and liquid phases. Reactivity feedback is modeled with point kinetics neutronics. The code incorporates special models to calculate responses of the RCPs, steam separators, and the core fuel pins. A significant code feature is a node stacking capability for calculating a single mixture height in a subdivided vertical region. A two-phase horizontal stratified flow model is also included.

21.6.2.1 Summary of AP600 Evaluations of the Use of the NOTRUMP Code

The NRC staff's evaluation of the use of the NOTRUMP code for the AP600 SBLOCA analyses is described in detail in Section 21.6.2, "NOTRUMP Computer Code for Small-Break LOCAs," of NUREG-1512. With the AP600, the applicant introduced new systems and protective features for which NOTRUMP had not been previously evaluated. These include the ADS, CMTs, PRHR HX, and IRWST. The applicant investigated the capability of NOTRUMP to model the AP600 systems as discussed in Westinghouse Topical Report WCAP-14206, "Applicability of the NOTRUMP Computer Code to AP600 SSAR Small-Break LOCA Analysis," issued November 1994. The existing code was determined to be adequate regarding most features of the AP600, however, several modifications were necessary. A summary of these modifications follows:

- implementation of the Simulator Advanced Real-time Code (SIMARC) drift flux methodology
- general drift flux model modifications
- modified Yeh drift flux correlation for use with the SIMARC drift flux method
- inclusion of general droplet flow correlation when void fractions are between 0.95 and 1.0 when using the improved TRAC-PF1 flow regime map
- modification of the bubbly and slug flow distribution parameter (C_0)
- use of a net volumetric flow-based momentum equation
- implementation of the flooding vertical drift flux model promulgated by the Electric Power Research Institute (EPRI)
- modifications to allow over-riding of the default NOTRUMP contact coefficient terms for formation of regions
- implementation of internally calculated liquid reflux flow links
- implementation of a mixture level overshoot model
- modified bubble rise/droplet fall model logic
- activation of the simplified pump model
- implicit fluid node gravitational head model implementation
- horizontal leveling model implementation
- revised unchoking model implementation

- implementation of a revised condensation heat link model
- implementation of the Zuber critical heat flux model
- revised two-phase friction multiplier logic
- addition of the Henry-Fauske/HEM critical flow correlation
- improved fluid node staking model logic
- revised iteration method for transition boiling correlation in metal node heat links

The description of these modifications along with code verification by comparison of calculational predictions to test data is discussed in Westinghouse Topical Report WCAP-14807, "NOTRUMP Final Validation Report for AP600," Revision 5, issued August 1998. Both integral system tests utilizing simulated reactor systems and separate effects tests modeling individual components were utilized. The NRC reviewed and approved the application of NOTRUMP for the analysis of an SBLOCA for the AP600 passive reactor design. The approval was made with the following conditions. The staff concerns that are addressed by these conditions also apply to use of NOTRUMP for AP1000 and, therefore, were considered in the staff's review for AP1000.

- The applicant did not predict core uncovery for any design-basis SBLOCA event for the AP600, so transition boiling or film boiling was not calculated to occur in the core. Consequently, the staff did not review the changes in the numerical solution techniques that were used to evaluate this condition in the NOTRUMP heat links. Moreover, the staff concluded that this methodology may not be invoked in applying the NOTRUMP code to the AP600 calculations. Should NOTRUMP be applied to calculations for which this methodology is being invoked, the review of the modified transition boiling correlation solution scheme will be revisited.

- The staff noted that NOTRUMP cannot calculate the effects of noncondensable gases injected into the primary coolant system during the AP600 SBLOCA. Noncondensable gases enter the PRHR late in the transient, when the PRHR HX no longer has a significant role in heat removal. Thus, the noncondensable gases do not appear to have a significant effect on the course of the event. If scenarios are found which cause noncondensable gases to reach the PRHR HX while it is actively removing heat from the primary system, NOTRUMP cannot be used to analyze those scenarios. The applicant removes consideration of PRHR HX heat flow prior to the ADS-4 actuation, which should prevent noncondensable gas from the accumulators from reaching the PRHR while it is included in the NOTRUMP model.

- NOTRUMP does not model the momentum flux terms in the conservation of momentum equation dealing with the effects of area and density change. The applicant performed an evaluation of the effect of the omitted momentum flux terms and concluded that they were of little significance with the exception of flow in the ADS-4 after reactor system pressure had decreased so that the flow velocity was no longer sonic. This deficiency and deficiencies in the ability of the code to calculate pressurizer drainage and reactor vessel downcomer level were accounted for by an imposed reduction in the IRWST level. The level reduction conservatively delays the time of IRWST injection and produces a net reduction in available volume of IRWST water. By comparison with data from the APEX facility, adjusted to account for scale, an IRWST level reduction of 0.91 m (3 ft) was determined to be appropriate. For added conservatism the applicant used an IRWST level reduction penalty of 1.83 m (6 ft).

- The NRC staff questioned the ability of the code to adequately predict liquid entrainment in branch lines. The most significant example occurs during ADS-4 operation. Flow through the ADS-4 valves exits from the reactor system hot legs from tees located at the top of the hot-leg piping. NOTRUMP assumes entrainment will occur when the mixture level in the hot legs reaches a preset elevation. That elevation is independent of the ADS-4 flow velocity. For very high ADS-4 fluid velocities, NOTRUMP may underpredict the amount of liquid entrained in the ADS lines. The resistance to vapor flow through an ADS-4 inlet line is reduced without entrained liquid. This may result in vapor flow rates through the ADS-4 that are too high resulting in an excessively high rate of reactor system depressurization. For the AP600, this effect was accounted for with the IRWST level penalty based on comparisons with the APEX- AP600 facility test data.

21.6.2.2 Evaluations of the NOTRUMP Code for the AP1000

DCD Tier 2, Section 15.6.5.4B.2, describes the SBLOCA analysis methodology for the AP1000 as consisting of three elements. Specifically, these are (1) the NOTRUMP code, (2) the NOTRUMP homogeneous model, and (3) critical heat flux evaluation during accumulator injection. The following discussion describe the staff's review of each of these three elements.

Use of NOTRUMP for the AP1000 SBLOCA evaluations is described in WCAP-15612 and WCAP-15644. WCAP-15612 contains a general description of the AP1000 and preliminary analyses of SBLOCAs for three postulated locations. Additional details and justification for use of NOTRUMP for the AP1000 SBLOCA analysis are included in WCAP-15644.

In WCAP-15613 the applicant provided a PIRT for an SBLOCA at the AP1000 and an AP1000 scaling assessment of the tests that were used to qualify NOTRUMP for the AP600. The applicant concluded that NOTRUMP is qualified to perform an SBLOCA for the AP1000 with no further modifications. The staff's evaluation of this assertion is discussed in Sections 21.6.2.2.1 to 21.6.2.2.4 of this report.

The AP1000 design is essentially a larger version of the AP600 design. Changes include increasing the core power, core power density, and the capacity of the passive safety systems. The design modifications that are of primary significance for modeling an SBLOCA include increasing the size of the CMTs, IRWST, ADS-4 valves, and PRHR HX. The core length was extended from 3.66 m (12 ft) to 4.27 m (14 ft) and the thermal power output was increased by approximately 76 percent. The average linear power was increased from 13.54 to 18.72 kw/m (4.10 to 5.707 kw/ft). The design of the RCPs has been modified and the SGs are larger. The RCPs are tripped on a safety injection signal and neither the primary coolant pumps nor the

SGs are expected to have a significant influence on the course of an SBLOCA event at the AP1000.

The accumulators are the same size for the AP1000 as for the AP600. The CMTs are 25 percent larger than for the AP600. Depressurization by the first 3 stages of ADS will be slower for the AP1000 since the plant is larger and the valves for the first 3 stages of ADS are the same size as for the AP600.

The PRHR HX is essentially the same design as for the AP600. The heat transfer area has been increased by 22 percent and the flow resistance in the inlet and outlet piping has been decreased so that the design heat flow rate is increased by 72 percent. The average heat flux for the PRHR HX in the AP1000 is expected to be 41 percent higher than for the PRHR HX in the AP600. In the AP600 review, the staff accepted the PRHR HX model because the heat transfer calculated by NOTRUMP for the SPES facility and the APEX facility experiments was lower than that measured in the experiments. PRHR heat transfer is given a medium importance in the PIRT (WCAP-15613). PRHR heat transfer is of greater importance for very small breaks, since most of the reactor decay heat would be removed by larger breaks.

In WCAP-14807, Revision 5, the applicant concluded that the NOTRUMP PRHR model contains a deficiency that needs to be monitored to ensure that excess PRHR heat transfer is not calculated. This is because the NOTRUMP code does not model the thermal plume in the IRWST that would occur from extended operation of the PRHR HX. For the AP1000, heat flux from the PRHR HX will be greater than for the AP600 and, therefore, will be more likely to produce a thermal plume in the IRWST. To account for possible nonconservatism in the PRHR HX model, the applicant has reduced the surface area by 50 percent in the NOTRUMP input for all AP1000 SBLOCA analyses. The staff requested that the applicant provide justification that the revised PRHR HX model is conservative. This information was provided in the response to RAI 440.054. The applicant provided a comparison of PRHR HX heat removal for the NOTRUMP model with the model in LOFTRAN which the staff has approved for AP1000 analysis based on comparisons with test data. See Section 21.6.1.1 of this report. The results of the NOTRUMP - LOFTRAN comparison was that the NOTRUMP model was not conservative by about 6 percent for total PRHR HX heat flow. When the 50 percent reduction factor was applied to the NOTRUMP PRHR HX heat transfer area, NOTRUMP was found to be conservative by about 12 percent. The staff concludes that the PRHR HX model in NOTRUMP is acceptable for AP1000 analysis with the 50 percent area reduction.

The CMTs for the AP1000 are about 25 percent larger than for the AP600 but they are expected to perform in a similar fashion. Following a LOCA, the CMT outlet valve will open to provide makeup water to the reactor core. Opening of the CMT outlet valve will cause relatively cool borated water to circulate from the CMTs into the reactor vessel. As the reactor system becomes voided, the CMTs will drain and provide cooling for the reactor core. For the AP600 review, the applicant performed comparisons of NOTRUMP predictions with data from two series of stand alone tests. The tests were designed to model CMT behavior in both the circulation and the drainage modes. The NOTRUMP code was found to predict the injected fluid to be at a higher temperature than the test data. The predicted time of the injection was usually delayed. These modeling results are conservative, and the NRC staff finds the model acceptable for the AP1000.

21.6.2.2.1 Calculation of ADS-4 Pressure Drop

For the design power increase of 76 percent, more reliance will be placed on the ADS-4 to depressurize the plant so that injection from the IRWST can begin and refill the core. The ADS-4 total vent area is increased by 76 percent. The resistance to flow in the inlet lines from the hot legs to the ADS-4 valves is decreased so that the total ADS-4 relief capacity is increased by 93 percent. Instead of the IRWST level penalty that was used in the analysis of the AP600 to account for deficiencies in the NOTRUMP ADS-4 model, the applicant uses an increased resistance model in NOTRUMP for the AP1000 evaluations. Specifically, the flow resistance in the ADS-4 flow paths is increased by 70 percent in the NOTRUMP input. The amount of increase was derived from comparisons with a stand-alone momentum flux model which was named FLOAD4 by the applicant.

The NRC staff requested the applicant to compare the pressure drop modeling of FLOAD4 to data. For frictional pressure drop, the applicant compared the predictions of FLOAD4 to those of the Darcy formula in the CRANE handbook ("Flow Through Valves, Fittings and Pipe," Crane Co., 1988) and with the CESNEF-2 correlation described in (C. Lombardi, et al., "CESNEF-3 Pressure Drop Correlation for Gas-Liquid Mixture Flowing Upflow in Vertical Ducts," ATTI XVIII Congresso Nazionale sulla Trasmissione del Calore, June 2000). The Darcy method compared well to data represented by the CESNEF-2 correlations for flow conditions representative of ADS-4 operation. Application of the Darcy method to the ADS-4 piping configuration resulted in reasonable comparison to the detailed FLOAD4 model.

The NRC staff independently verified the applicant's analysis of ADS-4 pressure drop. This was accomplished by developing a single phase network computer code employing a semi-implicit numerical scheme to simultaneously solve the conservation equations for mass, energy, and momentum. The momentum equation in the model contained momentum loss terms for friction, geometry and acceleration (momentum flux). Data given in the Crane manual for simple pipes containing friction and geometric losses was utilized, and the staff methodology was shown to reproduce the pressure drops for single phase conditions. The model was compared to two-phase flow pressure loss data across constrictions (at high qualities) to evaluate the modeling of the momentum flux pressure losses. The NRC staff's model was found to be conservative in comparison to data. The model also confirmed the pressure loss across the ADS-4 piping calculated by FLOAD4 and applied in the NOTRUMP code.

The applicant investigated the effect of having higher than expected flow resistance in the ADS-4 discharge lines. In this study, the form loss coefficients were increased by a factor of two for analysis of a postulated DEDVI line break. For the DCD base case, the total ADS-4 line resistance including form loss and friction is increased by 70 percent (based on the FLOAD4 evaluation) to account for the effect of area change on the fluid momentum. For the sensitivity study the total resistance was increased by an additional 50 percent. The result of the increased ADS-4 resistance was a slowing in reactor system depressurization after ADS-4 opened and the start of IRWST injection was delayed. The reactor vessel water inventory reached a minimum just before the beginning of IRWST injection with a brief period of core uncovery. A two phase level in the core was still calculated to be sufficiently high so that core cooling was maintained. The applicant's evaluation of adequate core cooling used adiabatic heat-up assumptions for the time period that the top of the core was calculated to be uncovered, which is conservative. Based on the apparent insensitivity of the core cooling result to uncertainty in ADS-4 modeling, the comparison of the applicant's ADS-4 modeling to correlations based on test data, and the staff's own independent verification, the NRC staff concludes that modeling the ADS-4 flow losses using the NOTRUMP code is adequate for the AP1000 SBLOCA analysis.

21.6.2.2.2 Liquid Entrainment

The ability of NOTRUMP to adequately predict liquid entrainment from the upper plenum and the hot legs to the ADS-4 was a concern to the staff as discussed in the DSER since the amount of entrainment will affect the ability of the ADS-4 to depressurize the reactor, as well as the liquid inventory of the reactor vessel. Hot-leg phase separation (entrainment) was DSER Open Issue 21.5-1. Upper plenum entrainment was DSER Open Issue 21.5-2. To justify the ability of NOTRUMP to predict liquid entrainment, the applicant referenced the validation of the code for the AP600 using test data which had been scaled to model the AP600 plant geometry. The NRC staff was concerned that higher steam velocities in the AP1000 upper plenum and hot legs would make the applicant's scaling conclusions for AP600 no longer valid. Additional details of the staff's review of the AP600 test facilities for the AP1000, including scaling issues and liquid entrainment, are discussed in Section 21.5 of this report.

In response to staff questions on the ability of NOTRUMP to model liquid flow rate and entrainment out of the ADS-4, the applicant originally provided comparisons of NOTRUMP predictions for SBLOCA at the AP1000 with those from a special version of the WCOBRA/TRAC computer code that was modified to provide for a better accounting of liquid entrainment in the reactor vessel, hot-legs and ADS-4. This code version was designated as "WCOBRA/TRAC-AP." The applicant provided comparisons of NOTRUMP predictions with those from WCOBRA/TRAC-AP in WCAP-15833-P, for the period in SBLOCA analysis for the AP1000 between actuation of the ADS-4 to the beginning of IRWST injection. The applicant concluded that the comparisons demonstrated that NOTRUMP could adequately simulate the overall core cooling behavior during this period.

The NRC staff questioned the validity of WCOBRA/TRAC-AP for predicting flow and entrainment out of the ADS-4 and asked for comparisons of the code predictions with experimental data. The applicant has not performed separate stand-alone tests for ADS-4, but concluded that data taken at the APEX facility for the AP600 was sufficient to benchmark the WCOBRA/TRAC-AP computer code for ADS-4 flow rates and entrained liquid fractions. The NRC staff raised concerns that higher steam velocities that would occur in the AP1000 upper plenum and into the horizontally oriented hot legs would make the applicant's scaling conclusions for the AP600 APEX facility no longer valid. See Section 21.5.7 of this report. In addition the staff was concerned that the models used in WCOBRA/TRAC-AP to describe the entrained liquid fraction in the upper plenum and hot legs had not been derived from data that describes the geometry of the AP1000. These concerns are also discussed in Section 21.5.7.4 of this report. As a result of the concerns expressed by the staff, the applicant decided not to rely on WCAP-15833-P to validate NOTRUMP (refer to Section 21.5.7.4 of this report), but relied on the direct benchmarking of NOTRUMP against the data from APEX-1000 to validate the SBLOCA methodology for AP1000. This benchmarking revealed deficiencies in NOTRUMP's prediction of entrainment.

Testing and Computer Code Evaluation

To address the deficiencies in NOTRUMP's modeling of liquid entrainment in the upper plenum, hot legs and ADS-4 piping, the applicant performed a bounding analysis using NOTRUMP in which these regions of the reactor system were set in the input to maintain a condition of homogeneity so that the steam and water phases would have the same velocity and that all water leaving the core would be carried out the ADS-4 by the exiting steam. See DCD Tier 2, Section 15.6.5.4B.3.7. The homogeneous flow assumption is bounding for treatment of liquid entrainment. In order to ensure conservative results, a back pressure penalty was added to the upper plenum to take into account the static head of the water that would no longer be allowed to accumulate there. The analysis was performed for a postulated DEDVI line break because this condition would present a limiting case for performance of the passive ECCS systems since approximately half of the emergency cooling water would be lost to the containment floor without passing through the core. The effect of entrainment is most severe for a DEDVI line break, as substantiated by the largest value of non-dimensional velocity (j_g*) the relevant parameter for entrainment. The applicant's evaluation of j_g* for various postulated SBLOCAs is discussed in Section 21.6.2.2.4 of this report. The net result of this sensitivity case was that the reactor vessel water inventory was substantially decreased over the base model which accounted for steam and water separation in the upper plenum, hot legs and ADS-4 piping. The core was shown to remain adequately cooled even with the bounding homogeneous flow assumption since water was continuously drawn through the core into the upper plenum and eventually out of the ADS-4. The NOTRUMP homogeneous model is the second element in the applicant's SBLOCA evaluation model.

The applicant's conclusion that core cooling would be maintained even if liquid entrainment was modeled using the bounding assumption of homogeneous flow was independently verified by the staff in an audit calculation using the RELAP5 computer code. In the staff's analysis of a postulated DEDVI line break, the upper plenum, hot legs and ADS-4 lines were assumed to be in the same homogeneous flow condition that was assumed for the NOTRUMP bounding analysis. The staff's results showed that core cooling would be maintained even under the bounding condition of homogeneous flow and confirmed the conclusion drawn by the applicant. The applicant's homogenous flow bounding analysis addresses the NRC staff's concerns stated in DSER Open Issues 21.5-1 and 21.5-2. With the additional confirmation provided by comparisons of NOTRUMP predictions with test data from the APEX-1000 facility discussed later in this section, these open issues are now closed.

21.6.2.2.3 Core Level Swell

During the later phases of ADS-4 blowdown and during the period of IRWST injection, NOTRUMP predicts the core to become highly voided as a result of boiling. The boiling process is predicted to cause liquid to be carried up through the core, into the upper plenum, through the hot legs and out of the ADS-4 valves. The average core void fraction is as high as 60 percent with considerable higher voiding at the top of the core. This "level swell" effect from boiling provides for cooling of the upper core regions as liquid is carried from the core out of the ADS-4 valves and is replaced by incoming liquid from the passive core cooling system. For the AP600 review, the applicant successfully correlated experimental test data using NOTRUMP for "level swell" at low pressures and for conditions that would be present in the AP600 following SBLOCA. These were data from the applicant's G2 series of tests and the ACHILLES tests in England. The G2 tests utilized a full size simulation of a Westinghouse 14 foot fuel bundle which is the same core length as that of the AP1000. The comparisons are in Chapter 4 of WCAP-14807, Revision 5, and in the applicant's response to RAI P69 (issued on September 17, 2001, during the AP1000 pre-application review). The predictions by NOTRUMP were conservative (more core uncovery) in comparison to the test data.

Because of the higher power density of the AP1000 as compared with the AP600, the staff requested additional justification for the adequacy of the Cunningham-Yeh void fraction correlation that is used to predict level swell in NOTRUMP. In response to RAI 440.164, the applicant prepared a detailed evaluation of Cunningham-Yeh with available level swell data. These evaluations are also discussed in WCAP-15644, Revision 2. In addition to the G2 and ACHILLES test data, the applicant evaluated data from the FLECHT-SEASET, FLECHT-skewed, Westinghouse G1 tests and the THETIS test series. In all, 28 sets of data were evaluated. Pressures, power density, power shape, core inlet flow and inlet subcooling expected for the AP1000 during the time of maximum core voiding were encompassed by the test data. The core level swell predicted by Cunningham-Yeh was within a 20 percent error band encompassing the data for all 28 tests. In the majority of cases NOTRUMP predicted a lower level swell than the test data. Predicting a level swell lower than test data is conservative since, for a given amount of liquid in the core, the under prediction of level swell would lead to prediction of uncovery in the upper region of the core. The applicant notes that the case of a partially filled core is never predicted for postulated design-basis SBLOCAs in the AP1000. Instead, a two-phase mixture is calculated to flow through the core, into the upper plenum, to the hot legs and out of the ADS-4 valves. Uncertainty in determining the void fraction of the two-phase mixture in the core under these conditions would not affect core cooling. The comparisons of Cunningham-Yeh predictions with applicable level swell data address DSER Open Item 21.5-3.

21.6.2.2.4 Benchmark Against APEX-1000 Tests

The APEX-1000 facility is the result of refurbishment of the APEX facility at OSU that was used to provide data for the AP600 review. Significant modifications of the facility were necessary before performing tests for the AP1000. The modifications included heater rods of increased power to simulate the reactor core and increased size of the ADS-4 piping and valves. In addition, the pressurizer and CMTs were increased in size and passive core cooling system injection line resistance was reduced. APEX-1000 tests DBA-2 and DBA-3 are designed to simulate a DEDVI line break in the AP1000. The difference in these tests is the location of the assumed single failure of one of the four ADS-4 valves. Test DBA-2 modeled a failed ADS-4 valve connected to the hot leg opposite from the pressurizer. Test DBA-3 modeled a failed ADS-4 valve connected to the hot leg with the pressurizer.

A DEDVI line break is believed to be the most severe small-break location for the AP1000. This is because approximately half of the ECCS water would not reach the reactor. This break location was shown to be the most severe break for the AP600 in the SPES-2 and APEX test series, as well as the staff's audit calculations using the RELAP5 code for the AP1000, as discussed in Section 21.6.2.3 of this report. Therefore, the staff performed NOTRUMP verification only for simulated DEDVI line breaks at the APEX-1000 facility. As additional confirmation that NOTRUMP only needed to be verified for this break location for the AP1000, the NRC staff asked the applicant to provide comparisons of the non-dimensional steam velocity leaving the core for a postulated DEDVI line break for the AP1000 with that of other break sizes and locations. These comparisons revealed that the DEDVI line break has the highest non-dimensional steam velocity (compared to the other postulated breaks) and, therefore, would be expected to be the most susceptible to dryout stemming from liquid entrainment out of the ADS-4 valves. The non-dimensional steam velocity (j_g*) is defined by the following equation:

$$J_g^* = J_g/(\sigma\ g\ \Delta\rho/\rho_g^2)^{0.25}$$

where:

j_g	is the vapor phase velocity leaving the reactor core
ρ_g	is the vapor phase density
$\Delta\rho$	is the density difference between the liquid and vapor phases
σ	is the liquid surface tension
g	is the gravitational constant

In performing the NOTRUMP predictions of the APEX-1000 tests, the applicant modeled the discharge configuration for the break and for the ADS-4 valves to closely follow the pressure decay in the tests. The amount of liquid entrainment leaving the core and discharged from the ADS-4 valves is indicated by the total mass discharged from the valves. In comparison to the test data, NOTRUMP predicted slightly more mass to be discharged from the ADS-4 valves than was measured for the tests. This is conservative since prediction of a greater water loss through the ADS-4 valves would lead to less water remaining to cool the core. However, the NRC staff determined that NOTRUMP did not predict the total liquid mass entrained for valid reasons. The staff did not believe the validity of placing reliance on these compensating errors in NOTRUMP to predict total liquid mass discharged under all conditions. The applicant's bounding analysis of entrainment (homogeneous model) verified that accurate modeling of entrainment was not necessary since the design was shown to have adequate margin.

A measure of the mass of water contained in the reactor vessel to cover the core is the collapsed liquid level. This is determined from the differential pressure between the bottom and top of the core section. For much of the simulations, NOTRUMP underpredicted the collapsed core levels compared to the tests. During the period when the ADS-3 and ADS-4 valves were open to continue the depressurization, and the intact CMT and accumulator were injecting, NOTRUMP predicted considerably more water to be in the core than occurred in the test data. This is the time of minimum core water mass for the two tests. At this time, the intact accumulator and the intact CMT are both injecting into the test vessel so that abundant water is available to cool the core.

NOTRUMP does a credible job in predicting flows into and out of the reactor vessel from the intact CMT, intact accumulator, the break, and the ADS. The phenomena occurring within the downcomer during this time are highly complex, with water discharging from one side of the downcomer, and cold accumulator and CMT water being injected into the other. Complex patterns of steam condensation would occur on the injected water streams before they reach the core inlet. The applicant attributes the discrepancy between the test data and NOTRUMP predictions for minimum core water mass to the one dimensional treatment of the downcomer in the NOTRUMP model and under prediction of steam condensation. These effects cause NOTRUMP to underpredict the temperature of the water entering the core inlet so that less steaming is produced and the collapsed core level is overpredicted. The NOTRUMP predictions for tests DBA-2 and DBA-3 were similar to the predictions derived by the code for simulated DVI line breaks at APEX and SPES-2 for simulation of the AP600. For other break locations in the APEX and SPES-2 AP600 test series, less complex downcomer phenomena occurred, and NOTRUMP closely predicted the collapsed liquid level or conservatively underpredicted the collapsed liquid levels for the tests.

The NRC had two concerns involving the over prediction of core inventory by NOTRUMP during the accumulator injection period for APEX-1000 tests DBA-2 and DBA-3. The first concern was that for analysis of the AP1000, an excess water mass would be predicted to be in the core, and would remain in the core throughout the analysis. This causes the entire analysis of DVI line breaks at AP1000 to be nonconservative. The second concern was that NOTRUMP would predict the core to be covered and cooled during the accumulator injection period when actually the core would uncover and heat up.

The applicant addressed the first concern by performing a NOTRUMP analysis in which the code was modified to force the prediction to match the core collapsed level data during the early portion of test DBA-2 where the code had performed poorly. The code was then returned to its original form for the remainder of the analysis. The NOTRUMP input and coding were modified so that in the early period for the analysis of test DBA-2, the accumulator water was assumed to be heated, downcomer condensation was increased and core interfacial drag was increased. These modifications caused the code to predict higher void fractions in the core so that the predicted results closely matched the test results for core collapsed level. In the later portion of the analysis when the code was returned to its original form, the prediction of core collapsed level was generally conservative and closely followed the predictions of the code when it was left in its original form for the entire analysis. This sensitivity study demonstrated to the NRC staff that the over prediction of core collapsed level early in the analysis when the accumulators are injecting is not propagated into the later phases of the analysis.

Since NOTRUMP over-predicts the minimum amount of water in the core for the accumulator injection period of the APEX-1000 tests, the NRC staff requested that the applicant provide an evaluation of core cooling during this period by a means that is not dependent on the amount of water predicted in the core by NOTRUMP. Since NOTRUMP's prediction of mass transfer into and out of the reactor vessel was adequate, code results can be used to provide core inlet conditions for evaluation of core cooling. Using a correlation for critical heat flux (CHF) by Chang (H.C. Chang, et al., "A Study of Critical Heat Flux for Low Flow of Water in Vertical Round Tubes Under Low Pressure," Nuclear Engineering and Design, 1991) the applicant demonstrated that the section of the core producing the highest power would not experience, by a considerable margin, dryout or overheating during the accumulator injection period. This calculation is considered conservative since no credit was taken for the water stored within the core but only credited the minimum core inlet flow, and back flow of water above the core as permitted by the rising steam. Additional conservatism is that the entire core was also assumed to act as the highest powered section. Core heat fluxes equal to or exceeding the CHF is not a prohibited condition for SBLOCA analysis, but if the core heat flux is less than the CHF, clearly no cladding heatup would be expected. The Chang correlation is based on data from flow conditions in very small tubes. The use of a correlation based on small tube data was proved conservative by comparison to CHF data for rod bundles at low flow (V.B. Khabensky, et al. "Critical Heat Flux in Rod Bundles Under Upward Low Mass Flow Densities," Nuclear Engineering and Design, 1998). The margin to CHF was shown to be larger for the Khabensky correlation, which is based on bundle data, than for the Chang correlation based on tube data. This showed use of the Chang correlation to be conservative. Based on comparisons of the Cunningham-Yeh void fraction correlation with the level swell test data, the comparisons of NOTRUMP predictions with the collapsed core level from APEX-1000 and the additional evaluation against applicable CHF correlations, Open Item 21.5-3 identified in the DSER concerning level swell is now closed. Evaluating of CHF during accumulator injection is the third element of the applicant's SBLOCA evaluation model for AP1000.

21.6.2.3 NRC Staff Audit Calculations using RELAP5

The NRC staff contracted to have RELAP5 input developed for the AP1000. This work was documented in Information Systems Laboratories, Inc (ISL) ISL-NSAD-NRC-01-003, "Preliminary Results of the AP1000 RELAP5/MOD3.3 Analysis for the Two-Inch Cold Leg and Main Steamline Breaks," issued August 2001. The model was developed from an existing RELAP5 input model for the AP600 and modified to describe the AP1000 using plant data supplied by the applicant. The NRC staff uses RELAP5 as an aid in understanding and evaluating the sequences and phenomena in postulated reactor accidents. RELAP5 is not a design-basis licensing tool. Conclusions on the acceptability or unacceptability of an SBLOCA for the AP1000 are based on the applicant's calculations using NOTRUMP and other Westinghouse methodology and not on results from RELAP5.

Conservative assumptions were built into the RELAP5 input so as to be consistent with those made by the applicant in running NOTRUMP:

- The analyses were initiated from 102 percent of full power.
- The failure of one of the four ADS-4 valves was assumed.
- Decay heat was set at 20 percent greater than American Nuclear Society (ANS) Standard ANS 5.1-1973, "Decay Energy Release Rates Following Shutdown of Uranium-Cooled Thermal Reactors."
- The containment pressure was set to atmospheric.

The core model in the RELAP5 analyses was somewhat more detailed than in the NOTRUMP analyses in that a hot rod was modeled, which simulates a higher heat flux than that for the average core. The increased heat flux of the hot rod allows for the possibility to assess fuel cladding heatup following a departure from nucleate boiling or an uncovery condition.

The staff performed the following analyses for comparison with the NOTRUMP results presented in DCD Tier 2, Chapter 15:

- the inadvertent opening of both 10.16 cm (4 in.) ADS-1 valves

- a cold-leg break of 5.08 cm (2 in.) equivalent diameter in the loop without the PRHR
- the DE rupture of a direct vessel injection line
- a cold leg break of 25.4 cm (10 in.) equivalent diameter

None of the breaks analyzed by the staff using RELAP5 resulted in core uncovery or cladding heatup. RELAP5 calculated approximately the same minimum core water mass for all break sizes. However a lower core water mass was predicted for the DEDVI line break than for the other breaks.

The NRC staff audit calculation originally predicted a small amount of core uncovery following a DEDVI line rupture after actuation of the ADS-4. The amount of core uncovery calculated by RELAP5 was minimal and was at a time when considerable cooling of the reactor core had already occurred. This analysis was later repeated with the benefit of additional data from the applicant describing the flow limiting devices in the DVI nozzles and in the CMT discharge lines. The revised analysis no longer predicts that the core will become uncovered following any SBLOCA.

Table 21-3 of this report shows a comparison of the sequence of events for a postulated design-basis DEDVI line break as calculated by the RELAP5 and NOTRUMP codes. The results show a faster reactor system depressurization for NOTRUMP until the time when the ADS-4 valves are discharging. The more rapid depressurization in NOTRUMP, which occurs early in the analysis, results from the more conservative model for subcooled break flow in NOTRUMP. NOTRUMP predicts earlier drainage for the CMT connected to the broken DVI line which causes earlier activation of ADS Stages 1, 2 and 3. After ADS-4 actuation, RELAP5 and NOTRUMP predict approximately the same reactor system depressurization rate. Once subsonic flow conditions are predicted for the ADS-4 valves, the applicant imposes a penalty on the flow resistance in the ADS-4 lines to account for the absence of a momentum flux model in NOTRUMP. RELAP5 contains a momentum flux model and, therefore, no penalty is imposed on the RELAP5 ADS-4 line resistance. Once the ADS-4 flow resistance penalty is imposed for NOTRUMP, NOTRUMP depressurizes much slower than RELAP5. For this reason RELAP5 predicts an earlier IRWST injection time than does NOTRUMP. As a sensitivity study, the staff delayed IRWST injection until the time predicted by NOTRUMP. Even with delayed injection, RELAP5 did not predict core uncovery. The intact CMT continued to inject during this period.

In general the amount of water in the core predicted by RELAP5 is less than that predicted by NOTRUMP. This is true even though both codes predict the core to remain covered by a two phase mixture of water and steam for all of the design-basis SBLOCA cases. The accuracy of a computer code in predicting core uncovery can be demonstrated by the ability of the same code to reproduce experimental test data. Comparison with experimental data indicate that the interfacial drag between the steam and water in the core calculated by RELAP5 is too high at low pressures resulting in over prediction of level swell, enhanced entrainment and loss of inventory from the top of the test section. For FLECHT-SEASET Boil Off Test 35658, RELAP5 was shown to predict core dryout earlier than the data and to lose coolant out of the top of the test bundle at a faster rate. Thus RELAP5 would be expected to predict less water in the core for the AP1000 than would actually be the case (see NUREG/CR-5535, "RELAP5/Mod3.3 Code

Manual Volume III: Development Assessment Problems," Revision 1, issued December 2001). During the the AP600 review, RELAP5 was benchmarked against test data taken at the integral test simulations for the AP600 at the SPES-2, APEX- AP600, and ROSA facilities. These comparisons are documented in report INEL-96/0400 ("Adequacy Evaluation of RELAP5/Mod3, Version 3.2.1.2, for Simulating AP600 Small-Break Loss-of-Coolant Accidents," Appendices A, B, C, and D, April 1997). For the integral system experiments, RELAP5 almost always predicted less water in the core than occurred in the tests.

As further confirmation of the ability of the RELAP5 code to predict the AP1000 response to an SBLOCA, code predictions for APEX-1000 tests DBA-2 and DBA-3 were compared to the test data. Early in the tests, when the ADS-3 and ADS-4 valves opened to continue the depressurization and the intact CMT and accumulator were injecting, RELAP5, as did NOTRUMP, predicted considerably more water to be in the core than was the case for the two tests. In the case of RELAP5, the cause of the over prediction in core collapsed level appears to be the result of poor modeling of the ADS-1, 2, and 3 stages and the resulting underprediction of pressurizer water mass. The deficiency in pressurizer mass between the code prediction and the data is more than enough to account for the overprediction in core collapsed level by RELAP5. During the period when RELAP5 overpredicts core collapsed level, abundant cooling water is being delivered to the test assembly by the intact accumulator and intact CMT, so loss of core cooling is not expected to occur during this period. The APEX-1000 facility is well scaled to model the AP1000 during this period of the postulated accident, so that the test data can be relied upon to demonstrate core cooling. The staff believes that the critical period for maintaining core cooling for a postulated SBLOCA in the AP1000 is the period during the ADS-4 blowdown just before IRWST injection. At that time, the accumulators would be empty and CMT flow would be reduced. This is the time that RELAP5 predicts the minimum core collapsed liquid level and the minimum core inlet flow to occur. At this time, although RELAP5 predicts the core to be covered by a two phase mixture of steam and water, RELAP5 predicts the core collapsed liquid level to be considerably lower than that calculated by the NOTRUMP code.

In order to provide additional verification that core cooling would be maintained even at the time of minimum core level and core inlet flow, the staff performed additional bounding calculations. Since RELAP5 is believed to calculate excessive interfacial drag in the core region at very low RCS pressures, liquid may be artificially entrained and carried into the upper core regions. For this reason a drift-flux model was employed to better determine the swelled level in the core using the collapsed liquid level computed by RELAP5 for this event. The swelled level computed by the drift-flux model was then used with a pool boiling heat transfer, heat-up model to compute the clad temperature response should the transition to steam cooling occur during the DVI line break simulation. This calculation also assumes subcooled water enters the core and only the water mass calculated to be in the core by RELAP5 is considered in the swell calculation.

This approach was used to compute and explain the heat-up experienced in test ROSA/AP600 Test AP-DV-03 and is described by K. Almenas, et al (SCIN-NRC-365-98, "RELAP5/MOD3.2.1.2 Analysis of ROSA/AP600 Test AP-DV-03 and the Effect of ADS-4 Flow Area," May 1998). The NRC staff's drift-flux model was again used to compute the level swell and to circumvent the excessive interfacial drag in the RELAP5 core model, which sometimes precludes heat-up in highly void core regions.

This modeling approach predicted a maximum core uncovery of 0.91 m (3.0 ft) at about 1000 seconds into the event. A heat-up model was then used to compute the fuel cladding temperatures in the uncovered regions. The heat-up model considers pool boiling heat transfer with nucleate boiling along the fuel rod below the two-phase level and forced convection to steam cooling plus thermal radiation to steam above the two-phase level. Below the two-phase level, nucleate boiling heat transfer coefficients fall in the range of 5678 to 11357 W/m^2-°C (1000 to 2000 Btu/hr-ft^2 -°F). With these heat transfer coefficients, the fuel rod surface temperatures will remain within 2.8 °C (5 °F) of the fluid saturation temperature. Since the reactor trips very early and there is a long flow coastdown period to remove the stored energy in the fuel, there is insufficient power in the rods to produce a DNB condition during the flow coastdown or forced convection portion of the blowdown. As such, the only mechanism that can cause the fuel rod to heatup is uncovery of the core and exposure of the top portion of the rods to steam cooling. During uncovery periods, the steam cooling heat transfer coefficients are computed based on the recommendations in NUREG/CR-2456, in which a convective heat transfer correlation based on a modified Reynolds number is recommended. Unlike most correlations for steam cooling, this method employs an evaluation of the vapor properties at the heated surface temperature that adjusts the correlation for the effects of vapor property variations. The correlation is equivalent to the McEligot correlation for the case of heat transfer to essentially ideal gases. The correlation is applied for Reynolds numbers above 2000. NUREG/CR-2456 demonstrated that this correlation predicts the Thermal Hydraulic Test Facility (THTF) bundle uncovery test and heatup data well. Below a Reynolds number of 2000, the Sieder-Tate correlation is used in this laminar steam cooling regime.

A top-peaked axial power distribution was used in this analysis. This shape corresponds to a transient power condition that would not be sustained long enough for decay heat to assume this shape following trip. This shape is clearly conservative for heat-up analyses. A hot rod peak linear heat generation rate of 49.2 kw/m (15.0 kw/ft) was also assumed in the staff analysis.

The clad temperature response showed that the uncovery produced a peak clad temperature for the DEDVI line break of 893.3 °C (1640 °F). This result is considered an upper bound for the clad temperature because the RELAP5 liquid level is considered to be less than the minimum inventory anticipated for a spectrum of small breaks in the AP1000 plant. This low clad temperature also ensures that clad oxidation is insignificant. The results of this bounding analysis supports the conclusion that cladding temperatures for the most limiting postulated small break in the AP1000 (i.e., the DE break of a DVI line) will remain below the limit of 1204 °C (2200 °F) as stated in 10 CFR 50.46, “Acceptance Criteria for Emergency Core Cooling Systems for light-water nuclear power reactors,” of the Commission’s regulations.

Since the interfacial drag between the steam and liquid in the core calculated by RELAP5 is thought to be too high, the staff performed a sensitivity study to verify that over-prediction of interfacial drag would be conservative for maintaining the core in a covered condition. For the sensitivity study the staff repeated the analysis of the postulated DEDVI line break for the AP1000 reactor using the Bestion interfacial drag correlation to predict the core void distribution rather than the EPRI model which is the default model in RELAP5. The Bestion correlation applies less interfacial drag than does the EPRI model. Using the Bestion correlation, a higher collapsed liquid level was predicted in the core than was predicted using the EPRI model confirming that RELAP5's over prediction of interfacial drag using EPRI model resulted in more water being expelled from the core and hence a lower prediction of collapsed liquid level, a conservative result. Even with the conservative collapsed liquid level prediction, RELAP5 calculations predicted that the core remained covered at all times by a two-phase mixture of steam and water, precluding core heat up.

21.6.2.4 NOTRUMP Code Conclusions

In the DCD Tier 2, Section 15.6.5.4B.2, "Small-Break LOCA Analysis Methodology," the applicant describes three elements of the AP1000 small-break LOCA evaluation model as the NOTRUMP computer code, the NOTRUMP homogeneous sensitivity model in the upper plenum and hot-leg regions, and CHF assessment during accumulator injection. Based on the foregoing evaluations, the NRC staff concluded that the use of NOTRUMP as described in WCAP-15612, WCAP-15613, and WCAP-15644 is acceptable as the first element in the AP1000 SBLOCA evaluation model for licensing calculations for the AP1000 subject to the following conditions.

During the review, the NRC staff determined that the NOTRUMP code was adequately verified to predict most phenomena associated with SBLOCA for the AP1000. For two types of phenomena, verification of NOTRUMP was found to be less than adequate so that additional bounding calculations were necessary to ensure that the acceptance criteria of 10 CFR 50.46 of the Commissions regulations are met. These phenomena are (1) liquid entrainment in the upper plenum, hot legs and ADS-4 lines (DSER Open Items 21.5-1 and 21.5-2), and (2) prediction of core water inventory in the early portion of the accident (DSER Open Item 21.5-3). As discussed in Section 21.6.2.2 of this report, the applicant bounded the uncertainty in the NOTRUMP prediction of liquid entrainment by performing a NOTRUMP calculation of the limiting small break in which the upper plenum, hot legs, and ADS-4 piping were assumed to be homogenous for steam and water flow. The applicant bounded the uncertainty in the NOTRUMP prediction of core water inventory in the early portion of SBLOCA by performing a CHF calculation using the Chang CHF correlation. The applicant also identified the NOTRUMP homogeneous sensitivity model and the critical heat flux assessment during accumulator injection, described in DCD Tier 2, Sections 15.6.5.4B.2.2 and 15.6.5.4B.2.3, respectively, as Tier 2* information. An AP1000 licensee may not depart from this Tier 2* information without prior NRC approval. The staff finds this to be acceptable.

With these considerations, the NRC staff concludes that the NOTRUMP code, when augmented with the bounding calculations described above, is an acceptable methodology for performing SBLOCA analysis for the AP1000 and that Open Items 21.5-1, 21.5-2 and 21.5-3, which were identified in the DSER, are now resolved.

21.6.3 WCOBRA/TRAC for Large-Break LOCA Analyses

21.6.3.1 Introduction

WCOBRA/TRAC applicability to the AP1000 BE LBLOCA analyses is based on (1) the NRC's approval of WCOBRA/TRAC for use in analyzing LBLOCAs for the AP600 and three- and four-loop Westinghouse plants, (2) analyses regarding the impact of behavior of the AP600 and AP1000 passive cooling features on the peak cladding temperature (PCT), and (3) the results of the review of related PIRT tables, which indicate that there are only minor differences in the expected response to a BE LBLOCA between the AP1000, AP600, and Westinghouse three- and four-loop plants. The applicability of WCOBRA/TRAC for the AP1000 BE LBLOCA references the review of the AP600, a summary of which is attached as Appendix 21.A to this report.

WCOBRA/TRAC Applicability for BE LBLOCA for Three- and Four-Loop Westinghouse Plants

In 1988, the NRC revised 10 CFR 50.46 to allow the use of realistic/best estimate (BE) computer models in calculating ECCS performance. The approach allowed BE computer models to be used to calculate a nuclear power plant's response to an LBLOCA, provided the uncertainty in the calculated results was quantified. The uncertainty is to be added to the calculated results, including the PCT, when comparing the ECCS performance to the acceptance criteria of 10 CFR 50.46. The applicant submitted to the NRC a BE methodology for performing LBLOCA analyses of Westinghouse three- and four-loop PWRs with cold-leg injection, WCAP-12945-P, "Code Qualification Document for Best Estimate LOCA Analysis," Volumes 1 to 5, dated June 1992 to June 1993. In the following discussion, WCAP-12945-P is referred to as the Code Qualification Document (CQD). The NRC approved the CQD for use in licensing analyses of three- and four-loop PWRs with cold-leg injection in a letter from the NRC to Westinghouse, "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Accident Analysis," dated June 28, 1996. The BE LBLOCA models are designed to show conformance of the ECCS to 10 CFR 50.46 requirements.

WCOBRA/TRAC Applicability for AP600 LBLOCA

The applicant submitted WCAP-14171, "WCOBRA/TRAC Applicability to AP600 Large-Break Loss-of-Coolant Accident," to document the application of WCOBRA/TRAC, together with the applicant's modifications to the approved BE methodology to the AP600 LBLOCA. The BE LBLOCA models are designed to show conformance of the ECCS to 10 CFR 50.46 requirements; guidance contained in Regulatory Guide (RG) 1.157, "Best-Estimate Calculations of Emergency Core Cooling System Performance," dated May 1989; and the Code Scaling, Applicability, and Uncertainty (CSAU) Methodology, in NUREG/CR-5249, "Quantifying Reactor Safety Margins," EGG-2552, December 1989.

This evaluation documented the results of the staff review of the applicant's BE LBLOCA methodology for licensing analyses of the Westinghouse AP600. The AP600 review included the method for conformance with the guidance contained in RG 1.157, the CSAU methodology, and how the method met the requirements and acceptance criteria of 10 CFR 50.46.

The staff reviewed the following AP600-specific material:

- WCAP-14171, "WCOBRA/TRAC Applicability to AP600 Large-Break Loss-of-Coolant Accident," Revision 2, dated March 24, 1998
- Westinghouse letter NTD-NRC-95-4598, dated November 17, 1995
- Westinghouse letter NSD-NRC-96-4908, dated December 10, 1996
- Westinghouse letter NSD-NRC-97-5171, dated June 10, 1997
- Westinghouse letter NSD-NRC-97-5291, dated August 27, 1997
- Westinghouse letter NSD-NRC-97-5332, dated September 8, 1997

WCAP-14171 was the basis for the review. The report includes the AP600 LBLOCA PIRT and compares the AP600 LBLOCA response to that for the North Anna plant. The applicant described how it would apply the WCOBRA/TRAC realistic methodology to the AP600 and presented the WCOBRA/TRAC results of the AP600 BE LBLOCA. In particular, the applicant described the changes and simplifications made to the CQD methodology for application to the AP600 analysis. The main difference from the approved methodology is the simplification of the uncertainty analysis by including a larger number of bounding parameters. The applicant chose this approach because of the large margin available in the AP600 relative to the 10 CFR 50.46 PCT limit.

This review also considered the information provided by the applicant's letter responses listed above to clarify a number of discussion items related to WCAP-14171. WCAP-14171, Revision 2, was issued in February 1998 to incorporate the applicant's discussion item responses, as well as document the application and methodology limitations listed in Section 21.A.12 of this report.

<u>Summary of 10 CFR 50.46 Review for AP600</u>

10 CFR 50.46 is the legal basis for the BE analysis of ECCS performance. This section summarizes how the applicant's AP600 methodology meets the requirements of 10 CFR 50.46, which describes the ECCS acceptance criteria for light-water reactors.

The portion of 10 CFR 50.46(a)(1)(i), that was the focus of this review states the following:

> Except as provided in paragraph (a)(1)(ii) of this section, the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and

> assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that, when the calculated ECCS cooling performance is compared to the criteria set forth in paragraph (b) of this section, there is a high level of probability that the criteria would not be exceeded.

In its evaluation of the CQD, the staff found the applicant's methodology for three- and four-loop plants met the 10 CFR 50.46(a)(1)(i) requirements. WCOBRA/TRAC realistically describes the behavior of a PWR during a LBLOCA on the basis of a review of the models, correlations and the code assessment results. Also, the staff reviewed all uncertainty distributions, response surface generation, and their applications in determining the 95^{th} percentile PCT. Uncertainties due to reactor input parameters were also included.

In WCAP-14171, the applicant showed the applicability of the WCOBRA/TRAC code to the AP600 and described the modifications made to the approved methodology for the AP600. The applicant showed the similarity of the AP600 and three- and four-loop plant Westinghouse BE LBLOCA responses by comparing the calculated response in North Anna to that of the AP600, including a DVI assessment. In addition the applicant showed that the effect of the CMTs and the PRHR HX on the evolution of the BE LBLOCA transient is small. The similarity of the AP600 and three- and four-loop plant BE LBLOCA responses and the DVI assessments are discussed in Section 21.A.3 of this report. Therefore, for the AP600 design, the applicant satisfied the 10 CFR 50.46(a)(1)(i) requirements that the methodology must realistically describe the behavior of the reactor during a BE LBLOCA and must make comparisons to applicable data.

On the basis of the information provided by the applicant concerning the modifications to the approved uncertainty methodology for the AP600, the staff concluded that the applicant had adequately justified the modifications. This review is discussed in Sections 21.A.5 and 21.A.8 of this report. For the AP600, the applicant satisfied the 10 CFR 50.46(a)(1)(i) requirements by quantifying and accounting for uncertainties when comparing the calculated ECCS performance to the criteria of 10 CFR 50.46(b). The five acceptance criteria for ECCS performance are as follows:

- the PCT is less than 1204 °C (2200 °F) [10 CFR 50.46(b)(1)]
- the maximum local cladding oxidation does not exceed 17 percent of total cladding thickness before oxidation [10 CFR 50.46(b)(2)]
- the maximum core-wide hydrogen generation does not exceed 1 percent [10 CFR 50.46(b)(3)]
- the core geometry remains coolable [10 CFR 50.46(b)(4)]
- long-term cooling shall be ensured [10 CFR 50.46(b)(5)]

Testing and Computer Code Evaluation

The staff determined that the applicant's BE LBLOCA methodology for the AP600 met these criteria as follows:

- The staff found the PCT methodology adequate to meet NRC requirements for 10 CFR 50.46(b)(1) realistic LBLOCA analyses. The applicant's methods for determining the 95^{th} percentile PCT were the subject of the review summarized and discussed in a number of sections of this report. The AP600 calculated 95^{th} percentile PCT is discussed in Section 15.2.6.5 of the AP600 SSAR.

- The applicant applied the approved methodology to the AP600 to show compliance with 10 CFR 50.46(b)(2). Because the AP600 has similar fuel and a similar LBLOCA response to plants for which WCOBRA/TRAC was previously approved, and because of the low calculated PCT, the staff determined that the approach for the approved methodology in the area of local oxidation calculation was applicable to the AP600.

- For core-wide oxidation, the AP600 methodology provides for evaluation of whether oxidation is significant at the estimated PCTs to show compliance with 10 CFR 50.46(b)(3). Oxidation is not significant below 982 °C (1800 °F). Because the AP600 has a low estimated PCT, at or below 941 °C (1725 °F), and corresponding low local oxidation estimates, the staff concluded that an evaluation approach for the core-wide oxidation calculation was applicable to the AP600.

- The applicant stated that meeting 10 CFR 50.46(b)(1) and (2) ensures that a coolable core geometry is maintained per 10 CFR 50.46(b)(4). In view of the foregoing discussion on these criteria, the staff found this acceptable. This is consistent with the approved methodology and consistent with 10 CFR Part 50, Appendix K, Evaluation Models, and use of a realistic LBLOCA methodology for the PCT and results of oxidation calculations would not change this conclusion.

- For long-term cooling, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived core radioactivity. Section 21.6.4 of this report describes the use of WCOBRA/TRAC for long-term cooling calculation.

On the basis of the above, the staff concluded that for AP600, the applicant met those portions of 10 CFR 50.46(a)(1)(i) that were the focus of the AP600 review as described in Section 15.2.6, "Decrease in Reactor Coolant Inventory," of NUREG-1512.

A detailed description and the comparison of the applicant's methodology and CSAU and the staff's conclusions can be found in Appendix 21.A of this report.

21.6.3.2 Phenomena Identification and Ranking Tables for AP1000 and AP600

Section 2 of WCAP-15613 contains separate PIRTs for LBLOCAs, SBLOCAs, and non-LOCA transients for the AP1000 design, as well as those for the AP600 design. The PIRTs provide a means to identify and classify, (in terms of importance) the T-H phenomena expected to occur in transients and accidents that must be included in the analytical models, and for which data must be available for their evaluation. The NRC staff evaluated the AP600 PIRTs during the AP600 design certification review, and found that they capture the important phenomena, processes, and components. The staff also noted that the AP1000 PIRTs are very similar to those of the AP600 design, with only minor deviations.

In the context of the LBLOCA, the AP1000 differs from the AP600 by having a higher power density, increased core height, increased diameter of the ADS-4 valves and the associated piping, and increased diameter of the injection pipes. The increased power density would increase the steaming rate after blowdown which, in turn, will increase the pressure drop through the ADS-4 valves. This could decrease the injection rate and delay the initiation of the IRWST injection. Likewise, the increased fuel element height will increase the time to reflood. However, the increased size of the ADS-4 valves and related piping will lower the depressurization flow resistance, offsetting the increased steaming rate. Likewise, the increased injection pipe diameter will offset the delay in reflood time due to increased core height. In summary, the increased pipe size will maintain core cooling during IRWST injection and sump recirculation.

The staff agrees with the applicant's positions that the AP600 and AP1000 PIRTs for BE LBLOCA, SGTR, and non-LOCA transients are very similar, and no new "high" ranked phenomena are expected. The minor changes in "low" and "medium" ranked processes are expected and considered appropriate. As described in WCAP-14727, Revision 2, "AP600 Scaling and PIRT Closure Report," expert review of the AP600 BE LBLOCA PIRT, compared to that of the three- and four-loop plants, stated that "the new and additional passive systems, which have been added to the AP600 (CMTs, IRWST, ADS), do not contribute to the core cooling in the short term, nor do they influence the calculated PCT for the BE LBLOCA transient. The PRHR can condense steam, which will enhance the AP600 reflood for some time period; however, it is not essential to an acceptable calculation of the PCT. The effect of the downcomer injection location for the AP600 has been addressed with specific additional code validation, which is contained in the WCOBRA/TRAC code applicability document." Since the PIRTs for the BELOCA, the SGTR , and non-LOCA transients are very similar for both the AP600 and AP1000, as discussed in Section 21.5.1 of the report, the conclusions reached in the AP600 are valid for the AP1000.

21.6.3.3 <u>Effect of AP1000 14 Feet Core Height on BE LBLOCA</u>

The AP1000 core height is 4.3 m (14 ft) versus 3.7 m (12 ft) for the AP600 and three- and four-loop Westinghouse plants for which a BE LBLOCA is available. The CQD and the CSAU methodology do not include core height as a separate item. In the PIRT tables, a comment was entered regarding the potential for increased reflood time corresponding to the increased core height. However, there was no increase in any of the related rating factors. Finally, the mechanism representing the thermal hydraulics in WCOBRA/TRAC are derived from local phenomenological data. Therefore, core height does not affect the transient phenomena.

21.6.3.4 <u>Acceptability of WCOBRA/TRAC for AP1000 BE LBLOCA Analyses</u>

Section 21.6.3.1 of this report summarizes staff approval for WCOBRA/TRAC BE LBLOCA applications to three- and four-loop Westinghouse plants and the staff review and approval of the WCOBRA/TRAC BE LBLOCA application to the AP600. This was a detailed review and included the quantification of uncertainties and addressed the CSAU methodology. The staff concluded that comparison of the AP1000 and AP600 LBLOCA PIRTs demonstrates that there are no significant differences regarding the phenomena and plant response to LBLOCAs. Therefore, because the AP1000 response to a LBLOCA is very similar to that of the three- and four-loop plants, because WCOBRA/TRAC was found acceptable for the BE LBLOCA analysis of the AP600 (including the effect of the DVI line), and because the PIRTs revealed no significant differences between the AP1000, the AP600, and the three- and four-loop Westinghouse plants, the staff concludes that WCOBRA/TRAC is acceptable for the analyses of AP1000 BE LBLOCA.

21.6.3.5 WCOBRA/TRAC Limitations for LBLOCA Applications

As stated above, the AP600 calculated PCT value is well below 982 °C (1800 °F) and, therefore, no significant cladding oxidation is expected to take place. However, for potential applications with higher power density, the expected PCTs would be higher than the AP600 values. The NRC staff identified several conditions that would apply in the event that the 95^{th} percentile PCT values (either blowdown or reflood) exceed 941 °C (1725 °F). The applicant then needs to (1) repeat the global matrix of uncertainty calculation in order to establish the final 95^{th} percentile PCT, (2) address the sensitivity of CMT and PRHR modeling parameters as a bias to the 95^{th} percentile PCT result, and (3) perform both local and core-wide oxidation calculations, using the techniques approved for the three- and four-loop plants. The applicant stated that these limitations are observed in the AP1000 LBLOCA analyses.

Additional limitations which resulted from the AP600 review and carried over to the AP1000 application are listed in Appendix 21.A of this report.

21.6.3.6 AP1000 Results of WCOBRA/TRAC BE LBLOCA Analysis

The plant boundary conditions for WCOBRA/TRAC, including the initial operating conditions and core power distribution are conservatively bounded, based on sensitivity studies to investigate the range of possible values. The resulting PCT is the sum of a calculated reference value (using bounding boundary and initial conditions) and an additional term which includes the model, bias and uncertainty values. The uncertainty is estimated in the manner described in the preceding paragraph. The analysis accounted for the CMT and the PRHR. The design control document presents graphs, tables and narrative description of the progression and the results of the transient, including PCT. The results demonstrate that the acceptance criteria in 10 CFR 50.46 (b) are satisfied for the AP1000. These include:

- Peak cladding temperature will not exceed 1204 °C (2200 °F).
- The calculated total maximum oxidation will not exceed 0.17 of the total cladding thickness.
- The calculated total amount of hydrogen (generated from cladding oxidation) will not exceed 1 percent of the amount that would be produced by total cladding oxidation.

- Core geometry will remain amenable to cooling, because cladding oxidation is very low.

- After initial operation of the emergency core cooling system, core decay heat will be removed for an extended period of time. (The methodology for this item is discussed in Section 21.6.4 of this report and the results of the application in Section 15.2.7 of this report.)

21.6.4 WCOBRA/TRAC for Long-Term Cooling

21.6.4.1 Introduction

The LTC phase of a LOCA initiates with the establishment of steady-state flow into the reactor vessel from the IRWST through either one or both of the DVI lines. As the IRWST empties, the water level in the sump rises, and the source of vessel injection flow switches to the containment sump. Unlike conventional operating reactors, the AP1000 long-term cooling process does not use pumps. The reactor coolant water boil-off in the core is condensed in the containment. The condensate is returned by gravity to the IRWST (or containment sump), and the heat is transferred to the environment through the containment shell. The coolant is returned to the IRWST and enters the reactor vessel through the DVI lines by gravity. For DVI line break cases, sump water also enters into the vessel through the break. These systems are designed to provide adequate reactor cooling for an extended period of time without outside intervention or a supply of power.

The LTC analyses should establish that the passive core cooling system will maintain core coverage and that boron precipitation will not be significant. Excessive boron precipitation could return the core to criticality or cause flow blockage in the lower plenum. The specific objectives of the long-term cooling analysis is to ensure that the analysis of the LTC part of a LOCA transient satisfies the requirements of 10 CFR 50.46(b)(5), which states that "[after] any calculated successful initial operation of the ECCS...decay heat shall be removed for an extended period of time required by the long-lived radioactivity remaining in the core." In the case of AP1000, which needs neither operator intervention nor outside power supply for long-term cooling, this is equivalent to demonstrating the following considerations:

- The core is effectively cooled throughout the LTC phase of the transient with neither operator intervention nor outside power supply.

- Boric acid concentration in the core will be stable at a value which precludes recriticality and flow blockage because of precipitation.

The AP1000 LTC phase of a LOCA transient is analyzed using the WCOBRA/TRAC code. WCOBRA/TRAC was accepted by the staff for analyses of the LTC part of AP600 LOCA transients. As described in Section 21.6.4, "WCOBRA/TRAC Computer Code for Long-Term Cooling," of NUREG-1512, the staff performed an extensive review of WCOBRA/TRAC for the AP600 long-term cooling evaluation. The code was validated against test data from the APEX low pressure integral systems test facility at OSU that simulated long-term cooling phenomena in the AP600. The OSU experiments and the code validation were reported in WCAP-14776, Revision 4, “WCOBRA/TRAC OSU Long-Term Cooling final Validation Report,” March 1998. The OSU facility was specifically designed to simulate LTC for passively cooled reactors. The OSU experimental results were analyzed with WCOBRA/TRAC. The methodology used in AP600 LTC was described in WCAP-14601, Revision 2, (“AP600 Accident Analysis, Evaluation Models,” 1998), which has been reviewed and approved by the NRC.

As discussed in the following section, acceptability of WCOBRA/TRAC for the AP1000 LTC analyses is based on the staff’s previous finding that it is acceptable for the AP600; review of the validation data shows they are adequate for the AP1000; and the results of comparative study of the AP600 and AP1000 PIRTs finds no new or different phenomena in the evolution of the AP1000 LTC phase.

21.6.4.2 Acceptability of WCOBRA/TRAC for the AP1000 LTC

In WCAP-15613, the comparison of the PIRTs for the AP600 and AP1000 shows no difference in the LTC phenomenology between the AP1000 and AP600. The same document also justifies that the scaling rationale for AP600 OSU LTC test facility applies to the AP1000 plant design. The NRC staff concludes that there are no additional phenomena that require different treatment or need additional validation for performing AP1000 LTC analyses. WCAP-14777, which reports the analysis and predictions of the OSU APEX-600 tests, also justifies the applicability of WCOBRA/TRAC for the AP1000 LTC analysis.

In Section 2.3.3 of WCAP-15644, Revision 2, “AP1000 Code Applicability Report,” the applicant provides additional validation of WCOBRA/TRAC for long-term cooling analyses against several G1 and G2 full-scale test data. These G1 and G2 test data consisted of boil-off tests at pressure, power level, and inlet subcooling, which are prototypical for AP1000 LTC low-pressure operating conditions. The G1 and G2 tests are used to characterize the void fraction distribution and the average void fraction within the core when the mixture level is above the top of the core. The results of the measured versus calculated mixture level (which is related to the average void fraction) show that WCOBRA/TRAC overpredicts the average void fraction. This overprediction was alleviated by applying a 0.80 multiplier to the interfacial drag coefficient. This interfacial drag coefficient multiplier of 0.8 is used in WCOBRA/TRAC when applied in the AP1000 DCD LTC analyses. The G1 and G2 validation of the average void fraction reinforces the conclusion that WCOBRA/TRAC is acceptable for the LTC analyses of AP1000.

However, the AP600 WCOBRA/TRAC LTC model used a two axial node configuration to represent the reactor core. The staff questioned the sufficiency of this noding for the representation of the AP1000 axial void fraction distribution in a core 4.3 m (14 ft) high and having a greater decay heat rate. In response, the applicant modified the LTC noding model with a detailed core noding model shown in Figure 2-18 of WCAP-15644-P, Revision 2. This detailed core noding includes four radial channels representing core radial regions, and a large number of axial nodes (with 17 axial nodes in each channel) to represent the AP1000 core. This nodalization model is consistent with the nodalizations used to validate WCOBRA/TRAC against the G1, G2, and FLECHT/SEASET tests. In addition, the upper plenum models the CCFL region above the upper core plate, and the nodalization is equivalent to the WCOBRA/TRAC LBLOCA model, which has been validated against full scale upper plenum test facility (UPTF) tests. Based on the consistency of the nodalization to the G1, G2, FLECHT/SEASET and UPTF the staff concludes that this detailed noding model is acceptable for long-term cooling analysis.

The Window Method

Due to the long duration of the LTC phase, simulation of the entire LTC phase would take up exceedingly long computer time. Instead, the applicant used the window calculational mode. In this mode, the plant initial conditions for a specific LTC time segment are specified as input to WCOBRA/TRAC, which calculates the evolution of the quasi-steady-state part of the transient corresponding to the specified window. Should the initial conditions deviate from the actual values at the beginning of the window, the code takes a short period of time to reach the actual values of the LTC transient. The window method was used in the OSU test simulations and the AP600 LTC analyses. Given the similarity of the AP600 and AP1000 LTC phases, the staff concludes that the window method is an acceptable and necessary complement of WCOBRA/TRAC for application to AP1000 LTC.

Limitations for AP1000 LTC Application

Section 21.6.4.5, “Summary and Limitations,” of NUREG-1512 identified three limitations for the AP600 analysis:

- The applicant should ensure that the nodalization of the AP1000 design LTC model corresponds to that used in the OSU calculations.

- The applicant should ensure that the window time span results in a quasi-steady-state solution.

- The applicant should ensure that the code is not applied outside the corresponding parameter range from the OSU experiments. In particular, WCOBRA/TRAC is not validated for core dryout and heatup.

In Section 2.3.3 of WCAP-15644, Revision 2, the applicant describes the means by which the AP1000 analysis will comply with each of these restrictions when used for reload analyses and the like. The staff concludes that the implementation of the AP1000 LTC satisfies the above limitations.

Summary and Conclusion

As stated above, WCOBRA/TRAC has been reviewed for application to the AP600 and was found acceptable. PIRT studies showed that there are no new phenomena in AP1000 LTC that would call for new or additional validation, beyond the OSU experiments used for the AP600 validation. The 4.3 m (14 ft) core in AP1000 and the higher decay heat rate necessitated a 17 node axial noding. The increased noding was benchmarked to additional prototypical experiments, further validating the WCOBRA/TRAC LTC application to the AP1000. The window method was introduced by the applicant to deal with the extremely long computation time needed for an LTC run. The method was reviewed and found acceptable by the staff for the AP600 and is also was deemed acceptable for AP1000. Finally, the limitations imposed on the use of WCOBRA/TRAC for the AP600 have been carried over to the AP1000 application. The staff review showed that the applicant complied with the limitations in the AP1000 LTC application of WCOBRA/TRAC. Accordingly, the staff concludes that the use of WCOBRA/TRAC is acceptable for the LTC analyses of AP1000.

21.6.5 WGOTHIC Computer Program for Containment DBA Analysis

Summary

This section presents a technical review of the WGOTHIC computer program the applicant used for the licensing analysis of containment pressure transients. The applicant developed the WGOTHIC computer program by adapting the GOTHIC computer program to model the PCS. This review is specifically limited to the use of WGOTHIC in the applicant's EM to evaluate containment performance. WGOTHIC is a thermal-hydraulic computer program used for the design-basis licensing analysis of the AP600 and AP1000 passive containment designs. The WGOTHIC computer program is used to conservatively calculate the containment thermal-hydraulic response to mass, momentum, and energy releases from postulated pipe break scenarios (e.g., design-basis LOCAs and MSLBs). Westinghouse uses WGOTHIC in a lumped parameter fashion to evaluate the pressure and temperature response of the passive containment to design-basis accidents (DBAs).

Initially, the DBA blowdown and PCS operation generate a nearly homogeneous distribution of steam and noncondensable gases. In the longer term, the actuation of the fourth stage automatic depressurization system valves (ADS-4) supports a circulation pattern which tends to sustain the homogeneity of the containment atmosphere. Under these conditions, the lumped parameter representation is acceptable for evaluating the peak containment pressure. Degradations to heat transfer caused by local nonhomogeneity tends to be self-correcting; for example, a concentration of noncondensable gases on one section of the containment surface will be offset by other steam-rich sections. These considerations justify the use of the WGOTHIC EM for peak pressure calculations. However, the WGOTHIC EM is not capable, or qualified, to predict the distribution of noncondensable gases in the containment.

For the MSLB, the degree of homogenization is a function of break location, direction, and momentum. The MSLB blowdown creates circulation patterns that tend to homogenize the containment atmosphere above the break location sufficiently to accept the lumped-parameter representation for the evaluation of the peak containment pressure. The applicant's EM conservatively places the MSLB at the highest possible location.

Westinghouse devised a program plan which included a number of elements to address the PCS concept. A series of studies, including a PIRT, a scaling analysis, and both separate and integral tests to obtain the information needed to develop models for use in WGOTHIC to evaluate the containment performance during DBAs, where carried out, as follows:

- A PIRT was prepared to identify the phenomena important to understanding the PCS performance: WCAP-14812, "Accident Specification and Phenomena Evaluation for AP600 Passive Containment Cooling System," Revision 2, April 1998.

- A scaling report was prepared to evaluate test data against the prototypical design: WCAP-14845, Revision 3, "Scaling Analysis for AP600 Containment Pressure During Design-basis accidents," dated March 1998.

- To better understand the effects of adverse weather conditions, severe terrain, adjacent structures, and building design variations on the air flow within the PCS annulus, Westinghouse conducted a series of wind tunnel tests on scale models of the AP600 containment: WCAP-13294, "Phase I Wind Tunnel Testing for the Westinghouse AP600 Reactor," WCAP-13323, "Phase II Wind Tunnel Testing for the Westinghouse AP600 Reactor," WCAP-14068, "Phase IVA Wind Tunnel Testing for the Westinghouse AP600 Reactor," and WCAP-14091, "Phase IVB Wind Tunnel Testing for the Westinghouse AP600 Reactor."

- Water distribution tests were conducted to determine the PCS water coverage fraction on the containment dome and cylindrical shell as a function of the PCS water flow rate: WCAP-13353, "Passive Containment Cooling System Water Distribution, Phase 1 Test Data Report," WCAP-13296, "PCS Water Distribution Test Phase II Report," and WCAP-13960, "PCS Water Distribution Phase 3 Test Data Report."

- Separate effects studies were performed: WCAP-12665, April 1992, Westinghouse Electric Corporation, "Tests of Heat Transfer and Water Film Evaporation on a Heated Plate Simulating Cooling of the AP600 Reactor Containment."

- Small scale integral (SST) tests were performed: WCAP-14134, "AP600 Passive Containment Cooling System Integral Small-Scale Tests Final Report," Westinghouse Electric Corporation, August 1994.

- Large scale integral (LST) tests were performed: WCAP-14135, "Final Data Report for PCS Large-Scale Tests, Phase 2 and Phase 3," Revision 1, April 1997.

- The heat and mass transfer correlation package, used in WGOTHIC to evaluate the PCS performance, was validated: WCAP-14326, "Experimental Basis for the AP600 Containment Vessel Heat and Mass Transfer Correlations," Revision 2, April 1998.

- The development and validation of the lumped-parameter model for use in WGOTHIC: WCAP-14382, "WGOTHIC Code Description and Validation," dated May 1995.

- The bounding AP600 evaluation model (EM) development, the analytical model development for the AP600 and the PCS specific features, and the validation of the WGOTHIC AP600 EM through sensitivity studies were presented in WCAP-14407, "WGOTHIC Application to AP600," Revision 3, dated April 1998.

Based on the staff's review of the Westinghouse program, the staff determined that the WGOTHIC computer program, combined with the conservatively biased evaluation model, was acceptable for the evaluation of the peak containment pressure following a design basic accident. Although the WGOTHIC code itself is essentially a best-estimate tool, Westinghouse has taken a conservative approach in the evaluation methodology it is using to support design certification. The WGOTHIC EM uses appropriately conservative input values and applies conservative multipliers on the correlations used for PCS heat and mass transfer.

The staff's evaluation concerning the application of WGOTHIC to the AP600 passive containment design was provided in NUREG-1512 (U.S. Nuclear Regulatory Commission, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," NUREG-1512, September 1998.). On the basis of that evaluation, the staff determined that the WGOTHIC computer program, combined with the conservatively biased AP600 evaluation model, was acceptable for the evaluation of the AP600 peak containment pressure following a DBA.

WGOTHIC Application for the AP1000

Westinghouse requested a pre-certification review for the AP1000 design to evaluate the applicability of the use of the AP600 computer programs and test databases used to support these programs for the AP600 standard plant design. The following documents were provided to the staff:

- Westinghouse Electric Company, LLC, "AP1000 Plant Description & Analysis Report," WCAP-15612, December 2000.

- Westinghouse Electric Company, LLC, "AP1000 PIRT and Scaling Assessment," WCAP-15613, February 2001.

- Westinghouse Electric Company, LLC, "AP1000 Code Applicability Report," WCAP-15644, April 27, 2001.

In its original submittal (WCAP-15612), Westinghouse provided scoping calculations that were not consistent with the approved models and methodology developed by Westinghouse for use of the WGOTHIC computer program and approved by the staff for licensing evaluations. Westinghouse provided the results of unverified studies using the approved modeling approach in response to the staff's RAIs (Westinghouse letter DCP/NRC1484, M.M. Corletti, "Westinghouse Responses to Requests for Additional Information Related to Pre-Certification Review of the AP1000," (Proprietary and Non-Proprietary), September 12, 2001.)

The AP1000WestinghouseGOTHIC model used for the design certification review is consistent with the approved models and methodology developed by Westinghouse for use of theWestinghouseGOTHIC computer program and approved by the staff for licensing evaluations.

Assessment of the AP1000 PIRT

In support of the AP1000 design, the applicant provided, in WCAP-15613, an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena compared to the AP600.

The staff reviewed WCAP-15613 and found that it did not sufficiently describe the expert review process of the PIRT. The staff requested that the applicant provide a summary of the experts' reasoning behind the conclusion that no changes were necessary for the AP1000 at the "component or volume" level, as used in Table 2.6-1 of WCAP-15613. In its letter dated September 12, 2001 (DCP/NRC1484) the applicant provided two letters, one from Professor Per Peterson and one from S.G. Bankoff, to indicate the considerations given to the PIRT process. The letters provide some insight into the process used by the experts in the PIRT process. Overall, the experts concluded that the differences between the AP600 and the AP1000 plants are modest to small and can be treated in the analysis.

In support of its determination that there is no need to account for new phenomena for the AP1000, Westinghouse provided information regarding the need to rewet a surface that has been heated above the saturation temperature. For the AP600, the PCS film temperature was calculated to increase to over 200 °F, but was not predicted to reach the boiling point. For the AP1000, there was a question as to whether the surface temperature would reach the saturation temperature before the PCS achieved full coverage for the LOCA. Given the results of the analyses presented by Westinghouse, the staff could not conclude that containment shell temperatures would not exceed 212 °F prior to full water coverage, at 337 seconds into the LOCA. In Westinghouse letter DCP/NRC1484, Westinghouse provided analyses which demonstrated that full water coverage would be achieved for the LOCA prior to the exterior shell temperature reaching 212 °F. The 337-second time period used for the AP1000 calculation was based on the AP600 design. Westinghouse has provided an analysis which shows that the delay time for full water coverage for the AP1000 is less than 337 seconds (Westinghouse letter DCP/NRC1484).

The shell heatup evaluation has been incorporated into WCAP-15846, Section 7, as part of the design certification. This evaluation also justifies the use of the 337-second delay time for the AP1000.

The larger height of the AP1000 (compared to the AP600) could cause more complex recirculation patterns, thereby influencing mixing. Less homogeneity of the containment atmosphere above the operating deck could result, with higher temperatures in the upper dome. However, WGOTHIC can conservatively predict the decreased homogeneity using the multi-node model.

Based on the foregoing, the staff agrees with the Westinghouse PIRT conclusions that the differences between the AP600 and the AP1000 do not change the ranking of the phenomena, that no new phenomena have been identified, and that the models developed to address the high and medium ranked phenomena for the AP600 remain applicable for the AP1000.

Assessment of the AP1000 Scaling Evaluation

Westinghouse used the AP600 scaling study to support the AP1000 review. However, the staff and Westinghouse agreed during the AP600 review that the LST was not properly scaled for transient situations. The LST is only valid for steady-state conditions, as acknowledged by the evaluation of PIRT. In response to a staff request (Westinghouse letter DCP/NRC1481), Westinghouse clarified that the LST is not well-scaled for either AP600 or AP1000. However, the LST does support the mass and heat transfer correlations used in the WGOTHIC code for the AP600 and AP1000 designs.

The staff noted that the test data for the chimney did not cover the range of Grashof and Reynolds numbers for the AP1000 standard plant design. Westinghouse noted (Westinghouse letter DCP/NRC1481) that the model conservatively does not use the “clime” heat and mass transfer correlations in the chimney region, so the range of test data is, therefore, not relevant.

Assessment of the Testing Program

The applicant has shown, in WCAP-15846, that the AP600 experimental database covers the expected range of the mass and heat transfer correlations during AP1000 DBA analyses. The staff agrees with the applicant that no new data are needed, and that the WGOTHIC computer program, when used with the appropriate EM, is applicable and acceptable for AP1000 licensing analyses. Table 21.6.5-8 of this report compares the expected AP600 and AP1000 ranges to the test data ranges for the PCS riser/downcomer region.

The staff agrees with the Westinghouse conclusion that the mass and heat transfer correlations are acceptable for the evaluation of the AP1000 and that the AP600 test program adequately covers the expected ranges for which these correlations are used.

Assessment of Potential Changes or Errors in GOTHIC

In response to the staff’s concerns regarding errors in the GOTHIC manuals and also improvements and error corrections in recent versions of GOTHIC, Westinghouse provided additional information (Westinghouse letter DCP/NRC1481) to address these issues.

As part of the AP600 review and certification, Westinghouse provided clarifications regarding discrepancies in the GOTHIC manuals, and the issues regarding these discrepancies were resolved as a part of the AP600 certification. The WGOTHIC version used by Westinghouse for the AP1000 design certification is based on the same GOTHIC code used for the AP600 review.

Regarding the correction of a number of errors and deficiencies in the GOTHIC code, Westinghouse indicated that its procedures call for evaluation of identified errors. The potential impact of any errors that could affect the results of safety analyses will be covered in a revision to the WGOTHIC documentation (WCAP-15644). In regard to improved physical models in newer versions of GOTHIC, Westinghouse concluded that the models that are currently used in WGOTHIC are conservative, so use of newer models is unnecessary. The staff agrees with this assessment because the newer models being implemented in GOTHIC are intended to better represent physical phenomena to reduce the conservatism in the program.

Synopsis

The AP600 and the AP1000 PCS and containment designs differ, in that the PCS system has a larger flow capacity for the AP1000, and the AP1000 containment volume is larger (since the height of the vertical shell is increased) and has an increased design pressure. Based on the staff's evaluation of these differences, as summarized above, the conclusion presented in the remainder of this section concerning the applicability of AP600 PIRT, scaling, and testing program to support the development of WGOTHIC are equally applicable to the AP1000.

The staff has concluded, based on the evaluation presented in this report, that the applicant's WGOTHIC computer program, combined with the EM methodology, can be used to demonstrate that the AP1000 passive containment design meets the requirements of General Design Criteria (GDC) 16, "Containment Design," and 50, "Containment Design Basis." The PCS performance characterization is an integral part of this conclusion. For the first 3 hours following initiation of the PCS, which encompasses the peak pressures, the PCS flow is maintained at a high value and the containment shell wetted surface area is near 100 percent. In the long term (after 3 hours), the PCS flow rate drops, decreasing the shell wetted surface area. A series of standpipes in the PCS water storage tank is used to control the PCS flow (see Section 21.6.5 of this report). After the peak pressure period, the atmosphere may stratify in temperature or noncondensable gas concentration or both. These phenomena increase the uncertainty of the WGOTHIC EM PCS long-term heat removal calculation.

Regulatory requirements for the long-term internal pressure performance of the containment do not specify quantitative limits. GDC 38, "Containment Heat Removal," in Appendix A to 10 CFR Part 50, requires that a system to remove heat from the reactor containment be provided which rapidly reduces containment pressure following any LOCA and maintains the pressure at an acceptably low level. While uncertainty exists in the long-term WGOTHIC heat removal calculation, the staff concludes that the WGOTHIC computer program, combined with the EM methodology, is sufficient to evaluate the trend in the long-term AP1000 pressure response and demonstrate that the requirements of GDC 38 have been met. The secondary objective for the long-term analysis is to demonstrate that the long-term pressure remains within the pressure envelope used for containment leakage calculations which support the siting evaluation.

The staff, therefore, approves the use of WGOTHIC with the EM methodology, subject to the limitations and restrictions identified in Section 21.6.5.8.3 of this report, for AP1000 licensing analyses for containment performance.

The material presented in the remainder of this section concerning the staff's review of material related to the AP600 is provided to describe the staff's review process and where the staff relied on the same information in conducting its evaluation of the AP1000. The staff considered this information only as it applies to the AP1000 design.

21.6.5.1 Introduction

WGOTHIC is a T-H computer program used for the design-basis licensing analysis of the applicant's passive containment cooling design. Specifically, the WGOTHIC computer program is used to conservatively calculate the containment T-H response to mass, momentum, and energy releases from postulated pipe break scenarios (e.g., design-basis LOCAs and MSLBs). The applicant uses WGOTHIC in a lumped-parameter fashion to evaluate the pressure and temperature response of the passive containment cooling design to DBAs. WGOTHIC is documented in the following Westinghouse topical reports:

- WCAP-14382, "WGOTHIC Code Description and Validation," Westinghouse Energy Systems, issued May 1995
- WCAP-14407, Revision 3, "WGOTHIC Application to AP600," Westinghouse Energy Systems, issued April 1998
- WCAP-14967, "Assessment of Effects of WGOTHIC Solver Upgrade from Version 1.2 to 4.1," Westinghouse Energy Systems, issued September 1997
- WCAP-15846, Revision 1, "WGOTHIC Application to AP600 and AP1000," Westinghouse Energy Systems, issued March 2004

WGOTHIC is a modified version of the GOTHIC containment analysis computer program. The GOTHIC base code is documented in the following reports:

- "GOTHIC Containment Analysis Package Users Manual, Version 4.0," Numerical Applications, Inc., NAI-8907-02, Revision 4, June 1994
- "GOTHIC Containment Analysis Package Technical Manual, Version 4.0," Numerical Applications, Inc., NAI-8907-06, Revision 3, September 1993
- "GOTHIC Containment Analysis Package Qualification Report, Version 4.0," Numerical Applications, Inc., NAI-8907-09, Revision 2, September 1993

The WGOTHIC additions include a special multicompartment heat structure component, referred to as the clime model, used to model the PCS. Figure 21.6.5-1 of this report is a schematic of the containment showing the essential features of the PCS. These include the steel shell, a large water storage tank, weirs for flow distribution, and an airflow path through the downcomer, riser, and chimney.

In support of design certification, the applicant elected to follow current staff guidance for conservative DBA analyses. To demonstrate that the design meets the requirements of GDC 16 and 50, the conservatively calculated containment peak pressure is required to be below the design pressure during the most limiting release of mass and energy within the containment. The PCS acts to reduce pressure during a DBA by removing energy through the containment shell. Pressure is also reduced by the compliance (i.e., the change in energy storage due to a change in pressure) of the gas within the large containment volume and by heat transfer to in-containment structures. These two mechanisms are essentially the same as in existing large dry PWR containments. However, existing containment designs also have active engineered safety features (i.e., sprays, fan coolers, and sump coolers) to remove heat to the ultimate heat sink. The applicant's passive containment cooling design does not include active, safety-grade heat removal systems. The PCS is unique and, therefore, its performance is central to this evaluation.

The primary mechanisms for heat transfer through the containment shell are condensation on the inside of the shell, conduction through the shell, and evaporative cooling on the outside of the shell. Water is released at a controlled rate and flows down the outside of the containment shell where it is heated and evaporated. The vapor formed during the evaporation process is carried away by the air flowing through the downcomer, riser, and chimney flowpath. The WGOTHIC EM of the PCS component uses conservatively biased heat and mass transfer relationships for licensing analyses.

The applicant uses the WGOTHIC computer program to perform conservative containment licensing analyses for the passive containment cooling design during DBAs. WCAP-14382 describes the WGOTHIC models and the WGOTHIC qualification and validation process. WCAP-14407 describes the application of the WGOTHIC methodology to the DBA analysis for the AP600 design. Supplemental documentation has also been provided in WCAP-14967 and in the applicant's letter DCP/NRC1247, dated February 20, 1998. WCAP-15846 describes the application of the WGOTHIC methodology for conducting DBA analysis for the AP1000 design. (Note: WCAP-15846 contains the material provided in WCAP-14407 supplemented with material applicable to the AP1000. For example, Section 4 of WCAP-15846 describes the AP600 and Section 13 describes the AP1000 nodalization models.)

21.6.5.2 Review Process and Scope

The WGOTHIC predecessor, GOTHIC, is widely used by utilities. The staff review of WGOTHIC focused on questions and concerns in areas critical to the PCS performance and the EM methodology. The EM uses the lumped-parameter modeling feature for containment analyses in support of design certification for the applicant's passive containment cooling design. The WGOTHIC computer program review effort examined the following areas:

- conservation equations
- closure relationships and correlations
- numerical methods and convergence
- general modeling approach and sensitivity studies
- modeling approach for PCS-specific features
- overall applicability/conservatism for the licencing application

Section 21.6.5.4 of this report documents the staff's review of the WGOTHIC computer program and specific modeling features, such as the PCS. Section 21.6.5.7 of this report documents the overall applicability of WGOTHIC and the EM for the containment DBA licensing analysis.

Unlike existing light-water reactor containment designs, the applicant's passive containment cooling design does not rely on active engineered safety features (e.g., systems such as containment sprays and fan coolers) to demonstrate that the design meets the requirements of GDC 16 and 50. Instead, the applicant's passive containment cooling design relies on passive mechanisms (i.e., heat transfer through the containment steel shell to an evaporating water film flowing over the exterior containment surface) referred to as the PCS. The PCS design goal is to provide a reliable first-principle-based heat removal capability. As part of the containment design process, the applicant prepared a PIRT in WCAP-14812, Revision 2, which identified and ranked the relevant phenomena based on the AP600 containment design. In support of the AP1000 design, the applicant provided an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT in WCAP-15613. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena. The staff evaluated the correctness and completeness of these reports, as documented in Section 21.6.5.5 of this report.

Demonstrating the effectiveness and performance of the PCS heat removal capability calls for technical data derived from various scale testing and mathematical modeling. Previously, the need for data was less critical because engineered safety features included robust, active cooling systems. However, with the reliance now being placed on passive cooling mechanisms, better analytical capability, supported by experimental data, is needed to confidently understand and assess the containment response to DBAs. The applicant's LST facility, which was part of the test program developed for the AP600 containment design, provided data to support design certification. The staff examined the LST facility scaling, instrumentation uncertainties, and distortions, as documented in Section 21.6.5.5 of this report. The staff evaluated the applicant's test program, which was used both for developing model conservatisms in the EM and for WGOTHIC validation studies. Section 21.6.5.6 of this report documents these evaluations. WGOTHIC heat and mass transfer relationships were evaluated against small- and intermediate-scale data in WCAP-14326, "Experimental Basis for the AP600 Containment Vessel Heat and Mass Transfer Correlations," and in WCAP-14135 and WCAP-14135, Revision 1. In support of the AP1000 design, the applicant provided an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT in WCAP-15613. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. Section 21.6.5.6 of this report examines the heat and mass transfer relationships and documents their appropriateness and conservatism over their range of applicability.

During the development of the applicant's EM for LBLOCA and MSLB DBA analyses, the staff identified a number of implementation issues. The applicant performed sensitivity studies to demonstrate the conservatism of the overall approach. Section 21.6.5.7 of this report documents the review of the EM and the sensitivity studies.

In separate efforts, the NRC staff performed independent analyses, using the CONTAIN computer program, for the AP600 LBLOCA and MSLB accidents. As set forth in NUREG-1512, the staff's calculations supported the reasonableness of the applicant's WGOTHIC results for the AP600. The staff performed similar analyses for the AP1000 LBLOCA and MSLB accidents and these calculations support the reasonableness of the applicant's WGOTHIC results for the AP1000.

21.6.5.3 Applicable Requirements and Acceptance Criteria

Chapter 6.2.1, "Containment Functional Design," of the Standard Review Plan (SRP) delineates the current guidance for demonstrating that a containment design complies with the requirements of GDC 16, 38, and 50. The SRP addresses the acceptance criteria and some specific model assumptions for design-basis LOCA and MSLB analyses for all existing containment types. The applicant elected to evaluate the PCS performance using these current guidelines. The applicant's documentation for the EM is, therefore, intended to be consistent with the guidelines in SRP Sections 6.2.1 and 6.2.1.1.A, "PWR Dry Containments, Including Subatmospheric Containments," as well as RG 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants." The applicant also used approved methods for the LOCA and MSLB mass and energy releases following the guidance provided in SRP Sections 6.2.1.3, "Mass and Energy Release Analysis for Postulated Loss-of-Coolant," and 6.2.1.4, "Mass and Energy Release Analysis for Postulated Secondary System Pipe Ruptures," respectively.

21.6.5.3.1 Peak Pressure Criteria (GDC 16 and 50)

Acceptance criteria for existing containments include a margin between the design pressure and a conservatively calculated peak accident pressure. The margin varies from 10 percent at the construction permit (CP) stage to a peak calculated pressure "less than the containment design pressure" at the operating license (OL) stage. Thus, even in instances in which much data and information are known, and the staff possesses an independent, confirmatory calculational capability, a 10 percent margin is expected at the CP stage. This margin will cover any uncertainties in meeting the requirements of GDC 16 and 50 after final construction at the OL stage.

For the passive containment cooling design, the applicant proposed a criterion that the calculated peak accident pressure not exceed the design pressure (a zero-margin criterion). In meeting this criterion, the applicant stated that it used a conservative approach consistent with current staff guidelines. For design certification, under 10 CFR Part 52, the staff does not necessarily need the same demonstration of margin as would normally be expected at the CP stage. An appropriate initial test program, combined with appropriate ITAAC, is in place to ensure that the assumptions about and performance characteristics of the passive containment cooling design and the PCS, as used in the licensing analyses, are verified before operation. DCD Tier 1, Section 2.2.2, "Passive Containment Cooling System," describes the PCS ITAAC. DCD Tier 2, Chapter 14, "Initial Test Program," describes the initial test program (ITP). Periodic testing, as part of the inservice testing program, will also be performed to demonstrate that the area coverage fractions are maintained over the life of the plant as described in TS 3.6.6, "Passive Containment Cooling System (PCS) - Operating."

21.6.5.3.2 Long-Term Pressure Analysis (GDC 38)

The objective of the long-term pressure analysis is to demonstrate that the containment design conforms to the objectives of GDC 38, which states the following:

> A system to remove heat from the reactor containment shall be provided. The system safety function shall be to reduce rapidly, consistent with the functioning of other associated systems, the containment pressure and temperature following any loss-of-coolant accident and maintain them at acceptably low levels.
>
> Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system safety function can be accomplished, assuming a single failure.

The guidance in Item II.b of SRP Section 6.2.1.1.A is used to evaluate compliance with GDC 38. It states that the containment pressure should be reduced to less than 50 percent of its peak value within 24 hours of the occurrence of a design-basis LOCA. This assures that the containment leak rate used for the siting evaluation is consistent with the design-basis analysis assumption. To be consistent with current guidelines related to GDC 38, the applicant proposed that the calculated pressure reduction be based on 50 percent of the design pressure. The staff found this approach to be acceptable, because the peak calculated pressures had been near the design value.

The applicant determined that it might not meet the proposed long-term objective (50 percent pressure reduction in 24 hours) with the original WGOTHIC analysis approach. The applicant, therefore, revised the analytical procedure to take credit for the effect of two-dimensional (2-D) heat conduction (between wet and dry regions of the containment shell) when less than full coverage of the containment shell is expected. The revised procedure was first presented in the applicant’s letter DCP/NRC 0885, dated May 23, 1997, and was discussed at an ACRS meeting in December 1997. The applicant did not identify, or at least account for, the need to consider 2-D heat transfer for the long-term containment pressure response (i.e., after 3 hours when the PCS flow rate is first cut back from its initial value) in selecting the analysis methodology (GOTHIC) and in developing a model for the PCS (WGOTHIC). With the coverage area less than the initially assumed 90 percent, heat would be transferred from the hot, dry regions of the shell into the cooler, wet regions of the shell. To account for this deficiency, the applicant performed an ancillary calculation to credit more PCS water in the evaporation process, effectively generating a correction factor, and applied it to the limited PCS flow model (see Section 21.6.5.4.2 of this report).

The staff believes that there is a real effect from 2-D heat conduction. However, as an insufficient amount of test data was available to validate this model, the staff was unable to determine how much credit should be given in evaluating the PCS design performance after 24 hours when 2-D heat conduction was included in the analysis.

After the peak pressure period, the uncertainty in the treatment of heat transfer processes continues to increase. These uncertainties, resulting from the EM treatment of noncondensable gas circulation and stratification and the effectiveness of the PCS cooling at a reduced flow rate, are difficult to quantify using the available test data. Nevertheless, the heat removal capability of the PCS (as calculated by the WGOTHIC EM) is sufficiently greater than the decay power to conclude that the containment pressure will decrease. Therefore, the system safety function to reduce rapidly, consistent with the functioning of other associated systems, the containment pressure and temperature following any LOCA and maintain them at acceptably low levels has been demonstrated.

The secondary objective for the long-term analysis is to demonstrate that the long-term pressure remains within the pressure envelope used for containment leakage calculations which support the siting evaluation. Therefore, a separate analysis is perform for the limiting LOCA without 2-D conduction, and included in DCD Tier 2, Section 6.2.1.1.3, "Design Evaluations." This separate analysis is used to confirm the assumption used in DCD Tier 2, Section 15.6.5.3.3 of reducing the containment leakage to half its design value after 24 hours.

21.6.5.3.3 10 CFR 52.47 Criteria

Demonstrating the effectiveness and performance of the PCS heat removal capability calls for technical data derived from various scale testing and mathematical modeling. For currently operating LWRs, the need for data was less critical because the engineered safety features included robust active cooling systems. However, with reliance now being placed on passive cooling mechanisms, better analytical capability, supported by experimental data, is needed to confidently understand and assess the containment response to DBAs.

The unique characteristics of the PCS are explicitly recognized in the regulations governing the evaluation of standard plant designs. The regulations in 10 CFR 52.47(b)(2)(i)(A) require, in the absence of a prototype plant that has been tested over an appropriate range of normal, transient, and accident conditions, that the following must be met for a plant that "utilizes simplified, inherent, passive, or other innovative means to accomplish its safety functions":

(1) The performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof.

(2) Interdependent effects among the safety features of the design have been found acceptable by analysis, appropriate test programs, experience, or a combination thereof.

(3) Sufficient data exist on the safety features of the design to assess the analytical tools used for safety analysis over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.

Consistent with these requirements, the applicant has developed and performed design certification tests of sufficient scope, including both separate-effects and integral-systems experiments, to provide data with which to assess the computer codes used to evaluate plant behavior over the range of conditions described in item 3 above.

Testing and Computer Code Evaluation

To satisfy the requirements of 10 CFR 52.47(b)(2)(i)(A), the applicant has developed test programs to investigate the passive containment safety systems. These programs were designed to include both component and phenomenological (separate-effects) tests and integral-systems tests. Section 21.6.5.6 of this report discusses the test programs.

21.6.5.4 WGOTHIC Code Description and Assessment

In 1991, the applicant purchased the GOTHIC computer program, Version 3.4c, from Numerical Applications, Inc. (NAI), in Richland, Washington. NAI had developed the program under EPRI and international utility sponsorship. GOTHIC is considered to be a realistic containment code and includes best-estimate heat and mass transfer model options. However, the applicant decided to use GOTHIC in a manner consistent with the guidance in SRP Section 6.2.1, which is based on conservative containment pressure calculation and input models. GOTHIC did not have models which addressed the special features of the applicant's passive containment cooling design, such as the PCS. The applicant, therefore, added models specific to the PCS to the EPRI version of GOTHIC for the DBA analyses.

The applicant modified GOTHIC by adding a special component, referred to as a clime, to model the energy removal by the PCS. Climes use new correlations and models for the following:

- mechanistic convective heat and mass transfer
- liquid film tracking
- one-dimensional wall heat conduction
- wall-to-wall radiant heat transfer

The modified GOTHIC code is called WGOTHIC and is documented in WCAP-14382, WCAP-14407, and WCAP-15846. In addition, the applicant developed an EM approach which bounds or conservatively treats many of the code and model uncertainties for DBA scenarios.

Figure 21.6.5-2 of this report displays the historical development of the GOTHIC code, with its connections to other previous well-known computer codes. The NAI version of the GOTHIC code is primarily based upon the COBRA-NC code (NUREG/CR-3262, "COBRA-NC: A Thermal-Hydraulic Code for Transient Analysis of Nuclear Reactor Components") and its features have since expanded beyond this ancestor. Figure 21.6.5-2 of this report indicates that the GOTHIC code development is the result of 20 years of continued software development.

The conclusions of an EPRI-sponsored independent review panel were published in the GOTHIC Design Review Final Report which was forwarded to the staff by the applicant's letter NTD-NRC-95-4462, dated May 15, 1995. The review panel found GOTHIC 4.0 adequate for containment evaluation because it offered the potential for more accurate and mechanistically based analyses than did the other available containment analysis codes. However, the panel recommended that nodal and junction methodology and the range of the verification database be justified for each intended application. This was particularly true for the first-of-a-kind situation represented by the applicant's passive containment cooling design for the AP600. To address the EPRI peer review concerns, the applicant purchased GOTHIC 4.0 in 1996 and installed the PCS-related modifications. GOTHIC 4.0 is considered to be the basis for WGOTHIC 4.2.

Figure 21.6.5-3 of this report displays the early Westinghouse in-house development of WGOTHIC, which incorporated the clime PCS heat and mass transfer models. As a result of the sensitivity studies performed as part of the WGOTHIC licensing effort, the applicant discovered and corrected several errors. Earlier WGOTHIC versions had been numbered 1.0, 1.1, and 1.2. The applicant chose to refer to the base WGOTHIC version as WGOTHIC 4.0 and the revised version as WGOTHIC 4.1, to establish a numbering system consistent with its GOTHIC parent. Version 4.1 incorporated the peer-reviewed and quality-assured changes to NAI's GOTHIC Version 4.0. The applicant submitted WCAP-14967 to demonstrate that the conclusions reached from the verification and sensitivity studies performed using previous versions of WGOTHIC were applicable up to WGOTHIC Version 4.1. WGOTHIC 4.2 included additional refinements and error corrections to the clime methodology. All versions of WGOTHIC were developed in accordance with the applicant's quality assurance program under Appendix B to 10 CFR Part 50. Unless otherwise stated, this review applies to WGOTHIC Version 4.2.

21.6.5.4.1 WGOTHIC Code Overview

WGOTHIC provides a two-component, three-field representation of multiphase flows in compartments in LWR containments. Multiple compartments with multiple connections can be modeled. WGOTHIC solves mass, momentum, and energy balances for the steam, liquid, drop, and ice (not applicable here) phases. The vapor phase can be a mixture of steam and noncondensable gases, and a separate mass balance is solved for each component of the mixture. The phase balance equations are coupled with mechanistic models for interface mass, energy, and momentum transfer, covering the entire flow regime from bubbly flow to film and drop flow, as well as single-phase flows (described in the following subsections). The interfacial models can account for thermal nonequilibrium effects between the phases, as well as unequal phase velocities.

WGOTHIC can be used for 3-D analysis of the T-H behavior of containment atmospheres and structures. Containment compartments can be modeled using a one-, two-, or three-dimensional rectangular grid (referred to as the distributed-parameter approach) or the lumped-parameter approach, or a combination thereof. For long-term containment analysis, finely noded multidimensional models are deemed impractical. Lumped-parameter analysis is traditional for these problems, and the applicant selected this approach for its WGOTHIC EM for the passive containment cooling design. The lumped-parameter volumes are connected by junctions which use a one-dimensional model for flow between compartments. WGOTHIC's models include treatment of the multidimensional momentum transport terms, with an optional one-parameter turbulence model for turbulent shear, mass, and energy diffusion. However, these features are neglected when the lumped-parameter nodalization is used.

GOTHIC thermal conductors model heat transfer surfaces in the containment. In addition, the clime model, a special model developed by the applicant, is used to simulate the PCS. Wall heat transfer correlations are incorporated for a wide range of containment conditions, including condensation heat transfer in the presence of noncondensable gases.

Testing and Computer Code Evaluation

Table 21.6.5-1 of this report lists WGOTHIC's overall features, as well as those of other well-known U.S. containment code packages.

21.6.5.4.1.1 Conservation Equations

This section discusses the conservation equations solved by WGOTHIC. These equations are formulated for a fixed volume in space bounded by surface areas. The volume may represent the entire containment or any part of its total volume. The GOTHIC (and WGOTHIC) conservation equations are based on the following major assumptions:

- Compressible flow occurs during all fluid phases.
- Separate mass conservation equations are solved for each fluid phase (liquid, vapor, drop), gas component, and ice phase.
- Separate energy conservation equations are solved for each fluid phase (liquid, vapor, drop); however, viscous dissipation and kinetic energy are neglected.
- The phases are at an equal pressure. Mass and energy transfer rates across phase interfaces are obtained from a set of constitutive relations.
- The normal component of the viscous stress is ignored.
- Prandtl mixing length theory is used to derive Reynolds stresses and thermal and mass diffusion. Thermal diffusion by conduction and turbulence is taken into account. Mass diffusion by turbulence is also taken into account; however, molecular mass diffusion is neglected.
- Turbulent and viscous stresses are only applied to the continuous phase (e.g., vapor in drop flow, liquid in bubbly flows). Turbulent stress due to interfacial interactions is neglected.

The GOTHIC development team adopted a number of assumptions for the convenience of the finite-volume numerical method, used in the distributed-parameter approach (one-, two-, and three-dimensional subdivision of control volumes). The WGOTHIC EM is based on the lumped-parameter approach and does not use a distributed-parameter approach; therefore, the following assumptions were not examined during the WGOTHIC review:

- The momentum equations are strictly valid only in the context of rectangular grid subdivisions.
- The full 3-D form of the momentum equation is solved for each phase, including momentum transport and viscous and turbulent stresses.
- When WGOTHIC lumped-parameter control volumes are connected to distributed-parameter control volumes, all conservation equation forms are reduced and momentum transport is completely eliminated in the distributed-parameter control volumes.

Application of WGOTHIC in the lumped-parameter mode introduces numerous simplifications which are discussed in the following sections.

21.6.5.4.1.1.1 Mass Conservation

Mass conservation equations are solved for four flow fields (called phases in the context of GOTHIC or WGOTHIC), steam, liquid, drop, and ice (not applicable to the applicant's passive containment cooling design), and for each of the preselected noncondensable gas components. The steam/air mixture, termed the vapor phase, can take the form of bubbles or a continuous vapor region. The liquid phase can exist as pools, films, or liquid drops. The drop phase results from break discharges, de-entrainment from condensate films, or spray nozzles.

The integral formulation carries the common storage, convective, and diffusion terms, in addition to terms characterizing contributions from boundary, interface, and equipment sources. Separate mass conservation equations are used for the vapor, liquid, drop, and ice phases. The vapor phase may consist of steam plus a number of noncondensable gases (i.e., it may have several components). The mass conservation equations for the liquid, drop, and ice phases do not account for mass diffusion.

For the lumped-parameter approach, where one computational cell is used per volume, the mass balance is maintained for a network of lumped-parameter nodes and junctions. However, the simplifying assumptions result in a reduced mass conservation equation in which junctions constitute the only flow connections to a lumped-parameter node. The integrals for the convective terms are replaced by sums over all the junction connections. This introduces a set of junctions connected to the volume, with respective junction areas. Junction velocities are not vector quantities in the lumped-parameter approach.

21.6.5.4.1.1.2 Energy Conservation

Energy conservation equations are solved for three fluid phases (vapor, liquid, and drop) and are considered for solid thermal conductors. In WGOTHIC, the fluid energy equation is formulated in terms of enthalpy rather than internal energy. Its integral formulation carries seven terms accounting for storage, convection and flow work, thermal diffusion, mass diffusion, and contributions from boundary, interface, and equipment sources. Neglected are kinetic energy, viscous dissipation, and other energy forms not explicitly represented in the integral form. All components of the vapor phase (e.g., steam and noncondensable gases) are assumed to be at the same temperature.

For the lumped-parameter approach, the energy balance is maintained for a network of lumped-parameter nodes and junctions. However, the modeling assumptions result in a simplification of no computed velocity gradients and, consequently, the turbulent diffusion is set to zero. Therefore, mass and thermal diffusion terms across junctions are not considered in the lumped-parameter mass and energy conservation equations. The integrals in the convective terms are replaced by summations over all junction connections. In addition, the boundary source and interface terms are defined differently than in a full 3-D formulation.

Energy Conservation for Solid Conductors

WGOTHIC uses thermal conductors to model heat sinks, such as concrete walls and floors, structural steel internals, stairwells, and gratings, as well as primary system components, such as pipes, vessels, and valves. WGOTHIC conductor geometries are limited to flat plates, solid cylinders, and hollow tubes. Therefore, only one-dimensional heat conduction models are implemented for flat-plate and cylindrical geometries. The energy equation for solid conductors accounts for storage, thermal diffusion, and boundary sources. The material properties can be functions of space, the local temperature, and the local volumetric heat source. Thermal conductors may consist of multiple layers of varying materials assuming that the density of each type of material is constant. Other thermal surface boundary condition options include the following:

- transient (or constant) surface temperature
- transient (or constant) surface heat flux
- convection and condensation heat transfer described by a total heat flux to or from a wall to the vapor and liquid phases, partitioned into respective heat transfer rates to the specific phases

In this latter option, the heat rates depend on the user-selected heat transfer options and the appropriate fluid and wall conditions. Sections 21.6.5.4.1.2.1 and 21.6.5.4.1.2.2 of this report discuss the available options.

The WGOTHIC (and GOTHIC) energy conservation equations do not provide for a volumetric source term. The surface areas of thermal conductors may be exposed to one or more fluid phases.

21.6.5.4.1.1.3 Momentum Conservation

WGOTHIC has momentum conservation equations for the vapor, liquid, and drop phases. The integral form of the momentum conservation equation contains the following seven terms:

(1) storage
(2) convection
(3) surface stress
(4) body source
(5) boundary source
(6) interface source
(7) equipment source

The general formulation, using stress tensor notation, includes contributions from the static pressure, viscous, and Reynolds stress terms. Because of the natural complexity of the momentum conservation equation, terms containing the momentum source per unit wall area (momentum source per unit interfacial area and momentum source from equipment) are especially difficult to specify for the three phases accounted for in WGOTHIC. Whereas all three phases are considered to move with different specific phase velocities, all components of the vapor phase (e.g., steam and noncondensable gases) are assumed to have the same velocity.

Of all of the conservation equations, the momentum conservation equation is the most affected by the change from the distributed-parameter to the lumped-parameter approach. Because a lumped node has no flow field, a momentum equation is not solved for the lumped-parameter volumes in the network. Momentum is conserved by the solution of the momentum equation in the junctions connecting the volumes constituting the lumped-parameter model for the given containment geometry under consideration.

Momentum Conservation in Junctions

One or more junctions may hydraulically connect two computational cells. They may represent doorways, pipe and cable penetrations, ductwork, vents, and stairways. Junctions are characterized by their cross-sectional area, length, and, for both ends, the lowest elevation of the volume interface and the interface height. The junction momentum equations for the three phases (vapor, liquid, and drop) are solved for each junction. Except for viscous and turbulent shear, the junction momentum equations are consistent with the momentum equations used for the subvolume face velocities for one-, two-, and three-dimensional meshes in the distributed-parameter model. Mass residing in the junctions is not taken into account; that is, mass leaving one lumped node through a junction is instantaneously moved into the connecting volume for purposes of mass balancing. An approximate junction fluid mass is computed for use in calculating the inertia of the junction flow. Junctions allow a pool in one volume to overflow into a connecting volume with the associated displacement of the vapor phase.

The WGOTHIC junction momentum equations simulate the specific phase momentum transport between computational mesh cells. The junction momentum equation includes terms for inertia, pressure gradient and local gravity head, junction gravity head, equipment source, momentum fluxes, wall shear, and interfacial drag. All of these terms call for the specification of coefficients by correlations and/or input data selection. The phase density in the junction is assumed to be the arithmetic average of the phase densities of the connected volumes. Junction momentum flux terms (cited above) are not used when connecting to a lumped-parameter node because the lumped node lacks velocity information.

To determine the donor fractions for flow out of a computational cell through a junction, the fluid in this cell is assumed to be in the form of a pool, with both a vapor phase and drops above the pool surface. This model is used to calculate an effective pool height and pool vapor fraction from the cell geometric parameters and the current cell phase volume fractions. The pool vapor fraction is needed to correctly calculate the pool surface elevation height in the presence of bubbles in the pool, which raise the liquid pool height. This is estimated by the Yeh correlation, which uses the vapor and liquid densities and the vertical vapor and liquid velocities beneath the pool surface. For the lumped-parameter approach, two-phase pool dynamics are neglected.

Because of the special pool model features in WGOTHIC (and GOTHIC), two sets of phase fractions are relevant to junctions, the donor cell phase and the junction phase fractions. The donor cell phase fractions determine the mass flows through junctions, and the junction phase fractions control junction inertia, gravitational head, and pressure forces, and are themselves dependent on the donor cell fractions.

The static pressure is determined at the vertical center of each volume. To account for buoyancy effects in the lumped-parameter approach, the variation in the static pressure within each volume must be estimated to provide the pressure at the respective junction ends. This is achieved by splitting the junction gravitational head into two contributions, the junction head (head across junction) and the local head (head from the cell center to the junction end elevation). The specific phase junction head is the product of the junction phase density and the difference in the junction end elevations.

In summary, for lumped-parameter volumes, mass and energy are conserved. However, the momentum conservation equations are neglected. Thermal-hydraulic conditions are represented by cell-averaged parameters. This limits the applicability of the lumped-parameter approach for the following modeling phenomena:

- thermal stratification
- concentration gradients
- velocity profiles
- mixing flow patterns

21.6.5.4.1.2 Closure Relationships and Correlations

To solve the equations for mass, energy, and momentum conservation for the three fluid fields, closure relationships, such as interfacial source terms and heat and mass transfer, are needed to describe interfacial interactions. Sections 21.6.5.4.1.2.1 and 21.6.5.4.1.2.2 of this report summarize and review these closure relationships.

Other closure relationships are necessary to model the heat and mass transfer between the three fluid fields and solid structures inside the containment. These encompass the wall source terms, which include convective heat transfer, condensation and boiling (evaporation) at the structural surfaces, friction at walls, and orifice drag in junctions. Correlations are used to compute these wall source terms. Section 21.6.5.4.1.2.2 of this report presents and discusses these correlations.

21.6.5.4.1.2.1 Interfacial Source Terms

The WGOTHIC conservation equations do not limit the thermodynamic and mechanical characteristics of the three fields. Rather, interface source terms are specified for the computation of mass, energy, and momentum balances at the interfaces, assuming that none of the quantities is stored at the interface. WGOTHIC accounts for the following five field interface combinations:

(1) liquid/vapor
(2) drop/vapor
(3) ice/vapor (not applicable to the applicant’s passive containment cooling design)

(4) ice/liquid (not applicable to the applicant's passive containment cooling design)
(5) drop/liquid

Interfacial transport processes are induced by heat transfer due to phase change, and by mechanical interactions generating interfacial mass and momentum exchanges. Correlations and/or input values have to be provided for the respective interfacial heat transfer coefficient and the associated areas of the vapor/liquid and vapor/drop interfaces.

For the conservation equations, different interface models are applied, based on the flow regime and whether the subdivided (distributed-parameter) or lumped-parameter approach is used. These interface models are described below.

Flow Regime Maps

The selection of the proper exchange coefficients (heat transfer, drag) and the related interfacial areas primarily depends upon the geometry of the phase distributions under consideration. Several flow regime maps have been proposed and implemented into current nuclear safety computer codes (for example, RELAP5, TRAC). Many of those apply only to the special technical or safety issue for which they were developed and cannot be applied to the whole spectrum of anticipated two-phase problems. Recognizing that an accurate prediction of flow regimes is beyond the current state of knowledge and current computational capabilities, and that the selection must agree with the nodal representation of the flow field by the computational control volumes, WGOTHIC contains simple, widely applicable flow regime maps. Although the flow regime map for vertical flows is somewhat sophisticated, a more simplified selection scheme is implemented for horizontal flows. The flow regime maps incorporated into GOTHIC (and WGOTHIC) are based on previous experience over a wide spectrum of applications with COBRA-NC (NUREG/CR-3262) and COBRA/TRAC (NUREG/CR-3046, "COBRA/TRAC - A Thermal-Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Coolant Systems").

The prevailing flow characteristics in a computational cell must be determined before the correlations for interfacial transfer can be applied. During a calculation, this information is available only for a given computational cell and its immediate neighbors. The flow regime selection is based on liquid and volume fractions. This approach requires that all volume fractions be present and that none be exactly zero, because the numerical solution procedure solves the full set of phase equations for each computational control volume for each time step. This requirement imposes the need to specify lower limits for volume fractions (see Section 12.9 of NAI's "GOTHIC Containment Analysis Package Technical Manual, Version 4.0").

Closure Relationships for Lumped-Parameter Approach

The interfacial heat transfer coefficients for the lumped-parameter approach account for the presence of pools and drops in lumped-parameter control volumes. In WGOTHIC, a pool configuration is assumed to exist in a control volume if the following conditions are met:

- the ceiling of the control volume is closed and

- the liquid volume fraction is larger than 0.2

or

- the ratio of liquid volume fractions of two axial neighboring control volumes is larger than 1.5 and
- the liquid volume fraction of the lower control volume is larger than 0.2

If the liquid volume fraction is less than 0.1, the liquid is assumed to be distributed as a film on all surface areas exposed to the atmosphere in the control volume, rather than forming a pool. For a liquid film, the interfacial area is assumed to be equal to the wetted surface area. These criteria are based on obtaining reasonable agreement with the data resulting from different modeling scenarios.

The heat transfer to the pool surface from a superheated vapor is determined from the maximum of heat transfer coefficients for turbulent natural convection and forced convection, based on the Reynolds analogy as applied to a flat plate and a user-specified minimum value. Increased heat transfer due to evaporation at the pool surface is accounted for by an evaporation factor, β_e, which considers the molecular weights of the steam and the noncondensable gas.

Drop Entrainment and Deposition

The WGOTHIC code has provisions for modeling drop entrainment and deposition phenomena. WGOTHIC includes a model (referred to as the fog model) which generates drops whenever the air-steam temperature is lower than the saturation temperature. The fog model is not used in the WGOTHIC EM analysis for the applicant’s passive containment cooling design, because the applicant assumes that a large fraction of the blowdown liquid flow is entrained into the containment atmosphere as drops which permanently remain in the atmosphere.

Combined Interface Source Terms

The interfacial source terms for the energy conservation equations are specified with the assumption that, for any mass transfer which results from interfacial heat transfer, the mass leaves the respective phase at the phase bulk temperature and enters the other phase at the saturation temperature. The latent heat is added to or subtracted from the phase generating the phase change.

The WGOTHIC formulation computes heat transferred to the interface from the vapor and liquid phases within the context of the standard Newton’s cooling law (vapor and liquid heat transfer coefficients, vapor and liquid bulk temperatures, and the interface temperature). Any excess heat at the interface is applied toward converting liquid to steam. This is achieved by calculating the rate of evaporation (or condensation) from the liquid and vapor heat transfer rates and the heat of vaporization (or condensation) using a mass transfer coefficient, an interface area, and the ratio of the difference of steam concentration at the interface and the steam concentration in the bulk to the difference between saturation and an air-steam concentration at the interface. The latter is determined by assuming saturation at the interface temperature. In this calculational step, a total set of five equations is solved iteratively for the unknown interface temperature, steam concentration, liquid and vapor side heat transfer rates, and the mass transfer rates.

The heat transfer correlations used on the vapor and liquid sides of the interface in WGOTHIC are the maxima of forced- and free-convection heat transfer coefficients. For free convection, the correlation is the same as that used in CONTEMPT for turbulent free convection. The heat transfer correlations are not adjusted to account for high mass transfer rates; however, a multiplier of 1.2 is used on the vapor side to enhance agreement with the experimental data.

Pool boiling initiates when the pool temperature is higher than the saturation temperature associated with the total pressure. High vaporization rates are enforced by high values for the liquid heat transfer rate and the mass transfer coefficient.

As a result of the full two-phase model in WGOTHIC, with separate conservation equations for liquid, vapor, and drops, the code does not model the “temperature flash” or “pressure flash” processes applied in CONTEMPT for the blowdown mass and energy sources. In the “temperature flash” process, the water-steam mixture from the break mixes immediately with the entire containment vapor region and instantaneously reaches thermal equilibrium. In the “pressure flash” process, the water-steam mixture from the break comes into thermal equilibrium at the total containment pressure prior to mixing with the entire containment vapor region. The mixture remains in this state long enough for the water to drop out of the atmosphere. Typically, the blowdown energy sources in WGOTHIC are specified by prescribing the enthalpy and the pressure of the injected fluid into the break subcompartment, together with an average drop diameter. Steam and drops are assumed to be in thermal equilibrium at the source pressure.

For completeness, WGOTHIC can simulate both “pressure flash” and “temperature flash” conditions by setting the source pressure to the blowdown compartment total pressure or by setting the steam partial pressure, respectively, together with an input specification that the liquid fraction of the blowdown fluid is deposited directly to the pool rather than as drops into the compartment atmosphere. Table 21.6.5-2 of this report lists the interfacial heat and mass transfer models in WGOTHIC and CONTEMPT, and Table 21.6.5-3 of this report lists the condensation and evaporation correlation used in WGOTHIC and CONTEMPT.

21.6.5.4.1.2.2 Heat Transfer Models

This section summarizes and evaluates the closure relationships and correlations in WGOTHIC. Single- and two-phase heat transfer, condensation, and evaporation models define the wall source terms in the energy conservation equations for the vapor and the liquid phases, respectively. The energy source term accounts for heat transfer between the atmosphere and the heat sink conductors through convection, radiation, condensation, and evaporation. It also accounts for heat transfer from pools to structures. WGOTHIC provides the code user with the following seven options to specify the relevant heat transfer mode for each thermal conductor in the model under consideration:

(1) turbulent natural convection
(2) direct condensation and evaporation
(3) Tagami blowdown (not used for the applicant's passive containment cooling design)
(4) specified revaporization
(5) wet-wall model
(6) specified time-dependent heat transfer coefficient
(7) built-in single-phase and two-phase heat transfer package

These seven options are common to both GOTHIC 4.0 and WGOTHIC 4.2. In addition, WGOTHIC contains the correlations that were implemented by the applicant for the clime model used to predict the PCS behavior. The approach used in WGOTHIC for interfacial heat and mass transfer is similar to the one used in CONTEMPT. However, because of GOTHIC's two-phase modeling approach, one important difference between CONTEMPT and WGOTHIC is that WGOTHIC calculates the interface temperature from first principles. CONTEMPT assumes the interface temperature to be equal to the saturation temperature. Therefore, WGOTHIC determines sensible heat transfer between the liquid and the pool surface and to the vapor phase, even when the vapor is saturated. This heat transfer mechanism is not possible with some general containment analysis codes, such as CONTEMPT. In addition, a similar feature of the drop field model allows calculation of heat and mass transfer to or from the drops.

The source terms associated with each of the seven options are summarized below with an emphasis on the heat transfer modes relevant to the applicant's passive containment cooling design.

Turbulent Natural Convection

The McAdams correlation (McAdams, W.H., Heat Transmission, 3rd Edition) is used for turbulent natural convection from vertical plates and large cylinders. This correlation uses the liquid or vapor thermal conductivity, the viscosity, fluid density, and the Prandtl (Pr) number. The length dependence is removed and the heat transfer coefficient depends only on local properties. The heat transfer coefficient actually used is either the maximum of the value determined by the correlation or a user-supplied minimum value. For the latter, the code's default value is zero (no heat transfer). The documentation defines the validity range of the McAdams correlation to be $10^9 < GrPr < 10^{12}$. The coefficient of linear thermal expansion, β, which enters the Grashof (Gr) number, is equal to the reciprocal of the vapor temperature, assuming ideal gas behavior. The characteristic length cancels out of the heat transfer correlation for turbulent natural convection.

The heat transfer correlation recommended for turbulent natural convection from horizontal surfaces is the same as that for vertical surfaces, except that the coefficient 0.13 changes to 0.14. However GOTHIC, and thus WGOTHIC (except for the climes), does not differentiate between the orientation of the thermal conductor surfaces. Both codes use the correlation for vertical surfaces, regardless of orientation, with the understanding that heat transfer from horizontal surfaces would be slightly underpredicted if this correlation were used inside the containment.

Direct Condensation and Evaporation

The total heat transfer from the thermal conductor surface for direct condensation includes (1) latent heat released by condensation, (2) convective heat flux between superheated vapor and saturated film, and (3) radiant heat flux from the surface to the vapor.

The condensation heat transfer is determined from the surface area for condensation, the condensation heat transfer coefficient, a multiplier for time-dependent function, and the minimum of zero and the difference between the surface and the condensate temperature, T_{sat} (the saturation temperature at steam partial pressure).

If the wall is superheated relative to the local steam, the condensation heat transfer is set to zero.

The following options are available for direct-condensation heat transfer to internal heat sinks in WGOTHIC 4.2:

- Uchida
- Gido/Koestel (not used for the applicant's passive containment cooling design)
- maximum of Uchida and Gido/Koestel (not used for the applicant's passive containment cooling design)

The Uchida-correlation implemented in WGOTHIC is actually a fit to the published data as a function of the ratio of steam density to the density of the noncondensable gas mixture raised to the power of 0.8. This presentation was contained in COBRA-NC (NUREG/CR-3262) and CONTEMPT (NUREG/CR-0255, "CONTEMPT - LT/028: A Computer Code for Predicting Containment Pressure-Temperature Response to a Loss-of-Coolant Accident") and used for their validation. The fit has upper and lower limit values of 594 and 4.3 kJ/hr-m^2-°C (278 and 2 BTU/hr-ft^2-°F), respectively.

The review of Uchida's test setup has led to the conclusion that the data include some effect, at least in the free natural-convection regime, of velocity on the heat and mass transfer. However, the velocity effect is not explicitly available. The Uchida correlation's independence of any velocity effect makes it suitable for incorporation into lumped-parameter models (e.g., CONTEMPT) because the computational control volume atmospheres are assumed to be at rest (i.e., stagnant).

Any model improvement to account for velocity effects leads to the additional need to define an approved representative control volume velocity, which is not computed in the lumped-parameter model. For distributed-parameter control volumes, the control volume velocity is obtained by averaging the computed control volume face velocities. The volume velocity for lumped-parameter control volumes must include the junctions, as no velocities are predicted for the control volumes. Because the orientation of junctions is unspecified in the lumped-parameter model, the control volume velocities can be only roughly approximated because of the limited information available. For the vertical component of the control volume velocity, the summation on junction flows includes only those that are vertically connected to the control volume. A multiplier of either +1 or -1 is used to make the sign of the junction flow consistent with the global coordinate system in deriving the control volume velocity. For the lumped-parameter model, which does not specify the junction direction through the momentum transport input, it is always assumed that the junction is horizontally connected to the computational control volume. In general, the control volume-centered velocity for any phase is computed from the square root of the sum of the squares of the vertical and the transverse velocities (as discussed above).

Once the total condensation heat transfer rate has been computed by one of the available options, the wall condensation rate is determined. The direct condensation option includes radiation heat transfer with the assumption of grey gas and grey surrounding walls. The surface emissivity is assumed to be 0.65 for dry walls, and 0.96 for wet surfaces (surface temperature below saturation temperature). The gas emissivity is also accounted for and complex geometries are considered by virtue of an effective beam length.

The convective contribution to the total heat transfer applies the convective heat transfer coefficient obtained from the built-in heat transfer package. With the individual contributions summarized above, the total wall mass and energy source terms are completely described for the direct condensation model.

Specified Revaporization

Regulatory guidelines (NUREG-0588, “Interim Staff Position on Equipment Qualification of Safety-Related Electrical Equipment”) recommend that a specified fraction of the condensation at the wall be revaporized by the superheated atmosphere. For licensing analysis, a value of 0.08 (per NUREG-0588) is acceptable. Therefore, WGOTHIC has an option to specify a revaporization factor between 0 and 1. For nonzero values, the normal interfacial heat and the related mass transfer for superheated vapor are set to zero. They are replaced by augmented wall source terms which include revaporization.

Wet-Wall Model

This option is not recommended for the lumped-parameter model approach because its underlying assumptions are inconsistent with the pool geometry assumed for lumped-parameter control volumes.

Specified Values

The user can specify a wall-to-vapor heat transfer coefficient as a function of time by providing a constant value and a time-dependent multiplier. The user can also specify the surface temperature, the surface heat flux as a function of time, or a vapor convection heat transfer coefficient and an ambient temperature. In these cases, no direct heat transfer to the fluid is computed.

Built-In Heat Transfer Package

GOTHIC and WGOTHIC contain a complete set of heat transfer correlations originating from the COBRA-NC and COBRA-TRAC codes, which cover the entire boiling curves. However, this heat transfer correlation package is not applicable to the lumped-parameter approach. The Dittus-Boelter correlation for turbulent forced convection for either vapor or liquid properties is implemented. For vapor conditions, the maximum of this and the previously discussed turbulent natural-convection (McAdams) correlation is determined. For single-phase liquid, the maximum of the Dittus-Boelter correlation and heat conduction through a liquid film is determined.

Momentum Source Terms

Momentum source terms account for drag effects due to wall friction, as well as local losses due to orifices and obstructions. The total drag force is the sum of both contributions and is computed for each phase—vapor, liquid, and drop. The drag coefficient is an input quantity for each flow connection, and the drag force is assumed to be proportional to the area fraction of the respective phase. Wall friction drag forces are determined only for the continuous vapor and liquid phases.

The friction factor used to calculate the wall friction drag force is specified for hydraulically smooth pipe conditions, and is determined from the maximum of the analytical result for laminar flows (64/Re) and the turbulent-flow friction factor that is obtained from a curve fit of the well-known Moody data. The Reynolds number for each phase is determined by simply assuming that the flow consists of only that phase. The GOTHIC documentation points out that this approach, coupled with the interfacial drag models, results in excellent agreement with the data for two-phase pressure drop over the entire range of vapor volume fractions. No proof or reference is provided in this context to show comparisons between data and predictions. However, in the case of two-phase annular flow, the GOTHIC documentation analytically demonstrates that the selected approach corresponds closely with common empirical relationships for the two-phase multiplier for annular flow.

Floor Drag

This is an extra flow resistance applied to the liquid flow out of a computational control volume through a junction when the liquid level in the control volume is near the junction elevation. In this situation, the junction flow changes from a liquid/vapor mixture to an all-vapor flow when the liquid level drops below the junction elevation. This causes large numerical oscillations in the liquid flow through the junction and the additional resistance is used to stabilize the solution. It is called floor drag because the current model has been developed for liquid flow across the floor into a center drain. This numerical stability enhancement feature is applied to any junction where the liquid level is approaching the junction level, whether or not the junction elevation is at the floor level.

21.6.5.4.1.3 Numerical Methods

WGOTHIC uses a semi-implicit numerical solution scheme to solve the coupled set of conservation equations for mass, momentum, and energy in the fluid cells, together with the heat conduction equations for the thermal conductors. The complete set of governing equations is solved simultaneously for the state and velocity variables for each new time value. Some of the terms in the equation set are nonlinear in the new time variables. Rather than iterating on the equation set to accommodate the nonlinear terms, an approximate solution is obtained by applying the one-step Newton method. The resultant matrix equation can be solved by direct solution (Gaussian elimination/back substitution) methods for small problems, such as those generated for most lumped-parameter models.

Solution of the Momentum Equations

The semi-implicit momentum equations for the three phases in one momentum control volume can be written in the form of three equations with coefficients A, B, and C. The A coefficients include the temporal terms, as well as the wall and interfacial drag coefficients. The B coefficients are the coefficients on the pressure gradient, and the coefficients $C_{i\,j}$ (i = 1, 2, 3; j = 1, 2, 3) represent all the explicit terms for the flow rates of the vapor, liquid, and drop phases, respectively. From these flow rates, approximate velocities can be computed.

Linearization of the Mass and Energy Equations

The mass and energy equations can be solved once the approximate velocities have been obtained from the momentum equations. The mass and energy conservation equations will generally not be satisfied when the newly computed velocities are used to calculate the convective terms. Rather, residuals for mass and energy will result from the equations because of the new velocities and changes in some of the explicit terms, such as phase changes at the wall. The set of conservation equations is satisfied when all residuals for all computational control volumes in the mesh or network are simultaneously equal to zero. This can be approximately achieved by using a one-step Newton-Raphson method which considers the variation of each independent variable to bring the residuals close to zero. The variations are obtained by simultaneously solving matrix equations for all cells.

Solution of the Pressure Matrix

The solution of the pressure matrix is the center of the solution procedure. The pressure equations can be written for simultaneous solution as a matrix equation with N equations for N unknowns (N is the number of computational control volumes). Generally, the coefficient matrix is sparse and shows a banded structure (all nonzero elements occupy a certain number of columns on either side of the diagonal). The solution and storage approaches take advantage of both matrix properties.

Unfolding of Primary and Secondary Variables

When the pressure variation in each computational control volume has been obtained, the variations for the other variables are determined by using the stored reduced control volume equation. The new values for each primary variable (pressure, P; vapor fraction, α_v; droplet fraction, α_d; vapor-, liquid-, and droplet-specific enthalpies, $\alpha_v h_v$, $\alpha_l h_l$, $\alpha_d h_d$, respectively; and vapor partial pressure, $\alpha_v P_{vg}$) are obtained by adding the variation to the old values.
The secondary variables (liquid fraction, α_l; vapor pressure, P_{vg}; and vapor, liquid, and droplet enthalpies, h_v, h_l, h_d) and the new time step are calculated. The new time densities, ρ_v, ρ_l, and ρ_d, are computed from the equations of state, and the flows are updated by the reduced

momentum matrix equation. Similar formulations are used for horizontal velocities and the junction velocities.

Oscillating Flow Control

In certain situations using GOTHIC and WGOTHIC, because of the semi-implicit nature of the solution procedure, the approximate flows obtained from the momentum equation, as described above, are opposite in direction to the flows computed from the residuals of mass and energy at the end of the time step. This effect may be introduced by a number of explicitly evaluated terms. As a result of the discrepancies in the flow, more of a convected quantity may be taken out of a computational control volume than was there at the beginning of the time step. Body forces, especially buoyancy driven flows, are affected by this problem because they are explicitly evaluated. To minimize this problem, a check is made between the approximate flow and the one from the previous time step to ensure that none of the convected quantities exceeds the available quantity in the computational control volume. This precautionary logic is applied for the mass and energy conservation equations and generally maintains a stable solution for the period when the pressure gradient is inconsistent with the flow direction.

Time Step Control

The time step in GOTHIC and WGOTHIC is limited by the Courant condition because the time step must be smaller than or equal to the ratio of the volume divided by the total volumetric flow out of a computational control volume. Compliance with this stability criterion is mandatory because of the explicit quantities in various transport terms.

Because of the explicitness of the body force terms, experience with the code over time made it necessary to limit the time step relative to the natural oscillation period of a gravity-driven system. The U-tube manometer problem is an excellent example. The natural period is given by

$$t_n = 2\pi\sqrt{L/g}$$

with L being the effective inertial length. The recommended time step limit is then $t \leq t_n/2$, which results in stable solutions for most cases. If a stable solution is not obtained, the time step size must be further reduced via input changes by the user.

GOTHIC and WGOTHIC employ additional checks to ensure that variations in the new time variables are within reasonable limits when compared to the old time values. This approach eliminates nonphysical values, such as negative or greater-than-one phase volume fractions. For these and similar cases, the time step size is automatically halved to ensure that the linearized equations are as close to being representative of the original set of nonlinear equations as possible.

Variable Limits

There are two different types of variable limits in GOTHIC and WGOTHIC. The first type of limits keeps specific variables within prespecified lower and upper bounds to ensure proper divisions, as well as physical parameters that remain within reasonable limits.

The second type of limits relate to the model approach for control volumes and junctions and the way vapor, liquid, and drops are treated in GOTHIC and WGOTHIC. Because the numerical solution procedure specifies that no phase is completely depleted, small amounts of each phase and noncondensable gas will be present in each computational control volume at all times (see Section 12.9 of NAI's "GOTHIC Containment Analysis Package Technical Manual, Version 4.0").

21.6.5.4.1.4 Technical Evaluation

21.6.5.4.1.4.1 Adequacy of the Conservation Equations

The major technical findings related to the WGOTHIC set of conservation equations are summarized below:

- The two-fluid, three-field set of conservation equations in WGOTHIC, together with the sets of interfacial and wall-heat transfer terms, form a complete and comprehensive model.

- The separate sets of conservation equations for continuous liquid, continuous vapor, and droplet fields provide the code user with the ability to account for possible thermodynamic and mechanical, nonequilibrium conditions between the fields.

- The documentation of the conservation equations in NAI's GOTHIC Technical Manual discusses the most general integral control volume formulation and the individual contributions of interfacial, wall, and heat flux terms. These discussions are primarily focused on features of the WGOTHIC model, that would only be available in a GOTHIC subdivided, distributed-parameter approach.

- The lumped-parameter approach is used in the applicant's passive containment cooling design EM. In the lumped-parameter approach, only mass and energy conservation equations are solved for the control volumes; the momentum conservation equation is solved for the junctions connecting the computational control volumes.

- The GOTHIC documentation emphasizes the features of the subdivided, distributed-parameter approach. Limitations associated with the lumped-parameter approach are listed, but their consequences for modeling physical phenomena of interest to the applicant's passive containment cooling design are not consistently documented. Model assumptions inherent in the lumped-parameter approach are not fully articulated in the documentation of the set of conservation equations; rather, they are spread throughout the multivolume GOTHIC manuals in terms of user guidance, modeling recommendations, and validation efforts.

- The lack of models for natural circulation, jet and plume entrainment, and mixing and related stratification phenomena in finite geometries limits descriptions of these physical processes in the applicant's passive containment cooling design with the lumped-parameter EM approach.

- The test simulations and sensitivity studies in Westinghouse WCAP-14407, WCAP-14382, and WCAP-14967 are sufficient to verify specific separate-effects models and demonstrate the correct operation of the WGOTHIC code. However, as discussed in Section 21.6.5.5 of this report, there are no integral tests, conducted at an appropriately scaled prototypic test facility, that can confirm the validity of the WGOTHIC code for the applicant's passive containment cooling design.

The shortcomings cited are common to all current containment analysis codes. The staff considers the WGOTHIC code (in the lumped-parameter mode) to present a more complete set of conservation equations than other lumped-parameter containment codes, such as CONTEMPT/LT, one of the currently accepted standards. In the lumped-parameter approach, the WGOTHIC junction model for pool and above-pool regions uses a fully integrated method of simulating buoyancy effects. The separate droplet field in control volumes and junctions offers an expanded code capability and user option, thereby eliminating the need for liquid-carryover fractions and dropout and flashing models commonly used in similar codes. Within the above-cited limitations and constraints of the lumped-parameter approach, the WGOTHIC conservation equations are suitable for peak pressure studies of the applicant's passive containment cooling design, when exercised by a knowledgeable user.

21.6.5.4.1.4.2 Technical Adequacy of Interfacial Source Terms

The major technical findings related to the set of interfacial source terms in WGOTHIC are as follows:

- The GOTHIC documentation of the interfacial source terms is focused on the sophisticated features provided by the distributed-parameter model option, and not on the options implemented in the EM. A number of these features, such as drop/liquid film interactions, entrainment, and deposition, do not apply for the lumped-parameter model option.

- Although some of the interfacial transport phenomena do not apply for the lumped-parameter model option in GOTHIC and WGOTHIC, the remaining interfacial source terms provide an acceptable mechanistic description of phase interactions.

- Because GOTHIC eliminates liquid film features at surfaces for the lumped-parameter model option, and thus is unable to properly model these important PCS phenomena (condensate film at inside steel shell surface, coolant liquid film at outside steel shell surface), the applicant expanded the code by implementing the concept of climes into WGOTHIC. The clime model provides the interfacial source terms specific to the applicant's passive containment cooling design PCS to model liquid films - the condensation film on the inside surface of the containment shell and the PCS water film on the outside of the containment shell.

- No ranges of applicability are listed for correlations and models used in the GOTHIC interfacial source term correlations and models. However, the ranges needed for the interfacial source term models during and after a LOCA and an MSLB in the applicant's passive containment cooling design are not very different from DBA conditions in current-generation containments; these are the conditions against which GOTHIC has been well validated.

The EM does not use the sophisticated interfacial models present in WGOTHIC, instead favoring a simple specification of the droplet mass released during LOCA events. No droplets are assumed to be released during MSLB events. Because the lumped-parameter approach does not properly account for many interfacial phenomena, the only drop deposition mechanism is gravitational settling. The applicant addressed this potential model deficiency by choosing drops of a sufficiently small drop diameter to allow them to remain suspended in the atmosphere for an "infinite" amount of time. The containment atmosphere is thus forced to remain saturated. Sensitivity analyses performed by the applicant showed that the WGOTHIC EM assumptions regarding droplets were conservative. In particular, the peak pressure was reduced when no droplets were assumed to enter the atmosphere. These sensitivity studies were provided in Section 5.8 of the applicant's WGOTHIC AP600 application report (WCAP-14407). Cases with 5 percent and 100 percent of the break flow liquid mass assumed to be in the form of droplets yielded essentially identical results. While the staff believes that the modeling of droplets in the EM has a number of nonphysical aspects, the applicant has demonstrated that the approach is conservative. This conservative droplet model is also used in the AP1000 EM calculations (Section 5.8 in WCAP-15846). Accordingly, the staff finds this approach acceptable for DBA pressure predictions.

21.6.5.4.2 Special Models for Westinghouse Passive Containment Cooling Design Analysis

The PCS provides post-accident containment heat removal. It uses natural forces, such as gravity-driven flow, condensation, evaporation, and density-driven air circulation, to transfer heat from inside the containment to the surrounding environment, which is the ultimate heat sink for the applicant's passive containment cooling design.

21.6.5.4.2.1 Description of the PCS

The applicant's passive containment cooling design (shown in Figure 21.6.5-1 of this report) consists of a water storage tank, with a TS-governed minimum useable capacity, located above the containment, and standpipes which discharge the water to a distribution bucket located over the center of the containment dome. The standpipes are configured to progressively decrease the PCS water release rate. During the initial postaccident period, the PCS flow rate is maintained at a high, initial value. After about 3 hours, the flow is reduced when the first standpipe uncovers. Subsequent reductions in the PCS flow rate are controlled as additional standpipes are uncovered. The water storage tank provides PCS flow for 72 hours at a rate sufficient to remove the initial energy released during the accident, as well as the decay heat and stored energy within the RCS metal, maintain the containment pressure below its design value, and reduce the long-term pressure to an acceptably low value. The peak pressure for both the LBLOCA and the MSLB occurs during the initial 3-hour period.

After the bucket is filled, the PCS flow spills over and spreads out onto the top of the dome. Radial spreading vanes attached to the top of the dome keep the flow from agglomerating into one sector of the dome. The PCS flow is then redistributed into a circumferentially uniform pattern by two successive circumferential weirs located radially from the spreading vanes. The steel shell (i.e., the dome and vertical sidewalls) is coated inside and out with an inorganic zinc coating to improve surface wettability and preclude the formation of PCS water flow fingers and rivulets.

The PCS water flows down the lower dome and sidewalls of the containment, cooling the containment by evaporating the water film. A fraction of the exterior shell is assumed to remain dry. Dry sections reject heat by radiative and convective heat transfer. However, these processes are only about 5 percent as effective in transferring heat as evaporation from the wet sections.

Heat transfer from the shell exterior is augmented by natural circulation airflow. Air enters the shield building which surrounds the containment through inlets near the top of the shield building structure. The air then flows through a U-shaped passage and exits through an elevated chimney atop the shield building. The U-shaped passage is formed by a baffle piece which separates the annulus between the shield building and the containment shell into downcomer and riser passages. The riser and downcomer are bounded by the containment shell and steel baffle, and the baffle and the shield building wall, respectively, to form an integrated path for natural circulation. Heat transfer from the shell to the riser air provides the driving head for natural circulation. Unrecoverable flow resistances were based on measurements from the PCS airflow path pressure drop test for the AP600, a 1/6th-scale, 14.32° wedge model of the PCS downcomer, riser, and chimney documented in WCAP-13328, “Tests of Air Flow for Cooling the AP600 Reactor Containment,” AP600 Document PCS-T2R-010, Revision 0, issued March 1988. As a result of the test, the applicant incorporated some changes into the final design of the air annulus flowpath in the passive containment cooling design. The resulting data were extended, by a factor of 1.5, to account for the higher-than-expected Reynolds number in the AP600. The form loss was later increased an additional 30 percent to account for the design of the baffle-turning vane in the AP600. Because the turning vane design in the AP1000 is identical to that in the AP600, the same increase in the form loss is used in the EM.

Following the tests, a design change was incorporated to move the drains in the plant to about 1 foot above the upper annulus drain floor. This effectively shortens the downcomer-to-riser turning region from about 1.83 m (6 ft) to 1.52 m (5 ft), once sufficient PCS water fills the region to the new drain elevation. The applicant determined that the geometry change does not impact the WGOTHIC modeling of the passive containment cooling design for DBA analyses, and the data from the test (as modified) are still valid for the EM. This region is the same in the AP600 and in the AP1000 and the existence of this pool of water will not significantly affect the already low velocity in the air entrance region. The possible effect of the cold water pool on the air density was shown to have a negligible effect on the buoyancy-driven airflow.

Testing and Computer Code Evaluation

The AP1000 airflow path is very similar to that of the AP600. The main difference is the longer length associated with the increase in containment height. This increase in the straight downcomer and riser portions of the airflow path has a very small impact on the overall flow resistance, and is calculated in WGOTHIC. The overall impact is small, because most of the pressure losses are in other portions of the flowpath (at the turning vane and at the chimney). Therefore, the airflow path pressure drop test is acceptable to the staff for use in the AP1000 design certification review.

The staff reviewed these PCS airflow path characteristics and, in light of the above, finds them to be acceptable for use in the WGOTHIC EM for the AP1000.

21.6.5.4.2.2 PCS Flow Characterization

After a LOCA or an MSLB event, a significant time will elapse following the high-2 pressure signal to the PCS discharge valves, as the PCS flow fills the piping, fills the water distribution bucket, and fills and overflows the two distribution weirs, to finally establish total coverage from the second weir to the upper annulus drain elevation. The shell surface temperature continues to increase during the initial blowdown period while full PCS coverage is being established. PCS flow filling times were measured in the full-scale unheated water distribution tests (WDT) at a flow rate equivalent to 832.7 liters/min (220 gpm). The WDTs are documented in WCAP-13353, WCAP-13296, and WCAP-13960. The applicant conservatively took no credit for PCS cooling prior to the time it takes to develop full coverage on the containment sidewall down to the upper annulus drain elevation in the EM model. The applicant calculated the EM PCS delay time for the AP600 to be 337 seconds by scaling the measured delay times from the WDTs (see Section 7 in WCAP-14407). While the PCS flow rate in the AP1000 is higher than that in the AP600 and the time to develop full coverage would be shorter, the applicant maintains the conservative 337-second delay in the EM (see Section 7 in WCAP-15846). The actual delivery rate provides additional assurance that the vessel surface will not overheat and inhibit film formation. Flat-plate tests (FPT) performed at the Science and Technology Center Flat Plate Facility (and documented in WCAP-12665, "Tests of Heat Transfer and Water Film Evaporation on a Heated Plate Simulating Cooling of the AP600 Reactor Containment," issued April 1992) demonstrated the ability to wet and rewet a hot, dry, coated surface at an estimated temperature of 115.5 °C (240 °F). For further conservatism, the shell exterior should not exceed 100 °C (212 °F) during the 337-second delay time. An analysis presented by the applicant in Section 7 of WCAP-15846 indicates that, for the AP600, the containment shell would heat up from the assumed initial temperature of 48.9 °C (120 °F) to about 100 °C (212 °F) in 350 to 670 seconds. For the AP1000, the containment shell would heat up from the assumed initial temperature of 48.9 °C (120 °F) to about 100 °C (212 °F) in 340 to 550 seconds. Therefore, the containment surface is not expected to overheat before the PCS water is credited and film formation is not expected to be inhibited.

The applicant modeled the PCS by assuming that 90 percent of the surface may be wet if sufficient PCS water is available, and 10 percent is always considered to be dry. These values were based on the original unheated WDT data, in which the maximum PCS flow rate was 832.8 liters/min (220 gpm). Characterization of the PCS flow patterns was also based on measurements and visual observations from the unheated WDT and the heated FPT, as well as small-scale tests (SST) documented in WCAP-14134, "AP600 Passive Containment Cooling

System Integral Small-Scale Tests Final Report," issued August 1994, and in the LSTs as documented in WCAP-14135. Based on these tests, the PCS flow is expected to form wavy film stripes centered under the notches in the water distribution weirs. In the WGOTHIC EM, the stripe widths are assumed to remain constant along the shell from the spring line to the upper annulus drain elevation until evaporation reduces the thickness of the water film to less than the minimum thickness needed for film stability. The applicant used a constant value for the minimum stable film thickness for surfaces with the specific inorganic zinc coating used in the applicant's passive containment cooling design. This value was selected to conservatively bound all available Westinghouse proprietary test data over the range of interest for the applicant's passive containment cooling design for both the AP600 and the AP1000 (see WCAP-15846, Table 7-10, "Companion of the Range of Film Coverage Parameters").

After reaching the minimum thickness for a stable film, the wetted perimeter (frontal width) of the film stripe is assumed to reduce exponentially, such that the film continues to evaporate at the stability limit. The applicant justified these assumptions by qualitative observations of the heated tests cited above. The staff found this to be acceptable because the model takes less credit for the PCS water to remove heat from the containment by neglecting some of the water that would remain on the shell after the stability limit is reached.

21.6.5.4.2.3 PCS Evaluation Methodology

The applicant developed three special models to analyze the PCS:

(1) the clime model for heat transfer to the environment
(2) PCS water coverage and film tracking
(3) 2-D heat conduction

The clime model is the applicant's major addition to the GOTHIC computer program. The other two models are evaluated externally to WGOTHIC using spreadsheet-based calculations. WGOTHIC is limited in its ability to track the time-, flow-, and heat-flux-dependent variations in wetted and dry areas, and the code does not calculate 2-D heat conduction. Instead, the applicant's EM uses other methods to calculate the following inputs to WGOTHIC:

- the time-dependent PCS flow which evaporates (the evaporated flow does not include runoff)

- a factor that increases this flow as a credit for the expected effects of 2-D heat conduction

The time-varying flow boundary condition supplied to WGOTHIC is the adjusted PCS flow which would evaporate if the WGOTHIC clime model did not have these deficiencies. The three models are discussed in the following sections.

21.6.5.4.2.3.1 Clime Model for Heat Transfer to the Environment

In the applicant's methodology, the PCS is modeled as stacks of special conductor types, called "climes." Climes model the heat transfer processes (condensation, conduction, evaporation, convection, and radiation) from inside the containment to the surrounding environment. Climes solve the one-dimensional heat transfer and tightly coupled mass transfer equations for these multiregion slices. The mass and heat transferred to or from the clime are coupled to the existing GOTHIC fluid nodes through source terms. These interfaces are part of the current GOTHIC program. Stacks of clime heat structures track the thickness of evaporating and condensing water films flowing down the interior and exterior containment surfaces.

Each clime represents a horizontal slice through the containment vessel and the other PCS heat structures (the baffle and the shield building), as well as their interaction with adjoining GOTHIC fluid cells. A clime includes an adjacent portion of the containment internal atmosphere, including the condensate film on the containment shell interior, the inorganic zinc coating on the inside of the steel shell, the vessel steel wall, the inorganic zinc coating on the outside of the steel shell, the PCS water film, the riser air region, the baffle plate, the downcomer air region, and the shield building concrete structure. PCS airflow passages are modeled in climes as embedded GOTHIC nodes. Figure 21.6.5-4 of this report depicts a single clime.

In the WGOTHIC EM, the containment shell is divided into a grid of climes. The applicant uses a course axial grid and splits the containment shell into four azimuthal quadrants. The air riser is not azimuthally segmented. Each quadrant is further subdivided into a pair of wet and dry stacks. The stacks each have two vertical segments, one from the top of the containment dome to the second weir, and one from the second weir along the sidewall surface and down to the upper annulus drain region, which is near the elevation of the operating deck.

Clime heat transfer mechanisms include condensation on the containment shell interior and conduction through the shell wall. PCS coolant evaporates from the wet portion of the shell exterior surface, and convective heat transfer cools the dry exterior portion. Heat transfer to the baffle from the riser air includes both convection and condensation. The baffle also receives wall-to-wall radiation from the containment shell.

Heat conducted through the thin steel baffle and convection from the baffle will warm the downcomer airflow and slightly reduce the density head in the downcomer region which drives the natural circulation. The baffle also dissipates heat by radiation to the shield building wall. Conduction into the shield building concrete wall is also modeled.

In WGOTHIC, the heat fluxes for each clime are calculated separately, with wet and dry climes modeled as parallel, noncommunicating heat conductors. Because the PCS flow is assumed to be uniformly redistributed at the second weir, clime stacks above the second weir and below the second weir are treated separately. The coverage fractions, expressing the fraction of the total clime surface covered by the water film, are based on measurements from the unheated WDTs. Visual observations from heated tests indicate that the coverage fraction increases as the surface temperature increases. To account for heat transfer between the wet and dry clime, the applicant developed a method, as discussed in Section 21.6.5.4.2.4 of this report, to modify the coverage fraction.

21.6.5.4.2.3.1.1 Clime Conservation Equations

Initially, the clime conservation equations were based on these assumptions:

- one-dimensional film flow along the wall
- one-dimensional radial heat conduction
- constant thermal fluid properties
- neglect viscous dissipation

The applicant chose well-known, widely used heat and mass transfer correlations for the clime heat and mass transfer methodology. The applicant applied additional, conservative bias multipliers for the heat and mass transfer correlations used for the climes. These multipliers were derived from both open literature and the applicant's proprietary supporting test data (see Section 21.6.5.6 of this report) and address the SRP guidelines for demonstrating conservatism in the peak containment pressure calculations.

The applicant later modified the clime methodology to include an adjustment factor to credit the 2-D heat transfer effects when the PCS flow is reduced and the water area coverage decreases. This modification accounts for 2-D conduction from the hot, dry region of a clime to its neighboring cold, wet region (see Section 21.6.5.4.2.4 of this report).

Clime Heat Transfer

The clime model uses the heat transfer correlations shown in Table 21.6.5-4 of this report. Heat transfer to the shield building and baffle from the downcomer is considered mixed-opposed convection, which WGOTHIC models using the Churchill correlation (Churchill, S.W., "Combined Free and Forced Convection Around Immersed Bodies" (Section 2.5.9) and "Combined Free and Forced Convection in Channels" (Section 2.5.10), Heat Exchanger Design Handbook, Hemisphere Publishing Corp., 1983). After entering the riser, the Colburn forced-convection correlation is used for the containment shell side of the riser (Colburn, A.P., "A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction," Transactions of the AIChE, 1933). Scaling analysis, as documented in the applicant's letter NSD-NRC-97-5152, dated May 23, 1997, showed that forced convection is warranted with as little as a 1.1 °C (2 °F) temperature rise. The baffle side of the riser is treated as mixed-assisted convection. At some point along the containment cylinder and dome, the riser air may be hotter than the PCS film. Above the springline, the riser flow area expands significantly into the chimney region. The Uchida correlation is used for condensation heat transfer in this region, as well as for the very top of the chimney. Uchida is also used for the miscellaneous heat structures in the airflow path. The conditions in the region are consistent with the use of the staff-approved Uchida correlation.

Clime Mass Transfer

Clime mass transfer correlations are used for condensation on the inside of the containment shell, evaporation from the outer surface of the shell, and condensation on the riser baffle surface during its short initial heatup period. Convective mass transfer is a result of a concentration gradient between the liquid surface and a flowing steam-air gas mixture. To approximate the concentration gradient, the WGOTHIC model uses the following approximations:

- The steam concentration gradient is approximated as the difference in steam partial pressure between the bulk gas and liquid surface. Sections 21.6.5.4.1 and 21.6.5.7.4 of this report discuss the appropriateness of this approximation, along with mixing and circulation issues.
- Condensation occurs when the bulk gas steam concentration is greater than the concentration at the surface of the liquid.
- Evaporation occurs when the bulk gas steam concentration is less than the concentration at the surface of the liquid.

These assumptions simplify the storage, thermal diffusion, and axial transport terms of the equations. Section 21.6.5.6.1.5 of this report discusses the mass transfer analogy used from the clime model.

21.6.5.4.2.3.1.2 Clime Numerical Approach

The EM does not solve the initial PCS flow transient; instead, PCS flow is only applied to the dome and the sidewall after coverage has been fully established. The clime flows are determined using a quasi-steady-state approach. The continuity, energy, and momentum equations for the airflow in the downcomer and riser are solved in the WGOTHIC clime calculation using embedded GOTHIC lumped-parameter nodes. These nodes represent the flow network from the ambient environment through the downcomer and riser flow passages, exiting back to the ambient environment at a higher elevation. Pressure boundary conditions are imposed on the two volumes representing the ambient environment. These volumes are treated outside the GOTHIC solution methodology for the field conservation equations. They only affect the source terms for the associated GOTHIC node liquid and vapor mass and energy conservation equations.

Stability and convergence problems can arise if the time steps are too large for the explicit linkage between the (implicit) clime conduction model and the (semi-implicit) GOTHIC calculation scheme. This could be a concern if the heat and mass transfer between the clime and the fluid cell were sufficiently high to cause a significant change in the temperature of the fluid in a time step, or if some condition resulting in rapid condensation occurred (such as at the initiation of PCS film flow). Numerical instability problems due to explicit coupling usually can be avoided through the use of a sufficiently small time step. If the time step used were not sufficiently small, a typical consequence would be the onset of an oscillatory instability (with a half-period of one time step). Water property routines often fail shortly after the onset of severe oscillations, so they usually do not go unnoticed. However, less severe oscillations can only be identified by examination of key plotted results, such as wet and dry clime heat flux versus time. The staff has determined that the energy transferred to the PCS through the shell for the AP600 and AP1000 DBA analyses does not result in any numerical oscillations. However, for calculations with higher energy transfer to the PCS through the shell (for example, for a future power uprate), the applicant should examine the stability of the clime heat and mass transfer solution (e.g., by plotting heat transfer rates versus time for both the wet and dry climes) to confirm that the calculation has not violated the time step stability (see Section 21.6.5.8.3 of this report).

21.6.5.4.2.3.2 PCS Water Coverage and Film Tracking

The second special model characterizes PCS water coverage and film tracking. This is not a model in the sense that it is included in the WGOTHIC computer program. This calculation is performed external to the WGOTHIC code.

21.6.5.4.2.3.2.1 The Evaporated-Flow Model

In the WGOTHIC EM, the fractions of the clime surfaces covered by the water film are held constant throughout the transient, independent of time, axial position, or variations in heat flux. Instead of time-varying these coverage areas, the applied PCS flow rate is limited to the mass expected to evaporate. The applicant developed an "evaporation-limited" model to account for the wetted surface area change. This model computes, outside of WGOTHIC (see Section 7 in WCAP-14407 or WCAP-15846), a boundary condition in the form of an input PCS flow-versus-time table. This table specifies the PCS flow which is expected to evaporate and omits the PCS flow that is expected to run off the bottom of the vertical sidewall. This allows the applicant to maintain a single, 90-percent-wet clime model throughout a WGOTHIC analysis. Instead of time-varying areas, the WGOTHIC boundary conditions specify time-varying PCS flows. These flows are applied to the top of each wet clime stack. WGOTHIC reduces the flow entering each downstream clime in a stack by the amount evaporated upstream. When the flow rate drops below the minimum necessary to maintain a stable film, the wetted perimeter in the clime is reduced. Therefore, wet climes need not be completely covered by the PCS water film.

Time, axial position, and heat flux on the PCS heat removal rate enter into the WGOTHIC calculation as boundary conditions for the time-dependent PCS flow. This external calculation proceeds as follows:

(1) A constant value for the dome coverage fraction (i.e., above the second weir) is used, based on data taken from the unheated WDTs.

(2) From the second weir down, the coverage fractions vary with time, are based on the WDT data, and account for the reduced PCS flow as each standpipe uncovers.

The modeling approach used by the applicant to determine coverage area and PCS flow characteristics is based on data from the WDTs. The data taken from the WDT were measurements of the wetted perimeter as a function of the flow rate. The wetted perimeter determines the coverage area and, as the tests showed, the water falls uniformly along the length of the sidewall. During the initial coverage period, more than adequate supplies of water are available to preclude dryout. Below the second weir, 90 percent coverage is used for the first 3 hours, and 10 percent of the surface is always considered to be dry. This period encompasses the time of peak pressure, for both the LOCA and the MSLB cases.

Testing and Computer Code Evaluation

Based on data from the WDT, as each standpipe uncovers, the coverage area is reduced based on the reduced PCS flow. These coverage values are also considered conservative relative to the WDT measurements and include the uncertainties in the WDT coverage fraction measurements. A combined license (COL) applicant will confirm these coverage fractions for the as-built containment as described in DCD Tier 1, Section 2.2.2, "Passive Containment Cooling System," during preoperational tests as described in DCD Tier 2, Section 14.2.9.1.4, "Passive Containment Cooling System Testing." Periodic testing, as part of the inservice testing program, will also be performed to demonstrate that the area coverage fractions are maintained over the life of the plant as described in TS 3.6.6, "Passive Containment Cooling System (PCS) - Operating." The staff, therefore, considers the method used to obtain the coverage fractions acceptable for use in the licensing analyses to support design certification.

Outside of WGOTHIC, a spreadsheet procedure is used to calculate the expected evaporation rate from the PCS surface. The applicant then revises the PCS flow-versus-time table to neglect the PCS water which would run off from the bottom clime. This revised table is used as a boundary condition for WGOTHIC. Based on data from tests (e.g., the WDT, the FPT, and the LST) that utilized inorganic zinc surface coating, the applicant developed an application-specific film flow stability criterion. This criterion is a value for the minimum wetted perimeter to maintain a stable film, which bounds the available unheated and heated test data and the Zuber-Staub theoretical model over the range of applicability. The applicant adopted this empirical approach to address staff concerns with the initial procedure, which used the Zuber-Staub correlation normalized to the unheated WDT data.

This film stability criterion is used in the spreadsheet calculation performed external to WGOTHIC. Other inputs to the spreadsheet are the expected time-dependent heat flux, PCS flow rate, and coverage fraction (see Section 7 of WCAP-14407 or WCAP-15846). The spreadsheet calculates the amount of water which is expected to evaporate from the containment shell surface. The adjusted time-dependent PCS flow rate is applied to a WGOTHIC calculation as a boundary condition. In WGOTHIC, the applicant fixed the wet clime coverage area (wetted perimeter) at 90 percent throughout an analysis. The flow entering a downstream clime is the flow which originally entered the top clime, minus the flow lost in the intervening node. It is assumed that evaporation is the only means of removing water, and a time-weighted average heat flux is used to calculate the evaporation rate. The coverage fraction for a downstream clime is assumed to be the same as its upstream neighbor, unless the flow drops below the minimum value required for film stability (as predicted by the applicant's film stability criterion). When the flow entering a clime decreases below this minimum, the coverage fraction used in the heat and mass transfer calculations for the clime is reduced by the ratio of the available flow to the minimum stable flow, and the wetted perimeter is assumed to exponentially decrease.

If, in the actual WGOTHIC calculation, PCS water remains unevaporated at the bottom of the shell, an iteration through the external spreadsheet calculation is performed and the WGOTHIC calculation is redone. As a last step, for times after 3 hours into an event, the applicant increased the calculated flow, augmenting the evaporation from the shell to credit 2-D heat conduction effects (see Section 21.6.5.4.2.3 of this report). This is referred to as the evaporated-flow model. During the critical LOCA peak pressure time frame, only about two-thirds of the available PCS water is used as the boundary condition. This model tends to remove heat preferentially from the upper regions of the containment. The applicant's sensitivity studies (see Chapter 7 of WCAP-14407 or WCAP-15846) show little sensitivity to vertical distribution of the applied flow, hence, little sensitivity to vertical stratification in the containment atmosphere. However, concentration gradients caused by the build up of an air-rich layer near the walls may affect the PCS flow. Consequently, acceptance of the evaporated-flow model is based on the validity of the well-mixed containment assumption. Chapter 9 of WCAP-14407 and WCAP-15846 and Section 21.6.5.7.4 of this report discuss this assumption.

From an analytical perspective, this approach leads to additional uncertainties in assessing heat transfer from wet climes, and circulation (mixing) and stratification within the interior upper region of the containment (the region above the operating deck). Table 21.6.5-5 of this report compares the conservatisms and nonconservatisms inherent in the evaporated-flow model. The use of the evaporated-flow model results in a conservative peak pressure calculation and is acceptable to the staff for the EM because it credits only that amount of water which is evaporated during the accident and not the full amount available. The evaporated-flow model conservatively reduces the amount of water provided to the containment shell, thus reducing its calculated effectiveness in removing heat from the containment.

21.6.5.4.2.3.2.2 WGOTHIC Water Film Thickness Model

As discussed in Section 21.6.5.4.2.3.2 of this report, WGOTHIC boundary conditions specify the time-dependent PCS water expected to be evaporated in each clime's stack. This water is applied to the top clime and flows down the stack of climes. In each clime, a portion of the input flow evaporates; the remaining flow enters the downstream clime.

To calculate the thermal resistance across the internal and external films, the applicant did not use transient mass balance equations to predict the film thickness; instead, the Chun and Seban correlation (Chun, K.R., Seban, R.A., "Heat Transfer to Evaporating Liquid Films," Journal of Heat Transfer, November 1971) is used to calculate the Nusselt (Nu) number as a function of the Reynolds number (laminar flow) or Reynolds and Prandtl numbers (turbulent flow). In effect, this correlation calculates the effective average thickness for heat transfer through a wavy film. The Chun and Seban correlation was originally developed for evaporating vertical films. Using condensing data from the Wisconsin tests, the applicant extended this model to condensation and nonvertical surfaces. The Chun and Seban liquid film conductance model was compared to additional data from Kutateladze, et al (Kutateladze, S.S., Gogonin, I.I., Grigo'eve, N.I. and Dorohkov, A.R., "Determination of Heat Transfer Coefficient with Film Condensation of Stationary Vapour on a Vertical Surface," Thermal Engineering, 1980). This comparison provided additional justification for the Chun and Seban correlation in the low Reynolds number range (about 700), with the comparison showing the correlation to be a good fit to the evaporation data and conservative for the condensation data. The liquid film conductance is a low-ranked phenomenon and the use of Chun and Seban is acceptable. Based on the above, the applicant's extensions to the Chun and Seban correlation are considered acceptable by the staff.

Use of the applicant's evaporated-flow methodology, together with the Chun and Seban correlation, may nonconservatively underestimate the film resistance during time phases when the evaporated flow is much lower than the actual applied flow. During those time phases, the applicant's methodology conservatively neglects the sensible heat of the runoff flow. Neglecting runoff sensible heat is conservative and offsets the nonconservatism introduced by the simultaneous use of the Chun and Seban correlation and the evaporated-flow model. As long as these two assumptions are employed together, the staff considers this model to be acceptable.

21.6.5.4.2.3.2.3 Nodalization Studies

The applicant's clime sensitivity analysis demonstrated that, at least numerically in WGOTHIC, a clime could be broken up into multiple sections, either vertically or horizontally, while maintaining a single containment node and riser air node on each side of the clime. The computed results were shown to be identical. This approach appears to be inconsistent with the applicant's previous studies in WCAP-14382. These studies used a one-to-one relationship between a clime (wet and dry pair) and a set of GOTHIC nodes (one inside containment and one in the air riser gap). For well-mixed containments, the staff considers this approach to be an acceptable modeling practice when the nodalization of the above-deck region inside containment is demonstrated to be reasonable (converged and numerically stable). The AP600 EM, as described in Chapter 4 in WCAP-14407 (or WCAP-15846), has been shown to be both converged (see Section 12 of WCAP-14407) and numerically stable (see Section 11 of WCAP-14407). The AP1000 EM is based on the AP600 model, as described in Chapter 13 of WCAP-15846. One additional level of nodes was added to the model to account for the increased height of the AP1000 containment. The AP1000 EM is acceptable for use in evaluating the applicant's passive containment cooling design because the modeling guidelines developed for the AP600 were applied to the development of the AP1000 models.

21.6.5.4.2.3.2.4 Sensitivity Studies

Another clime sensitivity analysis, performed by the applicant in Section 5 of WCAP-14407 or WCAP-15846, demonstrated that initial conditions, the relative humidity, and fog formation in the riser had little effect on the riser airflow velocity. Fog formation was also shown to have little impact on the riser-to-baffle radiation heat transfer, as documented in Section 4.4.7K of WCAP-14812. In addition, radiation heat transfer is a low-ranked phenomena. Low-ranked phenomena can be treated in a realistic or conservative manner. While the height of the AP1000 is larger than that in the AP600, the impact remains small because the area change, over which radiation heat transfer occurs, is also small.

21.6.5.4.2.4 Adjustment Factor for Two-Dimensional Heat Conduction

After 3 hours, and again after each standpipe uncovers, the flow applied to the exterior surface of the PCS shell is reduced. Data obtained from the unheated WDTs showed that at the lower flow rates, only a fraction of the PCS shell was covered. The WDT data were used to obtain the expected area coverage fraction based on the PCS flow rate.

To evaluate the containment pressure response when the water coverage fraction is reduced (after 3 hours), the applicant added a model to account for the effect of 2-D heat transfer on the long-term containment pressure response [WCAP-14407, WCAP-15846, and the applicant's letter dated May 23, 1997 (NSD-NRC-97-5152)]. This model was based on the following physical phenomenon—when the coverage area is reduced, heat will flow circumferentially from the hot, dry regions of the shell into the cooler, wet regions of the shell. To quantitatively correct for this previously unmodeled phenomenon, the applicant performed ancillary ANSYS 2-D heat transfer calculations to determine a credit factor as a function of coverage area. Each ANSYS calculation modeled an infinitely repeating cell which contained half of a wet and half of a dry stripe. The cell width was fixed by the width between weir V-notches, assuming that stripes have a uniform width and are each centered below a V-notch. The ratio of water evaporated in the ANSYS 2-D calculation to the water evaporated in the one-dimensional WGOTHIC calculation was used to generate a factor “M.” The “M” factor is always greater than 1, and becomes large at low coverage fractions. When the actual coverage fraction falls below 90 percent, “M” is used to multiply the applied evaporation-limited PCS flow.

Concerns with the 2-D conduction model include the following:

- the validity of the uniform-width/notch-centered stripe assumption, particularly on the dome and on the lower portions of the PCS shell
- the validity of the tradeoff of circumferential heat flux for greater PCS flow
- the PCS shell boundary conditions used by the applicant for the ancillary ANSYS calculations
- the limited test data available for validation studies at low PCS flow rates

While the 2-D conduction phenomenon exists, the applicant has not sufficiently demonstrated that its evaluation methodology for 2-D conduction is conservative.

The staff believes that 2-D heat conduction has a real effect. However, as an insufficient amount of test data was available to validate this model, the staff was unable to determine how much credit should be given in evaluating the PCS design performance after 24 hours

The secondary objective for the long-term analysis is to demonstrate that the long-term pressure remains within the pressure envelope used for containment leakage calculations which support the siting evaluation. Therefore, a separate analysis will be performed for the limiting LOCA without 2-D conduction, and included in DCD Tier 2, Section 6.2.1.1.3, “Design Evaluations.” This separate analysis is used to confirm the assumption used in DCD Tier 2, Section 15.6.5.3.3 of reducing the containment leakage to half its design value after 24 hours.

21.6.5.4.2.5 Clime Model Validation

The WGOTHIC clime model was benchmarked to the LST data. As discussed in Section 21.6.5.5 of this report, the LST was not appropriately scaled to be an AP600 prototypic test facility. The LST also had a plexiglass baffle and no downcomer. Because of the limitations, these tests could not validate the correctness of WGOTHIC calculations for the applicant’s passive containment cooling design. However, the LST did use a PCS-like evaporative cooling mechanism, and specific tests were performed with natural circulation airflow. The applicant used data from these tests to validate the clime calculations. This limited use of the LST data was found to be acceptable for clime model validation, as the analyses demonstrate that the clime model was implemented correctly into WGOTHIC. The clime model is used in WGOTHIC to calculate the energy removal from the containment by the PCS.

In addition to the LST data, the applicant presented separate-effects calculations and sensitivity studies to validate the heat and mass transfer models for a single clime component. These separate-effects studies verified the functionality of the clime calculation, as incorporated into WGOTHIC. The staff reviewed the separate-effects calculations and sensitivity studies performed by the applicant (WCAP-14407, WCAP-14832, and WCAP-14967) to verify (i.e., demonstrating the correct operation) the PCS models, including the clime model and the evaporated-flow model. These calculations showed that the models the applicant added to GOTHIC to form WGOTHIC were properly implemented, and the calculated results were consistent with the data from the tests. Therefore, the staff's found these models acceptable for licencing calculations.

21.6.5.4.3 Summary of Code Changes from WGOTHIC Version 1.2 to Version 4.2

21.6.5.4.3.1 WGOTHIC 4.0 Consistency with GOTHIC Version 4.0

Many of the changes NAI implemented in GOTHIC Version 4.0 were incorporated into WGOTHIC Version 1.2 as a result of the applicant working closely with NAI. From this collaboration, a number of code errors and upgrades identified early in the applicant's development program were corrected prior to configuring WGOTHIC Version 1.2. Most of the upgrades resulting from that interaction were implemented by NAI in GOTHIC Version 4.0. NAI made these code changes to correct deficiencies, including those noted in user reports, or to provide more realistic models. NAI tested each of the changes individually and confirmed correct implementation, and the entire change set was tested in the GOTHIC Version 4.0 code release testing. This process resulted in a limited number of differences between WGOTHIC solver Version 1.2 and GOTHIC solver Version 4.0.

The applicant assessed the effects of the differences between GOTHIC Version 4.0 and WGOTHIC Version 1.2. An intermediate configuration control version of WGOTHIC, Version 1.2.2, was created. The assessment showed that the difference in calculated pressure resulted from the improved droplet model.

WGOTHIC solver was upgraded from Version 1.2 to Version 4.0 to incorporate residual changes that had been made in the upgrade to GOTHIC 4.0. Consequently, WGOTHIC is consistent with GOTHIC Version 4.0, which was baselined under the NAI QA program.

21.6.5.4.3.2 Changes from WGOTHIC 1.2 to 4.1

The changes from WGOTHIC solver Version 1.2 to Version 4.1 did not affect the PCS heat and mass transfer correlations. The changes can be grouped as follows:

- GOTHIC 4.0 upgrades and error corrections
- GOTHIC 4.0 documentation updates

- GOTHIC 4.0 EPRI-sponsored peer review and quality assurance program
- upgrades to "ccvel" subroutine
- correction of errors in the WGOTHIC clime subroutines

The observed variation in results from WGOTHIC Version 1.2 to Version 4.1 can be attributed to the following changes:

- The minimum value of the Uchida condensation heat transfer coefficient was changed from 15 to 2, thereby reducing the condensation rate at low steam partial pressures.

- The existing method for calculating steam saturation pressure as a function of temperature was replaced by a more accurate method.

- The wall dryout criterion used for internal heat sinks was modified to allow water to remain on walls until the wall temperature is greater than T_{sat} (total pressure), rather than T_{sat} (steam pressure).

- The droplet drag and deposition models were improved. This change affects the drop energy exchange rates.

- An error in the clime dryout model was corrected.

- Variables in the underlying GOTHIC subroutines and in the WGOTHIC clime subroutines were converted to double precision. (GOTHIC versions prior to 4.0 had only used double precision where judged to be most significant, as in the matrix operations.)

- Several miscellaneous modifications were made to improve consistency and reliability.

The changes made to create WGOTHIC solver Version 4.1 and its documentation have improved the solution, models, and reliability of the code.

WGOTHIC 4.1—Upgrade to "ccvel" Subroutine

The "ccvel" subroutine was upgraded to improve the cell-centered velocity calculation associated with lumped-parameter fluid nodes. The cell-centered velocity is only used in calculating heat and mass transfer in the external annulus. The resulting cell-centered velocities calculated by the two versions were verified to be similar and, therefore, one can conclude that the differences between the velocities predicted by the two codes are not the primary reasons for the differences between calculated pressures.

WGOTHIC 4.1—Correction to Partially Wet Clime Logic

In performing verification activities with WGOTHIC solver Version 4.0, the applicant discovered that the clime subroutines incorrectly handled heat and mass transfer from a partially wet clime. The error in clime logic overpredicted the PCS heat removal at the point of dryout. Changes were made to the applicant's clime subroutines to correct that error. The subroutines were modified to check for dryout (i.e., to check if the evaporating mass flux times the clime area exceeds the liquid film mass flow delivered to the top of the clime). If dryout occurs, the code divides the liquid mass flow rate by the mass flux obtained from PCS correlations, and calculates the area needed to completely evaporate the film. The remaining area within that clime is then assumed to have only dry heat transfer. Properties, temperatures, and heat transfer for the dry portion of the clime are calculated assuming instantaneous quasi-equilibrium, dry conditions. This approach conservatively neglects the heat capacity of the steel shell as its temperature increases from the cooler, wet state to the hotter, dry state.

Other minor code changes were made to correct some noncalculational problems, and WGOTHIC Version 4.1 was created.

Summary of Code Changes from Version 4.1 to Version 4.2

The following changes were made to WGOTHIC Version 4.1 in creating Version 4.2:

- A new clime subroutine, "gvel," was created to provide cell-centered velocity direction for the clime calculations, allowing correct determination of assisting versus opposed convection in the downcomer.
- The modified GOTHIC "ccvel" subroutine, supplied by NAI, was replaced with the GOTHIC 4.0 "ccvel" subroutine which corrected the error in the effective-flow-area calculation.
- The single precision constants were replaced with double precision constants in subroutines "mixed.f" and "props1.f."
- The array dimensions were increased for the GOTHIC conductors.

Thus, known errors in the WGOTHIC clime subroutines have been corrected. In addition, known errors reported for GOTHIC Version 4.0, the basis for WGOTHIC Versions 4.0 and beyond, were evaluated and determined not to be applicable to sections of coding exercised in the WGOTHIC EM.

The applicant completed verification and validation of the code changes. As part of the validation effort, the applicant performed a regression test to confirm that the change from WGOTHIC Version 4.1 to Version 4.2 had no effect on calculated peak pressure.

The applicant stated that WGOTHIC 4.2, the current licensing version, contains no known errors.

21.6.5.4.4 Models Not Used for WGOTHIC EM Analysis

The staff's review of the GOTHIC documentation supporting the WGOTHIC computer program was limited to features and models used for the PCS DBA analyses. In letter NTD-NRC-95-4577, dated October 12, 1995, the applicant informed the staff that it did not use the following models in the analysis of the passive containment cooling design, as well as the supporting analyses of tests using the WGOTHIC computer program:

- Gido-Koestel condensation model
- Tagami heat transfer model
- drop entrainment and deposition
- tube and rod conductors
- emergency safety feature components (pumps and fans, valves, HXs, vacuum breakers, spray nozzles, coolers, and volumetric fans)
- coupled boundary conditions
- “door” components

Because the applicant did not use these components in the DBA analysis, the following models were also not considered during this review:

- distributed-parameter, finite-difference numerics
- BWR pressure suppression containment
- PWR ice condenser containment

21.6.5.5 PIRT and Scaling Analysis Methodology

WCAP-14812 presented the applicant’s AP600 containment PIRT. This report also discussed how these phenomena were treated in the WGOTHIC EM. WCAP-14845 documented the applicant’s scaling analysis. Both the PIRT and the scaling analyses departed from the methodology described in NUREG/CR-5809, “An Integrated Structure and Scaling Methodology for Severe Accident Technical Issue Resolution.”

In support of the AP1000 design, the applicant provided, in WCAP-15613, an evaluation of the differences between the AP600 and the AP1000 in terms of scaling and the PIRT. The purpose of this evaluation was to demonstrate that the AP600 test program adequately covered conditions expected in the AP1000. In addition, this assessment identified no new phenomena associated with the AP1000 and no changes in the PIRT ranking of the phenomena compared to the AP600.

The staff reviewed WCAP-15613 and found that it did not sufficiently describe the expert review process of the PIRT. The staff requested that the applicant provide a summary of the experts’ reasoning behind the conclusion that no changes were necessary for the AP1000 at the “component or volume” level, as used in Table 2.6-1 of WCAP-15613. In its letter dated July 31, 2001 (DCP/NRC1481) the applicant provided two letters, one from Professor Per Peterson and one from S.G. Bankoff, to indicate the considerations given to the PIRT process. The letters provide some insight into the process used by the experts in the PIRT process. Overall, the experts concluded that the differences between the AP600 and the AP1000 plants are modest to small and can be treated in the analysis.

Testing and Computer Code Evaluation

The larger height of the AP1000 (compared to the AP600) could cause more complex recirculation patterns, thereby influencing mixing. Less homogeneity of the containment atmosphere above the operating deck could result, with higher temperatures in the upper dome. However, WGOTHIC can conservatively predict the decreased homogeneity using the multi-node model.

The applicant used the AP600 scaling study to support the AP1000 design. WCAP-15613, Table 4.2-1, "Transient Phase Scaling Parameter Comparison," provides a comparison of the transient phase scaling parameters, comparing the LST to both the AP600 and the AP1000. However, the staff and the applicant agreed during the AP600 review that the LST was not properly scaled for transient situations. The LST is only valid for steady-state conditions. In response to a staff request (DCP/NRC1481), the applicant clarified that the LST is not well scaled for either the AP600 or the AP1000. However, the LST does support the mass and heat transfer correlations used in the WGOTHIC code for the AP1000 design. WCAP-15613, Table 4.2-2, "Operating Range Comparison for AP600 and AP1000 Heat and Mass Transfer Parameters," compares the experimental database for the heat and mass transfer parameters to both the AP600 and the AP1000.

The staff agrees with the Westinghouse PIRT conclusions. The differences between the AP600 and the AP1000 do not change the ranking of the phenomena, no new phenomena have been identified, and the models developed to address the high- and medium-ranked phenomena for the AP600 remain applicable for the AP1000.

The applicant demonstrated that the AP600 experimental database covers the expected range of the mass and heat transfer correlations during DBA analyses for the AP1000. The staff agrees with the applicant that no new data are needed, and that the WGOTHIC computer program, when used with the appropriate EM, is applicable and acceptable for licensing analyses.

Sections 21.6.5.5.1 and 21.6.5.5.3 of this report, respectively, describe the Westinghouse PIRT and the scaling approach for the PCS. Sections 21.6.5.5.2 and 21.6.5.5.4 of this report evaluate the PIRT and the scaling analyses of the PCS. These sections make reference to the AP600, but are also valid for the AP1000 because no changes to the PIRT were necessary, as described above..

21.6.5.5.1 Westinghouse PIRT Methodology

The NRC staff requested that the Westinghouse PIRT include an overview of the process used to justify the conservative EM for containment pressurization design analysis. Therefore, in addition to specifying accident scenarios and identifying and ranking important phenomena, the PIRT report summarizes the WGOTHIC EM treatment of all of the identified phenomena.

21.6.5.5.1.1 Accident Specification

The applicant chose two limiting pressurization transients as the basis for identifying and ranking phenomena to be considered in the EM. The two limiting scenarios are (1) the double-ended, cold-leg guillotine break from full power, and (2) the MSLB from 30-percent power. The MSLB is more limiting at lower power because the liquid inventory in a steam generator is greater than at full power. The PIRT contains a detailed description of each scenario.

The mass and energy release and the PCS water flow rate are specified as boundary conditions for the containment design analysis. Along with the specified inside containment initial conditions, these phenomena were also identified and ranked in the PIRT.

Because the relative importance of an individual phenomena can change as a transient progresses, the applicant considered four separate temporal phases for the LOCA, the blowdown phase (0 to 30 seconds), the refill phase (30 to 90 seconds), the peak pressure phase (90 to approximately 1200 seconds), and the long-term phase (beyond approximately 1200 seconds). Figure 21.6.5-5 of this report offers a schematic of the pressure response during these four temporal phases. The blowdown period is the time during which the primary coolant inventory is released to the containment, resulting in a rapid pressure increase. During the refill period, the accumulators are injecting into the system and condensing steam. There is little or no mass and energy release to containment, so the pressure decreases through steam condensation and heat absorption in structures. During the peak pressure phase, steam is generated by decay heat and from stored energy released from the reactor system internal heat sinks. This increased flow of energy is greater than the energy flow into the containment structures and the shell so the pressure again increases. During the long-term phase, the heat removal through the shell (by the PCS) exceeds the energy release to containment, so the pressure slowly decreases.

The mass and energy release from the MSLB consists of superheated steam only. The inventory available for release is limited by the assumed closure of the main steam isolation valves (MSIVs). The steam release lasts for approximately 600 seconds. After the release is completed, the containment pressure decreases because there is no further addition of mass and energy. Therefore, the blowdown is the only temporal period considered for the MSLB scenario.

21.6.5.5.1.2 Phenomena Identification and Ranking

The applicant used a combination of expert review, scaling analysis, testing, and sensitivity studies to identify and rank important phenomena. The identification and ranking process differed from that used in most PIRT studies because the applicant did not use a group of experts to identify and rank the important phenomena for the AP600. Rather, the applicant developed a list of phenomena and rankings which was then reviewed and commented on by two groups of experts.

One group of experts, referred to by the applicant as the internal experts, were all Westinghouse staff members knowledgeable about the AP600 project. The other group consisted of outside experts. There were four internal and four external experts. The two groups did not interact. Three of the four outside experts, referred to as the EPRI group, met and reviewed the Westinghouse PIRT. The fourth outside expert acted independently. The information in the AP600 PIRT report about the expert reviews is limited. The applicant's synopsis of the expert review process (Appendix A to WCAP-14812) is provided without identifying the input and opinions of individual experts.

Section 4.1 of the PIRT report describes in detail each of the phenomena identified by the applicant. Phenomena are grouped by component or volume into three categories—inside containment, containment shell, and outside containment. Table 4-1 of WCAP-14812 lists the phenomena associated with each component or volume.

Components or volumes inside containment consist of the break source, containment volume, containment solid heat sinks, initial conditions, break pool, and IRWST. From three to eight phenomena are identified and ranked for each of these components or volumes. The two components of the containment shell are the steel shell and the PCS cooling water. Fourteen phenomena are identified and ranked for the steel shell, and five phenomena are ranked for the PCS cooling water. Seven components or volumes are considered outside containment, including the riser annulus and chimney volume, baffle, baffle supports, chimney structure, downcomer annulus, shield building, and external atmosphere. From two to seven phenomena are identified and ranked for each of these components or volumes. The AP600 PIRT includes a total of 81 phenomena. Rankings are provided for each of the four LOCA phases and for the MSLB for each phenomenon. Table 21.6.5-6 of this report lists the phenomena. This table is the same as Table 4-1 in WCAP-14812.

The applicant justified the ranking assigned to each phenomenon. Most of the rankings were based on scaling results and expert opinion, but test results and sensitivity studies were also used to develop the ranking for some phenomena. Those phenomena that were ranked high, for any phase of the LOCA or for the MSLB, have more extensive justification, generally including test results and/or sensitivity studies. Where scaling studies or test results were used to develop a ranking, the applicant cited specific test runs and provided numerical values of the scaling **π** numbers to support the ranking.

21.6.5.5.1.3 Treatment of Phenomena in WGOTHIC Evaluation Model

In response to the staff's request, the applicant provided the basis for ranking each of the 81 phenomena and included discussions on how the phenomena were implemented in the WGOTHIC EM, justified the EM treatment, evaluated uncertainties, and discussed distortions in test facilities (i.e., the LST) in WCAP-14812. This information was a compilation of material presented in other reports, primarily the application reports (WCAP-14407 or WCAP-15846). Placing the ranking basis and the EM treatment of each phenomenon in the same report facilitated the comparative assessment of the rationale for the ranking and the degree of conservatism in the EM.

21.6.5.5.2 Containment PIRT Evaluation

The three aspects of the PIRT report (scenario identification, phenomena ranking, and treatment of phenomena in the EM) are discussed in Sections 21.6.5.5.2.1, 21.6.5.5.2.2, and 21.6.5.5.2.3 of this report, respectively. To facilitate discussion of the evaluation, Table 4-1 of the Westinghouse PIRT report has been reproduced in Table 21.6.5-6 of this report. In the following text and in the tables, L, M, and H signify low-, medium-, and high-ranked phenomena, respectively. N/A indicates that the phenomenon is not applicable for that event or time phase.

21.6.5.5.2.1 Evaluation of Westinghouse Scenario Specification

The two accidents identified by the applicant as being limiting for the passive containment cooling design (i.e., the double-ended, cold leg break from full power and the MSLB from 30-percent power) are essentially the same as might be expected for a conventional PWR dry containment. The limiting events are determined primarily by the mass and energy release, so this similarity with existing designs is expected. The applicant chose these two events as the basis for the phenomena identification and ranking and for the scaling analysis.

The final design calculations performed with the EM determine the actual limiting scenarios. The events chosen as the basis for the PIRT and scaling analysis are sufficiently representative of these limiting pressurization events to serve the stated purpose. The only differences are related to the actual mass and energy releases used in a final safety analysis report (FSAR) and minor changes to the containment layout. Therefore, the staff concurs with this choice of event scenarios.

The applicant also described the key assumptions and initial and boundary conditions for the two scenarios. Limiting conditions for peak pressurization, such as high initial temperatures based on plant TS limits and maximum mass and energy releases, were chosen. The applicant considered the initial conditions themselves to be a part of the PIRT phenomena. The applicant correctly included a single-failure-to-open assumption for one of the valves in the PCS cooling water system. The staff concurs with the assumptions and the applicant's choices of initial and boundary conditions on the basis that they are sufficiently representative to provide an adequate framework for PIRT and scaling evaluations of the maximum containment pressure. The values used are typical for expected nominal conditions, and the mass and energy releases are typical of those expected during a DBA.

21.6.5.5.2.2 Ranking of Phenomena Evaluation

The applicant's approach to the use and documentation of expert opinions in the PIRT process differs markedly from that taken in most prior PIRTs. The more standard approach is to hold a meeting with all of the experts present. The phenomena are discussed among the group and an attempt is made to achieve a consensus on the ranking of phenomena. In documenting the process, the opinions of individual experts are identified. Differences of opinion are then a matter of record.

As discussed in Section 21.6.5.5.1 of this report, the applicant first wrote a draft PIRT report, which included the report authors' rankings and discussions supporting the rankings. Separate groups of experts reviewed the draft and then offered comments. Appendix A to the PIRT report contains a summary of the experts' comments. The applicant did not identify the comments of individual experts, so it was not possible to identify who provided a particular comment or opinion. Because the PIRT performed by the applicant was not conventional, the staff put less weight on the experts' opinions and requested the applicant to provide a documented basis for each of the rankings. The staff asked the applicant to provide specific references to experimental runs, sensitivity studies, and scaling analysis π groups used to establish the rankings. The applicant revised the PIRT report to include this information, which was the basis for the staff's acceptance of the PIRT results. The staff's evaluation still considered the experts' opinions, but less weight was given to the opinions because of the nature of the PIRT process used by the applicant.

The first question in evaluating the PIRT was whether the applicant's list of 81 phenomena was complete. While the PIRT process used by the applicant was nonstandard in many respects, the staff concluded that it resulted in a list of phenomena which was comprehensive and complete. Even though the information provided in Appendix A to the PIRT is sparse, it does indicate that the experts were satisfied with the list of phenomena. The staff concurred that all relevant phenomena were included, and that the descriptions provided by the applicant clearly defined each phenomenon.

The applicant provided rankings for each of the four LOCA phases and for the MSLB for each phenomenon. Of the 81 ranked phenomena in the PIRT, 37 (less than half) were ranked medium or high during at least one phase of the LOCA or during the MSLB. The remaining 44 phenomena were ranked low or not applicable. The EM treats both medium- and high-ranked phenomena in a conservative fashion, so it is less important to distinguish between these two rankings. Low-ranked phenomena can be treated in a realistic or conservative manner, so it was important to establish that each phenomenon given a low ranking deserved that ranking.

The staff reviewed each of the low-ranked phenomena to identify any such phenomena that could have been incorrectly ranked as low. Appendix A to the PIRT shows that the experts did not disagree with the ranking of any of the initially low-ranked phenomena. No experts commented that a low-ranked phenomenon should have been ranked medium or high. However, some of the rankings in the initial report reviewed by the experts were changed. For example, phenomenon 1E, droplet/liquid flashing, was originally ranked high during the LOCA blowdown and refill phase. The ranking was changed from high to low in Revision 1. Experts had no opportunity to comment on this change in ranking. This is another shortcoming of the Westinghouse PIRT process. The staff notes, however, that lowering the ranking of some phenomena while establishing closure between the PIRT and the EM is to be expected. Initially, a conservative approach should be used to establish the rankings. Development of additional information from scaling, experiments, and sensitivity studies may be used to revise the rankings. If the initial rankings were conservative, then most of the revisions would be expected to result in lower rankings. In the Westinghouse PIRT, lower rankings were assigned to droplet/liquid flashing and five other phenomena in Revision 1. The staff gave special attention to these six phenomena because their final rankings differed from the rankings assigned by the experts.

In most cases, there is little question that the low-ranked phenomenon deserves its ranking. In the case of the droplets (Table 21.6.5-6 of this report, phenomenon 1E), the applicant changed the ranking based primarily on sensitivity studies reported in WCAP-14407, which showed an insignificant change in the peak pressure over the assumed range of "liquid fraction turned into drops" from 5 percent to 100 percent. For zero liquid turned to droplets, the peak pressure was lowered; therefore, the applicant demonstrated that it is conservative to assume that some droplets are present in the WGOTHIC EM. The staff believes that the treatment of droplets in the applicant's model is nonphysical. Droplets are assumed to remain in the atmosphere and to have a constant surface area throughout the LOCA scenario.

Nevertheless, the applicant has demonstrated, though sensitivity analyses, that the droplets are treated in a conservative manner, just as if they were a medium- or high-ranked phenomenon. Hence, the staff finds that the treatment in the model is acceptable. The low ranking assigned in the PIRT becomes irrelevant, because the model treats drops as though they were a high- or medium-ranked phenomenon.

Liquid film energy transport on containment heat sinks (phenomenon 3A in Table 21.6.5-6 of this report) was initially ranked high during the peak pressure and long-term phases of the LOCA, and medium during the LOCA refill phase and for MSLB. In Revision 1 of the PIRT report, this phenomenon was ranked low for all phases of the LOCA and the MSLB. The amount of energy carried off by the liquid film depends on the condensation rate and on the enthalpy difference between the saturated liquid and the reference enthalpy. A low level of uncertainty is associated with the enthalpy difference. The condensation rate is the main determinant of the magnitude of this term and the condensation is a high-ranked phenomenon. The applicant's internal experts commented that this phenomenon was really a part of condensation and should be combined with that phenomenon. Because the condensation rate is the main determinant of the value of this term, the staff agrees with the applicant's experts. The low ranking given to this term then applies to the enthalpy difference. Scaling analysis performed by the applicant showed that the value of the sum of the π groups ($\pi_{e,q,st} + \pi_{e,q,cc} + \pi_{e,f,jc}$) associated with this term was at most 0.08. Given the high ranking assigned to condensation, treating the enthalpy difference as a low-ranked phenomenon is acceptable (e.g., the π group value is less than 0.1).

The PIRT experts ranked compartment filling as medium importance during the LOCA long-term phase, and low for all other phases. Revision 1 has this phenomenon ranked low for all phases. As for the enthalpy of fluid in the pool, the present EM treatment is conservative, with hot fluid modeled at the surface, similar to a medium- or high-ranked phenomenon. The other aspect of filling is the closing off of flowpaths. In this regard, the uncertainty is low and volumes are estimated low (and will fill early), so the treatment is acceptable.

Phenomena 7A and 7B, convection and radiation heat transfer from the containment volume, were originally ranked medium in importance during the refill, peak pressure, and long-term cooling phases of the LOCA. The applicant argued that a low ranking was justified because the combination of radiation and convection heat transfer is small compared to mass transfer. Because radiation is neglected and a conservative multiplier is applied to the convection heat transfer, the phenomena are conservatively treated, just as if they had been ranked medium or high. Hence, the low ranking has no consequence. The conservative treatment of these phenomena in the EM is acceptable.

Convection to the downcomer (phenomenon 14A in Table 21.6.5-6 of this report) was ranked low in Revision 1 of the PIRT. It had initially been ranked medium during the peak pressure and long-term cooling phases of the LOCA. The temperature differences in the downcomer region are less than those in the riser section. The applicant's Figure 4-1, "Metais and Eckert

Plot," from WCAP-14845 shows that the downcomer is in the forced-convection regime (Metais, B., Eckert, E.R.G., Journal of Heat Transfer, 1964). A mixed-convection heat transfer correlation recommended by Churchill is conservatively applied, although nominal multipliers are used on the correlation. In spite of the low ranking, a reasonably conservative approach was used, which the staff found acceptable.

In one case, the staff questioned whether the applicant's assumptions about the phenomenon might have resulted in the low ranking, and whether a higher ranking might have resulted if a different set of assumptions had been made. In the case of outside film conduction on the shell (item 7L of Table 21.6.5-6 of this report), the applicant's analysis appeared to be based originally on an assumed 5-mil film thickness. The staff asked whether assuming a thicker film would have changed the ranking. The applicant responded that the film thickness was not generally measured in the experiments, but that an equivalent film thickness could be determined from the data. The film thermal conductivity is based on the Chun and Seban correlation, not on an assumed film thickness. Using the correlation, the film thermal conductivity is shown to be a small contributor to the overall thermal resistance across the shell. The staff concurs with the low ranking.

Those phenomena that were ranked medium or high importance during any phases of the LOCA or for the MSLB were conservatively implemented in the EM. The next section summarizes the staff's evaluation of the WGOTHIC treatment of the phenomena identified in the PIRT. All phenomena are included, with an emphasis placed on the high- and medium-ranked phenomena.

21.6.5.5.2.3 Evaluation of Implementation in the WGOTHIC Evaluation Model

Section 4.4 of WCAP-14812 provides a roadmap of how each phenomenon is addressed in the WGOTHIC EM. Details are generally given elsewhere; however, this section points to the location of the individual detailed discussions.

Table 21.6.5-7 of this report summarizes the staff's assessment of the EM treatment of the PIRT phenomena. In reviewing the PIRT phenomena, the staff emphasized the 37 medium- and high-ranked phenomena. Note that 18 of the 37 phenomena were ranked high, and 19 were ranked medium. When a detailed discussion is needed to document the assessment, the reader is directed to a subsequent section in this evaluation. When the treatment by the applicant is clearly acceptable and no further discussion is needed (e.g., a phenomenon conservatively neglected), Table 21.6.5-7 of this report lists the assessment results.

21.6.5.5.3 Westinghouse Scaling Methodology

The applicant's scaling evaluation in WCAP-14845 supported the PCS DBA conservative EM. First, the scaling analysis was used to develop the PIRT (i.e., identify and rank physical phenomena for the containment pressurization model). Second, the scaling evaluation identified constitutive relations and correlations to describe the identified phenomena. Once this was completed, the evaluation compared the range of the data used to develop the models to the range of the AP600. Similarity variables were used to characterize the constitutive relations and correlations. Finally, the scaling evaluation considered the use of LST data to validate conservatisms in the EM at the scale of the AP600. Distortions in the LST were identified, and their effect on the use of LST data for DBA model validation was discussed.

Containment pressure is the key variable for evaluating the performance of the passive safety systems. The EM must demonstrate that the passive safety systems act to maintain the peak containment pressure below its design limit. The scaling evaluation provides support for applying the EM.

One very significant element of the scaling evaluation is the pressure rate of change equation applied to two limiting scenarios, the double-ended, cold-leg LOCA and the MSLB. The dimensionless form of the pressure rate of change equation contains π groups whose relative magnitude is used to assist in ranking phenomena. Bottom-up, component-level evaluation of the individual phenomenological models included in the pressure rate of change equation is another key element of the scaling evaluation. In Section 10 of the scaling report, the applicant demonstrated that the database for the component models covered the range of similarity variables for the AP600. Therefore, the models were applicable at the scale of the AP600.

The integral test facility for the AP600 PCS containment test data was the LST. Some of the distortions in the LST facility were identified and evaluated by contrasting the pressure rate of change equation π groups for that facility to the same π groups in the equation applied to the AP600. Additional π groups were defined for the conservation of mass and conservation of energy equations. These π groups were also used in the comparison of the LST to the AP600. In WCAP-15613, Table 4.2-1, “Transient Phase Scaling Parameter Comparison,” the applicant provided a comparison of the LST π groups to the AP1000. The scaling distortions in the LST based on the AP1000 π groups remained similar to those identified for the AP600 π groups.

21.6.5.5.3.1 Component-Level Scaling—Constitutive Equations for Heat and Mass Transfer

Section 4 of the applicant’s scaling report, WCAP-14845, describes the constitutive relations for heat and mass transfer used in the scaling equation and, in most cases, in the EM. Section 10 of the applicant’s scaling report describes the ranging of the variables in the correlations compared to AP600.

The applicant chose to use established correlations from the literature to model radiation and convection heat transfer. The McAdams correlation

$$h_c = 0.13\ k/(\nu^2/g)^{1/3}(\Delta\rho/\rho)^{1/3}(Pr)^{1/3} \qquad \text{(Eq. 21.6.5.5-1)}$$

is chosen for turbulent free convection. The form of the McAdams correlation used depends only upon local conditions, including the ratio of the difference between the bulk and the surface density ($\Delta\rho$) and the bulk density (ρ). This correlation is used in the mass transfer model for condensation on the inside shell surface.

For turbulent forced convection, the Colburn correlation is used:

$$h_c = 0.023\ k/d_h\ (Re_d)^{0.8}(Pr)^{1/3} \qquad \text{(Eq. 21.6.5.5-2)}$$

This correlation is used in the model for evaporation mass transfer from the shell to the annulus. A standard laminar free-convection heat transfer correlation from Kreith (Kreith, F., Principles of Heat Transfer, Second Edition, 1956) is used for the heat transfer to the liquid drops in the atmosphere.

Condensation and evaporation mass transfer (m'') is modeled using a relationship from Kreith:

$$m'' = h_c\ \rho_{stm}\ (D_v/k)\ \Delta P_{stm}/P_{lm,air}\ (Sc/Pr)^{1/3} \qquad \text{(Eq. 21.6.5.5-3)}$$

In the previous equation, $P_{lm,air}$ is the log-mean air pressure defined by the following equation:

$$P_{lm,air} = (P_{air,bulk} - P_{air,srf})/\ln(P_{air,bulk}/P_{air,srf}) \qquad \text{(Eq. 21.6.5.5-4)}$$

D_v is the air-steam diffusion coefficient. The applicant calculates this coefficient using a correlation given by Eckert and Drake (Eckert, E.R.G., Drake Jr., R.R., Analysis of Heat and Mass Transfer, 1972).

Other correlations from the literature are also used. However, the relationships listed above govern the important energy transfer to and from the shell.

In Section 10 of the scaling report, the applicant compared the heat transfer correlations to the separate-effects test data. The condensation correlation was compared to the separate-effects data from the LST. The comparison is reasonable, and the data were shown to cover the range of the AP600. Similarly, for forced-convection evaporation, the Colburn correlation was compared to data from the flat-plate test conducted by the Westinghouse Science and Technology Center (STC), and the data were also shown to cover the range of the AP600. The applicant noted that the recommended range of the Reynolds number for the Colburn correlation included the range for the AP600.

Water coverage was scaled by the applicant based on three similarity groups, the Reynolds number, Marangoni number, and the Bond number for the liquid film. With one minor exception, the range of these dimensionless groups for the AP600 is covered by test data from the LST and the full-scale WDT. The film Reynolds number on the upper sidewall of the containment exterior surface is higher in the AP600 than covered in the LST and WDTs. However, the Marangoni and Bond numbers showed that the range was adequately covered.

The Chun and Seban correlation is used to model heat transfer through the liquid film on the inside and outside of the containment shell. The applicant provided a comparison of this correlation to the Chun and Seban data and included data from the University of Wisconsin tests. These data included surface inclinations from vertical to horizontal, but covered only the laminar range. Between the Wisconsin and Chun and Seban data, the Reynolds number range of AP600 operation was covered.

Section 10 also describes the scaling of PCS airflow path resistance. The applicant performed a 1/6-scale airflow test, as documented in WCAP-13328, on a geometrically scaled model of an early version of the AP600 design. A Reynolds-number-based correlation was developed considering the composition of the losses as partially form and partially friction.

21.6.5.5.3.2 System-Level Scaling—Pressure Rate of Change Equation

Sections 5 through 7 of the scaling report describe the development of the pressure rate of change equation. It is applied to the LOCA and MSLB in Section 8 of the scaling report. Section 9 of the scaling report discusses coupling to the airflow equation for the downcomer and annulus. Section 10 of the scaling report discusses top-down scaling of integral test data from the LST.

The applicant derived an equation which governs the rate of pressure change (RPC) inside containment based on its assumption of a completely mixed atmosphere. Section 21.6.5.5.4.2 of this report further addresses this assumption. The equation was developed from the conservation of energy equation and the equation of state in the form of a rate of change of internal energy relationship. Dimensional (WCAP-14845, equation 63) and nondimensional (WCAP-14845, pages 10–14) forms of the equation were presented. The RPC equation was rendered dimensionless by dividing all terms by a reference break gas work term. The coefficients of the various terms in the dimensionless form of the equation were referred to as pressure **π** groups.

Dimensionless forms of the conservation of energy, conservation of mass, and PCS momentum equation were also developed. Coefficients in the dimensionless forms of these equations were referred to as energy, mass, and momentum **π** groups, respectively. Dimensionless forms of the heat transfer relationships for the various heat sinks and the shell were also developed. Coefficients in these equations were referred to as conductance **π** groups.

Section 8 of the scaling report evaluated **π** groups for each phase of the LOCA and MSLB. The **π** group values were then used to calculate dP/dt values. The scaling model dP/dt values were then compared to corresponding values calculated with a WGOTHIC model, which was comparable to the scaling model. Some of the conservatism included in the WGOTHIC EM was not included in this case to facilitate comparison to the scaling model. Values of dP/dt were presented for each phase of the LOCA. Reasonable agreement was shown between the scaling model and the WGOTHIC calculations.

21.6.5.5.3.3 Westinghouse Evaluation of Distortions in the LST

Distortions in the LST data was the subject of Section 11 of the scaling report. The applicant stated that the LST could not be used as a direct simulation of the AP600, either for the LOCA or for the MSLB. The applicant presented arguments to support use of the LST as a system-level simulation for code validation, and argued that the LST data could be used to examine the influence of lumped-parameter code biases. The applicant also discussed the use of the LST to address component-level distortions.

The definition of distortion used by the applicant was based on differences in the values of the **π** groups. Many of the distorted phenomena (e.g., mixing and circulation) were not characterized by **π** groups. Nevertheless, all of the identified distortions, even those for which there was no associated **π** group, were addressed.

Seventeen LST distortions wre listed, along with descriptions of the effect of each distortion. The treatment of the distorted phenomena in the EM was discussed, as was the effect of the distortion on the use of LST data to validate the mass and heat transfer correlations used in WGOTHIC. A brief summary of each distortion follows. Section 21.6.5.5.4.3 of this report provides the staff's evaluation of how each distortion affects the use of LST data.

Area to Volume Ratio

One of the more significant distortions, because it involves high-ranked phenomena, was the area to volume ratio, which is eight times higher for the LST than for the AP600. The applicant argued that this distortion did not affect the use of the LST as a source of separate-effects data.

Break Source Flow Rate

The LST was run as a steady-state test; the energy addition rate from the break was approximately equal to the energy removal rate through the shell. During a transient, a considerable amount of energy, in excess of the amount removed, is added. This causes the pressure to increase. Because no excess energy was added in the LST, the power to volume ratio was much lower than for the AP600. The applicant argued that the break source flow rate was varied during the tests to cover a range of values typical of the AP600. Therefore, this was not a distortion in terms of separate-effects data.

Shell Thickness

Both the thermal resistance and heat capacity of the shell were affected by thickness. The thickness of the LST shell was slightly over one-half the AP600 shell thickness. The applicant argued that this was not a distortion for separate-effects data.

Break Source Superheat

The applicant argued that, while the relative distortion was high, the absolute distortion was small and, therefore, this was not significant.

Diffuser Used for Break Source

The diffuser produces a low-velocity flow, whereas a high-velocity jet is expected during blowdown. This is a distortion during blowdown, but becomes less of a distortion for the long-term phase.

No Downcomer

The LST used a fan to force flow in the riser. **π** groups for the downcomer flow were stated to be sufficiently small to prevent the downcomer flow from significantly affecting PCS performance. This was also a low-ranked phenomenon. The applicant argued that the downcomer was adequately treated in the EM as a flowpath, with thermal and hydraulic interactions with the baffle and the shield building.

Fan-Forced Riser Air Flow

The applicant argued that for separate-effects data, it did not matter whether the airflow is forced or induced by natural circulation.

Riser-Scaled 1/4

The LST riser was scaled 1/4 instead of 1/8 like the rest of the test. Consequently, the Reynolds number range for the separate-effects data covered a range of Reynolds numbers up to about one-half of the AP600. The applicant argued that the distortion had no effect over the range of Reynolds numbers covered, and that the range of Reynold numbers for the LST was adequately covered by other data sources.

No Circulation below Deck

There was no connection between the steam generator compartment, where the break occurred, and the other below-deck compartments. Therefore, the circulating flow field was distorted at the system level. The applicant argued that because local conditions were measured, this distortion did not affect the use of the LST for separate-effects data.

External Water Flow Too High

While many of the LST test cases had higher cooling water mass flow rates and higher subcooling than the AP600, some tests covered the AP600 range. Therefore, the applicant argued that this was a ranged parameter rather than a distortion.

External Water Coverage Too High

As a consequence of the high PCS flow rates, the wetted fraction of the exterior LST surface was greater than would occur in the AP600. While a given test may had a larger coverage fraction than a comparable AP600 case, the test series encompassed a range of coverages, including a dry shell. Therefore, water coverage was a ranged parameter.

External Water Flow Was Established Before Break

Two LST tests were run with water applied after the shell was heated. These tests are stated to provide separate-effects data to support validation of the external wetting and stability model.

External Water Flow Time Variations

The applicant argued that this was not a distortion because the reduced-flow portion of the cycle was only a small fraction of the total, and all but two of the tests had significantly more flow than could be evaporated. The separate-effects data were averaged over several cycles of the flow variation, the data were evaluated with both minimum and maximum flow rates and a conservative approach adopted, and data without flow fluctuations were used in the correlation comparisons. Therefore, it was argued that the flow fluctuations did not compromise the use of LST data in the separate-effects mode.

External Water Not Applied by Weirs

This was not considered to be a distortion because the method used to achieve water coverage gave distributions similar to the distribution expected for the AP600.

Internal Heat Sinks Not Prototypic

On a system level, the nonprototypical features only affected the period between the blowdown and the long-term phase. Because local measurements were made, the distortion did not affect the use of LST data for separate-effects correlation validation.

Crane Rails Not the Same

The applicant argued that the lack of a structure in the LST to simulate the crane rail wa-s not a distortion because the affected quantity was the film conductance, which had less than a second-order effect.

Condensate Drained Out

Draining the condensate to prevent filling up of the facility resulted in the lack of a break pool. Because the pool was shown by the scaling analysis to be less than a second-order effect, the applicant argued that this was not a distortion.

The above is a summary of the applicant's position on the LST distortions. The following section provides the staff's position on the scaling analysis and the use of LST data to support the scaling and WGOTHIC validation.

21.6.5.5.4 Evaluation of Westinghouse Scaling

In using the scaling analysis to support the PIRT rankings, the applicant considered, among other factors, the magnitude of the dimensionless coefficients of the RPC equation as a measure of importance to aid in ranking phenomena. Section 21.6.5.5.4.1 of this report evaluates the use of scaling to support the PIRT.

In developing the RPC equation, relevant correlations and constitutive relationships were described, and the validation data range was compared to that of the AP600. This is essentially a bottom-up scaling approach that establishes the applicability of basic heat and mass transfer relationships used in both the scaling and EMs over the range of the AP600. In WCAP-15613, Table 4.2-2, “Operating Range Comparison for AP600 and AP1000 Heat and Mass Transfer Parameters,” the applicant demonstrated that the validation data range is also applicable to the AP1000. Section 21.6.5.5.4.2 of this report discusses this aspect of the scaling evaluation.

The scaling study also addressed the use of the LST as a source of separate-effects heat and mass transfer data. LST data include condensation and evaporation heat and mass transfer across the shell. They were used both to validate the combination of standard correlations chosen by the applicant and to establish conservative multipliers for the EM. The applicant also argued that the LST data were useful for validating the WGOTHIC code in the short and long term. The staff sees the essentially steady-state LST data as having a more limited role in validating the transient WGOTHIC EM. Section 21.6.5.5.4.3 of this report discusses the role of the LST data in the scaling evaluation.

21.6.5.5.4.1 Scaling Analysis to Support the PIRT

The scaling evaluation provided information to support PIRT rankings in the form of the pressure rate of change equation, which was derived from first principles and applied to two limiting scenarios, the double-ended cold-leg LOCA and the MSLB. The dimensionless form of the pressure rate of change equation contains **π** groups whose relative magnitudes were used to assist in ranking phenomena. The conservation of mass and conservation of energy equations are also placed into dimensionless form to yield mass and energy **π** groups, which were also used to assist in the development of PIRT rankings.

Usually, **π** groups are the nondimensional coefficients of the governing equations, normalized such that the largest coefficient has a magnitude equal to 1. The values of the **π** groups are then in the range of -1 to +1, and the magnitude can be used to judge the importance of the term for which a given **π** group is the coefficient. The applicant did not follow this convention consistently, so the values of some **π** groups were slightly outside of this range. Given this, the applicant did not define a numerical value criterion for what constituted the dividing line between high-, medium-, and low-ranked phenomena. A subjective approach was used for ranking, which included consideration of expert opinion, test data, and sensitivity studies, in addition to the scaling **π** group numerical values. While the range of numerical values for **π** groups was slightly outside of the conventional -1 to +1 range, this difference did not prevent the use of the scaling results to support the PIRT ranking process.

The applicant calculated values for energy transfer conductances by normalizing all conductances with respect to the shell conductance. Numerical values of the conductances ranged from 0.01–202, in terms of energy transfer to the drops (see Table 8.2 in WCAP-14845). Values of the conductances were used to determine the importance of the various heat transfer mechanisms.

Values of mass, energy, and pressure **π** groups were also calculated for the four LOCA phases and the MSLB. As noted earlier, the normalizations were not chosen to ensure that the values of all **π** groups were in the range -1 to +1. However, the largest values were on the order of 1.0. The staff used the values of the **π** groups to confirm closure between the scaling analysis and the PIRT. Basically, any phenomenon with a calculated pi-value greater than about 0.10

during any phase of the LOCA or MSLB should be ranked as medium or high in importance, and, indeed, this was the case. While the applicant correctly used other input to assist in the ranking, the consistency of PIRT and scaling was an essential element of the analysis. The staff considered the scaling analysis performed by the applicant to be an acceptable manner in which to provide information for use in developing the PIRT, and also noted that the information in the scaling analysis and the PIRT is consistent.

The pressure **π** group values revealed the overwhelming importance of two related phenomena, heat and mass transfer to the evaporating shell and to the structural heat sinks. An acceptable EM must include these phenomena in a conservative manner and be applicable at the scale of an actual plant. These phenomena were thus given special attention in the staff's evaluation, especially the shell heat and mass transfer, because this aspect of the PCS design differs from present containment designs in operating LWRs.

π group values were also calculated by the applicant for the PCS airflow momentum equation during the LOCA phases and for the MSLB. These **π** groups showed that the downcomer has a very small effect on the buoyancy, except during the long-term LOCA phase when the value of the **π** group is 0.16, compared to the combined riser and chimney **π** group value of 1.16. This value confirmed the medium ranking given to phenomenon 13A (Table 21.6.5-6 of this report), downcomer annulus PCS natural circulation, during the peak pressure and long-term LOCA phases.

The applicant compared the scaling model and WGOTHIC results for each phase of the LOCA scenario. The quantity compared was dP/dt as calculated by the scaling RPC equation and by WGOTHIC for a case without most of the EM biases. The good comparison served as a confirmation that the scaling analysis was consistent with the WGOTHIC basic model and vice versa.

21.6.5.5.4.2 Applicability of Correlations and Constitutive Relations

The new and unique aspect of the PCS is the use of the water-cooled shell to remove heat from inside containment. Other features, such as the structural heat sinks and the large pressure-reducing volume, are similar to existing designs for large dry containments. The containment conditions will tend to be less mixed in the long term, due to the lack of sprays and fan coolers, so stratified and spatially varying steam concentrations could be more prevalent. It is, therefore, essential to show that the EM is conservative in its treatment of the shell and internal structures heat transfer at the scale of an actual plant.

The combination of correlations used to model condensation and evaporation heat and mass transfer across the shell were taken from engineering literature. The correlations are based on local conditions and, therefore, are independent of scale. Accordingly, these correlations can be used to model the AP1000 design. Similarity variables are used and the database includes the LST, where the complete phenomena across the shell were present and local variables were measured. As part of the conservative approach used in the EM, the applicant developed conservative multipliers to apply to the condensation heat and mass transfer (0.73) and to the evaporation heat and mass transfer (0.84), as discussed in Section 21.6.5.6.5.3 of this report.

The staff concurs that this model is appropriate for application to the applicant's passive containment cooling design. With the factors of conservatism applied by the applicant to obtain an EM, the correlations for heat and mass transfer across the shell are acceptable, assuming that the local conditions at the shell wall and in the riser are calculated in a conservative manner.

The containment atmosphere is considered to be homogeneous if the steam and noncondensable gas concentrations are uniformly distributed. Well-mixed conditions are nearly homogeneous, but may have small temperature gradients which drive natural circulation towards greater homogeneity. If the containment atmosphere approaches a well-mixed condition, lumped-parameter models, including WGOTHIC, will provide a reasonable prediction of the bulk steam concentration. The staff accepts that the break flow will be sufficient to mix the atmosphere during the LOCA blowdown and MSLB blowdown in the AP1000; therefore, a well-mixed assumption is appropriate. In this case, the shell heat and mass transfer model is acceptable at the scale of an actual plant.

For the LOCA, the containment will eventually stratify and will not be well mixed. However, as long as WGOTHIC can predict the bulk steam concentration in the nodes adjoining the shell, the heat transfer model will be conservative and applicable at the scale of an actual AP1000 plant. The lumped-parameter model characteristically gives conservative results for peak pressure because it does not include some of the mechanisms which drive the containment atmosphere to a homogeneous state (e.g., molecular diffusion, turbulent mixing, and plume dynamics). In a lumped-parameter model, a pressure gradient is needed to drive steamflow from the source to the condensing surfaces. While the mixing process is overpredicted within a lumped node, it is typically underpredicted between nodes, resulting in an overall conservative prediction of the steam concentration at condensing surfaces removed from the break. As discussed in Section 21.6.5.7.5 of this report, this conservatism is evident from lumped-parameter analysis of test data, such as HDR.

The bottom-up, component-level evaluation of the individual phenomenological models included in the pressure rate of change equation is a key element of the scaling evaluation. A number of models, in addition to the shell heat and mass transfer model, are included. Similarity variables are used to characterize the constitutive relations and correlations. The use of similarity variables is important because such variables include the effect of scale. In other words, if the data which support a correlation include the range of similarity variables necessary for the passive containment cooling design, then the correlation is applicable.

Because the LST integral tests are distorted relative to the AP600, arguments of applicability to the AP600 based on top-down scaling were weak. Therefore, the applicability of the EM hinges on the bottom-up scaling and the demonstration of a conservative approach.

While scaled testing and validation of a best-estimate model using the scaled test data is a preferred approach to demonstrating that maximum pressure design criteria are met, there are other acceptable approaches. The staff accepts that a conservative EM is an acceptable approach to performing design-basis analysis for the applicant's passive containment cooling design.

Testing and Computer Code Evaluation

The staff accepts that the heat and mass transfer correlations used in the scaling analysis are appropriate because the applicant has shown that the database (see Section 21.6.5.6 of this report) covers the range of similarity variables for the AP1000. The staff also accepts, based on the information provided, that the WGOTHIC lumped-parameter model conservatively predicts the steam concentration conditions at the shell surface for the AP1000.

21.6.5.5.4.3 Use of LST Experimental Data to Support the Evaluation Model

The applicant has submitted documentation in WCAP-14135 and WCAP-14326 which describes the LST tests and the use of the LST data to support the WGOTHIC EM.

As discussed in Section 21.6.5.5.3 of this report, the applicant did not attempt to use scaled testing and WGOTHIC prediction of scaled tests to directly validate the WGOTHIC model. A conservative EM approach was used in which the applicant showed that the model was applicable, using correlations based on experimental data generally developed at smaller scales. The staff concurred that this approach was acceptable. The LST data were used in a separate-effects mode to validate the heat and mass transfer correlations used to model shell heat and mass transfer. The local-condition correlations were based on data from the literature and were compared to the LST data, which incorporated all of the shell heat and mass transfer phenomena (i.e., condensation of the inside and evaporation of the outside of the shell) in a single test. The range of variables was shown to adequately cover the range of the AP600.

The applicant has also shown that the range of variables was adequate to cover the range of the AP1000 (see WCAP-15613, Table 4.2-2, "Operating Range Comparison for AP600 and AP1000 Heat and Mass Transfer Parameters"), as shown in Table 21.6.5-8 of this report. The use of conservative correlations in which bounds were developed from data, including the LST, ensures that these important correlations in WGOTHIC will result in a conservative peak pressure analysis for the applicant's passive containment cooling design in the AP1000.

The question of whether distortions in the LST can affect the usefulness of separate-effects data obtained from this facility was also addressed by the staff. Following is a discussion of each of the 17 specific distortions identified in Section 21.6.5.5.3.3 of this report, an evaluation of why the separate-effects data were not significantly affected by the distortion, and an explanation as to why the LST could be used in a limited context to validate the WGOTHIC code. In virtually every case, the distortions affected the use of the LST as an integral system test. The effects of distortions were significant enough to make the test not useful for this purpose. However, as a separate-effects test, where only the local environment of the shell is involved, the effect of most of the system distortions was small or inconsequential.

Area to Volume Ratio

The shell surface area to containment volume ratio is eight times higher for the LST than for the AP600. This distortion could strongly affect the transport of steam from the source to the condensation surface. However, local conditions measured near the surface were made to obtain the separate-effects data. The correlation and the conservative multipliers developed from the data were based only upon the measured local conditions, not on the global conditions in the containment. Similarity variables were used in the correlations. The range of the local measured variables covers the range of the AP600. Whatever effect the distortions may have on the local conditions was irrelevant, because the conditions were measured and covered the range of the AP600.

Break Source Flow Rate

The LST was run over a range of energy release (i.e., break source) conditions. Because the test was steady-state, the heat flux through the shell varied directly with the energy release rate. The separate-effects test conditions covered a range of shell heat fluxes, which included the range for the AP600. In a transient, there are times during the blowdown when the break source magnitude considerably exceeds the energy removed through the shell. While this mismatch between the break source and the shell heat flux causes the pressure to rise, it does not affect the nature of the heat flux through the shell. Use of steady-state, separate-effects data to verify a correlation for use during a transient is an accepted practice which has proven to be widely applicable. Therefore, no distortion was involved in using the steady-state, separate-effects LST data to validate and establish bounds for a correlation used during a transient.

Shell Thickness

The LST shell is slightly over one-half the thickness of the AP600 shell. Both the thermal resistance and heat capacity of the shell are affected by thickness. However, these items have a relatively low uncertainty. Furthermore, the internal heat transmission and energy storage phenomena associated with the shell metal are well-known functions of the thickness. Accordingly, the staff concurred that for separate-effects data, the shell thickness need not be identical.

Break Source Superheat

The use of the LST data in a separate-effects mode is independent of the break source superheat. Local steam concentration measured near the wall covered the range of the AP600, despite differences in the break source enthalpy. The break source superheat was not included in the separate-effects data used. Therefore, this distortion was irrelevant.

Diffuser Used for Break Source

During a transient, the character of the break source changes from a jet during blowdown to a buoyant plume during the long-term phase. The steady-state LST tests simulated only the late phase of the event, after the end of blowdown. On a system level this was a distortion, but it did not affect the separate-effects data, which were based on measured local conditions.

No Downcomer

For purposes of the separate-effects tests, the riser flow covered a range of Reynolds numbers. The range of conditions was covered without a downcomer, so the lack of a downcomer is not a distortion. When the LST was used to obtain separate-effects heat and mass transfer data, the lack of a downcomer was not a factor because local conditions were used in the correlation. As a system test, the lack of a downcomer in the LST was a distortion. Given the limited role of the LST (i.e., as a source of separate-effects heat and mass transfer data), the lack of a downcomer was not a significant issue.

Fan-Forced Riser Air Flow

The staff agreed that for purposes of separate-effects data, it did not matter whether the airflow was forced or induced by natural circulation. Given a local velocity in the riser, it cannot be determined whether the flow is driven by natural or forced convection.

Riser Scaled 1/4

Because the LST riser width was 1/4 scaled instead of 1/8 scaled, as was the rest of the test facility, the Reynolds number range for the separate-effects data covers Reynolds numbers up to about one-half of the AP600. Over the range of Reynolds numbers covered, the distortion had no effect. Because the applicant uses a standard forced-convection evaporation correlation, the staff accepted that the range of Reynold numbers not covered by the LST was adequately covered by other data sources.

No Circulation below Deck

The correlation validated by the separate-effects data did not depend on the circulation between the steam generator compartment, where the break occurred, and the other below-deck compartments. Therefore, this distortion did not affect the use of the LST for separate-effects data.

External Water Flow Too High

The range of external water flow rates in the LST covered the range of the AP600. Thus, the local conditions on the external shell surface were not distorted compared to the AP600. Accordingly, the data were acceptable for validating the steady-state correlation.

External Water Coverage Too High

The LST data were used to validate the total clime heat transfer package in a separate-effects mode. Local measurements were used, so water coverage fraction was not a variable used in validation of the clime package.

External Water Flow Was Established Before Break

Steady-state data can be used to validate a correlation for use during a transient. This is an accepted practice which has proven to give accurate results. The change in local conditions on either side of the shell is slow enough for the heat and mass transfer processes at the shell surfaces to be regarded as quasi-steady-state.

External Water Flow Time Variations

While flow fluctuations were an undesirable feature of the LST, the applicant minimized their effect on the separate-effects data by the data analysis techniques used. First, the flow did not cycle uniformly. Rather, a short, reduced-flow phase recurred periodically. The reduced-flow phase of the cycle was only a small fraction of the total cycle. The separate-effects data were averaged over several cycles of the flow variation, the data were evaluated with both minimum and maximum flow rates, and a data analysis approach was adopted which minimized the measured heat and mass transfer. The flow fluctuations added some level of increased uncertainty and scatter to the data, but they did not preclude the use of the data in a separate-effects mode. The applicant adjusted for the increased uncertainty by treating the correlation comparisons conservatively.

External Water Not Applied by Weirs

At the location where measurements were made to obtain the separate-effects data, the effect of the manner of application of the water film was dissipated. Therefore, this was not a distortion.

Internal Heat Sinks Not Prototypic

The separate-effects data were taken on the shell and not on the internal heat sinks. The nonprototypical features of the internal heat sinks were, therefore, not a factor from the separate-effects perspective.

Crane Rails Not the Same

The crane rail strips the liquid film from the inside shell wall, so that a new thinner film reforms below the rail. The conductance through the film is a minor component of the total thermal resistance from the inside to the outside of containment. While the crane rail can affect the local film thickness below the rail, the effect was included in the WGOTHIC model. At a system level, the lack of a crane rail was a minor distortion, but it did not affect the use of the LST for separate-effects data.

Condensate Drained Out

Draining the condensate to keep from filling up the facility did not affect the local conditions measured for the separate-effects data, because this process was physically remote from the measuring locations. Therefore, differences in the manner of accumulating and removing condensate did not distort the separate-effects data.

The applicant argued that the LST data could be used to qualify the WGOTHIC model in the short and long term. Given the steady-state nature of the LST versus the transient nature of the AP600 pressurization, the significant number of distortions in the LST, and the lack of up-front scaling, the staff believed that the LST data were of little value in directly validating WGOTHIC from a system perspective. The prediction of LST steady-state data, however, provided evidence that the WGOTHIC coding of heat and mass transfer correlations for the shell was correct.

The LST was used to obtain separate-effects data for use in validating correlations available in the literature and for placing conservative multipliers on those correlations. Use of the LST data to validate the local-condition correlations did not call for the same fidelity in all of the dimensions that would be required for a system-level scaling. Therefore, issues such as the LST height of 6.1 m (20 ft) versus a scaled height of 7.2 m (23.7 ft), and differences of 1–3 percent in the free volumes of various below-deck compartments, were not significant, in light of the more limited use of the LST data. Similarly, it was not necessary for the LST to produce measurements of the 3-D spatial distribution of noncondensable gases. The local measurement of noncondensable gas concentration was sufficient for the limited separate-effects data use.

The applicant's use of the LST data in a separate-effects mode did not employ measurements of the local velocity field. The data were used to validate a local-condition, turbulent free-convection correlation for heat and mass transfer, which did not involve velocity.

The spatial identity of the source of condensate could not be determined with any degree of accuracy in the LST. Condensate was collected into only two reservoirs from five locations. For the purpose of using the LST as a system test to validate WGOTHIC, this would be a major shortcoming. Given that the LST data were not being used for this purpose, lack of spatial distribution information on condensation was not a concern.

21.6.5.5.5 Summary

Based on the above, the staff has determined that the applicant's passive containment cooling design PIRT identifies the significant phenomena important to the evaluation of the PCS and the containment pressure response to DBAs. Because the LST was only used as a separate effects test facility, the distortions in the LST as a scaled test facility was no longer a concern.

The staff has determined that the PCS scaling analysis, combined with sensitivity studies presented in WCAP-14407 for the AP600 (and WCAP-15846 for the AP1000), supports the ranking of the phenomena in the AP1000 PIRT. In addition, the scaling analysis verifies that the mass and heat transfer correlations used in the WGOTHIC computer program to represent the PCS are appropriate for evaluating the containment pressure response following a DBA for the AP1000.

The scaling analysis also identified distortions in the LST that would make it difficult to use the data for direct comparison to an actual plant. The LST distortions have been addressed by the applicant in an acceptable manner through the development of the conservative EM. In view of the above, the staff has determined that the use of the LST to support the mass and heat transfer correlations used in the WGOTHIC computer program to represent the PCS is acceptable for the AP1000 design.

21.6.5.6 WGOTHIC Validation and Test Studies and Assessment

The advanced light-water reactor (ALWR) PCS design differs from past and current nuclear plant designs. This containment design concept represents one of the changes towards a simple, passively safe plant design, as permitted by 10 CFR Part 52.

The plant design utilizes a PCS to transfer heat from the containment shell to the environment following an accident. The PCS is designed to remove sufficient heat from containment during the limiting DBA to maintain containment pressure below the design limit, and to maintain the pressure at an acceptably low value in the long term.

The function of the PCS, in the applicant's passive containment cooling design, is to provide a safety-grade means for transferring heat from the containment to the environment following postulated events that result in containment heatup and pressurization. The applicant's passive containment cooling design utilizes passive cooling of the freestanding steel containment vessel. Heat is transferred to the inside surface of the steel containment vessel by convection and condensation of steam, and through the steel wall by conduction. Heat is then transferred from the outside containment surface by free convection to the air that enters an annular space around the steel containment shell. Cooling of the containment is enhanced by water distributed over the containment surface, heated, and then evaporated into the air stream. The heated air and water vapor rises by natural draft and exits the shield building through an outlet (chimney) located above the containment shell.

The performance of the PCS depends on the buoyant driving force of the cooling air, the airflow path pressure losses, the effective containment shell heat transfer coefficient, and the wetted PCS heat transfer area. Other factors that can influence PCS performance are wind conditions, nearby buildings and topography, inside-containment circulation patterns, water distribution patterns, and the effects of noncondensable gases inside the containment.

Key concepts and principles were evaluated by the applicant, and developed into a definition of an overall matrix of testing necessary to obtain the data in support of the design. When data were lacking, small basic research tests were conducted to demonstrate fundamental principles and feasibility of concepts. Based on these tests, larger and more sophisticated tests were designed to further evaluate the engineering and safety concepts of the design. The PCS LST facility is one example of this approach. To assess the PCS heat removal capability, a testing program was prepared that included the following series of tests:

- AP600 PCS wind tunnel test (Sections 21.3.7, 21.4.1, and 21.5.9)
- AP600 PCS water distribution test (Sections 21.3.9, 21.4.3, and 21.5.11)
- AP600 heated-plate test (Section 21.6.5.6.2.4)
- AP600 small-scale containment cooling test (Section 21.6.5.6.6.1)
- AP600 large-scale PCS test (Section 21.6.5.6.6.2)
- AP600 PCS airflow path pressure drop test (Section 21.6.5.6.6.3)

Testing and Computer Code Evaluation

21.6.5.6.1 Overview of Experimental Database

The staff reviewed the heat and mass transfer correlations, documented in WCAP-14326, Revision 2, “Experimental Basis for the AP600 Containment Vessel Heat and Mass Transfer Correlations,” issued April 1998.

The objective of the applicant’s evaluation of the separate-effects tests was to validate the correlations that can be used to calculate energy transfer, by heat and mass transfer, between the containment atmosphere and the external PCS airflow path, and between the PCS airflow path and the baffle, shield, and chimney. The correlations selected by the applicant represent the common phenomena of convective heat transfer and condensation and evaporation mass transfer.

The study included the following objectives:

- Identify the appropriate correlations for the various heat and mass transfer regimes for the PCS surfaces.
- Compare these correlations to separate-effects tests that cover the range of dimensionless parameters expected for PCS operation.
- Evaluate correlation uncertainties.
- Develop biases that can be applied to the correlations to bound the test data for use in licensing analyses, consistent with the conservative EM.

The correlations for heat and mass transfer developed for use in the EM were defined consistent with the way energy transfer was modeled across the containment shell and in the PCS airflow path. The EM energy transfer was calculated as follows:

- With condensation or evaporation, a liquid film is present. Energy is transported between the bulk gas and the liquid film free surface by radiation heat transfer, convection heat transfer, and mass transfer. Energy is transported by conduction through the liquid film to the solid surface.
- Dry surfaces do not have liquid films or mass transfer. Energy is transported between the bulk atmosphere and the solid surface by radiation heat transfer and convection heat transfer.
- The correlations assume the local bulk gas thermodynamic states are known both inside and outside containment. In the PIRT evaluation, WCAP-14812, phenomena that influence the distribution of bulk gas properties are evaluated separately to develop an overall conservative approach.

The Westinghouse PIRT and scaling analysis showed that condensation inside containment and evaporation outside containment are the dominant, high-importance transport phenomena for calculating containment pressure during a DBA. Heat transfer inside and outside containment and conduction through the liquid film were identified to be of low-to-moderate importance, but require correlations because they are included in the EM.

The McAdams free-convection and Colburn forced-convection heat transfer correlations were used by the applicant to model the PCS. The method recommended by Churchill was used to combine the free- and forced-convection correlations in the mixed-convection regime. The lower limit on the mixed-convection correlation for assisting free and forced flows was based on work by Eckert and Diaguila (Eckert, E.R.G., Diaguila, A.J., "Convective Heat Transfer for Mixed, Free, and Forced Flow Through Tubes," Transactions of the ASME, May 1954). The resulting single heat transfer correlation reduced to free-convection values at low Reynolds numbers, forced-convection values at low Grashof numbers, and a combination of the two for mixed convection. The mass transfer correlation was derived from the Nusselt number using the heat and mass transfer analogy. The Chun and Seban correlation for heat transfer by wavy laminar and turbulent conduction was used for both condensing and evaporating liquid films.

WCAP-15613, Table 4.2-2, "Operating Range Comparison for AP600 and AP1000 Heat and Mass Transfer Parameters," summarizes the expected operating range for the AP600 and AP1000 heat and mass transfer parameters, as determined by the WGOTHIC analyses, and the ranges covered by the applicant's test program. The test program covers the expected operating ranges.

21.6.5.6.1.1 Heat Transfer in the PCS Air Annulus Region

The flow regime for turbulent convective heat transfer is typically qualified as either free, forced, or mixed. The combination of free and forced convection in the mixed regime is either assisting (they work in the same direction, as in upward flow in a hot pipe) or opposed (they work against each other, as in downward flow in a hot pipe). Operating points for the AP600 air annulus region for the Grashof and Reynolds numbers were calculated in the scaling analysis for the PCS airflow path (downcomer, riser, and chimney) and plotted on a Metais and Eckert diagram to determine the heat transfer regime. The comparisons indicated that the riser and downcomer would operate in forced convection, and the chimney would operate in mixed convection. The convective heat transfer in the air annulus was expected to be turbulent rather than laminar because the Reynolds numbers were all greater than 3000.

Based on a review of the literature by the applicant, the turbulent free-convection heat transfer correlation for gas mixtures has the form $Nu = C(GrPr)^N$, with the value of C varying between 0.09 and 0.15 and the value of N varying between 0.3 and 0.4. The McAdams correlation with C = 0.13 and N = ⅓ was selected by the applicant for calculating turbulent free-convection heat transfer in the annulus:

$$Nu_{free} = 0.13(Gr_d Pr)^{1/3} \qquad \text{McAdams correlation} \quad \text{(Eq. 21.6.5.6.1)}$$

This correlation is widely used to calculate turbulent free-convection heat transfer from both vertical and inclined surfaces with either constant temperature or constant heat flux boundary conditions. The hydraulic diameter is the characteristic length in the Grashof (Gr_d) and Nusselt numbers. Based on the experimental work of Vliet (Vliet, G.C., “Natural Convection Local Heat transfer on Constant-Heat Flux Inclined Surfaces,” Journal of Heat Transfer, November 1969), the full gravitational acceleration is used by the applicant to evaluate the Grashof number and not just the vector component parallel to the plate.

The Colburn correlation was selected by the applicant to calculate the turbulent forced-convection heat transfer in the annulus:

$$Nu_{force} = 0.023 Re_d^{4/5} Pr^{1/3}$$ Colburn correlation (Eq. 21.6.5.6.2)

The Colburn correlation is applicable to both constant temperature and constant heat flux boundary conditions for fully developed flow in channels. The correlation is widely used to calculate turbulent forced-convection heat transfer in long tubes and ducts. The hydraulic diameter is the characteristic length in the Reynolds (Re_d) and Nusselt numbers.

A length- or distance-dependent multiplier can be used to account for the increase in forced-convection heat transfer as the boundary layer develops at the entrance of a heated channel. This is an important consideration when modeling heat transfer in short channels. Section 21.6.5.6.1.2 of this report describes the entrance effect multiplier in more detail.

Based on the Metais and Eckert diagram shown in Figure 4-1 of WCAP-14845, the turbulent-opposed, mixed-convection correlation, Equation 21.6.5.6.3, is used for the downcomer and chimney. Under opposed convection (downflow along a heated surface or upflow along a cooled surface), the mixed-convection correlation increases the value of the predicted Nusselt number over the value predicted using either the free- or forced-convection correlations alone. The outside surface of the containment shell is expected to operate in turbulent-assisted convection (upflow along a heated surface or downflow along a cooled surface) during a DBA.

Churchill recommended a method for combining separate free- and forced-convection heat transfer correlations into a single correlation that covers free, mixed, and forced convection. The applicant used this recommended method. For turbulent-opposed free and forced convection,

$$Nu_c = (Nu_{free}^3 + Nu_{force}^3)^{1/3}$$ (Eq. 21.6.5.6.3)

and for turbulent-assisted free and forced convection, Nu_c is the larger of the following three expressions:

$$[abs(Nu_{free}^3 - Nu_{force}^3)]^{1/3} \quad ; \quad Nu_{free} \quad ; \quad 0.75 Nu_{force}$$ (Eq. 21.6.5.6.4)

Consistent with experimental data trends (laminar and turbulent) presented by Churchill, the sign between Nu_{free} and Nu_{force} is reversed in both of these equations relative to the formulations for laminar flow. The lower limit in the latter equation, which prevents the value of Nu_c from going to zero when Nu_{free} and Nu_{force} are equal, comes from Eckert and Diaguila.

As the angles of inclination approach horizontal, the assisted- and opposed-convection heat transfer coefficients should become equal. Although the correlations used for the applicant's passive containment cooling design do not provide for this, the applicant does address it acceptably in the EM in the following manner:

- Only free convection is assumed inside containment, so the definition of mixed convection is not relevant inside containment.

- The downcomer and chimney have too little horizontal surface area and too little heat and mass transfer to be a concern.

- Below the first water distribution weir on the containment dome, the slope is greater than 30°, so opposed and assisting convection are well defined. Above the first weir, the liquid film is subcooled. Therefore, with little or no evaporation, and with the surface area less than 4 percent of the total shell areas, regions with shallow slopes are not a significant concern for the external containment shell.

21.6.5.6.1.2 Entrance Effects

The heat transfer coefficient at the entrance to a heated channel is significantly higher than the fully developed value predicted by the Colburn forced-convection heat transfer correlation. The increase in heat transfer at the entrance is attributed to the thinness of the boundary layer that develops with distance from the entrance. The entrance effect is important for modeling heat transfer in short channels, and is used by the applicant for the test data comparisons. Because the net entrance effect for the long riser channel is only a small increase in heat transfer, the applicant concluded that entrance-effect multipliers may reasonably be neglected for licensing calculations (see Section 21.6.5.6.1.2.2 of this report).

21.6.5.6.1.2.1 Entrance Effects for Use in Separate-Effects Tests Evaluations

The entrance-effect correlation and coefficients used by the applicant to assess the short-channel experiments are those recommended by Boelter, Young, and Iverson (Boelter, L.M.K., Young, G., Iverson, H.W., NACA-TN-1451, 1948). Entrance effects are not appropriate for, and are not applied to, free convection or the free-convection portion of the mixed-convection heat transfer correlations.

The heat and mass transfer correlations calculated with entrance effects were compared to the results for each of the five separate-effects heat transfer tests (see Sections 21.6.5.6.2.1 to 21.6.5.6.2.5 of this report) and to the three separate-effects mass transfer tests (see Sections 21.6.5.6.3.1 to 21.6.5.6.3.3 of this report). The comparisons showed that the heat or mass transfer coefficients, as represented by the Nusselt and Sherwood (Sh) numbers, were underpredicted by 2 to 14 percent in 6 of the data sets, overpredicted by 3 percent in 1 (Eckert and Diaguila tests, Section 21.6.5.6.2.2), and overpredicted by 18 percent in 1 (Hugot tests, Section 21.6.5.6.2.1). The overprediction in the Hugot tests is reduced to 10 percent if the heat transfer at $x/d_h < 1.0$ is not included in the comparisons. The multipliers become large and increasingly uncertain for $x/d_h < 1.0$. These comparisons show that, overall, the entrance-effect multipliers improve the agreement between the test data and the analytical heat or mass transfer predictions for these short-channel tests.

21.6.5.6.1.2.2 Entrance Effects for Use in the Evaluation Model

The riser channel differs from the test geometries because of the 1.8-m (6-ft) well, or turning region at the bottom of the baffle. For modeling simplicity, the applicant used a fully developed heat transfer coefficient over the full channel height. An evaluation by the applicant showed that the heat transfer decrease (relative to fully developed heat transfer) was more than offset by the heat transfer increase as a result of neglecting the entrance effect in the channel above the well, leading to a conservative model for use in the licensing analyses.

Heat Transfer in the Well Region below the Baffle

The annular duct created by the baffle starts 1.8 m (6 ft) above the bottom of an annular well. This well is about 1.4 m (4.5 ft) wide and is heated on the inside surface. In the EM, it is assumed, for simplicity, that the forced-convection heat transfer correlations used in the annular region can also be applied within this region. It would be more realistic to assume a free-convection heat transfer relationship on the heated containment shell side of the well region.

Although the upper half of the 1.8 m (6 ft) height may undergo transition to turbulent free convection, the laminar free-convection correlation is used for licensing analyses. That model predicts lower heat transfer coefficients. The effect of using forced convection in the 1.8-m (6-ft) well is evaluated by comparing the total heat transfer calculated with laminar free convection in the well to the total heat transfer calculated with forced convection everywhere.

The empirical formula of McAdams was chosen for the laminar free convection mean Nusselt number and is a function of the distance-dependent Rayleigh number (Ra_x):

$$\overline{Nu} = 0.555(Ra_x)^{1/4} \qquad \text{(Eq. 21.6.5.6.5)}$$

The Nusselt number used for forced-flow convection is calculated using the Colburn relationship (Eq. 21.6.5.6.2).

The evaluation was performed for both wet and dry containment surfaces at temperatures between 52 °C (125 °F) and 96 °C (205 °F) for annular flow velocities of 0.3, 2.1, and 6.1 m/sec (1, 7, and 20 ft/sec). The air temperature was set at 46 °C (115 °F), consistent with the EM used for the licensing analyses. The maximum effect was expected to be a 5.6-percent reduction in the net heat transfer from the shell because of the assumed laminar heat transfer below the baffle.

Entrance Effects in the Riser Annulus

The heat transfer enhancement resulting from the developing thermal profiles model selected by the applicant is based on eigenvalue solutions from Hatton and Quarmby (Hatton, A.P., Quarmby, Alan, "The Effect of Axially Varying and Unsymmetrical Boundary Conditions on Heat Transfer with Turbulent Flow Between Parallel Plates," Inter. Journal of Heat Transfer, 1963) for the developing thermal distribution within a hydrodynamically developed flow in an annulus. While the analytical solutions are quite complex, charts have been presented for enhanced heat transfer for Reynolds numbers of 7,100, 73,600, and 495,000 at Prandtl numbers of 0.1, 1.0, and 10.0. The Prandtl number is very nearly unity and the riser Reynolds number ramps to 189,000. For reference, a velocity of 2.1 m/sec (7 ft/sec) yields a Reynolds number of about 70,000.

The evaluation showed that on the average, for a Reynolds number of 73,600 and a Prandtl number of 1.0, the heat transfer over the first 18.3 m (60 ft) of the annulus will exceed the fully developed value by 14.7 percent. The average heat transfer coefficient increase over the 29.3-m (96-ft) length is 7.9 percent. The same calculation for a Reynolds number of 7,096 develops a heat transfer increase of 8.7 percent and, at 495,000, a 10.8-percent increase. The reason for the increase at the higher Reynolds number is that the thermal profile does not become fully developed in the PCS annulus region.

Conclusions

The heat transfer enhancement of 8 to 11 percent due to the entrance effect would more than offset the heat transfer degradation of approximately 6 percent due to free convection in the well.

The reduction and enhancement calculations are conservative for the following reasons:

- The presence of a turbulent eddy within the well region will disrupt the free-convection boundary layer and increase the heat transfer.

- Any deviation of the velocity profile from the profile for fully developed turbulent conditions at the entrance to the annulus will also increase the heat transfer.

The calculations show that it is conservative to neglect the free convection below the baffle and the entrance effects in the PCS riser channel, and to simply use a heat transfer correlation for fully developed turbulent flow over the full height from the bottom of the well to the first weir.

As discussed in Section 21.6.5.4.2.1 of this report, a design change to relocate the upper annulus drains from the upper annulus floor to a position about 0.3 m (1 ft) above the floor was evaluated by the applicant to confirm that the entrance treatment in the WGOTHIC EM was unaffected.

21.6.5.6.1.3 Heat Transfer Inside Containment

Heat is transferred from the containment atmosphere to the containment inner shell surface by condensation, radiation, and convection. The containment calculations assume condensation and convective heat transfer take place at the outer surface of a thin liquid film that develops on the inside surface (the condensate film) of the containment vessel. The liquid film provides a relatively small, additional resistance to heat transfer from the containment atmosphere to the wall. Heat transfer through the liquid film is characterized by the film Reynolds and Prandtl numbers.

On the basis of the applicant’s scaling studies (see WCAP-14845), the inside of the containment shell is expected to experience a high-velocity flow of steam and air during an MSLB event and during the blowdown phase of a large LOCA event as the break jet vigorously circulates the gas. The heat and mass transfers during this period are expected to be turbulent forced or mixed convection. After the LOCA blowdown is complete, the atmosphere is circulated less vigorously and the velocity of the steam and air flowing along the inside surface of the containment shell will be lower. This indicates that turbulent free-convection heat and mass transfer is appropriate after blowdown. The inside of containment is conservatively modeled using turbulent free convection throughout both the MSLB and the LOCA transients used for licensing analyses.

The height-based Grashof number representing the lower limit for turbulent free-convection heat transfer is approximately 10E10. After the first few seconds of the transient, the height-based Grashof number is greater than 10E10 over all but the lower 1.8 m (3 ft) (or less) of the interior shell surface. Because the turbulent free-convection heat transfer correlation underpredicts laminar free-convection heat transfer, its use is conservative over the lower 1.8 m (3 ft) of the interior shell surface.

The McAdams correlation was selected for calculating turbulent free-convection heat transfer inside containment. The correlation can be written as a function of local properties:

$$h_{free} = 0.13\frac{k}{L}(Gr_L Pr)^{1/3} = 0.13\frac{k}{(v^2/g)^{1/3}}[\frac{\Delta\rho}{\rho}]^{1/3} Pr^{1/3} \qquad \text{(Eq. 21.6.5.6.6)}$$

where h is the heat transfer coefficient
k is the thermal conductivity
v is the kinematic viscosity
g is the gravitational acceleration
$(v^2/g)^{1/3}$ has units of length

The term $(\Delta\rho/\rho)$ is the difference between the bulk density and the surface density, divided by the bulk density. The term $(v^2/g)^{1/3}$ has units of length and is used in the scaling analysis (see WCAP-14845). Consistent with Vliet, *g* is not reduced by the sine of the slope from the horizontal.

21.6.5.6.1.4 Liquid Film

The containment calculations assume that the liquid film is a distinct control volume with mass transfer, convection heat transfer, and radiation heat transfer into the free surface, and conduction to the solid surface. Heat is transferred through the thin films on both the inside and outside of the containment shell. The Chun and Seban correlation is used by the applicant to model both wavy laminar and turbulent heat transfer across the film. For wavy laminar films,

$$Nu = 0.822 Re^{-0.22} \qquad \text{(Eq. 21.6.5.6.7(a))}$$

For turbulent films (with Re > 5800 $Pr^{-1.06}$),

$$Nu = 0.0038 Re^{0.40} Pr^{0.65} \qquad \text{(Eq. 21.6.5.6.7(b))}$$

21.6.5.6.1.5 Mass Transfer Inside and Outside Containment

Convective mass transfer is a result of a concentration gradient between a flowing steam-air gas mixture and a surface. The steam concentration gradient is approximated as the difference in steam partial pressure between the bulk gas and liquid surface. Condensation occurs when the bulk gas steam concentration is greater than the concentration at the surface of the liquid. Evaporation occurs when the bulk gas steam concentration is less than the concentration at the surface of the liquid. The applicant used the definition of the steam mass flux between the surface and the bulk gas, based on work by Kreith:

$$m''_{stm} = k_g M_{stm} (p_{stm,srf} - p_{stm,bulk}) \qquad \text{(Eq. 21.6.5.6.8)}$$

where m''_{stm} is the condensing or evaporating mass flux
k_g is the mass transfer coefficient
M_{stm} is the molecular weight of the steam
$p_{stm,srf}$ is the steam partial pressure at the interface
$p_{stm,bulk}$ is the steam partial pressure in the bulk gas mixture

The mass transfer coefficient, K_g, can be predicted using empirical correlations similar to those for the convective heat transfer coefficient, h_c. The Sherwood number for mass transfer is analogous to the Nusselt number for heat transfer, and it is derived from the Nusselt number using the heat and mass transfer analogy,

$$Sh = \frac{Nu}{(Pr/Sc)^{1/3}} \qquad \text{(Eq. 21.6.5.6.9)}$$

where Sc is the Schmidt number.

The mass transfer coefficient for the gas phase mass transfer is defined as

$$k_g = \frac{h_c P D_v}{R T P_{lm}} \left(\frac{Sc}{Pr}\right)^{1/3} \qquad \text{(Eq. 21.6.5.6.10)}$$

where P is the total pressure
D_v is the air-steam diffusion coefficient
R is the universal gas constant
T is the absolute boundary layer temperature, $(T_{surf} + T_{bulk})/2$
P_{lm} is the log mean partial pressure of the air,
$(p_{air,bulk} - p_{air,surf})/\ln(p_{air,bulk}/p_{air,surf})$

P_{lm} accounts for the change in heat transfer at high mass transfer rates. The Nusselt number is based on the heat transfer correlation evaluated at the boundary layer temperature. The properties in the Prandtl and Schmidt numbers are evaluated at the boundary layer temperature. Equation 21.6.5.6.10 is used to calculate both condensation and evaporation mass transfer. Boundary layer properties are evaluated at the mean of the bulk and surface conditions.

21.6.5.6.1.6 Thermal Properties

All of the thermal properties used in the heat and mass transfer correlations are represented by correlations having an estimated accuracy of 1 percent, with the exception of the air-steam diffusion coefficient. The condensation and evaporation mass transfer are linearly proportional to the air-steam diffusion coefficient. The diffusion coefficient correlation that is used in WGOTHIC overpredicts the measured diffusion data from the literature and, hence, overpredicts the mass transfer rates by approximately 10 percent over the containment temperature range of approximately 38 °C (100 °F) to 149 °C (300 °F). However, the applicant used a mass transfer bias factor for the EM licensing analyses that offsets the diffusion correlation bias. Comparisons of WGOTHIC computer program predictions to test data led to the development of such bias.

The diffusion coefficient correlation used by the applicant is from Eckert and Drake (Table B-9, page 787). The Eckert and Drake correlation was compared to three data sets: (Kestin, J., et al., J. Phys. Chem. Ref Data, 13, 229, 1984), Rohsenow (Rohsenow, W. M., Hartnett, J. P., Handbook of Heat Transfer, 1973) and Eckert and Drake data. The applicant concluded from these comparisons that the model overpredicts the air-steam diffusion coefficient by approximately 10 percent. A comparison of the Eckert and Drake correlation to the theoretical development presented by Bird, Stewart, and Lightfoot (Bird, R.B., Stewart, W.E., Lightfoot, E.N., Transport Phenomena, 1960) shows that the diffusion coefficient is proportional to 1/P. Although data were not included at higher pressures to support 1/P, the references agree on the expected 1/P pressure dependence. The correlations all give the temperature dependence to be T^n, where n is greater than 1.5. The theoretical development of Bird recommends temperature exponents of 2.334 for water vapor diffusing through a nonpolar gas, and 1.823 for two nonpolar gases (water is a polar gas and air is nonpolar). However, the Eckert and Drake value of n = 1.81 in the correlation appears to represent the measured temperature dependence very well. The applicant concluded that the correlation properly represents the diffusion coefficient sensitivity to temperature change. In view of the above, the staff accepted the Eckert and Drake correlation for evaluating this diffusion coefficient.

21.6.5.6.2 Separate-Effects Heat Transfer Tests

21.6.5.6.2.1 Hugot Mixed-Convection Heat Transfer Tests

The Hugot mixed-convection heat transfer tests were conducted on a set of symmetrically heated, parallel, vertical, isothermal plates with closed sides. (Hugot, G., "Study of Study Natural Convection Between Two Plane, Vertical, Parallel, and Isothermal Plates," derived from doctoral dissertation University of Paris, 1972, translated by D.R. de Boisblanc, Ebasco Services Incorporated, June 1991.) The channel width was 1.0 meter (3.28 ft), the channel height was 3.3 m (10.83 ft), and the plate separation distance was variable at 10 to 60 cm (3.94 to 23.62 in.). The plate temperatures varied between 40 °C (104 °F) and 160 °C (320 °F).

The Hugot report presented the local heat transfer coefficient, but did not report the airflow rate or velocity induced in the heated channel; therefore, it was necessary to use a computer model to calculate airflow rates, as well as heat transfer. The tests were modeled by the applicant using the WGOTHIC code with nominal inputs. WGOTHIC calculated the buoyancy-induced air velocity, air temperature, and heat transfer coefficients. The calculations assumed a combined entrance and exit form loss of 1.5. Because the airflow rate was calculated and the channel loss coefficient was estimated to be 1.5, the heat transfer calculation includes the effect of uncertainties on the airflow rate.

The Nusselt number is defined as $Nu = hd_h/k$, where d_h is the channel hydraulic diameter. Entrance-effect multipliers, as described in Section 21.6.5.6.1.2 of this report, were used for the purpose of evaluating the experimental data. However, entrance-effect multipliers are not used in the containment EM. The test data validated the assisted-mixed-convection heat transfer for moderate Reynolds and Grashof numbers, i.e., Gr_d in the range from 2.4E09 to 4.7E09, and Re_d in the range from 1.1E04 to 3.5E04.

21.6.5.6.2.2 Eckert and Diaguila Mixed-Convection Heat Transfer Tests

Eckert and Diaguila conducted heat transfer tests on a vertical tube that was 4.1 m (13.5 ft) high with a 59.1-cm (23.25-in.) inside diameter. Inlet and outlet air pipes and dense screens were located at each end. A 3-m (10-ft) steam jacket supplied slightly superheated steam as the heat source. Sixteen condensation chambers collected and piped condensate to a station where the flow rate was measured and the local heat flux was determined. An airflow at approximately 27 °C (80 °F), at pressures from 1 atmosphere to 680 kPa (99 psia), was forced through the test section. Tests were conducted with forced flow in both the upward (assisted-mixed-convection) and downward (opposed mixed convection) direction. Thermocouples at the tube center and in the tube wall provided a temperature difference from which the local heat transfer coefficient could be determined.

The Nusselt number is defined as $Nu = hd_h/k$, where d_h is the hydraulic diameter. As in the Hugot evaluation, the applicant incorporated a model to account for entrance effects, as described in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. However, entrance-effect multipliers are not used in the containment EM. The mixed-convection Nusselt numbers were calculated as described in Section 21.6.5.6.1.1 of this report. The test data were used to validate the mixed-convection heat transfer correlation at prototypic Reynolds and Grashof numbers. For the tests, the $Gr_d Pr$ value range was 6.9E09 to 7.2E10, and the Re_d range was 3.6E04 to 3.8E05.

21.6.5.6.2.3 Siegel and Norris Mixed-Convection Heat Transfer Tests

Siegel and Norris conducted heat transfer tests on a set of symmetrically heated, parallel, vertical flat-plate channels. (Siegel, R., Norris, R.H., “Test of Free Convection in a Partially Enclosed Space Between Two Heated Vertical Plates,” Journal of Heat Transfer, April 1957.) The channel width was 1.346 m (4.417 ft), the channel height was 1.778 m (5.833 ft), and the plate separation distance ranged from 3.8 to 38 cm (0.125 to 1.25 ft). A constant uniform heat flux of approximately 3500 W/m^2 (1100 $Btu/hr\text{-}ft^2$) was applied.

The L/d_h ratio ranged from 3 to 24. Convection was treated as assisted mixed convection. The predicted Nusselt number matched the experimental values fairly well at low L/d_h, but the experimental values increasingly underpredicted the Nusselt number as L/d_h was increased. The effects of reduced airflow were also investigated by adding extensions to the bottom of the test section channel and successively decreasing the lateral area for flow into the test section. Only those tests that had the test section open at the bottom were examined for comparison. Four tests were performed at constant L/d_h to study the effects of progressively increasing the loss coefficient from 1.5 to 35.6. The Nusselt number was increasingly underpredicted as flow was reduced.

Because the airflow rate was not given, the tests were modeled using the WGOTHIC computer program. WGOTHIC calculated the velocity, air temperature, and heat transfer coefficients. The effects of reduced airflow were analyzed by relating the flow area reduction in the test to an increase in the inlet loss coefficient.

The Nusselt number is defined as $Nu = hd_h/k$, where d_h is the hydraulic diameter. The applicant incorporated a model to account for entrance effects, as described in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. However, entrance-effect multipliers are not used in the containment EM. The predicted Nusselt number matched the experimental values fairly well at low L/d_h, but the experimental values still increasingly underpredicted the Nusselt number as L/d_h was increased. The calculated Nusselt number also increasingly underpredicted the measured values as the airflow was reduced. The mixed-convection Nusselt numbers were calculated as described in Section 21.6.5.6.1.1 of this report. The tests generated data that validated the assisted-mixed-convection heat transfer model for low Reynolds numbers and moderate Grashof numbers. For the tests, the Gr_dPr ranged from 6.43E05 to 6.1E08, and Re_d ranged from 1.65E03 to 1.13E04.

21.6.5.6.2.4 Westinghouse STC Dry Flat-Plate Tests

The applicant's dry flat-plate tests (see WCAP-12665), which were performed at the Westinghouse Science and Technology Center, provided heat transfer data for channels with heat flux and a cooling air flow rate representative of the PCS air riser annulus during a DBA.

The test section was a vertical, 1.8 m (6 ft) long, heated flat steel plate that had been coated with the highly wettable, inorganic zinc coating used in the passive containment cooling design. A clear acrylic cover provided a channel 58 cm (23 in.) wide and 10 cm (4 in.) deep for the forced airflow. The plate temperature and airflow rates were varied for each test.

The Nusselt number, defined in terms of the channel hydraulic diameter, was used for the data comparison. A length-averaged, entrance-effect multiplier of 1.13 was calculated, as described in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. However, the containment EM does not use entrance-effect multipliers. The mixed-convection Nusselt number was calculated as described in Section 21.6.5.6.1.1 of this report. The data were compared with the mixed-convection correlation and shown as a function of the Reynolds number. Because these tests were dominated by forced convection, the results correlate well with the Reynolds number. The Re_d range was 3E04 to 1E05.

The applicant evaluated the measurement uncertainties for the dry flat-plate test facility. The uncertainty in the Nusselt number is about 20 percent, with higher uncertainty for lower heat flux tests. The uncertainty reduces to about 9 percent for tests with wall heat fluxes greater than 3200 W/m^2 (1000 $Btu/hr\text{-}ft^2$).

21.6.5.6.2.5 Westinghouse Large-Scale Dry External Heat Transfer Tests

The applicant performed a series of heat transfer tests at the LST facility at Westinghouse Science and Technology Center. The purpose was to compile data for developing and validating the analytical heat transfer models for use in the WGOTHIC computer program. Circumferentially averaged, external heat transfer data were determined from the dry LST data. Section 21.6.5.6.6.2 of this report describes the LST facility.

The dry heat transfer tests were performed over a range of internal test vessel pressures that bounded the AP600 containment design pressure to obtain heat transfer data at prototypic conditions, and to characterize heat transfer over a range of air cooling velocities.

Data that varied with time, angular position, and elevation were collected for each test. Nusselt numbers were calculated from the data using measured surface-to-bulk gas temperature and heat fluxes that were averaged over time and circumferentially averaged at each measuring elevation. Bulk gas temperatures in the annulus were not measured at each elevation where surface temperature and heat flux were measured, so the gas temperature was interpolated from values at the next higher and lower elevations.

The steady-state, circumferentially averaged heat transfer data from 14 of the 16 dry LST tests were used to define hydraulic, diameter-based Nusselt number values. Entrance-effect multipliers were calculated, as described in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. However, the containment EM does not use entrance-effect multipliers. The Nusselt number values were compared with predictions of the turbulent mixed-convection correlation, as described in Section 21.6.5.6.1.1 of this report. (Tests RC015 and RC016 were omitted from this comparison because the forced asymmetric annular airflow rate imposed for these tests affected the circumferential averaging.)

The wall heat fluxes for dry LST tests were typically very small, and the measured ΔTs across the wall were of the same order of magnitude as the ΔT measurement uncertainty. Therefore, the uncertainty in the Nusselt number measurements was high — greater than 100 percent for the lowest heat flux tests [320 W/m^2 (100 $Btu/hr\text{-}ft^2$)].

21.6.5.6.2.6 Summary of Heat Transfer Separate-Effects Tests

All the comparisons made were for channel geometry (heated, vertical parallel plates or pipe geometry). The comparisons were plots of calculated and experimental local Nusselt values versus a dimensionless distance, x/d. The local Nusselt values increased approximately linearly as a function of x/d, yielding heat transfer coefficients that are approximately independent of distance, if used in a relation of the form h = kNu/x. This is the expected behavior, with the exception of near the entrance, because the heat transfer coefficient should be approximately independent of distance down the channel. For channels, however, it is more usual to define the controlling, nondimensional numbers in terms of a width or hydraulic diameter (d), and evaluate h from h = kNu/d; thus defined, these Nusselt numbers should be independent of x/d, except for entrance effects. The comparisons were replotted in terms of Nu_d. The presentation shows that this convention was being used for the channel geometries (e.g., Reynolds and Grashof numbers (Re_d and Gr_d) based on the channel hydraulic diameter).

Entrance effects were included in the evaluation of the separate-effects tests. However, for the EM licensing analyses, the applicant used a simplified model which did not include entrance effects. Studies performed by the applicant, as discussed in Section 21.6.5.6.1.2.2 of this report, concluded that this simplified model was conservative. The staff accepted this simplification for the EM.

The combined convection heat transfer data consists of the Hugot, Eckert and Diaguila, Siegel and Norris, the applicant’s flat-plate (see WCAP-12665), and the applicant’s dry LSTs. The predicted-to-measured Nusselt number ratio was calculated from these data and Equation 21.6.5.6.4 for opposed-mixed convection, as a function of the Reynolds and Grashof numbers. The mean predicted-to-measured Nusselt number ratio was 0.976, with a standard deviation of 0.278. The mean predicted-to-measured Nusselt number value near 1.0 indicates that the heat transfer correlation fits the measured data very well. The applicant believes the large standard deviation resulted from poor fidelity in the data for the following reasons:

- The convective heat transfer correlation serves as the basis for the prediction of condensation and evaporation mass transfer. Because the mass transfer data did not show large scatter, the variation in the heat transfer data may be attributed to more uncertain data measurements.

- The deviation between predicted and measured Nusselt numbers was large in four of the Hugot tests. The entrance-effect multiplier overpredicted the Nusselt number at small distances from the channel entrance ($L/d_h < 1.0$) because of the asymptotic singularity at x = 0 in the entrance-effect relation.

- The LST dry heat transfer test data have an uncertainty in the measured wall heat flux (ΔT) that was as large as, or larger than, the value of ΔT.
- The Eckert and Diaguila data have a large variation that changes with distance because the tube centerline temperature was used to represent the bulk temperature.

- The Hugot and the Siegel and Norris tests may exhibit higher deviations due to the use of a predicted, rather than measured, test airflow rate.

The applicant concluded that Equation 21.6.5.6.4 provides an adequate mean prediction of the dry assisted-mixed-convection heat transfer for the containment vertical wall and dome. The test data encompassed the expected range of Reynolds and Grashof numbers. Because the phenomenon was not ranked high in the PIRT, it was unnecessary to bound the test results in the EM. However, the multiplier developed for mass transfer was applied to convective heat transfer for use in EM licensing analyses.

The applicant used a conservative approach for licensing analyses. Part of this conservative approach was a bias in the heat transfer correlation to account for uncertainties in the use of the separate-effects tests to qualify the heat transfer correlation. In addition, inside containment, only free convection was assumed in the licensing analyses.

21.6.5.6.3 Separate-Effects Mass Transfer Tests

21.6.5.6.3.1 Gilliland and Sherwood Evaporation Tests

Isothermal evaporation mass transfer rates were measured in a vertical pipe by Gilliland and Sherwood. (Gilliland, E.R., Sherwood, T.K., “Diffusion of Vapors into Air Streams,” Industrial and Engineering Chemistry.) A water film was applied to the inside wall of the pipe, and the evaporation rate was measured for both countercurrent and concurrent flow.

These tests studied the evaporation of downward-flowing liquid films on the inside of a vertical tube 1.17 m (3.84 ft) high and 0.0267 m (1.05 in.) inside diameter. Liquid and air were at approximately the same temperature [i.e., the tests were approximately isothermal, within 3 °C (5.4 °F)]. Temperatures were relatively low [25 °C (77 °F) to 56 °C (133 °F)]; therefore, vapor mole fractions were low. Because the liquid and air temperatures were nearly the same (isothermal) in these tests, the evaporative mass transfer was driven by the difference in partial pressure between the liquid film surface and bulk mixture. Under these conditions, buoyancy effects were presumably minimal. Reynolds numbers were 2E03 to 2.5E04, with values under 1E04 in the majority of cases.

The Nusselt number and Sherwood numbers were evaluated using the channel hydraulic diameter. Entrance-effect multipliers were calculated, as described in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. The containment EM does not use the entrance-effect multipliers.

21.6.5.6.3.2 Westinghouse STC Flat-Plate Evaporation Tests

The applicant performed a series of liquid film evaporation tests at the Westinghouse Science and Technology Center, as documented in WCAP-12665. The purpose was to observe the behavior of a liquid film and to provide data on evaporative mass transfer. The selected test conditions simulated the outside of the steel containment vessel with the PCS in operation.

The test section was a vertical,1.8 m (6 ft) long, heated, flat steel plate that was coated with the inorganic zinc coating used in the passive containment cooling design. A clear acrylic cover provided a 58 cm (23 in.) wide by 10 cm (4 in.) deep channel for the forced airflow and allowed observation of the applied liquid film. Each test varied the plate temperature, the applied liquid film temperature, and both the liquid and air flow rates. Six of the 23 tests were conducted with the plate sloped 15° from horizontal, with all other tests conducted on a vertical surface. Reynolds numbers ranged from about 2E04 to 1.2E05.

Relatively high airflow rates, in comparison to the evaporation mass transfer rate, were used in these tests. Therefore, inlet and outlet average properties were used to calculate the Sherwood number for comparison with the test data.

The Sherwood number was defined using the channel hydraulic diameter. The data from the applicant's 23 flat-plate evaporation tests were compared with predictions using the turbulent mixed-convection correlation with an entrance multiplier of 1.13, as defined in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. The containment EM does not use the entrance-effect multipliers.

The applicant evaluated the measurement uncertainties for the flat-plate test facility. The uncertainty in the Sherwood number was about 5 percent for the flat-plate evaporation tests, which were typically conducted with higher heat fluxes than the dry flat-plate tests (see Section 21.6.5.6.2.4 of this report).

21.6.5.6.3.3 University of Wisconsin Condensation Tests

The University of Wisconsin conducted a series of condensation tests to provide data on condensation mass transfer in the presence of a noncondensable gas at various inclination angles, velocities, and steam-air concentrations. WCAP-13307, "Condensation in the Presence of a Noncondensible Gas: Experimental Investigation," issued April 1991, documents the results.

The test section was 1.9 m (6.25 ft) long, with a 0.84 m (2.75 ft) entrance length, and a 1.1 m (3.5 ft) condensing surface length. The channel cross-section was square, with an area of 0.02 m^2 (0.25 ft^2). The top of the test section was a thick aluminum plate coated with the applicant's passive containment cooling design inorganic zinc coating. Seven 0.15 m (0.5 ft) long cooling plates were attached to the back of the aluminum test plate to remove heat. Each cooling plate had both flux meters and cooling coils with thermocouples to provide redundant, diverse energy measurements. The test section could be inclined from 0° to 90° from horizontal.

Relatively high airflow rates, in comparison to the mass transfer rates, were used in these tests. As a result, the change in the bulk-to-film steam partial pressure difference from inlet to outlet was small. Inlet-to-outlet average properties were used to calculate the predicted Sherwood number for comparison with the test data.

The data from the tests were converted to hydraulic, diameter-based Sherwood numbers and compared to Sherwood numbers calculated from the assisted-mixed-convection mass transfer correlation described in Section 21.6.5.6.1.1 of this report. An average entrance-effect multiplier of 1.20 was calculated, as described in Section 21.6.5.6.1.2 of this report, for the purpose of evaluating the experimental data. The containment EM does not use the entrance-effect multipliers. The data covered by the tests included Reynolds numbers (Re_d) ranging from 7E03 to 2.5E04, with the angle of inclination ranging from 0° to 90° and the steam mole fractions ranging from about 0.12 to 0.65.

Five of the Wisconsin tests were conducted without noncondensable gases. These tests were also used for the liquid film heat transfer correlation comparisons presented in Section 21.6.5.6.4 of this report.

In the tests for which comparisons were given, the experiments measured condensation rates for a steam-air mixture flowing through a channel with a cooled surface in an apparatus that could be tilted to study the effect of inclination angle upon condensation rates.

The test facility description indicated that the air-steam source was at the high end for the inclined tests, and that the assisted-mixed-convection correlation was appropriate for the low-angle comparisons. The applicant used a conservative model for the EM licensing calculation. The bias applied to the mass and heat transfer correlations bound the worst test data for the range of angles and steam mole fractions studied.

The test measurement uncertainties in the Wisconsin condensation tests resulted in a measured Sherwood number uncertainty of ±12 percent.

21.6.5.6.3.4 Large-Scale Test Facility—Internal Condensation

The applicant performed the Phase 2 (confirmatory) heat and mass transfer tests on the LST facility at the Westinghouse Science and Technology Center. The Phase 2 tests provided data on the transient heat transfer and distribution of noncondensable gas in a geometry similar to the AP600 containment vessel. These data were used to develop and validate heat and mass transfer models and are documented in WCAP-14135.

Testing and Computer Code Evaluation

The Sherwood numbers inside the LST are defined in terms of $(v^2/g)^{1/3}$ for the characteristic length parameter, as described in Section 21.6.5.6.1.3 of this report. The measured Sherwood numbers were based on surface-to-bulk gas density differences and shell heat fluxes that were averaged over time and averaged circumferentially at each measuring elevation. Steam partial pressures were not measured at each elevation, so the steam partial pressures were interpolated from the next higher and lower measurement elevations.

The steady-state, circumferentially averaged mass transfer data from 7 of the 25 Phase 2 tests were converted to Sherwood numbers and compared with predictions of the free-convection mass-transfer correlations described in Section 21.6.5.6.1.3 of this report. The Phase 2 tests had a diffuser located below the simulated steam generator. Only tests with film coverage greater than 90 percent were included in the comparison because lower film coverage biases the circumferentially averaged test measurement. This eliminated 17 of the tests. The data evaluation also excluded the blind test (RC062, or 220.1).

A compilation of the predicted-to-measured Sherwood numbers for all seven tests was presented. The mean value was 1.045, with a standard deviation of 0.167. The measured data were compared to the mass transfer correlation as a function of heat flux, steam mole concentration, and $\Delta\rho/\rho$. The correlation matched the trend in the data. The steam mole concentrations ranged from 10 to 50 percent.

The applicant argued that free-convection heat and mass transfer on the inside of the shell was conservative during blowdown, when a significant increase in the transfer coefficient was expected due to the blowdown-induced forced convection. The LST RC064 (test 222.3) and RC066 (test 222.4) predicted-to-measured mass transfer coefficients showed the effect of high internal break source kinetic energy. These two tests were conducted in a configuration that simulated an MSLB at the top of the steam generator. The steam source was a 7.6 cm (3 in.) inside-diameter pipe elevated to a level that simulated the top of the steam generator, rather than a steam diffuser under the simulated steam generator, as in the LOCA configuration. Each test consisted of two steady-state segments with an approximate factor of 2 difference in the steamflow rate. Test RC064 had the steam source pointed horizontally at the far wall, and test RC066 had the steam source pointed vertically.

The data show that the predicted-to-measured mass transfer ratios are 5 to 10 times greater than the free-convection mean value for LST tests with the diffuser below the steam generator. The location of the maximum ratio corresponds to the elevation where the jet impinges the vessel wall ($x/L = 0.4$ for the horizontal jet and $x/L = 1.0$ for the vertical jet). At all elevations, the measured mass transfer coefficients were as high as, or higher than, the mean of the measurements for free convection, with an average value approximately twice that of the free-convection mass transfer coefficient.

The applicant performed an uncertainty analysis for the LST. The results indicated that the measured Sherwood number uncertainty was 26 percent for tests with measured heat fluxes greater than 8050 W/m^2 (2500 $Btu/hr\text{-}ft^2$). For tests with heat fluxes between 3200 W/m^2 (1000 $Btu/hr\text{-}ft^2$) and 8050 W/m^2 (2500 $Btu/hr\text{-}ft^2$), the uncertainty was about 40 percent. Tests conducted at low heat fluxes, 1600 W/m^2 (500 $Btu/hr\text{-}ft^2$) to 2600 W/m^2 (800 $Btu/hr\text{-}ft^2$), had uncertainties in the 50 to 75 percent range.

21.6.5.6.3.5 Summary of Mass Transfer Separate-Effects Tests

The basic observations on these results are similar to those for the heat transfer correlations. The results clearly show that the correlations yield Sherwood numbers of the right order of magnitude and which might be defensible as best-estimate values, but not as unconditional conservative values. No "bridge" between these results and the quantitative implications for PCS DBA analysis was provided. No effort was made to evaluate a quantitative uncertainty for the correlations when they were applied to the passive containment cooling design, or to quantitatively assess their implications for the accuracy and/or conservatism of WGOTHIC results.

The Wisconsin condensation tests exhibited some weak trends that, if extrapolated to DBA conditions, suggested that the treatment of evaporation from the shell exterior could be somewhat nonconservative. The other test series considered exhibited no such trends.

The applicant has developed a conservative EM, and the mass transfer correlation includes a conservative bias.

21.6.5.6.3.5.1 Evaporation

The combined evaporation test data consisted of the applicant's flat-plate evaporation tests (see WCAP-12665) and the Gilliland and Sherwood evaporation tests. The predicted-to-measured Sherwood number ratio for the applicant's flat-plate evaporation tests was evaluated as a function of the Reynolds number, Grashof number, and dimensionless steam concentration. The mean predicted-to-measured Sherwood number ratio was 0.936, with a standard deviation of 0.139.

The evaporation test data covered a range in Reynolds numbers (Re_d, based on the hydraulic diameter) up to 1.2E05 and in Grashof numbers (Gr_d) up to 7.0E10. The evaporation test data covered the expected DBA range of both the Reynolds and Grashof numbers in the riser annulus during a DBA event.

The Gilliland and Sherwood evaporation tests provided a comparison of the measured and predicted total evaporation rates at relatively low Reynolds and Grashof numbers. The heat and mass transfer correlations predicted the measured total evaporation rates with a predicted-to-measured mean value of 0.925 and a standard deviation of 0.072. Local evaporation measurements were not made and internal variations in partial pressure varied too much to represent the data as an average Sherwood number. Therefore, comparisons between the measured and predicted Sherwood numbers were not meaningful for the Gilliland and Sherwood tests.

The applicant concluded that Equations 21.6.5.6.4 and 21.6.5.6.8 adequately modeled the evaporation mass transfer on the containment sidewall and dome. When multiplied by the factor developed for use in the EM licensing analyses, as discussed in Section 21.6.5.6.5.3 of this report, the evaporation correlation becomes an acceptable, conservative correlation appropriate for use in the EM. The range of the Reynolds and the Grashof numbers in the tests is sufficient to support the use of the correlation over the expected operating range of the AP1000 during a DBA.

21.6.5.6.3.5.2 Condensation

The combined condensation data consist of the Wisconsin condensation tests (see WCAP-13307) and the internal condensation data from the applicant's LST (see WCAP-14135). The predicted-to-measured Sherwood ratio was evaluated as a function of the Reynolds number, the ratio $\Delta\rho/\rho$, and the dimensionless steam concentration. The mean predicted-to-measured Sherwood number ratio was 0.988, with a standard deviation of 0.182.

The combined test data covered the Reynolds number (Re_d) density ratio range, $\Delta\rho/\rho$, expected during DBAs for passive containment cooling design. The Reynolds number will vary with time and position inside the containment vessel during a DBA event. During the relatively short blowdown phase, the velocity and corresponding Reynolds number will be largest on the wall nearest the break location and will decrease as the flow moves away from the break. A natural circulation flow pattern is expected to develop during the depressurization phase when the PCS is in operation. The Reynolds number along the wall will be small during natural circulation. The value of $\Delta\rho/\rho$ in the passive containment cooling design is expected to be the range of the test data, so it is bounded by the test data.

The applicant concluded that Equations 21.6.5.6.6 and 21.6.5.6.8 adequately model condensation mass transfer inside the containment. When multiplied by the factor developed for use in the licensing analyses, as discussed in Section 21.6.5.6.5.3 of this report, the condensation correlation becomes an acceptable, conservative correlation appropriate for use in the EM. The range of $\Delta\rho/\rho$ measured in the tests encompasses the range expected in the passive containment cooling design for the AP1000.

21.6.5.6.4 Chun and Seban Liquid Film Conductance Model

The Chun and Seban correlation is used to predict heat transfer through the condensing and evaporating liquid films. The applicant applied the correlation to both turbulent and wavy laminar films. The applicant used data from tests at the University of Wisconsin (see WCAP-13307) to extend the validity of the Chun and Seban correlation to condensing wavy laminar flow and to inclined surfaces, as in the dome region of the containment.

Section 21.6.5.6.3.3 of this report describes the Wisconsin test facility. Five of the 99 Wisconsin tests were conducted without a noncondensable gas present. Without a noncondensable gas, the gas-to-liquid heat transfer coefficient is so high that the gas-to-liquid temperature drop is negligible, when compared to the temperature drop across the liquid film. The temperature of the liquid film surface may be assumed equal to the gas temperature, and the liquid film heat transfer coefficient can be calculated from the heat flux divided by the liquid film temperature drop. Because the heat flux, solid-surface temperature, and liquid film surface temperature are known, the heat transfer coefficient may be derived directly from the measurements. The Wisconsin tests provided an indication of the liquid film heat transfer coefficient for a range of surface inclinations, from vertical to horizontal, covering a range of film Reynolds numbers in the wavy laminar regime.

Testing and Computer Code Evaluation

The Wisconsin (condensing) and Chun and Seban (evaporating) data were compared to the Chun and Seban laminar and turbulent correlations [Equations 21.6.5.6.7(a) and (b)]. In the mid-range Reynolds numbers (i.e., laminar to turbulent transition range), the correlation overpredicts the Wisconsin data by 25 to 35 percent. The range of the film Reynolds numbers on the outside surface of the containment vessel falls within the range of the test data. Reynolds numbers on the inside surface of containment are less, because film is removed at the crane rail and stiffener ring and the inside film flow rate starts at zero at the top of the dome and increases as the film flows down. The liquid film Prandtl number range is approximately $1.5 < Pr < 3.0$. The range of the Chun and Seban data Prandtl numbers is $1.77 < Pr < 5.9$, which adequately covers the PCS DBA range. A comparison of the correlation to the test data shows that the Chun and Seban correlation is a reasonable representation of the data. The large scatter in the Wisconsin liquid film heat transfer data is believed to result from operating the tests at (or beyond) the range of operation for which the test facility was designed. The presence of even small amounts of noncondensable gases would bias the results.

The Chun and Seban liquid film conductance model was compared to additional data from Kutateladze, et al., in WCAP-14326, Revision 2. This comparison provided additional justification for the Chun and Seban correlation in the low Reynolds number range (about 700), with the comparison showing the correlation to be a good fit to the evaporation data and conservative for the condensation data. The liquid film conductance is a low-ranked phenomenon, and the use of Chun and Seban is acceptable.

21.6.5.6.5 Summary of Separate-Effects Tests and Mass and Heat Transfer Correlations

The applicant’s evaluation of the separate-effects tests validates the correlations that are used to calculate energy transfer, by heat and mass transfer, between the containment gas and the external PCS airflow path, and between the PCS airflow path and the baffle, shield, and chimney. The correlations represent the common phenomena of convective heat transfer, condensation mass transfer, and evaporation mass transfer.

The objectives of the applicant’s analysis included the following:

- Identify appropriate correlations for the various heat and mass transfer regimes for the PCS surfaces.
- Compare the correlations to separate-effects tests that cover the range of dimensionless parameters for PCS operation.
- Evaluate correlation uncertainties.
- Develop biases that can be applied to the correlations to bound the test data.

21.6.5.6.5.1 Energy Transfer Model

The EM uses the correlations developed which are defined consistently with the way energy transfer is modeled across the containment shell and in the PCS airflow path. The EM energy transfer is calculated as follows:

- With condensation or evaporation, a liquid film is present. Energy is transported between the bulk gas and a solid through the liquid film by the following processes:
  - between the bulk gas and the liquid film free surface by radiation heat transfer, convection heat transfer, and mass transfer
  - by conduction through the liquid film to the solid surface
- Dry surfaces do not have liquid films or mass transfer. Energy is transported between the bulk gas and the solid surface by radiation heat transfer and convection heat transfer.
- The correlations assume that the local bulk gas thermodynamic states are known both inside and outside containment. Phenomena that influence the distribution of bulk gas properties are separately evaluated to develop an overall conservative approach in the PIRT evaluation.

21.6.5.6.5.2 Heat and Mass Transfer Correlation Validation

The applicant selected analytical correlations from the literature to represent heat and mass transfer to and from the containment shell and PCS airflow path surfaces. The correlations contain the physics necessary to model energy transport consistently with the energy transfer model described above. The correlations were compared to separate-effects test data and uncertainties were evaluated. The following correlations were selected for calculating heat and mass transfer, thereby achieving the four objectives of the analysis:

- Opposed-mix-convection heat and mass transfer both occur in the PCS airflow path on the downcomer side of the shield and baffle and on the chimney. Equation 21.6.5.6.3, from Churchill, is used to model turbulent-opposed, mixed-convection heat transfer in the PCS airflow path. Heat and mass transfer on the baffle and chimney are both low-ranked phenomena in the PIRT, so it is sufficient to model these without additional uncertainty, consistent with the conclusion from the PIRT that only high-ranked phenomena need to be modeled with uncertainties (or conservative values). However, the conservative bias factor, determined for evaporation mass transfer, is applied in the EM.
- Assisting-mixed-convection heat transfer occurs in the riser and chimney and involves portions of the PCS airflow path on the shell and baffle. Equation 21.6.5.6.4, from Churchill and Eckert and Diaguila, is used for turbulent-assisting, mixed-convection heat transfer in the PCS airflow path. Equations 21.6.5 6.1 and 21.6.5.6.2 define the free- and forced-convection components of the mixed-convection heat transfer correlation in

the PCS airflow path. Heat transfer on the shell and dome are ranked medium or low in the PIRT, so it is sufficient to model these without additional uncertainty, consistent with the conclusions from the PIRT that only high-ranked phenomena need to be modeled with uncertainties (or conservative values). However, the EM does apply the conservative bias factor, determined for evaporation mass transfer. Comparisons of the assisted-mixed-convection heat transfer correlation to test data were presented. The comparisons show that the correlation underpredicts the mean Nusselt number by 2.4 percent, and that the test Grashof and Reynolds numbers cover the range expected for AP1000 PCS conditions during a DBA.

- Assisting-mixed-convection evaporation mass transfer occurs in the riser and chimney portions of the PCS airflow path on the shell and baffle. The evaporation rate is based on the mass transfer analogy to heat transfer (Equation 21.6.5.6-9). A comparison of the assisted-mixed-convection evaporation predictions and the data was presented. The comparison shows that the nominal correlation underpredicts the mean data by 7.5 percent. Because this transport phenomena is ranked high in the PIRT, the data are bounded. The correlation is further biased with a multiplier of 0.84 to produce a conservative evaporation mass transfer correlation for use in licensing analyses. The comparison also shows that the range of the test data encompasses the expected range for AP1000 PCS conditions during a DBA.

- Free-convection heat transfer is assumed on the inside of the shell throughout all transients. Equation 21.6.5.6.6, the modified McAdams free-convection correlation, is used to calculate heat transfer to the shell inside containment. Only free convection is assumed inside containment for licensing analyses. The assumption of free convection will underpredict the actual heat transfer coefficients inside the shell. Free convection is ranked medium or low in the PIRT, so it is sufficient to model this without additional uncertainty. The McAdams modification replaces the characteristic geometric dimension, L, with the local fluid property $(v^2/g)^{1/3}$ in the Nusselt and Grashof numbers.

- Free-convection condensation mass transfer is assumed on the inside of the shell throughout all transients. Equations 21.6.5.6.8 and 21.6.5.6.10, from Kreith, and the mass transfer analogy, Equation 21.6.5.6.9, are used to calculate mass transfer in the PCS airflow path and inside containment to the shell. Free-convection mass transfer, similar to free-convection heat transfer inside containment, replaces the characteristic geometric dimension, L, with the local fluid property $(v^2/g)^{1/3}$ in the Sherwood and Grashof numbers. Comparisons of the free-convection condensation predictions and the data were presented. The nominal correlation underpredicts the mean data by 1.2 percent. Because this transport phenomenon is ranked high in the PIRT, the data are bounded. The correlation is further biased with a multiplier of 0.73 to produce a conservative condensation mass transfer correlation for licensing analyses. The comparisons also show that the range of the test data encompasses the expected range for AP1000 PCS conditions during a DBA.

- Conduction heat transfer through the liquid film occurs on the inside and outside of the containment shell, and may occur on the inside of the baffle and chimney if condensation takes place. Equations 21.6.5.6.7(a) and (b), from Chun and Seban, are used to calculate the heat transfer through the internal and external liquid films. Comparisons of predicted and measured film Nusselt numbers were presented. The comparisons show that the correlation is a good nominal prediction of the film Nusselt number for both condensing and evaporating films. The comparisons also show that the range of the test data encompasses the expected range for AP1000 PCS conditions during a DBA. Because film conduction is ranked medium or low in the PIRT, it is sufficient to model this phenomenon without additional uncertainty, consistent with the conclusions from the PIRT.

- Radiation heat transfer occurs on all surfaces, but is ranked low in the PIRT on all surfaces. Consequently, it is acceptable to use a traditional T^4 model with an emissivity and beam length for opaque gases. The radiation heat transfer model is not validated through use of the separate-effects tests.

21.6.5.6.5.3 Use of the Mass and Heat Transfer Correlations in WGOTHIC

The mass transfer correlations selected for use in EM licensing analyses have been compared to both separate-effects tests and to integral-effects tests, including the LST. The data comparisons were presented in the form of the predicted-to-measured Sherwood number. The comparisons indicate that the correlations tend to underpredict the data, with a mean value of 0.936 for evaporation and a mean value of 0.988 for condensation.

The applicant used a conservative EM for EM licensing analyses. Based on comparisons of the predicted-to-measured Sherwood numbers, the bias for the evaporation mass transfer is a multiplier of 0.84 for the correlations. For condensation, the bias multiplier is 0.73 for the mass transfer correlations. The same multipliers are applied to the heat transfer correlations, based on the mass and heat transfer analogy. The multipliers were chosen to bound the comparisons and are acceptable for AP1000 analyses.

21.6.5.6.6 Integral Tests

21.6.5.6.6.1 Small-Scale Test Program

The applicant’s passive containment cooling design includes a PCS to remove heat released to the containment following any postulated event, and to transfer this heat from the containment to the environment. This system employs natural draft air cooling and the evaporation of a water film from the outside of the steel containment shell to transfer heat from the containment vessel to the environment.

The purpose of the integral small-scale test (SST) program was to demonstrate the operation of the PCS over a range of operating conditions, including postulated severe accident conditions. Tests were also run at off-nominal conditions using hot and cold film water and cold cooling air. The purpose of these tests was to avoid ice formation in the annulus region and to determine any effects that cold weather could have on the PCS design and capabilities. WCAP-14134 documents the results of the tests.

The small-scale PCS integral containment cooling tests were conducted using the same facility originally constructed for demonstrating operation of the PCS. To permit testing over the broader range of operating conditions specified for the extension tests, the test facility was modified to test in cold weather and to simulate abnormal operating conditions. The test facility was also upgraded to improve or automate particular test measurements, such as condensate flow rate, based on experience gained from previous tests.

These tests were performed using the integral containment cooling test facility located at the Westinghouse Science and Technology Center in Churchill, Pennsylvania. The integral containment cooling test facility used a 7.3 m (24 ft) tall, 0.9 m (3 ft) diameter pressure vessel to simulate the AP600 steel containment shell. The vessel could contain air or nitrogen at 1 atmosphere when cold and was supplied with steam at pressures up to 655 kPa (80 psig). A transparent acrylic cylinder installed around the vessel formed the air cooling annulus. The test vessel wall was 0.95 cm (0.375 in.) thick. Water was added at the top of the pressure vessel, forming a film which flowed down over the vessel external surface. Airflow up the annulus outside the vessel cooled the vessel surface, condensing the steam inside the vessel.

Saturated steam from a boiler was throttled to a variable, but controlled, pressure and supplied to the bottom of the vessel, which initially contained 1 atmosphere of air. The steam was distributed inside the vessel by one of two steam distributor arrangements. One of these, a uniform steam distributor, provided for slow radial flow, uniform along and around the central supply pipe that ran the full height of the test vessel. The uniform distributor was expected to produce the most limiting steam condensation conditions.

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. Twenty-four thermocouples were located on the outer surface of the vessel. The thermocouple measurements were weighted by the respective vessel wall areas sensed by the thermocouples and summed to obtain the average vessel outside surface temperature.

An axial fan to control the cooling air velocity was located in the chimney region above the test vessel and formed the upper chimney for the cooling air flowpath.

Water could be added at the top of the vessel to create a water film on the external surface. External water film flow rates onto the vessel, as well as the flow rate of excess water from the bottom of the vessel that was not evaporated, were measured.

External cooling air temperature, humidity, and velocity could be surveyed by traversing measurements at several elevations in the cooling annulus. Air velocity was also measured at the inlet to the air heating coil. Thermocouple measurements were sequentially sampled and converted by data acquisition equipment and recorded on paper tape or computer memory and disk.

21.6.5.6.6.1.1 Test Matrix

The test matrix included a full range of expected design-basis external water flow rates, the maximum and minimum expected cooling air velocities, and the cooling air inlet temperature and relative humidity.

External Baffle Cooling Air Velocity

Based on the AP600 containment transient analyses available at the time, three cooling air velocities, 4.9 m/sec (16 ft/sec), 3.7 m/sec (12 ft/sec), and 2.4 m/sec (8 ft/sec), were examined. The 4.9 m/sec (16 ft/sec) cooling air velocity corresponded closely to (1) the maximum calculated air velocity during wetted heat transfer shortly after PCS initiation following a postulated LOCA, and (2) the calculated air velocity with a dry containment surface when containment internal pressure was 380 kPa (40 psig).

The 3.7 m/sec (12 ft/sec) velocity was the calculated air velocity in the baffle when the containment pressure was 240 kPa (20 psig).

The 2.4 m/sec (8 ft/sec) velocity was the air velocity calculated to generate natural circulation when the containment pressure was 172 kPa (10 psig). This pressure and air velocity define the condition in which containment cooling would transition from a wetted external surface to a dry surface after the stored PCS water had been used, if no operator action were taken within 3 days.

External Containment Surface Water Flow

The flow rates supplied to the top external surface of the test vessel corresponded to the prototypic water flow rates onto the AP600 containment, which were used in the LOCA response containment transient analysis. These AP600 maximum and minimum PCS water supply flows were 776 L/min (205 gpm) and 204 L/min (54 gpm), respectively. Because some of the supplied water would be evaporated from the containment dome, the amount of water which reached the top of the cylindrical portion of the containment would initially be about 570 L/min (150 gpm) and would be reduced to about 136 L/min (36 gpm) at 3 days when the PCS water would be exhausted. Based on the expected design perimeter of the cylindrical portion of the AP600 containment, the maximum and minimum flow rates around the containment top, exterior, vertical surface would be 0.453 L/min/m (0.398 gpm/ft) and 0.108 L/min/m (0.095 gpm/ft), respectively. These flows were matched on the 0.9 m (3 ft) diameter PCS test vessel, and an intermediate flow of 0.285 L/min/m (0.25 gpm/ft) was included in the test program.

Cooling Air Inlet Temperature/Relative Humidity

For all wetted test conditions, the cooling air inlet temperature was maintained at 54 °C (130 °F). This elevated air inlet temperature approximated the average air temperature that would occur in the full-sized AP600 cooling path, based on the maximum environmental air temperature of 46 °C (115 °F). The inlet air relative humidity was raised to 30 percent to approximate the average specific humidity that would be achieved in the full-sized AP600 PCS cooling path, based on the 29 °C (85 °F) maximum wet bulb temperature for the inlet air. For comparison, identical test conditions with low relative humidity inlet air were also examined.

21.6.5.6.6.1.2 Test Validation

The following acceptance criteria were established for the tests:

- Data on forcing functions were available (i.e., steamflow rate, fan speed, water flow rates, inlet temperatures of steam, water, and air). Strict adherence to the specific absolute pressures and flow rates was not necessary, but values should be nearly constant, as defined in the test matrix.

- Data were available on response variables. Condensate flow rates; excess water flow rates; air, water, and steam outlet temperatures; vessel pressure; 80 percent of the vessel and fluid temperatures; and vessel water coverage were measured.

- Unplanned excursions were evaluated on a case-by-case basis. Failures that may have resulted in faulty data outputs were not acceptable.

- The vessel pressure was maintained within the specified pressure limits during the constant pressure portions of these tests.

Heat balances were performed to roughly determine the acceptability of the test data and instrument performance. Heat loads were calculated for the reported tests by the following three methods:

(1) condensate mass flow rate
(2) external heat loss (water and air)
(3) heat flux across wall

21.6.5.6.6.1.3 Matrix Tests

Base Cases with Constant Steamflow

Seventeen base-case tests with constant steamflow were run to establish internal vessel pressures under nominal cooling conditions. The steamflow was 0.1 kg/sec (0.25 lb/sec). All other conditions were identical, except for the size of the annulus. Two tests were performed using the 13 cm (5 in.) annulus; the other 15 used the 38 cm (15 in.) annulus. Two of the tests, one using the 38 cm (15 in.) annulus (run 38, test 106-1SU), and one using the 13 cm (5 in.) annulus (run 70, test 106-5U) resulted in invalid data. Test 106-1SU was aborted because of rain, and test 106-SU was aborted because the annulus air velocity was incorrect.

Base Cases Repeated with Prototypic Steam Injection

Four tests were run in this category. They were all performed using the 13 cm (5 in.) annulus width. These tests were performed using prototypic steam injection through a 15 cm (6 in.)

diameter pipe at the 1.5–1.8 m (5–6 ft) elevation offset from the center of the test pressure vessel. All these tests generated valid data.

Water Film Limits of Cooling

Three tests were run in this category. These tests determined the effects of film flow rate on coolability. The flow rates used were 1.9, 3.8, and 9.5 L/min (0.5, 1.0, and 2.5 gpm). The flow rate was changed to degrade cooling until the limits of coolability were reached. One of these tests was not completed due to a computer failure.

Water Film Distribution Limits of Cooling

Nine tests were run in this category. These tests determined the effect of water film distribution on cooling. The water film distribution was varied from 100 to 66 to 33 percent. This variable was changed to degrade cooling until the limits of coolability were reached. All of these tests generated valid data.

Vessel Air Content Effect on Heat Transfer

Three tests were run to determine the effect of vessel air content on heat transfer. The initial air content was varied from 1.0 to 2.0 atmospheres. The 13 cm (5 in.) annulus was used with prototypic injection. All of these tests generated valid data.

Baffle Airflow Limits

Six tests were run to determine the limits of airflow in the baffle region. The airflow was varied from 3.7 m/sec (12 ft/sec) to natural circulation. All data generated from these tests were valid.

Water Film Temperature (Phases I and II)

There were two tests run in Phase I to determine the effects of the shell water film temperature. In both cases, the temperature was raised to 49 °C (120 °F), increased from the normal temperature of 27 °C (80 °F). These tests were performed with steamflows of 0.05 kg/sec (0.1 lb/sec) and 0.1 kg/sec (0.25 lb/sec). Both of these tests produced valid data. Phase II tests varied both the steamflow and the water film temperatures. In the Phase II tests, the temperatures were 4.4 °C (40 °F) and 27 °C (80 °F). These tests also produced valid data.

Transient Steamflow

These tests varied the steamflow rate. Rather than a steady-state value for steamflow, a transient rate from 0.68 kg/sec (1.5 lb/sec) to 0.05 kg/sec (0.1 lb/sec) over 30 seconds was used for both tests in the category. The data generated were valid.

Ice Formation and Melt Demonstration

These tests were run to determine the onset of ice formation in the annulus region, and any other effects of cold weather on the passive containment cooling capabilities of the system. Both tests produced valid data.

21.6.5.6.6.1.4 Test Summary

The applicant considered the SST program to be successful and the criteria of the program to be met. Assessment of the heat balances indicated that the majority of the tests were performed in a consistent fashion and were in agreement with respect to the three methods of heat balancing. The applicant concluded that the tests performed as expected, and their overall behavior was repeatable. The test program confirmed the expected operation of the PCS over the range of AP1000 operating conditions, including postulated severe accident conditions.

21.6.5.6.6.2 Large-Scale Test Facility

The large-scale containment cooling tests were performed at the LST facility, located at the Westinghouse Science and Technology Center in Churchill, Pennsylvania. The large-scale PCS test facility used a 6.1 m (20 ft) tall, 4.6 m (15 ft) diameter pressure vessel to simulate the steel containment shell, with a height-to-diameter ratio more typical of the actual containment shell than was available for the SSTs (see WCAP-14134). The larger vessel made it possible to study in-vessel phenomena, such as noncondensable mixing, steam release jetting, and condensation, as well as flow patterns inside containment. The vessel contained air at atmospheric pressure when cold and was supplied with steam at pressures up to 793 kPa (100 psig). A transparent acrylic cylinder installed around the vessel formed the air cooling annulus. Airflow up the annulus outside the vessel cooled the vessel surface, condensing the steam inside the vessel.

Superheated steam from a boiler was throttled to a variable, test-dependent flow rate, but at a controlled pressure. This superheated steam was supplied to an off-center compartment below the operating deck of the test vessel. A steam distributor provided low-velocity steam at a scaled height commensurate with that of the operating deck of the reactor plant.

To establish the total heat transfer from the test vessel, steam inlet pressure, steamflow, temperature, and condensate flow and temperature were measured. Seventy-eight thermocouples, located on both the outer and inner surfaces of the vessel’s 2.2 cm (0.875 in.) thick steel wall, indicated the temperature distribution over the height and circumference of the vessel. Additional thermocouples, placed throughout the inside of the pressure vessel on internal heat sinks (32), adjacent to the vessel wall (27), and throughout the internal volume (47), provided a measurement of the vessel bulk steam temperature as a function of position.

An axial fan at the top of the annular shell allowed the apparatus to be tested at higher air velocities than could be achieved during purely natural convection. The temperature of the cooling air was measured at the entrance of the annular region and upon exiting the annulus in the chimney region before the fan. The cooling air velocity was determined by calibrating the fan controls by conducting a velocity traverse on the cooling annulus and using a heated-wire anemometer at various fan control settings. A fixed-vane anemometer was also located below the fan in the air exit stream to provide a continuous output of the annulus air velocity. The heat transfer to the cooling air (i.e., its temperature rise multiplied by its specific heat and its measured flow rate) and the water evaporated provided a measurement of the total heat transfer.

21.6.5.6.6.2.1 Test Objectives

The purpose of the LST PCS heat transfer test was to examine anticipated T-H phenomena on a large scale, particularly, (1) the interior natural convection and steam condensation, (2) the exterior water film evaporation, (3) air cooling heat removal, and (4) water film behavior. This experiment was designed to induce the same sort of containment dome heat transfer processes and circulation and stratification patterns inside the LST as are expected in the containment; however, it was not meant to simulate specific accident scenarios. The LST data were used to verify the WGOTHIC computer code, which is used to analyze the containment.

Baseline tests consisted of 16 steady-state tests that were performed at three constant pressure conditions to investigate the effects of various water coverage levels, various external airflow rates, and the presence of internal structures.

Phase 2 tests provided data to validate the WGOTHIC containment heat and mass transfer correlations over a range of prototypic internal conditions, including the effects of external parameters. The tests provided data on the transient heat transfer and the distribution of noncondensable gases. The effects of noncondensable gases on the containment heat transfer were observed.

Follow-on tests (Phase 3) examined special effects, such as the location of the steam discharge and the concentrations of noncondensable gases. These tests were not strictly necessary for code validation, but aided in the overall understanding of the containment cooling phenomena.

21.6.5.6.6.2.2 Facility Scaling

Pressure Vessel

The containment vessel is cylindrical with 2:1 elliptical heads at the top and bottom of the cylinder. The containment area above the operating deck is cooled on the outside and is considered the active heat transfer area.

Below the operating deck in the containment building, there are free volumes where equipment is installed. These volumes are normally in communication with the volume above the operating deck, so any steam released in an accident can either enter or discharge into them. If a volume has more than one path, circulation will exist between this volume and the containment atmosphere above the operating deck. The volume is referred to as an open volume. A volume in which the containment fluid does not readily circulate with the containment atmosphere above the operating deck is called a dead-ended compartment.

The open volumes and dead-ended volumes approximate the following compartments:

- open volumes
  - refueling cavity
  - steam generator loop compartment (without break)

- dead-ended volumes
  - region below the 32.6 m (107 ft) elevation of containment
  - in-containment refueling water storage tank
  - reactor cavity
  - accumulator areas
  - chemical and volume control system module

The total free volume below the operating deck and the free volume occupied by each subcompartment were calculated. When the LST was being designed, the AP600 plant design showed that the open volumes occupied 21 percent of the total volume below the operating deck. The dead-ended volumes occupied 70 percent, and the steam generator compartment (with break) occupied 9 percent of the total free volume below the operating deck.

Two steam generator compartments exist in the applicant's passive containment cooling design. In the LST facility, one was considered to be part of the open volume. The other was considered to be the steam generator volume because steam release was simulated in it. In the applicant's passive containment cooling design, the two compartments are connected and communicate with one another; in the LST, there was no connection.

The Phase 2 and Phase 3 tests had representations of the open, dead-ended, and steam generator volumes. The open volume provided vertical communication with the vessel volume above the operating deck. The dead-ended volume had one entrance (from the open compartment) and no exit. It did not directly communicate with the containment atmosphere above the operating deck. The percentages given above were used to determine the volume of the open, dead-ended, and steam generator compartments below the operating deck in the LST. As built, the LST open volumes occupied 21 percent of the total volume below the operating deck. The dead-ended volumes occupied 70 percent, and the steam generator compartment occupied 9 percent of the total volume below the operating deck.

In the AP600 plant design, the open volumes occupy 19 percent of the total free volume below the operating deck, the dead-ended volumes occupy 73 percent of the total free volume below the operating deck, and the steam generator compartment occupies 8 percent of the total free volume below the operating deck. The volume percent occupied by each compartment in the LST was close to the volume percent occupied by each compartment in the AP600. The applicant found this to be sufficient to evaluate the capability of WGOTHIC to represent each type of volume in the AP600. The staff accepted these minor variations in the volumes.

Heat Sinks

The heat sinks in the passive containment cooling design are the equipment in containment and the containment structural materials. These constituents are divided into two groups, short-and long-term heat sinks. The short-term heat sinks are the materials that absorb heat quickly, whereas the long-term heat sinks continuously remove heat over the long term (e.g., concrete transfers heat to the soil around the bottom of the containment vessel).

Short-Term Heat Sinks

The initial steam release into the containment raises containment pressure. Internal masses absorb heat, condense steam, and reduce the transient pressure. To address the effect of thermal storage on initial pressurization and to evaluate noncondensable gas distributions, surface area and mass were added to the large-scale containment model.

As steam enters the containment from the steam generator compartment, steam and air are forced into the open and dead-ended compartments below the operating deck. Relatively large areas and masses condense the steam, and the remaining air is thermodynamically stable and is expected to remain within the compartments below the operating deck. The partial density of steam above the operating deck increases, together with the rate of diffusion for steam condensing on the vessel walls.

The steel in the compartment walls, deck supports, operating deck cover, and operating deck grating provides some heat storage. On the basis of the surface area available for heat transfer in the applicant’s passive containment cooling design, additional heat transfer area was needed in the LST. Aluminum plates were added to supply additional heat removal from the containment atmosphere. The aluminum plates were designed to provide a relatively short heat transfer time constant. The time constant for effective heat removal from the steam and air containment atmosphere was approximately 100 seconds.

The necessary surface area was provided by aluminum mounted in banks inside the LST facility. The plates were grouped in (1) the dead-ended compartment, (2) the open compartment, and (3) just above the operating deck. The three groups were representative of the additional surface area available in the passive containment cooling design in these three general locations.

Long-Term Heat Sinks

The purpose of representing long-term heat sinks in the LST was to model long-term heat removal and its effect on noncondensable gas distribution. The effect of the long-term heat sinks was modeled in the LST by removing the bottom insulation surrounding the open and dead-ended compartments. Information from AP600 analyses concerning long-term heat sinks, such as heat sink surface area, heat removal rate late in the transient, and the percent of heat removed by the long-term heat sinks, was considered when evaluating long-term heat sink representation in the LST. Tests 218.1, 219.1, 220.1, and 221.1 in the Phase 2 test matrix included the effects of long-term heat sinks.

21.6.5.6.6.2.3 Test Matrix

The tests were conducted in the following phases:

- baseline tests
- Phase 2 tests
- Phase 3 or follow-on tests

Phase 1 Test Matrix

WCAP-13566, "AP600 1/8th Large-Scale Passive Containment Cooling System Heat Transfer Test Baseline Data Report," AP600 Document PCS-T2R-003, Revision 1, October 1992, reported the baseline test results.

Phase 2 Test Matrix

The large-scale Phase 2 test matrix consisted of 12 tests for the AP600. The tests in the Phase 2 matrix covered a range of pressures and operating conditions that were judged by the applicant to be sufficient to verify the ability of the WGOTHIC code to predict pressure and temperature responses to accident scenarios. All the tests were performed with water from the PCS at a temperature of 10 °C (50 °F) to 27 °C (80 °F). The external water flow rates were chosen to simulate the amount of coverage expected on the AP600 plant. The annulus airflow was maintained at an external air velocity of 3.7 m/sec (12 ft/sec) by adjusting the fan speed for all of the tests performed during Phase 2. It was deemed unnecessary to vary the air velocity in this set of tests, because the focus was on internal distributions and heat transfer.

Tests 202.3 and 203.3 repeated the constant-pressure tests performed during the baseline test series (202.1, 202.2, 203.1, and 203.2). They were included to evaluate the effect of the addition of the steam generator model and the bottom insulation, and to obtain additional test data with the enhanced instrumentation.

Tests 212.1 through 221.1 were transient tests with a specified steamflow rate. The effects of the various parameters were investigated by changing one parameter, while all others were held constant. Tests 202.3 through 217.1 addressed the effects of the short-term heat sinks installed in the test facility. Long-term heat sinks were modeled in tests 218.1, 219.1, 220.1, and 221.1 by partial removal of the insulation on the bottom of the test vessel.

For tests 212.1 and 213.1, three steamflow rates were tested as the system approached a steady-state condition after each flow adjustment. The three nominal flow rates selected were 0.1134, 0.2268 and 0.3402 kg/sec (0.25, 0.5, and 0.75 lb/sec). These tests were used to verify the ability of WGOTHIC to predict transient behavior and to demonstrate the effects of different PCS water coverages.

Two tests (214.1 and 215.1) were performed which allowed airflow to develop by natural convection (before turning on the fan) to the 3.7 m/sec (12 ft/sec) air annulus flow. The steamflow rate was held at approximately 0.4 kg/sec (1 lb/sec) throughout the tests. After steady-state conditions were reached, the fan was turned on to exercise the ability of

WGOTHIC to model the transition between free and forced convection. Test 215.1 required that a 180° circumferential section be blocked off so that the annulus airflow only enters around the remaining 180° azimuthal section. This test examined the effect of partial blockage of the air inlet region. The 180° azimuthal blockage was centered around the steam generator.

Test 216.1 was a transient between two steady-state conditions—75-percent PCS coverage and 25-percent PCS coverage in quadrants. This test can be compared to tests 212.1 and 213.1 to evaluate the difference between PCS water coverage in stripes and in quadrants.

Tests 217.1 through 221.1 addressed the effect of long-term heat sinks, helium addition to simulate hydrogen from postulated severe accidents, and steam blowdowns. The tests were performed with helium to simulate the maximum possible hydrogen concentrations. (Helium was used instead of hydrogen for safety reasons.)

The purpose of tests 217.1 and 218.1 was to evaluate the effect of long-term heat sinks on noncondensable distribution. Test 218.1 was similar to test 217.1, with the only difference being the inclusion of long-term heat sinks. After the system had come to a steady state, helium was injected for 30 minutes, and the system was allowed to achieve a second steady state.

The purpose of test 219.1 was to evaluate how the noncondensable gases (specifically, helium) distribute in the following scenario—achieve steady-state without external water flow, inject helium, come to steady-state again, and then start the PCS flow. This test provided data on the effects of rapid cooling of a dry containment on noncondensable distribution.

Tests 220.1 and 221.1 addressed modeling heat transfer to heat sinks and the containment shell, as well as the effects on the flow field during the blowdown phase of a transient.

Test 220.1 modeled a blowdown of a small steamline break (SLB). The blowdown was over within a minute and was used to verify the ability of WGOTHIC to predict transient behavior. The blowdown rate for test 220.1 was based on an SLB at 102-percent power, with a full double-ended rupture and main steamline valve failure. The test represented an AP600 limiting case with respect to containment pressure and temperature. The SLB flow was scaled by volume (1:8) for the LST to produce the steamflow. The steamflow rate was a target test condition; a slightly lower peak flow rate would not have affected the test purpose of verifying WGOTHIC, and the test was not meant to simulate the prototypical accident. This test was used as the blind test for analysis verification.

Test 221.1 modeled long-term cooling during postaccident conditions. This was accomplished by starting the test with water flow on the outside, reaching a steady state after the initial steam blowdown, injecting helium, reaching a second steady state, shutting off the PCS flow, and reaching a final steady state. Noncondensible gas measurements were taken to evaluate the effect of this scenario on helium mixing. The helium injection and the steamflow rate for test 221.1 were based on a small LOCA with an in-containment refueling water storage tank check valve failure. The test was not meant to simulate the prototypical accident, although the prototypical accident was used as guidance so that the conditions in the plant and in the LST would be similar. The steam blowdown for the plant was scaled by volume (1:8) for the LST.

After the blowdown, the flow rate was maintained at a low constant flow of approximately 0.06 kg/sec (0.15 lb/sec).

Phase 3 Test Matrix

Seven tests were identified as part of the Phase 3 test program. The first four were rapid pressurization transients that investigated the effects of the steam discharge location and orientation, and the last three characterized the effect of the initial internal atmosphere on condensation mass transfer.

Test Series 222

LST data from the baseline and Phase 2 tests suggested that noncondensable gas concentrations increase dramatically below the elevation of steam injection, with considerable steam mixing above the operating deck. The effect of the higher steamline elevation could be to create a larger volume of air-rich mixture, which extends above the operating deck and reduces the active heat transfer area. The higher break elevation was representative of an SLB. This series of tests addressed the impact of the elevation and direction of the steamline break on the response of the test vessel and followed the transient blowdown behavior to an ultimate steady-state condition.

The following were the four configurations in this test series:

(1) Test 222.1—low-velocity steamflow from under the operating deck

(2) Test 222.2—low-velocity steamflow at 1.8 m (5.8 ft) above the operating deck

(3) Test 222.3—high-velocity steamflow with horizontal discharge 1.8 m (5.8 ft) above the operating deck

(4) Test 222A—high-velocity steamflow at 1.8 m (5.8 ft) elevation upward

Two steam injection directions were run with both pipe exits at the 1.8 m (5.8 ft) elevation, which was linearly scaled (1/8) to the location of a steamline coming off the top of the AP600 steam generator. The tests were run with nominal 75-percent water coverage and 3.7 m/sec (12 ft/sec) airflow.

Test 223.1

This test permitted a direct measurement of the liquid film heat transfer coefficient by reducing the noncondensable concentrations to a very low level by evacuating the test vessel. The large dome in the LST vessel produced data for nonvertical surfaces that were more prototypical, providing a link to similar data from the Wisconsin condensation tests with pure steam. The data also tested the validity of the Chun and Seban liquid film heat transfer model used in the WGOTHIC code.

Test Series 224

These tests permitted measurement of the effect of a higher noncondensable gas concentration on the transient and steady-state performance of the test vessel to verify the noncondensable partial-pressure effect in the WGOTHIC models at two different steamflow rates. The vessel pressure was increased to 2 atmospheres of air before the start of steamflow.

21.6.5.6.6.2.4 Test Summary

The applicant's evaluation of large-scale PCS test data yielded the following information and conclusions:

- Evaporation was the primary mode of heat removal from the outside of the vessel (approximately 75 percent of the total), followed by sensible heating of the subcooled liquid film (approximately 17 percent of the total). The remainder of the heat was transferred to the environment by convection and radiation.

- The heat removal rate was proportional to the film coverage area in quadrant-coverage cases, but had a weak dependence on the coverage area in striped-coverage cases. For the same film coverage area, striped coverage provided better heat removal than quadrant coverage.

- The heat removal rate appeared to be more strongly dependent on ambient air temperature than on liquid film temperature.

- The heat removal rate has a relatively weak dependence on annulus air velocity, which indicates that the resistance to heat transfer on the inside of the vessel is greater than on the outside.

- For all of the wetted LSTs (except for the horizontal, high-velocity steam jet injection case), the highest heat flux occurred near the top of the dome at the elevation where the external film was applied. Although the dome represented about 30 percent of the heat transfer surface area, approximately 40 percent of the total heat removal occurred on the dome and 60 percent on the cylindrical sidewalls.

- Injection of low-velocity steam resulted in relatively good mixing above the injection location, but stratification occurred below this area, causing air to be concentrated below the operating deck. The heat removal rate increased as the axial steam concentration gradient was increased (by raising the injection location).

- Injection of high-velocity steam resulted in a well-mixed vessel both above and below the operating deck.

- Injection of a light, noncondensable gas did not degrade the condensation heat transfer or affect the overall heat removal. The gas did not stratify (collect at the top of the vessel), but was well mixed above the injection location and was eventually well mixed throughout the entire vessel.

In the LST, condensate was collected from a girder, the inside vessel sidewall, a lower horizontal plane from which rain was collected, the inside vessel (below deck), and a simulated steam generator section. Numerous attempts were made during the course of testing to measure rainout within the test vessel. In no case was any rainout measured. The applicant stated that the lack of rainout was due to the wetting properties of the special coating applied to the interior of the LST shell. Rainout may occur at low PCS water temperatures as a result of condensation shock. However, the staff has determined that rainout should not increase the peak containment pressure, and may even be a slight improvement because these drops would slightly enhance energy removal from the atmosphere to the sump.

21.6.5.6.6.3 PCS Airflow Path Pressure Drop Test

The PCS airflow path pressure drop test was a 1/6-scale, 14.32°-wedge model of the PCS downcomer, riser, and chimney. WCAP-13328 documents the test results, and, as a result of the test, the applicant incorporated some changes to the final design of the air annulus flowpath in the passive containment cooling design. The resulting data were extended, by a factor of 1.5, to account for the higher expected Reynolds number in the applicant's passive containment cooling design. The form loss was later increased an additional 30 percent to account for the design change to the baffle-turning vane in the AP600. The AP1000 uses the same baffle-turning vane, and the same for loss is used in the AP1000 EM.

21.6.5.6.7 WGOTHIC Verification Using LST Data

The applicant used the lumped-parameter model to perform WGOTHIC analyses of selected LST tests. The purpose of comparing the WGOTHIC model to the LST data was to understand how the documented biases apply to the AP600, and to develop guidance for bounding the effects of those biases. The predicted and measured vessel pressures were compared for the priority and nonpriority tests (see Table 21.6.5-9). The initial comparisons were done with WGOTHIC, Version 1.2 (see WCAP-14382). As a result of changes to WGOTHIC resulting in Version 4.1 (see WCAP-14967), selected LST tests were reanalyzed. Data from the LST were also used for separate-effects verification of particular models, as discussed below. Additional changes to WGOTHIC were made, resulting in Version 4.2, which is the current licensing version. The applicant determined, through a regression test as part of the validation effort, that these changes had no impact on the calculated peak pressure.

WGOTHIC 1.2 Verification Studies

The priority tests run with the lumped-parameter EM were tests 212.1A, 212.1B, 212.1C, 2l4.1A, 214.1B, 216.1A, 216.1B, 219.1A, 219.1B, 219.1C, 222.1, 222.4A, and 222.4B.

The steam inlet configuration for tests 212.1A, 212.1B, 212.1C, 214.1A, 214.1B, 216.1A, 216.1B, 219.1A, 219.1B, 219.1C, and 222.1 was a steam diffuser within the simulated steam generator compartment. The steam entered the containment atmosphere as a buoyant plume, as in a post-blowdown LOCA event.

The steam inlet configuration for tests 222.4A and 222.4B was a 7.6 cm (3 in.) diameter pipe located 1.8 m (5.8 ft) above the operating deck. The steam entered the containment atmosphere as a high-velocity jet, as in an MSLB event.

Because the mixing and velocity magnitude inside containment differ significantly in the two configurations, they are discussed separately.

Buoyant Plume Tests

The LSTs conducted with the steam diffuser below deck simulated the postblowdown portion of a LOCA. The heat and mass transfer inside the LST vessel was dominated by free convection. The low-velocity steam injection resulted in relatively good mixing, and created small axial noncondensable gas concentration gradients above the injection location. However, stratification occurred below this location, causing air to be concentrated below the operating deck.

The applicant discussed test 222.1, which had noncondensable gas measurements at four locations within containment, in some detail to explain the characteristics of the lumped-parameter EM.

The lumped-parameter EM overmixes the air (noncondensable gases) from below the injection location and overpredicts the velocity in the vessel. The velocity meter along the wall at A-90° (near the vessel springline elevation) was the only meter functioning for this test. Although the measurement and prediction showed that the velocity was in the downward direction, the predicted velocity was much higher than the measured velocity.

For the lumped-parameter EM, the forced-convection component of mixed-convection heat and mass transfer inside the vessel was neglected, but the vessel was also overmixed. The overmixing carried air above the operating deck. Increasing the concentration of air above the operating deck degraded the mass transfer, thereby reducing the heat removed from the vessel.

The lumped-parameter EM overpredicted vessel pressure for test 222.1, as expected.

The predicted vessel pressure for tests 212.1A, 212.1B, 212.1C, 214.1B, 216.1A, 216.1B, 219.1A, 219.1B, and 219.1C were also overpredicted. The pressure during the initial part of test 214.1A was underpredicted.

The applicant concluded that the initial pressure underprediction for test 214.1A was caused by the modeling of the water coverage. The water-coverage fraction on the exterior vessel surface is a code input parameter. There was some question as to the water-coverage fraction. The water coverage was changed from 100 percent to 78 percent at 3000 seconds in the model, resulting in an underprediction of vessel pressure (for the time period from approximately 1500 seconds to 3000 seconds). The water coverage in the model should have been changed continuously, starting earlier. However, because coverage was not continuously monitored, it was simply modeled as a step change.

<u>High-Velocity Jet Tests</u>

The LSTs with a 7.6 cm (3 in.) steam source simulated the low-velocity portions of an MSLB.

The injection of the high-velocity steam source resulted in a well-mixed containment, based on noncondensable gas measurements. Based on measurements of internal velocity, the heat and mass transfer within containment had a significant forced-convection component.

The lumped-parameter EM uses only free-convection heat and mass transfer models, which conservatively biases the results, because the test actually had a significant forced-convection component. The vessel pressures calculated with the lumped-parameter EM overpredicted the measured pressures for tests 222.4A and 222.4B.

In the EM, the steam is injected at an elevated level as it was in the test. The model predicts a more stratified containment than the measurements. This is because the model entrains fluid into the jet from nodes at or above the steam injection point, resulting in a well-mixed atmosphere above the point of steam injection and an air-rich atmosphere below the steam injection point. This is contrary to the measurements, which show that the kinetic energy from the high-velocity jet mixes the entire containment.

Table 21.6.5-9 of this report shows the average steady-state, predicted-to-measured vessel pressures ratio for all the priority tests. The lumped-parameter EM overpredicts the measured steady-state vessel pressure for all the tests.

The nonpriority tests run with the lumped-parameter EM were tests 213.1A, 213.1B, 218.1A, 218.1B, 224.2, 221.1A, 221.1B, 202.2, 224.1, 217.1A, and 217.1B.

The predicted results for the priority tests were consistent with the nonpriority tests. Table 21.6.5-9 of this report presents the average steady-state, predicted-to-measured vessel pressures ratio for all the nonpriority tests.

<u>Lumped-Parameter Evaluation Model Conclusions</u>

The lumped-parameter EM overpredicts the vessel pressure for steam entering the vessel as either a buoyant plume or a high-velocity jet.

The lumped-parameter EM, used for DBA analyses, does not resolve internal velocity and concentration fields due to its simplified momentum model and large lumped volumes. Comparisons between preliminary versions of the EM and the system-level LST response showed that pressure was reasonably well predicted, with a modest conservative margin. Examination of internal processes by the applicant identified the existence of competing internal effects. The excessive velocities predicted by the lumped-parameter model overpredicted the velocity component of mass transfer. This overmixing underpredicted the steam concentration component of mass transfer. The effect of overpredicted velocities was resolved by using only free convection for internal heat and mass transfer, thereby eliminating velocity from the condensation correlation. The overmixing issue was resolved by examining and biasing the effects of circulation and stratification in the EM, as discussed in Section 21.6.5.7 of this report.

WGOTHIC 4.1 Verification Studies

The results of the WGOTHIC LST integral-model comparisons to the LST data have been used to understand the biases inherent in the WGOTHIC lumped-parameter formulation, as they apply to DBA containment pressure analysis, and to guide the development of the bounding EM. The LST model used nominal inputs for geometry, initial, and boundary conditions so that the effects of the code and noding used could be better isolated. The same WGOTHIC input decks that were used in the Version 1.2 studies were used as input for the WGOTHIC Version 4.1 studies. The inertial length input was modified to account for the change in the "ccvel" subroutine in WGOTHIC Version 4.1. This input change resulted in a similar annulus velocity for the two versions and was done to isolate the effects of other code version changes.

Because the lumped-parameter bias for a specific model is related to the noding chosen, the noding used in the containment pressure DBA EM corresponds to the noding used in the LST validation work (see Section 6 of WCAP-13328). Therefore, the applicant concluded that the biases and guidance developed from the LST models were applicable to the EM.

The upgrade of WGOTHIC solver from Version 1.2 to Version 4.1 does not invalidate conclusions of the LST integral-model validation. Therefore, the bounding approach to address lumped-parameter code biases in the EM remains acceptable.

The following sections summarize the differences in results of the WGOTHIC solver Versions 1.2 and 4.1 for representative LST tests in both the LOCA configuration and the MSLB configuration. The tests covered a range of boundary conditions. Three tests in the LOCA configuration were examined. Test 219.1 had both a dry and a wetted shell and had helium injection. Test 214.1 had natural and forced convection in the annulus. Water coverage for test 216.1 varied from 75 to 25 percent (in quadrants). Test 222.4, in the MSLB configuration, had an initial steam blowdown (lasting about 60 seconds), with an elevated 7.6 cm (3 in.) pipe.

Assessment of Variation in LST Test 219.1 Calculations

Test 219.1 was performed at a constant steamflow and with forced air cooling. The vessel pressure came to a steady state under constant steamflow without any PCS water on the vessel (219.1A). Helium was then injected, and the vessel pressure was allowed to come to a steady state again (219.1 B). The PCS water was then turned on and the vessel pressure steadied to a third level (219.1 C).

While the vessel is dry, the measured pressure lies between the predicted pressure of the two versions of WGOTHIC (i.e., versions 1.2 and 4.1). When the PCS water was turned on, the two versions of WGOTHIC predicted nearly identical pressures, with both about 55 kPa (8 psi) higher than measured.

From 0 to 7600 seconds, Version 4.1 and 1.2 predicted approximately the same vessel pressure. At about 7600 seconds, the two versions began to diverge. The applicant's examination of the steamflow boundary condition showed that, up to 7600 seconds, the model used as-measured steamflows which cyclically varied. From 7,600 seconds to about 16,600 seconds, a constant steamflow was used. Once the input steamflow boundary condition became constant, small variations in circulation due to code version differences began to have an observable effect.

From about 7,600 seconds until the water was turned on (at about 34,000 seconds), the predicted vessel pressure for Version 4.1 was lower (a maximum difference of 7 percent) than both the Version 1.2 predicted pressure and the measured test pressure. After the water was turned on, Version 1.2 and 4.1 predicted approximately the same vessel pressure (Version 4.1 was slightly lower), and both versions predicted pressures about 55 kPa (8 psi) higher than measured.

The difference in calculated pressure between the two versions was consistent with the difference in air concentration distribution during the wet phase C. The calculated air concentrations for tests 219.1A and B showed that the vessel air concentration was somewhat more uniform for Version 4.1 (i.e., more air above deck, less air below deck than Version 1.2). For test 219.1C, the calculated air and helium concentrations for both versions were very similar. In both code versions, the trends in air and helium concentrations were similar. During the dry phase A, the applicant noted that the pressure predicted by Version 4.1 was less than that predicted by Version 1.2, even though Version 4.1 predicted more air above the operating deck. Although the external surface was completely dry, the effect of different annulus cell-centered velocities was more pronounced in Version 4.1. With a completely dry external surface, the resistance to vessel heat removal in the annulus was dominant relative to the condensation resistance, so the different predicted steam concentrations in the two versions had a relatively weak effect on the calculated pressure. In phase C, with water on the outside surface, the external velocity effect was nearly eliminated, and Version 4.1 predicted lower pressure consistent with relatively higher above-deck steam concentrations.

Based on the results from LST test 219.1, the applicant concluded that the net effect of the code changes was not significant for input models that are dominated by an imposed boundary condition. Imposed boundary conditions that can be postulated to dominate the calculation, on the basis of the LST test 219.1 evaluation, include time-varying steamflow rates and actuation of the PCS.

Assessment of Variation in LST Test 214.1 Calculations

The initial part of test 214.1 involved natural convection in the air annulus (214.1A); the second part involved forced convection in the air annulus (214.1B). The steamflow rate was nearly constant throughout the test, with some cyclic variation. Water coverage was measured at the elevation of the outside gutter where the excess water was collected. The water coverage varied in each phase. Based on test observations, the applicant believed that the water coverage actually changed continuously from the beginning of the test until coverage was actually measured. The input model used constant coverage values.

The pressures in the two code versions began to diverge at the beginning of the transient. For this test, the predicted vessel pressure for Version 4.1 was always higher than the predicted vessel pressure for Version 1.2. After the step change in input water coverage, both versions predicted pressures 14 to 34 kPa (2 to 5 psi) higher than measured. The difference in relative code version results was not significantly affected by the change in external airflow when the fan was turned on (at about 9000 seconds). The pressure results were consistent with the noncondensable gas prediction. Version 4.1 predicts less axial noncondensable stratification than does Version 1.2. Because the volume of the below-deck region is only about 20 percent of the total volume, a change in air content below deck results in a relatively smaller change in air content above deck.

The relatively constant input steamflow in this test may have allowed the differences in code versions to be manifested in the air distribution early in the transient and, thus, in the predicted pressure. Both code versions predicted pressures higher than measured once the input water coverage (at 3000 seconds) was set to the measured value.

Assessment of Variation In LST Test 216.1 Calculations

Test 216.1 had a relatively constant steamflow and forced air cooling. The water was distributed over three quadrants for the first part of the test (216.1A), and over one quadrant for the second part of the test (216.1B).

The predicted vessel pressures for Versions 1.2 and 4.1 were very similar, with Version 4.1 being slightly higher. Both versions yielded results 28 kPa (4 psi) higher than those measured. For test 216.1B, Version 4.1 predicted a vessel pressure about 7 percent higher than that predicted by Version 1.2, with Version 1.2 predicting 55 kPa (8 psi) higher than measured, and Version 4.1 predicting 83 kPa (12 psi) or more higher than measured. Version 4.1 predicted more air at dome elevations and less air at lower elevations (operating deck and below deck) than predicted by Version 1.2. Version 4.1 predicted slightly less stratification than did Version 1.2.

Examination of the results for LST test 216.1 again showed that with a relatively constant steamflow, the differences between the two code versions are manifested early in the calculation in a slightly lower stratification gradient, consistent with the variation in pressure.

Assessment of Variation in LST Test 222.4 Calculations

Test 222.4 had a steam blowdown lasting about 60 seconds, followed by a steady steamflow (test 222.4A). The steamflow rate was then increased and allowed to come to a second steady state (test 222.4B). Steam was injected upward into the vessel through a 7.6 cm (3 in.) diameter nozzle, 1.8 m (5.8 ft) above the operating deck. The noncondensable gas measurements showed that this test had a relatively uniform axial air concentration, due to the high kinetic energy of the jet.

Version 4.1 predicted a lower vessel pressure than Version 1.2 throughout the transient, although the differences were small during phase A. The differences between the noncondensable gas predictions for Version 1.2 and 4.1 were small and had the same trend for the four elevations where measurements were taken. At 15,000 seconds, Version 4.1 began to deviate from Version 1.2, with Version 4.1 calculating slightly less air above the operating deck, consistent with the lower pressure in Version 4.1. Both Versions 1.2 and 4.1 predicted significantly more noncondensable axial stratification than was measured, consistent with the lumped-parameter code momentum bias.

The stratification above the assumed break node, inherent in multiple-node, lumped-parameter models, was apparent in both code versions.

Conclusions

Based on a comparison of solver Version 1.2 and solver Version 4.1 LST calculations for test 219.1 compared to tests 214.1 and 216.1, the net effect may be less significant for code input models that are dominated by an imposed, time-varying boundary condition. Imposed boundary conditions that can dominate the solution include changing steamflow rates and actuation of the PCS.

The lumped-parameter momentum bias in open volumes, represented by multiple lumped-parameter nodes, is apparent in both code versions. Thus, it is valid to impose stratification using lumped-parameter biases, as was done for an MSLB, independent of code version.

The following remarks apply to the LST calculations presented:

- When water was applied to the vessel shell, as was done in the containment EM, results from the LST calculations showed that the calculated pressures using solver Versions 1.2 and 4.1 were both higher than the measured pressures.

- The LST calculations can be sensitive to code changes, because the tests lack a flowpath into the simulated steam generator compartment, leading to nonprototypically high steam and air gradients between the above- and below-deck regions. Because of the sensitivity of condensation rate to noncondensable gas content, small increases in calculated circulation from the air-rich vessel heel (the region below deck) affected calculated pressure by as much as 7 percent in the LST.

- The “ccvel” subroutine was upgraded in Version 4.1 to improve the calculation of the cell-centered velocity associated with lumped-parameter fluid nodes. The cell-centered velocity is only used to calculate the PCS heat and mass transfer in the external annulus. The input decks for the evaluations of the effects of code versions discussed in this report differed only in the inertial length input for the external annulus nodes. The resulting cell-centered velocities calculated by the two versions were verified to be similar, so it can be concluded that the “ccvel” changes had no significant impact.

- The LST tests were superheated, so the drop model improvement had no effect.

- The climes did not experience dryout, so the differences noted for LST results were not affected by the clime dryout error correction.

Impact of WGOTHIC Version 4.1 on Separate-Effects Test Calculations

The applicant evaluated the separate-effects tests used to validate the selection of heat and mass transfer correlations by (1) examining the conversion of measured data to nondimensional parameters for direct comparison to correlation results, and (2) employing simple WGOTHIC once-through channel models.

For most tests, where the variation along the test channel (in the direction of flow) was small compared to the parameter of interest, and sufficient data regarding measured boundary conditions were available, a linear variation along the channel length may be assumed. The measured data may be converted to nondimensional parameters by hand calculations and compared directly to correlation results. Test series in this category are Eckert and Diaguila, the applicant's dry flat plate, the applicant's LST dry external heat transfer, Gilliland and Sherwood, the applicant's flat-plate evaporation, University of Wisconsin condensation, and the applicant's LST internal condensation. The code changes did not affect these separate-effects test evaluations used in selecting heat transfer correlations.

For two of the separate-effects test series, boundary conditions such as test section airflow were not provided, or there was significant variation along the channel. For these tests, the WGOTHIC code was used to model a one-dimensional series of nodes along the section length. The simple WGOTHIC models also served to verify the correct implementation of the selected heat transfer correlations. The two series, for which data evaluation was based on a simple WGOTHIC channel model, are the Hugot and the Siegel and Norris tests.

As further verification of the correct implementation of correlations in the WGOTHIC code, simple once-through channel models were documented as part of the applicant's quality assurance program for the applicant's dry flat plate, the applicant's flat-plate evaporation, and the University of Wisconsin condensation tests.

The code upgrades did not change the PCS heat and mass transfer correlations. The applicant concluded that none of the separate-effects tests used as a basis for WGOTHIC models of PCS heat and mass transfer were significantly affected by the code upgrades. Therefore, the basis for selecting PCS heat and mass transfer correlations was unaffected by the upgrade to WGOTHIC Version 4.1. Therefore the code upgrades do not effect the analysis performed for the AP1000.

21.6.5.7 Westinghouse Passive Containment Cooling Design DBA Evaluation

21.6.5.7.1 Key Assumptions

This section presents an evaluation of the applicant's EM for the analysis of DBA events (both the LBLOCA and the MSLB) in the passive containment cooling design. The technical adequacy of the key assumptions in the applicant's DBA EM is addressed. The assumptions underlying the applicant's WGOTHIC EM can be categorized into four technical areas:

(1) containment flow and circulation characteristics
(2) mass and energy releases into the containment
(3) heat transfer to internal structures
(4) heat transfer through clime to ambient (environment)

The following subsections list the key assumptions made in each of these areas by the WGOTHIC EM analyses for DBA LOCA and MSLB events in the containment.

21.6.5.7.1.1 Containment Flow and Circulation Characteristics

- The WGOTHIC lumped-parameter model is applicable, which completely dissipates break momentum in the break node.

- The containment noncondensable gas and steam distribution will be well mixed (nearly homogenized) as a result of the turbulent blowdown, and remain so throughout the peak pressure period. In the long-term period (3 to 24 hours), heat transfer through the containment shell will not be significantly degraded due to the buildup of noncondensable gases near the condensing surface.

- Loss coefficients for intercompartment vents and junctions are constant over all phases of the transient, from turbulent blowdown to relatively quiescent long-term conditions.

Section 21.6.5.7.2 of this report discusses the justification for these assumptions.

21.6.5.7.1.2 Mass and Energy Releases into the Containment

- The applicant's mass and energy release procedure is appropriate for the passive containment cooling design. This procedure neglects the reduction in containment pressure during the LOCA refill phase (when break releases are negligibly small) to conservatively maximize the pressure during the LOCA peak pressure phase, consistent with SRP Section 6.2.1.3.

- ADS-4 valve actuation occurs during the most limiting LOCA event.

21.6.5.7.1.3 Heat Transfer to Internal Structures

- Condensation and convective heat transfer in dead-ended compartments is "turned off" after 30 seconds (i.e., after the end of the turbulent blowdown phase) to address uncertainty in the global circulation pattern in the applicant's passive containment cooling design and any modeling limitations associated with the WGOTHIC lumped-parameter model.

- All compartment floors, including the operating deck, are removed as potential heat sinks to account for both the continuous flooding of most of the below-deck compartments and the detrimental effects of stratification on condensation and heat transfer phenomena, thereby reducing the available heat sink utilization in the EM containment below and above deck.

- Fifty percent of a LOCA liquid break release is arbitrarily converted into drops (as little as 5 percent conversion of the liquid is sufficient to keep the containment atmosphere at saturated conditions). The applicant performed sensitivity studies that showed that this procedure maximizes the peak containment pressure.

- The Uchida correlation is applicable to all containment internal heat sink surfaces and covers all transient phases, from blowdown to long term. The containment shell and dome region are modeled with the WGOTHIC-specific mass and heat transfer correlations, as described in Section 21.6.5.6 of this report.

- A small value (20 mils) is assumed for the gap between steel and concrete for steel-jacketed concrete heat sinks inside containment.

- The condensate film is stripped at the polar crane rail and internal stiffener ring and instantaneously transported to the sump. A similar approach is applied for condensate reaching the operating deck elevation.

- The initial conditions for pressure, temperature, and humidity inside the containment are assumed to be uniform throughout containment.

21.6.5.7.1.4 Heat Transfer through the Clime to the Ambient Environment

- Initiation of PCS water is delayed by 337 seconds after break initiation to conservatively account for the time needed to establish steady-state PCS film flow down the length of the containment sidewall.

- The heat and mass transfer package (see Section 21.6.5.4.2 of this report) embedded in the clime model covers all transient phases from blowdown to long term.

- Free-convection heat and mass transfer at the inside steel shell surface is conservatively assumed for both the LOCA and the MSLB to eliminate the potential bias resulting from overly high predicted velocities in the lumped-parameter modeling approach.

- The evaporation-limited flow model for the PCS film is conservative.

- A 2-D enhancement multiplier can be applied. This multiplier accounts for the expected nonuniformity of thermal conditions for wet and dry outside steel shell surface fractions (striping) over the long-term phase (greater than 3 hours) of the LOCA.

21.6.5.7.2 Containment Flow and Circulation Characteristics

The applicant described the post-LOCA circulation patterns in the passive containment cooling design as follows:

> Following the LOCA blowdown phase, natural circulation is expected to be the dominant mechanism for containment atmosphere circulation. Once the ADS Stage 4 valves are actuated, hot steam is expected to rise from the SG compartments up to the containment dome region. As the hot steam contacts the containment inside steel shell surface it is being condensed and the cooled noncondensable gas-steam mixture will flow downward along the containment

shell back towards the operating deck and CMT room floor, where the mixture may reenter the steam generator cubicles through the open doorways. The cool mixture will be entrained with the hot steam source from the ADS valves and rise again.

Because the EM utilizes the lumped-parameter approach, predictions of flows and directions along the flowpaths to match the anticipated global circulation pattern are of limited value. Open doorways in the east and west steam generator cubicles at the operating-deck elevation play a crucial role in the applicant's arguments for a sustained global circulation. The applicant pointed out that similar circulation patterns also develop over the height in the west containment quarter; however, Figures 4-130(a) and (b) in WCAP-14407 did not readily confirm this.

The applicant also referred to several flowpaths between volumes above the elevation of the reactor pressure vessel upper head flange and the operating-deck elevation which supposedly support atmospheric circulation between the regions below and above the operating deck. As a result, the applicant expected a homogenization of the atmosphere above the operating deck, such that no transverse steam-air concentration gradients exist. However, the figures in WCAP-14407 cited by the applicant did not show the time histories of steam-air concentrations across the operating-deck elevation. Rather, the figures showed flow rates and steam concentrations, which are not representative of typical operating-deck volumes.

The applicant's arguments and assertions that global circulation in the dome through doorways in the steam generator cubicles will homogenize the containment atmosphere were incomplete for the following reasons:

- The LST facility did not account for the doorway opening as a flowpath. Therefore, LST data could not be used to confirm that circulation loops were being sustained, given the prevailing sources, sinks, channel and doorway openings, and respective flow resistances along the circulation paths involving both east and west steam generator compartments in the applicant's passive containment cooling design.

- Above-deck circulation loops call for the existence of axial and transverse gradients as driving forces. The existence of such circulation patterns seems implausible, if in fact both experimental and analytical results are applicable to the conditions under consideration. A perfectly homogenized containment atmosphere would invalidate the simultaneous existence of the circulation loops.

- The applicant discussed circulation loops throughout WCAP-14407; for example, in Sections 4 and 9, the applicant asserted that atmosphere circulation through flowpaths connecting the below- and above-deck regions homogenize the atmosphere mixture so that "no significant concentration gradient exists across the operating deck."

- Even if the circulation loops were sustained over time, these loops only affect the dome volume in the vicinity of both steam generator cubicles, which is a rather small region compared to the total dome volume. Most of the dome volume would not be affected by the type of global circulation through the steam generator cubicles cited by the applicant.

- The lumped-parameter network model for the above-deck region tended to artificially overpredict flow rates and circulations.

- The long-term steam concentration of 45 percent, predicted by the WGOTHIC EM for most of the dome region, appeared to be high in view of the expected effectiveness of the PCS and may have been the result of (1) the artificially high predicted circulation, (2) numerous conservatisms implemented into the EM, or (3) a combination of both.

Appendix D to Section 9 in the applicant's WGOTHIC application reports (WCAP-14407 and WCAP-15846) addresses the treatment of heat transfer in a sufficiently conservative manner to accommodate temperature stratification and horizontal concentration gradients.

The applicant's theoretical model consists of three regions—region 1, the plume, including an upper region below the steel dome whose boundaries are undefined; region 2, the recirculating stratified region; and region 3, the negatively buoyant, turbulent gas boundary layer. A region just above the operating deck is undefined. The model, as presented, is based on first-principle elements, such as a jet/plume and a negatively buoyant boundary layer, coupled by a top feed and bottom source with some entrainment into both the plume and the boundary layer. The applicant did not list the thermal boundary conditions; however, during discussions held with the staff reviewers, the applicant indicated that the boundary conditions were obtained from the measured LST results. This theoretical model assumes that a Gaussian plume with a half angle of 7.5° reaches the dome, even though the plume must pass through an equipment-filled steam generator compartment. As time progresses, an air-enriched layer will move downwards from the dome and jet buoyancy will decrease. Strictly speaking, the applicant's model should apply only to momentum-controlled jets, although most break jets would be considered buoyant once blowdown ends and the primary system and containment pressures have equilibrated.

Although limited and oversimplified, this approach constitutes a working model, with quantitative results displayed in several tables in Appendix 9D to WCAP-14407. The applicant applied this boundary layer approach to two LST tests (tests 220.1 and 217.1). The comparisons presented showed good agreement with the measured bulk air concentration value, with the plume centerline air concentration value consistently slightly higher than the comparable measured values. The driving forces from the LOCA or MSLB in the AP1000 are similar to those in the AP600 and the model developed for WGOTHIC is also applicable to the AP1000.

Several of the applicant's observations warrant further discussion. One is that for the compared conditions, a substantial stratification existed low in the LST facility (between regions D and E) during both tests. The applicant chose to qualify these results as showing some level of stratification and attribute it to LST distortions (e.g., no flow connection from the simulated steam generator compartment). The staff believes that the elimination of global circulation throughout the LST did, in fact, lead to the accumulation of noncondensable air atop the operational deck. This phenomenon resulted from continuous condensation at the inside steel shell and applies to the applicant's passive containment cooling design. Moreover, the test data indicate that the rising plume is unable to entrain this accumulated air layer (as claimed by the applicant in Section 9 of WCAP-14407). WGOTHIC, however, conservatively treats this effect by not taking credit for the heat transfer from the operating deck itself;

consequently, the buildup of air on, or the entrainment of air from, the operating deck is not needed (see Section 21.6.5.8.3 of this report).

21.6.5.7.3 Break Scenarios

21.6.5.7.3.1 Loss-of-Coolant Accidents

The double-ended, cold-leg guillotine (DECLG) rupture is the most limiting design-basis LOCA for the containment pressure response because it postulates the break of a high-energy primary coolant pipe. A mixture of water, steam, and droplets is released into the break compartment and propagates to neighboring compartments below the operating deck.

The applicant identified the east steam generator compartment as the break compartment, with the break elevation beneath the operating deck. The applicant's passive containment cooling design relies on passive means to mitigate the containment pressure increase for DBAs. The applicant assumed that the non-safety-grade containment fan coolers do not operate.

The liquid released from the break and collected as condensate fills the reactor cavity and lower portions of the steam generator and the reactor coolant drain tank (RCDT) cavity during the blowdown of the primary system. As a result of the continued steam release from the break and the resulting condensation, as well as the ongoing operation of the PXS, the liquid level below the operating deck continuously rises during the containment transient and reaches the CMT room elevation. At this point, sufficient water has accumulated in the lower region to reach the CMT floor elevation. After this occurs, the flooded compartments and their interconnecting vent flowpaths cannot serve as long-term heat sinks and flowpaths.

The staff's acceptance of the lumped-parameter representation in the EM is based on the condition that the containment atmosphere is relatively homogenous as a result of the break momentum. In its letter dated March 25, 1998 (DCP/NRC1314), the applicant provided additional information for LBLOCAs, including a 17.8 cm (7 in.) CMT balance line break. The momentum, as denoted by the Froude number, for these breaks indicated that the containment atmosphere is relatively homogenous, even for these smaller breaks. Therefore WGOTHIC results, based on the lumped-parameter representation in the EM, are acceptable for addressing the LOCA break spectrum to determine the limiting break.

The staff has completed its review of the methods and assumptions used to calculate the LOCA mass and energy releases for the AP1000. The LOCA mass and energy releases are conservatively calculated with an approved model and are consistent with the guidelines in the SRP. This source term treatment, as discussed in Section 21.6.5.4.1.2 of this report, in the EM is acceptable.

The Office of Nuclear Regulatory Research (RES) presented the results of preliminary analyses for a coupled containment-to-RCS LOCA evaluation during the June 12, 1998, meeting of the ACRS Thermal-Hydraulic and Severe Accident Subcommittee. The coupled containment-to-RCS analyses were performed with the RELAP5 computer program using a model of the AP600. A special model was added to RELAP5 to simulate the AP600 PCS and containment response to a LOCA. The PCS heat transfer was characterized from NRR CONTAIN analyses.

Testing and Computer Code Evaluation

The RES analysis method differed from the staff-approved method used by the applicant for its DBA studies. The RES study included the containment-to-RCS interaction in determining the LOCA mass and energy releases. The RES analyses demonstrated the conservatism of the approved methodology that was used for the evaluation of the AP600 containment response to LOCAs. The RES analyses indicated that the energy released to containment, using the approved method, controls the calculated containment pressure response. RES Assessment Report RPSB-98-07, "Containment/RCS Analysis of a Large-Break Loss-of-Coolant Accident in the AP600 Using RELAP5/MOD3," issued August 1998, documents the analyses. This result remains valid for the AP1000.

21.6.5.7.3.2 Main Steamline Breaks

The applicant performed a parametric study of 16 cases (4 breaks at 4 initial power levels) to identify the worst-case scenario for the MSLB accident. The spectrum of break sizes examined included the following:

- a full, double-ended pipe rupture downstream of the steamline flow restrictor, with a nominal throat area of 0.129 m^2 (1.388 ft^2). The reverse flow from the intact steam generator is conservatively assumed to be controlled by the flow restrictor

- an intermediate-size, double-ended break with an area of 0.037 m^2 (0.4 ft^2)

- a small, double-ended break with an area of 0.009 m^2 (0.1 ft^2)

- a split rupture (the largest break that does not generate a steamline or feedwater isolation signal)

The applicant has shown that the availability of offsite power results in the most limiting case and maximizes the mass and energy releases from the break. All cases which were analyzed to determine the limiting MSLB event assumed the failure of one MSIV. The applicant identified the full, double-ended rupture at 30-percent power as the limiting MSLB break scenario for peak containment pressure. This is the result of a combination of mass and energy release and a high Froude number, indicating a momentum-driven jet.

The MSLB mass and energy release analyses were performed using an approved model and in compliance with the guidance provided in the SRP and NUREG-0588. The MSLB analyses used a value of 8 percent revaporization, consistent with acceptable guidelines developed by the staff in NUREG-0588.

Limiting MSLB Break Location

The path of the main steamline (MSL) begins at the top of the steam generator, where it bends 180° and follows a downward path to the CMT room. It then bends 90° to cross through the CMT room and exits through a containment penetration. A break at any position along this pathway would release very high-energy steam into the containment over a short time.

The applicant examined possible break positions in the steamline above the operating deck, as well as possible break positions in the steamline in the CMT compartment, to develop a conservative model which, for the purpose of a conservative containment pressure calculation, accounts for the potential effects of circulation and stratification inside the dome.

The applicant performed its analyses with the EM, including the stratification heat sink biases specifically developed for the DBA LOCA, for the break positions listed above.

The same lumped-parameter nodalization developed for the LOCA evaluations is used for the MSLB evaluations, including the treatment of dead-ended compartments and heat sinks. The only difference is the selection of the node for the break source. For MSLB breaks above the operating deck, the break location initially proposed by the applicant was a node just above the operating deck. The below-deck MSLB break was modeled in the CMT room. As the CMT room has large heat sink surfaces and provides access to the other below-deck compartments, the WGOTHIC-computed peak pressure was 11 kPa (1.6 psi) below the value obtained for the MSLB break position above the operating deck. Subsequent to this sensitivity study, and in response to staff concerns, the applicant moved the MSLB break location to an elevated node, which represents the highest steamline elevation for SSAR analyses.

The MSLB mass and energy releases are calculated with an approved model and are consistent with the guidelines in the SRP. This source term treatment in the EM is acceptable.

21.6.5.7.4 Conservative Input Parameters

Section 16 of NAI-8907-06, “GOTHIC Containment Analysis Package Technical Manual, Version 4.0,” Revision 3, provides general modeling guidance for GOTHIC/WGOTHIC. These general T-Hs modeling recommendations are intended to give best-estimate model performance. The applicant modified selected model parameters to add conservatism to the DBA EM to be consistent with the guidelines in the SRP and RG 1.70.

21.6.5.7.4.1 Break Mass and Energy Releases

Conservatively high mass and energy sources are used in the EM, consistent with the guidance provided in SRP Section 6.2.1.3. The LOCA refill period, during which there is no release, is conservatively eliminated. The staff accepts the use of conservatively high mass and energy release in the EM.

The blowdown is specified using constants or forcing-function tables to describe the transient pressure, enthalpy, and fluid flow condition. Because the boundary condition is connected to a lumped-parameter volume, it is not crucial that the boundary pressure trace the actual pressure, because the source momentum is dissipated.

21.6.5.7.4.2 Break Elevation and Direction

For the LOCA, the location, elevation, and direction of the break were taken to maximize the peak pressure by limiting interactions with the below-deck compartments. For the MSLB, the applicant originally assumed a break location considered unacceptable by the staff for the design application. The applicant revised its methodology to use the highest possible elevation for the MSLB. Since the break locations maximize the peak pressure, the staff finds both limiting-break locations acceptable.

21.6.5.7.4.3 Break Density and Droplet Diameter

Numerous researchers have documented the effect of entrained drops in the containment atmosphere during and after DBA LOCA events in the following references:

- Gido, R.G., and A. Koestel, "LOCA Generated Drop Size Prediction, A Thermal Fragmentation Model," ANS 1978 Winter Meeting, Washington, DC, November 12–17, 1978

- Koestel, A., and R.G. Gido, "LOCA Drop Size Estimates," NUREG/CR-1607, LA-8449-MS, August 1980

- Almenas, K.K., and J.M. Marchello, "The Physical State of Post-Loss-of-Coolant-Accident Containment Atmospheres," Nuclear Technology, Volume 44 (1979), pages 411–428

- Gido, R., D. Lamkin, and A. Koestel, "Mechanistic Dry-Pressure-Containment LOCA Analysis," NUREG/CR-2848, January 1983

The following observations can be made about the effect of entrained drops in the containment atmosphere during and after DBA LOCA events from the above literature:

- As a result of the drops, the atmosphere's thermodynamic conditions are completely saturated.

- The drop-mechanistic approach results in an approximately 5-percent lower atmospheric pressure and slightly lower temperature than the approach used in CONTEMPT, which assumes that blowdown is instantaneously transported to the sump and atmospheric liquid rains out.

- The drop-mechanistic approach results in an approximately 2-percent lower atmospheric pressure and significantly lower atmospheric temperature than does the partition approach. The partition approach considers the possibility that the break flow is partitioned into separate liquid and vapor phases. The liquid is assumed to go directly to the sump, whereas the vapor phase is introduced into the containment vapor/air volume to determine pressure and temperature.

A nominal liquid-drop diameter of 0.01 cm (0.00394 in.) is generally used for blowdown analysis based upon experimental test results. The influence of drop diameter on the containment pressure response should be examined over a range of 0.001 to 0.10 cm (3.9E-4 to 3.9E-2 in.). The forced-entrainment drop diameter in GOTHIC specifies the drop size to be used in lumped-parameter volumes when a portion of the wall condensation rate, representing condensation dripping from ceilings and suspended equipment, is converted to drops. The nominal, or default, value of 0.253 cm (0.1 in.) is based on experimental data comparisons of GOTHIC with blowdown experiments. The value used by the applicant is 0.0002 cm (8.5E-5 in.). This is relatively small, but acts together with the large droplet fraction (50 percent of the break source) assumed in the EM. Sensitivity studies performed by the applicant, as discussed in Section 21.6.5.4.1.4.2 of this report, showed that the droplet assumptions in the EM are conservative.

When the containment atmosphere is superheated, a portion of the condensate will revaporize from passive heat sink surfaces. NUREG-0588 recommends a maximum revaporization fraction of 0.08 (i.e., a mass condensation fraction of 0.92) which the applicant uses for the MSLB. Therefore, the staff finds this aspect of the model acceptable.

21.6.5.7.4.4 Hydrogen Release

No hydrogen is explicitly considered in the constituents of the break flow. However, the energy equivalent to 1 percent of the zirconium in the fuel region is included in the break energy. This is consistent with the guidance provided in SRP Section 6.2.1.3. The staff, therefore, finds this aspect of the model acceptable.

21.6.5.7.4.5 Heat and Mass Transfer

Economos, et al., surveyed state-of-the-art methods for condensing heat transfer modeling ("Condensation Heat Transfer Modeling for Containment Environmental Response Calculations - A Reappraisal for the Standard Review Plan," Brookhaven National Laboratory, Upton, NY, for US NRC, Office of Nuclear Reactor Regulation, June 1987) to examine the applicability of these methods for containment response to a postulated MSLB. The objective of this study was to develop a technical basis for possible use in improving the CONTEMPT series of computer codes, specifically in the area of condensing heat transfer, in the context of improving the SRP. This study presented an update of the investigation by Slaughterbeck for AEC in 1970. From the review, the following three correlations were selected for comparison in this study—(1) the Uchida correlation, (2) the Almenas correlation, an empirical model developed from German BMC and HDR experiments, and (3) the Gido-Koestel (G-K) correlation, a phenomenological method based on boundary layer concepts. The latter two correlations were implemented in CONTEMT4/MOD6 to allow comparative studies of the correlations with the approved licensing Uchida model. Brookhaven National Laboratory (BNL) performed 30 computations (with numerous parameter variations) for the CVTR (test 3), BMC (D-15), and HDR (V21, V42, V44) experiments, as well as for a typical PWR application. Lumped-parameter models ranging from one to six nodes were used for the simulations. The Uchida correlation was computed with 8-percent revaporization, unless turned off for the purpose of parameter variation.

The computational results were compared with the data and with each other. A major outcome of these comparisons was that neither of the two new heat transfer models provided any substantial improvement in predictive capability over the Uchida correlation, the currently approved licensing model.

George and Singh ("Separate Effects Tests for GOTHIC Condensation and Evaporative Heat Transfer Models," Proc. 3rd Intl. Conf. Containment Design and Operation, Toronto, Canada, October 19-21, 1994) evaluated the application of the GOTHIC code for two separate-effects test facilities:

(1) the University of Wisconsin condensation tests, which are also a major part of the applicant's basis for the validation of heat and mass transfer correlations (see WCAP-13307, "Condensation in the Presence of a Noncondensible Gas: Experimental Investigation," and I.K. Huhtiniemi,"Condensation in the Presence of Noncondensable Gas, Effect of Surface Orientation," PhD Thesis, Department of Nuclear Engineering and Engineering Physics, University of Wisconsin, Madison, Wisconsin, August 1991)

(2) Pacific Northwest Laboratories evaporation tests (see L.M. Bagaasen,"106-AN Grout Pilot-Scale Test HGTP-93-0501-02," PNL-8618/UC-510, 1993) on a grout mixture used for long-term storage of hazardous waste from a heated pool to a superheated atmosphere

University of Wisconsin Condensation Tests on Vertical and Inclined Flat Plates

The University of Wisconsin experiments reported results for the flat-plate geometry. Parameters varied in the experimental test series included the inlet temperature, steam partial pressure, flow rate, and plate inclination angle from the horizontal. The applicant provided an overview of these experiments in WCAP-13307. The heat transfer rates and coefficients were deduced from the measured temperature rise and flow rate of the oil coolant on the coolant plates at the back side of the condensing test plate, and from the measured temperature profile near the condensing surface of the test plate. Local heat transfer coefficients were obtained at seven axial locations and then combined, resulting in an average heat transfer coefficient for the total test section.

The GOTHIC model for this test section used a lumped-parameter single volume (for consistency with the common lumped-parameter approach), large computational nodes, and bulk conditions to compute heat and mass transfer. As the test transients were sufficiently slow relative to the air-steam turnover rate in the test section, the computed results could be considered quasi-steady and comparable to the data. A total of nine experiments, all with vertical plate orientations, were simulated with GOTHIC, covering a velocity range from 1 to 3 m/s (3.3 to 9.8 ft/s), a steam mole fraction from 0.312 to 1.000, and temperatures from 69.8 °C (157.6 °F) to 97.2 °C (207 °F).

The Uchida correlation returned a larger-than-measured heat transfer coefficient for velocities around 1 m/s (3.3 ft/s), while the G-K correlation provided a lower bound. Both correlations simulate the correct trend for increasing steam concentration. At higher velocities of 2 to 3 m/s (6.6 to 9.8 ft/s), the Uchida correlation (although its values remain unchanged) tended to underpredict the heat transfer coefficient with increasing velocities. The G-K correlation provided an upper limit at 3 m/s (9.8 ft/s) and matched the data very well. The cutoff value of about 1500 W/m^2K (264 $Btu/hr\text{-}ft^2$ °F) of the Uchida correlation at the velocity of 3 m/s (9.8 ft/s) is consistent with the upper limit set forth for licensing applications. The authors also mentioned that one- and two-dimensional GOTHIC models of the test section provided average heat transfer coefficients which were very close to those obtained from the lumped-parameter, single-volume model.

Pacific Northwest Laboratories Evaporation Tests

The comparisons with the PNL evaporative-pool tests confirmed the GOTHIC interfacial heat transfer logic and correlations. However, the authors pointed out the importance of selecting the proper heat and mass transfer correlations for the specific geometry and flow regime under consideration. In this context, local variations are especially important under low-flow conditions, and can only be accounted for with the distributed-parameter (subdivided) GOTHIC model in the region above the evaporating surface.

Additional Test Data

The determination of heat transfer coefficients during the blowdown phase was a major objective of the early BMC tests and HDR experiments. The focus shifted toward the post-blowdown phase in the mid-1980s, with added interest in severe accidents. Consequently, later HDR LOCA testing was expanded with numerous heat transfer blocks, fabricated from concrete, lead, and steel, and distributed at different axial positions throughout the HDR containment. Some blocks were mounted flush with concrete surfaces, while others were standalone units (those located at the operating deck). To obtain meaningful results for medium- and long-term post-blowdown time periods, inverse, multidimensional methods were applied to cope with continuously decreasing temperature differences over time.

The heat transfer coefficients were deduced from the HDR experiment T31.1 (Blowdown Experiments in a Reactor Containment, Quick Look Report, Test Group COND, Experiments T31.1-3, (in German), Technical PHDR Report No. 57/85, Nuclear Center Karlsruhe, Germany, 1985) for three different time periods of 0 to 200 seconds, 200 to 600 seconds, and 10 to 120 minutes. The calculated heat transfer coefficients using the Uchida correlation for the same time intervals were evaluated. The measured and computed heat transfer coefficients reflect the containment behavior over time at different axial elevations. Thus, they supplement the separate-effects tests results discussed above.

The HDR experiment T31.1 heat transfer coefficients computed from the Uchida correlation were below the measured values for most of the test duration and at all elevations shown. They were especially conservative during the blowdown phase in the break compartment and the compartments in its vicinity. During the time period of 200 to 600 seconds, the heat transfer coefficients were either conservative by a factor of 2 or approximately matched the data, depending upon position. During the long-term phase, 10 to 120 minutes, the Uchida correlation values were either conservative by a factor of 2 to 3 over a certain time window, or nonconservative by about the same factor, depending upon the position in the HDR containment. With time, however, this factor became smaller.

21.6.5.7.4.6 Material Properties

Material properties were chosen in a conservative manner with both heat capacity and thermal conductivity biased in the low direction. This conservative approach is acceptable.

21.6.5.7.4.7 Initial Conditions

Conservative values are used to specify the initial conditions consistent with the EM approach. This is an acceptable approach. Tables 21.6.5-10, 21.6.5-11, 21.6.5-12, and 21.6.5-13 of this report specify the conservative initial conditions selected for various physical quantities.

21.6.5.7.5 Geometry

21.6.5.7.5.1 Nodalization

The WGOTHIC model lumped-parameter nodalization was developed to minimize transport of steam to the containment shell, based on numerous nodalization sensitivity studies. This modeling approach minimizes intercompartmental flow. Table 21.6.5-14 of this report summarizes the conservative characteristics of the model.

The heat and mass transfer model for the shell is applicable, provided that the bulk steam concentration in the nodes adjoining the shell can be accurately or conservatively predicted. Bulk parameters are used in the heat and mass transfer correlations. When the containment is well mixed, the staff accepts the lumped parameter WGOTHIC model as adequate for calculating the peak containment pressure with the EM. As discussed in Section 21.6.5.7.2 of this report, the applicant has provided adequate information to justifiy the use of the lumped-parameter model.

The question of how long the containment remains well mixed following blowdown is difficult to answer. For an MSLB, the break source is nonzero only during the blowdown. The peak pressure occurs near the end of the blowdown. The calculated peak pressure is the licensing criterion. Following the peak pressure, without a break source, the pressure will decrease. Therefore, the shell heat transfer in WGOTHIC is acceptable for the conservative MSLB calculations.

For a LOCA, the containment atmosphere will eventually stratify. However, at least up to the peak pressure, a buoyant plume will continue to drive mixing. In NSD-NRC-98-5526, dated January 16, 1998, the applicant indicated that the steam concentration in the containment will have uniform gradients in the horizontal direction, except in the plume and in the boundary layer next to the wall. While the state which results is not well mixed, it is one for which lumped-parameter models are capable of calculating peak pressure in a conservative way, as discussed in Section 21.6.5.7.8 of this report.

To perform containment peak pressure design-bases analyses, the applicant selected a lumped-parameter modeling approach in WGOTHIC for use in the containment EM. Chapter 4 of WCAP-14407 documents the lumped-parameter control volumes, junctions, thermal conductor types, and their associated quantities for the AP600. Chapter 13 of WCAP-15846 documents the lumped-parameter control volumes, junctions, thermal conductor types, and their associated quantities for the AP1000. Special modeling assumptions for each major compartment are listed in individual subsections. Cutaway views, perspective views, and cross-sections of different planes supplement the descriptions, the tables of geometrical quantities, and input parameters listed in the respective subsections.

This information indicates that three distinct regions exist in the containment EM. The first region comprises all compartments below the operating deck, the second region represents the large, free dome space and the associated infrastructure, and the third region is the dome steel shell with its neighboring regions (i.e., riser, steel baffle, downcomer, and outer concrete (shield building) wall). WGOTHIC models the first two containment regions using the lumped-parameter representation in GOTHIC. The third region is modeled with the clime model. Section 21.6.5.4.2 of this report provides details of the clime model, which the applicant added to GOTHIC to model the PCS. The clime model connects the containment atmosphere to the shell by evaluating the mass and energy source term from the adjacent above-deck containment nodes to the interior shell surface (when dry) or the surface of the condensate film.

The regions below and above the operating deck are connected by a limited number of flow connections with small cross-sectional flow areas. These flowpaths represent the two steam generator compartments and a few auxiliary openings, such as staircases and the elevator shaft. The flowpaths allow for mass, momentum, and energy exchanges during the accident transients. The dome steel shell only transfers heat between the internal and external containment regions.

The loss coefficients used in the EM were selected to represent the longer term, post-blowdown flow rates expected. These same coefficients were used during the blowdown and are conservative with respect to the pressure response. Sensitivity studies performed by the applicant show that selected loss coefficients have a weak dependency on the pressure. Therefore, the method used to obtain the loss coefficients is acceptable for licensing analyses for the AP1000.

The below-operating deck compartments are modeled as single-control volume nodes connected by appropriately defined junctions. No further subdivision is applied over the axial extension of these compartments, except for the steam generator wells to accommodate the Stage 4 ADS valves. The large CMT room has been modeled as two nodes separated at the pinch line. This modeling choice provides the simplest representation possible in the lumped-parameter approach.

The large, above-operating deck region has been subdivided into a network of lumped-parameter nodes, with axial levels and radial regions over the height of the vertical cylindrical section of the containment. Above that vertical cylindrical section, radial nodes represent the curved dome shape with additional axial levels. Each radial region represents a quarter segment of the total dome circumference. Thus, at first sight, the above-operating deck lumped-parameter network is an unusually detailed model. All containment external airflow channels are also axially subdivided into levels to match the vertical and dome levels inside the containment. However, the detailed azimuthal subdivision exercised inside the containment is not used for the flow channels external to the shell. One flow channel represents the total circumference of the riser, and another represents the downcomer. This constitutes a lumped-parameter modeling approach emphasizing the axial direction. It does not model potential asymmetries in the circumferential direction.

Compartments below the operating deck are generally modeled as separate computational nodes. While the nodes above the operating deck are not necessarily bounded by walls, they are arranged in regular stacks and aligned based on structures and geometric changes (e.g., steam generator compartments and cylindrical sections of the dome). Adjacent stacks are defined such that they are aligned with the same elevations in accordance with the user guidelines provided in the NAI GOTHIC technical manuals. This modeling procedure reduces artificial flows induced by connecting nodes of different heights and elevations to a minimum and must be applied across the total model region of interest. Consequently, the applicant has consistently interfaced the inside containment nodalization structure to the climes and their associated elevations. In this way, a network of ordered stacks of lumped-parameter nodes inside the containment is coupled to similar stacks of climes representing the PCS and associated volumes for riser and downcomer annuli.

This lumped-parameter nodalization scheme has developed over time, along with the modeling of the LST experiments and the development of the WGOTHIC distributed-parameter models. It has been tested for most of the LST experiments. Although originally developed for the DECLG LOCA, the same nodalization and assumptions are used for evaluating MSLB accidents. Based on the above, the staff finds the nodalization scheme developed for use in the WGOTHIC EM for the peak pressure analyses of the applicant's AP1000 passive containment cooling design to be acceptable.

21.6.5.7.5.2 Break Source Momentum

The lumped-parameter model dissipates break source momentum in the break volume. Because increased momentum will promote mixing, this approach is generally conservative. However, momentum directing the break flow upward can potentially promote stratification; therefore, use of the lumped-parameter model alone does not ensure a conservative treatment of the break source momentum effects. Because break source momentum becomes enmeshed with the entire lumped-parameter treatment, it is evaluated as a part of the lumped-parameter modeling approach.

21.6.5.7.5.3 Heat Conductors

Condensation and convective heat transfer in dead-ended compartments is turned off after 30 seconds (i.e., after the end of the turbulent blowdown phase) to address uncertainty in the global circulation pattern in the applicant's passive containment cooling design, as well as in the modeling limitations associated with the WGOTHIC lumped-parameter model.

All compartment floors, including the operating deck, are removed as potential heat sinks to account for both the continuous flooding of most of the below-deck compartments and the detrimental effects of stratification on condensation and heat transfer phenomena. This reduces the available heat sink utilization in the EM containment below and above deck.

One-dimensional heat conduction in slab geometry with a conservatively large air gap between steel and concrete is an acceptable modeling approach because the large air gap reduces the heat transfer from the containment resulting in a conservative pressure calculation. The reduced heat transfer increases the containment pressure

The Uchida correlation has been demonstrated to be appropriate for use on the internal heat sinks; in addition, its use is consistent with the guidance found in SRP Section 6.1.2.

Free-convection heat and mass transfer at the inside steel shell surface is conservatively assumed for both the LOCA and the MSLB to eliminate the potential bias resulting from the overly high predicted velocities using the lumped-parameter modeling approach. Accordingly, the free-convection mass and heat transfer models are acceptable for use in the WGOTHIC EM for the AP1000.

21.6.5.7.5.4 Pools and Below-Operating Deck

Stratification in the break pool is included by vertical stacking of the nodes. Noding maximizes evaporation from a pool and minimizes condensation, allowing hotter liquid to remain at the pool's surface. Water pools are assumed to be homogeneous. A constant pool cross-sectional area is assumed. This is a conservative treatment and is acceptable to the staff.

21.6.5.7.6 Modeling Limitations

WGOTHIC automatically adjusts time step size during the transient solution, increasing the time step up to a maximum specified limit when the transient is nearly stable, and decreasing the time step down to a specified lower limit when rapid changes or convergence difficulties occur. The adequacy of the time step should be determined from the mass and energy error provided in the output file. The user's manual for WGOTHIC specifies a mass and energy error of less than 2 percent as acceptable for determining the maximum containment pressure response without need for a further reduction in time step size.

21.6.5.7.7 WGOTHIC Evaluation Model Validation

In Section 9.C of the applicant's WGOTHIC application reports (WCAP-14407 and WCAP-15846), the applicant documented the test results from a large set of international test facilities. These test results included comparisons with the computational results from WGOTHIC. The staff's review of this material reveals the following:

- The applicant provided extensive information for the Battelle Model Containment (BMC) tests and HDR experiments. Most of the material presented shows hydrogen/helium concentration histories rather than the equivalent set of steam concentration histories, which were also available.

- The applicant participated in the International Standard Problem on Nuclear Power Engineering Corporation (NUPEC) of Japan Test M-7-1, with a blind WGOTHIC prediction. The WGOTHIC results, with the predictions by other institutions, have been published by Organization for Economic Co-Operation and Development (OECD) in Nuclear Energy Agency (NEA)/CSNI/R(94)92. However, this experiment examined the mitigating effect of internal containment sprays. As the applicant's passive containment cooling design has no internal safety-related spray system, this validation effort for WGOTHIC does not apply directly to PCS-related issues.

- In preparation for test M-7-1, NUPEC also provided data from test M-4-3 for the development of proper input data for the facility geometry and boundary conditions. The applicant performed a WGOTHIC prediction for this experiment, the results of which have been presented in a paper by Ofstun, R.P.; Woodcock, J.; Paulsen, D.L., Westinghouse-GOTHIC Modeling of NUPEC's Hydrogen Mixing and Distribution Test M-4-3, 3rd Intl. Conf. On Containment Design and Operation, Toronto, Canada, October 19-21, 1994, which is summarized in Section 9.C of WCAP-14407 or WCAP-15846.

- The applicant also participated in the analyses of HDR test E11.2 (Narula, J.S.; Woodcock, J., Westinghouse-GOTHIC Distributed-Parameter Modeling of HDR Test E11.2, 3rd Intl. Conf. on Containment Design and Operation, Toronto, Canada, October 19-21, 1994).

Non-LST-Related WGOTHIC Validation Efforts

The GOTHIC code has been, and is still being, applied to a large spectrum of test data from differently scaled containment test facilities. An equally extensive effort has been, and is still being, put into direct code-to-code result comparisons, primarily by the members of the GOTHIC Users Group, consisting of 25 utilities, vendors, architect-engineers, and research organizations. This group includes a number of well-known international members. EPRI sponsors periodic meetings which have produced a wealth of GOTHIC comparisons to data and other computer codes. EPRI financed publication of the NAI GOTHIC validation report. The validation report documents comparisons between solutions of analytical problems and comparisons with data from blowdown experiments in the Carolina Virginia Test Reactor (CVTR), BMC, HDR, and HELD-LACE facilities. The frozen version of GOTHIC 3.4 was applied to all of the specified problems and experiments. Therefore, the validation report documents the status of GOTHIC at a specific period of its continual development.

The applicant re-ran the validation cases from the NAI GOTHIC validation report with WGOTHIC and documented the results in the form of comparison plots showing data and the GOTHIC and WGOTHIC computational results. The applicant used the same format as that used in the original EPRI report. The applicant performed the WGOTHIC analyses with the same GOTHIC nodalization and initial and boundary conditions used for generating the original GOTHIC computation for the EPRI validation report. As part of its software QA program, the applicant reran a selection of these benchmarks to document and confirm that the various WGOTHIC modifications it made to GOTHIC did not impact the predictive capability of the original GOTHIC code. These runs showed that the changes made by the applicant did not affect the original GOTHIC code.

21.6.5.7.8 Evaluation of the Westinghouse Passive Containment Cooling Design and the Lumped-Parameter Models with the International Database

21.6.5.7.8.1 Introduction

The applicant's passive containment cooling design response during and after LOCA and MSLB events, without an active internal spray system, is expected to be very similar to that of the large, dry, full-pressure containment of the German KWU design, at least until the PCS external liquid-film-induced cooling front reaches the inside steel shell surface. Both the applicant's passive containment cooling design and the German design have a primary steel shell containment surrounded by an air annulus with no active internal spray systems. The AP600 has a power rating of 600 MWe and the German BIBLIS A plant is a 1,167 MWe nuclear power plant (NPP). The AP1000 has a power rating of at least 1,000 MWe.

The BIBLIS A containment pressure response after a DECLG LOCA has been published and used in the German risk study (German Risk Study Nuclear Power Stations, An Examination of the Risk Caused by Accidents in Nuclear Power Stations, Main Volume, (in German), Verlag Tüv Rheinland 1979) of nuclear power plants. The peak pressure of 4.9 bar (71 psia) was obtained at the end of the primary system blowdown (~30 seconds) and accounted for all the appropriate conservatism in the input data and assumptions, as set forth in the German risk study guidelines. As a note of interest, the guidelines provided for adding an additional 10 percent to the conservatively calculated containment pressure history. There is no second pronounced pressure peak during or after reflood; however, a change of depressurization rate was noticeable. The design limit of the KWU full-pressure containment is 5.7 bar (82.6 psia), and the failure pressure is around 12–13 bar (174–188.5 psia).

The response of the large, dry containment is strongly dependent on the heat transfer to internal heat sinks during all phases of a DBA. During the long-term accident phase, the subatmospheric air gap in the German-designed, large, dry containment may also serve as a heat sink. Because of the tremendous importance of the heat transfer to heat sinks, German experimental and analytical efforts in the area of containment research focused on this issue and provide an additional database.

To validate the containment computer codes and the conservatism of the licensing approach and to generate a reliable database, German containment research embarked on a substantial research program utilizing the BMC and the HDR containment.

The staff considered this independent database, as well as the computer code analyses of the BMC and HDR experiments, to support the assessment of the applicability of the WGOTHIC EM to the containment evaluation as described below.

The BMC facility is scaled in accordance with the power-to-volume approach. The major features and characteristics of the BIBLIS A NPP were linearly scaled at 1:4 using a cylindrical rather than spherical shape. The BMC had a concrete containment wall (with removable top cover) rather than a steel shell. All nine subcompartments were empty and connected with uniquely defined orifices, nozzles, etc., rather than with oddly shaped doors, channels, and vents, as in the plant. This assumption provided a better basis for code comparisons.

The HDR constituted a real containment of a prototypical superheated steam reactor with large dimensions [volume ~11,000 m^3 (3.88E5 ft^3); dome volume ~5,000 m^3 (1.76E5 ft^3); diameter 20 m (66 ft); and height 60 m (197 ft)] and about 72 subcompartments. By comparison, the AP1000 containment volume is on the order of 58,330 m^3 (2.07E6 ft^3). Most compartments in the HDR were still filled with the original components during the test program. The HDR containment was not a scaled test. It was designed and licensed in accordance with the same rules and German risk study guidelines as the large BIBLIS A NPP (and all the other German reactors).

The HDR had an internal spray system installed, unlike a typical German NPP, mainly because the primary system was supposed to generate superheated steam. This originally installed internal spray system was activated during some of the later HDR containment experiments. The BMC and HDR databases supplement one another, and the combination of both should span most of the ranges regarding prototypical features. Therefore, computer codes that yield predictions that consistently match data obtained from different experiments in both facilities could be considered qualified to extrapolate from HDR size to large prototypical containments, with appropriate consideration of all applicable guidelines.

21.6.5.7.8.2 Linkage between Current PWRs and PCS Containment Behavior

Safety assurance and licensing of current PWR containments for DBA events rely on the effectiveness of active systems in the containment to mitigate pressurization and heatup of the containment atmosphere. Internal spray systems, fan coolers, and related heat-exchanging equipment typically constitute these active systems. Knowledge about their effectiveness, availability, data, and code modeling span the current licensing space.

The PCS containment design does not apply any of these active systems. Mitigative features are provided by passive systems which include the large containment and dome volume and surface and special provisions for heat sink efficiency, in combination with the PCS, which cools the outside steel shell. In evaluating this total passive safety system for its capability to mitigate pressure and heatup, the knowledge base for current operating reactors does not suffice.

To overcome this gap in the knowledge base, the applicant devised a careful roadmap which includes the following elements:

- a PIRT (WCAP-14812)
- a scaling report (WCAP-14845)
- validation of the heat and mass transfer correlation package (WCAP-14326)
- separate-effects tests (WCAP-12665)
- the SST (WCAP-14134)
- the LST integral tests (WCAP-14135)
- the lumped-parameter WGOTHIC modeling development and validation (WCAP-14382)
- the bounding EM development, the analytical model development for PCS-specific features, and the validation of the WGOTHIC EM through sensitivity studies presented in WCAP-14407 for the AP600 and in WCAP-15846 for the AP1000

Experimental evidence that could establish a linkage between current and future containment designs and operations during and after DBA events would assist the evaluation of the applicant’s DBA methodology. The staff believes information from the HDR test program provides this link. The linkage between current design and licensing practice and the new features of the applicant’s passive containment cooling design can be established on the basis of data from the large-scale HDR test facility, especially test series E11 (Cron, D. Schrammel, “Investigations on Hydrogen Distribution in a Reactor Containment,” Quick Look Report, Test

Group E11, Experiments E11.0-6, (In German), PHDR Technical Report PHDR 111-92, 1993 and Holzbauer, H., "Parametric Open Post-Test Predictions and Analysis of the HDR-Hydrogen Distribution Experiments E11.2 and E1.4 with the Computer Code GOTHIC," (In German), Battelle Institute e.v., Final Report BIeV/R67706-1, August 1992) .

Evidence for this linkage and experimental proof for the equivalence of mitigative features between internal spray operation and external spray operation (similar to the PCS) is found in HDR test series E11. The staff observed the following based on its review of test E11.2 with external sprays and test E11.1 with internal sprays (representative of small breaks high in containment):

(1) In the upper curved region of the dome, which was cooled at the outside steel shell surface during test E11.2 starting at 975 minutes, no axial or transverse temperature differences existed during the cooling period.

(2) The upper curved region of the dome was completely thermally homogeneous during all other test phases when the external cooling was not applied.

(3) Additional steam injections at low positions did not lead to thermal gradients in the upper region of the dome.

(4) Over the total height of the dome, from the operating deck to the dome apex, axial temperature gradients existed which changed sign and size depending upon the events examined (steam release, external cooling, etc.).

(5) The same observations hold for horizontal temperature gradients and temperature differences at the operating-deck level between the break (steam release) position and its opposite side.

(6) The size and sign of the temperature differences and thermal gradients in the HDR are considered maximum because only the upper part of the dome is cooled while the whole cylindrical part stays dry. This is considered an extreme condition and can serve as a possible upper bound.

(7) The operation of the internal spray leads to a completely homogeneous dome region. On stoppage of the spray, internally stored energy leads to a temperature increase at the upper dome.

(8) The external spray operation leads to similar temperature reductions in the dome as does the internal spray operation.

(9) While the internal spray operation barely affects conditions near the level of the operating deck (for the mass flow rate achieved through the spray nozzles, but equivalent to that of the external spray), and did not influence below-operating-deck compartments, the cold, air-enriched layer induced by the external cooling of the upper dome region advanced to the operating deck and even propagated equally into both vertical shafts and the associated compartments below the operating deck.

All of these observations are of major relevance to the PCS and to the WGOTHIC EM and its underlying assumptions. Specifically, observations (1), (2), and (3) confirm the applicant's assertion that the containment atmosphere is well mixed and its temperature is homogeneous in the dome region, which is externally cooled. This upper region is also homogeneous during periods of no external surface film cooling (i.e., dry surface, even during periods of additional steam injection).

Observations (4), (5), and (6) confirm the applicant's assertion that vertical and horizontal temperature differences over the total height and across the total containment diameter are about 10 °C (20 °F). The HDR data indicate that this would be the upper limit in the implausible situation that the PCS film on the whole cylindrical part of the containment shell would dry out (e.g., the conditions for which the HDR tests have been performed). The HDR data can be considered as an upper limit because its riser annulus is closed, while the PCS riser connects to the environment through the chimney.

Observations (7) and (8) confirm the close equivalence between the temperature decreases induced by the operation of an internal spray or an external spray. This establishes a link between current and future containment designs. For the HDR, it can be speculated that the experimentally demonstrated equivalence in the containment dome cooling would have been closer had the external cooling been initiated with 8 kg/s (17.6 lb/s), which is the value for the internal spray.

Observation (9) confirms the applicant's assertion that the PCS cooling affects below-deck compartments. The delay time between external cooling initiation and subcompartment cooldown below the operating deck is long for the HDR because the external cylindrical part of the dome is not cooled; however, the effect is very obvious approximately 130 minutes after spray initiation. Had the cylindrical part been cooled, as is the case for the applicant's passive containment cooling design, the impact on the below-deck subcompartments would be expected to be much stronger sooner.

In summary, the HDR data (tests E11.2 and E11.1) constitute a consistent framework for the confirmation of many of the applicant's assertions and positions on the basis of large-scale, fully transient experiments. An optimized GOTHIC lumped-parameter model yields conservative predictions of containment pressure and temperature for HDR test E11.2.

21.6.5.7.8.3 Application of GOTHIC and Other Codes to HDR and BMC Data

The staff reviewed a large database consisting of experiments at BMC and HDR, as well as various computer code predictions and analyses of these tests (see Section 21.6.5.9 of this report for a listing of the literature considered).

The experiments from the test series performed at the BMC and the HDR facility were chosen for the following reasons:

- The experiments were used for the GOTHIC (NAI) validation report.

- The experiments were used as International Standard Problems by OECD/CSNI to evaluate computational results from different codes using different lumped-parameter models and different correlations for heat and mass transfer.

- There were experiments showing specific features important to the applicant's passive containment cooling design issues:

  - T31.1–3 three large-break blowdowns with identical initial conditions but different break flow directions (orientation)

  - E11.1 operation of internal spray with sump heatup and boiling; high-elevation release position

  - E11.2 similar to test E11.1, but operation of external spray; stratified containment condition

  - E11.4 low-elevation release position and operation of external spray; homogeneous containment condition

  - E11.5 LBLOCA at low elevation with subsequent steam releases with sump heatup and boiling; homogeneous containment condition

  - T31.5 LBLOCA at high elevation with subsequent steam and gas mixture releases

  - V44 LBLOCA into different subcompartments

  - V21.1 LBLOCA

  - T31.1-3, T31.5, and V44 comparison of different blowdown experiments to determine upper and lower bounds of containment pressure histories in the HDR

- There were experiments with special instrumentation to measure such information as droplet velocities, droplet sizes, and local subcompartment pressures.

- There were experiments in which heat transfer coefficients were deduced from the heat transfer blocks over longer time periods (not all experiments and all heat transfer blocks have been evaluated).

Independent data from the BMC and HDR LOCA experiments for containment pressure, temperature, heat transfer, and droplet velocities and sizes have been reviewed. These data confirm the applicant's assertion that the blowdown peak pressure is nearly independent of break flow direction, and that heat transfer to internal structures is still best described by the Uchida correlation. In addition, comparisons between measurements and predictions based on Uchida heat transfer coefficients reveal that Uchida is very conservative during the blowdown phase and for a time period afterwards. The measured data and Uchida coefficients match the data during the long-term phase at times later than 1 hour. With respect to droplet velocities and sizes, measurements from the break subcompartment in the HDR show extremely high velocities; at 30 seconds after blowdown initiation, only drops with radii close to 5 µm were detectable.

International code benchmark exercises based on BMC and HDR experiments demonstrate that the application of the lumped-parameter approach leads to conservatively calculated blowdown peak pressures, even when these are set up to be "best estimate" predictions. Moreover, these comparisons show that when licensing and regulatory assumptions are added to the lumped-parameter model, predicted blowdown peak pressures become highly conservative as compared to the data. This independently confirms the applicant's assertion that use of the lumped-parameter approach in its WGOTHIC EM results in conservatively calculated blowdown peak pressure.

The following conclusions can be drawn from comparing GOTHIC predictions to the HDR test data:

- The steam release is more noticeable in the temperature measurements at, and above, the break elevation.

- Despite the LOCA, an axial temperature gradient exists over the height of the containment.

- GOTHIC, with a lumped-parameter model, simulates the axial temperature gradient and the transient temperatures over the whole 1-hour time period extremely well.

- GOTHIC predicts the steam release effect on temperatures at different axial elevations extremely well.

- Temperature predictions are too low compared with the data over the first 5 minutes after the blowdown initiation.

Overall, the comparisons confirm GOTHIC's applicability for high-positioned LBLOCAs in the HDR, which is similar to the break location in the AP1000 LOCA model. GOTHIC predicts a conservative pressure history and matches measured temperatures at different axial elevations (stratification) very well. GOTHIC tends to predict lower (conservative) temperatures during the early phase (~5 minutes) of the overall transient.

Comparisons of HDR tests E11.5 and T31.5 (Wolf, L., Mun, K., "Overview of Experimental Results for Long-Term, Large-Scale Natural Circulations in LWR-Containments After Large LOCAs," Vol. II, Assessment of HDR Experiments V21.1, V43, T31.5 and E11.5, DOE-Project, HDR Hydrogen Mixing Evaluation for Containment Safety Evaluations, Natural Global Circulation, Dept. of Materials and Nuclear Engineering, University of Maryland, College Park, MD, April 1996) provide sufficient evidence that the GOTHIC code with a lumped-parameter model has been demonstrated to reliably (and conservatively) predict containment pressure response, temperature, and even velocities with best-estimate input data and commonly used input parameters. Test E11.5 represented a LBLOCA with a hydrogen release in the lowest section of the HDR containment. Test T31.5 also represented a large LOCA with a hydrogen release, but the release point was high in the containment.

Tests E11.5 and T31.5 cover both ends of a spectrum of break locations tested at the HDR. Test T31.5, with the associated GOTHIC prediction, is deemed to be closer to the AP600 and AP1000 model because the break was located high in the HDR, which is similar to the break location in the AP600 and the AP1000 LOCA model.

The following are some additional observations on HDR test E11.4 (similar to test E11.2, but with the break position low in the containment):

- GOTHIC predicted the containment atmosphere response very well in all details for the various experimental phases (sump boiling period—43 hours, 30 minutes to 46 hours, 30 minutes; external cooling period—46 hours, 10 minutes to 50 hours, 12 minutes).

- Conditions in the containment during test E11.4 were in the realm of lumped-parameter models exercised in the context of current containment analysis codes.

- The GOTHIC predictions showed coherent and consistent results in all of the computed quantities as compared to the data.

21.6.5.7.9 Evaluation Conclusions

The staff has reviewed the following information:

- steady-state, separate-effects tests

- validation of heat and mass transfer correlations

- quasi-steady-state SST and LST tests

- WGOTHIC predictions for LST tests

- WGOTHIC application to NUPEC tests

- development of WGOTHIC EM on the basis of selected LST tests and WGOTHIC distributed-parameter models

- assessment of specific model assumptions, input data, and parameters

- independent transient data from large-scale facilities covering LOCAs initiated at different axial elevations with subsequent steam releases

- independent transient data establishing a linkage between the effects of internal spray operation and external spray operation

- independent assessment of different versions of the GOTHIC code

- assessment of the status of containment analysis code with lumped-parameter models

From this combination of experimental, analytical, and computational evidence, the following conclusions can be drawn:

- The applicant's major assumptions concerning the anticipated passive containment cooling design behavior and their treatment in the WGOTHIC EM have been confirmed through the staff's independent review of the supplemental BMC and HDR database and associated computations.

- All issues related to the blowdown time phase can be considered resolved and closed, both with respect to the anticipated containment behavior and to the WGOTHIC EM predictive capability. Specifically, it can be demonstrated that even a best-estimate, lumped-parameter model leads to a conservatively calculated peak pressure. Accordingly, predictions based on conservative input values and parameters will certainly result in conservative predictions.

- All issues related to long-term cooldown are considered to be resolved because many independent experiments in different facilities, as well as associated computations with GOTHIC, confirm the validity of the model assumptions and the model input. In the majority of cases, best-estimate, lumped-parameter, long-term analyses with GOTHIC demonstrate slightly conservative predictions for the pressure history.

- Only when the computational model is adjusted to best fit the blowdown phase (including the peak pressure) is there a potential for systematic, long-term pressure underprediction.

21.6.5.8 Conclusions

21.6.5.8.1 Introduction

The staff has reviewed the WGOTHIC computer program and the applicant's passive containment cooling design EM with regard to their ability to conservatively predict the pressure response of the primary containment to a DBA LBLOCA or MSLB. WGOTHIC solves the conservation equations for mass, energy, and momentum for multicomponent, two-phase flow. The momentum conservation equations are written separately for each phase in the flow field (drop, liquid pool, and atmosphere vapor). The applicant's EM represents the containment as a network of WGOTHIC lumped-parameter nodes. A special clime component is used to model the PCS, which provides the safety-related cooling of the containment by evaporating a water film applied to the exterior of the containment steel shell.

WGOTHIC is based on a modified version of the GOTHIC 4.0 computer program. The GOTHIC containment analysis package was developed by NAI, with financial support from EPRI and a national users group. The applicant's modifications to GOTHIC added the special models and features needed for passive containment cooling design licensing analyses, in support of design certification. The applicant added analytical models to represent the unique features of the PCS, which included modeling the condensation heat transfer in the presence of noncondensable gases on the interior wall of the containment, one-dimensional heat conduction through the containment wall, and heat rejection on the exterior of the containment shell via evaporative cooling, natural convection cooling, and radiative cooling. Section 21.6.5.4 of this report offers a full description of WGOTHIC Version 4.2, the current licensing version, and the staff's technical review.

21.6.5.8.2 Compliance with Regulatory Requirements

The applicant's containment EM is based on assumptions that maximize the initial stored energy within containment and minimize the rate of heat transfer from containment. The approach taken for the containment analysis has developed from the approach used for the WGOTHIC Version 1.0 and WGOTHIC Version 1.2 analyses. To address staff concerns with some of the assumptions and modeling features employed, the applicant has developed a model and uses assumptions and boundary conditions that are more consistent with current practices for containment analyses for current operating reactors. The approach is consistent with the guidance provided in SRP Section 6.1.1.2.A, "PWR Dry Containments, Including Subatmospheric Containments." The following evaluation is based on the staff's review of the WGOTHIC computer program, the EM model, and studies for the AP600 as presented in WCAP-14407 for the AP600 and in WCAP-15846 for the AP1000, the associated PIRT report (WCAP-14812 and WCAP-15613), scaling report (WCAP-14845 and WCAP-15613), and validation studies (WCAP-14382, WCAP-14967 and WCAP-15644). Sections 21.6.5.4 through 21.6.5.7 of this report provide a complete review of this information.

Compliance with Appendix A to 10 CFR Part 50

The current guidance for demonstrating that a containment design complies with GDC 16, 38, and 50 is delineated in SRP Chapter 6.2.1. The SRP addresses acceptance criteria and some specific model assumptions for design-basis LOCA and MSLB analyses for all existing containment types. The applicant elected to evaluate the PCS performance using these current guidelines. The applicant's documentation for the EM is consistent with the guidelines in SRP Sections 6.2.1 and 6.2.1.1.A and RG 1.70. The applicant also uses approved methods for the LOCA and MSLB mass and energy releases following the guidance provided in SRP Sections 6.2.1.3 and 6.2.1.4, respectively. Each GDC is evaluated below.

Peak Pressure Criteria (GDC 16 and 50)

Acceptance criteria for existing containments include a margin between the design pressure and a conservatively calculated peak accident pressure. The margin varies from 10 percent at the construction permit (CP) stage to a peak calculated pressure less than the containment design pressure at the operating license (OL) stage. Thus, even where much data and information are known, and the staff possesses an independent, confirmatory calculational capability, a 10 percent margin is expected at the CP stage to cover uncertainties in meeting GDC 16 and 50 at the OL state, after final construction.

For the applicant's passive containment cooling design, the applicant proposed the criterion that the calculated peak accident pressure not exceed the design pressure (a zero-margin criterion).

Testing and Computer Code Evaluation

In meeting this criterion, the applicant stated that it used a conservative approach, consistent with current staff guidelines. For design certification, under 10 CFR Part 52, the staff does not necessarily need the same demonstration of margin as is normally expected at the CP stage. An appropriate initial test program, combined with appropriate ITAAC, is in place to ensure that the assumptions about and performance characteristics of the passive containment cooling design and the PCS, as used in the licensing analyses, are verified before operation. DCD Tier 1, Section 2.2.2, "Passive Containment Cooling System," describes the PCS ITAAC. DCD Tier 2, Chapter 14, "Initial Test Program," describes the initial test program (ITP). Periodic testing, as part of the inservice testing program, will also be performed to demonstrate that the area coverage fractions are maintained over the life of the plant as described in AP1000 TS 3.6.6, "Passive Containment Cooling System (PCS) - Operating."

On the basis of this evaluation, the staff has determined that the WGOTHIC computer program, combined with the conservatively biased EM, is acceptable for the evaluation of the peak containment pressure following a DBA. Although the WGOTHIC code itself is essentially a best-estimate tool, the applicant has taken a conservative approach in the EM it is using to support design certification. The WGOTHIC EM uses conservative values which bound the range of most inputs, and applies conservative multipliers on the correlations used for PCS heat and mass transfer. Conservative models are used in the WGOTHIC EM to address the following areas:

- lumped-parameter network representation
- noncondensable gas circulation and stratification
- PCS flow and heat transfer models
- dead-ended and liquid-filled compartments

During the peak pressure period, these conservatisms compensate for the uncertainties introduced by the use of passive safety features, leading to an overall conservative result for the calculated peak containment pressure.

Long-Term Pressure Analysis (GDC 38)

The objective of the long-term pressure analysis is to demonstrate that the containment design conforms to the objectives of GDC 38, "Containment Heat Removal," in Appendix A to 10 CFR Part 50:

> A system to remove heat from the reactor containment shall be provided. The system safety function shall be to reduce rapidly, consistent with the functioning of other associated systems, the containment pressure and temperature following any loss-of-coolant accident and maintain them at acceptably low levels.
>
> Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power

is not available) the system safety function can be accomplished, assuming a single failure.

The guidance in Item II.b of SRP Section 6.2.1.1.A is used to evaluate compliance with GDC 38. It states that the containment pressure should be reduced to less than 50 percent of its peak value within 24 hours of the occurrence of a design-basis LOCA. This assures that the containment leak rate used for the siting evaluation is consistent with the design-basis analysis assumption. To be consistent with current guidelines related to GDC 38, the applicant proposed that the calculated pressure reduction be based on 50 percent of the design pressure. The staff found this approach to be acceptable, because the peak calculated pressures had been near the design value.

The applicant determined that it might not meet the proposed long-term objective (50 percent pressure reduction in 24 hours) with the original WGOTHIC analysis approach. The applicant, therefore, revised the analytical procedure to take credit for the effect of two-dimensional (2-D) heat conduction (between wet and dry regions of the containment shell) when less than full coverage of the containment shell is expected. The revised procedure was first presented in the applicant’s letter DCP/NRC 1181, dated May 23, 1997, and was discussed at an ACRS meeting in December 1997. The applicant did not identify, or at least account for, the need to consider 2-D heat transfer for the long-term containment pressure response (i.e., after 3 hours when the PCS flow rate is first cut back from its initial value) in selecting the analysis methodology (GOTHIC) and in developing a model for the PCS (WGOTHIC). With the coverage area less than the initially assumed 90 percent, heat would be transferred from the hot, dry regions of the shell into the cooler, wet regions of the shell. To account for this deficiency, the applicant performed an ancillary calculation to credit more PCS water in the evaporation process, effectively generating a correction factor, and applied it to the limited PCS flow model (see Section 21.6.5.4.2 of this report).

The staff believes that there is a real effect from 2-D heat conduction. However, as an insufficient amount of test data was available to validate this model, the staff was unable to determine how much credit should be given in evaluating the PCS design performance after 24 hours when 2-D heat conduction was included in the analysis.

After the peak pressure period, the uncertainty in the treatment of heat transfer processes continues to increase. These uncertainties, resulting from the EM treatment of noncondensable gas circulation and stratification and the effectiveness of the PCS cooling at a reduced flow rate, are difficult to quantify using the available test data. Nevertheless, the heat removal capability of the PCS (as calculated by the WGOTHIC EM) is sufficiently greater than the decay power to conclude that the containment pressure will decrease. Therefore, the system safety function to reduce rapidly, consistent with the functioning of other associated systems, the containment pressure and temperature following any LOCA and maintain them at acceptably low levels has been demonstrated.

The secondary objective for the long-term analysis is to demonstrate that the long-term pressure remains within the pressure envelope used for containment leakage calculations which support the siting evaluation. Therefore, a separate analysis will be performed for the limiting LOCA without 2-D conduction, and included in DCD Tier 2, Section 6.2.1.1.3, “Design evaluations." This separate analysis is used to confirm the assumption used in DCD Tier 2, Section 15.6.5.3.3 of reducing the containment leakage to half its design value after 24 hours.

Compliance with 10 CFR 52.47(b)(2)

The unique characteristics of the PCS are explicitly recognized in the regulations governing the evaluation of standard plant designs. The regulations in 10 CFR 52.47(b)(2)(i)(A) require, in the absence of a prototype plant that has been tested over an appropriate range of normal, transient, and accident conditions, that the following must be met for a plant that "utilizes simplified, inherent, passive, or other innovative means to accomplish its safety functions":

(1) The performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof.

(2) Interdependent effects among the safety features of the design have been found acceptable by analysis, appropriate test programs, experience, or a combination thereof.

(3) Sufficient data exist on the safety features of the design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.

Consistent with these requirements, the applicant has developed and performed design certification tests of sufficient scope, including both separate-effects and integral-systems experiments, to provide data with which to assess the computer programs used to analyze plant behavior over the range of conditions described in item (3) above.

To satisfy the requirements of 10 CFR 52.47(b)(2)(i)(A), the applicant has developed test programs to investigate the passive containment safety systems. These programs include both component and phenomenological (separate-effects) tests and integral-systems tests. The cold WDT (WCAP-13353, WCAP-13296, and WCAP-13960) was a full-scale representation of the PCS flow characteristics. To comply with requirement (3) above, additional separate-effects tests have been performed to extend the range of existing mass and heat transfer correlations used in the analysis codes (WCAP-14326).

The LST (WCAP-14135) is the only integral test for the PCS. While this test exhibited a number of shortcomings in scaling and prototypical features, the LST data were not used in an integral mode. Instead, the LST data were used in a separate-effects mode to demonstrate the conservatism of portions of the EM. The staff concluded that sufficient data have been provided to establish that the EM is conservative at the scale of the AP600 and the AP1000.

The staff concludes that the EM contains sufficient conservatisms, including factors to compensate for shortcomings in the LST, to accept WGOTHIC, in combination with the EM, for DBA licensing analyses to support design certification for the applicant's containment designs that include the PCS. Section 21.6.5.8.3 of this report details specific limitations and restrictions for future analyses.

21.6.5.8.3 Limitations and Restrictions

WGOTHIC, in combination with the EM, is approved for evaluating the peak containment pressure in the applicant's AP1000 passive containment cooling design resulting from DBA LOCA and MSLB events. It has not been qualified to predict other parameters of design interest, such as flooding levels, temperature profiles, and concentrations of noncondensable gases (e.g., air, hydrogen).

Because of the great flexibility a WGOTHIC user has in input selection, NRC reviewers of future WGOTHIC EM analyses used to support licensing actions should verify the following EM model conservatisms:

- The mass and heat transfer coefficients on the inner containment vessel surface are multiplied by a factor of 0.73. Only free convection is considered on the inner surface. The multiplier is based on an assessment of the LST and separate-effects tests, as discussed in Section 21.6.5.6.5.3 of this report.

- The mass and heat transfer coefficients on the outer containment vessel surface are multiplied by a factor of 0.84. Mixed convection is considered on the outer surface. The multiplier is based on an assessment of the LST and separate-effects tests, as discussed in Section 21.6.5.6.5.3 of this report.

- The vessel wall emissivity values are reduced by 10 percent to minimize the radiation heat transfer.

- The maximum passive containment cooling water storage tank (PCCWST) temperature allowed by the TS is used as an initial condition.

- The maximum containment air temperature and maximum internal pressure allowed by the TS are used as initial conditions. A zero-percent humidity initial condition is used to increase the initial stored energy inside containment.

- A single failure of one out of two valves controlling the PCS cooling water flow is assumed. This assumption provided the minimum PCS liquid film flow rate.

- The water coverage is based on the evaporation-limited flow model, as described in Section 21.6.5.4.2 of this report, and is based on the wetted surface areas provided in DCD Tier 2, Table 6.2.2-1, "Passive Containment Cooling System Performance Parameters."

- The minimum PCCWST inventory allowed in the TS is used to calculate the PCS flow rate for use in the evaporation-limited flow model.

- The PCS liquid film flow is credited only following a delay period (337 seconds) necessary to establish water coverage of the shell-wetted region. This corresponds to the time needed to establish a steady liquid film coverage pattern, on the basis on the initial flow rate.

- A 20 mil or larger air gap is assumed between the steel liner and the concrete on applicable internal heat sinks.
- The loss coefficient in the external annulus includes a 30-percent increase over the value derived from the test program.
- Condensation and convection on heat sinks in the dead-ended compartments, below the operating deck, are not credited after the blowdown period. This conservative assumption is also employed in the MSLB analyses.
- Heat transfer to horizontal, upward-facing surfaces, which may become covered with a condensation film, is not credited. In particular, heat transfer to the operating deck itself, which becomes covered with an air-rich layer, is not to be credited.
- Consistent with the heat sinks (structures), as identified in WCAP-15846, Section 13, all miscellaneous heat sinks identified by "Heat transfer coefficient = Insulated/Insulated" have been removed for licensing analyses through proper user input for the AP1000. These miscellaneous heat sinks are not considered in the AP1000 EM, Section 13 in WCAP-15846.

For future studies that support licensing actions, the WGOTHIC analyst should verify that the LOCA or MSLB DBA characteristics are consistent with the use of the lumped-parameter representation of the applicant's AP1000 passive containment cooling design. The staff has determined that the energy transferred to the PCS through the shell for the AP1000 DBA analyses does not result in any numerical oscillations. However, for calculations with higher energy transfer to the PCS through the shell (for example, for a future power uprate), the applicant should examine the stability of the clime heat and mass transfer solution (e.g., by plotting heat transfer rates versus time for both the wet and dry climes) to confirm that the calculation has not violated the time step stability (see Section 21.6.5.8.3 of this report).

In the evaporation-limited flow model, the applicant neglects PCS runoff sensible heat, which is conservative, and offsets the nonconservatism introduced by the simultaneous use of the Chun and Seban model and the evaporation-limited flow model. Therefore, these two assumptions must be employed together for the staff to consider this model to be acceptable for licensing analyses, as discussed in Section 21.6.5.4.2.3.2.3 of this report.

The 2-D enhancement to the evaporation-limited flow model, as described in Section 21.6.5.4.2.4 of this report, may not be used to credit leakage reduction for siting evaluations. A separate analysis may be performed for the limiting LOCA without 2-D conduction and included in DCD Tier 2, Section 6.2.1.1.3. This separate analysis may be used to confirm the assumption used in DCD Tier 2, Section 15.6.5.3.3 of reducing the containment leakage to half its design value after 24 hours.

21.6.5.9 <u>Literature on Containment Experimental Data and Analyses</u>

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21.7 Quality Assurance Inspections

The staff relied upon six principle test programs to demonstrate that AP1000 accident analyses analytical methods and computer codes described above were adequately and appropriately applied. The purpose of the test programs was to validate the capability of accident analysis computer models to predict plant T-H behavior for a variety of accident conditions. Five of these test programs were originally conducted to support design certification of the AP600 design. The remaining test program was conducted at the OSU APEX-1000 test facility to address specific concerns associated with the T-H behavior of the AP1000 plant under certain accident conditions. As discussed in the above sections, the staff concluded that, with additional elements (i.e., NOTRUMP homogeneous sensitivity model and critical heat flux assessment during accumulator injection) to augment the SBLOCA evaluation model, analytical methods and computer codes developed for the AP600 design were applicable to the AP1000 design.

As described in Section 17.3 of this report, the applicant has continuously maintained a QA program meeting the requirements of 10 CFR Part 50, Appendix B, that spanned AP600 and AP1000 design activities. Because testing activities used to confirm the validity of safety-related analytical methods and computer codes are within the scope of Appendix B QA requirements, the staff reviewed the QA program controls applied to testing activities. Specifically, the staff verified that test facilities implemented QA controls which met the requirements of the applicant’s QA program and 10 CFR Part 50, Appendix B. The staff previously reviewed the QA controls and their implementation for the five AP600 test programs during the AP600 design certification review. As part of the QA review for the AP600 test program, the staff reviewed the QA program used at each of the test facilities and performed an inspection to verify that the quality program was effectively implemented. For each of the five AP600 test programs, the staff concluded that reasonable and appropriate QA measures were used to control AP600 test activities. The results of the staff review and basis for the conclusions regarding the AP600 test program are set forth in greater detail in NUREG-1512. A description of the staff’s review of the AP600 test program has been included as Appendix 21.B to this report.

Because the accident analysis computer models have not changed since they were originally validated during the AP600 design certification review, the staff concludes that the previous QA reviews conducted to support AP600 design certification generally remain valid for the AP1000 design. However, as discussed in Section 21.5.7.4 of this report, the staff identified several limitations of the AP600 test program with regard to validation of certain T-H phenomena such as ADS-4 liquid entrainment, hot-leg phase separation, and upper plenum entrainment. Consequently, the applicant performed additional testing at the APEX-1000 test facility. As part of the AP1000 design certification review, the staff evaluated the QA controls applied to the additional AP1000 design-specific testing conducted at the APEX-1000 test facility. The results of this review are discussed in Section 17.3 of this report.

Table 21-1 Major Differences Between AP1000 and AP600 Designs

SYSTEMS/COMPONENTS	AP1000	AP600
Overall Plant		
Net Electric Output, MWe	1117	600
Hot-Leg Temperature, °F	610	600
Core		
Core Power, MWt	3400	1933
Number of Fuel Assemblies	157	145
Active Fuel Length, ft	14	12
Average Linear Power, kW/ft	5.707	4.10
Steam Generators		
Model	Delta-125	Delta-75
Heat Transfer Area/SG, ft^2	123,538	75,180
Number of Tubes/SG	10,025	6,307
Reactor Coolant Pumps		
Rated HP/pump, hp	6,000	3,500
Rated Head, ft	365	240
Pump Inertia, lb-ft^2	16,500	4,956
Rated Flow/pump, gpm	78,750	51,000
Pressurizer		
Total Volume, ft^3	2,100	1,600
Volume/MWt, ft^3/MWt	0.615	0.825
Containment		
Free Volume, ft^3	2.06E+6	1.71E+6

SYSTEMS/COMPONENTS	AP1000	AP600
Safety Injection		
Core Makeup Tanks		
Volume/CMT, ft^3	2500	2000
In-Containment Refueling Water Storage Tank		
Minimum Water Volume, ft^3	78,900	74,500
Minimum Water height, ft	28.79	27
Available driving pressure, psi	9.79	9.04
Injection Line Size, inches	8	6
Injection Line to Sump Tee Size, inches	10	6
Injection Line Resistance, %	32	100
Passive Residual Heat Removal System		
Heat changer Number of Tubes	689	671
Heat exchanger heat transfer area, ft^2	5278	4326
PRHR inlet/outlet line diameter, inches	14	10
PRHR Flow Path Resistance, %	33	100
Automatic Depressurization System		
ADS-4 squib valve diameter, inches	14	10
ADS-4 hot-leg off-take pipe diameter, inches	18	12

Table 21-2 Non-LOCA Transients To Be Analyzed Using LOFTRAN

- ❑ Feedwater system malfunctions
- ❑ Excessive increase in steam flow
- ❑ Inadvertent opening of a steam generator relief or safety valve
- ❑ Steamline break
- ❑ Inadvertent operation of PRHR HX
- ❑ Loss of external load/turbine trip/MSIV closure
- ❑ Loss of offsite power
- ❑ Loss of normal feedwater flow
- ❑ Feedwater line rupture
- ❑ Loss of forced reactor coolant flow
- ❑ Locked reactor coolant pump rotor/sheared shaft
- ❑ Control rod cluster withdrawal at power
- ❑ Dropped control rod cluster/dropped control bank
- ❑ Startup of an inactive reactor coolant pump
- ❑ Inadvertent actuation of the CMTs during power operation
- ❑ Inadvertent increase in coolant inventory
- ❑ Inadvertent opening of a pressurizer safety valve or ADS valve
- ❑ Steam generator tube rupture

Table 21-3 Double-Ended DVI Line Break Comparison Chart

Event	Time (seconds)	
	RELAP5	**NOTRUMP**
Break Initiates	0.0	0.0
Reactor Trip Signal	13.9	13.1
“S” Signal	17.3	18.5
Reactor Coolant Pump Trip	23.3	24.5
Intact CMT begins to drain	196.0	260.0
ADS-1 Actuates	247.0	182.7
ADS-2 Actuates	317.0	252.7
Accumulator Injection Begins	341.0	251.0
ADS-3 Actuates	437.0	372.7
ADS-4 Actuates	567.0	492.7
Intact Accumulator Empties	784.0	598.4
IRWST Injection Begins	1453.0	2076.0
Intact CMT Empties	2338.0	2006.0

Table 21.6.5-1 Comparison of Containment Codes

Capability or Model	WGOTHIC	CONTEMPT 4 MOD 6	CONTAIN
Mass Balances	1. Steam 2. Liquid films, pools 3. Drops 4. Ice 5. Each gas	1. Steam 2. Pools 3. Each gas	1. Steam 2. Each gas
Energy Balance	1. Steam/gas 2. Water 3. Droplet	1. Steam/gas 2. Pools	1. Steam/gas 2. Water in lower part of cell
Force Balance	1. Steam/gas 2. Film/slugs 3. Drops	1. Steam/gas	1. Steam/gas
Lumped-Parameter Analysis	Yes	Yes	Yes
Multidimensional Analysis	3-D Cartesian	No	No
Momentum Directions	3	0	0
Momentum Approach	Control volume or junctions	Junction	Junction
Turbulence	Yes	No	No
General Multiphase Flow	Yes	No	No
Buoyancy Dominated Flow	Yes	Yes	Yes
Momentum Dominated Flows (Jet Entrainment)	Yes	No	No
Sprays	Mechanistic drop transport. Different coefficients used for distributed- and lumped-parameters.	No drop transport, convective heat transfer.	No drop transport, convective heat transfer.
Engineered Safety Equipment (Pumps, Valves, etc.)	Yes	Yes	Yes
Ice Condenser, Suppression Pool	Basic modeling	Special compartment	Special compartment
PCS	Clime model for PCS convection, conduction, and internal/external condensation.	Heat transfer to ambient is a boundary condition.	PCS film wetted area is a boundary condition.

Table 21.6.5-2 Comparison Between WGOTHIC and CONTEMPT Interfacial Heat and Mass Transfer for Lumped-Parameter Modeling

WGOTHIC	CONTEMPT
Sensible heat transfer between the vapor and the pool surface, using turbulent free- and forced-convection heat transfer coefficients.	Sensible heat transfer between the vapor and the pool surface, using laminar and turbulent free-convection heat transfer coefficients.
Mass transfer at the pool surface. Mass transfer coefficient is for turbulent free or forced convection by heat and mass transfer analogy. Driving potential is $(x_{si} - x_{sb})$ Where x_{si} is the interface steam concentration x_{sb} is the bulk steam concentration	Mass transfer at the pool surface. Mass transfer coefficient is for turbulent free convection by heat and mass transfer analogy. Driving potential is $\left\lvert \frac{1-x_{sb}}{1-x} \right\rvert$
Sensible heat transfer between the pool and the pool surface, using turbulent free- and forced-convection heat transfer coefficients. Pool surface temperature is calculated using mass and energy balances at the interface.	Pool surface temperature assumed equal to T_{sat}.
Heat and mass transfer from sprays calculated using same basic model as for the pool interface. Heat and mass transfer coefficients appropriate for water droplets are used.	Heat and mass transfer from sprays calculated using specified spray efficiency.
Blowdown water and steam components adjust to containment conditions based on fundamental models for interface heat and mass transfer.	Blowdown water and steam is forced to equilibrium at either the containment total pressure or the steam partial pressure.
Homogeneous and heterogeneous nucleation fog models.	No fog model.

Table 21.6.5-3 Comparison of Correlations for Heat Transfer, Condensation, and Evaporation Implemented in WGOTHIC and CONTEMPT-LT/028

WGOTHIC	CONTEMPT-LT/028
Condensation heat transfer: • mass transfer analogy (to PCS shell) McAdams—free convection (interior) Colburn—forced convection (exterior) • Uchida—internal heat sinks • Tagami—not used for AP600 • Gido Koestel—not used for AP600	Condensation heat transfer: • Uchida • Tagami
Six correlations for free convection. Correlation for forced convection.	One correlation for free convection.
Convection to the air-steam mixture, water, or split between the two phases.	Convection to the air-steam mixture.
Specified heat transfer coefficient as function of time, Reynolds number, Rayleigh number, or any combination of GOTHIC calculated variables.	Specified heat transfer coefficient as function of time or temperature.

Table 21.6.5-4 Clime Heat Transfer Correlations

Heat Transfer Mechanism		Correlation	Comment
Free convection from the containment atmosphere to the condensing film on the inner surface of the containment shell.		McAdams Ref. 21.6.5.4.12	Assumes containment is well mixed. See discussion in Sections 21.6.5.4.1, 21.6.5.5.3, 21.6.5.6.1, and 21.6.5.7.4.
Conduction through condensate film.		Chun and Seban Ref. 21.6.5.4.13	Assumes wavy laminar flow. See discussion in Sections 21.6.5.4.2.4, 21.6.5.5.3, and 21.6.5.6.4.
Conduction through the steel shell.			
Conduction through PCS film.		Chun and Seban Ref. 21.6.5.4.13	Assumes wavy laminar flow. See discussion in Sections 21.6.5.4.2.4, 21.6.5.5.3, and 21.6.5.6.4.
From Wet Sectors to Riser	Evaporation of the PCS water film to air.	Heat/mass analogy	Bias factor included*
From Dry Sectors to Riser	Forced convection to air.	Colburn	Bias factor included*
	Radiation to the baffle.		
From Riser to Baffle	Mixed convection to baffle from the riser air.	Churchill Ref. 21.6.5.4.23	Bias factor included*
	Radiation from the shell.		
	Condensation on the baffle.	Heat/mass analogy	Bias factor included*
Conduction through the baffle.			
Opposed mixed convection from the shield building and downcomer side of the baffle and upper portions of the riser, including the top of the containment dome and shield building.		Churchill Ref. 21.6.5.4.23	Bias factor included*
Radiation between the baffle and the shield building.			
Conduction through the shield wall.			
Condensation/conduction to miscellaneous heat structures located in the downcomer, riser, and the top section of the chimney.		Uchida Ref. 21.6.5.4.10	

*   The conservative bias factors are discussed in Sections 21.6.5.6.1 and 21.6.5.6.4 of this report.

Table 21.6.5-5 Evaluation of Conservatism in Evaporated-Flow Model

Phenomena	Effect	Comment
Coverage area – height – stripe width	The applicant calculates the applied flow at the second weir assuming no evaporation occurs on the upper dome. The mass and energy of the flow applied at the second weir may be overpredicted. Constant 90-percent wet area throughout event.	These are small nonconservatisms. Significant evaporation occurs after the second weir. 90-percent flow from cold WDT tests at 220 gpm is conservative for actual plant flow rates (first 3 hrs.). After 3 hrs., effect is not significant if the containment above deck region is well mixed (i.e., nearly homogeneous in temperature and noncondensable distribution).
Heat convected by water film	Latent heat of PCS runoff is neglected.	This is a small conservatism for peak pressure period. May be significant for the time period up to 30-hour period when the runoff fraction becomes large.
Resistance of external water film	PCS film thickness may be significantly underpredicted. Film may reach saturation temperature earlier.	This nonconservatism may be significant after the peak pressure period when the runoff fraction is large.
Buoyancy-driven airflow	Artificial water coverage profile skews evaporation heat flux towards higher elevations.	Skew expected only after 3-hour period. Effect is small, conservative reduction in buoyant driving force.
Convection and radiation heat transfer from dry clime	Artificial water coverage profile lowers dry clime convection and radiation from upper elevations; raises convection and radiation from lower elevations.	Skew expected only after 3-hour period. Errors may be self compensating.

Table 21.6.5-6 Phenomena Identification and Ranking According to Effect on Containment Pressure

Component or Volume	Phenomenon or Parameter	LOCA Blowdown ~ 0–30 sec	LOCA Refill ~ 30–90 sec	LOCA Peak Pressure ~ 90–2400 sec	LOCA Long-Term >2400 sec	MSLB Blowdown ~ 0–900 sec
Inside Containment						
1 Break Source	A. Mass and energy	H	N/A	H	H	H
	B. Direction and elevation	H	N/A	H	L	H
	C. Momentum	H	N/A	H	L	H
	D. Density	H	N/A	H	L	H
	E. Droplet/liquid flashing (thermal)	L	L	L	L	N/A
2 Containment Volume	A. Circulation/stratification	H	H	H	H	H
	B. Intercompartmental flow	L	H	H	H	H
	C. Gas compliance	H	H	H	H	H
	D. Fog (circulation)	L	H	H	H	N/A
	E. Hydrogen release	L	L	L	L	N/A
3 Containment Solid Heat Sinks (Steel and Concrete)	A. Liquid film energy transport	L	L	L	L	L
	B. Vertical film conduction	L	L	L	L	L
	C. Horizontal film conduction	L	H	H	H	H
	D. Internal heat sink conduction	M	H	H	M	H
	E. Heat capacity	M	H	H	M	H
	F. Condensation	M	H	H	M	H
	G. Convection from containment	L	M	L	L	L
	H. Radiation from containment	L	M	L	L	L
4 Initial Conditions	A. Initial temperature	M	M	M	M	M
	B. Initial humidity	M	M	M	M	M
	C. Initial pressure	M	M	M	M	M

Component or Volume	Phenomenon or Parameter	LOCA Blowdown ~ 0–30 sec	LOCA Refill ~ 30–90 sec	LOCA Peak Pressure ~ 90–2400 sec	LOCA Long-Term >2400 sec	MSLB Blowdown ~ 0–900 sec
5 Break Pool	A. Circulation/stratification in the pool	L	L	L	M	L
	B. Condensation/evaporation	L	L	L	M	L
	C. Convection within containment volume	L	L	L	L	L
	D. Radiation within containment volume	L	L	L	L	L
	E. Conduction in pool	L	L	L	M	L
	F. Compartment filling	L	L	L	L	L
6 IRWST	E. Mixing/stratification (gas and water)	L	L	L	L	L
	F. Condensation	L	L	L	L	L
	G. Convection	L	L	L	L	L
	H. Radiation	L	L	L	L	L
	I. Conduction in liquid	L	L	L	L	L
	J. Liquid level changes	L	L	L	L	L
Containment Shell						
7 Steel Shell	A. Convection from containment	L	L	L	L	L
	B. Radiation from containment	L	L	L	L	L
	C. Condensation	H	H	H	H	H
	D. Inside film conduction	L	L	L	L	L
	E. Inside film energy transport	L	L	L	M	L
	F. Conduction through shell	H	H	H	H	H
	G. Heat capacity of shell	H	H	H	L	H
	H. Convection to riser annulus	L	L	L	M	L
	I. Radiation to baffle	L	L	L	M	L
	J. Radiation to chimney	L	L	L	L	L
	K. Radiation to fog/air mixture	L	L	L	L	L
	L. Outside film conduction	N/A	N/A	L	L	L
	M. Outside film energy transport	N/A	N/A	M	M	L
	N. Evaporation to riser annulus	N/A	N/A	H	H	M

Component or Volume	Phenomenon or Parameter	LOCA Blowdown ~ 0–30 sec	LOCA Refill ~ 30–90 sec	LOCA Peak Pressure ~ 90–2400 sec	LOCA Long-Term >2400 sec	MSLB Blowdown ~ 0–900 sec
8 PCS Cooling Water	A. PCCWST flow rate	N/A	N/A	H	H	L
	B. PCCWST water temperature	N/A	N/A	M	M	L
	C. Water film stability and coverage	N/A	N/A	H	H	L
	D. Film stripping	N/A	N/A	L	L	L
	E. Film drag	N/A	N/A	L	L	L
Outside Containment						
9 Riser Annulus and Chimney Volume	A. PCS natural circulation	L	L	M	M	M
	B. Vapor acceleration	N/A	N/A	L	L	L
	C. Fog	N/A	N/A	L	L	N/A
	D. Flow stability	L	L	L	L	L
10 Baffle	A. Convection to riser annulus	N/A	N/A	L	M	N/A
	B. Convection to downcomer	N/A	N/A	L	M	N/A
	C. Radiation to shield building	N/A	N/A	L	L	N/A
	D. Conduction through baffle	N/A	N/A	L	M	N/A
	E. Condensation	N/A	N/A	L	L	N/A
	F. Heat capacity	N/A	N/A	L	L	N/A
	G. Leaks through baffle	N/A	N/A	M	M	N/A
11 Baffle Supports	A. Convection to riser air	L	L	L	L	L
	B. Radiation from shell	L	L	L	L	L
	C. Conduction from shell	L	L	L	L	L
	D. Heat capacity	L	L	L	L	L
12 Chimney Structure	A. Conduction through chimney	L	L	L	L	L
	B. Convection from chimney air	L	L	L	L	L
	C. Heat capacity of structure	L	L	L	L	L
	D. Condensation on chimney	L	L	L	L	L
13 Downcomer Annulus	A. PCS natural circulation	L	L	M	M	M
	B. Airflow stability	L	L	L	L	L

Component or Volume	Phenomenon or Parameter	LOCA Blowdown ~ 0–30 sec	LOCA Refill ~ 30–90 sec	LOCA Peak Pressure ~ 90–2400 sec	LOCA Long-Term >2400 sec	MSLB Blowdown ~ 0–900 sec
14 Shield Building	A. Convection to downcomer	N/A	N/A	L	L	L
	B. Conduction through shield building	N/A	N/A	L	L	N/A
	C. Convection to environment	N/A	N/A	L	L	N/A
	D. Radiation to environment	N/A	N/A	L	L	N/A
15 External Atmosphere	A. Temperature	N/A	N/A	L	L	L
	B. Humidity	N/A	N/A	L	L	L
	C. Recirculation	N/A	N/A	L	L	L
	D. Pressure fluctuations	N/A	N/A	L	L	L

Table 21.6.5-7 Summary and References for Treatment of High/Medium-Ranked Phenomena

Component or Volume	Phenomenon or Parameter	Highest Ranking	Summary of Treatment (Reference Section for Treatment/Discussion)
Inside Containment			
1 Break Source	A. Mass and energy	H	Conservatively high mass and energy source (21.6.5.7.4.1).
	B. Direction and elevation	H	Limiting break scenarios (21.6.5.7.4.2).
	C. Momentum	H	Biased lumped-parameter noding (21.6.5.7.5).
	D. Density	H	Density of the break fluid is affected by the amount of droplets assumed to be entrained in the atmosphere. Limiting scenario selected based on sensitivity studies (21.6.5.7.4.3).
	E. Droplet/liquid flashing	L	One-half of liquid break flow is assumed to be in the form of drops with 8E-05 inch diameter for LOCA blowdown. This was shown to be a conservative assumption for pressurization (21.6.5.7.4.3).
2 Containment Volume	A. Circulation/stratification	H	Effect bounded by introducing biases and using limiting scenarios (21.6.5.7.5 and 21.6.5.7.7). Atmosphere approximates well mixed for first 1200 seconds (i.e., up to peak pressure). Afterward, the atmosphere may not be well mixed, but only trends are important.
	B. Intercompartmental flow	H	Select scenario to minimize intercompartmental flow (21.6.5.7.5).
	C. Gas compliance	H	Standard gas constituents and properties used with conservatively low containment free volume (21.6.5.7.1 and 21.6.5.7.5).
	D. Fog (circulation)	H	Conservative drop fraction and size established by sensitivity studies (21.6.5.7.4.3).
	E. Hydrogen release	L	Energy equal to reaction of 1 percent of zirconium in active fuel region included, but no hydrogen is included in break flow (21.6.5.7.4.4).

Component or Volume	Phenomenon or Parameter	Highest Ranking	Summary of Treatment (Reference Section for Treatment/Discussion)
3 Containment Solid Heat Sinks (Steel and Concrete)	A. Liquid film energy transport	L	Energy in condensed film instantaneously transported to pool (21.6.5.7.1).
	B. Vertical film conductance	L	Conduction included implicitly in Uchida (21.6.5.4.1.2.2).
	C. Horizontal film conduction	H	Upward facing horizontal surfaces assumed insulated (21.6.5.7.5.3).
	D. Internal heat sink conduction	H	One-dimensional heat conduction solution with air gap between steel and concrete (21.6.5.7.4.6).
	E. Heat capacity	H	Conservative material properties maximize peak pressure (21.6.5.7.4.6).
	F. Condensation	H	Uchida correlation used (21.6.5.4.1.2.2).
	G. Convection from containment	M	Nominal convection correlation used (21.6.5.4.1.2.2).
	H. Radiation from containment	M	Nominal radiation correlation used (21.6.5.4.1.2.2).
4 Initial Conditions	A. Initial temperature	M	All initial conditions are conservatively selected (21.6.5.7.4.7). Maximum tech spec temperature used.
	B. Initial humidity	M	Conservative initial humidity (0 percent) used (21.6.5.7.4.7).
	C. Initial pressure	M	Conservative initial pressure used (21.6.5.7.4.7).
5 Break Pool	A. Circulation/stratification in the pool	M	Stratification is included by vertical stacking of nodes (21.6.5.7.5.4).
	B. Condensation/evaporation	M	Evaporation from pool is maximized and condensation minimized by noding to keep hotter liquid at the pool surface (21.6.5.7.5.4).
	C. Convection within containment volume	L	A nominal convection correlation and pool area are used (21.6.5.7.5.4).
	D. Radiation within containment volume	L	Conservatively neglected.
	E. Conduction in pool	M	Water pools assumed homogeneous (21.6.5.7.5.4).
	F. Compartment filling	L	Constant pool cross sectional area assumed (21.6.5.7.5.4).

Component or Volume	Phenomenon or Parameter	Highest Ranking	Summary of Treatment (Reference Section for Treatment/Discussion)
6 IRWST	A. Mixing/stratification (gas and water)	L	IRWST modeled as a single well-mixed water volume with draining outflow as a specified function and flow calculated between IRWST and adjacent volumes. Initial level is tech spec minimum; transient level calculated from liquid inventory. These low-ranked phenomena related to the IRWST behavior are modeled in a best-estimate sense based on established conservation equation techniques. The staff finds this acceptable.
	B. Condensation	L	
	C. Convection	L	
	D. Radiation	L	
	E. Conduction in liquid	L	
	F. Liquid level changes	L	
7 Containment Shell	A. Convection from containment	L	Conservative multiplier applied to McAdams free-convection heat transfer coefficient (21.6.5.4.1.2.2 and 21.6.5.6.5.2).
	B. Radiation from containment	L	Conservatively neglected.
	C. Condensation	H	Conservative multiplier applied. Free-convection process only conservatively assumed (21.6.5.6.5.2 and 21.6.5.6.5.3).
	D. Inside film conduction	L	Chun and Seban correlation used (21.6.5.4.2.3 and 21.6.5.6.5.2).
	E. Inside film energy transport	M	Nominal model based on mass and energy conservation used to track condensate (21.6.5.4.2.1).
	F. Conduction through shell	H	One-dimensional conduction at high PCS flow rate and two-dimensional conduction at lower PCS flow rates. Conservative material properties used, including degraded coating (21.6.5.4.2.3 and 21.6.5.7.4.6).
	G. Heat capacity of shell	H	Conservative material properties used (21.6.5.7.4.6).
	H. Convection to riser annulus	M	Conservative multiplier of 0.84 applied to standard correlations for heat and mass transfer (21.6.5.6.5.2).
	I. Radiation to baffle	M	Conservative model used with low emissivities and high sink temperature.
	J. Radiation to chimney	L	Conservatively low emissivities used.
	K. Radiation to fog/air mixture	L	Conservatively neglected.
	L. Outside film conduction	L	Chun and Seban correlation used (21.6.5.4.2.3 and 21.6.5.6.5.3).
	M. Outside film energy transport	M	Conservation of mass and energy solved with low PCS flow and high initial liquid temperature (21.6.5.4.2.3).
	N. Evaporation to riser annulus	H	Conservative multiplier of 0.84 applied to standard correlations for mass transfer (21.6.5.6.5.2 and 21.6.5.6.5.3).

Component or Volume	Phenomenon or Parameter	Highest Ranking	Summary of Treatment (Reference Section for Treatment/Discussion)
8 PCS Cooling Water	A. PCCWST flow rate	H	Applied flow restricted to evaporated flow. Sensible heating of runoff flow neglected (21.6.5.4.2.2).
	B. PCCWST water temperature	M	Conservatively high PCCWST temperature assumed (21.6.5.4.2.2).
	C. Water film stability and coverage	H	External shell water coverage area is input as a boundary condition (21.6.5.4.2.3).
	D. Film stripping	L	Neglected (21.6.5.4.2.3).
	E. Film drag	L	Neglected (21.6.5.4.2.3).
Outside Containment			
9 Riser Annulus and Chimney Volume	A. PCS natural circulation	M	Momentum equation is solved with 30-percent conservatism added to loss coefficients (21.6.5.6.6.3).
	B. Vapor acceleration	L	Neglected.
	C. Fog	L	Neglected.
	D. Flow stability	L	Potential for flow instability is negligible and, therefore, is neglected.
10 Baffle	A. Convection to riser annulus	M	Nominal mixed convection model used (21.6.5.4.2.1 and 21.6.5.6.5.2).
	B. Convection to downcomer	M	Nominal mixed convection model used (21.6.5.4.2.1 and 21.6.5.6.5.2).
	C. Radiation to shield building	L	Conservative model used with low emissivities and high sink temperature.
	D. Conduction through baffle	M	One-dimensional conduction model with conservative material properties (21.6.5.4.2.1 and 21.6.5.7.4.6).
	E. Condensation	L	Nominal model including free- and forced-convection mass transfer (21.6.5.4.2.1 and 21.6.5.6.5.2).
	F. Heat capacity	L	One-dimensional conduction model with conservative material properties (21.6.5.4.2.1 and 21.6.5.7.4.6).
	G. Leaks through baffle	M	Flowpath included to model leakage.
11 Baffle Supports	A. Convection to riser air	L	All baffle support-related phenomena are neglected. This is acceptable to the staff for these low-ranked phenomena.
	B. Radiation from shell	L	
	C. Conduction from shell	L	
	D. Heat capacity	L	

Component or Volume	Phenomenon or Parameter	Highest Ranking	Summary of Treatment (Reference Section for Treatment/Discussion)
12 Chimney Structure	A. Conduction through chimney B. Convection from chimney air C. Heat capacity of structure D. Condensation on chimney	L L L L	Nominal heat and mass transfer correlations used with conduction model. Conservative emissivities and material properties used. These low-ranked phenomena related to the chimney structure are modeled in a best-estimate sense based on established techniques. The staff finds this acceptable.
13 Downcomer Annulus	A. PCS natural circulation	M	Momentum equation is solved with 30-percent conservatism added to loss coefficients (21.6.5.6.6.3).
	B. Airflow stability	L	Potential for flow instability is negligible and, therefore, is neglected (21.6.5.6.6.3).
14 Shield Building	A. Convection to downcomer	L	Nominal mixed convection model used (21.6.5.6.5.2).
	B. Conduction through shield building	L	One-dimensional conduction model with conservative material properties (21.6.5.7.4.6).
	C. Convection to environment	L	Nominal heat and mass transfer correlations used with conservative material properties (21.6.5.6.5.2).
	D. Radiation to environment	L	Conservative model used with low emissivities and high sink temperature.
15 External Atmosphere	A. Temperature	L	Maximum tech spec value is used (21.6.5.7.4.7).
	B. Humidity	L	Held constant at initial value (21.6.5.7.4.7).
	C. Recirculation	L	Negligible and, therefore, not considered.
	D. Pressure fluctuation	L	Pressure held constant at initial value (21.6.5.7.4.7).

Table 21.6.5-8 Heat and Mass Transfer Parameters—
Operating Range for AP600 and AP1000 (from Table 3-3, WCAP-15862,
"<u>W</u>GOTHIC Application to AP600 and AP1000," April 2002, Nonproprietary)

Heat Transfer Correlation	**Parameter**	**Test Data Range**	**AP600 Range**	**AP1000 Range**
Internal Free Convection: $h = 0.13 \cdot \frac{k}{\left(\frac{v^2}{g}\right)^{1/3}} \cdot \left(\frac{\Delta\rho}{\rho}\right)^{1/3} \cdot Pr^{1/3}$	Δρ/ρ	0.08 to 0.55	< 0.40	< 0.42
	Pr	0.72 to 0.90	0.72 to 0.90	0.72 to 0.90
	Sc	~ 0.52	~ 0.52	~ 0.52
External Mixed Convection: $Nu_{force} = 0.023 \cdot Re_d^{0.8} \cdot Pr^{1/3}$ $Nu_{free} = 0.13 \cdot (Gr_d \cdot Pr)^{1/3}$	Re_d, Riser	< 120,000 evap < 500,000 dry	< 189,000	< 210,000
	Re_d, Downcomer		< 151,000	< 190,000
Opposed Mixed Convection: $Nu_{mix} = (Nu_{force}^3 + Nu_{free}^3)^{1/3}$	Re_d, Chimney [1]		< 1,400,000	< 1,800,000
	Gr_d, Riser	< 7.0x10^{10} evap < 1.0x10^{11} dry	< 1.2x10^{9}	< 1.5x10^{9}
Assisted Mixed Convection: $Nu_{mix} = Max\left\{\begin{array}{l}\left(Nu_{free}^3 - Nu_{force}^3\right)^{1/3}, \\ Nu_{free}, \\ 0.75 \cdot Nu_{force}\end{array}\right\}$	Gr_d, Downcomer		< 6.2x10^{9}	< 2.1x10^{10}
	Gr_d, Chimney [1]		< 2.1x10^{12}	< 8.0x10^{12}
	Pr	~ 0.72	~ 0.72	~ 0.72
	Sc	~ 0.52	~ 0.52	~ 0.52
Liquid Film Heat Transfer: $Nu_{turbulent} = 0.0038 \cdot Re^{0.4} \cdot Pr^{0.65}$ $Nu_{wavy-lam} = 0.822 \cdot Re^{-0.22}$	Re	10,000	< 3,200	< 3,500
	Pr	1.77 to 5.9	1.5 to 3.0	1.5 to 3.0

Note 1: The evaluation model conservatively does not use the clime heat and mass transfer correlations in the chimney region and the range of test data is not relevant. (Ref: M.M. Corletti, "AP1000 Pre-application Review—Acceptance Review of Codes Submission and Responses to Requests for Additional Information Pertaining to the AP1000 Pre-Certification Review," <u>W</u> letter DCP/NRC1481, July 31, 2001.)

Table 21.6.5-9 WGOTHIC Analyses of LST Using Lumped-Parameter Modeling Approach

Test	**Predicted/Measured Pressure (WGOTHIC V1.2)**	**Predicted/Measured Pressure (WGOTHIC V4.1)**
Priority		
212.1A	1.15	
212.1B	1.17	
212.1C	1.20	
214.1A	1.03	> 1.2 both 14–34 kPa (2–5 psi) higher than measured
214.1B	1.12	> 1.2 both 14–34 kPa (2–5 psi) higher than measured
216.1A	1.11	Similar (both 28 kPa (4 psi) higher than measured)
216.1B	1.19	7 percent higher—V1.2—55 kPa (8 psi) higher V4.1—83 kPa (12 psi) higher
219.1A	1.03	About the same
219.1B	1.07	Lower (maximum 7 percent difference)
219.1C	1.31	Slightly lower (both about 55 kPa (8 psi) higher than measured)
222.1	1.18	
222.4A	1.15	V4.1 lower, small during this part
222.4B	1.28	V4.1 lower
Nonpriority		
213.1A	1.13	
213.1B	1.18	
217.1A	1.06	
217.1B	1.32	
218.1A	1.11	
218.1B	1.19	
221.1A	1.22	
221.1B	1.19	
224.1	1.25	
224.2	1.24	
202.3	1.07	

Table 21.6.5-10 Conservative Input Values for EM
for Environmental (Outside Containment) Initial Conditions

Initial/Conservative Conditions Input Parameters	**Value**	**Basis for Value in EM**	**Reference**	**Comments**
Environmental Atmospheric Temperature	115 °F	Set to maximum safety air temperature limit by the site interface parameters	FSAR Chap. 2 WCAP-15846 Sec. 5.7 Sensitivity Study	Maximizes downcomer inlet temperature, reduces buoyancy effects.
Environmental Total Pressure	14.7 psia	Standard		
Environmental Relative Humidity	22 percent at 115 °F	Limit defined by site interface parameters	FSAR Chap. 2 WCAP-15846 Sec. 5.6 Sensitivity Study	

Table 21.6.5-11 Conservative Input Values for EM for Inside Containment Initial Conditions

Initial/Conservative Conditions Input Parameters	Value	Basis for Value in EM	Reference	Comments
Containment Atmospheric Temperature	120 °F	Maximum technical specification value. Maximizes internal heat sink temperature.	Tech. Spec. 3.6.5 (FSAR Chap. 16) WCAP-15846 Sec. 5.5 Sensitivity Study	
Containment Total Pressure	15.7 psia	Maximum technical specification value. Maximizes initial pressure, amount of air, retards mass transfer.	Tech. Spec. 3.6.4 (FSAR Chap. 16) WCAP-15846 Sec. 5.4 Sensitivity Study	Maximizes initial inside containment pressure prior to blowdown initiation. Maximizes initial amount of noncondensable gas content.
Containment Relative Humidity	0 percent	Maximum air content.	WCAP-15846 Sec. 5.3 Sensitivity Study	Maximizes initial amount of noncondensable gas content, minimizes liquid volume fraction in containment atmosphere.
Initial Heat Sink Temperature	120 °F	Maximum technical specification value. Maximizes initial heat sink temperatures to minimize heat transfer rate.	Tech. Spec. 3.5.6 (FSAR Chap. 16) WCAP-15846 Sec. 5.5 Sensitivity Study	Maximizes all initial internal thermal conductor temperatures in order to minimize heat transfer and energy storage capacity.
IRWST Liquid Volume Fraction	0.868	Minimum technical specification IRWST water volume.	Tech. Spec. 3.5.6 (FSAR Chap. 16)	Minimizes available amount of water storage for core cooling. However, maximizes noncondensable gas volume fraction from containment point of view.
IRWST Water Temperature	120 °F	Maximum technical specification IRWST water temperature.	Tech. Spec. 3.5.6 (FSAR Chap. 16)	Minimizes core cooling capability of replenished core coolant.

Table 21.6.5-12 Conservative Input Values for EM for Primary System and Secondary System Conditions

Initial/Conservative Conditions Input Parameters	Basis for Value in EM	Reference	Comments
RCS Initial Conditions	Maximum operating temperature and pressure. Allowances for error and instrument dead band.	FSAR Chap. 6, Section 6.2.1.3.2.1	
RCS Volume	RCS volume increased by 1.4 percent (uncertainty).	WCAP-10325-P-A	
Core Stored Energy	Core stored energy increased by 15 percent. Maximized in terms of burnup and maximum core fluid temperature.	WCAP-10325-P-A	
Steam Generator Mass	Initial mass increased by 10 percent. Maximizes energy in the system.	WCAP-10325-P-A	
Initial Power Level	102 percent of full power, accounting for calometric error. Maximizes energy in system.	WCAP-10325-P-A	
Zircon-Water Reaction	1 percent of Zirconium reacts. Bounds guidance of FSAR for no appreciable reaction.	FSAR Chap. 15	Addition of energy to maximize energy release into containment.
LOCA Mass and Energy Releases	Westinghouse primary system safety computer code SATAN78	WCAP-10325-P-A	
Steam Generator Heat Release	Intact loop—1 hour Broken loop—0.5 hour		Substantial energy sources in SG compartments (e.g., not component) beyond containment peak pressure phase.
MSLB Mass and Energy Releases	Westinghouse primary/secondary system safety computer code	FSAR 6.2.1.4	

Table 21.6.5-13 Conservative Input Values for EM for Primary PCS Characteristics

Initial/Conservative Conditions Input Parameters	Basis for Value in EM	Reference	Comments
Initial Shell Temperature	Maximum technical specification value for containment air temperature, which bounds initial shell temperature.	Tech. Spec. 3.6.5 (FSAR Chap. 16)	
Applied External Film Flow Rate	Assumption of single failure of one of two PCS drain headers. Delivered flow is reduced by amount predicted to run off based on water coverage model. EM applies concept of flow limit by complete evaporation.	WCAP-15846, Sec. 7	
External PCS Liquid Film Temperature	Set to upper bound value 120 °F. Minimizes film subcooling effect.	Tech. Spec. 3.6.6 (FSAR Chap. 16)	
Film Coverage Fraction	Held constant consistent with water coverage model and flow limit specified by evaporation.	WCAP-15846, Sec. 7	
PCS Coating Properties	Thermal conductivity of shell paint reduced to 25 percent of nominal value.		
PCS Emissivity	Surface emissivities of shell, baffle, downcomer boundary reduced to 90 percent of nominal value.		
PCS Coatings Thickness	Maximum coating thicknesses used.		
Delay Time for PCS Initiation	No credit for PCS film flow prior to 337 seconds after blowdown initiation.	WCAP-15846, Sec. 7	Minimizes energy transfer to PCS, maximizes energy content inside containment.
Internal Heat and Mass Transfer Correlation	Assumption of free convection only. Include multiplier of 0.73.	WCAP-14326, Sec. 4.5	Neglects forced-convection contribution, reduces energy transfer to PCS, maximizes energy content inside containment, eliminates potential bias of too high predicted velocities by LP approach.
External Heat and Mass Transfer Correlation	Assumption of mixed convection. Include multiplier of 0.84.	WCAP-14326, Sec. 4.5	

Table 21.6.5-14 Conservative Input Values for EM for Geometry and Flow Characteristics

Input Parameter	Basis for Value in EM	Reference	Comments
Containment Free Volume	Nominal cold value which neglects the volumetric increase at higher temperature.		Minimizes total free, inside containment volume by discarding volume increase due to thermal expansion at higher blowdown-induced temperatures.
Internal Heat Sinks—Area and Volume	General arrangement drawings. Smaller trays, piping, and miscellaneous structures are ignored.		Ignoring heat sink surfaces and volumes maximizes energy content in atmosphere. No cut-off values or total volume/surface of ignored structures provided.
Internal Flow Paths Area and Loss Coefficient	General arrangement drawings. The smaller flow paths are ignored.		
External (Downcomer/Riser) Flow Paths—Loss Coefficients	General arrangement drawings. Loss coefficients based on 1/6 scale annulus pressure drop test.	WCAP-13328	30-percent add-on values derived from experiments conservatively increases pressure drop in bend and riser.

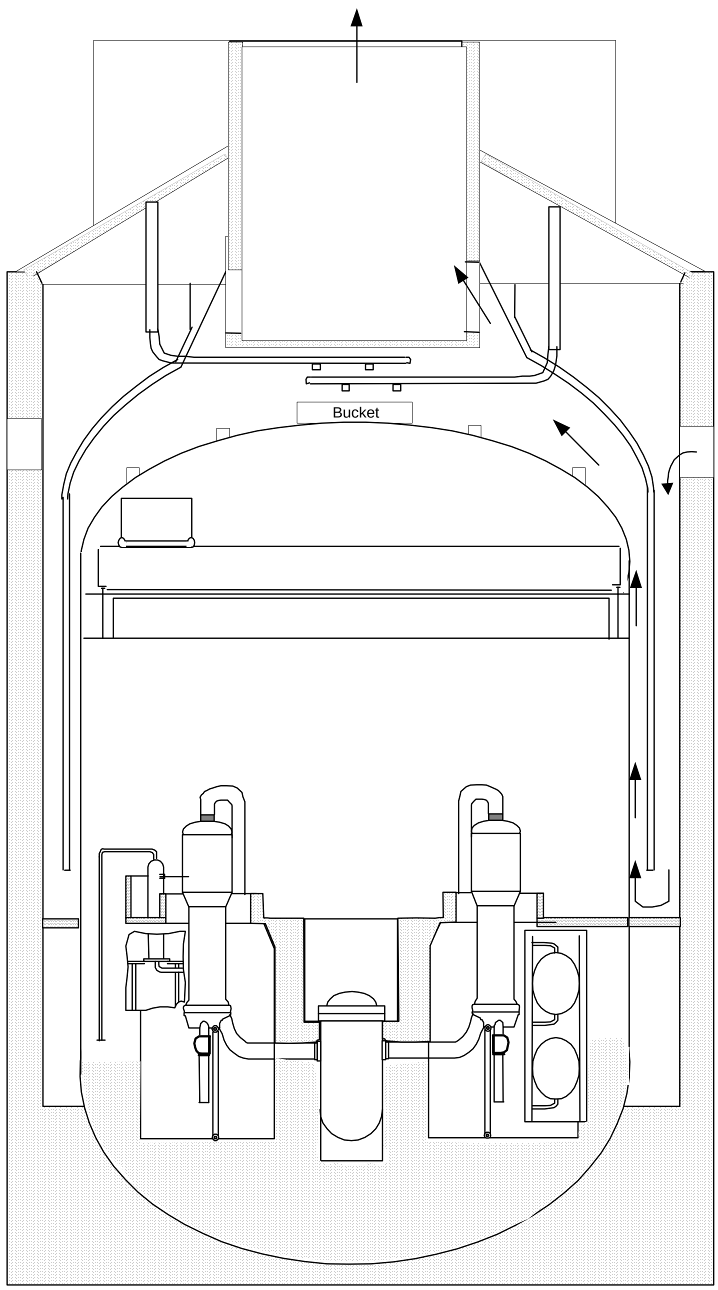

Figure 21.6.5-1 Westinghouse Passive Containment Cooling Design

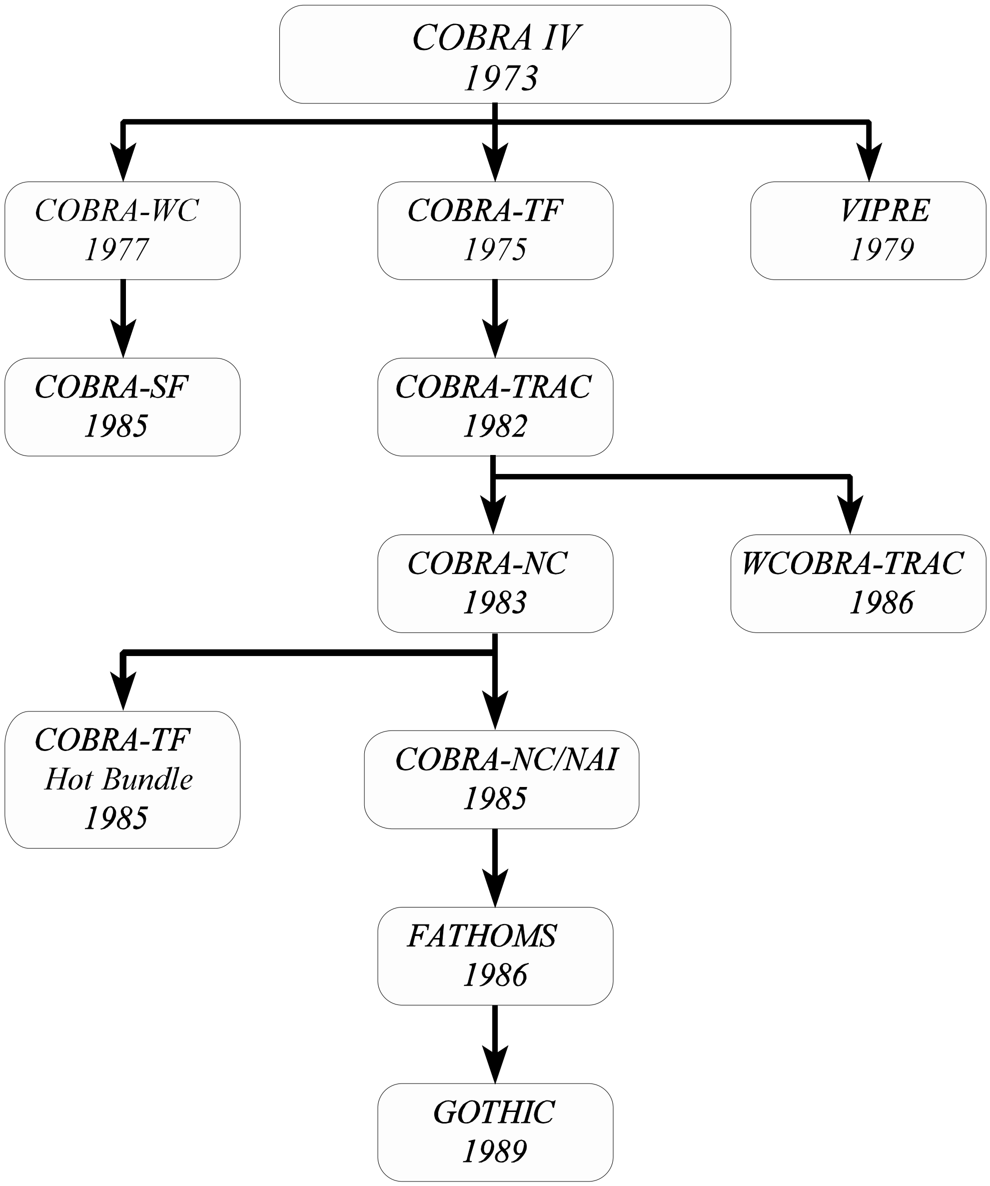

Figure 21.6.5-2 Historic Development of the GOTHIC Code

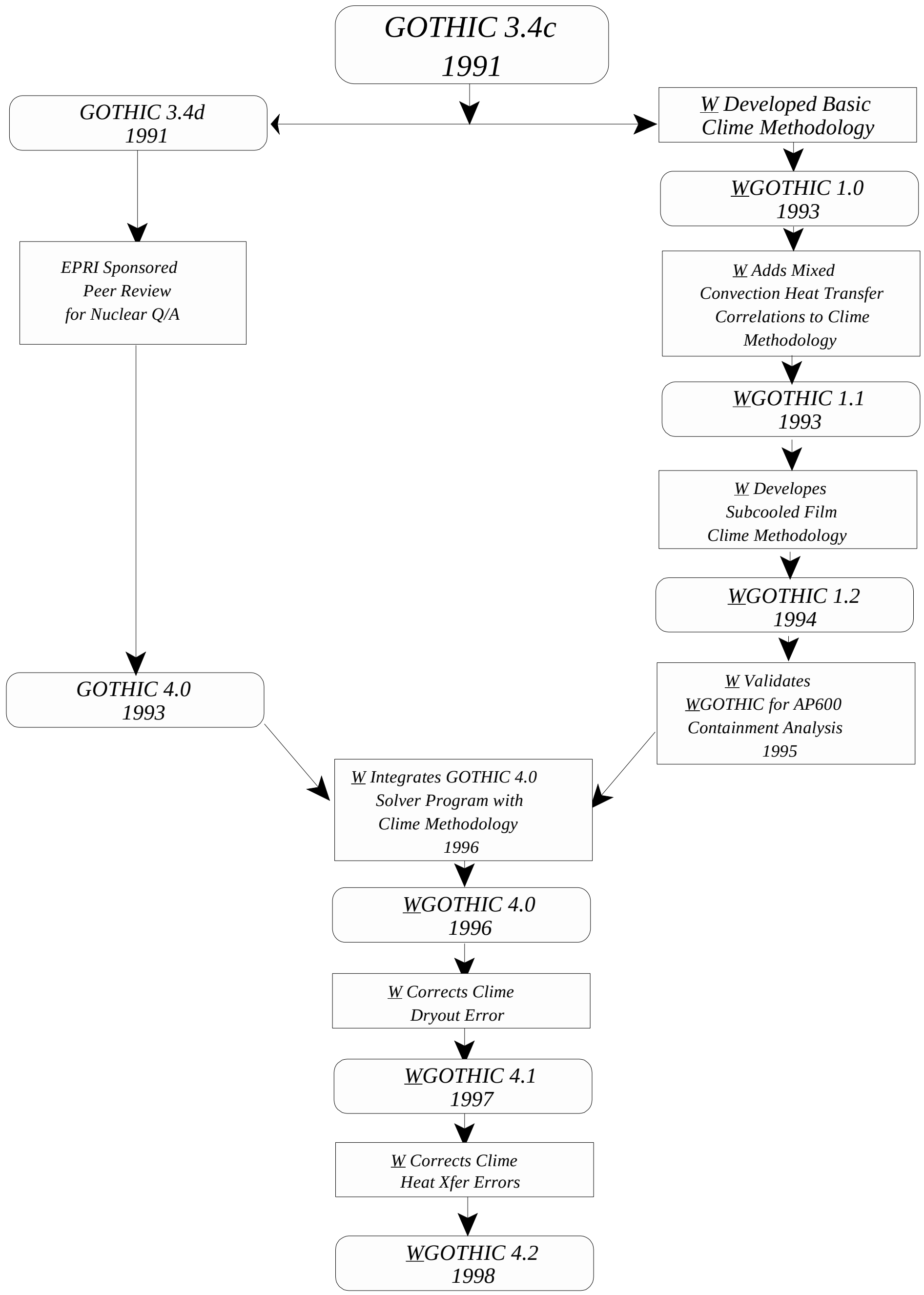

Figure 21.6.5-3 Development of WGOTHIC

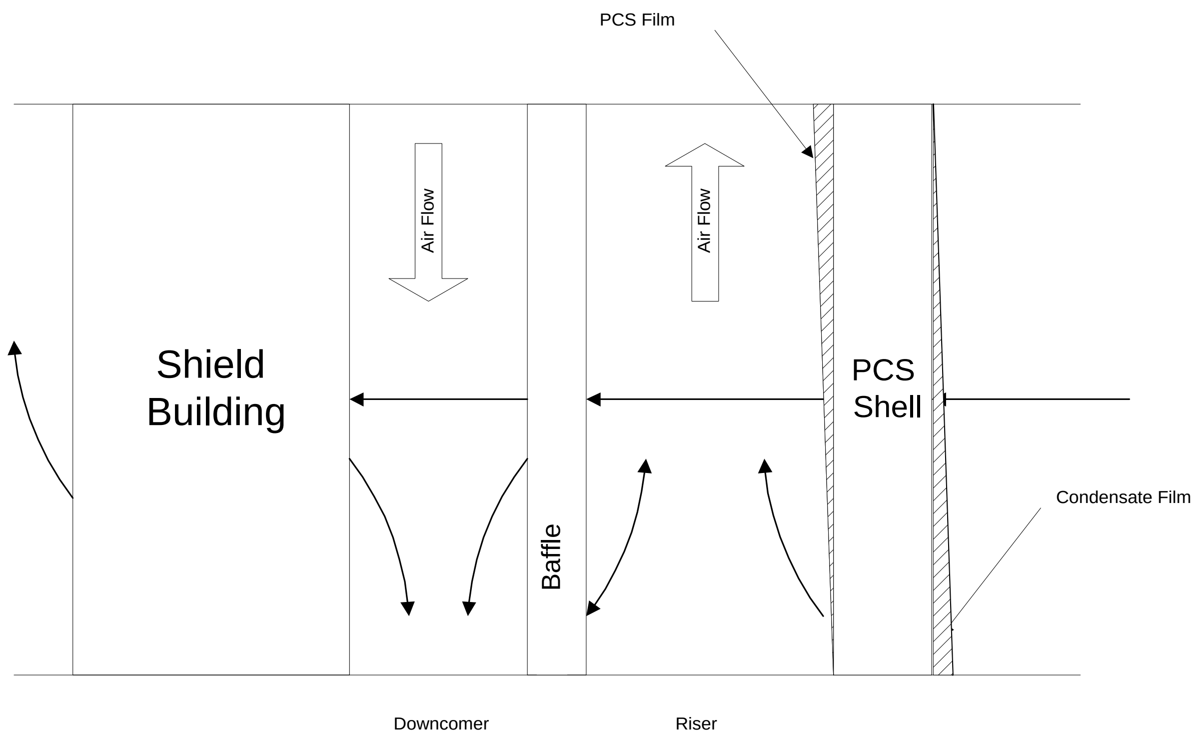

Figure 21.6.5-4 Simplified Representation of a Clime Heat Structure

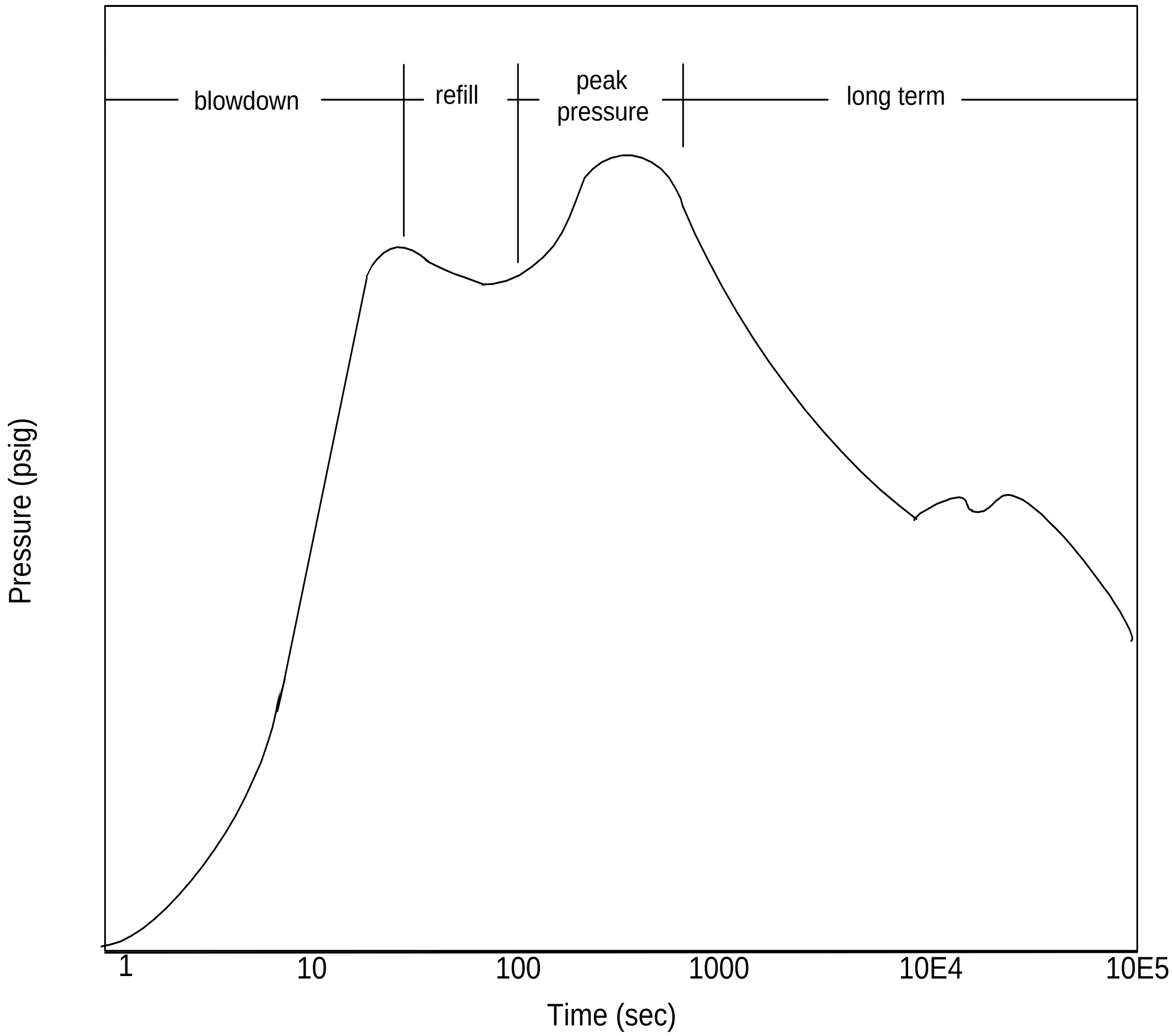

Figure 21.6.5-5 LOCA Time Phases

Appendix 21.A Safety Evaluation of AP600 Best-Estimate Large-Break LOCA Analysis Methodology

21.A.1 Westinghouse Methodology and Comparison to the CSAU Methodology

For the AP600 design review, the applicant submitted a comparison of its BE LBLOCA methodology for WCOBRA/TRAC to the CSAU methodology of NUREG/CR-5249. This section summarizes that comparison and, where appropriate, references the sections in this report that describe the applicant's methodology and the review in more detail. The information is presented by following the three elements and 14 steps in the CSAU methodology.

21.A.1.1 Element 1 - Requirements and Capabilities*

This element consists of the first 6 steps of the CSAU methodology*. These steps are intended to determine the scenario modeling requirements and compare them to computer code capabilities to determine the applicability of the computer code to the particular scenario. Element 1 is also used to identify potential limitations in the application of the code.

Step 1: Specify the Scenario

The capabilities of a computer code are scenario dependent. For example, the requirements for properly calculating an LBLOCA are different than those for an SBLOCA. This is because the dominant phenomena and processes are different. Therefore, the first step in the CSAU methodology is to specify the scenario being considered. The CSAU and Westinghouse AP600 realistic methodologies selected the LBLOCA. In identifying the specific scenario, the applicant fulfilled CSAU Step 1.

Step 2: Select the Nuclear Power Plant.

The response of a particular PWR plant to a LBLOCA will vary from plant to plant. Therefore, the type of plant or plants being considered needs to be identified.

For CSAU, a Westinghouse four-loop PWR with 17x17 fuel bundles was selected. In the context of analyzing the AP600, the applicant selected a 17x17 fuel bundle and passive ECC injection into the reactor downcomer. By specifying the type of plant considered, the applicant fulfilled CSAU Step 2.

Step 3: Identify and Rank Phenomena

Not all phenomena are equally important in calculating a plant's response to a LBLOCA. Therefore, the phenomena should be identified and ranked relative to their importance in calculating the primary safety criteria for a LBLOCA. For the LBLOCA, the primary safety criterion is the PCT. Phenomena important to each phase of the LBLOCA are identified and

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*The term "requirements," as used in this appendix does not refer to NRC regulatory requirements (unless specifically noted), rather, it refers to the demands of the CSAU methodology.

ranked separately in the PIRT. By using a PIRT, the list of phenomena needing to be considered in the analysis is simplified and reduced to a manageable size.

In the CSAU methodology, expert opinion and user experience formed the basis for the PIRT developed during the review as described in NUREG/CR-5047.

The applicant developed a PIRT for the AP600 similar to that in the CSAU methodology. The applicant's PIRT is discussed in Section 21.A.2, including how the important phenomena were identified and ranked. This was done for each phase of an LBLOCA. Since the applicant developed a PIRT similar to that developed in the CSAU study, the applicant fulfilled CSAU Step 3.

Step 4: Select a Frozen Code

Selecting a frozen code is important because it ensures that changes to the code after an evaluation is completed do not impact the conclusions of the study. Also, it ensures changes occur in an auditable and traceable manner.

The CSAU methodology used TRAC-PF1 MOD1, Version 14.3 (NUREG/CR-3858).

The applicant selected WCOBRA/TRAC, MOD7A. Revision 1, for AP600 analyses; the NRC approved this code version in the three- and four-loop plant methodology. As discussed in Sections 21.A.8.1 and 21.A.12, the applicant made several minor modifications to the code to allow for the modeling of AP600 passive safety features during the CMT injection phase of a LBLOCA. However, the applicant also indicated the changes had a negligible impact on the calculated PCT as stated in response to comments 4(a) and 4(b) in Westinghouse letter NSD-NRC-97-5240, dated July 18, 1997. Because the AP600 95^{th} percentile PCT shows a large margin to the 10 CFR 50.46 PCT limit [the AP600 SSAR shows 913 $^\circ$C (1675 $^\circ$F) versus the 10 CFR 50.46 limit of 1204 $^\circ$C (2200 $^\circ$F)], this is not considered safety-significant.

Because the applicant selected an approved code, and because the modifications made do not impact the calculated PCT, the staff considered that the applicant met the underlying purpose of CSAU Step 4.

Step 5: Provide Code Documentation

This step provides documentation that is consistent with the frozen code version. Adequate documentation allows confirmation of the applicability of the code to the specific scenario and evaluated plants. NUREG/CR-5249 recommends the documentation include a user manual, user guide, developmental assessment reports, and a models and correlations quality evaluation report.

TRAC code documentation available to the CSAU methodology included a code user manual and code description, a models and correlations document, and developmental code assessment reports.

The applicant documented its realistic LBLOCA methodology for three- and four-loop plants in the five-volume CQD. The CQD included a description of the WCOBRA/TRAC models and correlations, a series of code assessments, a description of how to apply the methodology to a PWR, and an uncertainty evaluation. Significant documentation was also generated during the review of the approved methodology as a result of the applicant's responses to NRC questions. NRC review of the CQD and the other Westinghouse-generated documentation is found in an NRC letter entitled "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996. In WCAP-14171, the applicant provided arguments for the applicability of WCOBRA/TRAC to the AP600 and described the modifications of its approved methodology as applied to the AP600. Review and approval of the application of WCOBRA/TRAC and the modified methodology to the AP600 is described in this appendix.

The applicant provided the revised CQD in a submittal dated March 24, 1998, which documents the WCOBRA/TRAC code and realistic/best estimate methodology to incorporate the applicant's commitment and other changes made during the NRC's review of the AP600 design certification application.

Except for the user manual and user guide, documentation equivalent to that outlined in CSAU Step 5 was provided by the applicant. The user manual and guide were not included in the scope of the review. Therefore, the staff considered that the applicant met the underlying purpose of CSAU Step 5.

Step 6: Determine Code Applicability

The applicability of a computer code is determined by evaluating the conservation equations, closure relationships, code numerics, and structure and nodalization relative to the important phenomena identified by the PIRT in Step 3. This step determines the applicability of the code and helps to identify areas that need modification or need to be considered in the uncertainty evaluation.

To determine code applicability, the CSAU methodology used the PIRT to identify important phenomena and evaluated the capabilities of the chosen code, TRAC-PF1, to calculate those phenomena. The CSAU study concluded the TRAC-PF1 code was applicable to LBLOCA analyses.

In the CQD, the applicant performed a similar evaluation for three- and four-loop plants, but described the LOCA transient in terms of physical processes, including fluid flow, structural heat transfer, and structural distortion. The applicant assessed the capabilities of WCOBRA/TRAC to predict the phenomena associated with the above processes by a direct review of the models and comparisons to experimental data, and the applicant concluded the code was applicable to LBLOCA analyses. The applicant compared the AP600 response to a North Anna LBLOCA analysis in WCAP-14171, Section 2. As shown by the applicant, the AP600 LBLOCA response was very similar to that for North Anna. The applicant also developed a PIRT for the AP600 and showed it was similar to that developed for three- and four-loop plants with cold-leg injection. Therefore, the applicant concluded WCOBRA/TRAC could be applied to the AP600

LBLOCA. Review of WCAP-14171 and the PIRT found nothing to contradict the applicant's conclusion in this area. Therefore, the applicant met the intent of CSAU Step 6.

21.A.1.2 Element 2 - Assessment and Ranging of Parameters

In Element 2, Steps 7 to 10 are used to determine the effects of the important parameters over the specified ranges. The effects to consider include those associated with code accuracy, effects of scale, and parameter ranges for the uncertainty evaluation.

Step 7: Establish an Assessment Matrix

In this step, the data set used to determine the code uncertainty on the basis of comparisons to test data is established. The PIRT table is used to help determine the assessment matrix, which should include both separate effects and integral tests. The assessment matrix is used to provide a database for evaluating (1) the code accuracy to calculate phenomena important to the scenario, (2) the capability of the code to scale up phenomena to the full-size plant, and (3) the influence of nodalization on the calculation.

The CSAU study reviewed prior TRAC-PF1 assessments to confirm they examined the dominant phenomena identified in the PIRT. Tests used in the CSAU study included the Upper Plenum Test Facility (UPTF) for ECC bypass; Marviken for break flow; LOFT for scaling and nodalization; the Slab Core Test Facility (SCTF) and the Cylindrical Core Test Facility (CCTF) for scaling, heat transfer, and steam binding; and the INEL film boiling tests for heat transfer, two-phase pump data, and rewet data.

The approved Westinghouse methodology for three- and four-loop plants included assessment of WCOBRA/TRAC against approximately 100 separate effects and integral tests. In WCAP-14171, the applicant demonstrated the similarity of the AP600 LBLOCA response to that for current-generation plants. By showing this similarity, the applicant extended the applicability of the approved methodology from the three- and four-loop plant assessment to the AP600. In response to comment 1 in its July 18, 1997 letter (NSD-NRC-97-5240), the applicant compared the WCOBRA/TRAC assessment for three- and four-loop plants against the highly ranked phenomena in the Westinghouse three- and four-loop plant PIRT. This comparison was reviewed by the NRC in the three- and four-loop plant review. The staff found that all important phenomena identified in the three- and four-loop plant PIRT were covered in the assessment tests (see NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996). In addition, the applicant in WCAP-14171 provided assessments for those features specific to the AP600 LBLOCA such as DVI. These AP600 assessments are discussed in Section 21.A.3 of this report.

Also, as discussed by the applicant in response to comment 16 of its June 10, 1997 letter (NSD-NRC-97-5171), the range of the tests was found to adequately cover the range of the conditions expected in the AP600 (see Section 21.A.9.2 of this report) for the important parameters defined in RG 1.157 and the applicant's PIRT. Therefore, the applicant established an assessment matrix consistent with CSAU Step 7.

Step 8: Define Nuclear Power Plant Nodalization

The nodalization studies discussed in this step were intended to define a PWR nodalization sufficient to provide needed detail yet economical to run full-scale PWR analyses.

The CSAU study used previous studies with developmental versions of TRAC-PF1 to define the noding detail for the PWR. The basic rule was to use the same number of nodes as in the LOFT code assessment work. The core model did not include a separate channel to represent the hot assembly.

The applicant established the AP600 noding in the vessel on the basis of system geometry (location of guide tubes and support columns) and the LBLOCA processes discussed in Step 3. This AP600 nodalization is similar to the three- and four-loop plant nodalization in the approved methodology. Some changes were made in the AP600 nodalization to account for AP600 geometry differences. To meet RG 1.157 recommendations, a hot assembly was represented as a separate channel; AP600 plant calculations were used to determine the hot assembly location in the core. The AP600 nodalization was applied to the AP600-specific experiment simulations.

To allow use of the CQD assessment calculations in determining the CQD WCOBRA/TRAC code uncertainty, the three- and four-loop plant PWR nodalization was applied to the CQD experiment simulations to ensure nodes of similar axial length. The similarity of the AP600 and three- and four-loop plant nodalizations allowed for the application of the CQD code uncertainty to the AP600. Review of the experiment and PWR nodalizations is discussed in Section 21.A.4 of this report. Therefore, the staff concluded that the applicant developed the AP600 plant nodalization consistent with CSAU Step 8.

Step 9: Determine Code and Experiment Accuracy

This step discusses two approaches in determining the code accuracy. First, code accuracy may be directly compared to experimental data. Second, experimental data may be used to determine parameter ranges for use in PWR sensitivity studies.

In the CSAU study, this step consisted of two parts: (1) ranging of parameters for the uncertainty evaluation and (2) code and experiment accuracy. In the first part, models were assessed and ranges determined by comparing code predictions to data and using scatter plots. The code bias was estimated and applied as a multiplier on a calculated result or as an additive term to correct the tendency of the model to overpredict or underpredict the data. The scatter about the bias line was used to develop the model uncertainty. In most cases, a uniform distribution was assumed because of a lack of data. In the second part, code calculations of PCT were compared to experimental data for separate and integral effects tests.

In the approved Westinghouse methodology, several T-H model ranges were determined for parameters including critical flow, fuel rod parameters, heat transfer, minimum film boiling temperature (T_{MIN}), pump/nozzle resistance, and condensation for the uncertainty evaluation. Other models were confirmed not to be important or were conservatively biased. The applicant, in response to comment 12(k) of its July 18, 1997 letter (NSD-NRC-97-5240), evaluated each of these items for applicability to the AP600. Further information on the review of this area is given in Sections 21.A.5 and 21.A.8 of this report. In the second part, the applicant performed the extensive code assessment discussed above and used it to determine an experimentally based code bias and uncertainty. Review of the experimentally based bias and uncertainty is discussed in Section 21.A.5.5 of this report.

The applicant included both types of approaches in its determination of the code and experiment accuracy; however, there are some differences, such as the comparison of the model and code-based uncertainties discussed in Sections 21.A.5.1 and 21.A.5.5 of this report. The applicant's methodology was considered to be consistent with the underlying purpose of CSAU Step 9.

Step 10: Determine the Effect of Scale

Step 10 is based on the recognition that not all of the code assessment work will be performed on tests completed at full-scale test facilities. This step provided for assessment of the effects of the scale differences on the code uncertainty estimate.

In the CSAU study, it was concluded that power-to-volume scaled test facilities adequately simulate the PWR response except in the areas of the downcomer (ECC bypass) and upper plenum entrainment. Sensitivity studies were performed for the PWR to determine the effects of scale on the basis of the developed parameter ranges. For upper plenum entrainment, TRAC-PF1 calculations with the entrainment models altered were run to determine the bias for the effect of steam binding on PCT. In the case of ECC bypass, full-scale UPTF data were used to develop a bias applied to the calculated PCT. The CSAU study also identified critical flow and pump two-phase performance as needing additional review because of the lack of full-scale data. The study included variations in these models in the run matrix used to develop the PCT response surface.

The applicant determined that the CSAU conclusions on the applicability of power-to-volume scaled facilities also applied to its approved methodology. Thus, the applicant evaluated the effects of ECC bypass and upper plenum entrainment. However, full-scale UPTF test data was not available in these areas. To evaluate the effects of ECC bypass with DVI, WCOBRA/TRAC was assessed against UPTF Test 21, and the applicant found the WCOBRA/TRAC results were conservative relative to the test data (see WCAP-14171, Section 3.2). For upper plenum entrainment, UPTF Test 29B was evaluated as part of the three- and four-loop plant review, and the applicant also found a conservative (negative) bias in its WCOBRA/TRAC calculations (see NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996). In both cases, the applicant did not apply the negative bias. The applicant accounted for critical flow directly in the uncertainty analysis with the effect determined by PWR sensitivity calculations. For pump two-phase performance, the applicant's evaluations in response to comment 12(g) of its June 10, 1997, letter (NSD-NRC-97-5171), showed that, just as for three- and four-loop plants, single-phase pump performance in AP600 is more important. The applicant included this parameter directly in the uncertainty evaluation. The variations for critical flow and single-phase pump performance are discussed in Section 21.A.5.2 of this report.

On the basis of the above, the staff concluded that the applicant met the underlying purpose of CSAU Step 10 and that conservative biases for ECC bypass and upper plenum entrainment were not used by the applicant to adjust the final calculated PCT.

21.A.1.3 Element 3 - Sensitivity and Uncertainty Analysis

In this element, the effects of individual contributors to the total uncertainty are determined and combined to provide a statement on the total uncertainty of the analysis.

Step 11: Determine the Effect of Reactor Input Parameters and State

Uncertainty in the operating state of the PWR at the time of the accident results in uncertainty in the calculated PCT. This step assesses the effects of the plant initial conditions on the accident results.

The CSAU study evaluated the peaking factor and fuel stored energy to define an operating point. Plant inputs were on the basis of the assumption of base load operation.

The applicant considered the effects of a wide range of parameters on the calculated PCT, and both plant initial conditions and boundary conditions were considered. For AP600, the applicant determined the impact of the following four conditions:

(1) Plant physical configuration—steam generator tube plugging, hot assembly location, and pressurizer location relative to the break

(2) Power distributions and operating history—to simplify the overall AP600 analysis, bounding parameters on the basis of AP600 sensitivity calculations were used in this area (e.g., peaking factors and axial power distribution)

(3) Initial fluid conditions—reactor pressure, reactor T_{avg}, and accumulator conditions

(4) Boundary conditions—break location, type, and size; containment pressure; and offsite power availability

The above items are discussed in more detail in Section 21.A.7 of this report, but it is noted here that the AP600 analysis used bounding values for the items listed in Items (1), (3), and (4), above, in addition to those already noted for Item (2).

Through this bounding approach, the applicant's methodology accounted for the effects of the uncertainty in the initial plant operating conditions on the overall analysis. Therefore, the applicant's methodology was consistent with CSAU Step 11.

Step 12: Perform PWR Sensitivity Calculations

This step provides information on the effects of the plant input conditions and code model uncertainties on the code output (primarily PCT). This is done by performing code sensitivity calculations with the input varied to determine the effects on the calculated results.

For the CSAU study, a T-H run matrix that varied break flow, pump two-phase head degradation, T_{MIN}, core entrainment, and combinations of break flow and pump two-phase head degradation was developed. Local effects were calculated using the TRAC supplemental rod option. This allowed different rods to be modeled, but the rods did not feed back into the T-H analysis. The CSAU study used these rods to determine the effect of peaking factor, fuel conductivity, gap heat transfer coefficient (HTC), forced convection HTC, and combinations of gap HTC and fuel conductivity and gap HTC and forced convection HTC.

For the AP600, the effects of power distributions (both peaking factors and power shapes) and the effects of initial conditions were determined through WCOBRA/TRAC calculations. The applicant then used a bounding approach to account for these uncertainties in the AP600 analysis. The applicant's T-H or global model run matrix looked at the effects of break flow, broken loop vessel nozzle loss coefficient, and condensation multiplier. Local effects of hot rod peaking factor, gap HTC, fuel density, fuel conductivity, cladding burst temperature, cladding burst strain, metal-water reaction, convection HTC, and various cross products of these parameters were accounted for through HOTSPOT simulations. These simulations used the HOTSPOT code with global model run matrix results as boundary conditions. These are discussed in more detail in Sections 21.A.5.4 and 21.A.8.4 of this report.

The applicant performed the sensitivity calculations discussed above to determine the effect of code input and models on the WCOBRA/TRAC calculated PCT. Thus, the applicant's methodology was consistent with CSAU Step 12.

Step 13: Combine Biases and Uncertainties

In this step, the uncertainties associated with the various parts of the methodology (e.g., code limitations, scale effects, and initial operating conditions) are combined. One approach is to use a Monte Carlo simulation to determine the PCT distribution.

In the CSAU study, the results of Step 12 were used to determine response surfaces for the blowdown and reflood PCTs using seven variables. The 95^{th} percentile PCT was assessed through Monte Carlo simulation.

The applicant bounded the effects of power distributions (both peaking factors and power shapes) and initial and boundary conditions in the WCOBRA/TRAC analyses performed with the global model run matrix developed in Step 12. The applicant developed response surfaces from the results of these WCOBRA/TRAC analyses. The 95^{th} percentile PCT was developed through Monte Carlo simulation. This is discussed in Section 21.A.5 of this report. The applicant combined the various components of uncertainty. In doing so, the methodology is consistent with CSAU Step 13.

Step 14: Determine Total Uncertainty

In this step, a final statement of total uncertainty given as a probability for the limiting value of the primary safety criteria is made for the code. On the basis of RG 1.157, the staff used the 95th percentile as the basis for determining compliance with the high probability requirement of 10 CFR 50.46. Biases may be applied to account for uncertainty contributors that could not be quantified or because it was not economical to quantify the effect of uncertainty contributors.

The CSAU study estimated the 95th percentile PCT with a Monte Carlo simulation using the response surfaces developed in Step 13 and randomly sampling the assumed distributions for the seven parameters. A number of biases were then applied on the basis of the results of studies performed during the CSAU development.

The applicant's methodology also used a Monte Carlo simulation to determine the 95th percentile PCT. In this way, the applicant's methodology was consistent with the CSAU approach in Step 14. The power distribution (peaking factors and power shapes) and the initial condition effects were bounded. The model response surfaces developed in Step 13 were used to calculate a bias and uncertainty associated with the global model run matrix parameters using randomly sampled variables. The uncertainties from the models response surfaces were used as discussed in Sections 21.A.5.1 and 21.A.5.5 of this report. No biases were applied after the PCT is calculated, although several negative biases were estimated.

In the approved methodology, the Monte Carlo analysis combined various uncertainties by superposition. To correct for inaccuracies in the superposition approach, the applicant developed a correction to the superposition approach that was applied during the Monte Carlo analysis. Because of the bounding of the power shape and initial condition effects for the AP600, superposition and the superposition correction are not needed for the AP600. However, the applicant did include a verification step for the response surfaces used in the AP600 methodology. On the basis of the above, the staff concluded that the applicant used a methodology consistent with CSAU Step 14.

21.A.1.4 Summary of Review

This CSAU comparison summary showed that the applicant's methodology closely followed the CSAU methodology, and that the applicant accounted for the 14 steps of the CSAU methodology. Specific similarities include using a PIRT to identify important phenomena, ranging parameters and sensitivity studies to determine code uncertainty propagation, and use of Monte Carlo simulations and response surfaces to determine the 95th percentile PCT.

However, some differences were noted in the details of the Westinghouse application of the CSAU methodology because of the applicant's need to address the concerns of operating plants, the justification of operating plant limits, the different codes involved, and additional full-scale data then available. For example in Step 11, the CSAU study assumed that the plant to be analyzed was in baseload operation. The applicant, to justify AP600 operating limits, needed to consider Technical Specification limits for a number of parameters. Another example was the use of biases in Step 14. In some cases, the CSAU methodology applied biases at the end of the analysis to account for uncertainties for which it did not account in other ways. In the applicant's methodology, some uncertainties were accounted for by showing the code had a conservative bias on the basis of comparing the code results to test data not available to the CSAU study, but the negative bias was not applied to the analysis. The staff judged these types of differences not significant. This is because they reflected the applicant's need to justify plant operating limits that were not considered in the development of the CSAU methodology, or they represented a more conservative approach than that used in the development of the CSAU methodology. Overall, it was concluded that, on the basis of the discussion above, the applicant's methodology was consistent with the CSAU methodology.

21.A.2 PIRT Evaluations (CSAU Step 3)

As noted in Section 21.A.1.1, Step 3, of this report, a PIRT helps identify the important phenomena that control a specific accident scenario and ranks them for their relative importance. In this way, the important phenomena can be identified and accounted for in the uncertainty analysis. It also provides a means of reducing the phenomena needing to be considered to a manageable number. The applicant provided the WCOBRA/TRAC AP600 PIRT in WCAP-14171, and it is reproduced in Table 21.A-1 of this report. Review of the PIRT is discussed below.

The applicant's AP600 PIRT discussion included their own ranking of phenomena for AP600, comparisons to the Westinghouse three- and four-loop plant PIRT, and to the PIRT done by the expert panel during the CSAU review, as described in NUREG/CR-5047. The applicant's PIRT used a ranking scale of 1 to 9 with 9 being the most important and 1 being the least important. This is the same ranking scale used in the CSAU review. Comparison of the three PIRTs found them very similar. In general, there was good agreement between the PIRTs, and only occasionally was a phenomenon ranked differently by more than two. On the basis of NUREG/CR-5047, the staff considered a ranking difference of three or more an indication of a significant difference of opinion between the PIRTs.

Differences between the three- and four-loop plant PIRT and the CSAU expert PIRT were covered during the staff's review of the approved methodology. In many cases, the applicant's AP600 PIRT showed similar differences with the CSAU expert PIRT, and the reasons the applicant gave for the differences were similar to those for the earlier three- and four-loop plant review. The staff considered this appropriate because of the similarity of the AP600 and three- and four-loop plant LBLOCA responses. Items handled in this way are marked by an asterisk in Table 21.A-1 of this report. Therefore, the staff focused on the areas where the AP600 design and/or phenomena impacted the PIRT evaluation.

Cladding oxidation was rated lower by the applicant for the AP600 relative to the CSAU PIRT and the PIRTs for the three- and four-loop plants. The applicant noted that this was because of the significantly lower PCT in the AP600 LBLOCA analysis, and the lower PCT was the result of the lower peak power in the AP600 core design. The staff agreed with this position because the AP600 PCTs [WCOBRA/TRAC calculated PCTs were approximately 760 $^\circ$C (1400 $^\circ$F) in blowdown, 649 $^\circ$C (1200 $^\circ$F) in reflood, and 95th percentile PCT was 913 $^\circ$C (1675 $^\circ$F)]. These

PCTs were much lower than the cladding temperature [approximately 982 °C (1800 °F)] where oxidation becomes a concern.

The applicant's AP600 ranking for pump two-phase performance during blowdown was the same as that for three- and four-loop plants, and both were ranked lower than the CSAU expert PIRT. Because the AP600 pumps are different from those in three- and four-loop plants, the applicant was asked to justify the AP600 ranking. In response to comments 1(i)1 and 12(g) in its letter (NSD-NRC-97-5171) dated June 10, 1997, the applicant showed that the AP600 pumps performed similarly to those in three- and four-loop plants. For example, the applicant showed that the homologous curves for the AP600 pumps are similar to those for three- and four-loop plants, and that the pumps experience similar inlet conditions. On the basis of this information and its earlier acceptance for the three- and four-loop plants, the staff concluded that the AP600 pump two-phase performance ranking was appropriate.

The ranking by the applicant for noncondensable gases in the cold leg during reflood differed also, because of the DVI used in the AP600. In the downcomer, the accumulator nitrogen cover gas is also not important because the AP600 accumulators do not empty until after the core is completely quenched (see Figure 21.A-1 versus Figure 21.A-2 of this report). In addition, on the basis of the applicant's response to comment 1(g) in its letter (NSD-NRC-97-5171) dated June 10, 1997, 60 percent of the initial liquid remains in the accumulators at the time of PCT so that small changes in the analysis results or the AP600 design will not cause the accumulators to empty before the time of PCT. In the approved methodology, the applicant results presented in response to Volume 1, question 134, of the applicant's letter (NTD-NSA-MYY-95-12) dated April 21, 1995, discussed the effects of dissolved nitrogen coming out of solution in the primary system, and the applicant showed that effect was negligible.

During the review, the applicant was requested to clarify the phenomena for which the AP600 was ranked lower than the three- and four-loop plants since it was not clear based on the physical differences between the plant types. One of these phenomena was oxidation, which is discussed above. Others include reflood heat transfer, core entrainment/de-entrainment, and containment pressure.

The applicant discussed the reasons for these ranking differences in response to comments 1(a) and 1(b) in its letter (NSD-NRC-97-5171) dated June 10, 1997, and noted that the AP600 methodology was conservative for each of these phenomena and/or the phenomena were covered in the uncertainty analysis. Therefore, the applicant's AP600 methodology accounted for these items even though they were ranked lower.

Overall the staff found good agreement between the applicant's AP600 PIRT and the Westinghouse three- and four-loop plant and CSAU expert PIRTs. Where a phenomenon ranking differed by three or more, the staff found the difference appropriately justified by the applicant. Consequently, the staff concluded that the applicant's PIRT was adequate for the Westinghouse AP600 plant.

21.A.3 Code Assessment (CSAU Step 7)

Code assessment is required by 10 CFR 50.46(a), and may conform to the guidance of RG 1.157, and the CSAU study. The applicant used the results in determining an experiment-based uncertainty for WCOBRA/TRAC.

In WCAP-14171, the applicant assessed the AP600 plant LBLOCA processes relative to those in three- and four-loop plants. These processes included critical flow, heat transfer, ECC injection, and steam generator and pump behavior. As discussed in Sections 1, 2.1, and 2.2 of WCAP-14171, the applicant found few LBLOCA processes that were different for the AP600 relative to current plants, except for DVI and the CMTs. The applicant found the CMTs did not contribute to core cooling in the AP600 LBLOCA early phase; therefore, the CMTs did not need to be addressed for LBLOCAs. Also, the applicant showed that AP600 and three- and four-loop plant LBLOCA responses were similar. In addition, the AP600 response to upper head flow during blowdown, structural heat transfer because of the core reflector, use of canned motor pumps, and the longer accumulator discharge found in AP600 were different from current generation plants. However, the applicant concluded that specific assessment of these areas was not needed because they were not completely new areas for the AP600 relative to current plants. The applicant concluded that the extensive code assessment performed for three- and four-loop plants could be applied to AP600, but also that WCOBRA/TRAC needed specific assessment against DVI data.

Regarding the above issues, in the review of WCAP-14171, the staff drew the following five conclusions:

(1) The CMTs inject during the ECC bypass period and, therefore, the coolant injected does not contribute to core cooling. In fact, the applicant stated in WCAP-14171 that an AP600 analysis was run without the CMTs and the PRHR HX, and the PCT differed by less than 5.5 °C (10 °F) from the base case.

(2) The staff noted that items such as upper head flow during blowdown, core reflector structural heat transfer, use of canned motor pumps, and longer accumulator discharge do not represent components or situations that are completely new or that cannot be represented by appropriate input modifications to models used for current plants. For example, the AP600 canned rotor pumps are vertical single-stage centrifugal pumps (the same as pumps for three- and four-loop plants) that are modeled by using the appropriate homologous curves and pump characteristic parameters. Also, while the AP600 experiences enhanced blowdown cooling relative to three- and four-loop plants, the staff noted this was an enhancement of a phenomenon present in an operating plant LBLOCA. The applicant provided some assessment of the upper head to upper plenum flow in the LOFT assessments in its letter NSD-NRC-97-5332, dated September 8, 1997, and the global model run matrix varied the flow split from the upper plenum to the core and hot-legs.

(3) The applicant showed the similarity of the AP600 and three- and four-loop plant LBLOCA response.

(4) The applicant's conclusion regarding what AP600-specific assessment needed to be performed was supported by the review of important LBLOCA processes in Section 1 of WCAP-14171, which showed that there was little which was unique to the AP600 LBLOCA. Also, the PIRT comparisons provided by the applicant in Section 2.1 of WCAP-14171 and reviewed in Section 21.A.1 showed few unique and important phenomena for AP600 LBLOCA.

(5) In an NRC letter entitled, "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996, the staff reviewed the code assessment work the applicant performed on WCOBRA/TRAC. That review found all the highly ranked phenomena for three- and four-loop plants were covered by the tests. This, combined with Items 3 and 4, meant that the three- and four-loop plant assessment in the approved methodology could be applied to the AP600. A summary of the applicant's WCOBRA/TRAC assessment for three- and four-loop plants is provided in Section 21.A.3.1 of this report.

When applied to the AP600, Items (1) to (5), above, meant that the areas unique to the AP600 could be addressed by appropriate input for models used in current plants, were addressed by the uncertainty evaluation, or were addressed by AP600-specific assessments. (Only the AP600 use of DVI was directly assessed.) The DVI assessments performed by the applicant are discussed in Section 21.A.3.2 of this report.

21.A.3.1 Summary of Westinghouse WCOBRA/TRAC Assessment for Three- and Four-loop Plants

The details of the three- and four-loop assessment review are found in NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996; however, they are summarized here. The applicant assessed WCOBRA/TRAC against a large number of separate effects, integral effects, and special tests. Facilities analyzed included a wide range of scales, small-scale to full-scale.

<u>Separate effects tests</u>: WCOBRA/TRAC calculated reasonably well the results from the blowdown tests in the Oak Ridge National Laboratory Thermal-Hydraulic Test Facility and Westinghouse tests from the G-1 and G-2 test facilities and G-2 refill tests. For forced reflood tests in various FLECHT facilities and the German FEBA facility, WCOBRA/TRAC gave a good to slightly conservative PCT calculation, but it had difficulty calculating turnaround time, cooldown rate, and quench time accurately. For PCT, the applicant addressed these effects by determining heat transfer multipliers on the basis of comparisons to test data that were applied in the uncertainty evaluation. The applicant addressed these issues for oxidation by applying a time shift to the oxidation calculations. The applicant also covered the effect of turnaround time in the methodology through the global model run matrix.

Integral effects tests: Although break flow mispredictions caused the WCOBRA/TRAC calculated PCTs for LOFT to be lower than the data, the WCOBRA/TRAC uncertainty evaluation directly accounted for the effect of break flow uncertainty on the calculated PCT. Therefore, the applicant's LOFT assessments were considered adequate. On the basis of conservative predictions, the staff considered the CCTF and SCTF assessments adequate. Also, the applicant's comparisons showed the WCOBRA/TRAC results were good to conservative, relative to UPTF test data.

Other assessments: Based on the applicant's comparisons, WCOBRA/TRAC results were conservative to good relative to the test data from the Westinghouse/EPRI one-third-scale steam/water mixing tests and the Creare-scaled ECC bypass tests. For the National Research Universal (NRU) Reactor comparisons, WCOBRA/TRAC adequately simulated the NRU tests because PCTs were reasonably calculated, as were the burst parameters. However, NRU results showed there was some uncertainty in the transient rod internal pressure (RIP) calculation that affected the burst temperature criterion in WCOBRA/TRAC analyses. The applicant showed that the effect of the RIP uncertainty on the burst temperature criterion was small and well within the burst temperature uncertainty accounted for with the local effects models in HOTSPOT. Therefore, for local effects, the applicant's methodology accounted for the uncertainty in transient RIP. The applicant also calculated hot assembly (HA) rod burst in the full WCOBRA/TRAC analyses called for in its methodology. If WCOBRA/TRAC calculated an HA rod reflood PCT greater than 871 °C (1600 °F) but not rod burst, the applicant in the approved methodology committed to increasing the initial RIP in the WCOBRA/TRAC HA rod until burst was calculated and choosing the more limiting of the burst and non-burst cases. This adequately accounted for transient RIP uncertainties and their effect on rod burst in the full WCOBRA/TRAC runs.

21.A.3.2 Westinghouse DVI Assessments

The assessment of WCOBRA/TRAC's ability to calculate DVI is summarized below. The applicant analyzed two tests to evaluate WCOBRA/TRAC's ability to simulate DVI; those tests were CCTF Run 58 and UPTF Test 21.

CCTF Run 58

The cylindrical core test facility (CCTF) was a large-scale test facility designed to study the refill and reflood system response to a LBLOCA in a four-loop PWR. The flow area scale factor for CCTF was 1/21.4 of the reference PWR. The core represented a full height heated length of 3.66 m (12 ft), and there were three intact loops and one broken loop. In the core, three power levels could be simulated. Run 58 modeled downcomer injection as part of the ECCS, similar to the AP600. The test data collection began at 85 seconds, and, during portions of the test, accumulator water was also injected into the cold leg (from 85 to 116 seconds) and into the lower plenum (from 85 to 103 sec). The experiment initiated with heat-up at t=0 seconds while reflood was initiated at t=93 seconds.

The applicant compared the calculated and measured results for a number of parameters. The cladding temperature response is illustrated in Figures 21.A-3 to 21.A-8 of this report. All the comparisons of cladding temperature response are found in Figures 3.1-16 to -30 of WCAP-14171. The comparisons showed that the calculated results overpredicted the cladding temperatures, with the greatest overprediction coming at the 2.4 m (8 ft) and 3 m (10 ft) elevations. While the cladding PCTs were higher, the calculated cooldown after the PCT was more rapid, and quench times were earlier than indicated by the data (Figures 21.A-9 to 21.A-11 of this report). The applicant attributed the more rapid quench progression in the WCOBRA/TRAC analysis relative to the data to the fact that the calculated results did not show the core/downcomer oscillations observed in the test. As discussed in the applicant's response to comment 8 of its July 18, 1997 letter (NSD-NRC-97-5240), this difference was because of the calculated downcomer level stabilizing below the downcomer injection port, whereas the downcomer level recovered to submerge the port in the test. The lower downcomer level was the result of a small overprediction of entrainment out of the vessel.

The upper plenum pressure was overpredicted for most of the test (Figure 21.A-12 of this report) because the more rapid quench advancement in the calculation resulted in higher steam production relative to the test. Downcomer and core differential pressure comparisons (Figures 21.A-13 and 21.A-14 of this report, respectively) showed that the calculated downcomer pressure difference was within the band of the oscillations observed in the test, and the measured core pressure difference was well predicted. Regarding loop flows, the comparisons showed that, in general, WCOBRA/TRAC results were relatively close to the test data except for the Cold Leg 1 and Hot Leg 4 steam mass flows, which were overpredicted (Figures 21.A-15 to 21.A-19 of this report).

The applicant concluded that, overall, WCOBRA/TRAC gave a good calculation of the system response measured in CCTF Run 58. The staff's review of the WCOBRA/TRAC results provided showed that the calculated results do overpredict the cladding temperatures especially at the upper elevations. The test PCT was overpredicted by approximately 17 °C (30 °F) [WCOBRA/TRAC 871 °C (1600 °F) and test 854 °C (1570 °F)]. Evaluating the other code result/data comparisons, the staff agreed with the applicant's conclusions regarding the agreement between the code results and the data as discussed above. As noted by the applicant, one of the major factors causing the difference in the code results relative to the test data was the lack of oscillations in the calculated results. This was a result of the lower calculated downcomer level. Overall, the WCOBRA/TRAC results for CCTF Run 58 were in reasonable agreement with the data, and the PCT results were conservative relative to the data.

UPTF Test 21

UPTF is a model of a German four-loop PWR that was part of the international 2D/3D research program. The facility included a vessel with the top quarter of the core and upper plenum represented at full size. The core was not simulated but was represented by a steam/water injection system to set up the appropriate flow conditions in the vessel. The loops were also full size, and they represented three intact loops and one broken loop. They included steam generator simulators and adjustable flow resistance to simulate tripped pumps. Test 21 consisted of five runs, two of which simulated DVI. These runs were Run 272, Phase A, and Run 274, Phase B. The runs and their subphases differed in terms of the injection rate, steam flow rate, and ECC subcooling.

The applicant compared the calculated and measured results for a number of different parameters. The important ones included lower plenum liquid inventory and integrated break flow. The comparisons showed that WCOBRA/TRAC underpredicted the liquid penetration into the lower plenum (i.e., WCOBRA/TRAC underpredicted the liquid inventory during the test). Consistent with this, WCOBRA/TRAC also overpredicted the integrated break flow (i.e., WCOBRA/TRAC overpredicted the ECC bypass).

On the basis of the code/data comparisons, the applicant concluded that WCOBRA/TRAC gave a conservative calculation of ECC bypass for the UPTF DVI injection tests. The staff review of the UPTF Test 21, Run 272, Phase A, and Run 274, Phase B, WCOBRA/TRAC results found that they supported the applicant's conclusions. The calculations resulted in less liquid penetration into the lower plenum and higher ECC bypass relative to the test results. While this indicated WCOBRA/TRAC overpredicted ECC bypass in the test, the staff noted there was one issue relating to the DVI location in UPTF relative to the AP600. In WCAP-14171, the applicant noted the DVI location in UPTF was at approximately the elevation of the hot and cold legs while the DVI location in the AP600 was approximately 0.9 m (3 ft) below the cold-leg centerline. The applicant addressed the impact of this difference on extending the UPTF results to the AP600 in response to comments 8(g) and 8(i) in its letter (NSD-NRC-97-5171) dated June 10, 1997. While the AP600 configuration should result in a more favorable ECC bypass condition (see page 3-80, WCAP-14171), the applicant showed that ECC bypass ended in the AP600 analysis at a lower downcomer steam mass flux relative to the UPTF test data. This indicated that other factors in the AP600 calculations (e.g., code models or plant nodalization) were keeping the WCOBRA/TRAC analysis conservative. Therefore, the staff agreed that the UPTF results supported the fact that WCOBRA/TRAC gave a conservative ECC bypass calculation for DVI and the AP600.

Conservatism in the ECC bypass calculation was accepted by the staff in its review of the applicant's realistic methodology for three- and four-loop plants. With the conservative ECC bypass calculation, which leads to a higher PCT, the applicant could have argued for the application of a negative bias in the final PCT calculation. Instead, the applicant chose to ignore the negative bias and instead retained the conservative ECC bypass calculation as a conservatism in the overall approved methodology. On this basis, the conservative ECC bypass calculation for DVI, with the applicant ignoring the negative bias, was considered adequate.

21.A.4 <u>Plant Nodalization (CSAU Step 8)</u>

The applicant's methodology addressed the AP600 nodalization issue consistent with the guidance of RG 1.157, Section 3.5, and CSAU Step 8. The applicant developed the AP600 nodalization so that it was similar to that used for three- and four-loop PWRs. The three- and four-loop PWR nodalizations were used as the basis for the nodalizations developed for the separate effects and integral assessment analyses in the CQD. The AP600 nodalization was used for the DVI assessments in WCAP-14171. This was done because the applicant desired to apply the code bias and uncertainty developed from the assessment studies to the PWR calculations. Although there are geometric differences between PWRs, the applicant's methodology is flexible enough to accommodate differences in design and still maintain consistency with the assessment nodalizations. If a consistent nodalization methodology is used for the assessment and PWR calculations, then the applicant concluded, and the staff agreed, that geometric differences/nodalization did not add significantly to the code bias and uncertainty.

The review of the three- and four-loop plant nodalization is discussed in NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996. The review found that the applicant's methodology provided consistent nodalizations between the tests and plants.

In WCAP-14171, the applicant discussed the WCOBRA/TRAC nodalization for the AP600. The applicant included explicit modeling of the hot assembly (HA) in the location that leads to the least flow during blowdown. The intent was to limit the HA blowdown cooling and bound the effect on the PCT.

On the basis of the consistency between the AP600, PWR, and assessment nodalizations, the staff considered the AP600 nodalization adequate for realistic LBLOCA analyses. Also, review of the AP600 nodalization found the applicant considered important information such as upper plenum structures in determining the types of core channels and the location of the HA, low-power assemblies on the core periphery, and loop components in determining the nodalization. In particular, the staff considered placing the HA in the location minimizing blowdown flow an appropriate bounding assumption in the analyses.

21.A.5 Code/Experiment Accuracy (CSAU Step 9)

The need to determine the code and experiment accuracy is discussed in RG 1.157, Section 4, and CSAU Step 9. The applicant described its method of uncertainty evaluation for the AP600 in WCAP-14171. The basic approach was to use the approved methodology but to simplify where appropriate for the AP600. The applicant's approach and the review of it are discussed below.

In the approved uncertainty evaluation, the applicant identified initial plant conditions and model effects as the important factors to consider. The plant conditions were further subdivided into initial conditions and core power distributions. In addition, a model or plant condition may be global or local in its effect. A parameter has a global effect if it can affect the entire thermal and hydraulic transient. It has a local effect if it only affects the local conditions at the PCT location. The interrelationship of the uncertainty parameters is shown in Figure 21.A-20 of this report.

The major simplification of the approved methodology for the AP600 was the decision to bound the plant conditions (both initial conditions and power distributions) in the WCOBRA/TRAC analyses. As a result, only the global model and local effects needed to be directly included in the AP600 uncertainty analysis.

There are a large number of phenomena and parameters in a LBLOCA analysis. To reduce the number involved in the uncertainty analysis, only those ranked 7, 8, or 9 in the PIRT were addressed. In WCAP-14171, supplemented by the applicant's response to comment 12(k) in its letter (NSD-NRC-97-5240) dated July 18, 1997, the applicant evaluated the important items from the approved methodology uncertainty analysis relative to their application for the AP600.

Because of the similarity of the AP600 and three- and four-loop plant responses to a LBLOCA, and because the same types of equipment/materials are used in both types of plants, the applicant showed that most of the same important parameters apply to AP600. In particular, these included the following parameters:

- critical flow
- pump single-/two-phase performance (broken loop relative resistance)
- fuel rod conditions such as power distributions, stored energy, decay heat, cladding burst, cladding reaction, and gap conductance
- core heat transfer and T_{MIN}
- ECC bypass; entrainment and steam binding
- condensation

The applicant either conservatively calculated, bounded, or directly included the above items in the AP600 uncertainty methodology.

The following discussion clarifies how the applicant evaluated each item above. An overview or roadmap of the applicant's methodology is given first, and it is followed by more detailed discussion on the models and the plant conditions. Then the impact of local effects on models and plant conditions will be discussed.

21.A.5.1 Westinghouse Realistic LBLOCA Methodology Roadmap

This section gives a brief overview or roadmap of the applicant's AP600 realistic LBLOCA methodology. References to those sections in this appendix that describe and summarize the review of the methodology are given.

The applicant's AP600 realistic LBLOCA methodology consisted of several parts. To determine the 95^{th} percentile PCT, the applicant used the WCOBRA/TRAC code and then performed an uncertainty analysis. The WCOBRA/TRAC base code was described in CQD. Then, there was the analysis to determine the 95^{th} percentile PCT. This analysis is discussed below and in Sections 21.A.5.2 to 21.A.5.5 of this report. The applicant's use of WCOBRA/TRAC is described first, followed by the 95^{th} percentile PCT determination.

For the AP600, the applicant used the WCOBRA/TRAC program to analyze the plant's response to changes in initial conditions and to account for power distribution (peaking factor and power shape) effects through one-at-a-time sensitivity studies. The effect on PCT was measured by the PCT change (ΔPCT) as a result of the initial condition change or power distribution change. These sensitivity studies are discussed in Section 21.A.7. For the AP600, the sensitivity studies determined the bounding conditions to be used in the WCOBRA/TRAC analyses for the global model run matrix. This is the simplification of the approved methodology noted above for the AP600.

Next, the applicant analyzed the same global model run matrix developed in the approved methodology for the AP600. This provided the ΔPCT information needed to develop response surfaces that it used to account for code model uncertainties in the uncertainty analysis. The response surfaces are also discussed in this and following sections of this appendix.

The next part of the uncertainty evaluation was to account for local or hot spot uncertainties. The applicant used the HOTSPOT model, discussed in Section 21.A.8.4 of this report, to perform the local uncertainty evaluation. The parameters affecting the local uncertainty included the following:

- hot rod (HR) calculational uncertainty
- hot rod pellet diameter, enrichment, and rod bow uncertainties
- fuel density and conductivity
- gap and cladding HTC
- rod internal pressure
- cladding burst temperature and strain
- metal-water reaction; and fuel relocation

For selected WCOBRA/TRAC runs from the global model run matrix, the applicant performed a direct Monte Carlo analysis using the HOTSPOT model to determine the spread of the PCT distribution due to local uncertainties. The PCT distributions, as a result of local uncertainties for the selected runs in the global model run matrix, were then fit to two response surfaces, one for the biases of the distributions and one for the standard deviations of the distributions that were obtained from the HOTSPOT runs. The response surface variables were the models varied in the run matrix. The applicant combined the model global and local effects as discussed in Section 4.2.3 of its letter (NTD-NSA-SAI-95-391, “Revisions to Westinghouse Best-Estimate Uncertainty Methodology”) dated October 13, 1995. The second part of the uncertainty evaluation used data on the basis of experimental results and a nodalization uncertainty. This was divided into two parts. The first uncertainty, B1, was the uncertainty based on comparisons between the code calculated PCT and the measured PCT in all the applicable assessment cases plus a nodalization uncertainty (combined using square root sum of the squares). The second uncertainty was on the basis of experimental cladding temperature data scatter about the average cladding temperature at a given elevation (uncertainty B2). In the approved methodology, the B1 and B2 uncertainties were used to provide lower bounds to other uncertainty estimates. With the simplified AP600 uncertainty methodology, these two uncertainties were still used to provide lower bounds to other uncertainties but in a different way than in the approved methodology as follows:

(1) The uncertainty B1 was used in the approved methodology to establish a lower bound on the uncertainty determined from the superposition correction. The superposition correction was used to correct for inaccuracies in the superposition assumptions made

in the approved methodology. Superposition was used to combine various uncertainties. For the AP600, superposition was no longer used because of the simplifications in the AP600 methodology, and the uncertainty B1 was used to provide a lower bound to the correction needed to ensure the accuracy of the global model response surface for ΔPCT previously developed.

(2) The uncertainty B2 was used in the approved methodology to establish a lower bound on the uncertainty determined from the global models/local uncertainty. For the AP600, B2 provided a lower bound to the uncertainty in the global model response surface for the standard deviation.

Upon completing the above steps, the applicant had the information needed to perform a Monte Carlo simulation to determine the 95th percentile PCT (i.e., the PCT greater than that expected to occur in 95 percent of possible LBLOCAS). The general steps of a single Monte Carlo iteration are described next, and the steps are illustrated in Figure 21.A-21 of this report. The applicant sampled the model parameter distributions (Box 1) and used them in the response surfaces for model bias and uncertainty (Box 5) to get the ΔPCT because of model uncertainties. This was added to the base PCT to get a preliminary PCT, $PCT_{p,i}$, for the iteration (Box 6). The applicant then used HOTSPOT results from the selected global model run matrix analyses to determine the corrections for uncertainties in the global model response surfaces (both ΔPCT and standard deviation, Box 7). For ΔPCT, the correction was compared to the B1 uncertainty (discussed above), and the larger value was selected. The resulting distribution was sampled to get the model uncertainty ΔPCT. This was added to $PCT_{p,i}$ to get the preliminary corrected hot spot PCT for the Monte Carlo iteration, $PCT_{p,ci}$. The applicant then compared the B2 uncertainty (discussed above) to the standard deviation correction, and the larger uncertainty value was selected. The resulting distribution was sampled and added to $PCT_{p,ci}$ to get the final hot spot PCT for the Monte Carlo iteration, PCT_i. To determine the 95th percentile PCT, the above process was repeated many times. For each iteration, i, the calculated PCT_i was binned. The PCTs in each bin were counted starting from the highest PCT. When 5 percent of the PCTs were counted, the 95th percentile PCT is determined.

21.A.5.2 Models - Global Effects

For the AP600, the global models of importance were the same as for three- and four-loop plants (i.e., critical flow, broken loop relative resistance, and condensation). The applicant justified the use of the same models for AP600 in response to comment 12(k) in its letter (NSD-NRC-97-5240) dated July 18, 1997. This is discussed in more detail in Section 21.A.8.2 of this report, but here it is noted that the same parameters applied because of the similarity of the different plant types regarding LBLOCA response, equipment, and materials.

The uncertainties in the above models were accounted for in the applicant's uncertainty methodology using the following process. The uncertainty distributions for each parameter were determined. Then T-H sensitivity studies were performed in which each parameter was varied (singularly and in combination with the other two parameters) over a range that appropriately bounded the expected range of model variation as follows. The ranges used for the sensitivity studies for each parameter were as follows:

(1) Break flow—100 percent of the data in the break flow uncertainty distribution.

(2) Break flow resistance ratio—The uncertainty in this parameter was ranged as discussed in CQD Section 26-4 and Sections 3.1.2 and 4.4.2.1 of the applicant's letter (NTD-NSA-SAI-95-391, "Revisions to Westinghouse Best-Estimate Uncertainty Methodology") dated October 13, 1995.

(3) Condensation—For the run matrix, the maximum and minimum multipliers were based on test data. [See Figure 3.1.7-1 of the applicant's letter (NTD-NSA-SAI-95-391, "Revisions to Westinghouse Best-Estimate Uncertainty Methodology") dated October 13, 1995.] Although the sampled range in the uncertainty evaluation was larger, the run matrix covered almost 77 percent of the sampled range. The staff considered this adequate because the extrapolation was small.

The applicant called this the global model run matrix, and it is shown in Table 4.5-1 of WCAP-14171. The results of this run matrix were used as input to the HOTSPOT code to determine the local HR temperature uncertainty as discussed in Sections 21.A.5.4 and 21.A.8.4 of this report. The global model and HOTSPOT effects were then used to develop response surfaces for the Monte Carlo analysis.

21.A.5.3 Plant Conditions - Global Effects

The applicant accounted for the uncertainty in the initial plant conditions. As mentioned above, this included power distributions (peaking factors and power shapes) and initial conditions. The uncertainty in plant initial conditions was accounted for in the analysis by assuming bounding conditions in the run matrix discussed in Section 21.A.5.2 of this report. The conditions selected were developed from plant sensitivity studies. As previously noted, this was different from the approved methodology, but it did provide conservative PCT results.

21.A.5.4 Local Effects Models/Parameters

Having established the global uncertainties for models and bounded plant conditions, the applicant addressed the effects of local HR uncertainties on the global model results. The parameters involved for AP600 were the same ones in the approved methodology. They included HR calculational uncertainty; hot rod pellet diameter, enrichment, and rod bow uncertainties; fuel density and conductivity; gap and cladding HTC; rod internal pressure; cladding burst temperature and strain; metal-water reaction; and fuel relocation. In the response to comment 12(j) in its letter (NSD-NRC-97-5171) dated June 10, 1997, the applicant discussed the basis for this approach. The applicant noted that the AP600 uses a standard Westinghouse fuel product. This indicated that the important items for local models/parameters were the same for AP600 relative to three- and four-loop plants.

These sources of HR local uncertainty were evaluated using the HOTSPOT model. This model (see Section 21.A.8.4 of this report) is a stand-alone calculation of local effects at the PCT locations (i.e., blowdown, first reflood, and second reflood) and the burst node location. (See page 165 of the applicant's letter (NTD-NSA-SAI-95-391, "Revisions to Westinghouse

Best-Estimate Uncertainty Methodology") dated October 13, 1995.] The HOTSPOT model was run many times in a direct Monte Carlo simulation. Boundary conditions input to the HOTSPOT model were taken from WCOBRA/TRAC runs in the global model run matrix. For each HOTSPOT run, the applicant developed a bias and distribution that described the effect of the local uncertainties on the PCT. In this way, local effects were combined with global effects for models. For the WCOBRA/TRAC runs taken from the global model run matrix, two response surfaces were fit to the distributions developed with HOTSPOT for the individual runs, one to the biases and one to the uncertainties. These response surfaces were used in the Monte Carlo simulation to account for local uncertainty propagation.

21.A.5.5 WCOBRA/TRAC Experiment Based Uncertainty

In the applicant's methodology, the code uncertainty is based on comparisons to experimental results, a nodalization uncertainty, a data scatter uncertainty, and a code uncertainty on the basis of ranging of model parameters. For the AP600, the applicant divided the experiment-based uncertainty into two parts, which was the same as for the approved methodology. (See previous discussion in Section 21.A.5.1 of this report.) Because superposition was not used for the AP600 due to the applicant's AP600 methodology simplifications, the applicant used the experiment-based uncertainty differently, as follows. First, the code uncertainty on the basis of comparisons to experimental results, plus the nodalization uncertainty, were compared to the global model ΔPCT response surface uncertainty, rather than the superposition correction. These are items related to the uncertainty in the bias or the ability of the code to calculate the average PCT. Second, the data scatter uncertainty was compared to the global model standard deviation response surface uncertainty rather than the global model/local uncertainty. These items are related to the uncertainty associated with local effects. In both cases, the larger of the two uncertainties was used in the Monte Carlo calculation of the 95th percentile PCT.

21.A.5.6 Other Parameters/Factors Considered by Westinghouse

The applicant's list of important parameters in the approved methodology considered a number of items not discussed in the previous sections. These include ECC bypass, entrainment/steam binding, and accumulator nitrogen. NRC approval of the applicant's handling of each item is discussed in NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996; however, that review is summarized here. For ECC bypass and entrainment/steam binding, the applicant showed that WCOBRA/TRAC provided conservative calculations in these areas, but the applicant did not apply a negative bias to account for these conservatisms. The staff found this acceptable. For accumulator nitrogen, the applicant chose to limit the beneficial effects of accumulator nitrogen discharge on heat transfer in HOTSPOT calculations by setting a maximum HTC. For the AP600, this is not important because accumulator nitrogen does not discharge until long after the PCT has been calculated to be reached and the core quenched.

Because of the use of DVI in the AP600, the applicant directly evaluated ECC bypass when DVI is used. The applicant found that a negative bias could be applied to analyses because of delayed and reduced ECC penetration relative to full-scale UPTF tests (see WCAP-14171). However, the bias is not applied at this time step in the calculations, resulting in conservative PCT calculations. Given that a conservative bias is ignored, the staff concluded that the applicant's approach for the AP600 ECC bypass uncertainty results in a conservative PCT calculation. As discussed earlier, this type of conservatism was accepted by the NRC in the review of the approved methodology for three- and four-loop plants.

21.A.5.7 Review of Uncertainty Propagation

As the above description shows, the applicant's uncertainty methodology is very complex. Therefore, the staff carefully reviewed the methodology to assess whether it included the important parameters and whether the uncertainty distributions for the important parameters were justified.

The review considered the list of important parameters identified by the applicant in WCAP-14171. The highly ranked phenomena from the applicant's AP600 PIRT were considered, and this review found them to be ranged directly in the uncertainty analysis, modeled directly in WCOBRA/TRAC analyses, bounded in WCOBRA/TRAC analyses, covered in the variation of items ranged directly, or conservatively calculated in WCOBRA/TRAC analyses.

Assumed uncertainty distributions are at the heart of the uncertainty methodology. The review considered the applicant's justification for each parameter range and the associated uncertainty distribution in Section 21.A.8.2 of this report. That review found the applicant's justification for the distributions adequate on the basis of information provided.

In the approved methodology, the NRC, in a letter to the applicant, "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996, found the applicant's approach for uncertainty propagation for three- and four-loop plants acceptable because WCOBRA/TRAC and HOTSPOT calculations cover the LBLOCA through reflood. This allowed the effects of uncertainty in parameters and combinations of parameters to be calculated through the entire accident. The Staff also found run matrix development and response surface generation acceptable. These same approaches were applied to AP600. Given the similarity of the AP600 and three- and four-loop plant LBLOCA responses, the staff found this approach acceptable for the AP600 application.

21.A.6 <u>Effects of Scale (CSAU Step 10)</u>

The effects of scale on the calculated results need to be evaluated to ensure the code models can appropriately calculate full-scale PWR behavior given that most of the code assessment matrix is on the basis of smaller-scale test facilities. This is discussed in RG 1.157, Sections 4.1 and 4.2, and in the CSAU study, Step 10. The applicant evaluated the effects of scale on the WCOBRA/TRAC code in its letter (NTD-NSA-SAI-95-391, "Revisions to Westinghouse Best-Estimate Uncertainty Methodology") dated October 13, 1995. As noted in Section 21.A.1.2, Step 10, of this report, power-to-volume scaled test facilities adequately simulate the PWR response except in the areas of ECC bypass and steam binding; also, critical flow and pump performance needed to be considered because of the lack of full-scale data. Staff review of the scaling issues for three- and four-loop plants (see NRC letter “Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis,” dated June 28, 1996) concluded that the applicant had adequately addressed scaling issues in these areas. The NRC review is summarized here.

ECC Bypass

Using data at various scales, the applicant showed that WCOBRA/TRAC had a conservative bias in its ECC bypass calculation as facility size approaches full-scale. That is, the code overpredicted the amount of fluid bypassing the vessel and going out the break.

Steam Binding

Using data for several test facilities at different scales, the applicant showed that WCOBRA/TRAC had a conservative bias as facility scale increased. This implies greater steam binding will be calculated by the code in plant calculations relative to the steam binding observed in the experiments.

Critical Flow

The applicant accounted for the uncertainty in break flow by directly including critical flow in the uncertainty evaluation.

Pump Performance

The applicant showed that single-phase pump performance was more important than two-phase performance and included the single-phase pump performance directly in the uncertainty evaluation.

Because of the similarity of the AP600 and three- and four-loop plant LBLOCA responses, the applicant only needed to readdress ECC bypass because of the use of DVI in the AP600.

To address ECC bypass with DVI for the AP600, the applicant compared WCOBRA/TRAC results to CCTF and full-scale UPTF data to evaluate WCOBRA/TRAC’s capability to calculate this phenomenon. The comparisons showed that WCOBRA/TRAC overpredicted the PCT for the CCTF tests, and it also overpredicted the ECC bypass in the UPTF DVI tests. That is, the code overpredicted the amount of fluid bypassing the vessel and going out the break in the UPTF. These tests are discussed in more detail in Section 21.A.3 of this report. The applicant also addressed test-to-plant differences that could affect the interpretation of the UPTF results relative to the AP600.

The review considered the applicant’s submittal for ECC bypass. The DVI ECC bypass calculation was conservative, and the applicant addressed the test-to-plant differences that could affect the interpretation of the test results relative to the AP600. On the basis of the above, the staff considered the applicant to have adequately addressed issues relating to scaling.

21.A.7 Reactor Input Parameters/State (CSAU Step 11)

Both RG 1.157, Section 3.1, and CSAU Step 11 discuss the need to identify the effects of the reactor input and initial/boundary conditions on the calculated PCT. The applicant addressed this issue in WCAP-14171.

21.A.7.1 Westinghouse's Methodology

In WCAP-14171, Section 4.4, the applicant evaluated the approved three- and four-loop plant methodology relative to its application for the AP600 in the area of reactor input parameters and initial state. In general, the applicant proposed a simplification of the three- and four-loop plant approach for the AP600. This simplification for the AP600 was made by taking a bounding approach for a larger number of parameters relative to the uncertainty evaluation for three- and four-loop plants.

The parameters/models in the approved methodology were discussed in CQD Section 21; these include the plant physical configuration, plant initial operating conditions (including core power parameters and primary fluid conditions), accident boundary conditions, and WCOBRA/TRAC models needing further analysis because of a lack of prototypical assessment or because of the need to consider the effects of different transient time scales in the tests and a PWR.

In Table 4.4-1 of WCAP-14171, the applicant compared the AP600 methodology to that for three- and four-loop plants for plant physical configuration, initial operating conditions, and accident boundary conditions. As found in this comparison, the applicant's AP600 methodology bounded most of the parameters that were directly included in the uncertainty evaluation for the approved methodology. These include, for example, core peaking factors and initial conditions. In the AP600 methodology, the bounding value for the parameters was determined through one-at-a-time sensitivity studies using WCOBRA/TRAC. The sensitivity studies used plant design information or Technical Specification ranges to determine what ranges to consider, as discussed in the applicant's response to comment 3 in its letter (NSD-NRC-97-5240) dated July 18, 1997. The methodology then used these bounding values in the AP600 input model for the WCOBRA/TRAC global run matrix.

For the AP600, the applicant also reviewed the approved methodology's approach for dealing with models not adequately assessed, models that were simplified or lacking basic knowledge, and phenomena that may have more important effects on a PWR LBLOCA than they would have on a scaled experiment. These included models for break flow, pumps, accumulator nitrogen, entrainment, condensation, ECC bypass, core heat transfer, and fuel rods.

On the basis of the information in the response to comment 12(k) of letter NSD-NRC-97-5240, dated July 18, 1997, the applicant justified that only certain models identified in Section 4.4 of WCAP-14171 needed additional review for application to the AP600. The applicant noted that other areas did not need additional review because of the similarity of the different plant types regarding LBLOCA response, equipment, and materials. For example, the different plants operate at the same pressure and temperature conditions; thus, the critical flow uncertainty from the approved methodology applies to the AP600. The pumps in the different plants are vertical, single-stage centrifugal with similar homologous curves, and they experience similar inlet conditions. Thus, the approved methodology pump uncertainty applies to the AP600. As a final example, the same fuel is specified for the AP600 as in three- and four-loop plants. Thus, the uncertainties related to fuel parameters in the approved methodology apply to the AP600.

The applicant's response to comment 12(k) in its letter (NSD-NRC-97-5240) dated July 18, 1997, also clarified how it dealt with the models needing additional review, such as T_{MIN} and blowdown cooling heat transfer. The applicant proposed a replacement value for T_{MIN} to be used in WCOBRA/TRAC during blowdown and reevaluated blowdown cooling heat transfer to generate an AP600-specific uncertainty distribution. These two areas are discussed in more detail in Section 21.A.8.2 of this report.

In the approved methodology, the applicant also used sensitivity studies to evaluate the effects of time step control (CQD Section 22-5), break spectrum (CQD Section 22-6), and fuel rod burnup (CQD Section 22-7) on calculated PCT for three different plants. These studies are discussed below.

In its letter (NSD-NRC-97-5240) dated July 18, 1997, in response to comment 2(a), the applicant noted and justified that the time step controls developed for the approved methodology applied to the AP600 model. This was because of the similarity of the controlling phenomena for the different plant types during the important LBLOCA periods.

The applicant discussed the break spectrum analyses for the AP600 in its letter (NSD-NRC-97-5240) dated July 18, 1997, in response to comment 2(b). On the basis of an earlier analysis for the AP600 SSAR, the limiting LBLOCA for the AP600 was determined to be the double-ended cold-leg guillotine (DECLG) break with $C_D = 0.8$. Because the plant input model and the code version have remained basically the same, the applicant concluded, and the staff agrees, that the previous break spectrum study was still valid. In addition, the applicant's realistic methodology for the AP600 does not directly identify the limiting break size associated with the 95^{th} percentile PCT. This is because the effect of critical flow uncertainty on PCT is included in the uncertainty evaluation through the global model response surface and through sampling the full range of discharge coefficients developed from the Marviken test comparisons in the Monte Carlo simulation to determine the 95^{th} percentile PCT. Therefore, the AP600 realistic methodology accounted for the break flow uncertainty but in a different way than an analysis conducted in accordance with Appendix K to 10 CFR Part 50. The AP600 methodology was also consistent with the approved realistic methodology for three- and four-loop plants.

To account for the uncertainty in the break type (i.e., split or guillotine), the determination of the 95^{th} percentile PCT included separate Monte Carlo simulations for the guillotine breaks and the limiting split break from the break spectrum study.

Fuel rod burnup studies were presented in Section 22-7 of the CQD for three- and four-loop plants. In these studies, beginning-of-life (BOL) fuel was found to be limiting. In its letter (NSD-NRC-97-5240) dated July 18, 1997, in response to comment 2(a), the applicant noted that the fuel type used in AP600 is equivalent to that of many three- and four-loop plants, and the same burnup criteria were applied to the HR and the HA rod. Therefore, the CQD burnup studies apply to the WCOBRA/TRAC AP600 application.

21.A.7.2 Review Summary

In reviewing WCAP-14171, the staff found that the applicant provided an exhaustive list of important LBLOCA parameters to be considered in the plant sensitivity studies and included AP600-specific parameters. This review did not identify any parameters to add to the applicant's list.

The staff noted that the applicant performed AP600 sensitivity studies to determine the effect of the parameter or model variation on the calculated PCT. These analyses were presented in the AP600 SSAR. Using the results of these sensitivity studies, the applicant's AP600 methodology chose bounding assumptions for use in the WCOBRA/TRAC global run matrix. Therefore, these studies were part of the AP600 methodology for the determination of boundary conditions and did not impact the WCOBRA/TRAC applicability evaluation.

Because of the similarity of the controlling phenomena between three- and four-loop plants and the AP600, the staff concluded that the time steps control strategy used in the approved methodology was applicable to the AP600 model.

The uncertainty in break flow was appropriately accounted for in the uncertainty analysis. The applicant's CQD study on rod burnup showed that BOL is the limiting time-in-life, and this was applied to AP600 because of the equivalent fuel type.

On the basis of the review summarized above, the staff concluded that the applicant's methodology included AP600 sensitivity studies to determine the effect of reactor input parameters and state. These were provided in the AP600 SSAR. Previous studies in the approved methodology for rod burnup and time steps also applied for the reasons stated above. Because the sensitivity studies showed which parameters were important to PCT calculations and the effect of the parameter change on the calculated PCT, these sensitivity studies provided an adequate basis for determining bounding conditions for use in the AP600 methodology.

21.A.8 <u>Additional Method Description and Review</u>

This section describes those parts of the applicant's realistic LBLOCA methodology for the AP600 that are important but did not fall directly into the steps of the CSAU methodology. First, the WCOBRA/TRAC code is discussed. This is followed by a discussion of the AP600 uncertainty distribution review and the applicant's handling of split breaks and the HOTSPOT model. Conclusions are provided at the end of each subsection and summarized in Section 21.A.8.5 of this report.

21.A.8.1 LBLOCA Method Description/Review — Code Selection

The NRC approved WCOBRA/TRAC, MOD7A, Revision 1, for the analysis of LBLOCAs in three- and four-loop plants in NRC letter “Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis,” dated June 28, 1996. This approval came after a detailed review of the models and correlations used in the code, as well as of the large assessment database provided by the applicant. As stated in the applicant’s response to comment 4(a) in its letter (NSD-NRC-97-5240) dated July 18, 1997, this is the code version that the applicant used to analyze the AP600 LBLOCA. The applicant stated that several small modifications to the code were necessary to analyze the AP600 and its passive safety features; however, these modifications only affected passive safety features that do not impact the initial AP600 response to a LBLOCA. Also, the LBLOCA responses are very similar for the AP600 and three- and four-loop plants. Therefore, the staff considered WCOBRA/TRAC, MOD7A, Revision 1, adequate for AP600 LBLOCA analyses.

21.A.8.2 LBLOCA Method Description/Review — Uncertainty Distributions and Assumptions

In NRC letter “Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis,” dated June 28, 1996, the staff reviewed and approved all the uncertainty distributions assumed by the applicant in its uncertainty evaluation for three- and four-loop plants. In WCAP-14171, supplemented by its responses to comments 12(j) and 12(k) in letters dated June 10 and July 18, 1997, respectively (NSD-NRC-97-5171 and NSD-NRC-97-5240), the applicant discussed the basis for the application of these uncertainty distributions to the AP600. Except for T_{MIN} and blowdown cooling, whose uncertainty distributions the applicant modified for application to the AP600, the applicant justified these uncertainty distributions as discussed below using the three- and four-loop plant distributions for the AP600. The justification was on the basis of similarity of the different plant types regarding LBLOCA response, equipment, and materials.

<u>Critical flow</u>

The different plants operate at the same pressure and temperature conditions; thus, the critical flow uncertainty from the approved methodology applied to the AP600.

<u>Pump uncertainty/break path resistance</u>

The pumps in the different plants are vertical, single-stage centrifugal pumps with similar homologous curves, and they experience similar inlet conditions. Thus, the approved methodology pump uncertainty applied to the AP600. The broken loop cold-leg nozzle (BLCL) has a similar K-factor so the approved methodology BLCL nozzle uncertainty applied.

Fuel rod parameters

The same fuel is specified for the AP600 as for three- and four-loop plants. Thus, the uncertainties related to fuel parameters in the approved methodology applied to the AP600. For the AP600, the bounding axial power shape was identified and used in the WCOBRA/TRAC analyses, and peaking factors were also bounded at Technical Specification values.

Heat transfer

(Blowdown cooling heat transfer and T_{MIN} are discussed separately.)

For reflood heat transfer, the applicant performed additional assessment to verify WCOBRA/TRAC for the lower initial cladding temperatures expected in the AP600 at the start of reflood. The applicant showed the reflood heat transfer uncertainty distribution from the approved methodology bounded the uncertainty distribution on the basis of this initial cladding temperature data on the lower end of the range. The approved methodology uncertainty distribution also gave a lower median multiplier than the uncertainty distribution on the basis of the cold temperature data. These are both conservative because a lower multiplier results in lower heat transfer in the HOTSPOT calculations. At the upper end of the distribution, however, the approved methodology distribution extends slightly beyond the upper limit of the initial cladding temperature data. The staff dids not consider this a problem for several reasons. First, only 3 percent of the approved methodology distribution extends beyond the cold temperature data distribution, so the effect was small. Second, the higher PCTs in the HOTSPOT PCT distribution were those that result from the application of smaller multipliers. With lower minimum and median multipliers, the approved methodology distribution provides conservative results relative to the cold data distribution. Finally, the 95^{th} percentile PCT reported by the applicant in the AP600 SSAR is 913 °C (1675 °F). This indicates that the small extension of the approved methodology distribution beyond the upper end of the cold data distribution was not a safety issue.

During the blowdown heatup period, the AP600 plant responds in the same way as three- and four-loop plants. The heatup period is approximately 5 seconds, similar to three- and four-loop plants. The fuel specified for the AP600 is a typical Westinghouse product; therefore, the LOFT and Oak Ridge tests used to develop the blowdown heatup uncertainty for three- and four-loop plants are also applicable to the AP600. These support the application of the approved methodology blowdown heatup heat transfer uncertainty distribution to the AP600.

Also, the staff used information in the applicant’s letter dated September 8, 1997, to verify that the lower core power density for the AP600, which enters into the equation used to establish the blowdown heatup uncertainty, did not impact the application of the approved methodology distribution for blowdown heatup heat transfer to the AP600.

During refill, the core is voided, core flow is minimal, and all plants with a given fuel design will experience similar heat transfer. Because the AP600 is equipped with typical Westinghouse fuel and the refill heat transfer in the core is independent of other plant design features, the approved methodology refill heat transfer uncertainty distribution was applicable to the AP600.

ECC bypass

The DVI assessments in Section 21.A.3 of this report showed that WCOBRA/TRAC provided a conservative estimate of ECC bypass.

Steam binding/hot-leg entrainment

Assessments performed in this area for the approved methodology showed that WCOBRA/TRAC provided conservative predictions for steam binding. This was supplemented by the CCTF Test 58 (a DVI test) results that showed hot-leg liquid flows to be slightly overpredicted.

Noncondensible gases/accumulator nitrogen

For the AP600, accumulator nitrogen cover gas was not important because the AP600 accumulators do not empty until after the core is completely quenched (see Figures 21.A-1 and 21.A-2 of this report). In addition, on the basis of the applicant's response to comment 1(g) in the letter (NSD-NRC-97-5171) dated June 10, 1997, 60 percent of the initial liquid remains in the accumulators at the time of PCT, so small changes in the analysis results or the AP600 design will not cause the accumulators to empty before the time of PCT. In the approved methodology, the applicant results presented in response to Volume 1, Question 134, of its letter (NTD-NSA-MYY-95-12) dated April 21, 1995, discussed the effects of dissolved nitrogen coming out of solution in the primary system, and the applicant showed that effect was negligible.

Condensation

The approved methodology developed the condensation multiplier range on the basis of separate effects test data. The AP600 downcomer is dimensionally similar to a three-loop plant. Therefore, the condensation multiplier range from the approved methodology was considered applicable.

The staff also noted that the applicant applied bounding assumptions for the power distributions (peaking factors and axial shapes) and initial conditions. The bounding assumptions were determined from WCOBRA/TRAC analyses in which the input was varied over the expected operating range of the AP600 plant (see Section 4.4 of WCAP-14171). The use of bounding parameters for initial conditions and power shapes significantly reduced the number of parameter uncertainty distributions needing justification.

As mentioned above, the applicant modified the handling of T_{MIN} and the blowdown cooling HTC multipliers. The changes in these areas are discussed below. The T_{MIN} changes are discussed first followed by the blowdown cooling changes.

$\underline{T_{MIN}}$

For the AP600, the applicant elected to modify the T_{MIN} model in WCOBRA/TRAC during blowdown from the approved three- and four-loop plant methodology. The T_{MIN} model in the HOTSPOT code remained unchanged for application to the AP600. The reason for the change in the WCOBRA/TRAC code was the need to ensure a conservative T_{min} calculation during the AP600 blowdown cooling period.

The applicant chose to take a bounding approach for the blowdown T_{MIN} in WCOBRA/TRAC AP600 calculations. The value chosen and the basis for that selection is discussed in Section 4.1 of WCAP-14171. The review considered the data provided by the applicant and found that the value chosen was adequately supported. The bases for this conclusion include the following:

- The applicant chose appropriate data to use in the evaluation.
- The applicant selected a T_{MIN} value that is slightly lower than the 5^{th} percentile value of the T_{MIN} data. The data base supports an average T_{MIN} greater than about 538 °C (1000 °F). Use of the value chosen by the applicant's results in a T_{MIN} value that was clearly lower than the average of the blowdown data base.

Blowdown Cooling

The applicant reevaluated the ability of WCOBRA/TRAC to analyze blowdown cooling heat transfer in WCAP-14171, Section 4.2. The WCOBRA/TRAC calculations used the T_{MIN} value discussed above. The database the applicant analyzed comprised 10 Oak Ridge National Laboratory dispersed flow film boiling tests (NUREG/CR-2435). As shown in Section 4.2 of WCAP-14171, the 10 tests provided data that covered the range of conditions expected during the AP600 blowdown cooling period. The approach to determine the blowdown cooling HTC multipliers used in the uncertainty analysis was consistent with the approach for the other LBLOCA phases.

The staff considered that the new blowdown cooling HTC uncertainty distribution was adequate for AP600 analyses. This was because data that covered the range of AP600 conditions such as pressure and flow were used, and the uncertainty distribution was developed consistent with other LBLOCA phases. The staff also noted that the new distribution provided results that were conservative relative to a direct application of the blowdown cooling distribution from the approved methodology as discussed in the applicant's letter (NSA-SAI-96-102), dated March 25, 1996. This was because, although the minimum multipliers for the two distributions were similar, the AP600 median and maximum multipliers were less than those from the approved methodology. For this application, lower multipliers were more conservative because they result in lower heat transfer at the cladding surface in HOTSPOT calculations.

In addition to evaluating the uncertainty distributions, the review also considered the simplifying assumptions the applicant made to make the uncertainty evaluation manageable. In the approved methodology, the applicant made simplifying assumptions in the following areas:

(a) combining initial condition uncertainties

(b) break type (guillotine versus split) selection

(c) approach for the resistance ratio (R_B, the ratio of the resistance from the core to the break via the various possible flow paths)

(d) combining uncertainties in peaking factors, F_Q and $F_{\Delta H}$.

Of these simplifying assumptions, Items (a) and (d) were not applicable to the AP600 because of the simplifications to the approved methodology implemented by the applicant. For Item (b), the applicant used the same approach of analyzing each break type separately for the AP600, but this was not impacted by the AP600 application. Only Item (c) was potentially affected by the AP600 application because of the canned motor pumps used in the AP600.

The applicant discussed the AP600 approach for R_B in its June 10, 1997, letter responses to comments 12(g), 12(h), and 12(i) dated June 10, 1997 (NSD-NRC-97-5171). The information provided showed that the pumps for the AP600 and three- and four-loop plants had similar homologous curves and were subject to similar conditions during a LBLOCA. Also, the AP600 broken loop cold-leg nozzle has a radius of curvature similar to that found in three- and four-loop plants; this indicates the AP600 nozzle K-factor is similar to that developed for the approved methodology. Finally, the applicant showed that the AP600 2 x 4 configuration does not have an impact on the analysis. According to these considerations, it was concluded that the applicant had adequately justified the application of the approved methodology approach for R_B to the AP600.

Because of the simplifying assumptions made by the applicant for AP600 analyses in the areas of initial conditions and power shapes, superposition was not used in the AP600 application. Therefore, the superposition validation step in the approved methodology (see Attachment 2 of the applicant's letter NSA-SAI-96-019, dated January 24, 1996) did not need to be included in the AP600 analysis. However, the applicant did use a similar process to ensure that any uncertainties in the global model response surfaces were accounted for in the analysis.

21.A.8.3 LBLOCA Method Description/Review — Split Breaks

In RG 1.157, the staff indicates that split breaks should be considered in the break spectrum analysis used to determine the 95^{th} percentile PCT. The applicant addressed split breaks for the AP600 in the same manner established for three-and four-loop plants as discussed in its letter response to comment 13 (NSD-NRC-97-5171) dated June 10, 1997. The applicant addressed split breaks in the AP600 SSAR.

This review considered the AP600 split break results presented in the AP600 SSAR and compared them where possible to North Anna split break calculations as discussed in the applicant's letter (NTD-NSA-SAI-95-391, "Revisions to Westinghouse Best-Estimate Uncertainty Methodology") dated October 13, 1995. The comparison showed that the AP600 and North Anna respond similarly to the split break spectrum. During blowdown for example, the North Anna limiting split break occurred at C_D = 1.4, and the AP600 split break occurred at

C_D = 2.0. But the North Anna C_D = 2.0 split break PCT was within 15 °C (27 °F) of the C_D = 1.4 case, and the AP600 C_D = 1.4 split break PCT was within 21 °C (38 °F) of the C_D = 2.0 case. In addition, the North Anna PCTs for C_D's from 1.2 to 2.0 were within 26 °C (47 °F) of each other. In the AP600 cases for the same C_D range, the PCTs were within 39 °C (70 °F) of each other. Finally, both the AP600 and North Anna have the limiting reflood PCT occur at a C_D = 1.0. This analysis demonstrates that although a different C_D was limiting for blowdown, the AP600 and North Anna responses for the different split break sizes were very similar.

The applicant also showed that the AP600 and North Anna responded similarly to a double-ended cold-leg guillotine break. On the basis of the similarity of the AP600 response to that for North Anna for split and guillotine breaks, the staff considered the application of the approved methodology approach to AP600 split breaks adequate.

21.A.8.4 LBLOCA Method Description/Review — Westinghouse HOTSPOT Model

The applicant developed a model to evaluate the effects of the uncertainties associated with local parameters on the calculated PCT called the HOTSPOT model (see the applicant's letter NTD-NSA-SAI-95-5 dated March 6, 1995). It models a portion of a fuel rod at the PCT or burst location including fuel, gap, and cladding. The HOTSPOT model is a simple physical model that allows the effects of uncertainties to be calculated directly by running the model many times with parameter values that vary randomly according to specified distributions. The parameter uncertainties considered are linear power, fuel density after cladding burst, fuel conductivity before and after burst, metal-water reaction rate, gap pressure, gap conductance, HTC, T_{MIN}, burst temperature, and burst strain. The applicant's letter (NTD-NSA-MYY-95-5) dated March 6, 1995, provides additional details on the HOTSPOT model.

The staff review of the HOTSPOT model found it acceptable for realistic LBLOCA analysis in three- and four-loop plants. The staff determined that it was appropriate to extend this approval to the AP600 because the same fuel is specified for AP600 as for three- and four-loop plants as discussed in the applicant's response to comment 12(j) in its letter (NSD-NRC-97-5171) dated June 10, 1997. Thus, the models in HOTSPOT also apply to the AP600.

21.A.8.5 Summary of Review

This section summarizes the results of the review of the applicant's realistic LBLOCA methodology. The following conclusions were reached:

(1) <u>NRC review of the WCOBRA/TRAC code models</u>—The staff's review found that the models were acceptable for realistic analysis of LBLOCA results. The details supporting this conclusion are found in the NRC's letter concerning "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996. Because the AP600 and three- and four-loop plant LBLOCA responses are very similar, the staff determined that WCOBRA/TRAC, MOD7A, Revision 1, was adequate for AP600 LBLOCA analyses.

(2) Uncertainty distributions/assumptions—On the basis of the information provided, the applicant justified the uncertainty distributions used for the AP600. Application of the approved methodology distributions was justified on the basis of similarity of the different plant types regarding LBLOCA response, equipment, and materials. Appropriate information was provided by the applicant for the AP600-specific distributions used for blowdown cooling and T_{MIN}.

(3) Split breaks—The applicant addressed split breaks in the same manner as three- and four-loop plants. On the basis of the similarity of the AP600 response to that for North Anna for split and guillotine breaks, the staff considered the application of the approved methodology approach to AP600 split breaks adequate. The applicant addressed split breaks in the AP600 SSAR.

(4) HOTSPOT—The HOTSPOT model is acceptable for realistic LBLOCA analysis in three- and four-loop plants. The staff determined that it is appropriate to extend this approval to the AP600 because the same fuel is specified for AP600 as for three- and four-loop plants. Thus, the models in HOTSPOT also applied to the AP600.

21.A.9 Comparison with Regulatory Guide 1.157

The recommended features of a realistic LBLOCA analysis are described in RG 1.157. Comparison of the applicant's methodology with RG 1.157 is summarized in Section 21.A.7.1 of this report. Additionally, in RG 1.157, the staff discussed determining the range of applicability for a number of different models. Consistency with the RG 1.157 recommendations in this area is discussed in Section 21.A.9.2 of this report.

21.A.9.1 Summary of Westinghouse Methodology/RG 1.157 Comparison

The staff review of the approved Westinghouse methodology found it either met the RG guidance in Part C, Section 3, "Best-Estimate Code Features," and Section 4, "Estimation of Overall Calculational Uncertainty," or else the applicant provided adequate justification for the approach presented. For example, the applicant used a point kinetics model to analyze fission heat as recommended by RG 1.157, Section 3.2.2, and the fission product decay heat model was on the basis of the 1979 ANSI/ANS standard recommended by RG 1.157, Section 3.2.4. Where the applicant took an alternative approach to that outlined in RG 1.157, the staff found that the applicant provided adequate justification for the approach presented. For example, the applicant used the Cathcart-Pawel model (ORNL/NUREG-17) to calculate the Zircaloy-water reaction at temperatures above 816 °C (1500 °F). In RG 1.157, Section 3.2.5, the Cathcart-Pawel model is recommended but only for temperatures greater than 1038 °C (1900 °F). The applicant showed that the Cathcart-Pawel model overpredicts the reaction rate at temperatures below 1038 °C (1900 °F); therefore, it is conservative to use it at the lower temperatures. Such conservatism is consistent with RG 1.157 (see Part C, Section 1).

For the AP600, the applicant used a modified version of the approved methodology discussed in WCAP-14171. The main difference from the approved methodology was the simplification of the uncertainty analysis by the inclusion of a larger number of bounding parameters. The applicant chose this approach because of the large margin available in the AP600 relative to the 10 CFR 50.46 PCT limit. The staff noted that this bounding approach added conservatism to the WCOBRA/TRAC calculated results for the AP600 and, as noted above, conservatism is consistent with RG 1.157.

It is also noted that one change made to a WCOBRA/TRAC model affected the LBLOCA PCT calculation. This was to use a low estimate of T_{MIN} during blowdown in the WCOBRA/TRAC calculations. Again, this made the AP600 application more conservative than the approved methodology because it would result in the AP600 analysis calculating rod quench during blowdown at a lower temperature than the approved methodology. The change to T_{MIN} is discussed in more detail in Section 21.A.8.2 of this report.

In RG 1.157, Section 4.5, the staff notes that the CSAU methodology was originally used to evaluate the overall calculational uncertainty in PCT predictions for NRC developed BE computer programs. As set forth in Section 21.A.1 of this report, the staff found that the applicant's AP600 methodology was consistent with the underlying purpose of the CSAU methodology.

Based on the previous NRC approval and the information provided during the AP600 review, the staff concluded that the applicant met RG 1.157 guidance or provided adequate justification for its alternate approach for the AP600 realistic methodology.

21.A.9.2 WCOBRA/TRAC Range of Conditions/Applicability

In RG 1.157, the staff identified certain models for which the range of applicability needed to be justified. This meant that WCOBRA/TRAC needed to be assessed and/or the individual code models needed to be on the basis of data that cover the range expected in the AP600 analyses. In RG 1.157, the staff identified the following models as needing justification for the range of applicability:

- critical flow
- ECC bypass
- frictional pressure drop
- critical heat flux
- transition and film boiling heat transfer
- single-phase vapor heat transfer
- level swell

Also, the applicant's PIRT identified the following models as important:

- critical flow
- pump
- condensation
- entrainment
- ECC bypass
- core heat transfer including T_{MIN}

- fuel rod including stored energy, decay heat, and gap conductance

To address these issues for the AP600, the applicant, in response to comment 16 in its letter (NSD-NRC-97-5171) dated June 10, 1997, stated that the three- and four-loop plant assessment ranges were applicable to the AP600 except for blowdown cooling and reflood heat transfer. The applicant's response also identified and addressed the following areas of the PIRT evaluation that were ranked high for the AP600 but not for three- and four-loop plants: rewet, upper head phenomena, accumulator discharge during reflood, and DVI. The staff focused its review in these areas:

(1) Blowdown cooling: In Table 4.2-1 of WCAP-14171, the applicant showed that the blowdown cooling assessment covered the appropriate range of conditions for the AP600 in the areas of pressure, mass flux, inlet water temperature, and power.

(2) Reflood heat transfer: In response to comment 16 in its letter (NSD-NRC-97-5171) dated June 10, 1997, the applicant noted that it performed WCOBRA/TRAC assessments to cover the lower cladding temperatures calculated for the AP600 at the start of reflood. Based on information from the applicant's letter dated September 8, 1997, the staff found that the previous WCOBRA/TRAC reflood heat transfer assessments in the CQD also appropriately bounded the AP600 results for pressure, reflood rate, initial core power, and inlet subcooling.

(3) Rewet: In Table 4.1-1 of WCAP-14171, the applicant showed that conditions appropriate for the AP600 were covered in the T_{MIN} assessment in the areas of pressure, mass flux, inlet subcooling, and power. The staff also noted that T_{MIN} was directly included in the uncertainty evaluation.

(4) Upper head phenomena: The applicant used a conservative upper head temperature per the response to comment 12(e) in its letter (NSD-NRC-97-5171) dated June 10, 1997. In addition, the full-pressure, full-temperature LOFT test analyses in the CQD simulated upper head draining as discussed by the applicant's response to comment 16 in its letter (NSD-NRC-97-5171) dated June 10, 1997, and the information provided in its letter (NSD-NRC-97-5332) dated September 8, 1997.

(5) Accumulator discharge during reflood: The applicant noted that accumulator discharge is more important for the AP600 relative to existing plants because the AP600 accumulator is larger and discharges longer, but existing assessments of accumulator discharge were adequate for AP600. The staff agreed with this conclusion because, except as noted below, the AP600 accumulators are similar in design to those in current plants, using pressurized nitrogen over water. Also, modeling the larger accumulator water volume and longer discharge in the AP600 can easily be done with standard modeling techniques used to represent accumulator differences in existing plants. Finally, the applicant used a bounding accumulator discharge model in its AP600 analyses as discussed in the response to comment 12(f) of its letter (NSD-NRC-97-5171) dated June 10, 1997.

The one accumulator design difference between the AP600 and current plants that needed to be addressed was the use of a spherical accumulator tank for the AP600 versus a cylindrical tank for current plants. This geometric difference was not important because the accumulator discharge is driven by the expansion of the nitrogen cover gas, which acts like an ideal gas, and is controlled by the accumulator to primary system pressure difference. Because the nitrogen acts like an ideal gas, the discharge of 28 L (1 ft^3) of liquid from either a cylindrical or a spherical accumulator tank will cause the same pressure decrease in the driving force even though the geometry is different. This is the same result that would be seen in current plants with two cylindrical accumulator tanks of different cross-sectional area. Also, at the large pressure difference that develops between the accumulator tank and the primary system during discharge, the staff believed that any other geometrical effects (such as surface area and liquid/gas interface area) was negligible.

(6) DVI: Comparison of Tables 3.2.7-1 and 3.2.7-2 in WCAP-14171, showed that the appropriate range of conditions for DVI were covered in the areas of DVI flow, core steam flow rate, and ECC subcooling.

This comparison demonstrated that the WCOBRA/TRAC assessment covered the appropriate range of conditions for the important AP600 models and/or the methodology directly accounted for or bounded the uncertainty. Other parameters were covered through the approved methodology.

21.A.10 Other Technical Issues

In the AP600, CCFL modeling was important because of the effect it had on the calculation of ECC bypass and fall-back at the upper core plate (UCP). For the AP600, CCFL needed to be reviewed because of plant differences relative to three- and four-loop plants that affect the ECCS configuration and the potential for fall-back at the UCP due to the lower core power density. This topic is discussed below. This section also discusses the issue of compensating errors as it relates to the AP600 analysis.

21.A.10.1 WCOBRA/TRAC CCFL Modeling Assessment

The proper calculation of CCFL is important to correctly predict the PCT in a LBLOCA, and the CCFL calculation can be evaluated by comparing it to accepted CCFL correlations and/or test data. This section discusses the WCOBRA/TRAC approach to CCFL, summarizes the staff evaluation of the WCOBRA/TRAC CCFL calculation during the review of the approved methodology, and discusses those CCFL calculations important to the AP600 that needed to be considered.

The main PWR areas of importance are the downcomer annulus for ECC bypass and the UCP for fall-back of liquid carried out of the core. WCOBRA/TRAC does not use empirical CCFL correlations; rather it calculates CCFL directly from the basic code equations and constitutive relationships (for example, the interphase area, interphase heat transfer, and interphase drag correlations). As a result, the WCOBRA/TRAC approach is different from the application of a

CCFL correlation. When a CCFL correlation is used, the correlation imposes a limit on the calculated flow solution that the code is not allowed to violate. For example, if a code uses the Wallis correlation to model CCFL, then the flow solution is not allowed to violate the Wallis equation $[j_g^*]^{½} + m[j_f^*]^{½} = C$, where m is often set equal to 1.0 and C would be selected by the code developer to represent the geometry being modeled. In WCOBRA/TRAC, no such limit is imposed on the flow solution, and the CCF calculated comes directly from the constitutive relations and the solution of the basic equations.

The evaluation of the applicant's calculation of CCFL with WCOBRA/TRAC for three- and four-loop plants is discussed in detail in the NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996, and summarized here. To determine whether WCOBRA/TRAC was properly calculating CCFL, that evaluation considered test facility and plant nodalization, the basic equations, the constitutive relationships, and comparisons to data. The CCFL test nodalizations and the plant nodalizations were consistent, which allowed the assessment results to be applied to the plant calculations. The staff found that the code models and correlations were adequate in such areas as interfacial drag and condensation. The review also found that WCOBRA/TRAC gave good to conservative results for the assessments on the basis of tests in facilities ranging from small- to full-scale.

For the AP600, two areas of the previous review needed to be reconsidered. They were ECC bypass calculations with DVI and fall-back at the UCP due to the lower core power density in the AP600. The staff considered the comparisons between the WCOBRA/TRAC results and the data for the parts of UPTF Test 21 that represented DVI. For all cases, conservative results were found. Also, the PCT in CCTF Run 58 was conservatively calculated. These results are discussed in more detail in Section 21.A.3 of this report. The applicant also assessed the potential for fall-back from the upper plenum to the core at the UCP in the response to comment 1(e) in its letter (NSD-NRC-97-5171) dated June 10, 1997. That response showed that little fall-back is calculated in the AP600 analyses. The staff noted that, even if this result was not realistic, it was conservative. On the basis of the review summarized above, the staff concluded that WCOBRA/TRAC's models conservatively represented CCFL in the downcomer and at the UCP for the AP600.

21.A.10.2 Compensating Errors

Compensating errors are defined as errors which, taken one at a time, may produce demonstrably incorrect results, but when combined provide acceptable but misleading results. For example, PCT could be calculated well but only because the heat transfer model overpredicted the local HTC, thus compensating for a low core flow rate.

In the review of the approved methodology, the applicant provided a detailed evaluation of compensating errors in WCOBRA/TRAC as applied to three- and four-loop plants. In general, that evaluation was considered applicable to the AP600 analysis because (a) the AP600 response is similar to three- and four-loop plant LBLOCA response, (b) the AP600-specific assessments for DVI showed that WCOBRA/TRAC gave conservative estimates of ECC bypass and core cooling, and (c) while AP600 has better blowdown cooling than three- and four-loop plants, the global model run matrix ranges the calculated blowdown PCT and cooling.

The applicant provided information supporting the conclusion that no compensating errors exist which might compromise the ability of WCOBRA/TRAC to predict the conditions during a large-break LOCA in its response to RAI 440.739F dated February 1, 1998. The additional information related to AP600 is summarized as follows:

(1) In the ORNL steady-state film boiling test predictions, the non-equilibrium vapor conditions observed experimentally were also predicted. This provided confidence that an important component of the heat flux model, the vapor heat sink, was predicted correctly. While differences existed between the predicted and measured values, these differences were captured in the heat flux uncertainty which was applied in the overall uncertainty analysis.

(2) The validation of the CCFL model by the simulation of UPTF Test 21, considering effects of condensation, demonstrated that compensating errors did not exist in the prediction of ECC bypass for the direct vessel injection geometry.

(3) The detailed analysis of CCTF Test 58 indicated that the T-H response of the core to loop flow was proper, and not the result of a compensating error.

21.A.11 <u>Compliance with 10 CFR 50.46 Requirements</u>

This section discusses how the applicant's AP600 methodology met the requirements of 10 CFR 50.46. This section of the Commission's regulations describes the ECCS acceptance criteria for LWRs.

The portion of 10 CFR 50.46(a)(1)(i) that was the focus of the AP600 review states the following:

> Except as provided in paragraph (a)(1)(ii) of this section, the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that, when the calculated ECCS cooling performance is compared to the criteria set forth in paragraph (b) of this section, there is a high level of probability that the criteria would not be exceeded.

This indicates that (a) the analytical technique must realistically describe reactor LOCA behavior, (b) comparisons to applicable experimental data must be made, (c) uncertainties in the analysis method and inputs must be assessed so the uncertainties in the calculated results can be estimated, and (d) the uncertainty must be accounted for when comparing the calculated ECCS performance to the criteria set forth in 10 CFR 50.46(b) so that there is a high level of probability that the criteria would not be exceeded.

The staff determined that the applicant's methodology for three- and four-loop plants met the above requirements as documented in NRC letter "Acceptance for Referencing of the Topical Report, WCAP-12945 (P), Westinghouse Code Qualification Document for Best-Estimate Loss-of-Coolant Analysis," dated June 28, 1996. The review included the following:

(1) The WCOBRA/TRAC code and code assessment - According to the review of CQD Volume 1 and Westinghouse's comparisons to over 100 tests described in CQD Volumes 2 and 3, the staff concluded that WCOBRA/TRAC realistically described the behavior of a PWR during an LBLOCA.

(2) Uncertainty evaluation - In Volumes 4 and 5 of the CQD and Reference 19, the applicant described its methods for determining the uncertainty of the analysis methods and inputs and applying them to the calculated ECCS performance. NRC review of the uncertainty methodology included reviewing all uncertainty distributions, response surface generation, and their applications to determine the 95^{th} percentile PCT. Uncertainty because of reactor input was also reviewed.

In WCAP-14171, the applicant demonstrated the applicability of the WCOBRA/TRAC code to the AP600 and described the modifications made to the approved methodology for the AP600. The applicant's approach was to demonstrate the similarity of the AP600 and three- and four-loop plant LBLOCA responses and to provide DVI assessments. Because of the similarity of the LBLOCA responses, the staff concluded that the previous NRC code and code assessment review applied to AP600. For the DVI assessments provided, the applicant demonstrated that WCOBRA/TRAC conservatively predicted the PCT for CCTF Test 58 and overpredicted the ECC bypass for UPTF Test 21. The conclusion of the previous NRC code and code assessment review plus the conservative DVI assessments supported the staff conclusion that WCOBRA/TRAC was adequate to provide realistic evaluations of the AP600 LBLOCA with the tendency toward conservative results. The review of the similarity of the AP600 and three- and four-loop plant LBLOCA, and the DVI assessments, are discussed in Section 21.A.3 of this report. Thus, the staff concluded that the applicant met, for the AP600, those parts of 10 CFR 50.46(a)(1)(i) which require justification that the methodology realistically describes reactor behavior during a LBLOCA and those which require comparisons to applicable data.

Modifications to the WCOBRA/TRAC code were made but were applied only to model passive safety equipment that does not impact the initial AP600 response to an LBLOCA. In response to comment 4(a) in its letter (NSD-NRC-97-5240) dated July 18, 1997, the applicant asserted that the changes only negligibly affect the PCT, but they are needed to analyze the AP600 LBLOCA CMT injection phase which occurs after the accumulators empty and CMT injection begins. Because the AP600 95^{th} percentile PCT showed a large margin to the 10 CFR 50.46 PCT limit [the AP600 SSAR shows 913 $^{\circ}$C (1675 $^{\circ}$F) versus 1204 $^{\circ}$C (2200 $^{\circ}$F)], this was not considered safety-significant. On this basis, the staff concluded that the code changes did not impact the previous NRC review.

The applicant also discussed the modifications to the approved uncertainty methodology for the AP600 in WCAP-14171 as supplemented by responses in the applicant's letters dated June 10, July 18, and September 8, 1997 (NSD-NRC-97-5171, NSD-NRC-97-5240, and NSD-NRC-97-5332, respectively). These modifications simplified the approved methodology by bounding a larger number of parameters relative to the approved methodology. The review of these changes is discussed in Sections 21.A.5 and 21.A.8 of this report. On the basis of the information provided, the staff concluded that the applicant justified the changes. Therefore, the applicant satisfied the requirements of 10 CFR 50.46(a)(1)(i) dealing with quantifying the uncertainty and accounting for the uncertainty when comparing the calculated ECCS performance to the criteria of 10 CFR 50.46(b), for the AP600.

10 CFR 50.46(b) of the regulations states the five acceptance criteria for the ECCS. Specifically, the ECCS must ensure the following:

- The PCT is less than 1204 °C (2200 °F) [10 CFR 50.46(b)(1)].

- The maximum local cladding oxidation does not exceed 17 percent of the total cladding thickness before oxidation [10 CFR 50.46(b)(2)].

- The maximum hydrogen generation shall not exceed 1 percent of the amount that would be generated if all the cladding surrounding the fuel, except that around the plenum volume, were to react [10 CFR 50.46(b)(3)].

- Calculated changes in core geometry shall be such that the core remains amenable to cooling [10 CFR 50.46(b)(4)].

- After the successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat removed for the extended period of time required by the long-lived radioactivity in the core [10 CFR 50.46(b)(5)].

The applicant's realistic LBLOCA methodology for the AP600 met these criteria as follows:

(1) The applicant's method of determining the 95^{th} percentile PCT is summarized in Section 21.A.5 of this report.

(2) To determine the maximum calculated local oxidation, the applicant used the same approach as for three- and four-loop plants in the approved methodology.

(3) Determination of the maximum core wide hydrogen generation was on the basis of an evaluation using the PCT and maximum local oxidation.

(4) According to their AP600 calculations, the applicant provided sufficient justification to conclude that the coolable geometry criterion is met when 10 CFR 50.46 PCT and oxidation criteria are met. This is the same approach as for three- and four-loop plants.

(5) The applicant met the long-term cooling criterion for AP600 using methods that were reviewed separately.

The staff's review of the PCT methodology determined that it was adequate to meet NRC requirements for realistic LBLOCA analyses. As stated earlier, the applicant's methods for determining the 95th percentile PCT were the subject of the review summarized in this appendix and discussed in a number of sections.

The staff considered the following items in concluding that the three- and four-loop plant local oxidation methodology was applicable to AP600. First, the fuel used in AP600 is not significantly different from that used in three- and four-loop plants. Second, the AP600 LBLOCA response is similar to that for three- and four-loop plants. Finally, in the response to comment 15 in its letter (NSD-NRC-97-5171) dated June 10, 1997, the applicant stated that the 95th percentile PCT was below 927 °C (1700 °F), the limit for significant metal-water reaction to begin. The low PCT results in the 95th percentile of the peak local oxidation equaling 0.2 percent versus the 10 CFR 50.46 limit of 17 percent. These three factors (similar fuel, similar LBLOCA response, and low PCT calculation which results in a low local oxidation calculation) demonstrated that the approach for the approved methodology in the area of local oxidation calculation was applicable to the AP600.

For core-wide oxidation, the applicant determined that the small peak local oxidation and the low 95th percentile PCT provided substantial margin for the core-wide oxidation calculation. As noted above, the low PCT calculated for the AP600 resulted in a negligible peak local oxidation calculation. These factors (low PCT and local oxidation calculations) demonstrated that an evaluation approach for the core-wide oxidation calculation was applicable to AP600.

For the coolable geometry criterion, the staff agreed that meeting 10 CFR 50.46(b)(1) and (2) ensures that a coolable core geometry will be maintained. Past NRC experience has shown that meeting the PCT criterion [10 CFR 50.46(b)(1)] ensures that changes in core geometry because of the LBLOCA transient (e.g., cladding swelling and burst and LOCA loads) do not prevent adequate core cooling as evidenced by the highest calculated PCT. This is consistent with the evaluation models in Appendix K to 10 CFR Part 50, and the use of a realistic LBLOCA methodology for the PCT and oxidation calculations would not change this. Also, a similar argument was used in the approval of the Westinghouse-realistic methodology for three- and four-loop plants. The staff judged that AP600-specific changes did not invalidate the same approach for the AP600. In addition, in the response to comment 15 in its letter (NSD-NRC-97-5171) dated June 10, 1997, the applicant noted that no fuel rod rupture was calculated in the AP600 LBLOCA analyses because of the low calculated PCT.

On the basis of the above, the staff concluded that for the AP600, the applicant met the requirements of those portions of 10 CFR 50.46(a)(1)(i) that were the focus of the review. The applicant also demonstrated methods adequate to show compliance with 10 CFR 50.46(b)(1)–(4) for the AP600. Compliance with 10 CFR 50.46(b)(5), long-term cooling, was reviewed separately.

21.A.12 Conclusions and Limitations

The realistic AP600 LBLOCA methodology submittal by the applicant was reviewed to determine its compliance with 10 CFR 50.46 and compatibility with NRC guidance in RG 1.157 and the CSAU methodology. On the basis of the review of the information provided by the applicant in WCAP-14171 and responses to NRC questions, the staff found the Westinghouse-realistic AP600 methodology acceptable subject to the following methodology and application restrictions.

The application restrictions include the following:

(1) Section 21.A.11 of this report discusses the applicant's methods for meeting the five criteria listed in 10 CFR 50.46(b). AP600 long-term cooling issues were addressed separately. Therefore, the evaluation documented in this appendix does not apply to the application of WCOBRA/TRAC to AP600 long-term cooling. AP600 long-term cooling was evaluated elsewhere. The description of the staff's evaluation of WCOBRA/TRAC in this appendix was restricted to the initial phase of the LBLOCA. As seen in Figures 21.A-1 and 21.A-2 of this report, this corresponds to the end of the reflood phase, which occurs at about 130 seconds from the initiation of the transient.

(2) Application of the methodology and WCOBRA/TRAC to SBLOCA was not considered in the AP600 review.

(3) Based on National Research Universal (NRU) reactor assessment results noted during the review of the approved methodology, there was some uncertainty in the transient rod internal pressure (RIP) calculation that affects the burst temperature criterion in WCOBRA/TRAC analyses. The approved methodology review found the applicant's uncertainty methodology adequately accounted for the uncertainty in transient RIP for local effects. However, the applicant also calculated hot assembly (HA) rod burst in the full WCOBRA/TRAC analyses called for in its methodology. If WCOBRA/TRAC calculated a HA rod reflood PCT greater than 871 °C (1600 °F) but not rod burst, the applicant in letter NSA-SAI-96-156 dated April 30, 1996 (List II, Item 2), committed to increasing the initial RIP in the WCOBRA/TRAC HA rod until burst was calculated and choosing the more limiting of the burst and non-burst cases. This adequately accounted for transient RIP uncertainties and their effect on rod burst in the WCOBRA/TRAC runs.

(4) On CQD page 7-24, the applicant stated that the fuel pellet thermal expansion model in MATPRO-11 (NUREG/CR-0497, Revision 1) used in WCOBRA/TRAC was simplified by omitting the corrections for mixed-oxide (Pu) fuel. In the applicant's letter NSA-SAI-96-156 dated April 30, 1996 (List II, Item 6), the applicant committed to resubmitting the relevant WCOBRA/TRAC models for NRC review if the code will be used to analyze U.S. licensed plants with mixed-oxide fuels.

(5) In the approved uncertainty methodology, a number of assumptions for distributions were supported using plant-specific data; therefore, in its letters dated April 30, 1996 (NSA-SAI-96-156, Attachment 5) and May 9, 1996 (NSA-SAI-96-167, Attachments 1

and 2), the applicant committed to verify the following assumptions on a plant-specific basis:

(a) The process used to account for the response surface uncertainty assumes the data points are normally distributed, with constant variance, around a straight line. The normality must be checked for each phase of the accident for each plant.

(b) HOTSPOT PCTs are normally distributed. This must be checked at each point where the HOTSPOT PCT is varied in a Monte Carlo sample [i.e., the points used to build the response surface for the HOTSPOT standard deviation ($\sigma_{\iota\alpha\beta\bullet}$) and the validation points].

(c) Response surface for $\sigma_{\iota\alpha\beta\bullet}$ is accurate or conservative. This should be checked by comparing the response surface estimate with the Monte Carlo standard deviation at each validation point. The applicant identified the methodology for this on a plant-specific basis in the applicant's letter NSA-SAI-96-167 dated May 9, 1996 (Attachment 1).

(6) The distributions corresponding to WCOBRA/TRAC uncertainty on the basis of experiments ($\sigma_{WC/T}$) and the uncertainty as a result of experimental data scatter (σ_{2p}) will be checked for normality if the code is modified or the assessment data base changes. See the applicant's letter NSA-SAI-96-156 dated April 30, 1996, List III, Item 2.

(7) The applicant, in its letter NSA-SAI-96-156 dated April 30, 1996 (List II, Item 10), committed to use the multiplier given in Attachment 4 of the same letter to account for rod-to-rod radiation effects in the heat transfer multiplier database.

(8) The staff notes that the applicant's response in letter NSA-SAI-96-028 dated January 26, 1996 (Attachment 5) derived the expressions for the shear stress to the wall and to the vapor shown in CQD Equations 6-120 and 6-121. The applicant concluded that the wall shear stress equation used the incorrect friction factor. To assess the effect, the applicant reevaluated FLECHT-SEASET Test 31805 with a corrected version of WCOBRA/TRAC. There was little impact on the PCT, and the results from the corrected code version had slightly later quench times. The applicant concluded the effect was small, and the NRC agreed. Therefore, the applicant proposed that the error be tracked and corrected when other changes to the code are required.

Application restrictions on the AP600 methodology include the following criteria:

(1) Approval of the applicant's methodology depended on the time step sizes used to show small mass and energy errors and used in PWR time step convergence studies. [See Volume 4, question 50, of the applicant's letter (NTD-NSA-MYY-95-15) dated May 12, 1995.] If the time step sizes used in the methodology change, the applicant must justify results similar to those identified above are obtained with the new time step scheme.

(2) The applicant, in its letter NSA-SAI-96-156 dated April 30, 1996 (List II, Item 8), committed to not changing the value and range of the broken loop cold-leg nozzle loss coefficient for plant-specific applications. Also, the values developed apply only to LBLOCA before core quench.

(3) If the 1 percent core-wide oxidation limit is exceeded with the base methodology, the applicant in letter NSA-SAI-96-156 dated April 30, 1996 (List III, Item 5), committed to identifying, in the licensing submittal or the engineering report, which of the options described in its response to Volume 2, question 62, of the applicant's letter NSA-SAI-96-156 dated April 30, 1996 (Attachment 12), were used to bring the calculated core wide oxidation below the 1 percent limit by reducing the margin in the calculated results.

(4) In WCAP-14171, Revision 1, the applicant documents the application of its LBLOCA best-estimate methodology to the AP600. In developing that methodology, some parameters were not included in the uncertainty analysis. Some of these parameters were conservatively bounded, while others were judged to have an insignificant impact on the low-calculated PCT results and for simplicity were not considered. Among the latter set of parameters were (1) the AP600-unique passive safety system (CMTs and PRHR) modeling, and (2) fuel rod oxidation models. A bounding assessment of the potential impact of the PRHR and the CMT systems modeling on the calculated PCT was obtained by eliminating those systems from the LBLOCA transient calculation. As noted on page 2-33 of WCAP-14171, the effect of these systems is minor. The blowdown phase PCT values for the WCOBRA/TRAC case in which these systems were eliminated each decreased by 3 °C (5 °F) from the base case blowdown PCT results. The reflood phase PCT results in the WCOBRA/TRAC case without PRHR and CMT systems modeled were the same as the base case reflood PCT results.

The AP600 LBLOCA 95 percent PCT values for blowdown and reflood were reported in Table 15.6.5-9 of the AP600 SSAR. The limiting PCT was that for the blowdown, at 913 °C (1676 °F). In the event that either the blowdown or reflood phase PCT exceeds 941 °C (1725 °F) in a future AP600 best estimate methodology LBLOCA analysis for any reason, the applicant shall perform the actions described below:

(a) Repeat the global model matrix of calculations and the final 95-percent uncertainty calculations.

(b) Address the sensitivity to the CMT and residual heat removal system (RHRS) modeling parameters that are not included in the AP600 uncertainty methodology. Repeat the study that identifies the PCT sensitivity to PRHR/CMT elimination, and add the blowdown and reflood PCT impacts as a bias to their respective 95-percent PCT results.

(c) Perform an analysis of the maximum local oxidation using the techniques approved for 3/4 loop plant applications to show compliance with the applicable 10 CFR 50.46 criteria. A transient with PCT in excess of the 95 percent PCT value identified in step (a) above, augmented by the biases identified in step (b) above, would be used for the oxidation analysis. The core-wide oxidation analysis would also be performed using the methods approved for use in three- or four-loop plant applications.

(d) The results of these calculations will be submitted for staff review before their implementation.

Table 21.A-1
Westinghouse AP600 LBLOCA PIRT with Comparisons to the
CSAU LBLOCA PIRT and Westinghouse's Three- and Four-Loop Plant LBLOCA PIRT
Note: B = Blowdown RF = Refueling RD = Reflood

	AP600 PIRT			Three- and Four-loop Plant PIRT			CSAU PIRT		
COMPONENT/PHENOMENA	B	RF	RD	B	RF	RD	B	RF	RD
FUEL ROD									
Stored Energy	9	5		9	5		9		
Oxidation			5			7			8
Decay Heat		5	8		5	8			8
Reactivity - Void	6			6					
Reactivity - Boron			5			5			
Gap Conductance	8			8					8
CORE									
DNB	8			8					
Post-CHF Heat Transfer	8	8		8	8		7	8	
Rewet	7	5		6	5		8	7	
Reflood Heat Transfer			7			9			9
Nucleate Boiling									
Single-Phase Vapor Natural Circulation									
3-D Flow	7		5	7		5			9
Void Generation /Distribution	7			7					9
Entrainment/Deentrainment			6			8			
Flow Reversal/Stagnation	8			8					
Radiation Heat Transfer									
Level			8			8			
UPPER HEAD									

Table 21.A-1
Westinghouse AP600 LBLOCA PIRT with Comparisons to the
CSAU LBLOCA PIRT and Westinghouse's Three- and Four-Loop Plant LBLOCA PIRT
Note: B = Blowdown RF = Refueling RD = Reflood

	AP600 PIRT			Three- and Four-loop Plant PIRT			CSAU PIRT		
COMPONENT/PHENOMENA	B	RF	RD	B	RF	RD	B	RF	RD
Initial Water Temperature	8			5					
Flow Path Area	8			5					
Blowdown Flow	8			5					
UPPER PLENUM									
Hot Assembly Location	7			7					
Entrainment/Deentrainment			6			6			9
Phase Separation			6			6			
CCFL/Fall-back									
Two-Phase Convection									
HOT LEG									
Entrainment/Deentrainment									9
Flow Reversal	5			5					
Void Distribution									
Two-Phase Convection									
PRESSURIZER									
Early Quench/Flow	5			5			7		
Critical Flow in Surge Line									
Flashing									
Automatic Depressurization System (ADS) Interaction	NA	NA	NA						

Table 21.A-1
Westinghouse AP600 LBLOCA PIRT with Comparisons to the
CSAU LBLOCA PIRT and Westinghouse's Three- and Four-Loop Plant LBLOCA PIRT
Note: B = Blowdown RF = Refueling RD = Reflood

	AP600 PIRT			Three- and Four-loop Plant PIRT			CSAU PIRT		
COMPONENT/PHENOMENA	B	RF	RD	B	RF	RD	B	RF	RD
STEAM GENERATOR									
Steam Binding			7			7			9
Delta-P, Form Losses									
Passive Residual Heat Removal									
PUMP									
Two-Phase Performance	5			5			9		
Delta-P, Form Losses	8	5	7	8	5	7			8
COLD LEG/ACCUMULATOR									
Condensation		NA			8	5		9	
Noncondensible Gases			5			5			9
Discharge		8	9		8	6			
Flow Asymmetries	6			5					
High-Pressure Injection Mixing									
CMT Mixing/Interaction	NA	NA	NA						
DOWNCOMER									
Entrainment/Deentrainment		8	6		8	7		8	
Condensation		8			8			9	
CCF, Slug, Nonequilibrium		8			8				
Hot Wall (Vessel/Barrel)			7			7		5	7
Hot Wall (Radial Reflector)			5						
Two-Phase Convection									

Table 21.A-1
Westinghouse AP600 LBLOCA PIRT with Comparisons to the
CSAU LBLOCA PIRT and Westinghouse's Three- and Four-Loop Plant LBLOCA PIRT
Note: B = Blowdown RF = Refueling RD = Reflood

	AP600 PIRT			Three- and Four-loop Plant PIRT			CSAU PIRT		
COMPONENT/PHENOMENA	B	RF	RD	B	RF	RD	B	RF	RD
Saturated Nucleate Boiling									
3-D Effects	5	8		5	8			9	
Flashing									
Liquid Level Oscillations			7			7			
DVI - Accumulator		8	7						
IRWST Mixing	NA	NA	NA						
CMT Mixing/Interaction	NA	NA	NA						
LOWER PLENUM									
Sweep-Out		6			6			7	
Hot Wall			7			7			
Multidimensional Effects									
BREAK									
Critical Flow	9	6		9	6		9	7	
Flashing									
Containment Pressure			6			8			
ADS Flow	NA	NA	NA						
LOOP									
Two-Phase Delta-P							7		
Oscillations								7	9
Flow Split	8	5		8	5			7	

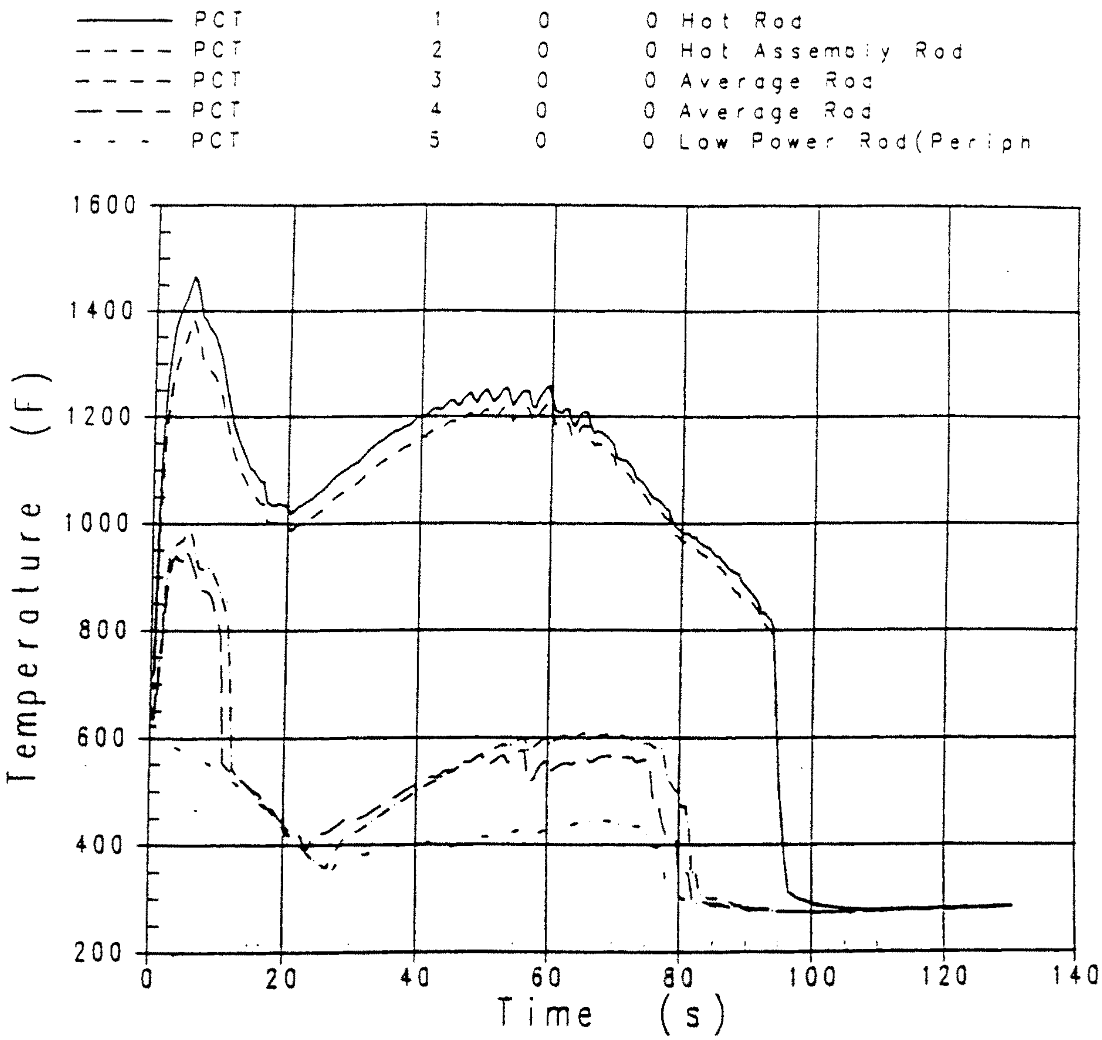


Figure 21.A-1
AP600 Peak Cladding Temperature Transient for the AP600 C_D = 0.8 DECLG Break

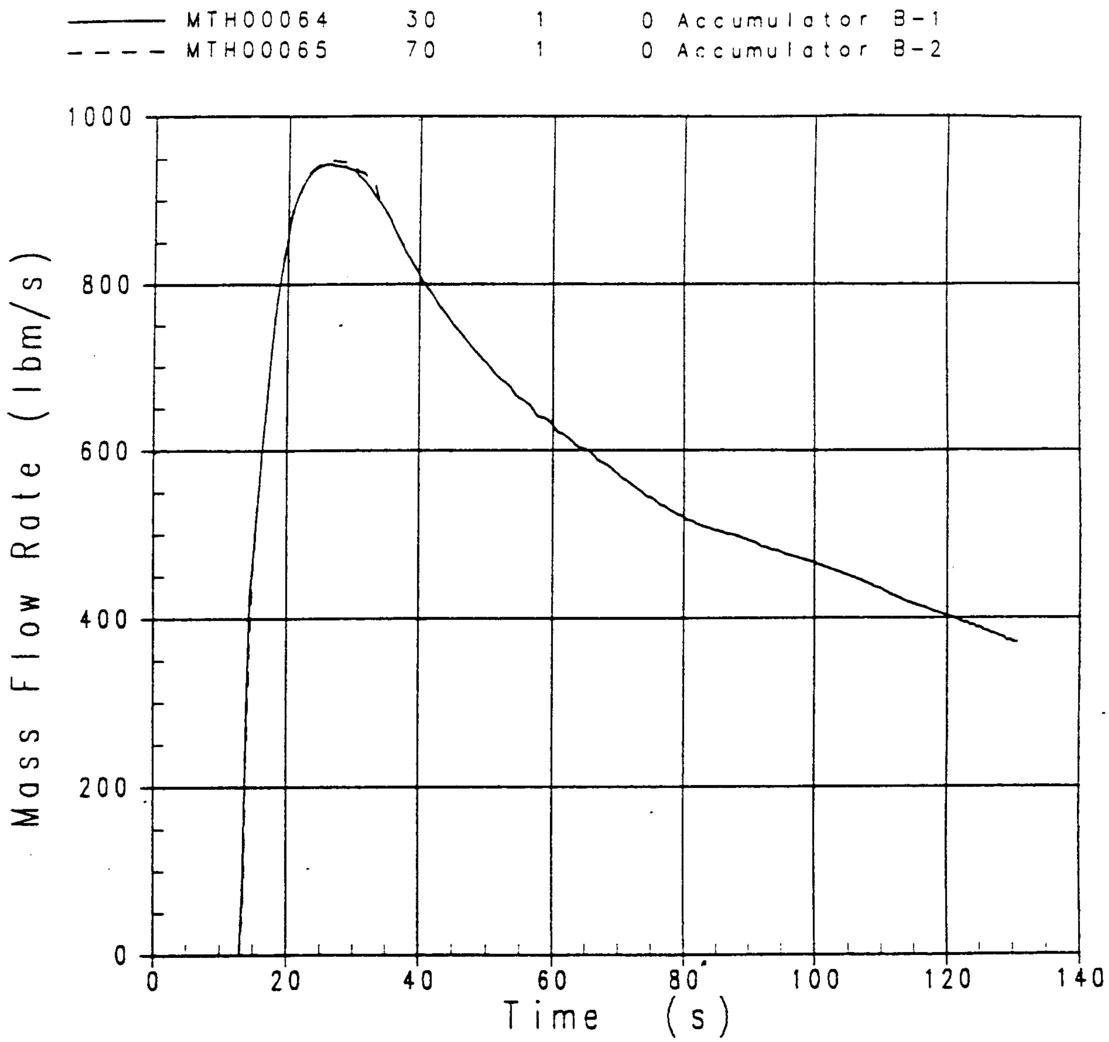


Figure 21.A-2
C_D = 0.8 DECLG Transient, Accumulator Flow Rate From One Tank

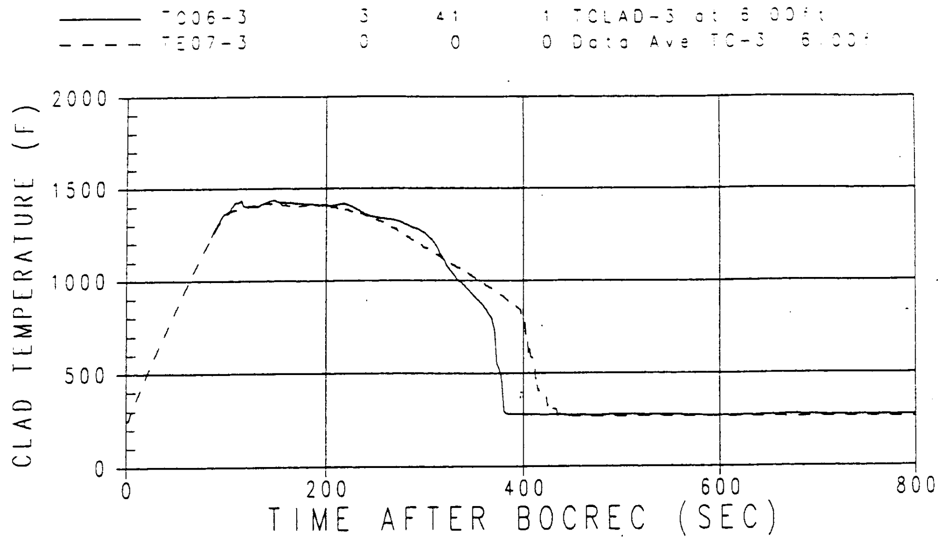


Figure 21.A-3
CCTF Run 58, Medium-Powered Rod, Clad Temperature Comparison at 6 ft

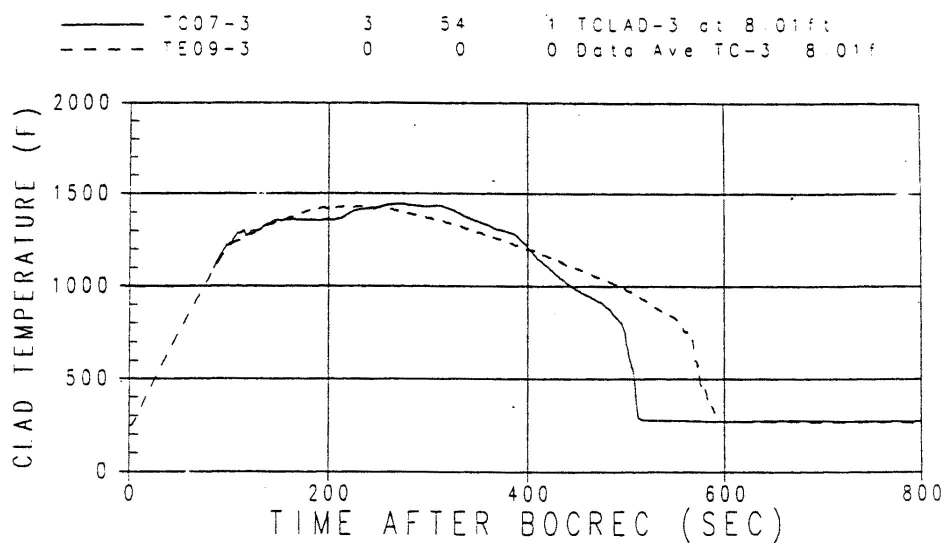


Figure 21.A-4
CCTF Run 58, Medium-Powered Rod, Clad Temperature Comparison at 8 ft

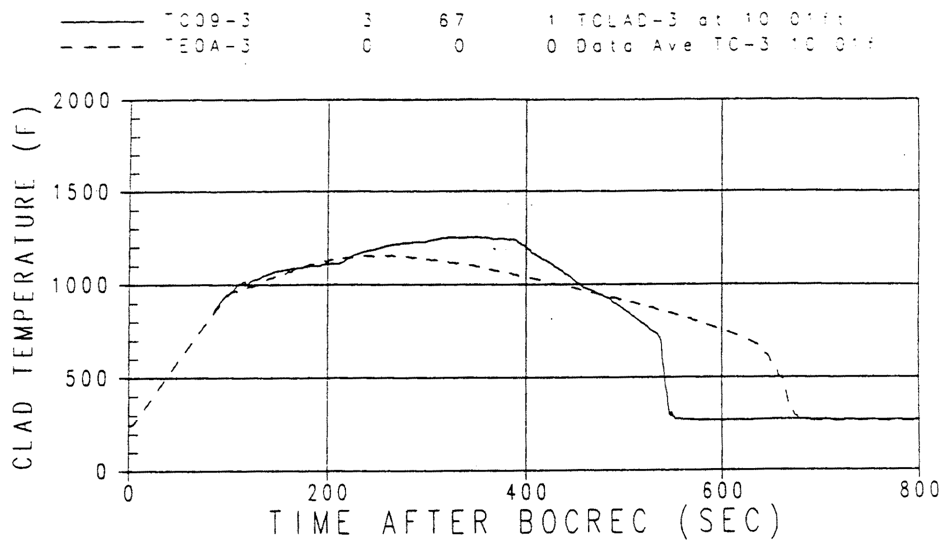


Figure 21.A-5
CCTF Run 58, Medium-Powered Rod, Clad Temperature Comparison at 10 ft

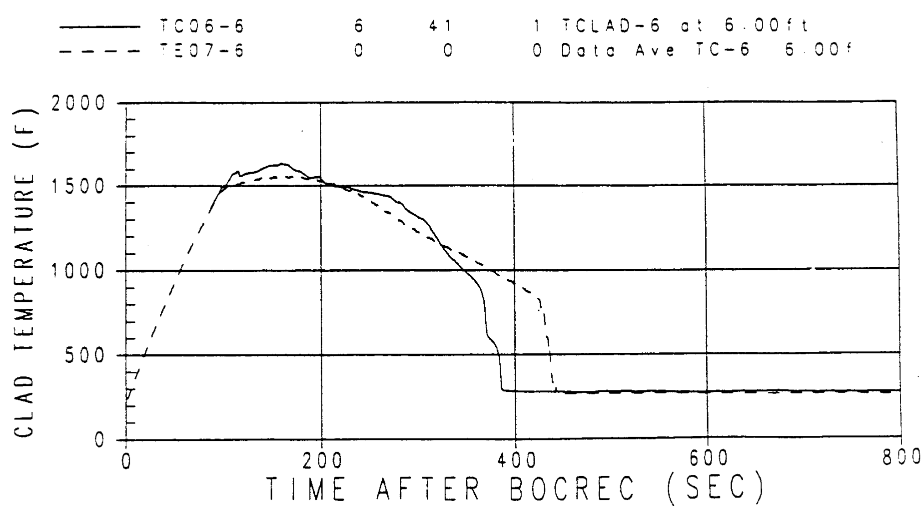


Figure 21.A-6
CCTF Run 58, High-Powered Rod, Clad Temperature Comparison at 6ft

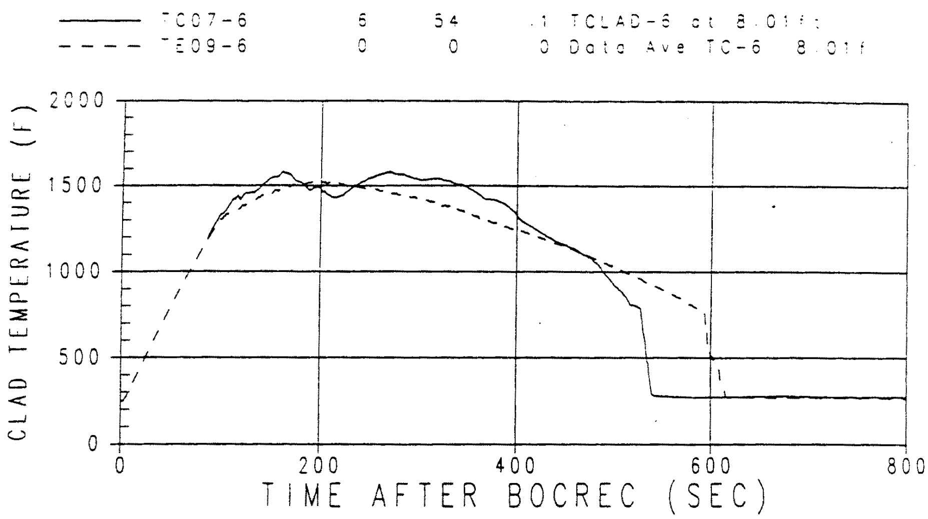


Figure 21.A-7
CCTF Run 58, High-Powered Rod, Clad Temperature Comparison at 8 ft

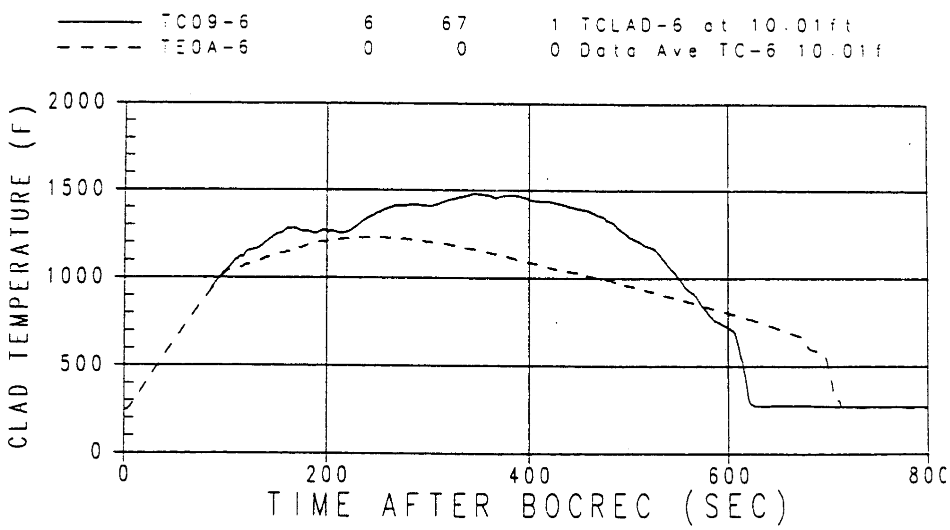


Figure 21.A-8
CCTF Run 58, High-Powered Rod, Clad Temperature Comparison at 10 ft

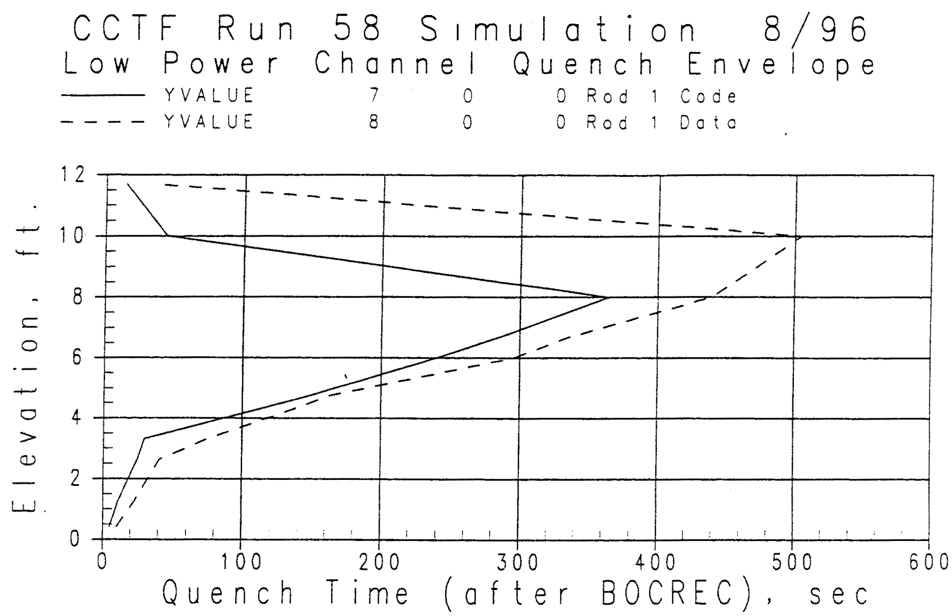


Figure 21.A-9
CCTF Run 58, Quench Envelope Comparison - Low-Powered Rod

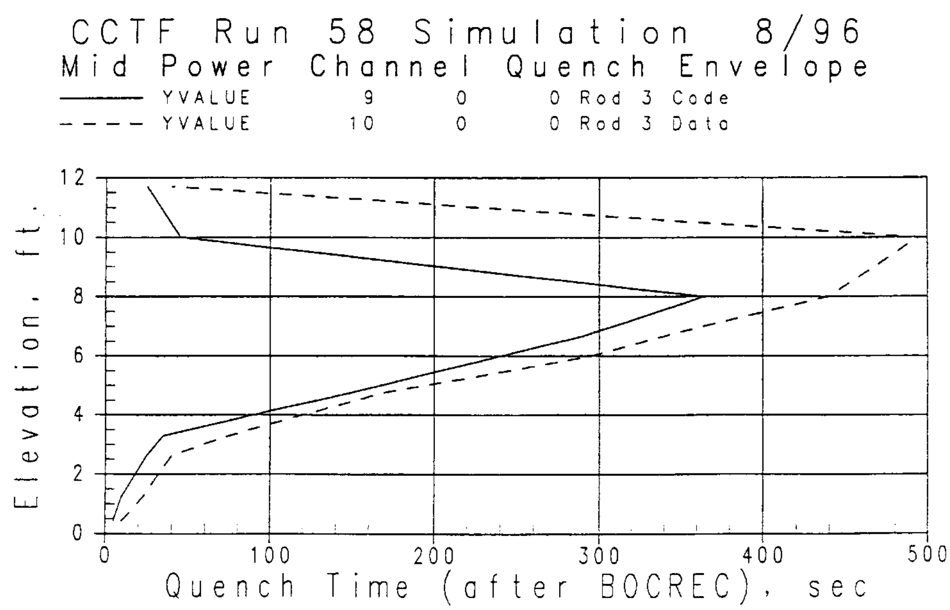


Figure 21.A-10
CCTF Run 58, Quench Envelope Comparison - Medium-Powered Rod

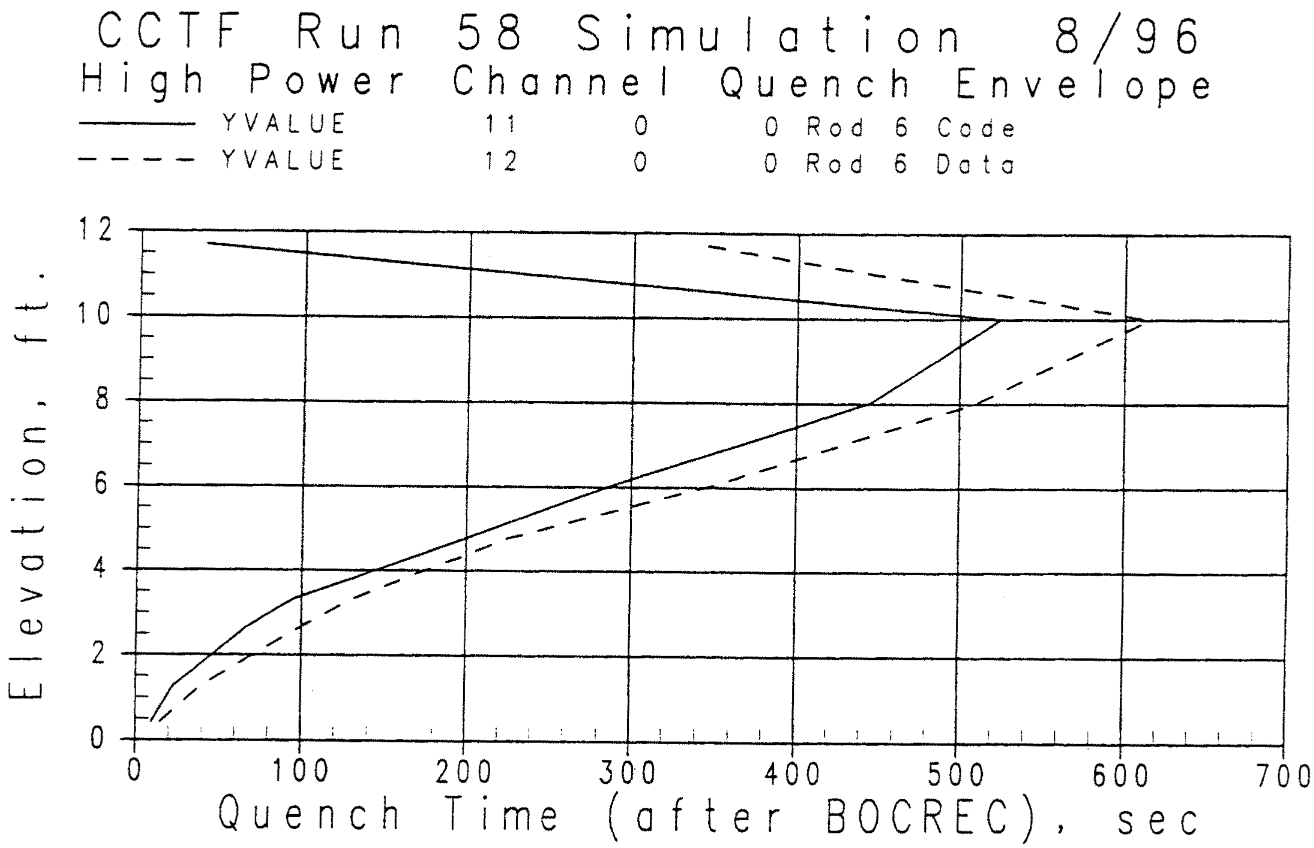
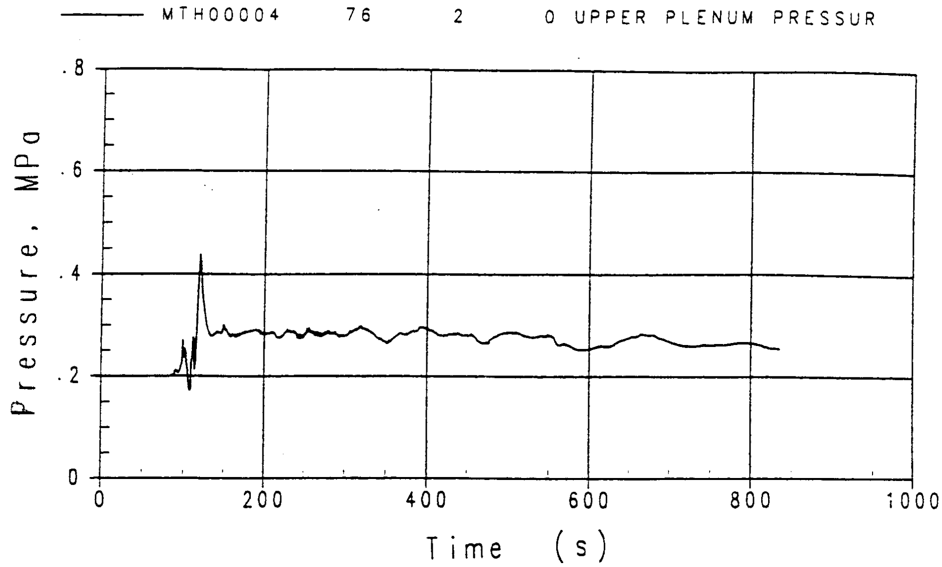


Figure 21.A-11
CCTF Run 58, Quench Envelope Comparison - High-Powered Rod



W COBRA/TRAC CCTF Run 58, Upper Plenum Pressure

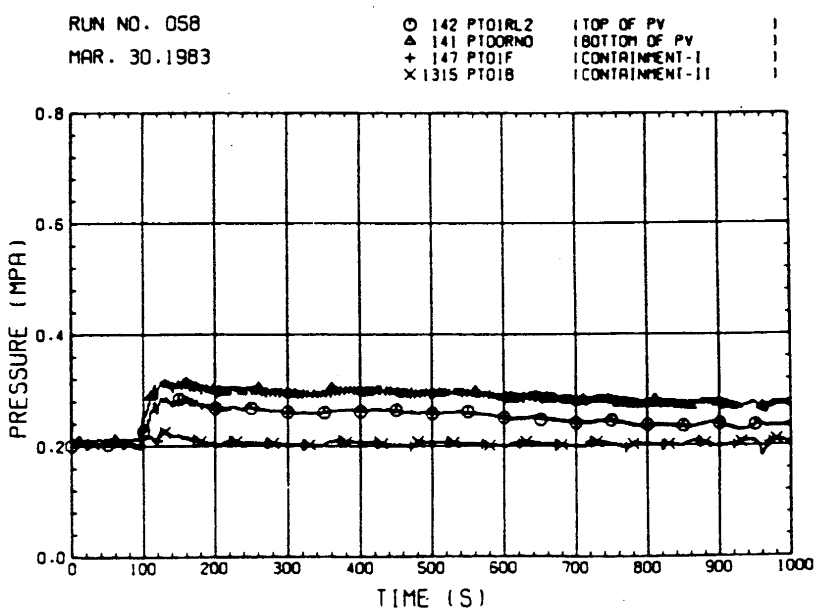
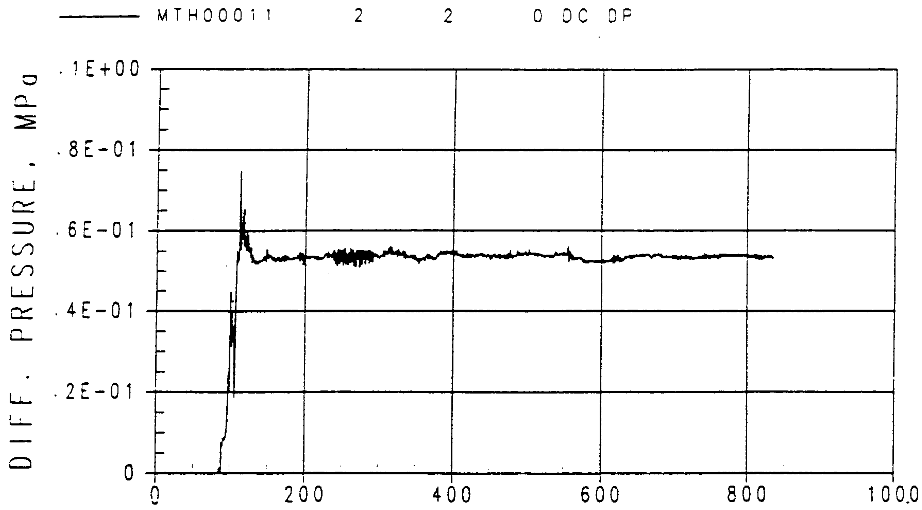


Figure C-292 from JAERI-memo 59-44b

Figure 21.A-12
CCTF Run 58, Upper Plenum Pressure Comparison



W COBRA/TRAC CCTF Run 58, Downcomer Differential Pressure

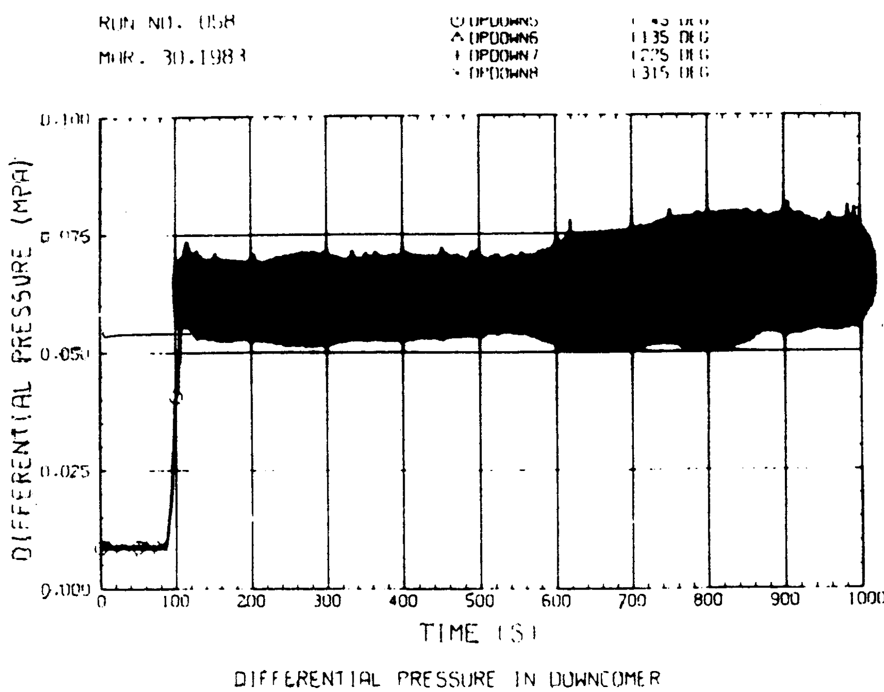
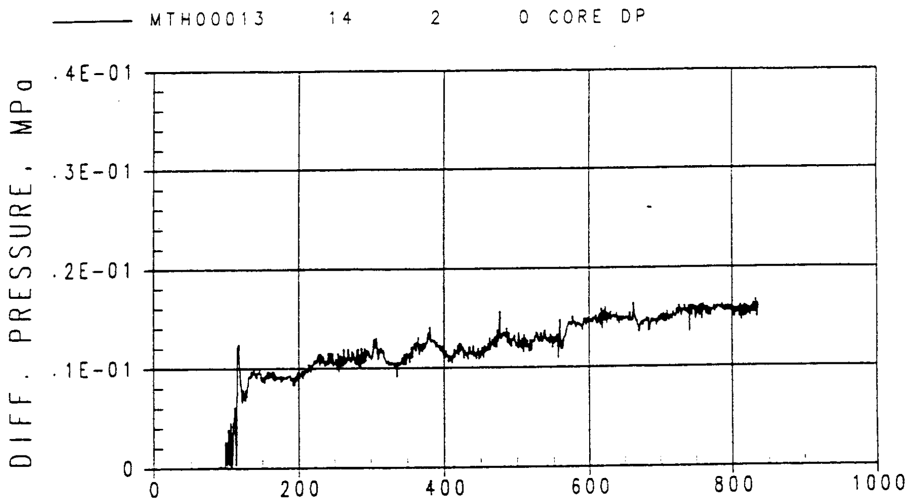
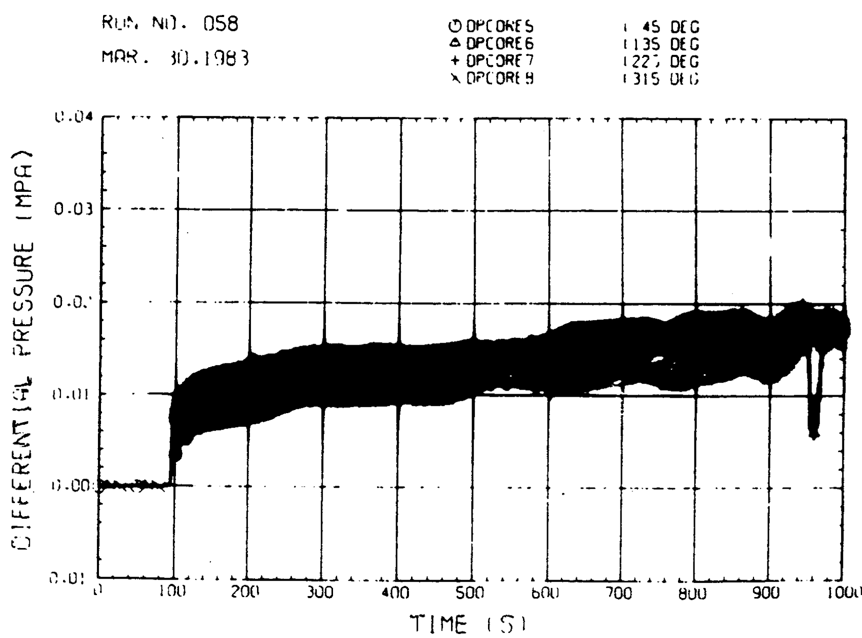


Figure D-33 from JAERI-memo 59-44b

Figure 21.A-13
CCTF Run 58, Downcomer Differential Pressure Comparison



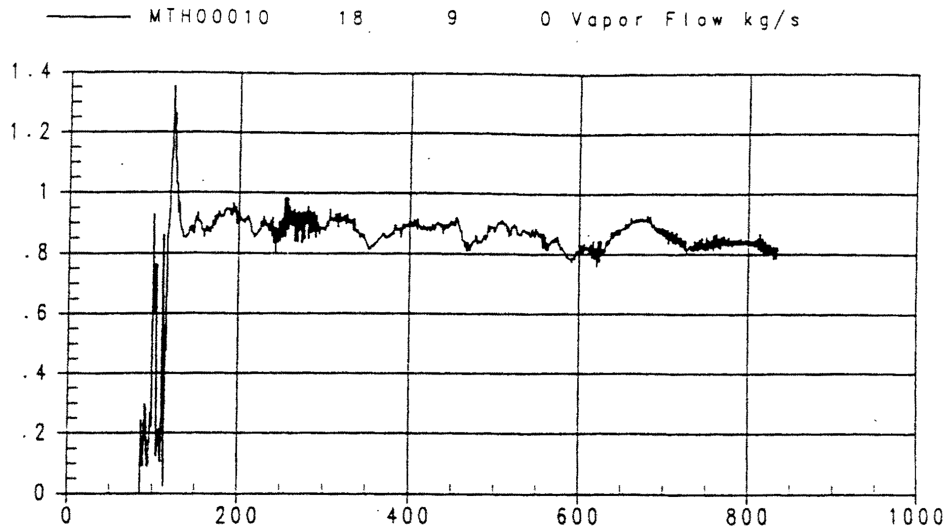
W COBRA/TRAC CCTF Run 58, Core Differential Pressure



DIFFERENTIAL PRESSURE IN CORE

Figure D-34 from JAERI-memo 59-44b

Figure 21.A-14
CCTF Run 58, Core Differential Pressure Comparison



W COBRA/TRAC CCTF Run 58, Loop 1 Cold Leg Steam Mass Flow

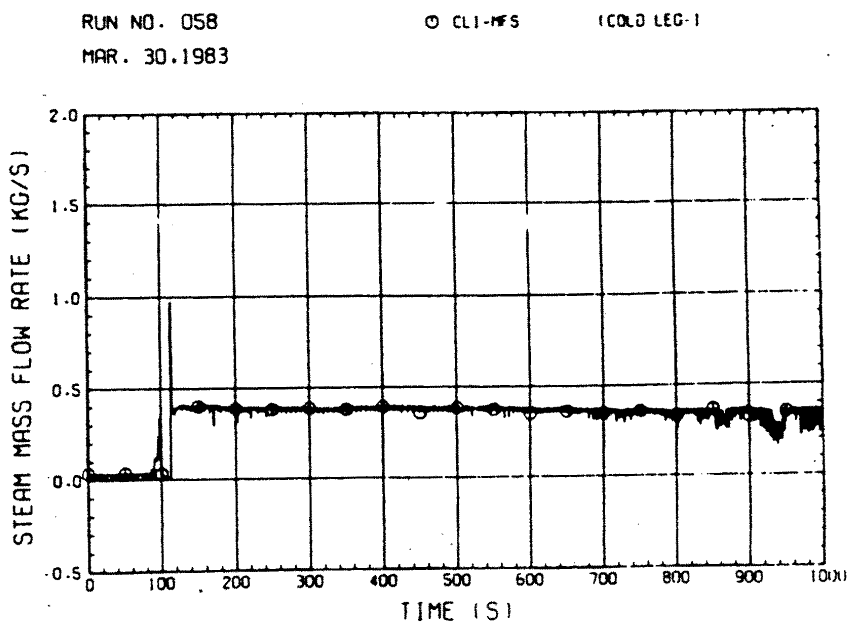
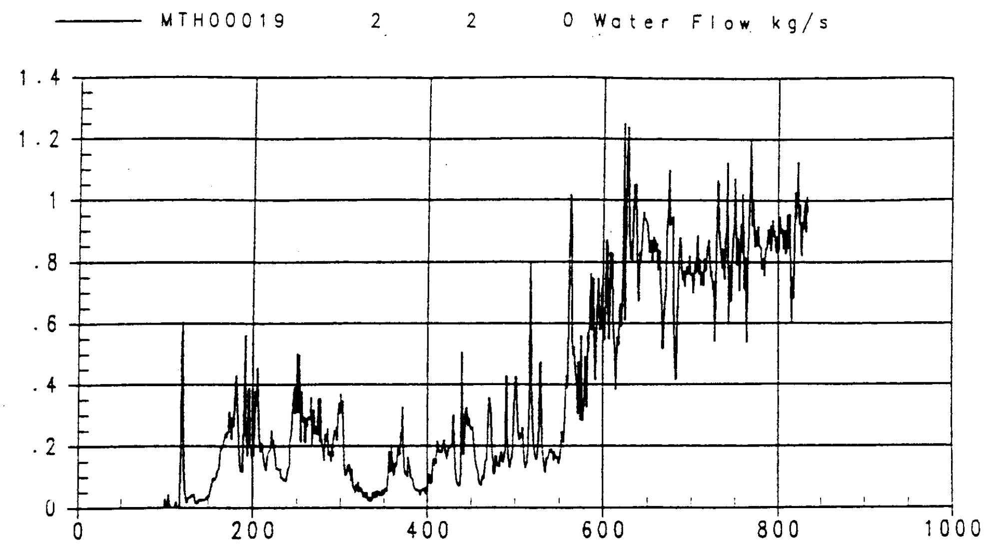


Figure E-172 from JAERI-memo 59-44b

Figure 21.A-15
CCTF Run 58, Loop 1 Cold Leg Steam Mass Flow Comparison



W COBRA/TRAC CCTF Run 58, Loop 1 Hot Leg Water Mass Flow

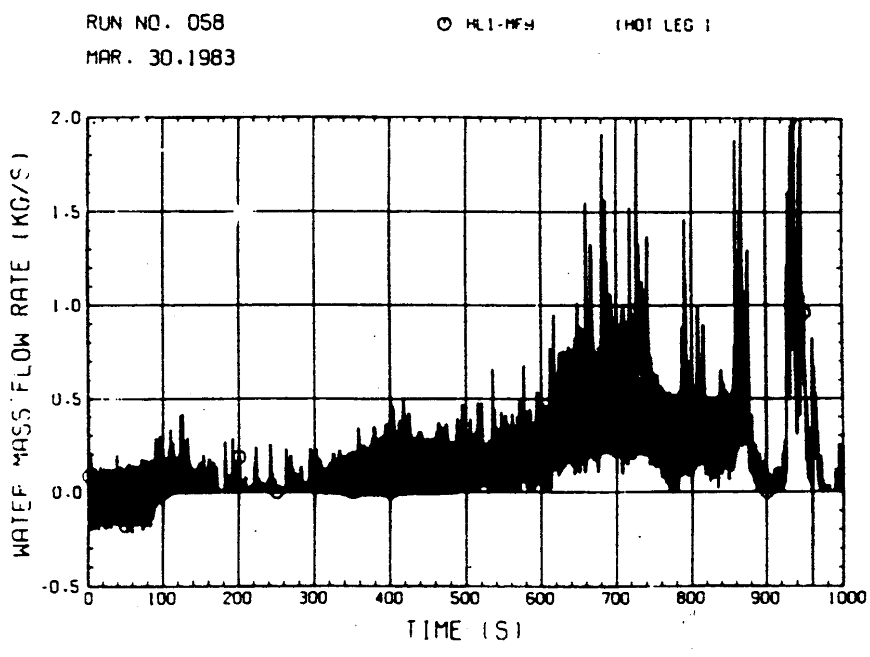
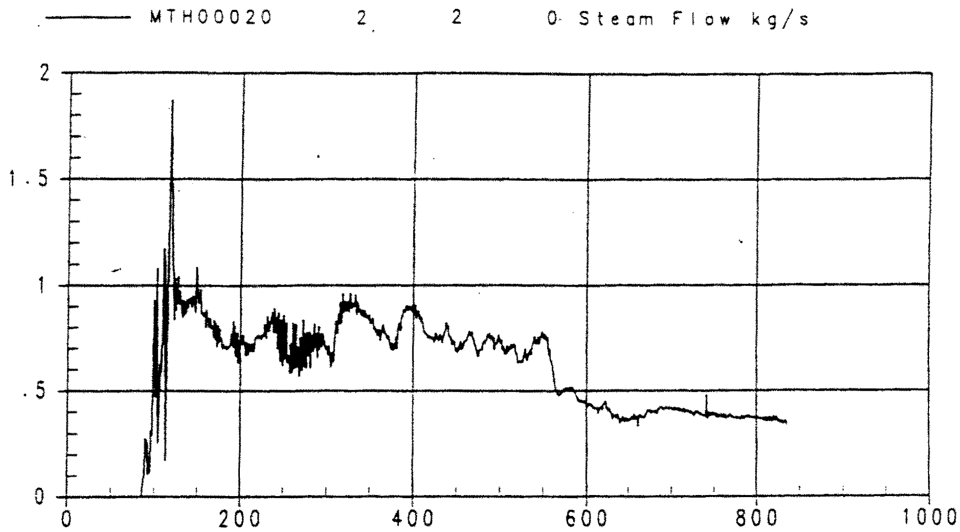


Figure E-161 from JAERI-memo 59-44b

Figure 21.A-16
CCTF Run 58, Loop 1 Hot Leg Water Mass Flow Comparison



W COBRA/TRAC CCTF Run 58, Loop 1 Hot Leg Steam Mass Flow

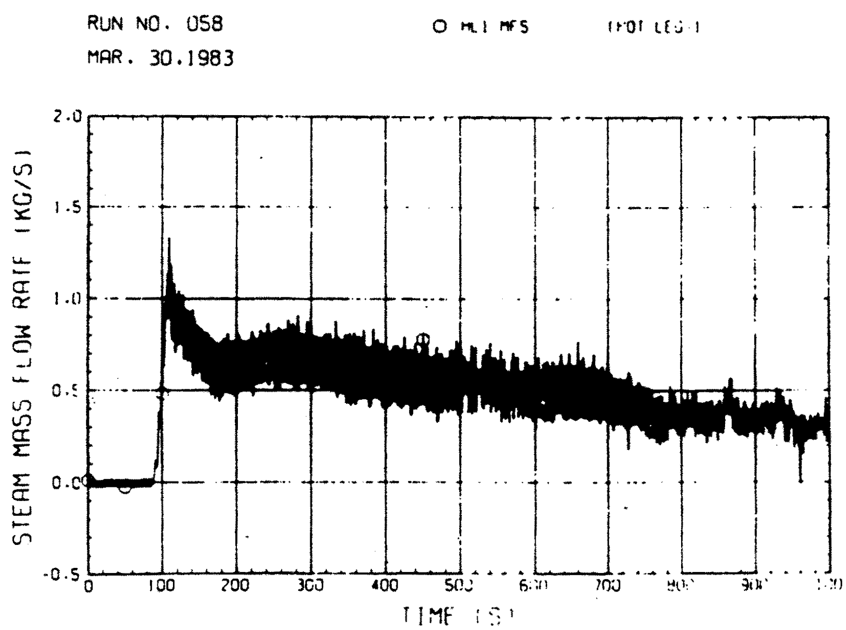
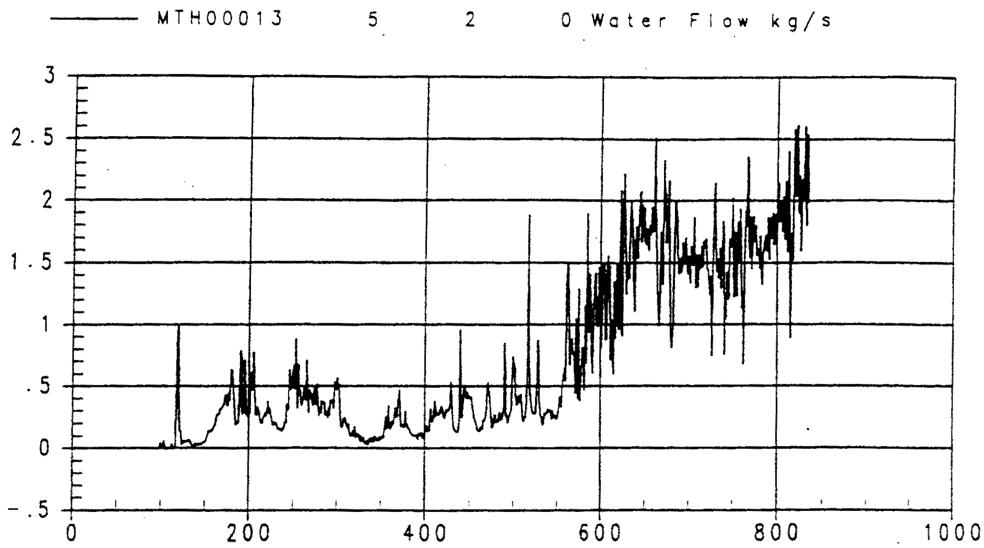


Figure E-160 from JAERI-memo 59-44b

Figure 21.A-17
CCTF Run 58, Loop 1 Hot Leg Steam Mass Flow Comparison



W COBRA/TRAC CCTF Run 58, Loop 4 Hot Leg Water Mass Flow

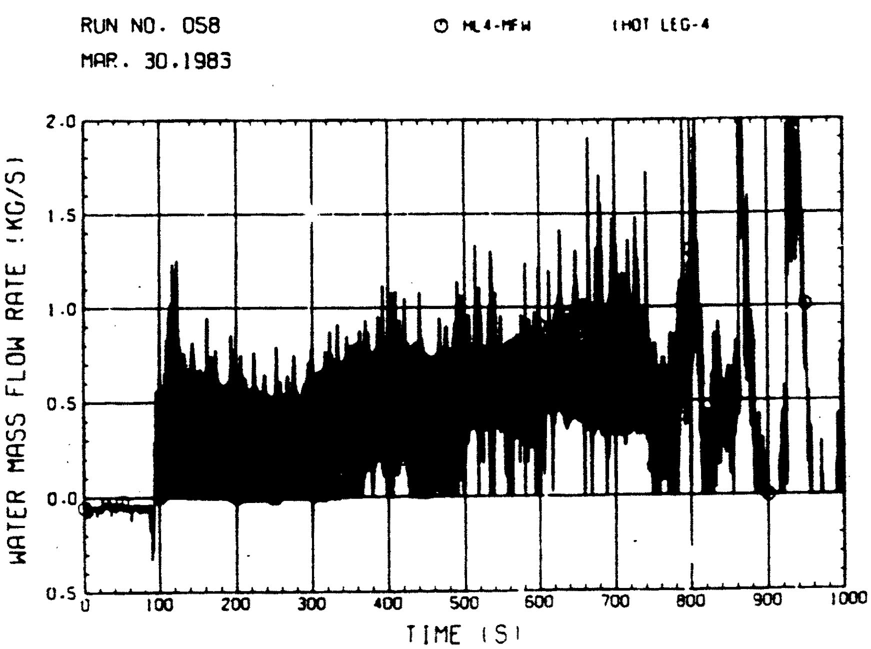
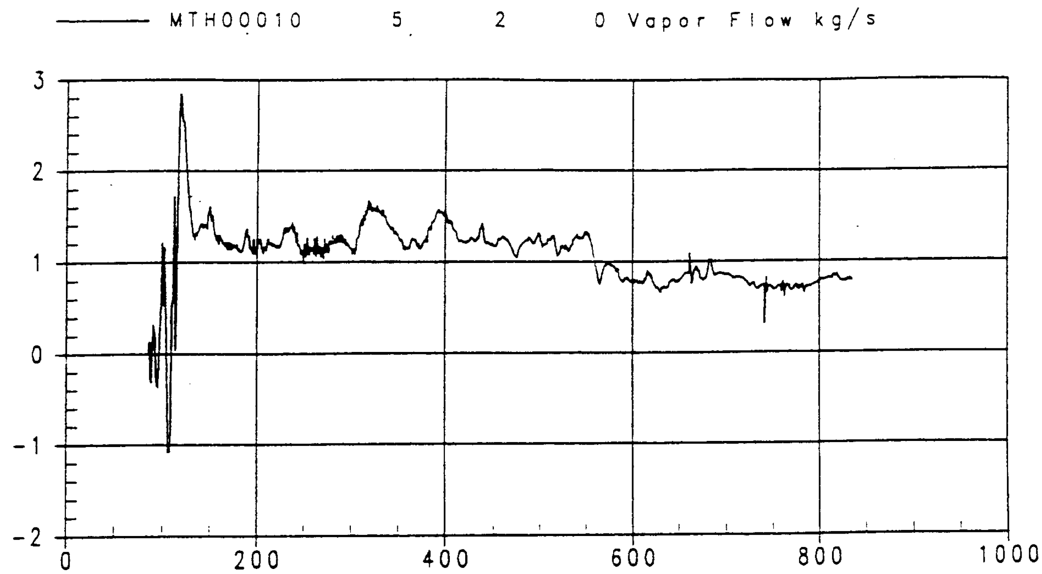


Figure E-170 from JAERI-memo 59-44b

Figure 21.A-18
CCTF Run 58, Loop 4 Hot Leg Water Mass Flow Comparison



W COBRA/TRAC CCTF Run 58, Loop 4 Hot Leg Steam Mass Flow

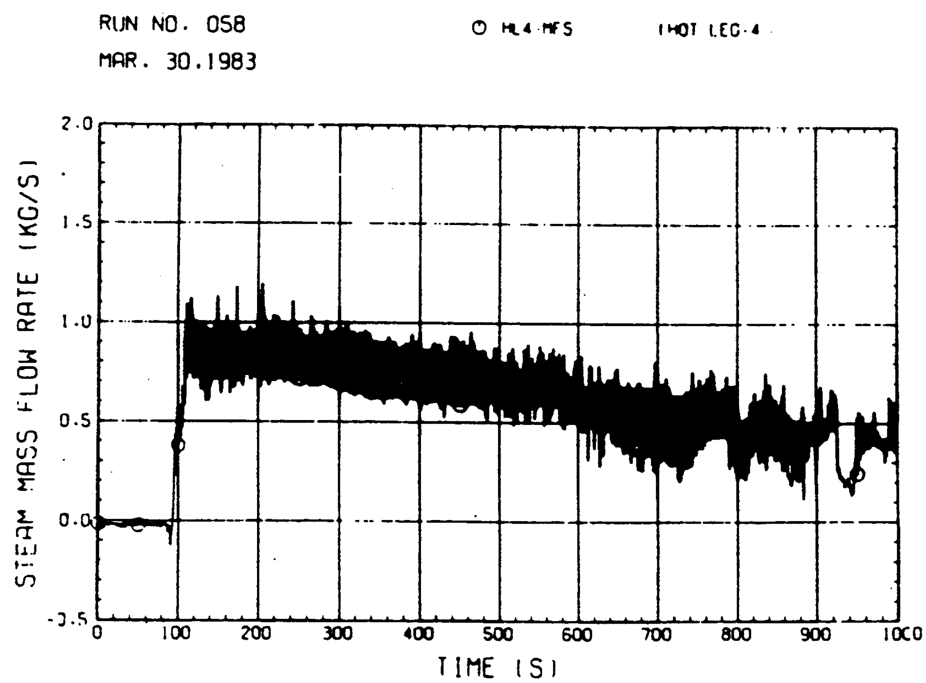


Figure E-169 from JAERI-memo 59-44b

Figure 21.A-19
CCTF Run 58, Loop 4 Hot Leg Steam Mass Flow Comparison

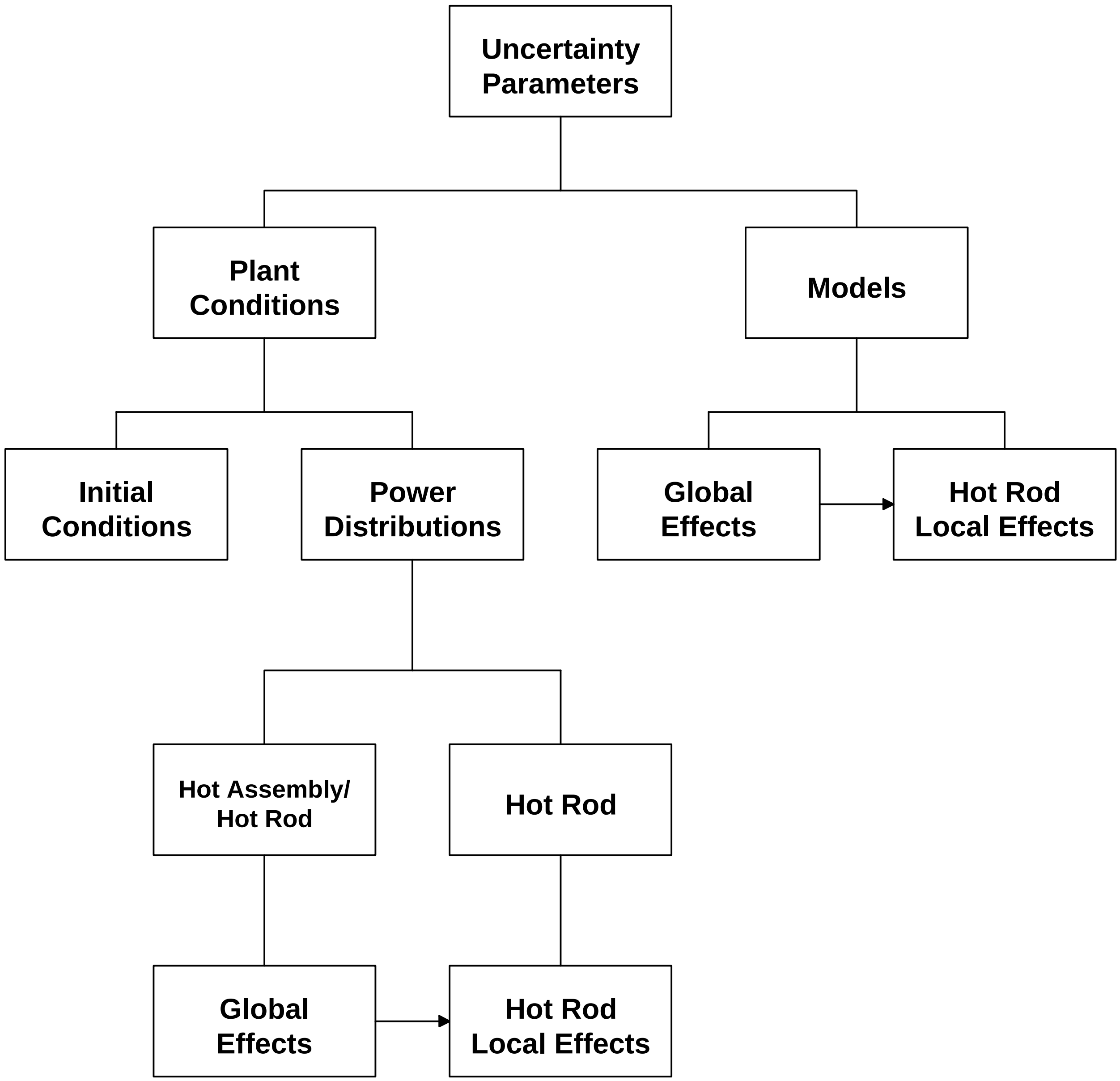


Figure 21.A-20
Breakdown of Westinghouse's Uncertainty Parameters

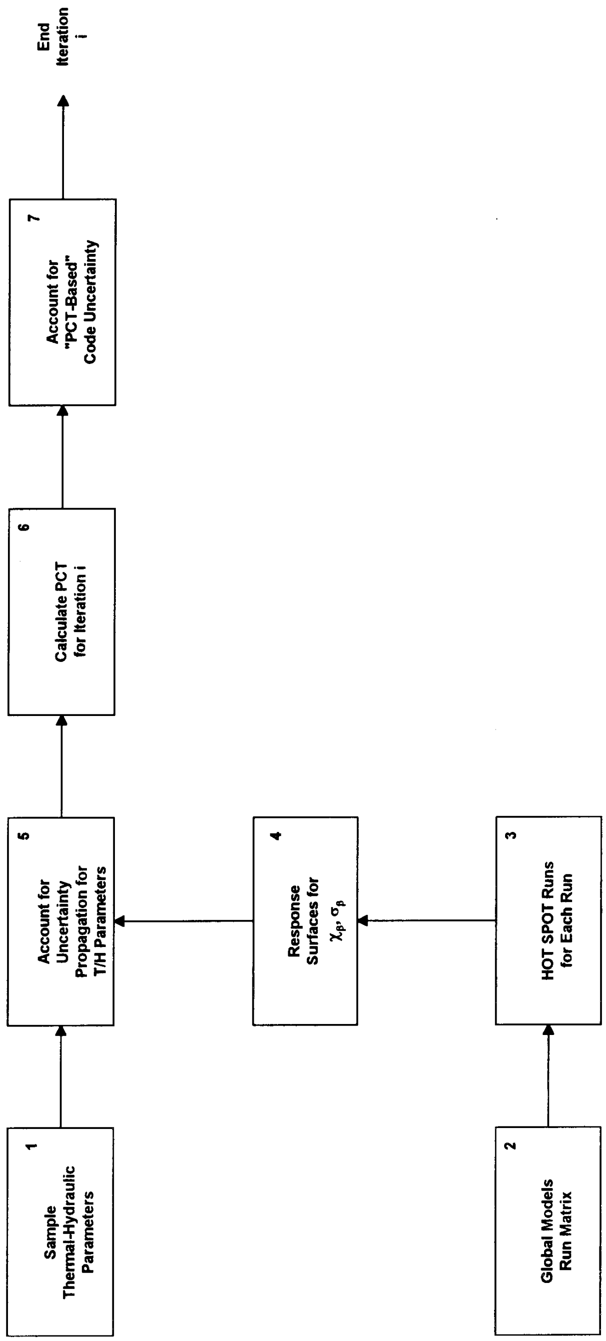


Figure 21.A-21
Flow Chart of Monte Carlo Procedure (AP600)

Appendix 21.B Safety Evaluation of AP600 Quality Assurance Inspections

21.B Quality Assurance Inspections

The staff reviewed Westinghouse's design requirements for the AP600 design, as described below.

21.B.1 QA Requirements for AP600 Design Certification Testing Activities

In Chapter 17 of the AP600 SSAR, Westinghouse described its QA program for the design phase of the AP600 ALWR Plant Program.

In Revision 5 to SSAR Chapter 17, Westinghouse stated that effective March 31, 1996, activities affecting the quality of items and services for the AP600 Project during design, procurement, fabrication, inspection, and/or testing would be performed in accordance with the quality plan described in Westinghouse's "Energy Systems Business Unit - Quality Management System," (QMS) Revision 1. The staff's review and approval of Revision 1 to the Westinghouse QMS was documented in a letter from Suzanne Black (NRC) to N. J. Liparulo (Westinghouse), dated February 23, 1996.

Activities performed before March 31, 1996, were performed in accordance with the QA plan described in Westinghouse topical report WCAP-8370, "Energy System Business Unit - Power Generation Business Unit, Quality Assurance Plan," Revision 12a, dated April 1992. Also, activities performed before November 30, 1992, were performed in accordance with the QA plan described in topical report WCAP-8370/7800, "Energy Systems Business Unit - Nuclear Fuel Business Unit, Quality Assurance Plan," Revision 11A/7A. Both versions of WCAP-8370 applied to all Westinghouse activities affecting the quality of items and services supplied to nuclear power plants and established Westinghouse's compliance with the provisions of Appendix B to 10 CFR Part 50.

WCAP-12600, "AP600 Quality Assurance Program Plan," dated January 1997, a project-specific QA plan, was developed by Westinghouse to enhance the QMS in specific areas and to establish additional commitments needed to support the AP600 Design Certification and First-Of-A-Kind (FOAKE) program. WCAP-12600 established the responsibility of the Nuclear Projects Division of the Energy Systems Business Unit for AP600 Design Certification and FOAKE programs and for control of the technical interface between Westinghouse and engineering groups and suppliers providing engineering services under these programs. WCAP-12600 also addressed Westinghouse's commitments to the provisions of ANSI/ASME NQA-1-1989 Edition through NQA-1b-1991 Addenda for the AP600 project.

Westinghouse also developed WCAP-12601 ("AP600 Program Operating Procedures") to establish requirements and responsibilities for developing, approving, implementing, revising, and maintaining operating procedures to meet the QA and administrative requirements of the AP600 program.

Overall, the staff conducted in-depth inspections of the five principal Westinghouse AP600 design certification test programs. The programs were inspected to determine if design and testing activities performed to support design certification of the AP600 advanced reactor were conducted under the appropriate provisions of WCAP-12600.

21.B.1.1 Core Makeup Tank Test Program

The staff conducted a QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01). During the inspection, the team assessed the Westinghouse implementation of the applicable QA criteria essential to support the AP600 design certification application, including design certification testing. Specifically, the team evaluated the effectiveness of the QA program and controls in governing the implementation of the AP600 CMT design certification testing programs.

For testing activities performed by the Westinghouse Test Engineering Group at the Waltz Mill facility, including the CMT test program, Westinghouse developed a specific QA plan or project quality plan (PQP) to implement the applicable provisions of WCAP-12601. This PQP established QA controls for the conduct of testing activities and encompassed design, construction, and configuration control criteria for the CMT test program.

The inspection team reviewed the PQP and the CMT test program specification to determine if design certification testing activities performed at the Waltz Mill facility were conducted in accordance with the appropriate provisions of Westinghouse's 10 CFR Part 50, Appendix B, QA program (WCAP-8370). Specifically, the inspection team examined the areas of performance and activities within the scope of the PQP, such as organizational responsibilities of the testing group to confirm that activities in the pertinent areas were performed under suitably controlled conditions by properly trained personnel, and the test data collected during such activities were appropriately recorded and maintained.

The inspection team found that Westinghouse, in general, was adequately implementing the AP600 QA program plan with one exception. Westinghouse had conducted one inadequate audit at Alden Research Laboratory, Inc. (Alden Research). On October 20, 1994, the Energy System Business Unit (ESBU) Projects QA organization had established the acceptability of calibration services provided by Alden Research for AP600 design certification activities on the basis of an audit conducted on March 4, 1992. The audit, however, had not given adequate objective evidence that Alden Research was a supplier of calibration services as a "basic component" (as defined in 10 CFR Part 21), nor had it demonstrated the acceptability of Alden Research's technical and quality program capabilities with respect to the requirements in 10 CFR Part 21. This was identified as Nonconformance 99900404/95-01-03.

In letter NTD-NRC-95-4549 (September 12, 1995), Westinghouse responded to Nonconformance 99900404/95-01-03. Westinghouse stated that Alden Research had been audited on May 25, 1995, and that although Alden Research's QA program needed improvement in several areas of its implementation, nothing had been found that would affect the calibrations performed on instrumentation for the AP600 design certification testing program. The staff found Westinghouse's reply responsive to the inspection finding and, in a letter dated December 5, 1995, told Westinghouse of its conclusion and stated that it would confirm during a future inspection the implementation of the proposed corrective and preventive actions related to the nonconformance to establish that full compliance had been achieved and maintained. This was identified as Confirmatory Item 21.B.1.1-1.

During an inspection (NRC Inspection Report 99900404/97-02) on November 17 through 21, 1997, the NRC verified that these actions had been completed and documented. On the basis of the limited scope of calibration services as a Basic Component performed by Alden Research, and regarding Westinghouse's conclusions that no audit findings identified impacted the calibration activities performed to support AP600 testing, the inspection team agreed that corrective actions taken by Westinghouse were appropriate. On these bases, Confirmatory Item 21.B.1.1-1 was closed.

21.B.1.2 Automatic Depressurization System Test Program

The staff conducted a QA implementation inspection at the Ente per le Nuove Tecnologie, L'Energia e L'Ambiente's (ENEA's) Valve and Pressurizer Operating Related Experiments (VAPORE) test facility in Cassacia, Italy, during the week of July 24, 1995 (NRC Inspection Report 99900404/95-02). ENEA implemented the pertinent provisions of WCAP-8370 at the VAPORE facility through its use of ENEA document AP600-GQ9402 ("Quality Assurance Plan Description: AP600 Test Program Conducted at the VAPORE Plant in ENEA Cassacia (Phase B)").

Under a technical cooperation agreement, Westinghouse, ENEA, and Ansaldo S.p.A. combined resources to conduct testing at the ENEA's VAPORE test facility with two major objectives (1) advance knowledge and understanding of passive safety system operations and (2) conduct testing of the AP600 ADS to provide both design information and data for computer code validation efforts needed to support AP600 design certification.

The VAPORE test specification required that testing designed to demonstrate overall ADS performance verification be conducted under a QA program that conformed to ASME standard NQA-1, "Quality Assurance Program Requirements for Nuclear Facilities," 1989 Edition through NQA-1-1991 Addenda.

During the inspection, the team reviewed the pertinent documents to determine if design certification testing activities performed at the ENEA VAPORE test facility during the ADS test program were conducted in accordance with the appropriate provisions of Westinghouse's 10 CFR Part 50, Appendix B, QA program (WCAP-8370). The team examined the performance of activities in specific areas within the scope of ENEA document AP600-GQ9402 (e.g., test control, test instrument calibration, facility and records configuration control) to confirm that activities in these areas were performed under suitably controlled conditions by properly trained personnel and that the test data collected during such activities were appropriately recorded and maintained.

On the basis of its review of these areas, the team concluded that the QA program described in AP600-GQ9402, in conjunction with Westinghouse's implementation of the pertinent criteria of WCAP-12601, gave sufficient evidence of overall QA program implementation appropriate to design certification testing, except for one finding and one unresolved item. These were identified as Nonconformance 99900404/95-02-01 and Unresolved Item 99900404/95-02-02, respectively.

Nonconformance 99900404/95-02-01

The team found that test facility as-built drawings, as required by the test specification and by ENEA document AP600-GQ9402, had not been prepared for the AP600 ADS Phase B testing at VAPORE.

In letter NTD-NRC-95-4591 (November 9, 1995), Westinghouse responded to Nonconformance 99900404/95-02-01. Westinghouse stated that an audit of ENEA conducted in June 1995 had also uncovered an issue concerning the as-built configuration documentation of the VAPORE test facility. Ansaldo had been hired to modify the facility for AP600 testing and was responsible for preparing the appropriate documentation.

A Westinghouse review of all documentation at Ansaldo offices in Genoa, Italy in July 1995 revealed that Ansaldo had used a combination of shop drawings and field measurements to create the as-built documentation. After assessing the elements used to define the as-built configuration of the ADS test facility as well as the supporting documentation on the procurement and fabrication of the piping sections, Westinghouse concluded that the as-built documentation was in compliance with AP600 project and QA requirements. The staff reviewed Westinghouse's response and found it responsive to the concern raised in the nonconformance. In a letter dated December 5, 1995, the staff notified Westinghouse of its finding and stated that the implementation of proposed corrective and preventive actions related to the nonconformance would be reviewed during a future inspection to establish that full compliance had been achieved and maintained. This was identified as Confirmatory Item 21.B.1.2-1.

During an inspection (NRC Inspection Report 99900404/97-02) on November 17 through 21, 1997, the NRC reviewed a summary of Westinghouse's assessment activities at Ansaldo and concluded that appropriate actions were taken to resolve this nonconformance. Accordingly, Confirmatory Item 21.B.1.2-1 was closed.

Unresolved Item 99900404/95-02-02

The team found that the ENEA QA program did not have adequate measures to effectively control the calibration status of reference instruments or standards. No provisions were in place to require their recalibration at the requisite intervals. The test specification required that the following measures be included in the detailed test procedure(s): (1) provisions for ensuring that calibration of test equipment is traceable to recognized national standards and (2) verification and documentation, to be submitted to Westinghouse, by the testing organization that the facility instruments were calibrated before testing. The ENEA QAPD document, AP600-GQ9402, provided procedures for implementing these requirements.

During the inspection, the team confirmed that all test instruments used in the ENEA VAPORE test facility had been calibrated, both before and after testing, using standards or reference instruments traceable to the Servizio Italiano di Taratura (SIT) (Italian calibration system). Also, the team reviewed the calibration records of the VAPORE test facility which provided evidence of traceability to the appropriate ENEA-controlled SIT-certified standards. This review also gave evidence of the adequacy of the calibration status of facility instrumentation during each testing phase. The team found, however, that the ENEA QA program did not contain adequate measures to effectively control the calibration status of reference instruments or standards used for instrument calibration, as no provisions were in place to require recalibration by SIT at the requisite intervals. Pending confirmation by Westinghouse that this lapse in the SIT-certified calibration interval for the ENEA reference instruments and standards did not undermine or adversely impact the VAPORE ADS test results, this issue would remained unresolved.

In letter NTD-NRC-95-4591 (November 9, 1995) Westinghouse responded to Unresolved Item 99900404/95-02-02. Westinghouse stated that ENEA had submitted seven instruments involved in AP600 test instrument calibrations to a nationally certified laboratory. Westinghouse added that as of October 1995, five of the instruments were within expected tolerances. The remaining two instruments were to be tested by the end of November 1995. The staff found Westinghouse's reply responsive to the concern raised in the unresolved item. In a letter dated December 5, 1995, the staff notified Westinghouse that the implementation of proposed corrective actions related to the unresolved item would be reviewed during a future inspection to establish their acceptability. This was identified as Confirmatory Item 21.B.1.2-2.

During an inspection (NRC Inspection Report 99900404/97-02) on November 17 through 21, 1997, the NRC verified that ENEA submitted the seven instruments involved in AP600 test instrument calibration to a nationally certified calibration laboratory in Italy (ERG/ING/PITER Division). Test results confirmed that VAPORE ADS test results had not been adversely impacted. Accordingly, Confirmatory Item 21.B.1.2-2 was closed.

21.B.1.3 Passive Residual Heat Removal Heat Exchanger Test Program

When Westinghouse conducted this test program, a configuration of straight vertical tubes represented the in-plant configuration of the PRHR HX. However, Westinghouse modified the PRHR HX design to a vertical C-shaped tube bundle. The staff asked Westinghouse to justify in detail the applicability of the straight tube PRHR HX test data to the new C-tube configuration. This was identified as Open Item 21.3.3-1 in the DSER.

While conducting a QA implementation inspection of the CMT and passive containment cooling system (PCCS) LST test programs at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01), the staff reviewed the PRHR test program design files. Although Westinghouse did not seem to have conducted formal design reviews, all meetings, discussions, and other communications relevant to the test program had been documented in memoranda at the initiative of the responsible test engineer. As a result, a record of decisions concerning facility design and operation for this test program exists.

The team questioned the apparent lack of as-built drawings or identification of critical dimensional attributes for the PRHR test program. In discussions with the test engineer who was responsible for the program and the manager of test engineering, the team learned that there were only three critical attributes for this relatively small-scale, separate-effects test, i.e., the length, diameter, and thickness of each of the three tubes used to simulate the operation of the PRHR HX. These "critical dimensions" were measured and documented in the final test report for the program. Although these critical dimensions were not formally identified as such, the team concluded that the PRHR test report would contain sufficient information for the staff to issue its finding on the technical acceptability of the program.

The staff completed its review of the PRHR HX test program, and has concluded that HX heat transfer models using the 3-tube test data were applicable to the C-tube design in the AP600. Discussion of data applicability and the details of the staff's review of this program can be found in Sections 21.3.3 and 21.5.3, of the staff's safety evaluation report for the AP1000 design respectively.

21.B.1.4 OSU/APEX Test Program

The staff conducted an inspection at the Oregon State University (OSU) Advanced Plant Experiment (APEX) test facility in Corvallis, Oregon, during the week of August 29, 1994 (NRC Inspection Report 99900404/94-01). Specific quality provisions applicable to the OSU facility were identified in AP600 Document Number LTCT-GAH-001 ("AP600 Long Term Cooling Test Project Quality Plan") (PQP). This plan established controls for the design and construction of the test facility as well as for the conduct of testing activities.

The inspection indicated that Westinghouse, in general, was adequately implementing the AP600 project QA program at OSU, except for a few findings in certain areas. Specifically, the team identified findings with program implementation with respect to (1) the calibration of instrumentation, and (2) the accuracy of the facility as-built drawings. These issues were identified in Nonconformances 99900404/94-01-01 and 99900404/94-01-02. Also, a concern about OSU's acceptance of test results that failed to meet established test acceptance criteria, without an evaluation and disposition being included in the test design record file, was identified as part of Unresolved Item 99900404/94-01-03.

Nonconformance 99900404/94-01-01

The team found that contrary to the provisions of the PQP, The Industrial Company (TIC) which calibrated thermocouples at the OSU/APEX test facility, had hired Industrial Instruments, Inc. to calibrate the primary standards and had accepted the calibration certificates without having performed audits or a surveillance of that company. Also, OSU had failed to verify the validity of the flowmeter calibration certificates received from Foxboro Company, an unaudited commercial supplier.

In letter NTD-NRC-95-4408, dated February 15, 1995, Westinghouse responded to Nonconformance 99900404/94-01-01. Westinghouse stated that a review, performed to identify suppliers of calibration services to the OSU test facility, revealed six suppliers for which

QA oversight was needed to support test instrument calibration certifications. Because four of these suppliers were not on the Westinghouse qualified suppliers list (QSL), they were audited. Westinghouse added that these audits revealed no conditions that would invalidate the calibrations performed on any OSU test facility instruments. After the audit, Westinghouse sent all devices used to perform the post-calibration checks to a qualified supplier of calibration services for calibration. To prevent future problems, Westinghouse revised the OSU PQP to describe the requirements for procurement of calibration services and calibration of commercially procured test instrumentation and calibration equipment.

During a subsequent QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01), the team reviewed the Westinghouse audit reports of the four suppliers of calibration services not on Westinghouse's QSL to confirm that the supplier's QA programs were suitable to ensure reliable instrument calibration. In general, the reports demonstrated that calibration services supplied by these companies were adequate. Some questions were raised with regard to the audit of Morris Scale, but it was determined that the instruments in question (load cells) were not used for any critical measurements or to determine key facility parameters, such as energy and mass balances. Calibration results were included as part of the final data report for the APEX test program. Westinghouse submitted this report on June 13, 1995.

The team confirmed that Westinghouse had revised the OSU APEX PQP to describe requirements for procurement of calibration services and calibration of commercially procured test instrumentation and calibration equipment as stated by Westinghouse in its letter of February 15, 1995. The team verified that all other corrective and preventive actions identified in the subject letter had been completed and documented. On this basis, Nonconformance 99900404/94-01-01 was closed.

Nonconformance 99900404/94-01-02

The team found that contrary to the provisions of the PQP (1) no procedures or instructions had been available identifying methods, accuracy, and/or the acceptance criteria to be used for determining the as-built elevations and dimensions of the OSU/APEX test facility and (2) the TIC Calibration Procedure 19, used to calibrate thermocouples for the long-term cooling tests at the OSU facility, had not noted who originated, reviewed, or approved the document.

In letter NTD-NRC-95-4408, dated February 15, 1995, Westinghouse responded to Nonconformance 99900404/95-01-02. Westinghouse stated that a specific set of requirements were being incorporated into the OSU PQP for documenting critical dimensions, and that the two TIC procedures cited in the nonconformance had been superseded by two OSU procedures which corrected the inadequacies identified by the team. As preventive actions, Westinghouse stated that Procedure AP-3.11 in WCAP-12601 was being revised to address documentation of critical attributes of test facilities, and that the OSU APEX PQP was being revised to include requirements for preparing instrument calibration procedures.

During a subsequent QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01), the team verified that Westinghouse had incorporated a set of requirements into the OSU/APEX

PQP for documenting critical attributes of the facility design. The reverification of critical dimensions had been completed, and a report was being prepared.

The team also verified that two thermocouple calibration procedures used by TIC for APEX had been replaced by two OSU procedures which were incorporated into the APEX facility maintenance plan. The team verified that the two procedures properly indicated originator and management approvals and that other corrective and preventive actions identified in the February 15, 1995, letter had been completed and documented by Westinghouse. On this basis, this part of Nonconformance 99900404/94-01-02 was closed.

Unresolved Item 99900404/94-01-03

The team found that OSU had accepted test results which had failed to meet established test acceptance criteria, without placing an evaluation and disposition in the test design record file. It appeared that at least two facility characterization tests did not meet the acceptance criteria. Nevertheless, these two tests were not rerun, and no documentation was available at OSU to indicate the disposition of the apparent deviations.

Westinghouse's QA procedures require that test acceptance documentation contain evidence that any deviations occurring during a test have been evaluated and, if necessary, dispositioned. Westinghouse stated that acceptability of a test is documented in the quick-look report (QLR) for that test. Also, the FDR for each test program would contain a full listing of all tests performed in the program, would identify invalid tests, and explain why invalid tests were disqualified. Westinghouse's Test Engineering Group performed the evaluations and prepared the QLRs and the FDRs. Westinghouse added that it, not the testing organization (OSU), makes the final determination about the acceptability of test results and that documentation of this evaluation and its disposition is placed in the official design record file at Westinghouse offices in Monroeville.

During a subsequent QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01), the team discussed the results of the OSU inspection with Westinghouse's Test Engineering Group. The team learned that for one of the tests related to the unresolved item at OSU, the data had been determined, after the fact, as not essential for facility characterization. For the second test, the flows that were attained in the test had not met the acceptance criteria but were determined to be useful to characterize the system and were accepted on that basis.

Discussion of the reasoning used in making these decisions was included in the FDR and the TAR. Although the reports had not been issued at the time of the inspection and, therefore, could not be reviewed to ascertain that the disposition of these deviations had been appropriately documented, after speaking with Westinghouse's Test Engineering Group, the team concluded that the evaluations had been performed, that the reasoning behind the decisions on data acceptability and usefulness was sound, and that the QA program requirements were met. Subsequent review of the OSU FDR confirmed that discussion on the acceptance basis had been included. Therefore, this part of Unresolved Item 99900404/94-01-03 was closed.

21.B.1.5 SPES-2 High-Pressure, Full-Height Integral Systems Test Program

The staff conducted a QA implementation inspection at the Societa' Informazioni Esperienze Termoidrauliche (SIET) SPES-2 test facility in Piacenza, Italy, during the week of October 10, 1994 (NRC Inspection Report 99900404/94-01).

The quality-related activities associated with the AP600 full-height, full-pressure integral system tests performed at SPES-2 were conducted under the auspices of a cooperative agreement between Westinghouse, ENEA, ENEL, and SOPREN-Ansaldo. The test program provided thermal-hydraulic data for computer code validation and simulated the operation of the AP600 passive safety systems. SIET described the general features of its QA system in its quality manual, 00001-QQ. Additional quality plan provisions specific to AP600 testing were also detailed in Procedure 00006-QQ-92, "Quality Plan Relative to Nuclear Area Orders," which cross referenced European quality standards to the criteria of NQA-1. In order to conduct these confirmatory tests, SIET had implemented an internal quality system which incorporated the standards of both the International Organization for Standardization (ISO) Code Series 9000 (UNI-EN 29000) and the Italian Code UNI-8450 (1983).

During the inspection, the team found that Westinghouse had established appropriate procedural controls at the SPES-2 test facility which properly incorporated the applicable provisions of WCAP-8370 except for a few findings in certain areas. Specifically, the team identified a nonconformance with program implementation with respect to the accuracy and preparation of facility as-built drawings. These issues were identified as part of Nonconformance 99900404/94-01-02. Also, the team identified an unresolved item concerning SIET's acceptance of test results that had failed to meet established test acceptance criteria, without an evaluation and disposition being placed in the test design record file. This was identified as Unresolved Item 99900404/94-01-03.

Nonconformance 99900404/94-01-02

The team found that, contrary to the provisions of WCAP-8370 and WCAP-9565, no instructions or procedures were available at the SIET SPES-2 test facility to verify critical dimensions or configuration of commercial manufacturing drawings before accepting these drawings as representing the as-built design condition and placing them under the SIET QA system. In addition, the procedures for determining system and component elevations and arrangements at the SPES-2 test facility did not prescribe the required accuracy or include any acceptance criteria for such measurements.

In Letter NTD-NRC-95-4408 (February 15, 1995), Westinghouse responded to Nonconformance 99900404/95-01-02. Westinghouse stated that SIET had prepared a procedure for AP600 test configuration control, which would list the applicable portions of SIET Document 00006-QQ-92 related to the requirements for component inspections. Also, SIET confirmed that inspections had been performed for all vessels constructed to simulate parts of the AP600 design. SIET had compiled all inspection records and would verify that the component acceptance inspections were performed in accordance with SIET Document 00006-QQ-92. With respect to the other issue identified in the nonconformance, Westinghouse stated that SIET had prepared an AP600 test configuration control document (00011-QQ-94), which contained specific requirements related to the identification of critical facility dimensions, including applicable tolerances. Also, SIET would revise the SPES-2 test specification to identify the critical dimensions of the facility and the required tolerances. As preventive actions, Westinghouse stated that it would revise relevant procedure(s) in WCAP-12601 to address documentation of critical attributes of test facilities.

In the course of a subsequent QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01), the team verified that SIET had developed a procedure for inspecting components acquired from commercial contractors. In addition, SIET had reviewed records of equipment inspections for the SPES-2 test facility, and had confirmed that vendor drawings and specifications properly reflected as-built attributes of relevant components. The team verified that the SPES-2 test specification was modified to identify facility critical dimensions and associated accuracy, and that as-built critical attributes were confirmed by SIET. On this basis, this part of Nonconformance 99900404/94-01-02 was closed.

Unresolved Item 99900404/94-01-03

The team identified an unresolved item concerning SIET's acceptance of test results that failed to meet established test acceptance criteria, without an evaluation and disposition being placed in the test design record file. Westinghouse's QA procedures require that test acceptance documentation contain evidence that any deviations occurring during a test have been evaluated and, if necessary, dispositioned. Westinghouse stated that acceptability of a test is documented in the QLR for that test. Also, the FDR for each test program would contain a full listing of all tests performed in the program, identify invalid tests, and explain why an invalid test had been disqualified. Westinghouse's Test Engineering Group performed the evaluations and prepared the QLRs and the FDRs. Westinghouse stated during the inspections that it, not the testing organization, makes the final determination about the acceptability of test results and that documentation of this evaluation and its disposition is placed in the official design record file at Westinghouse offices in Monroeville, Pennsylvania.

During a subsequent QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01), the team discussed Westinghouse's process for the evaluation and disposition of test results that do not meet the acceptance criteria, as described above. After discussing this process with Westinghouse's Test Engineering Group, the team concluded that the review procedure fulfills Westinghouse's documented AP600 QA requirements. On this basis, this part of Unresolved Item 99900404/94-01-03 was closed.

21.B.1.6 Large-Scale Passive Containment Cooling System Test Program

The staff conducted a QA implementation inspection at Westinghouse's facilities in Monroeville, Pennsylvania during the week of May 1, 1995 (NRC Inspection Report 99900404/95-01). During the inspection, the team reviewed the Westinghouse implementation of the applicable QA criteria essential to support the AP600 design certification application, including design certification testing. Specifically, the team evaluated the effectiveness of the QA program and controls in governing the implementation of the AP600 PCCS LST design certification testing program.

Testing activities performed at Westinghouse's Science and Technology Center (STC), including the PCCS LST test program, were conducted under direct oversight by the ESBU QA organization. A separate STC-based QA plan was not identified as a requirement for STC project tasks. The quality-related activities associated with the PCCS LST tests were controlled in accordance with the test specifications and the test procedures. No specific LST quality plan was developed; however, a one-page quality plan that was prepared for the integral extension test was applied to the LST.

The results of the inspection indicate that Westinghouse, in general, was adequately implementing the AP600 Quality Assurance Program Plan with the exception of a few findings in certain areas. Specifically, the team identified nonconformances with program implementation with respect to (1) test facility configuration control, and (2) the accuracy of the facility as-built drawings. These findings were identified as part of Nonconformances 99900404/95-01-01 and 99900404/95-01-02, respectively. Also, the team identified a concern with respect to the disposition of test deviations between the Test Engineering group and the Containment and Radiological Analysis group (SDSER Confirmatory Item 21.B.1.6-1).

<u>Nonconformance 99900404/95-01-01</u>

The team found (NRC Inspection Report 99900404/95-01) that the PCCS LST specification did not accurately reflect the instrumentation that was procured and installed in the PCCS Large-scale Test Facility as required by the provisions of WCAP-12601. In a letter dated September 12, 1995, Westinghouse responded to Nonconformance 99900404/95-01-01. Westinghouse stated that it would revise the PCCS LST specification to reflect the final configuration of the PCCS LST. The staff found Westinghouse's reply responsive to the concern raised in the nonconformance. In a letter dated December 5, 1995, the staff notified Westinghouse of its finding and stated that the implementation of proposed corrective and preventive actions related to the nonconformance would be reviewed during a future inspection to establish that full compliance had been achieved and maintained. This was identified as Confirmatory Item 21.B.1.6-2.

During an inspection (NRC Inspection Report 99900404/97-02) on November 17 through 21, 1997, the NRC verified that PCS-T1P-002 had been revised to reflect the final configuration of the Large-Scale Test Facility. As preventive actions, Westinghouse revised test specifications for subsequent tests (including the Core Make-Up, Long-Term Cooling, and Full-Height/Full Power tests) to reflect the final configuration of the respective facilities. The inspection team verified that these actions had been completed and documented. Therefore, Confirmatory Item 21.B.1.6-2 was closed.

<u>Nonconformance 99900404/95-01-02</u>

The team found (NRC Inspection Report 99900404/95-01) that procedures or instructions for determining the as-built elevations and critical dimensions of the PCCS LST had not been available to or utilized by the Containment and Radiological Analysis Group as required by WCAP-9565. In Letter NTD-NRC-95-4549 (September 12, 1995), Westinghouse responded to Nonconformance 99900404/95-01-02, stating that it would remeasure appropriate critical dimensions in accordance with a written procedure. Measurements obtained would be compared to those previously recorded and additional remeasurements would be taken if necessary. Westinghouse added that after the PCCS LST program had been completed it had revised AP600 Procedure 3.11 to require that a written procedure be used to obtain the specified critical dimensions of any safety-related AP600 test facility. The staff reviewed Westinghouse’s response and found it responsive to the concern raised in the nonconformance. In a letter dated December 5, 1995, the staff notified Westinghouse of its finding and stated that the implementation of proposed corrective and preventive actions related to the nonconformance would be reviewed during a future inspection to establish that full compliance had been achieved and maintained. This was identified as Confirmatory Item 21.B.1.6-3.

During an inspection (NRC Inspection Report 99900404/97-02) on November 17 through 21, 1997, the NRC verified that proposed corrective and preventive actions had been completed and documented by Westinghouse. Therefore, Confirmatory Item 21.B.1.6-3 was closed.

Confirmatory Item 21.B.1.6-1

During the inspection (NRC Inspection Report 99900404/95-01), the team reviewed Test Procedure 219.1, Revision 0, which was used during Runs 54 and 57 to verify acceptable implementation of the AP600 quality plan. The purpose of Test 219.1 was to investigate the distribution of noncondensables as a result of changes in vessel cooling. While reviewing the test data for this test, the team noticed that the rate of water flow to the top of the vessel had not been constant, as is required by the test procedure. Another target test parameter was an inlet steam flow of 0.09 ± 0.02 kg/s (0.2 ± 0.05 lb/s). This steam flow was lowered to approximately 0.054 kg/s (0.12 lb/s) to limit the vessel pressure and baffle temperatures to an acceptable range. The team considered the failure of the test conditions to meet the target test parameters to be a deviation from the test procedure.

In accordance with AP-3.11, “AP600 Testing,” these deviations were recorded in the test logbook and the Test Engineering Group was notified of the deviations. The Test Engineering Group was responsible for evaluating the reported test deviations and documenting the disposition of deviations by sending an official test engineering transmittal to the test group. Representatives of the Test Engineering Group stated that it was normal practice to document deviations in the FDR. The team verified that the deviations had been documented in the FDR for Test 219.1. The engineering procedure also required the concurrence of the cognizant design group, in this case the Containment and Radiological Analysis Group, for disposition of a deviation affecting compliance with the test specification.

Representatives of the Test Engineering Group stated that the Containment and Radiological Analysis Group acknowledged the disposition of these and other deviations by their acceptance signatures on the QLR and FDR. The staff would confirm the disposition of test deviations between the Test Engineering Group and the Containment and Radiological Analysis Group during a future inspection. This was identified as Confirmatory Item 21.B.1.6-1.

During an inspection (NRC Inspection Report 99900404/97-02) on November 17 through 21, 1997, the NRC discussed the PCCS LST acceptance criteria with appropriate Westinghouse staff. The following test acceptance criteria were established for the LST:

(1) Data on forcing functions were available (e.g., steam flow rate, fan speed, water flow rates, inlet temperature of steam, water and air). Strict adherence to the specific absolute pressures and flow rates was not necessary but values were to be nearly constant as defined in the test matrix.

(2) Data on response variables available, (e.g., condensate flow rates, excess water flow rates, air, water and steam outlet temperatures, vessel pressure, 80 percent of the vessel and fluid temperature, and vessel water coverage measurements) were taken.

(3) Unplanned excursions were evaluated on a case-by-case basis. Failures that could result in faulty data outputs were not acceptable.

(4) The vessel pressure was maintained within specified pressure limits during the constant pressure portions.

Variations in the PCS water coverage flow rate were not considered in the development of the test acceptance criteria. The important criterion was the target coverage area, as specified in the test matrix. Even then, the acceptance criteria did not call for strict adherence to the target value, only that a nearly constant value could be determined for a test. With respect to the specific steam flow rate for test 219.1, the test acceptance criteria were followed. On these bases, Confirmatory Item 21.B.1.6-1 was closed.

21.B.2 Summary

After considering the QA implementation inspections of Westinghouse's design certification test facilities and/or programs, the staff concluded that the QA programs governing Westinghouse's AP600 design certification test programs satisfied the requirements of 10 CFR Part 52 and the pertinent provisions of Appendix B to 10 CFR Part 50.