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AP1000
Code Applicability
Report

Westinghouse Electric Company LLC

AP1000 DOCUMENT COVER SHEET

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WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-15707

AP1000
Code Applicability Report

July 2001

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont.)

LIST OF ACRONYMS AND ABBREVIATIONS

ACRS	Advisory Committee on Reactor Safety
ADS	Automatic Depressurization system
APEX	Advanced Plant Experiment
CCFL	Counter Current Flow Limitation
CCTF	Cylindrical Core Test Facility
CFD	Computational Fluid Dynamics
CHF	Core Heat Transfer
CMT	Core Makeup Tank
COSI	Condensation of Safety Injection
CQD	Code Qualification Document
CSAU	Code Scaling, Applicability, and Uncertainty
DBA	Design Basis Accident
DCD	Design Control Document
DECLB	Double-Ended Cold Leg Break
DEG	Double-Ended Guillotine
DEDVI	Double-Ended Direct Vessel Injection
DNB	Departure from Nucleate Boiling
DNBR	Departure from Nucleate Boiling Ratio
DVI	Direct Vessel Injection
ECCS	Emergency Core Cooling System
EM	Evaluation Model
EPRI	Electric Power Research Institute
FLECHT-SEASET	Full-length Emergency Cooling Heat Transfer – Systems Effects and Separate Effects Test
FSER	Final Safety Evaluation Report
GDC	General Design Criteria
GE	General Electric
HDR	Heissdampfreaktor
HX	Heat Exchanger
IRWST	In-Containment Refueling Water Storage Tank
LBLOCA	Large Break LOCA
LOCA	Loss-of-Coolant Accident
LOFT	Loss-of-Fluid Test
LST	Large Scale Test
LSTF	Large Scale test Facility (ROSA IV)
MSLB	Main Steam Line Break
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulation
ORNL	Oak Ridge National Laboratory
OSU	Oregon State University
PCCWST	Passive Containment Cooling System Water Storage Tank
PCS	Passive Containment Cooling System
PCT	Peak Clad Temperature

LIST OF ACRONYMS AND ABBREVIATIONS (cont.)

PIRT	Phenomena Identification and Ranking Table
PRHR	Passive Residual Heat Removal
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
ROSA	Rig of Safety Assessment
RTDP	Revised Thermal Design Procedure
SBLOCA	Small-break LOCA
SDSER	Supplemental Draft Safety Evaluation Report
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SIMARC	Simulator Advanced Real-time Code
SLB	Steam Line Break
SPES	Simulatore per Esperienze di Sicurezza
THTF	Thermal Hydraulic Test Facility
TMI	Three-Mile Island
UPTF	Upper Plenum Test Facility
V&V	Verification and Validation

EXECUTIVE SUMMARY

This report documents an assessment performed by Westinghouse of the analysis codes that were developed and approved for the AP600 Design Certification to determine their applicability and use for Design Certification of an AP1000. The analysis codes that were approved for the purposes of performing safety analyses of the AP600 passive plant are:

- LOFTRAN – transient analyses
- NOTRUMP – small-break LOCA analyses
- WCOBRA/TRAC – large break LOCA & long-term cooling analyses
- WGOTHIC – containment analyses

The report describes a plan to use these safety analysis codes approved for the AP600, a plant design with passive safety features for a Design Certification of an AP1000. For each of the thermal-hydraulic analysis codes, the report discusses the basis for that approval as described in NUREG-1512, Final Safety Evaluation Report Related to Certification of the AP600 Standard Design (Reference 1). This report also provides an assessment as to how that basis can be applied to AP1000.

Background

As part of the pre-certification review of the AP1000, Westinghouse submitted WCAP-15612, "AP1000 Plant Description and Analysis Report" (Reference 2) to the NRC. That report provides an overview description of the AP1000 plant, and compares its important design features to those of the AP600. The AP1000, which is based on the AP600 design, has the same plant footprint as the AP600. In addition, the configuration and operation of the reactor coolant system and the passive safety features are the same. Components and pipe dimensions have been increased, where needed, to accommodate the higher core power of the AP1000, but the basic configuration (i.e. number of components and how they are interconnected) is the same. In Reference 2, analyses of representative design basis accidents for the AP1000 and are compared to the results from the AP600 safety analyses. These analyses were performed using the codes and methods that were utilized and approved for the AP600. These analyses do not represent the complete spectrum of design basis accidents for AP1000. Rather, they represent a sampling of the design basis accidents where the performance of the passive safety systems is critical in mitigating the consequences of the accident. These assessments are, therefore, useful in characterizing the performance of and assessing the phenomena associated with the AP1000 passive safety systems. Results of these analyses show similar behavior for both the AP600 and AP1000

Westinghouse has submitted WCAP-15613, "AP1000 PIRT and Scaling Assessment" (Reference 3) to the NRC. The report provides an assessment of the AP600 test program and its applicability to AP1000 and provides Phenomenon Importance Ranking Tables (PIRT), which were developed for the AP1000 based on an independent review performed by several industry experts. The report addresses the applicability of each of the AP600 test facilities that were important for Design Certification. The important separate effect tests and integral effects tests were evaluated in more detail, to demonstrate that the test data and conclusions obtained from these tests are applicable to AP1000. In-depth scaling analyses of the AP600 integral effects tests such as OSU and SPES-2 were performed to demonstrate that the integral effect tests are adequately scaled for AP1000. The major conclusion from this report is that the AP600 test program can be judged to meet the requirements of 10 CFR Part 52 for an application for Design Certification for AP1000. More specifically, the tests provide an adequate database to validate analysis codes for the purposes of performing safety analysis for an AP1000. Analysis codes that are validated against this test data can be used to perform the required accident analyses for AP1000.

Scope of this Report

In this report, Westinghouse describes the plan for the use of the analysis codes previously validated and approved for AP600 for Design Certification of the AP1000. For each of the thermal-hydraulic analysis codes that were developed and approved as part of AP600 Design Certification, (LOFTRAN, NOTRUMP, WCOBRA/TRAC, and WGOTHIC), the report discusses the basis for that approval, as described in Reference 1. A summary of the major issues for each code is provided with a discussion of the applicability of the AP600 code approval basis to the AP1000. This provides the justification for the continued use of these codes for AP1000.

The following summarizes the conclusions of this report:

- The LOFTRAN-AP code that was approved for AP600 can be used for the purposes of performing conservative analyses of the transient events presented in Chapter 15 for AP1000. The basis for this conclusion is that when considering transient events, no new phenomena are identified for AP1000, when compared to AP600, and the test database that supported validation of this code for AP600 is applicable to AP1000. Furthermore, the means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000. Assessments indicate that the AP1000 passive safety systems operate in the same way as the AP600, and that large margins to the regulatory limits exist for the transient events analyzed. It is expected that large margins will exist for the AP1000 Chapter 15 accident analysis events analyzed with LOFTRAN.

- The NOTRUMP code that was approved for AP600 can be used for the purposes of performing conservative (Appendix K) analyses of the small break LOCA events presented in Chapter 15 for AP1000. For small break LOCA events, no new phenomena are identified for AP1000, when compared to AP600, and the test database that supported validation of this code for AP600 is applicable to AP1000. Also, the means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000. Preliminary assessments indicate that the AP1000 passive safety systems provide large margins to the regulatory limits for the small break LOCA events analyzed. It is expected that large margins will exist for the Chapter 15 accident analysis events analyzed with NOTRUMP. It was noted in Reference 3 that some phenomena previously addressed for AP600 could be judged to be of higher importance for AP1000 (i.e., entrainment in the hot leg during the transition from ADS to IRWST injection of the SBLOCA event). To better address this phenomenon, as well as to address the importance of momentum flux during this same phase, a supplemental analysis using WCOBRA/TRAC will be used to demonstrate that conservative results are attained using NOTRUMP analysis methods for AP1000. This supplemental analysis, including validation against relevant test data, will be provided to the NRC for their review. This AP1000 supplemental analysis will be performed to support the assessment of conservative results for the Chapter 15 NOTRUMP accident analyses.

- The WCOBRA/TRAC code that was approved for AP600 large break LOCA analysis can be used for the purposes of performing best-estimate analysis for AP1000. The basis for this conclusion is that for large break LOCA events, no new phenomena are identified for AP1000, when compared to AP600, and the test database that supported validation of this code is applicable to AP1000. Furthermore, the means of resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000. The additional validation of WCOBRA/TRAC to address the uniqueness of the passive safety system direct vessel injection (DVI) has been performed and approved by the NRC for AP600. As the AP1000 DVI is the same as AP600, this validation is applicable to AP1000 as well. The WCOBRA/TRAC computer code and large break LOCA methodology approved by the NRC for AP600 are applicable to the 10CFR50.46 Emergency Core Cooling System performance analysis of the AP1000 for 95th percentile calculated peak clad temperature values up to the 2200°F licensing limit.

- The WCOBRA/TRAC code that was approved for AP600 long-term cooling analysis can be used for the purposes of performing conservative (Appendix K) analysis of long-term cooling for LOCA events presented in Chapter 15 for AP1000. The basis for this conclusion is that for LOCA events, no new phenomena are identified for AP1000, when compared to AP600, and the test database that supported validation of this code for AP600 is applicable to AP1000. Also, the means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000. Preliminary assessments indicate that the AP1000 passive safety systems provided large margins to the regulatory limits for the long-term cooling analysis, and it is expected that large margins will exist for the final accident analysis events analyzed with WCOBRA/TRAC for long-term cooling. Note however that in Reference 1, the use of WCOBRA/TRAC for long-term cooling in the "window" mode (as approved for AP600) was compared to an analysis using a "continuous" mode for the limiting long-term cooling event. Results of that analysis demonstrated good agreement between the window mode analysis and the continuous mode analysis. Westinghouse will perform the limiting long-term cooling analysis using the continuous mode methodology presented in Reference 1, but will retain the windows mode methodology for the less limiting events to minimize the resources expended to perform this analysis. Comparison of the results of the continuous mode to the window mode supports the assessment of conservative results for the "window" mode analyses.

- The WGOTHIC code that was approved for AP600 can be used for the purposes of performing conservative containment analysis of the events presented in Chapter 6 for AP1000. The basis for this conclusion is that regarding the events that challenge containment integrity (i.e., large LOCA and large steam line break), no new phenomena are identified for AP1000, when compared to AP600, and the test database that supported validation of this code for AP600 is applicable to AP1000. Furthermore, the means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000. Preliminary assessments indicated the AP1000 has sufficient margin to the containment design pressure when bounding-type analyses are performed using WGOTHIC.

Conclusion

The analysis codes were extensively reviewed by the NRC as part of the AP600 Design Certification process. The review conducted by the staff included key elements of Draft Regulatory Guide DG-1096. There are no new phenomena associated with the AP1000, and scaling demonstrates that the AP600 test database used to validate the analysis codes is applicable to AP1000. Similar plant margins exist between AP600 and AP1000. Therefore, the analysis codes should be approved for use on AP1000 without extensive incremental review subject to the proposed stipulations outlined in this report.

References

1. NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," September 1998.

2. WCAP-15612, "AP1000 Plant Description and Analysis Report," December 2000.

3. WCAP-15613, "AP1000 PIRT and Scaling Assessment," February 2001.

1.0 INTRODUCTION

Westinghouse Electric Company has designed an advanced 600 MWe nuclear power plant called the AP600. The AP600 uses passive safety systems to enhance plant safety and to satisfy U.S. licensing requirements. The use of passive safety systems provides significant and measurable improvements in plant simplification, safety, reliability, investment protection, and plant costs. These systems use only natural forces such as gravity, natural circulation, and compressed gas to provide the driving forces for the systems to adequately cool the reactor core following an accident. The AP600 received Design Certification by the Nuclear Regulatory Commission in December 1999.

To further improve AP600 economics and in response to market demand for larger plants, Westinghouse initiated development of the AP1000 standard nuclear reactor design, with an output of approximately 1000 MWe, based upon the AP600 design. The design features of the plant have been selected to preserve key features and performance characteristics embodied in the AP600. By preserving the design basis of the AP600 in the AP1000, Westinghouse seeks to preserve the licensing basis of the plant as well.

Westinghouse submitted the "AP1000 Plant Analysis and Description Report" (Reference 1) to the NRC. The report provides a description of the AP1000 plant design as well as accident analyses using the AP600 validated analysis codes and preliminary models of the AP1000 plant. These preliminary safety analyses are not a complete set of analyses as prescribed by 10CFR Part 50, but rather, were provided to characterize the expected performance of the AP1000.

Westinghouse submitted the "AP1000 PIRT and Scaling Assessment" (Reference 2) report to the NRC. The report provides Phenomena Identification and Ranking Tables (PIRT) for the AP1000 and demonstrates through scaling that the AP600 test program is applicable to the AP1000 and sufficiently covers the range of conditions expected for the AP1000. The report concludes that the AP600 test program provides a test database sufficient for code validation for AP1000 in accordance with 10CFR Part 52.

This report documents the acceptability of the analysis codes approved for AP600 for application to AP1000. The basis for approval for AP600 is discussed along with major code-related issues identified during the AP600 Design Certification review, and the means to address these issues as the codes are applied to the AP1000 are presented. Each section provides an assessment of how the AP600 code approval basis can be applied to AP1000.

Section 2 addresses acceptance of the WCOBRA/TRAC code for AP600 large break LOCA and long-term cooling analysis. It also addresses the acceptability of the WCOBRA/TRAC code for AP1000 large break LOCA and long-term cooling analysis. Sections 3, 4 and 5 address the acceptability of the NOTUMP, LOFTRAN and WGOTHIC codes, respectively, for use in analyzing AP1000. Section 6 provides conclusions regarding the applicability of the AP600 analysis codes to AP1000.

References

1. WCAP-15612, "AP1000 Plant Description and Analysis Report," December 2000.

2. WCAP-15613, "AP1000 PIRT and Scaling Assessment," February 2001.

2.0 WCOBRA/TRAC COMPUTER CODE VALIDATION FOR AP1000

2.1 AP1000 LARGE BREAK LOCA PHENOMENA

Table 2-1 shows key processes for the large break LOCA (LBLOCA) transient. The LBLOCA transients include double-ended guillotine (DEG) breaks, and large cold-leg split breaks with flow area greater than 1 ft^2. These transients are initiated at full-power conditions with the plant parameters either at best estimate values or bounded in a conservative manner. The uniqueness of the AP1000 plant is assessed relative to AP600 and to existing PWRs to identify any differences in the plant design that could affect WCOBRA/TRAC's capabilities for modeling the AP1000.

The assessment of safety analysis code capability for the AP1000 LBLOCA analysis is performed for WCOBRA/TRAC, the code that will be used to perform the analysis. The bases for using WCOBRA/TRAC are:

- It is the highest level of thermal-hydraulic technology among the industry LOCA analysis licensing codes. It has the most complete thermal-hydraulics model for analyzing the complex behaviors associated with large LOCA events.

- It has already been reviewed by the NRC and approved as a best-estimate code consistent with Regulatory Guide 1-157, "Best-Estimate Calculations of ECCS Performance" (Reference 1). Westinghouse and EPRI developed this best-estimate LOCA methodology under the revision to the Appendix K rule (1988), and it has been used in more than ten Westinghouse four-loop and three-loop plant LBLOCA licensing analyses to date to calculate the peak cladding temperature at the 95th percentile.

- A code qualification document (CQD) (Reference 2) exists for WCOBRA/TRAC, and a nodalization scheme of the AP600 design was approved in WCAP-14601 (Reference 3). WCOBRA/TRAC has also been validated against experiments that capture the key LBLOCA processes for the AP600. Section 2.3 of WCAP-15613, "AP1000 PIRT and Scaling Assessment" (Reference 4) presents the AP1000 LBLOCA PIRT and concludes that the new and additional passive systems do not significantly influence the LBLOCA calculated peak clad temperature (PCT). Only the downcomer injection requires specific additional validation of WCOBRA/TRAC for passive plants.

- This additional validation of WCOBRA/TRAC to address the uniqueness of the passive safety system direct vessel injection (DVI) has been performed in WCAP-14171, Rev. 2 (Reference 5) and approved by the NRC for AP600. This validation, which also applies to the AP1000, used test data that exist on DVI from the full-scale upper plenum test facility (UPTF) (Reference 6) tests, part of the NRC cooperative program with the Federal Republic of Germany, and the Japanese cylindrical core test facility (CCTF) (Reference 7) reflood system effects tests that model a four-loop Westinghouse PWR with the DVI configuration. Further, sufficient data existed for the DVI configuration that no specific AP600 test was needed to provide data to validate WCOBRA/TRAC for injection into the reactor vessel downcomer. Section 2.3 of Reference 4 concludes that the downcomer injection location validation of WCOBRA/TRAC performed for AP600 addresses the issue for AP1000.

Examples of the WCOBRA/TRAC validation documented in the CQD are provided in Table 2-2.

Although a very small effect, the core makeup tanks (CMT) actuate during a LBLOCA event before the accumulators inject. The amount of CMT injection that occurred in the AP600 LBLOCA analysis is small (Figure 2-1). Only about 0.5 percent of the CMT liquid inventory was injected before accumulator flow shut off the CMT injection for AP600, and this water did not contribute to core cooling because it bypassed the reactor vessel. A similar result is anticipated for AP1000 because its passive safety system design is very similar to AP600.

A CMT test was performed to provide thermal-hydraulic data that covered the expected range of conditions for the AP600. WCOBRA/TRAC modeled these experiments in order to validate the correlations in the code used for condensation. There is very little CMT injection during a LBLOCA because the rapid depressurization causes the accumulator flow to begin early in the transient, shutting off CMT injection. As a result, the core recovered and the peak cladding temperature excursion is terminated via accumulator flow, not CMT flow. The same result is anticipated for AP1000 large break LOCA analyses. The AP1000 Passive Residual Heat Removal (PRHR) is actuated during a large LOCA event but has little impact because of the massive depressurization that occurs due to the postulated double-ended cold leg break (DECLB).

The PIRT review of the key LBLOCA phenomena presented in Reference 4 indicates that, as is true for AP600, the unique passive safety systems of AP1000 play almost no role in the plant's response during the PCT excursion of a LBLOCA event because the transient is so rapid. Westinghouse evaluated the need for performing a LBLOCA test and considered it to be unnecessary for AP600; the same conclusion holds true for AP1000. Furthermore, the AP1000 design features that are no different from conventional Westinghouse plants require no testing. Data for computer code validation exist for the phenomena associated with DVI during the AP1000 LBLOCA transient.

The long-term cooling aspects of the LBLOCA are the same as for the small break LOCA (SBLOCA) that were studied at the Oregon State University (OSU) test facility. Long-term cooling will be analyzed as an event separate from the initiating event, as discussed in Subsection 2.3.

2.2 WCOBRA/TRAC CODE VALIDATION FOR AP1000 LBLOCA ANALYSIS

2.2.1 WCOBRA/TRAC Acceptance for AP600 LBLOCA Analysis

In Section 21 of the AP600 FSER (Reference 8), the NRC staff reported the results of its review of the Westinghouse LBLOCA methodology submittal. The staff concurred that the extensive assessment of the WCOBRA/TRAC computer code performed for conventional three-loop and four-loop plant LBLOCA analysis applied to AP600 because of the similarity of the transient responses. Based on their previous review of the three-loop and four-loop plant large break LOCA methodology, together with the AP600-related validation and assessments provided in WCAP-14171 (Reference 5), the staff further concluded that the WCOBRA/TRAC code is "adequate to provide realistic evaluations of the AP600 LBLOCA with the tendency toward conservative results."

The Phenomena Identification and Ranking Table (PIRT) performed for the AP600 large break LOCA in WCAP-14171 and the corresponding AP1000 PIRT in Reference 4 indicate that the new, additional passive safety systems did not influence the calculated peak clad temperature; the one issue that was identified in the AP600 PIRT is the DVI configuration. The effect of the downcomer injection location was addressed by specific additional validation. First, the Japanese CCTF DVI test number 58 has been simulated with WCOBRA/TRAC. The CCTF test facility is a full-height, lower pressure model of a four-loop Westinghouse PWR. The scale factor for the facility compared to a four-loop plant is about 1/20. The facility was specifically designed to investigate the gravity reflood systems behaviors following a LBLOCA. Test 58 simulates the reflood portion of the large-break transient, during which the accumulator and low-pressure pumped flow is injected into the downcomer of the test vessel to quench the heated core. The test models the heated core with full-length heater rods, the reactor vessel, steam generators, and associated piping. The DVI configuration is not exactly the same as the AP600 or AP1000, since there is no flow-turning device in the CCTF downcomer simulation. As a result, the injected flow will spread more in this test facility than in either advanced passive plant.

Figure 2-2 shows the CCTF facility, and Figure 2-3 shows the facility downcomer and the injection locations. Modeling this test with WCOBRA/TRAC has verified the ability of the interfacial heat and mass transfer models used in the downcomer to calculate the amount of condensation that occurs during accumulator injection and safety injection with the DVI configuration.

To address the issue of the effects of DVI on emergency core cooling (ECC) bypass during the AP600 LBLOCA event, the UPTF experiment with DVI was also modeled with WCOBRA/TRAC. The UPTF facility was constructed to investigate the LBLOCA ECC bypass phenomena. The UPTF uses a full-scale, four-loop reactor vessel and downcomer. Experiments were conducted with DVI using the accumulator and the pumped flows of LBLOCA refill conditions. Figure 2-4 shows the UPTF, and Figure 2-5 shows the UPTF test vessel. Prediction of this test also confirmed the interfacial heat and mass transfer models used in the WCOBRA/TRAC code. The NRC stated in Reference 8, the AP600 FSER, that the WCOBRA/TRAC computer code realistically predicts the DVI test configuration data from the CCTF and UPTF facilities in WCAP-14171.

Additional validation was also performed to ensure that the WCOBRA/TRAC models and correlations apply over the extended ranges of blowdown cooling and reflood cooling conditions exhibited by the AP600 design. The results of ORNL test and FLECHT-SEASET test simulations presented in WCAP-14171 resolved any questions relating to the range of parameter validation that existed for the WCOBRA/TRAC large break LOCA heat transfer predictions of the AP600. Elements of the three-loop and four-loop plant best estimate LOCA methodology approved for Westinghouse plants were not performed for AP600 because the calculated PCT at the 95th percentile was below 1700°F in the AP600 SSAR (Reference 9) analysis.

The AP600 LBLOCA methodology was found to be acceptable relative to 10CFR50.46 and to the Regulatory Guide 1.157 guidance, subject to certain methodology and application restrictions. The large majority of these application restrictions are the same as those identified in the acceptance of the WCOBRA/TRAC large break LOCA methodology for three-loop and four-loop Westinghouse plant designs and are not repeated. The AP600-related restrictions in Section 21 of Reference 8 that deal with a reanalysis situation are discussed in the following subsection.

2.2.2 WCOBRA/TRAC Acceptability for AP1000 LBLOCA Analysis

As discussed in Section 2.2.1, WCOBRA/TRAC is the licensing code used for the LBLOCA analysis of the AP600. Table 2-1 indicates that, for a LBLOCA, AP1000 thermal-hydraulic performance is very similar to existing Westinghouse PWRs, with the exception of DVI. As discussed in Section 2.2.1, WCOBRA/TRAC was validated for predicting DVI phenomena in WCAP-14171; it had already been validated against ample data, on different scales, for the other thermal-hydraulic phenomena associated with a LBLOCA, as documented in Reference 2, the WCOBRA/TRAC Code Qualification Document.

As previously stated, the PIRTs for the AP600 and AP1000 LBLOCA events are almost identical. There are no additional phenomena that require any further validation or assessment of WCOBRA/TRAC for AP1000 LBLOCA analysis, so no novel features are needed in WCOBRA/TRAC and the LBLOCA model accepted for AP600 is acceptable for AP1000. The code will be applied as described below.

Code Version

A special version of the WCOBRA/TRAC computer code was created for the AP600 SSAR analysis by incorporating additional capability to model the unique features of the AP600, as documented in WCAP-14776 (Reference 10), Section 4. A similar approach will be used to perform the AP1000 large break LOCA design certification analysis. The same updates added to WCOBRA/TRAC for the AP600 analysis will be used in the creation of an "AP" version to perform the AP1000 large break LOCA licensing analysis. The "AP" version of WCOBRA/TRAC will include the discretionary and non-discretionary code changes that have been made since the AP600 SSAR analysis was performed, which constitute the "2000 formulation" of the code and which have been reported to the NRC by Westinghouse (Reference 11) per the 10CFR50.46 annual reporting process. The details of the code changes made since the AP600 analysis was performed are provided in Appendix A. The impact of implementing these changes into WCOBRA/TRAC is judged to be minor on the AP600 large break LOCA results, including having little effect on the 95th percentile calculated PCT value. The "AP" code version will also include some new models to enable WCOBRA/TRAC to supplement the NOTRUMP analysis of the ADS-4 IRWST transition phase of AP1000 small break LOCA events. These small break LOCA-related models are presented in Appendix B. These models, which are activated through code input flags, will not be used in the AP1000 LBLOCA calculations. See Section 3.4.6 for a discussion of the WCOBRA/TRAC analysis that will be performed to supplement the NOTRUMP analysis results for AP1000.

AP600 FSER Restrictions

The AP600 FSER (Reference 8) identified several items as restrictions on further AP600 WCOBRA/TRAC LBLOCA analyses, in the event that the 95th percentile PCT values for either blowdown or reflood exceeded 1725°F. The 95th percentile PCT for AP1000 will exceed this value. The NRC-specified requirements follow, together with the means by which the AP1000 analysis will comply with each:

1. Westinghouse shall "repeat the global model matrix of calculations and the final 95 percent uncertainty calculations." The reference transient and the global model matrix of cases will be executed in the AP1000 LBLOCA analysis in order to establish the final 95th percentile PCT value using the same uncertainty methodology as AP600.

2. Westinghouse shall "address the sensitivity to the CMT and PRHR modeling parameters...as a bias to the 95 percent PCT result." An AP1000 WCOBRA/TRAC case will be run in which the CMT is not modeled and another, separate case will be run in which the PRHR is not modeled. If either case produces a higher PCT than the base case, the PCT difference will be applied as a bias in determining the final 95th percentile PCT value. Individual biases will be applied to the blowdown and reflood phase PCT results.

3. Westinghouse shall perform both local and core-wide oxidation calculations using the techniques approved for three-loop and four-loop plants. The oxidation calculation will be performed using the methods approved for use in three- and four-loop plant applications, as stipulated in the AP600 FSER, Section 2.1.6.3.

The AP1000 design certification large break LOCA analysis will conform to the identified restrictions. The methodology for determining the operation involves core heatup calculations and is independent of the passive plant design.

Major Issues

Inasmuch as the major issues identified during the AP600 review were resolved successfully in the AP600 design certification, and the AP600 approval is grounded in the generic PWR test database rather than AP600-specific testing, there are no major issues associated with the AP1000 large break LOCA analysis approach and/or phenomena. The WCOBRA/TRAC computer code and the large break LOCA best estimate methodology approved by the staff for AP600 are applicable to AP1000 for 95th percentile calculated PCT values up to the 2200°F licensing limit.

Resolution of Issues

The AP1000 LBLOCA Emergency Core Cooling System (ECCS) performance analysis will comply with the AP600 FSER restrictions, as indicated above. The nodalization used for the AP600 LBLOCA analysis in WCOBRA/TRAC will be adjusted to model the 14-foot core length of AP1000.

Conclusions

The calculated PCT for the AP1000 large break LOCA event will exceed the AP600 result because of the increase in core power. However, there are no new phenomena involved, and the AP1000 passive safety systems (other than accumulators) do not significantly impact the PCT for large break LOCA. The large break LOCA methodology used in the AP600 SSAR, including use of the WCOBRA/TRAC code version described above, is directly applicable to the 10CFR50.46 ECCS performance analysis of the AP1000 design.

2.3 WCOBRA/TRAC VALIDATION FOR AP1000 LONG-TERM COOLING ANALYSIS

2.3.1 Long-Term Cooling Phenomena

The AP1000 long-term core cooling process is different from that of conventional PWRs; under design basis safety analysis assumptions, there are no recirculating pumps to provide flow to the reactor vessel to maintain core cooling for post-accident situations. The AP1000 uses gravity-driven flow from the In-containment Refueling Water Storage Tank (IRWST) for the initial period of long-term cooling. Later, when the containment sump has filled with water, the containment recirculation phase begins. Containment recirculation provides decay heat removal for days and weeks following a LOCA event, with energy being removed through the containment shell to the air and water of the containment cooling system. During the containment recirculation phase, ECCS water flows again by gravity into the reactor vessel through the DVI lines. In post-LOCA long-term cooling, gravity-driven phenomena dominate, and the processes are simple for any size break.

The long-term cooling phase of AP1000 LOCA events continues to be defined as it is for AP600 in Section 1 of WCAP-14776 (Reference 10). The long-term cooling processes are shown in Table 2-3. The plant configuration during this post-accident phase is characterized by the reactor vessel being partially filled, the vessel volume either in boiling or in single-phase convective flow, the core covered by either a two-phase or single-phase mixture, and the downcomer containing subcooled water. The primary system above the reactor hot legs has drained, and the main vent path out of the primary system is through the fourth stage ADS valves on the hot legs. The fourth-stage ADS valves are above the flood-up level of the sump. The IRWST and/or containment sump will inject flow into the reactor vessel once the isolation valves open and vessel pressure is lower than the driving head available. The reactor primary system and containment taken together form a closed natural circulation system in which the steam generated in the core is vented through the ADS and condensed on the containment shell, fed to the IRWST and/or containment sump as condensate, then injected into the reactor vessel downcomer.

WCOBRA/TRAC is the computer code used to model this post-accident period. The code's important modeling features are the ability to simulate multiple break points in the RCS and to preserve correct elevation heads in the natural circulation process. WCOBRA/TRAC is also accurate at low pressure and has been compared to several reflood system effects tests in the CQD (Reference 2), that have thermal-hydraulic characteristics similar to the post-LOCA accident phase for the AP1000.

As shown in Table 2-3, data existed for several but not all phenomena, prior to the AP600 Oregon State University experiments that examined the gravity-driven long-term cooling behavior of a passive safety system design similar to the AP1000. Reference 4, Section 2.4 concludes that there are no new long-term cooling phenomena for AP1000 relative to AP600. It further concludes that the AP600 test facilities are adequately scaled for AP1000. Therefore, no specific data are needed on the AP1000 long-term cooling phenomena beyond that identified in Table 2-3.

2.3.2 WCOBRA/TRAC Acceptance for AP600 Long-Term Cooling Analysis

The WCOBRA/TRAC code was used to analyze the long-term cooling portion of the AP600 plant transient. The WCOBRA/TRAC calculations characterize the long-term cooling behavior of the plant. WCOBRA/TRAC has been validated against OSU low-pressure integral systems tests that simulate the long-term cooling phenomena anticipated for the AP600 in WCAP-14776 (Reference 10).

The key parameters that are of interest include:

- Transient mass distribution in the primary system when the system is in the long-term cooling phase
- Reactor vessel inventory and behavior of the fourth-stage ADS vent valves
- The mass and energy flow of the primary system, since the flowrate and the amount of subcooling or boiling in the core affects the potential for boron plate-out on the fuel rods
- Coupled behavior between the injection source flowrate and the amount of vaporization generated in the core
- The effect of different break locations and single failure assumptions

The OSU test facility was specifically designed to model the long-term cooling portion of the AP600 transient. Sufficient instrumentation was provided to identify and quantify the long-term cooling phenomena, so that validation of WCOBRA/TRAC was accomplished. The methodology used in AP600 long-term cooling analysis cases is described in WCAP-14601 (Reference 3) and was approved by the staff for AP600.

Several issues were identified and resolved during the Staff review of the AP600 long-term cooling methodology. Foremost was the test basis for characterization of long-term cooling phenomena and the performance of WCOBRA/TRAC in predicting the tests. The scaling rationale of the OSU APEX facility during the long-term cooling phase was shown to be adequate, as were the WCOBRA/TRAC simulations of selected tests as documented in WCAP-14776. A second issue was the use of "window" mode calculations of segments of the long-term cooling transient. Using this technique the plant boundary conditions at a given time in the transient are specified as input to WCOBRA/TRAC, and the system behavior is calculated by the code for the quasi-steady-state situation under those boundary conditions. In this way, the limiting time intervals during long-term cooling can be analyzed without the need to invest in the long computer running time necessary to execute a problem for the entire long-term cooling phase. The OSU test simulations and the AP600 plant predictions were performed as windows. The Staff concluded that the WCOBRA/TRAC window mode methodology was acceptable for demonstrating the long-term cooling capability of the AP600.

2.3.3 WCOBRA/TRAC Acceptability for AP1000 Long-Term Cooling Analysis

The PIRT prepared for AP600 long-term cooling (LTC) behaviors continues to apply to the AP1000 design with no major changes, as previously noted. Reference 4 justifies that the scaling rationale of the OSU long-term cooling test facility also applies to the AP1000 plant design. Therefore, there are no additional phenomena that would require the addition of novel features to, and/or further validation of WCOBRA/TRAC for performing AP1000 long-term cooling 10CFR50.46 LOCA analyses. The simulations in WCAP-14776 predicting the OSU tests validate and justify the application of WCOBRA/TRAC to the AP1000 design certification long-term cooling ECCS performance analyses.

The WCOBRA/TRAC computer code will be applied to the AP1000 design certification long-term cooling analysis as follows:

Code Version

A special version of the WCOBRA/TRAC computer code was created for the AP600 SSAR analysis by incorporating additional capability to model the unique features of the AP600, as documented in WCAP-14776, Section 4. A similar approach will be used to perform the AP1000 design certification long-term cooling LOCA analysis. The same updates identified in WCAP-14776, Section 4 as being added to WCOBRA/TRAC for the AP600 analysis will be used in the creation of an "AP" version to perform the AP1000 long-term cooling licensing analysis. The "AP" version of WCOBRA/TRAC will include the discretionary and non-discretionary code changes that have been made since the AP600 SSAR analysis was performed, which constitute the "2000 formulation" of the code and which have been reported to the NRC by Westinghouse (Reference 11) per the 10CFR50.46 annual reporting process. The details of the code changes made since the AP600 analysis was performed are provided in Appendix A. The impact of implementing any or all of the changes in WCOBRA/TRAC is judged to be minor on the simulations of AP600 long-term cooling scenarios because they deal primarily with large break LOCA-related phenomena. The "AP" code version will also include some new models to enable WCOBRA/TRAC to supplement the NOTRUMP analysis of the ADS-4 IRWST transition phase of AP1000 small break LOCA events. These small break LOCA-related models are discussed in Appendix B.

AP600 FSER Restrictions

The AP600 FSER (Reference 8) identified three restrictions on the approval of WCOBRA/TRAC for AP600 long-term cooling analyses. The FSER-specified restrictions follow, together with the means by which the AP1000 analysis will comply with each:

1. Westinghouse shall ensure the nodalization of the AP600 design long-term cooling model corresponds to that used in the OSU calculations: the same WCOBRA/TRAC nodalization presented in WCAP-14601 (Reference 3) for AP600 will be employed in AP1000 design certification long-term cooling computations to assure that this correspondence exists. The new models added to the code to analyze the ADS-4 IRWST transition phase will not be used in the AP1000 DCD LTC analyses.

2. Westinghouse shall ensure the window time span results in a quasi-steady state solution: the window mode long-term cooling computations performed for AP1000 will be executed until the quasi-steady state condition is achieved. The AP600 SSAR Subsection 15.6.5.4C long-term cooling analyses were performed using "windows" to investigate ECCS performance at the most limiting time intervals during post-LOCA core cooling. The window mode analysis technique will again be employed in the AP1000 long-term cooling design certification cases. In addition, the case in which sump recirculation occurs earliest in time among the AP1000 long-term cooling transients (a double-ended DVI (DEDVI) LOCA break which drains the IRWST directly to containment) will be analyzed from the start of long-term cooling until containment recirculation is established. This continuous calculation technique is compared with the window mode approach result for the DEDVI break for the time interval bracketing the start of recirculation in the preliminary analysis presented in Section 3.3.3 of the AP1000 Plant Description and Analysis Report. The comparison of results shows that the WCOBRA/TRAC predictions are equivalent whether the code is run continuously or with the window-mode approach.

3. Westinghouse shall ensure 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." The design of the AP1000 Passive Core Cooling Systems precludes the possibility of core uncovery and heatup occurring during long-term cooling phase of design basis accidents.

Major Issues

The NRC staff approval of the WCOBRA/TRAC long-term cooling calculational methodology was specific to the AP600 design, based on the parameter range of the OSU experimental validation. In particular, WCOBRA/TRAC was not considered valid for the prediction of core dryout and heatup phenomena during long-term cooling because the OSU tests simulated by Westinghouse did not exhibit any core heatup or dryout phenomena.

Resolution of Issues

No core uncovery and no fuel rod heatup are predicted to occur in the AP1000 preliminary analysis of the limiting case condition. Based on this confirmation of the AP1000 design basis, no core uncovery or fuel rod heatup is anticipated to occur in the long-term cooling phase of any postulated scenario in the AP1000 design certification analysis. The LTC analyses are conservative because they are performed in accordance with Appendix K of 10CFR50.

As stipulated in NUREG-1512, the WCOBRA/TRAC nodalization used in the DEDVI break analysis in the AP1000 Plant Design Report (Reference 12) is unchanged from the AP600 SSAR noding; this same nodalization will be used in the AP1000 design certification long-term cooling ECCS performance analyses.

Conclusions

The PIRT and scaling review of WCAP-15613 shows that there are no new phenomena involved in the AP1000 safety performance during LTC relative to AP600, and that the OSU facility data continue to apply to the AP1000. Therefore, the validation of the WCOBRA/TRAC computer code for post-LOCA long-term cooling analysis against the OSU data applies to AP1000 as well. The WCOBRA/TRAC computer code and nodalization scheme previously approved for AP600 long-term cooling analysis therefore applies to the AP1000 design certification long-term cooling ECCS performance analysis.

2.4 ASSESSMENT OF DG-1096 RELATED ISSUES

In a recent workshop (April 9, 2001) held to discuss Draft Regulatory Guide DG-1096, several attributes were discussed which should be considered in determining the extent to which the DG process should be used in the development, assessment, and application to an evaluation model. These are:

- Novelty of the evaluation model compared to the currently acceptable model.
- The complexity of the event being analyzed.
- The degree of conservatism of the evaluation model.
- Risk or safety importance of the event.

For the AP1000 analysis program, the WCOBRA/TRAC-AP code contains the models and correlations which were reviewed by the NRC staff and approved as comprising a best-estimate large break LOCA code for 3-loop and 4-loop Westinghouse plants consistent with the guidance provided in Regulatory Guide 1-157. WCOBRA/TRAC was later approved for the AP600 large break LOCA analysis application in Reference 8. There are no novel changes in WCOBRA/TRAC-AP for large break LOCA analysis relative to the code version approved for AP600, only the discretionary and non-discretionary changes delineated in Appendix A.

Therefore, WCOBRA/TRAC-AP has already undergone the type of review envisioned for a best-estimate large break LOCA analysis computer code in DG-1096.

The DG-1096 attributes are discussed for the AP1000 LTC application of WCOBRA/TRAC-AP below:

- The code version to be utilized for the AP1000 program, is the same as that utilized for the AP600 program with the discretionary and non-discretionary changes being implemented as discussed in Appendix A of this document. As such, no significant changes are being made to the code as approved for AP600 applications.

- The AP1000 long-term cooling period is not considered to be a complex event. Nevertheless, this event and WCOBRA/TRAC were thoroughly reviewed for application to the AP600 plant design. Preliminary analyses with the approved AP600 code version did not indicate the existence of new phenomena for the AP1000 design compared to those observed for the AP600 design during LTC.

- The LTC evaluation model and methodology continue to be based on the use of Appendix-K required features. As such, the result will be a conservative calculation with respect to the expected plant response.

- The preliminary AP1000 analyses, presented in Reference 9, indicate no significant change in the margin to core uncovery during the limiting LTC event. As such, significant margins to the 10 CFR 50.46 limits exist for this plant design.

2.5 REFERENCES

1. Regulatory Guide 1-157, "Best-Estimate Calculations of Emergency Core Cooling System Performance."

2. WCAP-12945-P-A, Volumes 1-5, "Code Qualification Document for Best-Estimate LOCA Analysis," Bajorek, S. M., et al, 1998.

3. WCAP-14601, Revision 2, "AP600 Accident Analyses - Evaluation Models," 1998.

4. WCAP-15613, "AP1000 PIRT and Scaling Assessment," February 2001.

5. WCAP-14171, Rev. 2, "WCOBRA/TRAC Applicability to AP600 Large-Break Loss-of-Coolant-Accident," Hochreiter, L. E., et al, March 1998.

6. Siemens Report E314/90/17, "Upper Plenum Test Facility, Test 21," Seimens, A. G. (KWU), 1990.

7. JAERI-Memo 59-446, "Data Report on Large-Scale Reflood Test-78 (RUN 058)," Okubo, T., et al, 1985.

8. NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," U.S. Nuclear Regulatory Commission, September 1998.

9. AP600 design Control Document (DCD), Westinghouse Electric Corporation, 1999.

10. WCAP-14776, Revision 4, "WCOBRA/TRAC OSU Long-Term Cooling Final Validation Report," Garner, D. C., et al., March 1998.

11. Letter LTR-NRC-01-6 from H. A. Sepp, Westinghouse to J. S. Wermiel, USNRC, "10CFR50.46 Annual Notification and Reporting for 2000," March 13, 2001.

12. WCAP-15612, "AP1000 Plant Description and Analysis Report," December 2000.

Table 2-1 Assessment of the AP1000 LBLOCA Processes

LOCA Process	AP1000 Uniqueness WRT W Plants	WC/T Validation Does It Exist	AP1000-Specific Validation Needed	Comments
BLOWDOWN				
Critical flow	None	Yes	None	
Post-critical heat flux heat transfer Transient critical heat flux Rewetting Film boiling	None	Yes	None	
Structure heat transfer	Yes, internals	Yes, not AP1000-specific	Not needed, code can calculate	
Accumulator mixing	None	Yes	None	
Accumulator bypass	None	Yes	None	
2φ differential pressure in loops	None	Yes	None	
SG heat transfer	None	Yes	None	
High-head safety injection	Yes, CMT delivery, behavior	No	Not needed, code can calculate	Very little CMT delivery occurs before PCT is calculated
Pump 2φ behavior	Yes, canned rotor	No	No	Homologous curve data used in WCOBRA/TRAC

Table 2-1 (cont.) Assessment of the AP1000 LBLOCA Processes

LOCA Process	AP1000 Uniqueness WRT W Plants	WC/T Validation Does It Exist	AP1000-Specific Validation Needed	Comments
REFILL/REFLOOD				
ECCS bypass entrainment	Yes, accumulator delivery in downcomer	No	No; validation for AP600 applies to AP1000	Model UPTF, CCTF downcomer injection tests
Noncondensable gas effect	None	Yes	None	LOFT, W steam/water mixing
Post-CHF heat transfer	None	Yes	None	
Structural heat transfer	Yes, internals	Not specific	None	Not needed, code can calculate
Safety Injection	Yes, delivery into downcomer	No	No; validation for AP600 applies to AP1000	No CMT delivery during this period
Steam generator behavior	None	Yes	None	
Two-loop differential pressure	None	Yes	None	
REFLOOD				
Safety Injection	Yes, downcomer delivery	No	No; validation for AP600 applies to AP1000	UPTF, CCTF downcomer DVI injection data exist
Accumulator behavior	Long-term delivery	Yes, short-term for LOFT	No	LOFT data provides verification; other plant data available
Core heat transfer	None	Yes	None	
Structure heat transfer	Yes, internals	Not specific	Not needed	LOFT test had structures typical of a PWR

Table 2-1 (cont.) Assessment of the AP1000 LBLOCA Processes

LOCA Process	AP1000 Uniqueness WRT W Plants	WC/T Validation Does It Exist	AP1000-Specific Validation Needed	Comments
SG effects	None	Yes	None	
Vessel/de-entrainment	None	Yes	None	
Pump differential pressure	Yes, canned rotor	Yes, other pumps	None	Pump is a known resistance

Table 2-2 WCOBRA/TRAC Validation
Core Heat Transfer
FLECHT-SEASET reflood
FLECHT COSINE reflood
FLECHT SKEW reflood
G-2 reflood
FEBA reflood
G-1 blowdown
G-2 blowdown
Oakridge National Laboratory film boiling
Fuel Rod Cladding Materials/Nuclear Rod
NRU reflood
NRU materials test
Fluid Mechanics Two-Phase Flow
Creare 1/15-, 1/5-scale ECCS bypass
UPTF ECCS bypass cold leg injection
1/14-, 1/3-scale cold-leg steam/water mixing
UPTF cold leg steam/water mixing
APWR 2-Phase pressure drop
Marviken critical flow tests
UPTF upper plenum de-entrainment
WCOBRA/TRAC Systems Effects Tests Verification
System Response
LOFT L2-2, L2-3, L2-5, LB-1
Semiscale mod 3 series 7
CCTF cold-leg injection tests
SCTF cold-leg injection tests

Table 2-3 Long-Term Cooling Processes

Long-Term Cooling Process	AP1000 Uniqueness WRT W Plants	Long-Term Cooling Model/ Verification Does It Exist	AP1000 Specific Validation Needed	Comments
Natural circulation	Loop 2-phase natural circulation	Yes, but not with passive safety systems	No, systems data available on AP600 specific geometry apply to AP1000	Frictional/elevation heads of the OSU APEX facility are properly scaled for AP1000
	Multiple breaks	No		
	Water delivery into downcomer	No		
	Mass distribution	No		Code can handle multiple breaks and flow paths
Long-term core heat removal	Gravity feed natural circulation, possible 2-phase flow effects	No, not in AP1000 configuration	No, OSU APEX integral systems test data apply to AP1000	Code can handle multiple breaks and flow paths; OSU systems test data has been used for code validation
Long-term SG heat removal	Yes, ADS reduces flow to SG	Yes, FLECHT-SEASET ROSA-IV, LOFT, Semiscale	None	AP1000 is less sensitive to SG behavior than conventional PWR

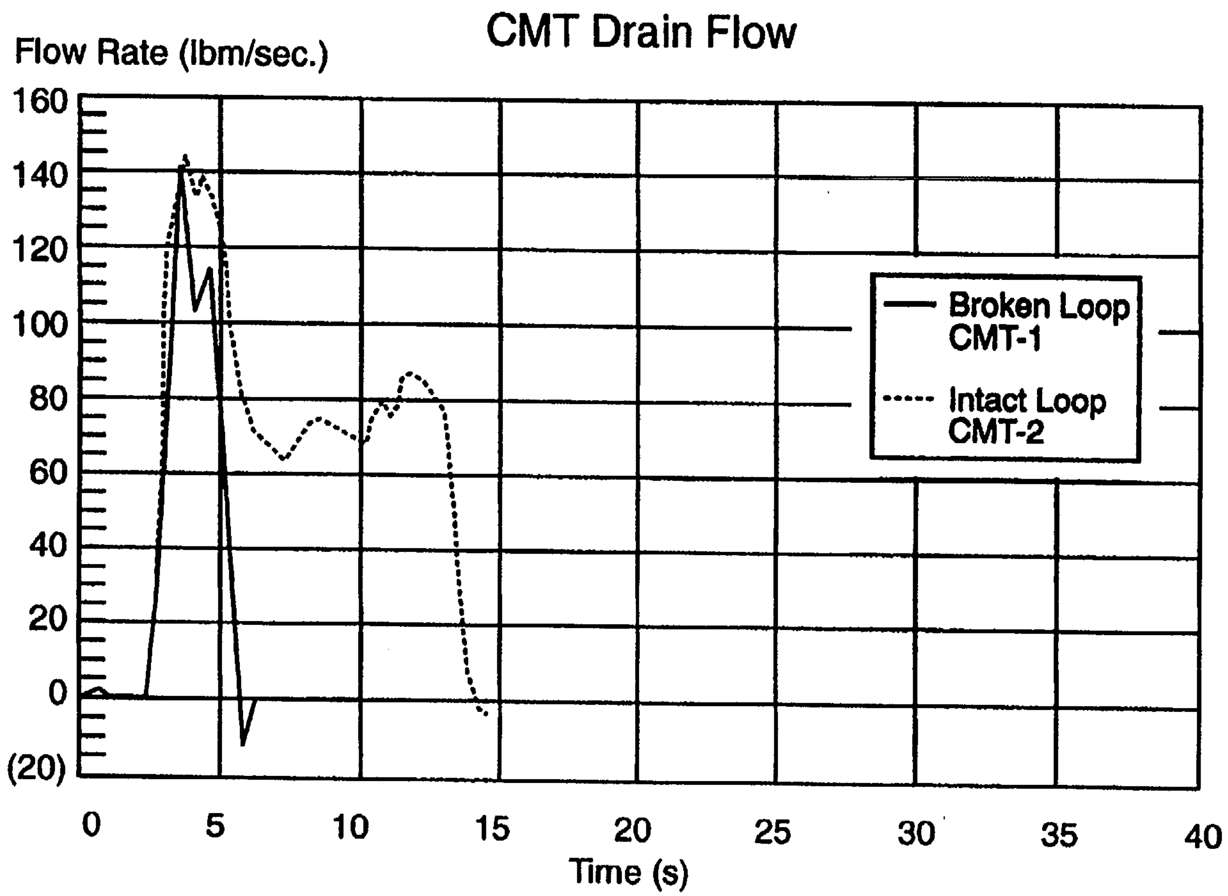

Figure 2-1 CMT Injection for an AP600 LBLOCA

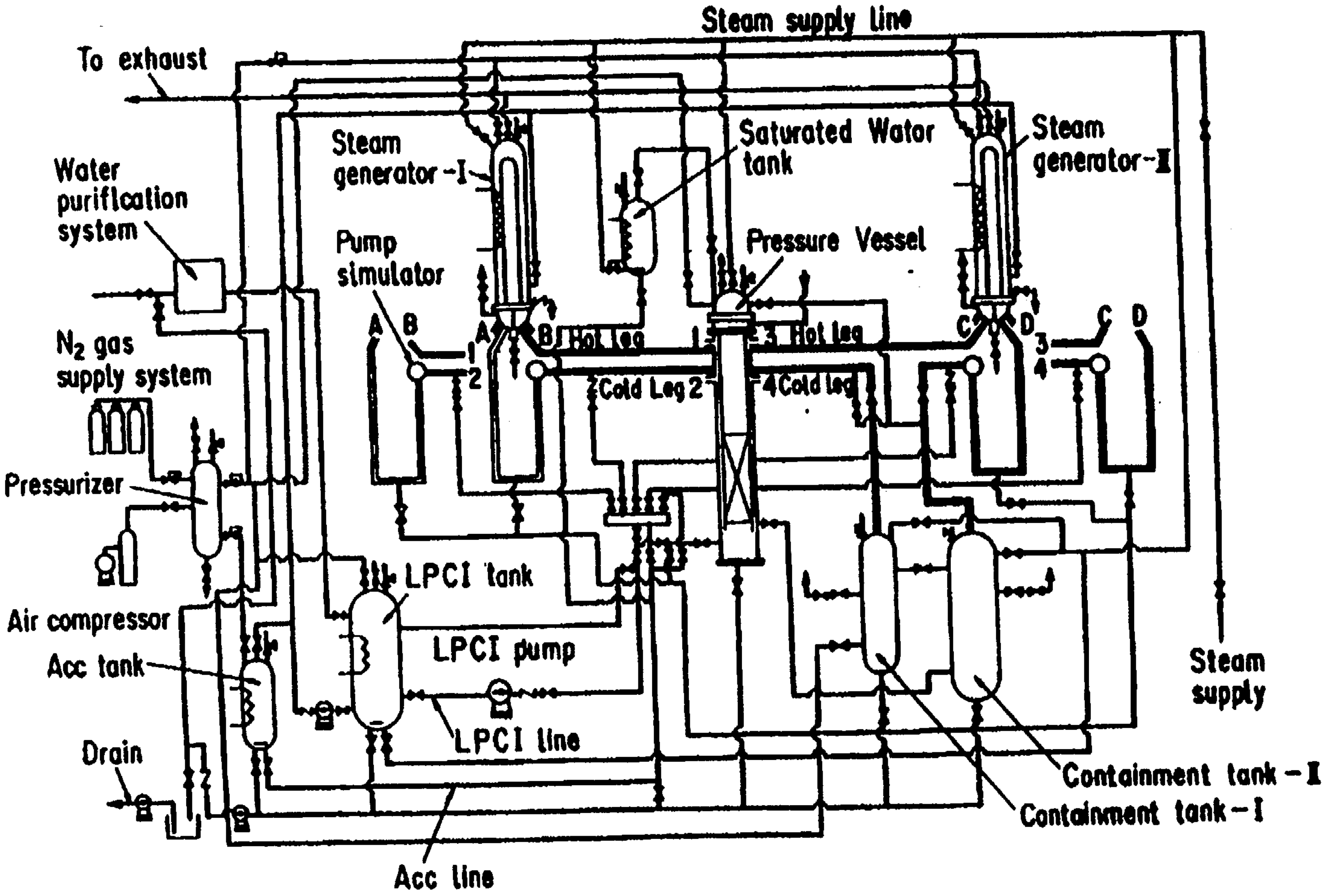

Figure 2-2 Japanese CCTF Test Facility

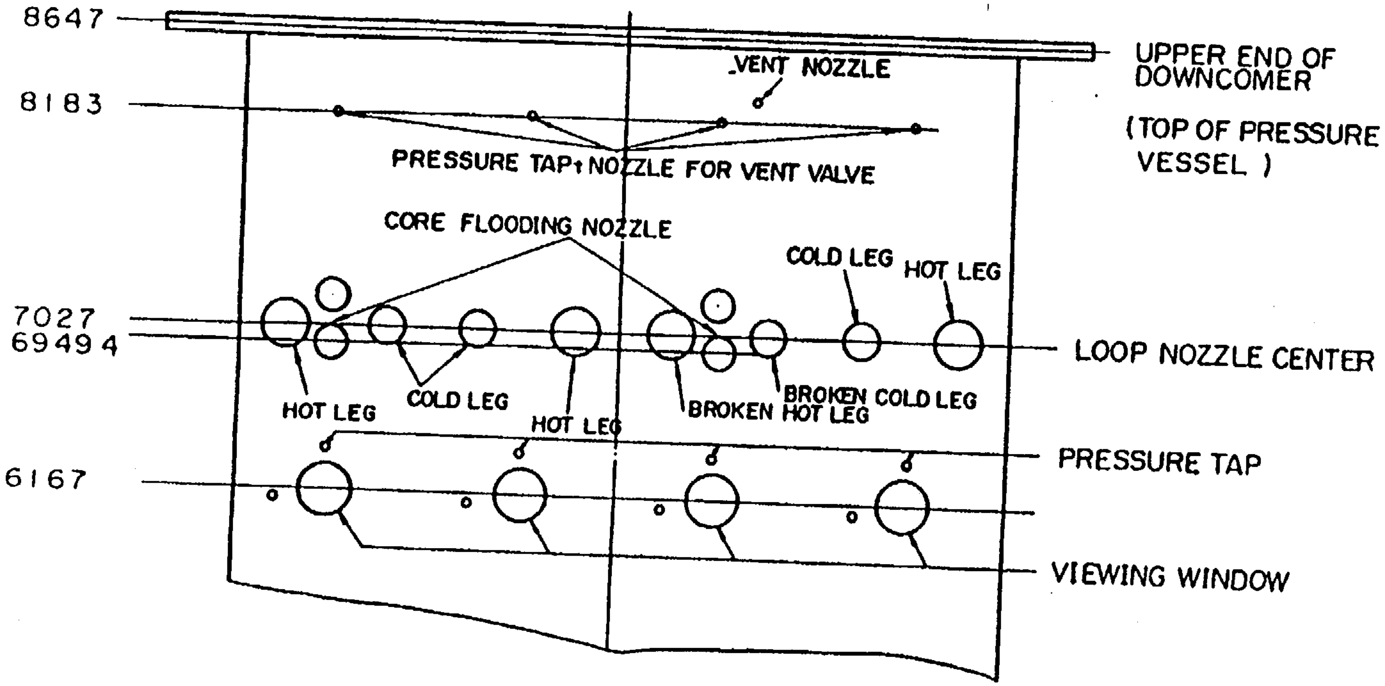

Figure 2-3 Japanese CCTF Vessel and Downcomer Geometry

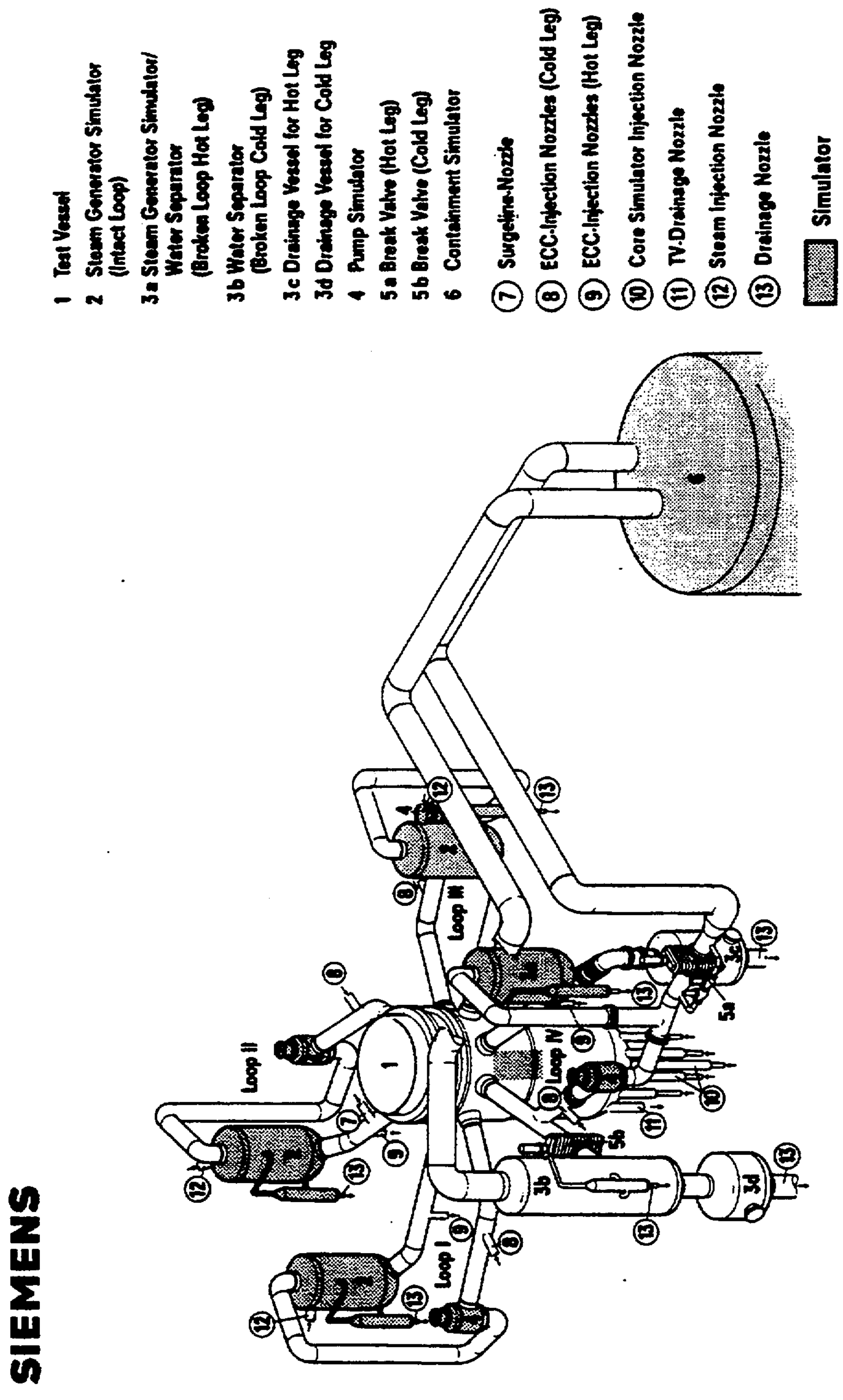

Figure 2-4 Upper Plenum Test Facility

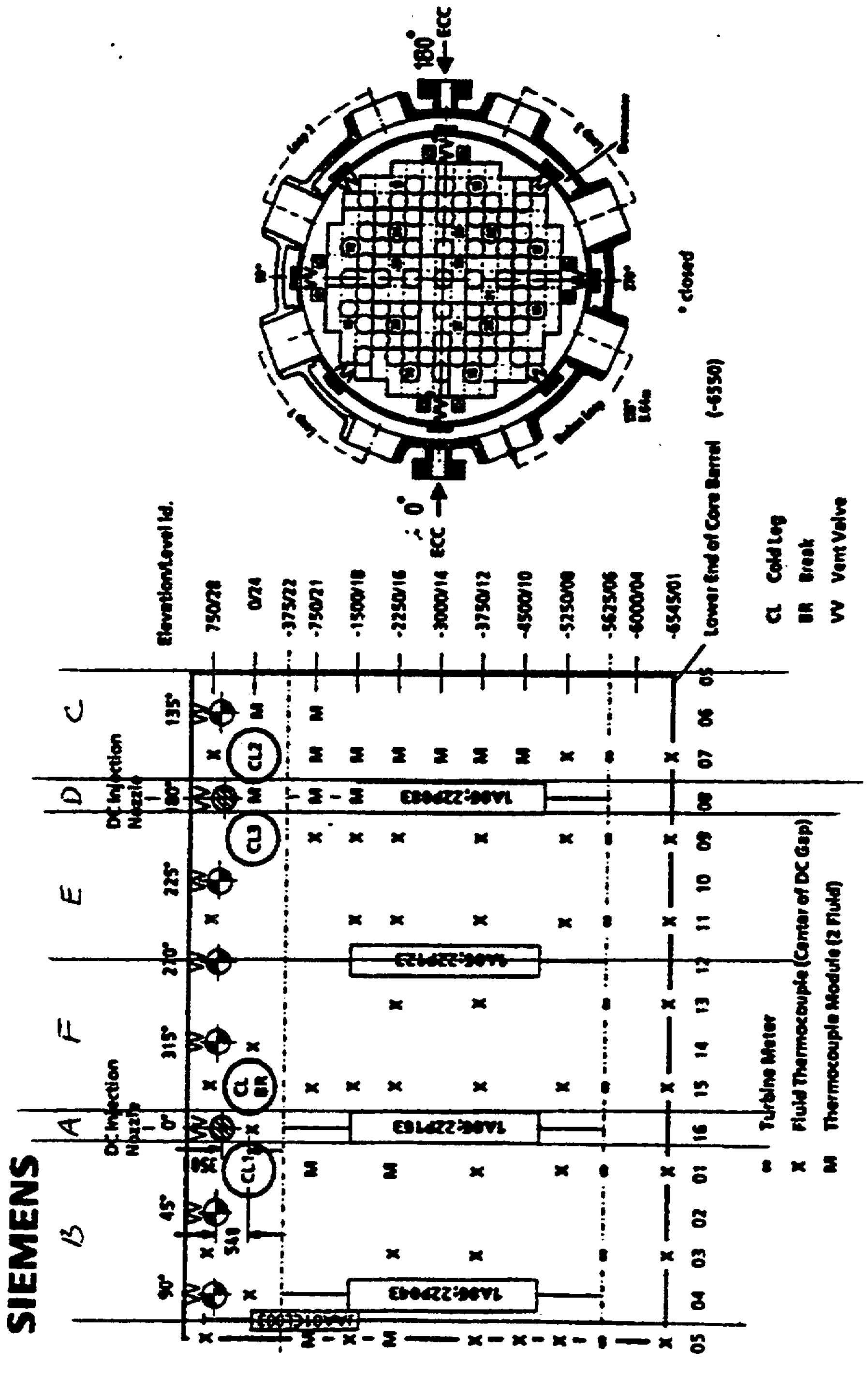

Figure 2-5 Upper Plenum Test Facility Vessel and Downcomer Geometry

3.0 NOTRUMP VALIDATION FOR SMALL BREAK LOSS-OF-COOLANT ACCIDENT

3.1 BACKGROUND

The NOTRUMP code used for the AP600/AP1000 calculations consists of the modeling features that meet the requirements of Appendix K to 10CFR Part 50. The NOTRUMP code as documented in WCAP-10079-A and WCAP-10054-A (References 1 and 2), was previously approved by the NRC for small break LOCA (SBLOCA) analyses on conventional Westinghouse Pressurized Water Reactors (PWRs). The acceptance criteria for Emergency Core Cooling Systems (ECCS) for light-water nuclear power reactors, given in 10CFR50.46, require that ECCS performance be calculated in accordance with an acceptable evaluation model. Two approaches may be taken to demonstrate that an acceptable model has been applied to an ECCS design. In one approach (commonly referred to as a "best estimate"), the evaluation model must contain sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a LOCA. This necessitates comparisons to applicable experimental data along with identification and assessment of uncertainty in the analysis methods and inputs so that the uncertainty in the calculated results can be estimated. This uncertainty must then be accounted for in subsequent calculations. Alternatively, an ECCS evaluation model may be developed in conformance with the required and acceptable features of 10CFR Part 50, Appendix K, and ECCS evaluation models. Westinghouse chose to demonstrate the acceptability of the SBLOCA response of the AP600 passive reactor design using an Appendix K ECCS evaluation model.

To support this effort, a version of the NOTRUMP code, modified for the AP600 application, was developed and is documented in WCAP-14807, "NOTRUMP Final Verification and Validation Report" (Reference 3). Modifications performed to the basic NOTRUMP model enabled proper analysis of the AP600 and the supporting test matrix. A summary of the features added to NOTRUMP, which comprises the AP600 version (notrump-ap600), is as follows:

- SIMARC (SIMulator Advanced Real-time Code) drift flux methodology implementation
- 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 EPRI/Flooding vertical drift flux model

- 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 the 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 Levelizing model implementation
- Revised Unchoking model implementation
- Implementation of a revised Condensation heat link model
- Implementation of Zuber Critical Heat Flux model
- Revised Two-Phase Friction Multiplier logic
- Addition of the Henry-Fauske/HEM Critical Flow Correlation
- Improved Flux Node Stacking model logic
- Revised iteration method for Transition Boiling Correlation in metal node heat links

NOTRUMP was validated against the AP600 test data that includes all the unique features of the AP600 passive safety system design. This validation includes the Automatic Depressurization System (ADS), Core Makeup Tank (CMT), and integrated system response from SPES-2 and OSU. The AP600 Code Applicability Document (Reference 4) discusses NOTRUMP and its application to the AP600 SBLOCA analysis, providing the basis for NRC review of NOTRUMP for the AP600 design. The purpose for the integral systems tests was to provide the database to cover the range of applicability for NOTRUMP, as well as other codes.

The NOTRUMP code was compared to the separate effects AP600 test results and both integral systems tests. The process of comparing the code to the data is shown in Figure 3-1, in which the specific correlations in the code were compared to the separate effects tests while the code, as a whole, was compared to the integral systems tests. Figure 3-2 shows the relationship between the separate effects tests and the integral systems tests for the NOTRUMP code.

Using the integral test results as a guide, the separate effect tests and/or the literature were used to improve particular models or correlations. The resulting improved code, with revised correlations, was then compared to the integral systems test results, as shown in Figure 3-1. The detailed documentation associated with the NOTRUMP validation effort can be found in Reference 3 and subsequently resulted in the issuance of the NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design" (Reference 5) by the USNRC. This FSER applies to Version 35.0 of the NOTRUMP code utilized for AP600 applications (i.e., notrump-ap600).

For application to the AP1000 plant design, the same NOTRUMP computer code, as approved for AP600 analyses, will be utilized with only code error corrections, as reported and assessed in the annual 10CFR50.46 reporting letters (References 6–8), and additional user convenience features being implemented. Summaries of the corrections performed and their impact on the AP600 analyses were determined by performing an AP600 specific calculation (see Appendix C for additional details). A summary of the impacts are as follows:

- Correction to a coding error for the implicit treatment of gravity head in NOTRUMP continuous contact flow links. This correction was deemed to have a negligible impact on the AP600 plant response.
- Correction to an error discovered in the implementation of certain droplet fall models in NOTRUMP. This correction was deemed to have a negligible impact on the AP600 plant response.
- Inconsistent updating of certain mass and volumetric rate variables during portions of the SBLOCA transient. [

  ]^{a,b,c}

Errors were discovered in the AP600 NOTRUMP code following the termination of code error tracking (subsequent to the release of NOTRUMP Version 37.0). These errors, while corrected in the standard NOTRUMP Evaluation Model (Version 38.0), were not implemented in the code utilized in the scoping analysis (Reference 9). Since an AP600 specific assessment of these errors was not available, the estimated impact on the AP600 design was determined based on the results from traditional PWR simulations [ ]^{a,b,c}.These errors will be corrected prior to utilizing the NOTRUMP code for the AP1000 analysis. The errors and their expected impact on AP600/AP1000 analyses are as follows:

- Correction to mixture level tracking/region depletion model errors. A majority of this correction involved the implementation of the AP600 developed mixture level tracking model into the standard Evaluation Model; however, an improvement (non-error correction) was performed which would impact the AP600 version of the code as well. The correction involves the treatment of metal node properties when fluid nodes, to which the metal nodes are connected, have depleted their inventory in a given time step. Due to the nature of the AP600/AP1000 SBLOCA transient, this change is expected to have a negligible impact on results.

To confirm the conclusion reached regarding the impact of the region depletion model correction on the AP600 design, an AP600 specific simulation will be performed with the corrected code version. However, [ ]^{a,b,c} implementation of this correction did not have a significant impact on conventional Westinghouse PWRs, and it is not expected to have a significant impact on the passive plant analysis.

3.2 CODE ACCEPTABILITY AP600

The following sections present the basis for the acceptability of the NOTRUMP code to the AP600 plant design as excerpted from the AP600 FSER (NUREG-1512, Reference 5). The italicized text is excerpted directly from the AP600 FSER.

3.2.1 Code Acceptability Basis – FSER

Westinghouse performed SBLOCA analyses using the NOTRUMP code as documented in WCAP-14206 (Reference 4) and WCAP-14807 (Reference 3). NOTRUMP was assessed as a 10CFR50.46, Appendix K evaluation model. The acceptability of NOTRUMP for AP600 application was documented in NUREG-1512 (Reference 5). This acceptability was based on the review of the AP600 SBLOCA analytical results, Phenomena Identification and Ranking Table, analytical models, component models, code qualification, regulatory compliance and ACRS review. The following sections present the major areas of review and the conclusions reached by the ACRS and the NRC staff.

3.2.1.1 SBLOCA Analysis Results

The SBLOCA analyses performed in support of the AP600 design met the following acceptance criteria for the calculated ECCS performance:

- *The calculated peak cladding temperature (PCT) is less than 1204°C (2200°F).*
- *The calculated total oxidation of the cladding is within 0.17 times the total cladding thickness before oxidation.*
- *The calculated total amount of hydrogen generated is less than 0.01 times the hypothetical amount that can be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, are to react.*
- *Any calculated changes in core geometry will be such that the core remains amenable to cooling.*
- *After any calculated successful initial operation of the ECCS, the calculated core temperature will be maintained at an acceptably low value and decay heat will be removed for the extended time required by the long-lived radioactivity remaining in the core.*

These criteria were established to provide significant margin for ECCS performance following a LOCA. The staff found that these acceptance criteria were consistent with the requirements of 10CFR50.46 (b)(1) – (b)(5) for ECCS performance and, therefore, were acceptable.

Westinghouse performed the SBLOCA analyses with the NOTRUMP code for eight cases:

1. *25.4-cm (10-inch) cold-leg break*
2. *double-ended CMT balance line break (17.8-cm [7-inch] in equivalent diameter)*
3. *double-ended rupture of direct vessel injection line (10.2-cm [4-inch] in equivalent diameter)*
4. *5.08-cm (2-inch) cold-leg break in the Passive Residual Heat Removal (PRHR) loop*
5. *5.08-cm (2-inch) cold-leg break in the CMT loop*
6. *6.14-cm (2.4-inch) inadvertent opening of ADS flow paths*
7. *1.27-cm (0.5-inch) cold-leg break*
8. *5.08-cm (2-inch) hot-leg break*

Major assumptions made in the SBLOCA analyses were as follows:

- *As required by Appendix K to 10CFR Part 50, the initial core power is assumed to be 102 percent of the nominal core power and the ANS-1971 decay heat plus 20 percent is used.*
- *Accumulators are initiated at a pressure of 4.83 MPa (700 psia).*
- *The PRHR is opened with the maximum delay of 21.2 seconds after initiation of an "S" signal to delay the cooling capability of the heat exchanger to the RCS.*
- *The "S" signal is actuated when the pressurizer pressure decreased below 11.72 MPa (1700 psia). The CMT isolation valves are opened with the maximum delay of 21.2 seconds after the "S" signal to minimize its contribution to RCS inventory in the initial stage of larger SBLOCAs. The main feedwater isolation valves are ramped closed between 5 and 10 seconds after the "S" signal. The RCPs are tripped 16.2 seconds after the "S" signal.*
- *The ADS actuation signals are taken from the lower of the two CMT levels to be consistent with the CMT actuation delay feature.*
- *The SG isolates (by closure of the turbine stop valves) 1 second after the reactor trip signal to maximize the SG secondary energy. The SG safety valves actuate when the SG pressure reaches 7.58 MPa (1100 psia).*

The results showed the 10-inch break case to be the limiting SBLOCA case with a calculated PCT of 453°C (848°F). The analytical results met the acceptance criteria of 10CFR50.46, Appendix-K with large margins to the acceptance limits. As a result, the staff concluded that the SBLOCA analysis was acceptable.

3.2.1.2 Phenomena Identification and Ranking Table

It was important to identify all physical phenomena that would occur in the AP600 under accident conditions of interest to ensure that the important physical processes and phenomena were modeled. One method of identification was through the development of a PIRT. The PIRT methodology provides a framework where physical processes and phenomena in a specific hardware geometry under anticipated accident sequences are first identified and then ranked in terms of their importance to the course of the analysis. A PIRT is generally developed from expert opinions provided by a group of knowledgeable analysts. The use of a group of experts, rather than a single analyst, increases the chances that all important phenomena have been identified and included in the PIRT, and that the rankings have accurately characterized each specific phenomena as being of high, medium, or low importance to the integral quantities of interest. A properly established PIRT acts as a road map through a transient, identifying and ranking the important phenomena and functions necessary to predict and deal with each phase of a transient. The PIRT for AP600 SBLOCA can be found in WCAP-14807.

The staff also developed a PIRT as part of the review and confirmatory process. The NRC PIRT for the AP600 SBLOCA is documented in a report from Idaho National Engineering Laboratory, INEL-94/0061, Revision 1. The PIRT prepared by Westinghouse divided the SBLOCA into four intervals: (1) blowdown, (2) natural circulation, (3) ADS blowdown, and (4) In-containment Refueling Water Storage Tank (IRWST) injection cooling. Within each interval, the specific hardware and phenomena were evaluated as having high (H), medium (M), or low (L) importance. The NRC PIRT contained five intervals. The hardware functions and phenomena within two of the NRC PIRT intervals, "Passive Decay Heat Removal" and "CMT Drain to ADS Actuation," were accounted for in the Westinghouse PIRT interval "Natural Circulation." Therefore, all hardware functions and phenomena were accounted for. The Westinghouse PIRT and the NRC PIRT were deemed to be comparable.

Westinghouse also submitted a list of the important phenomena and hardware items identified in the PIRT with a description of the test program, and planned benchmark and assessment calculations which would provide supporting validation for the plant analyses.

The staff compared the Westinghouse and NRC PIRTs and found that all high- and medium-ranked phenomena are captured both in the PIRTs and in the testing program. As a result, the NRC staff found the Westinghouse PIRT to be applicable to the AP600 passive reactor design.

Refer to Section 2.4 of the AP1000 PIRT and Scaling Assessment (Reference 10) for the details of the SBLOCA PIRT.

3.2.1.3 Evaluation of the NOTRUMP Analytical Models

NOTRUMP is a general (variable) nodalization code. Plant models are constructed from generalized control volumes (fluid and metal nodes), flow links, heat sources, and heat sinks. The nonequilibrium thermodynamics and hydraulics include several drift-flux options to calculate relative vapor/liquid velocities (slip). Fission heat is calculated using reactivity and reactor kinetics. The code has an extensive number of forced- and natural-convection heat transfer correlations covering the spectrum of the boiling curve.

Critical flow correlations available include the Moody model, a modified Zaloudek model, and the Murdock-Baumann model. Special-purpose models include flooding, bubble rise, mixture level tracking, a continuous contact flow link, variable flow links, a horizontal stratified flow model, and externals which provide the user flexibility to "program" user specific modifications. Component models include an accumulator, a centrifugal pump, steam separators, and a fuel rod model. The user has available control volumes, flow paths, and heat slabs which can be used to control pressure, enthalpies, mixture levels, mass flows, and heat fluxes as a function of time. Simple valves are simulated as input flow loss coefficients.

Application of the approved NOTRUMP computer code to the AP600 passive reactor design required a number of modifications, or enhancements, to the basic NOTRUMP models. Nineteen modifications were made to the models as follows:

1. *Add the SIMARC drift-flux model.*
2. *Modify the drift-flux correlations.*
3. *Recast the momentum equations for net volumetric flow.*
4. *Add the NOTRUMP EPRI/Flooding Drift-Flux Model.*
5. *Modify contact coefficients.*
6. *Add internally calculated liquid reflux flow links.*
7. *Add mixture overshoot logic.*
8. *Add implicit treatment of bubble rise.*
9. *Modify the pump model.*
10. *Add implicit treatment of momentum equation gravitational head terms.*
11. *Modify horizontal flow drift-flux levelizing model.*
12. *Add an Unchoking Model.*
13. *Add Shah condensation correlation.*
14. *Add Zuber critical heat flux correlation.*
15. *Change the two-phase friction multiplier.*
16. *Add Henry/Fauske model and homogenous equilibrium model.*
17. *Modify fluid node stacking logic.*
18. *Modify transition boiling correlation solution.*
19. *Revised code numerics.*

All models described above were reviewed by the staff and deemed to be acceptable for analysis of the AP600 SBLOCA.

3.2.1.4 Evaluation of the NOTRUMP AP600 Component Models

In addition to the NOTRUMP model modifications, hardware-specific component models were added to represent AP600-unique hardware features. Component model additions comprise the following:

- *ADS*
- *CMT*
- *PRHR Heat Exchanger (HX)*
- *IRWST*

The following is a brief summary of the component models added to the NOTRUMP code.

Automatic Depressurization System

The ADS is designed to depressurize the RCS to values near the prevailing containment pressure to enable gravity injection from the IRWST. Three stages of the ADS come off the top of the pressurizer; the fourth-stage ADS paths are connected to the hot legs. The first stage ADS is actuated when 33 percent of a CMT liquid has drained, resulting in the depressurization of the plant via the ADS valves to the IRWST. The second and third stage ADS valves open on the basis of timers that are started with the actuation of the first stage and also discharge to the IRWST. If the CMTs continue to drain, the fourth stage ADS will actuate when 80 percent of the liquid has drained from a CMT. The fourth stage ADS valves, located on the hot legs, open directly to the containment to facilitate depressurization to the containment pressure.

For critical flow, the NOTRUMP code compared well with flow data from the ADS tests, which indicates that the critical flow models in NOTRUMP perform acceptably for the calculation of flow through the ADS valves. This is a highly ranked PIRT item. However, NOTRUMP tends to underpredict the upstream piping pressure drop in the tests and overpredicts the pressure drop of the ADS valve. When the flow in the ADS valve is choked, NOTRUMP overpredicts the pressure drop. However, the overall ADS system pressure drop is predicted well, resulting in correct prediction of ADS choked flow. This situation raised a concern about the models and how they affect the fluid conditions at the entrance to the ADS piping. Westinghouse reviewed the ADS 1-3 test data and determined that the data reduction was performed correctly. The staff reviewed a comparison of the pressure, flow rate, and timing results for the SPES and OSU tests, and the responses to the staff's concerns and found them acceptable.

Core Makeup Tank

There are two CMTs connected to the RCS by normally open isolation valves on the cold-leg balance lines and normally closed isolation valve on the CMT discharge lines. The CMTs provide high-pressure, gravity-driven, borated coolant injection into the RCS to provide reactivity control and core cooling. The CMT discharge valves open on a safety (S) signal and remain open. During normal operation, the CMTs and the cold-leg balance lines are completely filled with liquid.

The AP600 CMTs are new hardware designed subsequent to the guidance of NUREG-0737. WCAP-14807 documents the results of comparisons between the data obtained in the tests and the NOTRUMP calculations. The comparisons indicate that NOTRUMP, when using a multi-node CMT model, gives a reasonable prediction of the temperature distribution within the CMT. Also, the CMT pressure is predicted reasonably well and the outflow of the CMT is predicted within the error bounds on the data. Because the NOTRUMP code does not have a thermal stratification model, the predicted temperature of the injected CMT fluid is usually higher than the measured temperature, and the start of CMT draining is frequently delayed. Each of these inaccurate code predictions was deemed to be conservative; therefore, the staff found the NOTRUMP model for the CMTs acceptable for evaluations of the AP600 SBLOCA.

Passive Residual Heat Removal Heat Exchanger

The PRHR system is a C-shaped, single-pass, downflow heat exchanger, submerged in the IRWST. The system inlet connects to the top of the horizontal hot-leg section containing the pressurizer loop. The system outlet connects to the bottom of the pressurizer loop steam generator outlet plenum. Normally closed isolation valves open to actuate the system on a safety (S) signal.

The PRHR HX is immersed in the IRWST. Heat transfer is modeled using the standard NOTRUMP heat transfer correlations plus, on the inside of the tubes, the Shah correlation, as discussed above for condensation modeling, and the Lienhardt and Dhir modified Zuber correlation for critical heat flux on the IRWST side of the tubes.

After review of the integral system assessments included in WCAP-14807, the staff notes that the PRHR HX heat transfer calculated by NOTRUMP for the SPES and OSU transients is lower than that measured in the experiments. This is a conservative result, and therefore, the staff accepted the NOTRUMP PRHR model for analysis of the AP600 SBLOCA.

In-Containment Refueling Water Storage Tank

The IRWST provides a source of water for gravity feed injection into the RCS once RCS pressure has been reduced to values near the containment pressure. The IRWST also serves as a heat sink for the removal of heat via the PRHR discussed above and a discharge reservoir for the first three stages of the ADS. Condensation of steam in the containment provides a long-term source of water to the IRWST, which can then return to the RCS. Although not part of the IRWST, the containment sump provided a second source of gravity fed coolant injection into the RCS over the long term.

The NOTRUMP analyses were performed for a range of SBLOCAs for both the SPES and OSU integral facilities. The comparisons between NOTRUMP calculations and experimental data for the SPES and OSU tests, documented in WCAP-14807, show acceptable agreement. The IRWST injection line flows, outlet flows, and PRHR inlet and outlet temperatures were predicted reasonably well. The staff found the NOTRUMP IRWST model acceptable for analysis of the AP600 SBLOCA.

3.2.1.5 Code Qualification

Qualification, or assessment, of the NOTRUMP code and its models was carried out in three areas: (1) benchmark calculations, (2) separate-effects tests, and (3) integral systems tests. The combination of benchmark calculations, separate-effects tests, and integral systems tests, when properly applied, leads to overall conclusions regarding the ability of a computer code to adequately predict the behavior of a nuclear power plant subjected to upset and accident conditions. Because no single test captures all of the relevant phenomena, it is necessary to utilize all three categories to adequately cover the phenomena of interest. The three categories are discussed below.

Benchmark Calculations

Benchmark calculations are useful to demonstrate that logic interactions do not result in numeric instabilities, or physically unrealistic results. In general, these benchmark problems consist of thought *problems (hypothetical problems not on the basis of data from an actual test facility) and simple nodal models to verify a particular code function or single phenomenological behavior. Assessment of the NOTRUMP code via benchmark calculations was performed for areas involving changes to the previously approved code such as the reactor coolant pump models, plus those areas involving logic changes and additions to the code. Extensive logic modifications were made, as previously discussed, involving mixture level overshoot, fluid node stacking, and bubble rise. Many of these logic models interact during the calculation of the SBLOCA. Separate from the assessment of the overall performance of these models in predicting the integral test facility behavior, benchmark calculations were performed for the following models:*

- *NOTRUMP EPRI/flooding drift-flux model*
- *Horizontal drift-flux levelizing model*
- *Net volumetric flow-based momentum equation*
- *Implicit treatment of gravitational head*
- *Implicit treatment of bubble rise*
- *Pump model*
- *Fluid node stacking logic*

In WCAP-14807, Westinghouse used the benchmark calculations to demonstrate that NOTRUMP calculated results for each case that agreed with the logical expectations for that case. No unrealistic model interactions were uncovered and no numeric instabilities were encountered. The staff reviewed each of the benchmark calculations performed and found the models acceptable for the analysis of AP600 SBLOCA events.

Separate Effects Tests – Two-Phase Level Swell

Assessment of the NOTRUMP code against separate-effects tests permits the isolation of individual models within the code such that the capabilities of the model can be determined while remaining within the context of the code.

The two-phase level swell can be an important phenomenon during an SBLOCA. Although the AP600 SBLOCA is not predicted to result in core uncovery, a two-phase mixture will exist in the upper vessel regions and therefore, the code must be capable of predicting the location of a two-phase level. The two-phase level swell model extensions to accommodate the low pressures anticipated in the AP600 SBLOCA were assessed by comparisons with data obtained in three test facilities. Westinghouse analyzed tests from the G-2 test program, from the General Electric (GE) level swell test program, and from the Achilles systems test program.

The three test programs, given above, were chosen to encompass the anticipated pressure and flow conditions in the AP600 design for the assessment of the two-phase level swell model in NOTRUMP. The GE tests covered the intermediate pressure of 6,894.7 kPa (1,000 psia); the G-2 tests covered the range from 5,515.8 kPa (800 psia) to 101.3 kPa (14.7 psia); and the Achilles tests provided integral system data at 101.3 kPa (14.7 psia) and 202.6 kPa (29.4 psia) pressure. In addition to the coverage of the anticipated pressure range, the three test programs provided data for different scale facilities.

The assessment of two-phase level swell under the anticipated pressure and power conditions of the AP600 SBLOCA was difficult because of the lack of low-pressure two-phase level swell data. All data currently available are from test facilities with flaws in the tests and data collection that make it necessary to make assumptions in the computer code modeling of the facilities and tests. Thus, there are no known ideal test results for assessment of the two-phase level swell capabilities of the code at low pressure. When reasonable assumptions are made to account for the facility problems noted in this section, the NOTRUMP code does an acceptable job of predicting two-phase level swell. The results of the assessments, presented in WCAP-14807, indicate that NOTRUMP underpredicts the mixture level over a wide range of thermal-hydraulic conditions that may be found during AP600 SBLOCAs. The predicted level is consistently conservative or within the test data uncertainty. The staff finds that the tests used in the assessment of NOTRUMP two-phase level swell sufficiently test the code's capability to permit the judgment that the NOTRUMP code adequately predicts two-phase level swell at low system pressure.

Integral Systems Tests

Integral systems tests permit an assessment of the entire code, including all pertinent models, acting as a unit to predict the full system behavior. Westinghouse analyzed selected SPES and OSU integral tests for the final verification and validation effort. Comparison between several of the related tests assists in understanding the effects of scale on the analysis results.

Assessments were performed to compare the results of NOTRUMP calculations to data from SPES and OSU tests for a variety of transients covering a wide range of break sizes and locations. The NOTRUMP code was found to provide reasonable predictions of the highly ranked PIRT phenomena, including the following:

- *Pressurizer pressure and level*
- *Core inlet and outlet temperatures*
- *CMT injection flow rates and collapsed liquid level*
- *The steam generator collapsed liquid level as well as pressure and temperature*
- *The cold leg balance line levels*
- *The upper plenum and upper head collapsed liquid levels*
- *The PRHR inlet and outlet temperatures*
- *The break flow rate*

An exception to the above-noted acceptable results is the double-ended guillotine break of a DVI line. The calculated results for core level during a double-ended guillotine break of a DVI line were nonconservative (higher) than the measured value. The Westinghouse explanation of the differences in core and downcomer behavior in the DVI line break is primarily because of the one-dimensional nature of NOTRUMP. The test data indicate that a two-dimensional temperature pattern develops in the downcomer that NOTRUMP is not able to predict. This allows portions of the downcomer to remain saturated and to flash when ADS 1-3 open. Less mass is then stored in the downcomer. Also, the vapor generated in the core exits through the broken DVI line and not through the intact DVI line. NOTRUMP predicts vapor exiting by both paths. The staff believes that the AP600 will perform in a manner that is more similar to the behavior of the test facilities than to the behavior predicted by NOTRUMP. This discrepancy is resolved by the time ADS 1-3 blowdown is completed, as evidenced by good agreement between the measured and predicted core levels in both the SPES and OSU tests. Thus, *the discrepancy does not adversely affect the prediction of core level. Although the NOTRUMP code is unable to predict the two-dimensional behavior of the design, the staff concludes that this discrepancy is acceptable because the core does not uncover in either the tests or the calculations. Core heatup does not occur in either case. A two-dimensional analytical capability would be desirable, but would not appreciably change the results.*

3.2.1.6 Regulatory Compliance

Following the accident at TMI, the NRC focused attention on the SBLOCA and proposed revisions to the methods and analyses performed to better demonstrate compliance with the requirements set forth in 10CFR50.46. With regard to Westinghouse-designed PWRs, the NRC outlined technical issues in NUREG-0611 ("Generic Evaluation of Feedwater Transients and Small Break Loss-of-Coolant Accidents in Westinghouse Designed Operating Plant") regarding the capabilities of the WFLASH computer program used to simulate the reactor coolant response to a SBLOCA. WFLASH was an early methodology that Westinghouse developed for simulation of SBLOCA response. In NUREG-0611, the staff identified specific models in the WFLASH computer code that were considered deficient. Furthermore, the NRC issued NUREG-0737, Section II.K.3.30 to clarify the post-TMI requirements regarding SBLOCA modeling. In essence, Section II.K.3.30 of NUREG-0737 recommends that licensees of Westinghouse-design PWRs revise their SBLOCA models in accordance with the guidelines specified in NUREG-0611, or justify continued acceptance of the current model. Section II.K.3.31 further recommends that each licensee submit a new SBLOCA analysis using an approved evaluation model that meets the criteria of NUREG-0737, Section II.K.3.30.

In response to these requirements, Westinghouse developed the NOTRUMP code for reference in the new SBLOCA ECCS evaluation model calculations. As such, the NOTRUMP code was developed to overcome the deficiencies identified in the WFLASH computer program while also addressing the post-TMI requirements. Following NRC review, the NOTRUMP code was approved for evaluating SBLOCA response in Westinghouse-design PWRs.

10CFR Part 50, Appendix K

Westinghouse modified the approved NOTRUMP code for application to the AP600 design for analysis of the SBLOCA in compliance with the requirements of 10 Part CFR 50, Appendix K. Of the many requirements specified in Appendix K, only one refers both to portions of NOTRUMP that have been modified and to phenomena that are anticipated in AP600 SBLOCAs. 10CFR Part 50, Appendix K, Section C.2, requires that the frictional loss in pipes and other components, including the reactor core, be calculated using models that include realistic variation of friction factor with Reynolds number, and realistic two-phase friction multipliers that have been adequately verified by comparison with experimental data, or models that prove at least equally conservative with respect to maximum clad temperature calculated during the hypothetical accident. Appendix K then specifies acceptable correlations.

The friction factor calculations within the AP600 version of NOTRUMP are largely the same as found in the approved version of NOTRUMP with the exception of some smoothing and an extension of two-phase multipliers down to atmospheric pressure. The effectiveness of this modified model was evaluated and documented in WCAP-14807. The outcome of these evaluations demonstrated that the NOTRUMP code *results agreed reasonably well with data from two-phase level swell experiments (G-2, GE, and Achilles). The code results were also reasonable for the SPES and OSU test assessments. The staff found the frictional loss model in NOTRUMP acceptable for the analysis of AP600 SBLOCA.*

NUREG-0611 and NUREG-0737

As the motivation to develop the NOTRUMP code arose from the guidance in NUREG-0611 and NUREG-0737, the modifications and applicability of the modified code to AP600 SBLOCA evaluations have been reviewed regarding the following TMI small break modeling concerns:

1. *Provide calculated validation of the SBLOCA model to adequately calculate the core heat transfer and two-phase coolant level during core uncovery conditions.*

   The NRC requested that the heat-up methodologies be compared to the core cooling tests performed by the Oak Ridge National Laboratory (ORNL) at its Thermal Hydraulic Test Facility (THTF). The ORNL tests provide a good database to assess the heat transfer capabilities of a fuel rod subjected to uncovery and the resultant steam cooling conditions that can occur in the upper portion of the bundle. The tests cover a wide range of pressures and rod powers for both transient film boiling and bundle uncovery steam-cooling conditions. Predictions of two-phase level swell as well as the steam cooling convection heat transfer are essential to successful predictions of SBLOCA response.

   Evaluation

   The AP600 integral data did not indicate core uncovery and, therefore, the heatup model was not exercised. The assessments in WCAP-14807 of the G-2, GE, and Achilles tests provided verification of the steam cooling model and level swell in NOTRUMP during core uncovery conditions at the low pressure and low flow anticipated in the AP600 design. The staff found the NOTRUMP code acceptable to evaluate core heat transfer and two-phase level swell in the AP600 SBLOCA.

2. *Validate the adequacy of modeling the primary side of the steam generators as a homogeneous mixture.*

   It is necessary to demonstrate that there is sufficient spatial detail to model the primary and secondary systems to properly account for forward and reverse heat transfer as liquid drains from the primary active tubes. Because the steam generators can act as a heat source following some SBLOCAs, proper accounting for the steam-water behavior and associated depressurization rates is required.

   Proper accounting of the annular and slug flow regimes as they may occur in the steam generators should be incorporated into the modeling of this region. One must, therefore, ensure that the flow region behavior in the generators is consistent with the heat transfer conditions throughout the transient. If there is a potential for flooding or "hold-up" of the liquid in the generators, then the hydraulic model should also account for this behavior. Also, if a stratified flow model is used in the hot-leg piping, this flow regime should be justified.

Evaluation

Steam generator heat transfer has a secondary role in AP600 since the PRHR system functions along with the ADS to control system pressure and depressurize the plant. This low importance of steam generator heat transfer is reflected in the low PIRT ranking. Nevertheless, the models contained in NOTRUMP are applicable to the AP600 plant performance.

In the AP600, the PRHR HX functions in a manner similar to the steam generators as a major heat removal system. The PRHR uses the same models; thus, the staff considered its modeling under this item. The PRHR heat transfer was not properly predicted in the SPES and OSU comparisons since the code was unable to predict the correct outlet temperature. The NOTRUMP code tends to overpredict the outlet temperature. This result is conservative; therefore, the staff found the NOTRUMP model for the steam generator and PRHR system acceptable.

NOTRUMP contains provisions for stratified and dispersed flow regimes in the loop piping and steam generators. The flooding models in the code capture the potential for liquid hold-up in the loop and steam generators should steam velocities be sufficient to entrain and limit drainage in the loops. The PIRT ranking for flow-regime-related phenomena is low, so that this phenomenon does not appear to have a significant impact on AP600 performance. Comparisons between the NOTRUMP calculated fluid conditions and the measured fluid conditions from SPES and OSU tests demonstrated that the models used in NOTRUMP for the stratified and dispersed flow regimes are appropriate. The staff found the NOTRUMP models for the stratified and dispersed flow regimes in the hot leg piping acceptable for analysis of the AP600 SBLOCA.

3. *Validate the condensation heat transfer model and effects of noncondensable gases.*

The condensation correlation used in the blowdown hydraulics code must be justified as to the applicability to the two-phase flow conditions in the active tubes of the steam generators. The need for a best-estimate correlation was stressed as opposed to empirical relationships containing "conservatisms." Particular emphasis should be placed on the applicability of the correlations to U-tube steam generators since most correlations used to date are on the basis of flat-plate geometries. Noncondensable gases should also be accounted for.

Evaluation

Westinghouse added the Shah condensation correlation to the NOTRUMP condensation correlation package previously approved. The staff found the addition of the Shah correlation acceptable for analysis of the AP600 SBLOCA.

The NOTRUMP code can not calculate the effects of the noncondensable gases injected into the primary coolant system during the AP600 SBLOCA. The presence of noncondensable gases is of concern because of the possible degradation in performance of the PRHR HX for system depressurization and heat removal. During the conduct of the test program, noncondensable gases entered the system but were not tracked as they moved through the system. The gases either exited the system or were found to end up in the PRHR HX or the CMTs. It was noted *that the noncondensable gases entered the PRHR HX late in the transient, when the PRHR system no longer had a significant role in heat removal. At this point in the transient, the noncondensable gases do not appear to have a detrimental effect on the system. Since the noncondensable gases do not play a role in the AP600 SBLOCA, the staff accepted the NOTRUMP code for evaluation of AP600 SBLOCA in spite of its inability to calculate the effects of noncondensable gases. This position will be re-evaluated if scenarios are found which cause noncondensable gases to reach the PRHR HX while it is actively removing heat from the primary system.*

4. *Demonstrate, through noding studies, as part of the sensitivity studies, the adequacy of the SBLOCA model to calculate flashing during system depressurization.*

Evaluation

The adequacy of the NOTRUMP code to model the system effects, as well as local fluid conditions, during the AP600 SBLOCA is demonstrated through the consistency in noding between the scaled, integral system test facilities (SPES-2 and OSU) and the AP600 design. The staff found the noding acceptable for analysis of the AP600 SBLOCA on the basis of analyses performed on the noding differences used in the PRHR and downcomer models for the test facilities and AP600.

5. *Validate the polytropic expansion coefficient applied in the accumulator model.*

Evaluation

The accumulator model was not changed from the approved NOTRUMP code to the AP600 version of the code. Also, the accumulator in the AP600 design is similar to that employed in the current generation operating Westinghouse PWRs. The staff therefore accepted the model as it was applied to the AP600 SBLOCA.

6. *Break discharge model*

Since Appendix K to 10CFR Part 50 requires use of the Moody critical flow model, the blowdown hydraulic code must contain this methodology.

Evaluation

The Moody critical model is used in the NOTRUMP code as specified by Appendix K (10FR Part 50) for saturated break flow. It is noted that the flow rate out the ADS is being predicted through the addition of the Henry/Fauske and HEM critical flow models previously discussed. Because the ADS is a depressurization system and not an actual break, this is considered acceptable based in part on the precedents established by the depressurization system used in the boiling water reactors. The staff found that Westinghouse demonstrated that the treatment of the ADS is conservative.

7. *Validate the SBLOCA model with loss-of-fluid test (LOFT) facility tests L3-1 and L3-7. In addition, validate the model with the Semiscale S-UT-08 experimental data.*

    There is a need for integral as well as separate-effects test comparisons. The NRC identified the LOFT and Semiscale integral-system tests which should be included as part of the code verification process. These tests include LOFT and Semiscale integral system tests addressing SBLOCA transients, including an examination of the continued operation of the main coolant pumps on the system response following initiation of a small break (L3-6). Semiscale S-07-10D was also identified as an integral test that could be used in the benchmarking of codes against a SBLOCA transient where long-term core uncovery was simulated.

    Evaluation

    The purpose of this requirement was to demonstrate the ability of the code to adequately deal with plugging and clearing of the steam generator to the reactor coolant pump loop seal. The AP600 design eliminated the loop seal, as well as placing the steam generators entirely above the hot-leg reactor vessel nozzle, which is above the reactor core. Accordingly, the staff found that this requirement was not applicable to the analysis of the AP600 SBLOCA since there is no loop seal to prevent the steam generator tube contents from flowing into the reactor vessel. The staff noted that Westinghouse provided other integral effects assessments of NOTRUMP that address the highly ranked PIRT items.

    The staff was aware that Westinghouse submitted modifications to the NOTRUMP code incorporating a condensation model on the basis of results of the COSI safety injection (SI)/steam condensation experiments. The COSI test facility is a scaled representation of the cold-leg and SI injection ports in a Westinghouse designed PWR. The pressure range covered by the COSI tests is outside of the range of interest for the low-pressure conditions expected in the AP600 SBLOCA. In addition, the AP600 design uses direct vessel injection for SI. Accordingly, the staff position was that the COSI condensation model is neither applicable nor acceptable for evaluation of the AP600 SBLOCA.

In addition to the above modeling concerns, NUREG-0737 recommendations indicate that the effect of the operation of the main coolant pumps on SBLOCA response should be assessed. The AP600 design is such that a safety-grade, single-failure- proof, reactor coolant pump trip is provided. As such, Westinghouse was not required to evaluate AP600 performance with the main coolant pumps operating.

3.2.1.7 ACRS Review

Two meetings were held with the ACRS Thermal-Hydraulic Subcommittee for review of the NOTRUMP code. Those meetings resulted in numerous additional review items and concerns. As a result the staff required that Westinghouse fully document the code numerics, providing detailed derivations of all equations modified or changed from the source form to the difference form as applied in the code. This was in addition to fulfilling the commitments Westinghouse made during the meetings. Subsequently, Westinghouse documented responses to the following six issues:

1. *Momentum Flux – Deficiencies were benchmarked against additional detailed calculations using actual two-phase flow equations that include the effects of compressibility and the condition of constant entropy.*

2. *ADS 1-3 – The test data analysis report was revised to show that the data reduction was performed correctly.*

3. *Entrainment – Entrainment was considered as part of the overall scaling and IRWST-level penalty development.*

4. *IRWST-Level Penalty – A multiloop scaling analysis was performed for the time period of ADS-4 and IRWST draining. The basis for ADS flow was justified, along with ADS-4 flow affected by entrainment of liquid and the corresponding effect on the pressure loss as a result of two-phase flow.*

5. *Pressurizer Surge Line Flooding – An evaluation similar to that applied to the IRWST level penalty was performed.*

6. *Noding – Additional justification was provided for the basis used which differs from the accepted approach developed under the CSAU work. This applies in particular to the PRHR and downcomer.*

Several of these items involved phenomena that are not well represented or modeled in NOTRUMP, because of the structure of the code. Nonetheless, overall code calculations of the plant's performance showed large margins to licensing limits and all issues were addressed in a conservative fashion. Therefore, the staff concluded that these issues did not alter the staff's determination that NOTRUMP was suitable for analyzing the behavior of the AP600.

3.2.1.8 Conclusions

The NOTRUMP computer code was developed by Westinghouse to assess the consequences of an SBLOCA. The code was modified through introduction of model additions and changes in 18 of the approved code's models. In addition, component models for the ADS, CMT, PRHR HX, and IRWST were added to make the code applicable to the AP600 passive reactor design. The staff reviewed the code's application to the AP600 SBLOCA, the component test program, and the integral systems tests, which resulted in a large number of RAIs. Westinghouse responded to the RAIs and documented the responses in the NOTRUMP Final Verification and Validation Report, WCAP-14807.

Additional assessment calculations were considered important to the assessment of the level swell models in NOTRUMP. The additional requests for benchmarking were on the basis of the lack of level swell benchmarks provided by Westinghouse in the documentation and the nonconservative predictions displayed by NOTRUMP in several of the SPES and OSU tests. The NOTRUMP code, in these cases, overpredicted the liquid inventory in the core and upper plenum regions of the reactor vessel. Because there was a basic lack of low-pressure data to qualify codes for level-swell phenomena, the staff concluded that additional tests needed to be analyzed for model qualification.

The staff expressed concerns regarding the assessment of many of the models modified in the approved NOTRUMP code. In particular, the changes to the drift-flux models, bubble rise model, and momentum equations significantly alter the two-phase level swell capabilities of the code. An adequate assessment of the two-phase level swell was essential to properly understand the predictions of the code in an SBLOCA situation since it is a depressurizing, two-phase condition. Westinghouse performed numerous assessments of the logic models and the two-phase level swell models to demonstrate the adequacy of the models in predicting two-phase level and void fraction distribution in the AP600 SBLOCA.

In addition, the staff expressed concern about the extensive logic models added to the code to control mixture level, region birthing, etc. It was requested that Westinghouse demonstrate that the interaction of the logic models did not lead to unrealistic results. Also, the staff required Westinghouse to demonstrate that mass and energy were conserved as mass and energy and are redistributed when mixture regions pass through flow links. The "mechanical" movement of mass and energy in these logic schemes suggested that the models be exercised through the benchmark calculations to assure that the conservation laws are not being violated.

Westinghouse added options to NOTRUMP to permit use of the momentum equation in volumetric form and flow partitioning in the analysis of the AP600 SBLOCA. The staff does not consider the "options" added to improve the performance of NOTRUMP in analyzing the AP600 SBLOCA to be options. The staff position is that the "options" added to NOTRUMP for AP600 SBLOCA analyses are required to be used for those analyses.

Because transition boiling was not expected to occur in the AP600 core under SBLOCA conditions, the changes in the numerical solution techniques used in the NOTRUMP heat links when transition boiling is predicted to occur were not reviewed. It was noted by Westinghouse that the core model methodology was unaffected by the change in the transition boiling heat link methodology as these two models are completely separate in the code. Therefore, this revised methodology would not be invoked in the core region of AP600 calculations. Should this revised methodology be applied to core calculations, the review of the modified transition boiling correlation solution scheme would need to be revisited.

The staff noted that the NOTRUMP code could not 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 did not appear to have a significant effect on the course of the event. The staff accepted the NOTRUMP code for evaluation of the AP600 SBLOCA in spite of this shortcoming. However, if scenarios are found which cause noncondensable gases to reach the PRHR HX while it is actively removing heat from the primary system, NOTRUMP could not be used to analyze those scenarios.

Notwithstanding the limitations that the staff identified in its review of the application of the NOTRUMP code to analyses of the AP600 design and the conditions that Westinghouse must observe as it applies the code, the staff has confidence that the use of NOTRUMP is acceptable for AP600. This is because the phenomena expected during a SBLOCA are modeled reasonably well in the test facilities, code comparisons with the experiments are reasonable, and they indicate that there are large margins to licensing limits which are unlikely to be challenged by uncertainties in the code models.

In a letter dated February 27, 1998, Westinghouse submitted Revision 4 to WCAP-14807, NOTRUMP AP600 Final Verification and Validation Report. Therefore, with the limitations and conditions described in this report, the staff concluded that the NOTRUMP code had been appropriately modified to include the features necessary to model the AP600 plant and the phenomena expected during an AP600 SBLOCA. Therefore, it could be applied to the AP600 passive reactor design.

3.3 ISSUES FOR AP600 NOTRUMP – FSER

During the review process associated with the NOTRUMP code, issues were identified during the generation of NUREG-1512 (Reference 5). The following details the issues identified and the method utilized to address them such that a conservative calculation results. This information is excerpted from the NOTRUMP Final Validation Report (Reference 3), Section 1.17. This represents a consolidation of the issues raised by both the NRC and ACRS as agreed to by Westinghouse. These issues will be specifically addressed as part of the AP1000 program.

The definitions used for quantification are as follows (As excerpted from Section 1.5 of Reference 3):

- EXCELLENT – The calculation lies within the data uncertainty band at all times during the transient phase of interest. This is interpreted that the code had no deficiencies that are significant. No action is required for this level of agreement.

- REASONABLE – The calculation sometime lies within the data uncertainty bands and shows the same trends as the data. This is interpreted that the code deficiencies are minor. Minor actions and/or discussions are used to explain differences.

- MINIMAL – Major data trends and phenomena are not predicted. The code has significant deficiencies, and incorrect conclusions may be drawn based on the calculations without the benefit of data. If the deviation of the code calculations is known, then the minimal agreement may be acceptable for lower-ranked items in the PIRT.

- INADEQUATE – Modeling the phenomena is beyond the capability of the code. The questions then becomes how important are these phenomena for describing the transient and having confidence in the results and their application to the plant.

ADS-4: Two-Phase Pressure Drop

The assessment results were deemed to be minimal due to the lack of momentum flux terms, which resulted in [$]^{a,b,c}$ of two-phase pressure drop during [$]^{a,b,c}$ flow conditions. The utilization of [$]^{a,b,c}$ loss coefficients in this flow path and the application of a [$]^{a,b,c}$ treated this deficiency in the AP600 analyses. This treatment results in a conservative prediction of IRWST injection, which is the long-term cooling source for the AP600 design.

Downcomer Mixture Level

For the DEDVI simulation, the downcomer mixture level was deemed to be minimal due to the fact that NOTRUMP code is a one-dimensional code and the DEDVI transient is two-dimensional during the early portions of the transient. The application of the [ ]^{a,b,c} and the use of a range of discharge coefficients (Cd) were utilized to account for this deficiency for this break simulation.

Phase Separation at Tees

The phase separation at Tee junctions in the cold legs was deemed to be conservative in that the treatment in the NOTRUMP code results in artificial balance line refilling which causes a delay in CMT draining and subsequent ADS system actuation. No change to the model was required due to its conservative nature.

The phase separation at Tee junctions in the hot legs was deemed to be minimal due to the use of an ad-hoc model. The impact was deemed to be small as the liquid flow out of the ADS-4 paths are controlled by constant system inventory and are thus self-correcting. The application of the [ ]^{a,b,c} was used to conservatively bound the expected impact.

Pressurizer and Surge Line CCFL

This model was assessed as minimal, but conservative, provided the vapor flow to the component was correct. This apparent weakness was caused by low vapor flow to this component resulting from [ ]^{a,b,c} through the ADS-4 paths when [ ]^{a,b,c} flow was predicted to occur.

Pressurizer and Surge Line Level Swell

This model was assessed as minimal, and nonconservative, during the pressurizer drain period following ADS-4 actuation. This was caused by the poor ADS-4 [ ]^{a,b,c} prediction, which was confirmed by studies with [ ]^{a,b,c}. For the AP600 application, this deficiency was compensated for by the application of the [ ]^{a,b,c} that [ ]^{a,b,c} IRWST injection.

PRHR Heat Transfer/Recirculation Flow

These areas were deemed to be minimal, but conservative, provided the primary flow through the PRHR is low. Westinghouse committed to confirm that the flow velocity through the PRHR primary tubes would be less than [ ]^{a,b,c} in all AP600 simulations. In addition, the PRHR is [ ]^{a,b,c}. Should the flow rate through the PRHR be higher than [ ]^{a,b,c} for any significant period of time, the calculation for the limiting case (minimum mass or highest PCT) would be repeated with the PRHR heat transfer surface area reduced by [ ]^{a,b,c} to account for the potential heat transfer overprediction.

Noncondensable Gas Injection

Since the AP600 NOTRUMP code does not contain a noncondensable gas model, it can not accurately predict the plant behavior as a result of the introduction of noncondensable gasses from the Accumulators. To assure conservatism in accounting for this deficiency, [

]^{a,b,c}. This conservatively bounds the effect of the introduction of noncondensable gases into the PRHR heat exchanger. It was determined that the accumulation of noncondensable gases into other model locations such as steam generator tubes and the CMTs would not adversely impact plant performance.

3.4 NOTRUMP CODE ACCEPTABILITY FOR AP1000

This section contains a review of the pertinent information associated with the application of the NOTRUMP code, as approved for AP600, to the AP1000 plant design. It provides a review of the PIRT issues, phenomenological issues, scaling issues, and margin issues as well as addressing the issues identified from the AP600 program.

3.4.1 PIRT Issues

A review of the PIRT was performed in Section 2.0 of the AP1000 PIRT and Scaling Assessment report (Reference 10) and concluded the following related to important SBLOCA phenomena:

- ADS-4 subsonic, two-phase flow should be raised to a high importance.
- Upper plenum/hot leg entrainment during the post-ADS period should be raised to a high importance level.
- Pressurizer surge line countercurrent flow/flooding during the ADS-IRWST period should be raised to a high importance level.

The above items are not really new phenomena but rather the change in rankings is a result of the lessons learned from the AP600 test and analysis program. The issues identified above apply to both the AP600 and AP1000 designs and do not constitute new issues. These issues were previously reviewed by the ACRS/NRC during the review of the NOTRUMP application to the AP600 plant design.

3.4.2 Phenomena Issues

As a result of the scoping analyses performed in WCAP-15612 (Reference 9), no new phenomena were observed.

3.4.3 Scaling Issues

As a result of the efforts performed in the AP1000 PIRT and Scaling Assessment report (WCAP-15613, Reference 10), it was concluded that the AP600 test program can successfully be applied to the AP1000 plant design. In addition, it was also stated that "For small break LOCA events, computer codes that acceptably predict SPES-2 and OSU behavior can be used to conservatively analyze the performance of the AP1000. Moreover, codes that predict the high-pressure phases of the transient (i.e., prior to ADS-4 actuation) will acceptably predict the high-pressure portion of the SBLOCA transient for the AP1000 plant. Codes that predict the lower pressure phases (i.e., post ADS-4 will acceptably predict the performance of the AP1000 for the low pressure phases of the SBLOCA transient."

The NOTRUMP code has been validated against both the OSU and SPES-2 integral test facilities (Reference 3) and deemed to provide reasonable predictions of the highly ranked PIRT phenomena, as described in Section 3.2.1.5 of this document. As such, the NOTRUMP code can be utilized for the prediction of SBLOCA phenomena anticipated in the AP1000 plant design. Additionally, the scoping analyses performed in Reference 9 indicate no new phenomena with comparable safety margins to those observed for the AP600 plant design.

3.4.4 Margin Issues

As a result of the SBLOCA scoping analyses performed in WCAP-15612 (Reference 9), the AP1000 plant performance was observed to exhibit safety margins comparable to that observed for the AP600 plant design. In fact, due to the component size increases associated with the AP1000 design, the breaks analyzed respond like smaller breaks in the AP600 plant design. As a result, comparable break sizes respond in a more benign fashion than observed for the AP600 plant design. Although a complete break spectrum has not been completed, no new phenomena have been observed as a result of the scoping analyses and it is expected that the plant margins will be comparable to those observed for the AP600 plant.

3.4.5 How Issues Are Addressed for AP1000

The approach being utilized to address the code issues identified as part of the AP600 design is as follows:

1. Start with the computer codes as approved for passive plant analysis in the AP600 design certification program.
2. Confirm the adequacy of the codes for analysis of the AP1000 design.
3. Address potential concerns identified as a result of the AP600 design certification review.
4. Reach a consensus regarding the acceptability of the methods utilized.

The confirmation of the adequacy of the computer codes for analysis of the AP1000 design is addressed via the following steps:

1. Identification of important phenomena (via PIRTs) that must be addressed by the code. (Completed via the submittal of the AP1000 PIRT and Scaling Report, Reference 10)

2. Identification of correlations and model used in the code to address important phenomena. (Completed via the AP600 Design Certification Program, References 3 and 5)

3. Demonstration of the existence of an adequate test data base to support validation of the models/correlations via scaling analyses. (Completed via the submittal of the AP1000 PIRT and Scaling Report, Reference 10)

4. Demonstration that the limitations identified in the AP600 FSER are adequately addressed for the AP1000 program. (Addressed in this report.)

Of the items listed above, only the approach to address the limitations identified during the AP600 review have yet to be performed. To address code limitations, one of the following approach(s) should be utilized:

1. Performance of plant design modification to increase available margin.

2. Performance of additional validation efforts with the computer codes versus appropriate test(s).

3. Performance of an evaluation of the available plant margin.

4. Performance of supplementary analyses using appropriate means (e.g., alternate code simulations).

5. Performance of code/model enhancements to address the identified deficiencies.

6. No change required if the model is deemed to result in a conservative calculation.

The following discussion addresses how the issues identified in the AP600 program (and discussed in Section 3.3) are addressed for the AP1000 program.

For application to the AP1000 program, the validation program developed/analyzed for the is AP600 once again be utilized as supported by the work performed in Reference 10. Note that areas identified/assessed as being "minimal" in terms of acceptability, per Section 1.17 of Reference 3 and as stated in Section 3.2.2, evaluated for adequacy in the AP1000 program. A summary of the assessment items are provided in Table 3-1. Of these items, the areas that need to be addressed via the criterion defined above, in the sequence presented in Section 3.3, are as follows:

ADS-4: Two-Phase Pressure Drop

The methods utilized to address this item are the use of a previously evaluated modeling modification [ ]^{a,b,c} and the performance of a supplementary analysis utilizing the WCOBRA/TRAC code as described later.

The need for momentum flux terms to accurately model the ADS flow paths (particularly ADS-4 during the [ ]^{a,b,c}) will result in the need to improve this modeling. This was an area previously deemed to be inadequate in the AP600 test and analysis program and required the implementation of penalties [ ]^{a,b,c} to compensate for this deficiency. For the AP1000 program, this deficiency will be addressed via the implementation of an [ ]^{a,b,c}. This methodology was demonstrated on AP600 analyses to be similar in nature to the imposition of the [ ]^{a,b,c} while more directly addressing the NOTRUMP code deficiency (i.e., lack of a detailed momentum flux model in the ADS-4 flow paths). The [ ]^{a,b,c} will be developed in the same fashion as utilized in response to the Request For Additional Information (RAI 440.796F, Part a). Specifically, a detailed stand-alone momentum flux model will be developed for the AP1000 ADS-4 specific flow geometry. The results of this detailed model will then be utilized to generate an [ ]^{a,b,c} to be implemented into the NOTRUMP model at the time when the ADS-4 flow paths transition to [ ]^{a,b,c}. Use of this method will more accurately reflect the ADS flow distributions and ultimately the onset of IRWST injection flow.

For the scoping study results presented in WCAP-15612 (Reference 9), the ADS-4 flow path [ ]^{a,b,c}. The [ ]^{a,b,c} utilized were based on the detailed stand-alone momentum flux model results of the ADS-4 flow paths generated for the AP600 plant design. The application of the [ ]^{a,b,c} methodology was previously demonstrated to significantly improve the match between the model prediction and the test data. The results of this revised methodology were presented to the ACRS during the May 11th and 12th 1998 Thermal Hydraulic sub-committee meetings. The information presented included comparisons with the OSU 2-inch cold leg break test data as well as AP600 2-inch cold leg break simulations. Subsequent to this meeting, the complete AP600 break spectrum was re-performed utilizing the [ ]^{a,b,c} methodology. The results obtained indicated that the [ ]^{a,b,c} results were comparable to the [ ]^{a,b,c} results, which serve as the basis for the AP600 DSER. While the [ ]^{a,b,c} utilized in the scoping studies (Reference 9) were not AP1000 plant specific, they provide a determination of the overall plant response. The use of the AP600 derived [ ]^{a,b,c} is expected to be conservative for the AP1000 plant design and will be confirmed and adjusted as necessary as part of the detailed AP1000 analysis effort.

To provide additional confidence, select AP1000 SAR predictions obtained with the NOTRUMP code will be supplemented by calculations of the ADS-4 depressurzation to IRWST injection performed with the WCOBRA/TRAC-AP code, which contains a detailed momentum flux model and the appropriate physics necessary to model the ADS-4/IRWST initiation phase, as described in Appendix-B. The WCOBRA/TRAC model will be validated against appropriate test information to demonstrate the code's predictive capabilities.

The use of the WCOBRA/TRAC analysis tool as a supplemental calculation is a desirable approach as it leverages the use of state of the art technology to address the identified deficiency in the NOTRUMP code. The methodology involves starting the WCOBRA/TRAC calculation at the time of the ADS-4 actuation setpoint. Following the opening of the ADS-4 valves, the flow through the ADS-4 valves for AP1000 is initially critical. Note that the lack of a momentum flux model in the NOTRUMP model is important only after the ADS-4 flow path [ ]^{a,b,c}. Starting the WCOBRA/TRAC simulation at a point [ ]^{a,b,c} provides an overlap period in which the NOTRUMP code results are considered valid. The WCOBRA/TRAC simulations will be utilized to confirm and demonstrate the overall conservative nature of the NOTRUMP results.

Downcomer Mixture Level

The method utilized to address this item is the use of a previously evaluated modeling modification [ ]^{a,b,c} and break discharge coefficient study).

While not specifically addressing the multi-dimensional aspects of the downcomer behavior that results from this break location, the modifications imposed assure conservative behavior prior to the onset of IRWST injection, which terminates the inventory depletion period. As observed during the code validation, the discrepancy in downcomer behavior is resolved by the time ADS 1-3 blowdown is completed as evidenced by the good agreement between the test and NOTRUMP predictions for both SPES and OSU. It is also noted that this mis-prediction in downcomer behavior does not adversely impact core mixture level, which is of foremost importance.

For the DEDVI line simulation, the downcomer mixture level was deemed to be minimal due to the one-dimensional nature of the NOTRUMP code and the two-dimensional nature of the DEDVI transient during the early portions of the transient. This was addressed via the implementation of the [ ]^{a,b,c} and the performance of a range of break discharge coefficients for the AP600 program.

Application of the ADS-4 resistance increase and a range of discharge coefficients (C_d) will be applied to the DEDVI line break for the AP1000 program to assure the limiting break size has been captured.

Phase Separation at Tees

The phase separation at Tee junctions in the cold legs was deemed to be conservative in that it resulted in delayed draining of the CMT and subsequent ADS system actuation. No change in the model was required due to its conservative nature. This model will remain unchanged in application to the AP1000.

The method utilized to address the hot leg Tee junction item is the performance of a supplementary analysis utilizing the WCOBRA/TRAC-AP code to demonstrate the conservative nature of the NOTRUMP code results.

The phase separation at Tee junctions in the hot legs connected to the ADS-4 paths was deemed to be minimal due to the use of an ad-hoc model. Entrainment/phase separation can impact the flow quality encountered at the ADS-4 discharge valves and affect the capability of the plant to achieve stable IRWST injection flow. The use of the ad-hoc model to account for the effects of entrainment/phase separation was utilized in the analysis of the AP600 and integral test facilities and was determined to have a negligible impact on plant results. For application to the AP1000 design, select AP1000 Safety Analysis Report (SAR) cases will have supplemental information cases performed with the WCOBRA/TRAC-AP code, as described in the ADS-4 two phase pressure drop section, to demonstrate the impact of entrainment. WCOBRA/TRAC-AP contains specific models to determine the onset of entrainment into a branch line and the quality present in the branch line. This information will then be utilized to justify the continued use of the ad-hoc NOTRUMP model.

Pressurizer and Surge Line CCFL

This model was deemed to be minimal but conservative provided the vapor flow to this region was correct.

Due to deficiencies in the ADS-4 flow path modeling, early IRWST injection relative to the OSU integral test data was thought to be related to pressurizer draining, particularly surge line flooding. However, as shown in [ ]^{a,b,c} studies performed with the NOTRUMP code for AP600, pressurizer draining and IRWST injection initiation times more closely match the behavior observed in the test data. The [ ]^{a,b,c} were implemented to account for the lack of a detailed momentum flux model in the NOTRUMP code. The [ ]^{a,b,c} utilized were based on the results of a detailed stand-alone momentum flux model of the ADS-4 flow paths as discussed in the response to RAI 440.796, Part a. As such, with the implementation of the [ ]^{a,b,c} it is expected that the pressurizer drain behavior will be conservatively captured and no additional modification to this model is required.

Pressurizer and Surge Line Level Swell

The methods utilized to address this item are the use of a previously evaluated modeling modification [ ]^{a,b,c} and the performance of a supplementary analysis utilizing the WCOBRA/TRAC-AP code.

This model was assessed as minimal, and non-conservative, during the pressurize drain period following ADS-4 actuation. This was caused by the poor prediction of the ADS-4 [ ]^{a,b,c} which was confirmed by studies with [ ]^{a,b,c}. The poor prediction of ADS-4 [ ]^{a,b,c} results in the core vapor being preferentially discharged through the ADS-4 locations. As a result, the vapor flow entering the pressurizer component is low resulting in the under-prediction of CCFL in the pressurizer surge line and the pressurizer drains more rapidly then observed in the test. As observed in Figure 3-3 and 3-4, the [ ]^{a,b,c} more accurately reflects the behavior observed in the test. For the AP1000 application, the application of the [ ]^{a,b,c} is expected to correct this behavior for the reasons stated previously. In addition, supplementary calculation(s) will be performed with the WCOBRA/TRAC-AP code, as described in the ADS-4 two phase pressure drop section, to provide additional confidence in the NOTRUMP generated results.

PRHR Heat Transfer/Recirculation Flow

These areas were deemed to be minimal, but conservative, if primary flow through the PRHR was low. As such, the methodology associated with the confirmation of the PRHR heat exchanger flow velocities and implementation of heat transfer modifications, as discussed in Section 3.3 will be followed, as necessary, to assure conservatism. In addition, the PRHR model will be removed prior to ADS-4 actuation as done for AP600.

Noncondensable Gas Injection

The removal of the PRHR model prior to the introduction of noncondensable gases conservatively bounds the expected behavior.

Per discussions with the NRC, the methods utilized in the SBLOCA analyses to account for noncondensable gas introduction [ ]^{a,b,c} will be utilized on the AP1000 design as well.

Transition Boiling Model Related

Per the AP600 FSER issued by the NRC (Reference 5), the use of the transition boiling correlation, for fuel rod heat transfer, was not specifically reviewed by the NRC as part of the AP600 program. This model is unchanged from the standard NOTRUMP Evaluation Model as documented in Reference 2. Since the correlation being utilized is standard in many Westinghouse analytical tools, its range of applicability to the AP600/AP1000 operating conditions will be confirmed should core uncovery be observed which is not expected to occur from the preliminary analysis (Reference 9).

3.4.6 Additional NOTRUMP Considerations for AP1000

For the AP600 and AP1000, SBLOCA events are not the most limiting events with regard to calculated PCT. However, this category of events is the most challenging with respect to the integrated performance of the passive core cooling system features such as automatic depressurization and gravity injection. The AP600 test and analysis programs showed that the transition from ADS depressurization to IRWST injection during the SBLOCA is of greatest concern as minimum reactor vessel inventory typically occurs during this transition phase. Consequently, the pivotal SBLOCA-related issue identified during the AP600 Design Certification review with the ACRS became the ability of the NOTRUMP code to conservatively predict the onset of IRWST injection following actuation of the ADS, as gravity injection is critical in providing long-term recovery of reactor vessel inventory. Therefore, the primary means of resolution for this issue was to demonstrate that the NOTRUMP code could conservatively predict the onset of IRWST injection in the AP600 integral effects tests, which were shown to be adequately scaled to the AP600 during this transition phase. As the AP1000 has also been shown to be adequately scaled to the AP600 integral effects tests (Reference 3), the same means of resolution will be used for AP1000 except instead of conservative treatment of the [

]^{a,b,c} as described below. In addition, a supplemental calculation will be performed using WCOBRA/TRAC for the most limiting SBLOCA event (DE DVI) to support the NOTRUMP calculation.

The reason for using an [ ]^{a,b,c} to ensure conservative prediction of the onset of IRWST injection in NOTRUMP for AP1000 as opposed to using an [ ]^{a,b,c} as in AP600 is that there is little uncertainty associated with single-phase gravity injection from the IRWST. The gravity head and single-phase hydraulic resistance are well known and understood. However, the onset of IRWST injection is also very dependent upon the backpressure in the reactor vessel (downcomer). Reactor vessel pressure is in turn controlled by the venting of steam through the ADS outlet paths. Steam venting through the ADS paths is strongly influenced by complex, two-phase flow interactions in the hot legs and ADS piping involving entrainment and two-phase pressure drop through the ADS valves and piping including momentum flux. These phenomena have a much higher uncertainty, are not as well understood, and, in general, are not accurately predicted by two-phase thermal-hydraulic codes. Therefore, if any adjustment is made to the analysis code model, it should be done to the [ ]^{a,b,c} associated with the ADS-4 vent paths.

As NOTRUMP does not have a functional momentum flux model, a flow regime map for the hot legs or a detailed entrainment model, a supplemental calculation with WCOBRA/TRAC incorporating these key features will be performed. Westinghouse plans that this supplemental calculation will address the most limiting SBLOCA event and will be used to evaluate the various two-phase processes influencing the ADS vent paths in greater detail than can be accomplished with NOTRUMP. WCOBRA/TRAC embodies the state of the art in two-phase physical modeling of integral effects of thermal-hydraulic systems. Westinghouse plans on submitting a full topical report including validation against separate and integral effects tests for review by the NRC staff. Appendix B of this report contains some validation against separate effects tests. Westinghouse plans to use WCOBRA/TRAC to predict key processes in the transition phase of integral effects tests and use these results as the basis to conservatively predict plant performance.

NOTRUMP ADS-4 Resistance Increase Effect

In order to demonstrate the effect of the [ ]^{a,b,c} on the NOTRUMP results, the information generated in support of the May 11th and 12th 1998 ACRS Thermal Hydraulic subcommittee meeting is summarized below.

As presented in the response to RAI 440.796F, Part a, the detailed momentum flux model, developed for the OSU facility, calculated a required [ ]^{a,b,c} of approximately [ ]^{a,b,c} would be necessary to account for the model deficiency in the NOTRUMP OSU model. NOTRUMP simulations for the OSU facility were performed in which a [ ]^{a,b,c} was applied to the ADS-4 flow paths at the [ ]^{a,b,c} flow conditions. The [ ]^{a,b,c} was available from a series of sensitivity studies performed with the NOTRUMP OSU model. While the value is not an exact match to the required [ ]^{a,b,c} as calculated by the detailed stand-alone momentum flux model, it provides an estimate of the impact of the model adjustment. Figures 3-3 through 3-7 present comparisons of the OSU 2-inch cold leg break simulation (Test SB18) between the test data, the base NOTRUMP model used in Final Validation Report (Reference 3), and the adjusted NOTRUMP model results generated in support of the ACRS Thermal Hydraulic subcommittee meeting. As can be seen by these figures, the pressurizer drain behavior (Figures 3-3 and 3-4), ADS-4 integrated flow behavior (Figure 3-5), and IRWST-1 injection flow (Figures 3-6 and 3-7) are more accurately reflected by the adjusted NOTRUMP model and result in a conservative prediction of the IRWST injection flows. This demonstrates that the major contributor to the deviations between the NOTRUMP model and the test data results from the deficiency in the [ ]^{a,b,c} during the non-critical flow period. It also demonstrates that this is a more direct means of adjusting the NOTRUMP model in lieu of the originally utilized [ ]^{a,b,c} adjustment.

WCOBRA/TRAC Supplemental Calculation

The NOTRUMP small break LOCA cases performed in the AP1000 SAR will include a supplemental calculation of system performance during the ADS Stage 4 depressurization to IRWST injection. This supplemental calculation is intended to demonstrate that:

- The thermal-hydraulic models in NOTRUMP, with the adjustment to [ ]^{a,b,c} provide an appropriate conservative prediction of the AP1000 during the ADS 4th stage depressurization.
- The injection of water from the IRWST does not occur prematurely in NOTRUMP.

In this way, the issues in ADS Stage 4-IRWST initiation predictions associated with the shortcomings in NOTRUMP predictive capabilities are addressed through an analysis that uses more suitable models for highly ranked PIRT phenomena. The adjusted NOTRUMP model can be demonstrated to conservatively predict the test and plant results during this phase of the transient.

This supplemental calculation to support the adjusted NOTRUMP result will be performed using the "AP" version of the WCOBRA/TRAC computer code, which will contain the detailed models necessary to calculate the pertinent phenomena during this phase of the transient. The phenomena which led to the imposition of an [ ]^{a,b,c} in the AP600 licensing analysis, and the adjustment to [ ]^{a,b,c} in the AP1000 NOTRUMP small break LOCA analysis cases are momentum flux in the ADS-4 flowpaths and entrainment in the hot legs and ADS-4 flowpaths. With its more detailed models, WCOBRA/TRAC-AP will provide a physically-based calculation of each of these phenomena as follows:

- The momentum equation as solved in the TRAC components used for ADS Stage 4 piping contains all significant terms, including the momentum flux terms.
- COBRA channels will be used to model the hot legs in the AP1000 supplemental calculation. Within the hot legs, horizontal flow regimes will be identified using the Taitel-Dukler flow map. The Ishii-Grolmes criteria will be used to predict entrainment off the horizontal surface. The onset of entrainment into the ADS Stage 4 offtake piping atop the hot legs will be determined using a Froude-number relationship. In the event entrainment is predicted to occur, the quality in the ADS-4 pipe will be calculated using a correlation for a vertical upward branch connection. Refer to Appendix B for detailed discussion of flow regime maps and entrainment models to be used in WCOBRA/TRAC-AP code version.

The WCOBRA/TRAC "AP" code version to be used in the AP1000 small break LOCA supplemental calculations will be validated for this application against the ADS Stage 4 IRWST initiation phase of AP600 integral effects tests. The WCOBRA/TRAC "AP" code version will be used as an Appendix K type code. It will embody models for important processes such as entrainment that may be adjusted to conservatively predict the AP600 integral effects test during the ADS-IRWST transition phase. As the AP600 integral effects tests have been shown to be acceptably scaled to AP1000, the test-validated models will then serve as the basis on which the code will be used to predict the behavior of the AP1000 during the ADS-IRWST transition phase. Initial and boundary conditions will be supplied from the test data and the NOTRUMP simulation of the tests to accomplish the validation. The use of WCOBRA/TRAC with its more detailed models for momentum flux and entrainment will provide more indepth understanding of these phenomena to support conservative treatment of ADS-4 resistance in NOTRUMP analysis.

Among the phenomena which are important to AP1000 performance during the ADS-4 IRWST initiation phase are those that deal with flow patterns in the hot legs and the removal of liquid and vapor from the hot legs into the ADS-4 flow paths. The models and correlations that have been added to the large break LOCA version of WCOBRA/TRAC to calculate these phenomena for horizontal pipe flow are presented in Appendix A, together with results of the separate effects test validation calculation performed.

3.5 ASSESSMENT OF DG-1096 RELATED METHODS

In a recent workshop (April 9, 2001) to discuss Draft Regulatory Guide DG-1096, several attributes were discussed which should be considered in determining the extent to which the DG process should be used in the development, assessment, and application to an evaluation model. These are:

- Novelty of the evaluation model compared to the currently acceptable model.

- The complexity of the event being analyzed.
- The degree of conservatism of the evaluation model.
- Risk or safety importance of the event.

For the NOTRUMP AP1000 analysis program, these issues are addressed as follows:

- The evaluation model, which will be utilized for the AP1000 program, is the same as that utilized for the AP600 program with minor error corrections and user convenience features being implemented as discussed in Section 3.1 of this document. As such, no significant changes are being made to the evaluation model as approved for AP600 applications.
- While the SBLOCA event is typically not considered to be a complex event for traditional PWRs, the nature of the AP600/AP1000 designs are such that the behavior involved (automatic depressurization to low pressure conditions) results in calculation complexities. The event and underlying methodology was thoroughly reviewed for application to the AP600 plant design. Preliminary analyses with the approved evaluation model did not indicate the existence of new phenomena for the AP1000 design as compared to that observed for the AP600 design.
- The evaluation model and methodology used continues to be based on the use of Appendix-K required features. As such, the model and modeling features will result in a conservative calculation with respect to the expected plant response. In addition, since the preliminary analyses performed in Reference 9 indicate no core uncovery exists, significant margin to the 10 CFR 50.46 limits occurs for the AP1000 plant design.
- The preliminary AP1000 analyses, presented in Reference 9, indicate no significant change in the margin to core uncovery. Therefore, significant margins to the 10 CFR 50.46 limits exist for this plant design.

The code being utilized in support of the AP1000 design has previously undergone a detailed review as part of the AP600 design certification process with the required aspects of DG-1096 having been met. As such, the code has been approved for use on the AP600 and is considered by Westinghouse to be applicable for use on the AP1000.

3.6 CONCLUSIONS/RECOMMENDATIONS

To appropriately apply the NOTRUMP code to the AP1000 plant design, the deficiencies noted during its application to the AP600 plant are addressed as discussed in Section 3.4.5 and summarized in Table 3-1. The methods described in the previous section address the identified issues in an effective manner thereby allowing Westinghouse to demonstrate the conservative nature of the NOTRUMP code. As such, Westinghouse believes that the NOTRUMP code utilized for the AP600 test and analysis program can be appropriately utilized in support of AP1000 Design Basis Accident (DBA) analyses. It is expected that the large plant margins to safety limits observed in the SBLOCA analysis will be demonstrated for AP1000, as indicated by the preliminary analysis (Reference 9), as it was for AP600.

3.7 REFERENCES

1. WCAP-10079-P-A, "NOTRUMP A Nodal Transient Small Break And General Network Code," Meyer, P. E., 1985.

2. WCAP-10054-P-A, "Westinghouse SB ECCS Evaluation Model Using the NOTRUMP Code," Lee, N., et al., 1985.

3. WCAP-14807, Revision 5, "NOTRUMP Final Verification and Validation Report for AP600," Fittante, R. L., et al., 1998.

4. WCAP-14206 "Applicability of NOTRUMP Computer Code to AP600 SSAR Small Break LOCA Analysis," Kemper, R. M., 1994.

5. NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," U.S. Nuclear Regulatory Commission, September 1998.

6. NSD-NRC-99-5839, "1998 Annual Notification of Changes to the Westinghouse SmallBreak LOCA and Large Break LOCA ECCS Evaluation Models, Pursuant to 10CFR50.46 (a)(3)(ii)," Letter from J. S. Galembush (Westinghouse) to J. S. Wermiel (NRC), July 15, 1999.

7. NSBU-NRC-00-5970, "1999 Annual Notification of Changes to the Westinghouse Small Break LOCA and Large Break LOCA ECCS Evaluation Models, Pursuant to 10CFR50.46 (a)(3)(ii)," Letter from H. A. Sepp (Westinghouse) to J. S. Wermiel (NRC), May 12, 2000.

8. NSBU-NRC-00-5972, "NRC Report for NOTRUMP Version 38.0 Changes," Letter from H. A. Sepp (Westinghouse) to S. J. Collins (NRC), June 30, 2000.

9. WCAP-15612, "AP1000 Plant Description and Analysis Report," Corletti, M. M., et al., December 2000.

10. WCAP-15613, "AP1000 PIRT and Scaling Assessment," February 2001.

11. WCAP-14292, Revision 1, "Low-Pressure Integral Systems Test at Oregon State University, Test Analysis Report," September 1995, T. S. Andreychek, et. al.

Table 3-1 NOTRUMP Issue Assessment Summary for AP1000

Component Phenomenon	Assessment Results	AP600 Treatment	Comments	AP1000 Treatment
ADS-4:				
Two-phase pressure drop	Minimal; due to lack of momentum flux terms, [ ]^{a,b,c}.	[ ]^{a,b,c}	[ ]^{a,b,c} resulting in early Pressurizer drain and IRWST initiation.	[ ]^{a,b,c} Perform supplemental WCT simulation for select limiting cases.
COLD LEGS:				
Phase separation at tees	Minimal, but conservative.	No change.	Balance line refilling delays CMT drain and subsequent ADS actuation.	No change.
CMT:				
Thermal stratification	Minimal, but conservative.	No change.	Inability to accurately track thermal stratification increases CMT exit temperature, reduces core subcooling.	No change.

Note:

1. [ ]^{a,b,c} is indirect correction for most significant deficiency, lack of momentum flux in ADS-4. All SAR cases run with [ ]^{a,b,c} to confirm [ ]^{a,b,c} approach.

Table 3-1 NOTRUMP Issue Assessment Summary for AP1000 (cont.)

Component Phenomenon	Assessment Results	AP600 Treatment	Comments	AP1000 Treatment
DOWNCOMER:				
Level	Minimal for DEDVI.	[ ]^{a,b,c} Range Cd for break to assure limiting case found.	Downcomer model does not predict 2-dimensional temperatures. Excess condensation during IRWST injection.	[ ]^{a,b,c} Range Cd for break to assure limiting case found. Downcomer misprediction does not impact core level response.
HOT LEGS:				
Stratification, phase separation at tees	Minimal due to ad hoc model; impact is small.	[ ]^{a,b,c}	Liquid flow out ADS-4 is controlled by constant system inventory, inlet flow, self-correcting system.	[ ]^{a,b,c} Perform supplemental WCT simulation for select limiting cases.
PRESSURIZER AND SURGE LINE:				
CCFL	Minimal but conservative provided vapor flow is correct.	No change; given correct or high vapor flow, CCFL is conservative.	[ ]^{a,b,c}	[ ]^{a,b,c}

Table 3-1 (cont.) NOTRUMP Issue Assessment Summary for AP1000

Component Phenomenon	Assessment Results	AP600 Treatment	Comments	AP1000 Treatment
Level swell	Minimal non-conservative during draining.	[ ]a,b,c	Rapid draining due to poor [ ]a,b,c confirmed by studies with [ ]a,b,c	[ ]a,b,c Perform supplemental WCT calculations for select limiting cases.
STEAM GENERATOR:				
Heat transfer	Minimal, but conservative	No Change.	Under-prediction in PRHR, CMT increases SG heat transfer/reliance on ADS.	No Change.
PRHR:				
Heat transfer	Minimal, conservative if primary flow is low.	[ ]a,b,c	Heat transfer not over-predicted as long as primary side is limiting.	[ ]a,b,c
Recirculation flow	Minimal, conservative if primary flow is low.	[ ]a,b,c	Under-predicted flow reduces PRHR heat transfer.	[ ]a,b,c
NON-CONDENSABLE GAS INJECTION:				
Accumulator nitrogen injection	Model not available in code.	[ ]a,b,c	[ ]a,b,c	[ ]a,b,c

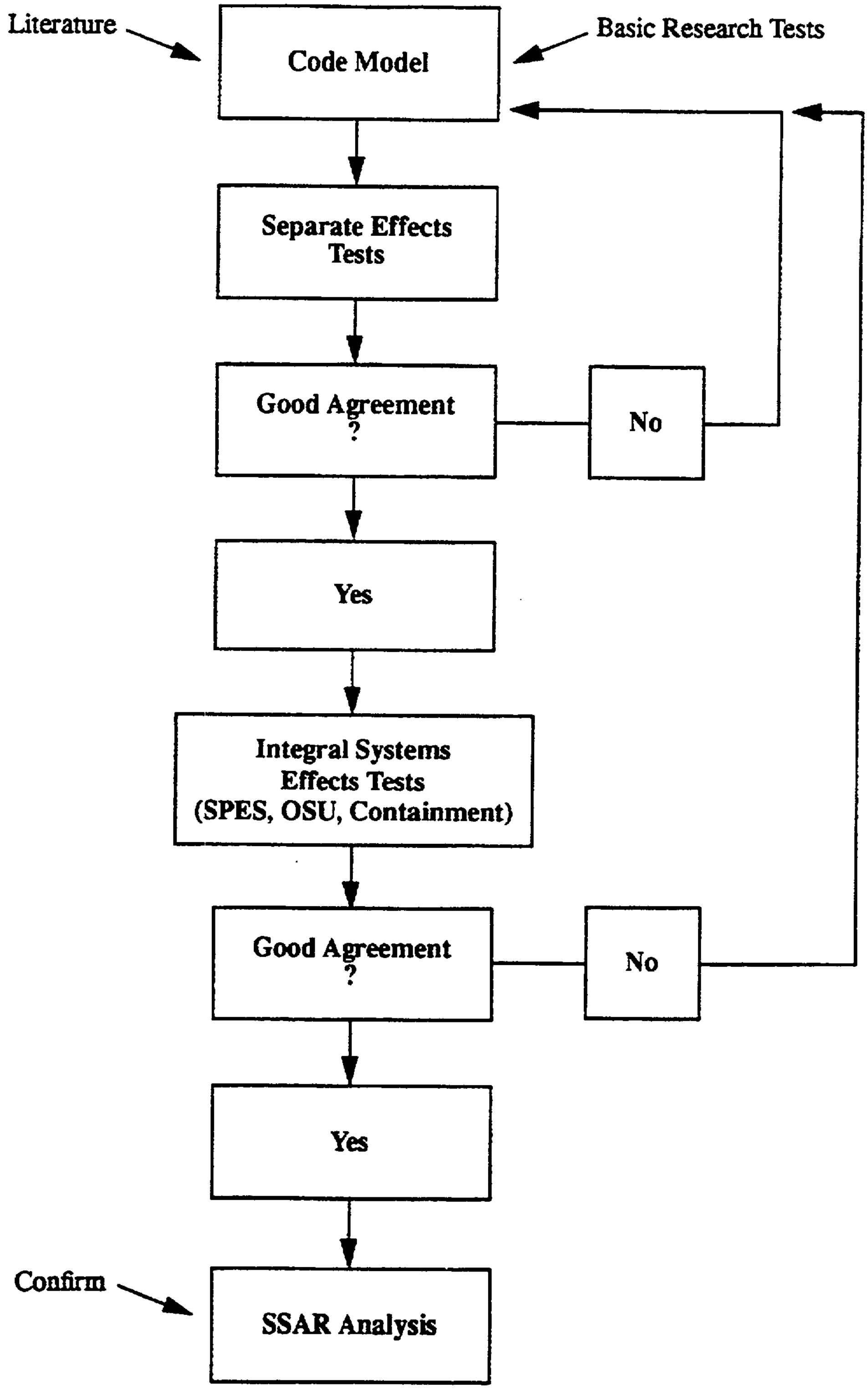

Figure 3-1 Model Development and Verification Process for Code Validation

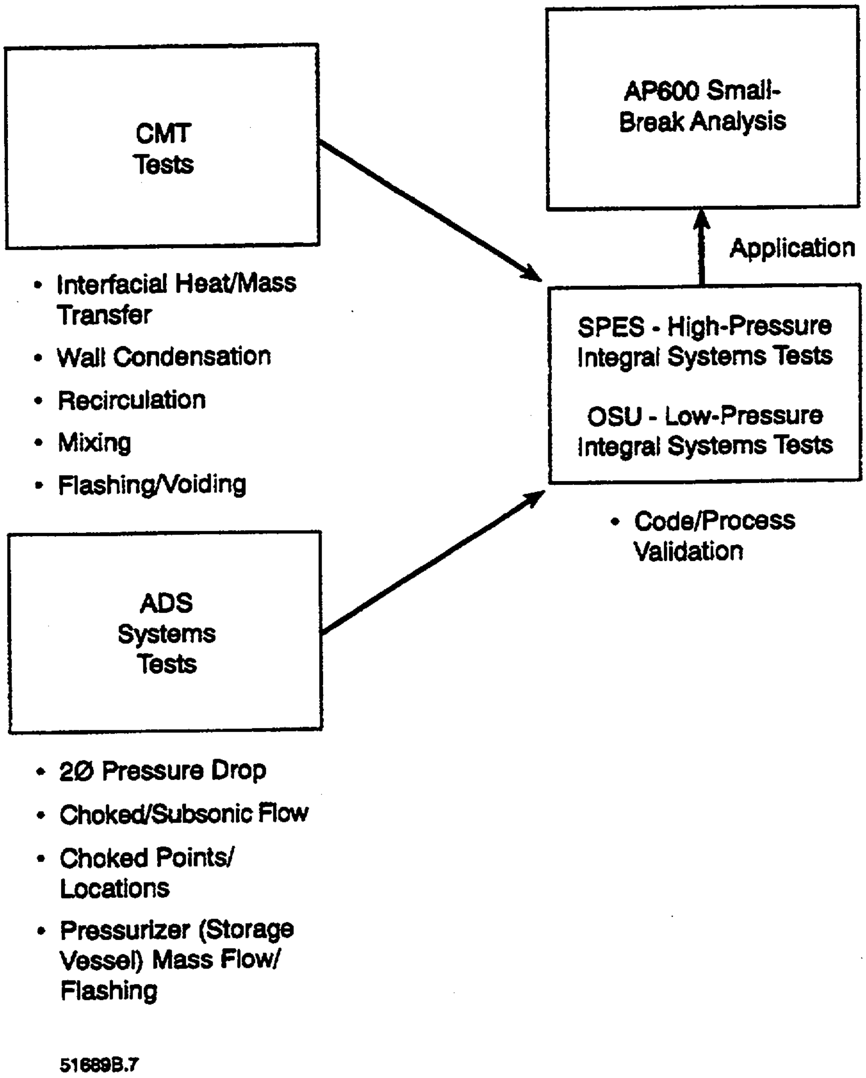

Figure 3-2 NOTRUMP Verification with Separate Effects Tests and Validation with Integral Systems Tests

a,b,c

Figure 3-3 OSU Test SB18 2-Inch Cold Leg Break Pressurizer Level (Relative to Bottom Tap)

a,b,c

Figure 3-4 OSU Test SB18 2-Inch Cold Leg Break Pressurizer Level (Relative to Bottom Tap)

a,b,c

Figure 3-5 OSU Test SB18 2-Inch Cold Leg Break ADS Stage 4 Integrated Flows

a,b,c

Figure 3-6 OSU Test SB18 2-Inch Cold Leg Break IRWST Injection Line Mass Flow

a,b,c

Figure 3-7 OSU Test SB18 2-Inch Cold Leg Break IRWST Injection Line Mass Flow

4.0 LOFTRAN-AP CODE VALIDATION

4.1 INTRODUCTION

The original LOFTRAN computer code (Reference 1) was developed to simulate behavior in a multi-loop pressurizer water reactor with active safety systems during non-LOCA events. The code simulates a multi-loop system by modeling the reactor core and vessel, hot and cold leg, steam generator (tube and shell sides), pressurizer, and reactor coolant pumps, with up to four reactor coolant loops. The code has an extensive history of use in performing design and licensing basis non-LOCA analyses and has been reviewed and approved for use in non-LOCA analyses by the U.S. NRC. The code is currently used for licensing analyses in support of operating plant fuel reloads and plant upgrades (upratings, steam generator replacement programs).

Several specialized versions of LOFTRAN have been developed for steam generator tube rupture (SGTR) analyses and for non-LOCA analyses that use passive safety systems for event mitigation. The LOFTRAN code family consists of the following versions:

- LOFTRAN – operating plant non-LOCA analyses
- LOFTTR2 – operating plant SGTR analyses
- LOFTRAN – AP-passive plant non-LOCA analyses
- LOFTTR2 – AP-passive plant SGTR analyses

The relationship between the code versions is illustrated in Figure 4-1.

The LOFTTR2 code is a specialized version of the LOFTRAN code modified for the analysis of SGTR events. LOFTTR2 includes an enhanced steam generator secondary side model, a tube rupture break flow model, and improvements to allow simulation of operator actions. This code version is documented in References 2, 3 and 4 and has been reviewed and approved by the NRC for SGTR analyses. LOFTTR2 is currently used for licensing analyses in support of operating plant fuel reloads and plant upgrades.

For non-LOCA events relying on passive safeguards features and SGTR analyses of the AP600, modifications to LOFTRAN and LOFTTR2 were made to simulate the passive plant features. The AP600 is a two-loop pressurized water reactor with passive emergency safeguards features. The passive plant versions of LOFTRAN and LOFTTR2 are referred to as LOFTRAN-AP and LOFTTR2-AP. The principal changes made for the passive plant code versions for design basis analyses consist of adding models for the passive residual heat removal (PRHR) system and the core makeup tanks (CMTs).

A description of the models added to LOFTRAN-AP and LOFTTR2-AP is provided in Revision 1 of WCAP-14234 (Reference 5). Comparisons between tests performed for the AP600 program and LOFTRAN-AP/LOFTTR2-AP are provided in Revision 1 of WCAP-14307 (Reference 6). WCAP-14234 and WCAP-14307 have been reviewed by the NRC and also include NRC review questions and the responses to the questions.

4.2 NRC AP600 LOFTRAN REVIEW

The NRC approved the use of LOFTRAN codes for AP600 analysis in the AP600 FSER, NUREG-1512 (Reference 7). The NRC review of the LOFTRAN codes, summarized in Section 21.6.1 of NUREG-1512, addressed the following areas, which are discussed below:

- Use of auxiliary codes in conjunction with LOFTRAN
- Partial loss of forced RCS flow analysis methodology
- Phenomena Identification and Ranking Table (PIRT)
- Primary and secondary system analytical models in previously approved LOFTRAN versions
- Passive plant components and systems:
  - Automatic Depressurization System (ADS)
  - Core Makeup Tanks (CMTs)
  - Passive Residual Heat Removal (PRHR) Heat Exchanger and In-containment Refueling Water Storage Tank (IRWST)

4.2.1 Use of Auxiliary Codes in Conjunction with LOFTRAN

Transient analyses performed with LOFTRAN are conducted in conjunction with additional support codes. In particular, the FACTRAN code (Reference 8) is used for detailed fuel or heat flux modeling. The THINC (References 9, 10, 11 and 12) or WESTAR (Reference 13) codes were used for Departure for Nucleate Boiling Ratio (DNBR) calculations. These supporting codes were found to be acceptable for AP600 use by the NRC based on previous NRC reviews of these codes and because the fuel design conditions of the AP600 fell within the codes range of validity.

AP1000 analyses will use the FACTRAN support code for detailed heat flux modeling. However an additional support code, VIPRE (Reference 14) will also be used for DNBR calculation. The VIPRE code was developed by Battelle Pacific Northwest Laboratories under sponsorship of the Electric Power Research Institute (Reference 15). VIPRE is widely used throughout the industry and the NRC has given generic approval for its use. The NRC has also reviewed and approved submittals by several utilities for the use of VIPRE for core reload evaluations.

The VIPRE code is flexible and contains input options to permit numerous applications. Like THINC-IV, the VIPRE code is a three-dimensional subchannel thermal-hydraulic code used for describing the reactor core with core boundary conditions supplied by other codes. However VIPRE is also a transient code and temporal variations are calculated. The VIPRE code also includes models of the fuel pin interior comparable to those of FACTRAN for calculation of the transient temperature distribution in a cross section of a fuel rod and the transient heat flux.

Application of the VIPRE code for core thermal-hydraulic analyses by Westinghouse has been previously reviewed and approved for use by the NRC in Reference 14. As described in Reference 14, options selected in the VIPRE code for the Westinghouse methodology give results comparable to those of THINC-IV and FACTRAN codes. The transient core design conditions of the AP1000 non-LOCA analyses are within the validity of the use of the auxiliary codes used in conjunction with LOFTRAN.

4.2.2 Partial Loss of Forced RCS Flow Analysis Methodology

The advanced passive plant designs use reactor coolant systems with two cold legs per reactor coolant loop. The LOFTRAN code simulates only a single cold leg per reactor coolant system (RCS) loop. No changes have been made to the codes to simulate the twin cold leg arrangement. The cold leg arrangement is simulated by lumping the twin cold legs into one. With the lumped cold leg assumption, uniform flow is predicted for the twin cold legs on each RCS loop. This is acceptable for simulation of all events except for those where asymmetric flow conditions are expected. The only events analyzed with LOFTRAN where asymmetric flow conditions within a reactor coolant loop are the following:

- Partial loss of forced reactor coolant flow events
- Locked or broken reactor coolant pump (RCP) shaft events
- Startup of an inactive RCP

Calculation of the net reactor coolant loop flows for use in LOFTRAN is accomplished through the use of auxiliary programs, hand calculations and conservative assumptions. As part of the AP600 licensing effort an outline of the methodology used for calculating conservative transient asymmetric cold leg flows external to LOFTRAN was submitted to the NRC (RAI 440.279 - see Appendix B of WCAP-14234 [Reference 5]). Additionally, sample calculations illustrating the method were also submitted to the NRC (Supplemental Draft Safety Evaluation Report, SDSER Open Item 21.6.1.7-3 - see Appendix B of WCAP-14234).

The NRC concluded that the methodology used for calculation of the effects of a partial loss of flow or locked rotor/broken shaft were conservative. Issues related to simulation of asymmetric cold leg flows were resolved and SDSER Open Item 21.6.1.7-3 was closed.

The reactor coolant loop architecture of the AP1000 is similar to that of the AP600. Twin cold legs and reactor coolant pumps are used in each RCS loop. The conservative approach used for AP600 analyses with asymmetric RCS loop flows is also applicable and acceptable for the AP1000.

4.2.3 Phenomena Identification and Ranking Table (PIRT)

As part of the NRC's review of the AP600, a PIRT was developed for non-LOCA and steam generator tube rupture events. The NRC PIRT was compared to the Westinghouse PIRT submitted in WCAP-14234. The NRC noted that the Westinghouse PIRT was more extensive in depth of coverage of non-LOCA transients. General agreement between the NRC and Westinghouse PIRTs was observed with slight differences.

The NRC PIRT for SGTR ranks the upper head flashing as medium importance while the Westinghouse PIRT ranked the importance of this phenomenon as low. The staff found the differences to be acceptable because it was noted that calculations indicate that the upper plenum of the vessel stays subcooled with up to 10 ruptured tubes, which is beyond the design basis event.

The NRC PIRT ranked the importance of CMT balance line initial temperature distribution as medium, while the Westinghouse PIRT ranked this phenomenon as low. The differences between the NRC and Westinghouse PIRT's were found to be acceptable because the initial temperature distribution is explicitly input to LOFTRAN and the difference in ranking does not affect the analyses results.

The staff concluded that the PIRT developed for the AP600 transient analyses using LOFTRAN to be applicable and acceptable.

The PIRT developed for the AP600 non-LOCA events was reviewed for applicability to the AP1000. The PIRT review included industry experts and the AP1000 PIRT is presented in Section 2.5 of WCAP-15613 (Reference 16). The basic configuration of the AP1000 is the same as the AP600. AP1000 system and component capacities have been adjusted to accommodate the higher core power rating of AP1000. Due to the similarities of the two designs it is expected that the AP1000 PIRT would be similar to that of the AP600. The review identified no additional phenomena for AP1000 non-LOCA and SGTR analyses. However, the ranking of the CMT "gravity draining injection" phenomenon was changed from "Not Applicable" to medium for steam line and feedwater line ruptures. This is because the pressurizer volume-to-power ratio and the increase in steam generator secondary side volume of the AP1000 could make the RCS more sensitive to shrink and swell events. It was postulated that large enough RCS pressure decreases may occur, such that the CMTs could operate in the gravity drain injection mode rather than the recirculation injection mode. However, this behavior is not expected to occur. A ranking of medium is appropriate at this time until AP1000 analyses confirm that gravity drain CMT injection does not occur during non-LOCA transients.

4.2.4 Primary and Secondary System Analytical Models in Originally Approved LOFTRAN Versions

The NRC approved the original version of LOFTRAN for non-LOCA design basis analyses in 1983 (WCAP-7907-P-A - Reference 1). The NRC approved the specialized steam generator tube rupture code version (LOFTTR2) in WCAP-10698-P-A (References 2). For the AP600, LOFTRAN and LOFTTR2 were modified to include additional models for passive system features. The analytical models in the previously approved versions of LOFTRAN and LOFTTR2 for primary and secondary coolant systems were unchanged for use in the AP600. During its review of AP600, the staff requested additional information on the applicability AP600 thermal-hydraulic conditions to several of the phenomenological models in the previously approved LOFTRAN and LOFTTR2 code versions. The staff concerns included the pressurizer location, wall friction, global pressure location, compressibility effects, reverse flow, and heat transfer options. When the SDSER was issued, Westinghouse had not yet submitted responses to all the staff's RAIs related to the LOFTRAN codes. Submittal of outstanding RAI responses was SDSER Open Item 21.6.1.4-1. Responses to all the outstanding RAIs related to the LOFTRAN codes were completed and submitted to the NRC. Copies of the RAIs and the responses to the NRC were incorporated into Revision 1 of WCAP-14234. The NRC completed its review of these responses and found them to be technically complete and sound, and SDSER Open Item 21.6.1.4-1 was closed. The resolution of the staff concerns on AP600 also apply to AP1000.

4.2.5 Passive Plant Components and Systems

The passive plant designs (AP600 and AP1000) contain features or systems important to the analysis of non-LOCA events that differ from licensed operating Westinghouse plants with active safeguards features. These systems include:

- Automatic Depressurization System
- Core Makeup Tanks
- Passive Residual Heat Removal heat exchanger
- In-containment Refueling Water Storage Tank

Additional models or options to existing models were added to the approved LOFTRAN and LOFTTR2 versions to deal with these passive plant features. The code versions modified to deal with passive plant features were called LOFTRAN-AP and LOFTTR2-AP. These new models were reviewed and approved by the NRC for the AP600. The AP1000 models are based on the approved AP600 models with dimensional input adjustments for the configuration changes.

4.2.6 Automatic Depressurization System

As summarized in NUREG-1512, it was the staff's position that LOFTRAN be restricted from application to analysis involving actuation of the ADS, since the code has not been benchmarked against ADS actuation experiments. ADS actuation involves global two-phase flow behavior for blowdown and LOFTRAN does not have the capability to model this behavior. This was SDSER Open Item 21.6.1.7-5 (see Appendix B of Revision 1 to WCAP-14234).

The Westinghouse response to SDSER Open Item 21.6.1.7-5 noted that the ADS system is not activated to mitigate non-LOCA or steam generator tube rupture events. Therefore, detailed modeling of this system is not required in LOFTRAN. In Section 15.6.1 of the AP600 Design Control Document (DCD), (Reference 17), the results of an inadvertent RCS depressurization are presented. This analysis historically covered the RCS depressurization due to inadvertent opening of pressurizer relief valves. The analyses are short-term analyses that demonstrate that the protection system will detect the depressurization and trip the reactor prior to exceeding DNB limits. For this type of analysis, the most limiting transient is one that will result in the most rapid depressurization of the RCS.

The AP600 DCD Section 15.6.1 included a short-term analysis of the inadvertent opening of an ADS path connected to the pressurizer. Analysis of this type of event was performed with LOFTRAN using assumptions that conservatively maximize the relief from the ADS path under consideration. No credit for ADS piping interactions or interactions with the IRWST that may reduce the rate of RCS depressurization is assumed in the analysis. This results in the maximum rate of RCS depressurization. This is the only analysis performed with LOFTRAN that involves the ADS.

In conclusion, the ADS piping interactions and possible interactions with the IRWST have not been assessed in the LOFTRAN code, since the ADS is not used for mitigation of any transients analyzed with the code. The NRC and Westinghouse agreed that the inadvertent opening of the ADS valves is the only transient that may be analyzed with LOFTRAN in which the ADS plays a part. In this case, the ADS is treated in the same manner as an open power-operated relief valve, for which LOFTRAN has been found acceptable. Consequently, SDSER Open Item 21.6.1.7-5 was closed.

This approach is planned for use on the AP1000 and continues to provide an acceptable and conservative approach for the AP1000.

4.2.7 Core Makeup Tank

The core makeup tanks provide gravity driven borated coolant injection to the reactor coolant system. The tops of the CMTs are connected to the cold leg by the cold leg balance lines, which have normally open isolation valves. The balance lines maintain the CMTs at the same pressure as the reactor coolant system. Discharge lines connect the bottoms of the CMTs to the reactor vessel. Isolation valves in the discharge lines are normally closed. During normal operation, the CMTs and the connection lines are filled with liquid. When the CMTs are actuated by opening the discharge line valves, the CMTs can operate in two modes, re-circulation injection mode and gravity drain injection mode. During non-LOCA transient events, the CMTs work in the re-circulation injection mode. In non-LOCA events the CMTs provide the emergency boration function for the reactor coolant system. Once activated the CMTs may inject sufficient fluid such that the reactor coolant system is overfilled. This system is important in non-LOCA transients as indicated in the AP1000 PIRT presented in WCAP-15613.

A re-circulation injection mode CMT model was added to LOFTRAN for the AP600 program. The model uses 15 fluid nodes for the tank proper, 3 nodes for the balance line and 8 nodes for the injection line. Heat transfer through the core makeup tank wall is also simulated.

The LOFTRAN CMT model was reviewed by the NRC during the AP600 program. The major NRC issue with the LOFTRAN CMT model revolved around the possibility of steam entering the balance line or fluid flashing within the balance line. The LOFTRAN CMT model is not written for the simulation of two-phase flow transients. This issue (SDSER Open Item 21.6.1.7-4) was resolved by the inclusion in LOFTRAN of a penalty that penalizes the CMT buoyancy head such that natural circulation flow within the CMT is terminated.

The architecture of the AP1000 CMT design is the same as that of the AP600. The AP1000 CMT size has been increased relative to the AP600 and flow control orifices have been modified to increase injection flow. The connection points of the CMT and the number of nodes is hardwired in the LOFTRAN CMT model. However, the dimensional characteristics of the core makeup tanks and the connection lines are provided as input to the code. No changes to the LOFTRAN CMT model are needed to simulate the AP1000 CMT.

Validation of the CMT model of LOFTRAN was conducted by comparing code predictions to the AP600 CMT test facility data. These comparisons are documented in Reference 6. Scaling of the CMT test data for the AP600 was reviewed in Reference 16 and the data was found to be applicable to the AP1000.

4.2.8 Passive Residual Heat Removal (PRHR) Heat Exchanger and In-containment Refueling Water Storage Tank (IRWST)

The PRHR heat exchanger, a C-shaped, down-flow single pass heat exchanger, is submerged in the IRWST. Following depressurization of the RCS, the IRWST also supplies inventory to the RCS by gravity feed injection. This injection function of the IRWST is not used in non-LOCA analyses and is not modeled in LOFTRAN. The PRHR system is used for decay heat removal in non-LOCA analyses and is of high importance in several transient events.

PRHR and IRWST models were added to LOFTRAN for AP600 analyses. The PRHR model can contain up to 45 nodes divided into five regions. Heat exchanger tube nodes may have a horizontal or vertical orientation for buoyancy head and heat transfer calculations. The model transfers heat from the PRHR to the IRWST. The IRWST is simulated as a single homogeneous node. Once the fluid in the IRWST reaches the saturation point then steaming from the IRWST is accounted for.

The LOFTRAN PRHR and IRWST models were reviewed by the NRC during the AP600 program. The principle issues with the LOFTRAN model centered on the inability of the model to calculate thermal stratification within the IRWST if a single homogeneous fluid region model is used and the selection of the appropriate pool boiling heat transfer coefficient used on the outside of PRHR tubes.

The NRC questioned the validity of using a homogeneous, mixed condition in the IRWST when temperature stratification is likely. This issue was resolved by performing sensitivity studies with the LOFTRAN model using temperature stratification profiles from the SPES and PRHR test programs and demonstrating that using a homogenous IRWST temperature produces conservative non-LOCA transient analysis results.

The correlation used for pool boiling in the LOFTRAN PRHR model was developed from the Westinghouse PRHR test program. The PRHR test program used a configuration with three straight tubes. The NRC questioned the validity of these tests for defining the heat transfer of the PRHR. This issue was resolved based on comparisons of the LOFTRAN PRHR model to other tests. LOFTRAN simulations of SGTR tests at the SPES-2 facility were performed. The PRHR performance during these tests was accurately predicted by LOFTRAN. Westinghouse performed further blind test analyses of the PRHR heat transfer by calculating the performance of the full height C-tube heat exchanger used in the ROSA AP600 confirmatory tests. The analyses of the ROSA tests indicated the heat transfer correlation used in the LOFTRAN model conservatively predicted the heat transfer measured in the experiment.

The architecture of AP1000 PRHR design is the same as that of the AP600. The AP1000 uses a larger heat exchanger and the inlet and outlet piping sizes of the AP1000 have been increased. The architecture of the PRHR model is hardwired in LOFTRAN. However, the dimensional characteristics of the PRHR are set as input and can be adapted for the increased size. The acceptable resolution of NRC concerns on AP600 apply to the AP1000.

4.3 CODE VERSIONS FOR AP1000 ANALYSES

The AP600 non-LOCA analyses were performed using Version 1.8 of LOFTRAN-AP and the steam generator tube rupture analysis was performed using Version 1.6 of LOFTTR2-AP. The advanced plant code versions were developed by adding passive system features to the licensed operating plant analysis versions of LOFTRAN and LOFTTR2 available during the AP600 program.

Enhancements and upgrades to the LOFTRAN version used for operating plants have continued independent of the AP600 and AP1000 passive plant programs. The principal upgrades to the operating plant LOFTRAN version includes the following:

- Data transfer interfaces to other auxiliary computer codes
- Enhanced pressurizer safety and relief valve models
- Enhanced secondary side safety and relief valve models
- Input and output formatting
- VVER system models
- Enhanced RCS thick metal heat transfer model (description submitted to the NRC as Supplement 1 of WCAP-7907-S1 (Reference 18)

As part of the AP1000 project, the LOFTRAN-AP code will be upgraded to be consistent with the LOFTRAN version used for operating PWRs. Many of the enhancements to the operating plant version of LOFTRAN are not applicable to the passive plant analyses and therefore will not be used. Two of the upgrades that will be incorporated and used in the passive plant code include the data transfer interfaces to auxiliary computer codes, and the enhanced pressurizer and secondary side relief valve models. The data transfer interfaces to auxiliary computer codes upgrade will allow data to be transferred to auxiliary codes such as FACTRAN or the core subchannel DNBR analysis codes such as VIPRE. The enhanced pressurizer and secondary side relief valve models, which use more detailed models to allow individual valve inputs rather than a lumped valve model, improves the realism of the relief characteristics and aids in evaluating the cycling processes of the safety valves. The realistic safety valve model was used in supporting analyses submitted to the staff in response to RAIs during the AP600 Design Certification review. As shown in the analyses, inclusion of this model results in an increase in the pressurizer level swell, and therefore, tends to reduce the predicted margin to pressurizer overfill for transient events when safety valve opening is predicted. The staff review for AP600 included review of the model. The new LOFTRAN-AP version is consistent with the LOFTRAN code version currently in use for analysis support of operating PWRs. Models for the passive system which are approved for the AP600 remain unchanged and are applicable for the AP1000.

Many of the non-LOCA analyses do not rely on passive system features for mitigation of the events. These events behave in a similar manner as licensed operating PWRs and can be analyzed using the same versions of LOFTRAN as operating plants. Table 4-1 summarizes the transients analyzed using the LOFTRAN code family and identifies which code versions can be used for the analyses. The AP600 or AP1000 results of those transients that can be analyzed using either the operating plant version or the passive plant code version are the same independent of the version used. The passive plant models in LOFTRAN approved during the AP600 Design Certification review are the same models that will be used for AP1000. Other changes associated with the transitions to the latest revisions of LOFTRAN have been approved for operating plants and are acceptable for AP1000 because they do not affect the models associated with the passive features.

4.4 CONCLUSIONS

NRC review of the LOFTRAN codes was performed for the AP600. In NUREG-1512, the staff concluded that LOFTRAN had been modified to include the necessary models for the AP600 plant features and behavior expected during non-LOCA transients and was acceptable for the AP600 passive reactor design.

Preliminary AP1000 analyses were performed for selected non-LOCA and SGTR design basis events using the methods and LOFTRAN versions validated for the AP600. The results of these AP1000 analyses are presented in WCAP-15612 (Reference 19). The results of the AP1000 analyses showed safety margins comparable to those of the AP600 and resulted in no new phenomena or significant differences in plant performance characteristics.

AP1000 PIRT and scaling assessments are summarized in WCAP-15613. The results of the preliminary AP1000 analyses indicate that non-LOCA and SGTR transients for passive plants are similar to conventional operating PWRs with the exception of the PRHR heat exchanger and the CMT injection models. Models for the PRHR heat exchanger and the core make up tanks were incorporated into LOFTRAN for the AP600 project. As the PIRT and scaling of these two effects are similar for AP600 and AP1000, analysis codes that acceptably predict AP600 performance will acceptably predict AP1000 performance.

The basic configuration of the systems and components of the AP1000 remains the same as that of the AP600. The capacities of AP1000 systems and components have been adjusted to accommodate the higher core power of the AP1000 relative to the AP600. With respect to systems and components important to non-LOCA and steam generator tube rupture safety analyses, the general configuration of the AP1000 is the same as that approved for the AP600. While the architecture of the models needed for safety analyses within the LOFTRAN code are hardwired, the geometric dimensions are set by input parameters and will be modified for the AP1000 analyses without modifications to the computer code. In applying the LOFTRAN code family to the AP1000 analyses, conservative treatments for input parameters will be applied consistent with the analyses performed for the AP600 and operating plants. This includes the use of uncertainties on initial conditions, the use of upper and lower bound core reactivity coefficients, bounding protection system setpoints and actuation delays, and bounding performance parameters for emergency safeguards systems such as the PRHR and CMTs. The selection of the upper or lower bound input values is established on an event-by-event basis to produce conservative results with respect to acceptance criteria.

4.5 REFERENCES

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16. WCAP-15613, "AP1000 PIRT and Scaling Assessment," February 2001.
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Table 4-1 Applicable Code Versions for Passive Plant Design Basis Analysis

Events	SAR Section	Code Version		
		LOFTRAN	LOFTRAN-AP	LOFTTR2-AP
Feedwater system Malfunction that Result in a Decrease in feedwater Temperature or an Increase in Feedwater flow	15.1.1 15.1.2	X	X	
Excessive Increase in Secondary Steam Flow	15.1.3	X	X	
Inadvertent Opening of a Steam Generator Relief or Safety Valve and Steam System Piping Failure	15.1.4 15.1.5		X	
Inadvertent Operation of the PRHR	15.1.6		X	
Loss of External Electrical Load	15.2.2	X	X	
Turbine Trip	15.2.3			
Inadvertent Closure of Main Steam Isolation Valves	15.2.4			
Loss of Condenser Vacuum and Other Events Resulting in Turbine Trip	15.2.5			
Loss of ac Power to Plant Auxiliaries	15.2.6		X	
Loss of Normal Feedwater Flow	15.2.7			
Feedwater System Pipe Breaks	15.2.8		X	
Partial Loss of RCS Flow	15.3.1	X	X	
Complete Loss of RCS Flow	15.3.2			
RCP Pump Shaft Seizure	15.3.3	X	X	
RCP Pump Shaft Break	15.3.4			
Uncontrolled RCCA Bank Withdrawal at Power	15.4.2	X	X	
Startup of an Inactive RCP at an Incorrect Temperature	15.4.4	X	X	
Inadvertent Operation of the CMT During Power Operation	15.5.1		X	
Chemical and Volume Control system Malfunction that Increase Reactor Coolant Inventory	15.5.2		X	
Inadvertent Opening of a Pressurizer Relief Valve or Inadvertent Opening of an ADS Valve	15.6.1		X	
Steam Generator Tube Rupture	15.6.3			X

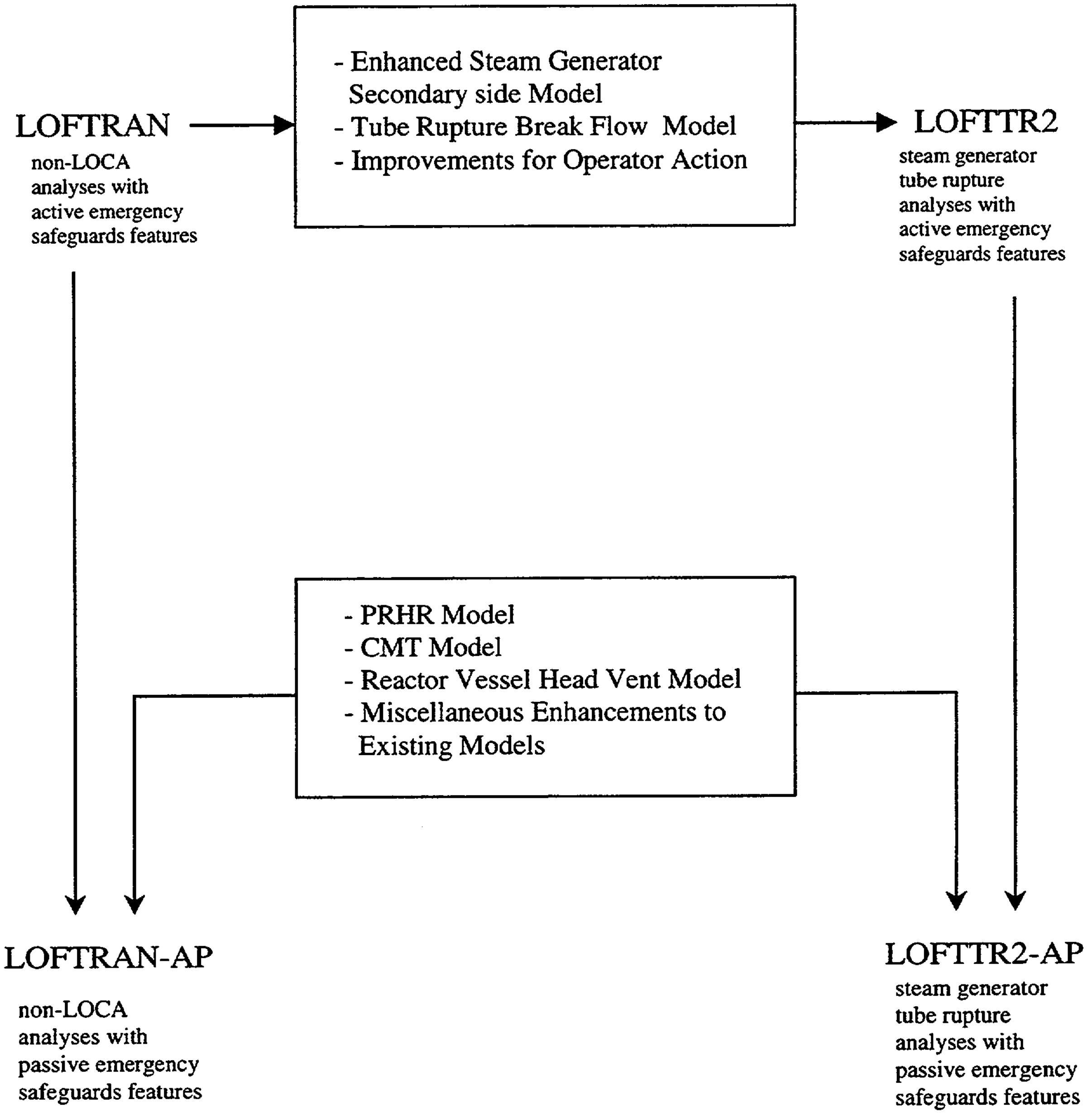

Figure 4-1 Relationship of LOFTRAN Code Versions

5.0 APPLICABILITY OF WGOTHIC FOR AP1000 CONTAINMENT INTEGRITY ANALYSES

5.1 BACKGROUND

The GOTHIC code is a state-of-the-art program for modeling multi-phase flow. The GOTHIC code was developed over a period of time from other qualified thermal-hydraulic computer codes as shown in Figure 5-1.

GOTHIC consists of three separate programs, the preprocessor, solver, and postprocessor. The preprocessor allows the user to rapidly create and modify an input model. The solver performs the numerical solution for the problem. The postprocessor, in conjunction with the preprocessor, allows the user to rapidly create graphic and tabular outputs for most parameters in the model.

The GOTHIC solver program calculates the solution for the integral form of the conservation equations for mass, momentum, and energy for multi-component, two-phase flow. The conservation equations are solved for three fields: continuous liquid, liquid drops, and the steam/gas phase. The three fields may be in thermal nonequilibrium within the same computational cell. This allows the modeling of subcooled drops (for example, containment spray) falling through an atmosphere of saturated steam. The gas component of the steam/gas field can be comprised of up to eight different noncondensable gases with mass balances performed for each component. Relative velocities are calculated for each field, as well as the effects of two-phase slip on pressure drop. Heat transfer between the phases, surfaces, and the fluid are also allowed.

The GOTHIC solver program is capable of performing calculations in three modes. A model can be created in the lumped-parameter nodal-network mode, the two-dimensional distributed parameter mode, or the three-dimensional distributed parameter mode. Each of these modes may be used within the same model. The lumped parameter nodal-network mode is used for the AP600 containment Evaluation Model.

The GOTHIC code also contains the options to model a large number of structures and components. These include, but are not limited to, heated and unheated conductors, pumps, fans, a variety of heat exchangers, and ice condensers. These components can be coupled to represent the various systems found in any typical containment.

The GOTHIC code has an extensive validation history which was an important consideration in the selection of the code for further development for modeling of the PCS. The GOTHIC code validation program includes both a comparison of code-calculated results with analytical solutions to specified standard problems and a comparison of code-calculated results with experimental data. The results of the EPRI-sponsored GOTHIC code validation program are presented in Reference 1, Enclosure 1. Table 5-1 lists some of the tests used in the GOTHIC code validation program. The phenomenological models validated by each test are cross-referenced and presented in Table 5-2. In addition, industry experience using GOTHIC in the lumped parameter mode, as well as attempts to improve results using multi-dimensional analyses, are described in WCAP-14407, Rev. 3, (Reference 2) Appendix 9.C.3.

After reviewing the qualifications of the available containment analysis codes, Westinghouse selected and purchased the GOTHIC code for further development and application to modeling of the AP600 passive containment design. Westinghouse developed special subroutines to mechanistically calculate the heat and mass transfer and to track the liquid films for the passive containment cooling system (PCS). These subroutines were incorporated into GOTHIC Version 4.0 to create WGOTHIC Version 4.2. See WCAP-14407 (Reference 2), Sections 3.3–3.5 for a detailed description of the Westinghouse Clime Model.

The GOTHIC Version 4.0 validation test problems were re-run with WGOTHIC to determine if any of the changes that were made to incorporate the PCS heat and mass transfer models would affect the validation results - they did not. The WGOTHIC PCS heat and mass transfer models were validated by comparison with various separate effects tests as listed in Table 5-3. The results of this comparison are documented in WCAP-14326 (Reference 3).

Both lumped parameter and distributed parameter (3-D) models of the large-scale test facility were constructed with WGOTHIC for validation of the passive containment, evaluation model methodology. The "well mixed" assumption, implicit in the lumped parameter modeling approach, in combination with the neglect of the velocity component for the internal condensation heat and mass transfer, resulted in the lumped parameter model significantly over-predicting the system pressure in the LST facility. A more complete description of the validation models and results of the comparison are presented in WCAP-14382 (Reference 4).

The WGOTHIC AP600 containment evaluation model makes use of the lumped parameter modeling approach. The WGOTHIC AP600 containment evaluation model is a complicated structure consisting of a large number of lumped parameter volumes, some of which contain heat sinks and/or PCS clime components. The lumped parameter volumes are connected with flow paths. Boundary conditions are used to supply the transient mass and energy release from the break source. A complete description of the AP600 containment evaluation model is provided in Section 4.0 of WCAP-14407.

The lumped parameter modeling approach is based on 30 years of nuclear industry experience. The industry experience has identified limitations and biases in the lumped parameter modeling approach that are due primarily to the oversimplification of the momentum formulation. These limitations and biases were identified based on model comparisons to international tests at different scales.

Several limitations and biases were applied to models for important phenomena in the WGOTHIC AP600 containment evaluation model to develop a bounding methodology for calculating the containment pressure. The WGOTHIC AP600 containment evaluation model limitations and biases includes:

- The use of lower bound multipliers on the heat and mass transfer correlations to reduce condensation and evaporation on the PCS,

- The use of only the free convection correlation (no forced convection component is allowed) to calculate the condensation heat and mass transfer to the inside surface of the shell,
- A 10-percent reduction of the containment shell emissivity input value,
- The use of the maximum Passive Containment Cooling System Water Storage Tank (PCCWST) water temperature allowed by the Technical Specifications to minimize sensible heat transfer to the applied liquid film,
- The use of an "evaporation limited" PCS water flow rate to minimize sensible heat transfer to the applied liquid film,
- The assumption of a single failure of one of two PCS cooling water flow control valves, along with the assumption of the minimum initial PCCWST water inventory allowed by the Technical Specifications to minimize the initial PCS water flow rate,
- The use of a 337 second delay time to establish the steady state external film coverage and initiate evaporation heat and mass transfer from the shell,
- The use of a PCS annulus loss coefficient that is 30-percent larger than the value measured in the test program to minimize the air flow rate and evaporation from the shell,
- The use of the maximum containment internal air temperature and pressure allowed by the Technical Specifications as the model initial conditions,
- The use of an initial zero-percent relative humidity to maximize the internal stored energy inside containment
- The elimination of compartment floors as potential heat sinks,
- The elimination of heat transfer to conductors within dead-ended volumes after blowdown, and
- The use of a 20-mil air gap between the steel and concrete on jacketed heat sinks,

5.2 RESOLUTION OF MAJOR ISSUES

Before accepting the WGOTHIC AP600 containment evaluation model, the NRC and ACRS identified several issues that had to be resolved. The three main issues were:

- modeling circulation and mixing within the containment (requires justification for the use of lumped-parameter noding),

- modeling the Passive Containment Cooling System (PCS) condensation and evaporation heat removal (requires justification for the water coverage input and the clime heat and mass transfer models), and
- validation of the WGOTHIC AP600 containment evaluation model (requires justification for the use of the LST and other test facilities).

Westinghouse provided documentation (Section 9 of WCAP-14407, Rev. 3) to support the use of lumped parameter noding to model circulation and mixing in the WGOTHIC AP600 containment evaluation model. Experimental results from various international tests were examined for applicability to loss-of-coolant (LOCA) and main steam line break (MSLB) events in a passive (externally cooled) containment design. Assuming an initially well-mixed atmosphere within the facility, the tests showed global circulation would occur when the break source was located in a lower compartment and there were relatively large openings between interconnected compartments (similar to a LOCA within the AP600). In addition, the Large Scale Test (LST) and Heissdampfreaktor (HDR) tests also showed that circulation and mixing were enhanced after the application of external cooling water to the top of the test facility. Steam condensing at the top inside surface of the test facility resulted in negatively buoyant plumes of cooler air falling downward, increasing the global circulation and mixing within the test facility.

The passive containment structure employed by AP600 and AP1000 was designed to promote global circulation following a LOCA event. There are large openings between compartments to minimize flow restrictions. The RCS piping is located in the lower compartments; this maximizes the driving force for global circulation by the buoyant steam plume. Finally, the PCS water is applied at the top and flows down along the containment shell; this maximizes the driving force for global circulation by the negatively buoyant plumes generated by condensation on the inside surface of the containment shell.

Due to the break location, some of the lower compartments within the passive containment may not be as strongly affected by the naturally-induced global circulation as others. To account for the potential effect of stratification within compartments of the WGOTHIC AP600 containment evaluation model, heat transfer to floors is eliminated and, after blowdown is complete, heat transfer to conductors within dead-ended compartments is turned off.

Westinghouse provided documentation (WCAP-14326 [Reference 3]) to support the use of the heat and mass transfer correlations for condensation and evaporation in the WGOTHIC AP600 containment evaluation model. Data from separate effects heat and mass transfer tests were used to validate the correlations. The range of the independent dimensionless parameters from the tests covered the operating range of the AP600. Bounding multipliers (0.73 for condensation and 0.84 for evaporation) were used to conservatively bound (reduce) heat and mass transfer in the WGOTHIC AP600 containment evaluation model.

Westinghouse provided documentation (Section 7 of WCAP-14407, Rev. 3) to support the PCS water coverage model in the WGOTHIC AP600 containment evaluation model. Test data from a full-scale section of the containment dome was used to determine the initial water coverage fraction input values for the AP600 containment evaluation model. The time-dependent water flow rate input for the AP600 containment evaluation model was limited to either the actual PCS flow rate (assuming a failure of one of two parallel valves to open) or the conservatively estimated transient evaporation rate, whichever is smaller. This conservatively ignores the effect of sensible heating of the runoff flow rate.

The standard set of GOTHIC code qualification tests includes comparisons with data from a number of different test facilities to validate the code and lumped parameter modeling technique. This same set of tests was run with WGOTHIC. The results of these tests confirmed that the changes Westinghouse made to the software had no effect on the results of the GOTHIC code qualification.

Westinghouse provided documentation (WCAP-14845 [Reference 5], Section 10.2) to support the use of steady state test data from the LST to validate the WGOTHIC code and AP600 containment evaluation model. Problems with the design and scaling of the LST facility limited its usefulness for AP600 transient comparisons, however, the steady-state data was determined to be acceptable for validating the heat and mass transfer correlations as well as providing comparison points during the slowly changing long term cooling transient. The calculated results from a lumped parameter model of the LST facility were compared to the test data (WCAP-14382 [Reference 3] and WCAP-14967 [Reference 6]) to support the WGOTHIC AP600 containment evaluation model. The lumped parameter model calculated a pressure response that was conservative (higher) relative to the test data.

The NRC received this information and reviewed it using a process similar to the one that is outlined in the current Draft Standard Review Plan Section 15.0.2 of NUREG-0800 and the Draft Regulatory Guide, DG-1096. After completing a thorough review of this information, the NRC determined that the WGOTHIC computer program, combined with the conservatively biased AP600 containment evaluation model, could be used to demonstrate that the AP600 containment design meets the requirements of General Design Criteria (GDCs) 16, 38 and 50. This approval was subject to the limitations and restrictions described in Section 5.1 and listed in subsection 21.6.5.8.3 of NUREG-1512, AP600 Final Safety Evaluation Report (FSER) (Reference 7).

With regard to the modeling of circulation and mixing for the LOCA event, the AP600 FSER states: "Initially, the DBA blowdown and PCS operation generate a nearly homogeneous distribution of steam and non-condensable gases. In the longer term, the actuation of the fourth stage automatic depressurization system valves (ADS-4), at approximately 1000 seconds, 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 AP600 peak containment pressure." With regard to the modeling of circulation and mixing for the MSLB event, the AP600 FSER states: "The degree of homogenization is a strong 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 AP600 peak containment pressure."

With regard to the PCS heat and mass transfer correlations, the AP600 FSER states: "The staff was concerned with uncertainties in the correlations and the data base, and Westinghouse has biased the correlations to account for these uncertainties. Based on comparisons of the predicted-to-measured Sherwood numbers, the bias for the evaporation mass transfer is a multiplier of 0.84 on the correlations. For condensation, the bias multiplier is 0.73 on 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."

With regard to validation testing, the AP600 FSER states: "The staff concludes that the evaluation model contains sufficient conservatism, including factors to compensate for shortcomings in the LST, to accept WGOTHIC in combination with the AP600 evaluation model for DBA licensing analyses to support design certification."

5.3 JUSTIFICATION FOR THE USE OF THE WGOTHIC CODE AND AP600 CONTAINMENT EVALUATION MODEL METHODOLOGY FOR APPLICATION TO THE AP1000

Both the AP1000 and AP600 employ a Passive Containment Cooling System. The AP1000 containment structure is taller, but maintains the same diameter and internal layout as the AP600. A detailed comparison of the AP600 and AP1000 plant designs is provided in WCAP-15612 (Reference 8).

The capability requirements for the AP1000 containment evaluation model are the same as AP600. To be able to model the passive containment cooling system, the evaluation model must be able to model:

- The transport of break mass and energy (steam) to the containment shell,
- The condensation of steam on the inside surface of the containment shell,
- The transport of the condensate film on the inside surface of the containment shell,
- The conduction of heat through the containment shell,
- The transport and heating of the applied liquid film on the outside surface of the containment shell,
- Evaporation from the applied liquid film on the outside surface of the containment shell and,
- The natural draft cooling air flowing through the downcomer, riser and chimney of the shield building.

As described earlier, Westinghouse developed special subroutines to mechanistically calculate the heat and mass transfer and to track the liquid films for the passive containment cooling system. These subroutines were appended to the GOTHIC Version 4.0 code to create WGOTHIC Version 4.2.

To determine the applicability of using the WGOTHIC code (Version 4.2) and AP600 containment evaluation model methodology for performing the AP1000 containment DBA analyses, Westinghouse performed the following:

- Reviewed the AP600 containment PIRT for application to the AP1000,
- Reviewed the AP600 containment scaling analysis for application to the AP1000 and,
- Compared the test data ranges of the important dimensionless parameters for heat and mass transfer and water coverage with the operating range for the AP1000.

The AP600 containment PIRT was reviewed to determine if there were any new phenomena or any change in the importance ranking of the existing phenomena with respect to the AP1000 containment and RCS design changes. This review was documented in WCAP-15613 [Reference 9], Section 2.6. No new phenomena were identified and there were no significant changes in the ranking of phenomena as a result of the AP1000 design changes.

An LST scaling assessment was performed for AP1000 and compared with AP600 (see WCAP-15613, Section 4.2). Due to its relatively low and constant steam injection flow rate, the LST was not well scaled to model the blowdown transient response for either AP600 or AP1000. However, the phenomena were well scaled in the quasi-steady state phase. Therefore, the steady state LST data were determined to be acceptable for use as a source of separate effects test data for internal condensation, above-deck steam distribution, external heat transfer, and external water coverage.

The ranges of the dimensionless parameters for the heat and mass transfer correlations were examined to determine if the existing test data covered the AP1000 operating range (see WCAP-15613, Section 4.2). The test data covered the upper range of the AP1000 dimensionless parameters for the heat and mass transfer correlations in the important riser region of the annulus. Therefore, the correlations are also considered to be valid for the AP1000 containment evaluation model.

Experimental test data and correlations were reviewed to determine if the increase in containment height would affect the thermally-induced mixing within the open volume above the operating deck. Both the correlations and test data suggest that increasing the containment height would increase the turbulence and improve the mixing (see WCAP-14407, Section 9C).

An alternate analysis methodology was used to independently assess the relative degree of mixing in the open volume above the operating deck for the AP600 and AP1000. Detailed, 2-dimensional slice Computational Fluid Dynamics (CFD) models representing this region were constructed for both the AP600 and the AP1000 (see WCAP-15613, Section 4.2). The flow and velocity patterns for the AP600 and AP1000 were very similar. Both models predicted cold falling plumes near the walls and a hot rising plume near the center of the volume. Except for the small boundary layers very close to the walls and within the central plume, the temperature profile within the volume was nearly uniform. Therefore, based on the experimental test data, correlations, and results from the alternate analysis approach, the well-mixed assumption for this region was also considered to be valid for the AP1000 containment evaluation model.

The operating ranges of the liquid film coverage parameters for AP600 and AP1000 were compared to the composite PCS test data. The test data covered the operating range of the important film coverage parameters (minimum film Reynolds number and maximum heat flux) for both AP600 and AP1000. Therefore, the constant coverage area input values and the model for calculating the evaporation-limited PCS water flow rate input that was used for AP600 are also applicable to the AP1000.

In summary, both the AP600 and AP1000 employ the same passive containment cooling system design features so the events and phenomena to be analyzed in the AP1000 containment evaluation model are the same as the AP600. The range of important dimensionless parameters from the PCS test data covers the operating range of both the AP600 and AP1000, so the WGOTHIC heat and mass transfer correlations remain acceptable. Since the containment designs are similar and since the heat and mass transfer correlations remain acceptable. WGOTHIC source code changes are not required for the AP1000 containment evaluation model. The AP1000 containment evaluation model will use the same bounding methodology that was accepted by the NRC for the AP600.

5.4 CONCLUSIONS

The bounding WGOTHIC AP600 containment evaluation model was accepted by the NRC to demonstrate that the AP600 containment design meets the requirements of GDCs 16, 38, and 50 (subject to the limitations and restrictions listed in Section 21.6.5.8.3 of the AP600 FSER). Both the AP600 and AP1000 employ the same passive containment cooling system design features so the events and phenomena to be analyzed in the AP1000 containment evaluation model are the same as AP600. To justify the use of the WGOTHIC and the AP600 containment evaluation model for application to the AP1000. Westinghouse provided documentation to demonstrate that:

- The AP1000 containment PIRT is unchanged from the AP600.
- The AP1000 operating range of the important dimensionless parameters for heat and mass transfer and liquid film coverage are bounded by the existing test data.
- The experimental test data, correlations, and alternate analysis methodology confirm the volume above the AP1000 operating deck is also sufficiently mixed to allow the use of the lumped parameter modeling approach.

Therefore, Westinghouse intends to use the previously accepted, bounding AP600 containment evaluation model, which is based on WGOTHIC version 4.2 to perform the AP1000 containment DBA analyses with appropriate input modifications to reflect the AP1000 containment design changes.

5.5 REFERENCES

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Table 5-1 GOTHIC Validation Tests

Battelle-Frankfurt Tests D-1, D-15, D-16 (BFMC)	Modeling: 7 lumped parameter volumes, junctions Phenomena: Blowdown transients, subcompartment pressurization, wall differential pressures
Battelle-Frankfurt Test 6 (BFMC)	Modeling: 1 distributed parameter volume (55 cells), conductors, junctions Phenomena: Hydrogen transport by convection and diffusion
Battelle-Frankfurt Tests 12, 20 (BFMC)	Modeling: Combination of 5 lumped and 1 distributed parameter volumes (2 cells), conductors, junctions Phenomena: Hydrogen transport by convection and diffusion
Battelle-Frankfurt Tests C-13, C-15 (BFMC)	Modeling: 10 lumped parameter volumes, conductors, junctions Phenomena: Main steamline break, pressure/temperature response
Hanford Engineering Development Laboratory Tests HM-5, HM-6 (HEDL)	Modeling: 1 distributed parameter volume (300 cells), conductors, junctions Phenomena: Hydrogen mixing in a large, simulated containment
Light Water Reactor Aerosol Containment Experiments Tests LA-5, LA-6 (LACE)	Modeling: Combination of 1 lumped and 1 distributed parameter (2 cells) volumes, conductors, junctions Phenomena: Severe accident response to sudden containment failure
Marviken Full-Scale Containment Tests 17, 24 (MARV)	Modeling: 21 lumped parameter volumes, conductors, junctions Phenomena: Pressurized high temperature steam blowdown
Carolina's Virginia Tube Reactor Tests 3, 4, 5 (CVTR)	Modeling: 2 lumped volume and a 2 distributed parameter volume (20 cells) models, conductors, junctions Phenomena: Steam blowdowns (T31.5 includes hydrogen/helium)
Heissdampfreaktor Tests V21.1, T31.1, T31.5, V44 (HDR)	Modeling: 37 lumped parameter volumes, conductors, junctions Phenomena: Steam blowdowns (T31.5 includes hydrogen/helium)

Table 5-2 GOTHIC Phenomenological Models Validated by Test

Item	BFMC	HEDL	LACE	MARV	CVTR	HDR
Fluid momentum	X		X	X		
Energy transport	X		X	X		
Noncondensable gases	X	X	X	X	X	X
Equations of state	X		X	X		
Pressure response	X	X	X	X	X	X
Temperature response	X	X	X	X	X	X
Humidity response	X	X	X	X	X	X
Hydrogen transport	X					
Energy sources	X	X	X		X	X
Subcompartment analysis	X			X		
High energy line breaks	X					
PWR standard containment			X			
BWR pressure suppression				X		
Fluid/structure interaction	X					
Conductors	X					
Subdivided volumes	X					
Turbulence	X					
3-D calculations	X	X		X		

Table 5-3 WGOTHIC PCS Heat and Mass Transfer Model Validation

STC Dry Flat Plate	Forced convection heat transfer, heated flat plate in channel-type geometry
Westinghouse Large Scale Test – Dry External Heat Transfer	Mixed convection heat transfer, 1/8-scale AP600 containment, internally steam heated, externally cooled by air
Hugot Heated Channel Tests	Mixed convection heat transfer, isothermal parallel plates in channel-type geometry
Eckert and Diaguila Tests	Mixed convection heat transfer, externally steam heated tube
Siegel and Norris Tests	Mixed convection heat transfer, parallel vertical flat plates in channel-type geometry, constant heat flux
STC Wet Flat Plate	Forced convection evaporation heat and mass transfer, heated flat plate in channel-type geometry
Gilliland and Sherwood Evaporation Tests	Mixed convection evaporation heat and mass transfer from the inside surface of a vertical heated pipe
University of Wisconsin Condensation	Forced convection condensation heat and mass transfer in channel-type geometry
Westinghouse Large Scale Test – Internal Condensation	Free convection condensation heat and mass transfer, 1/8-scale AP600 containment, internally steam heated, externally cooled by evaporation

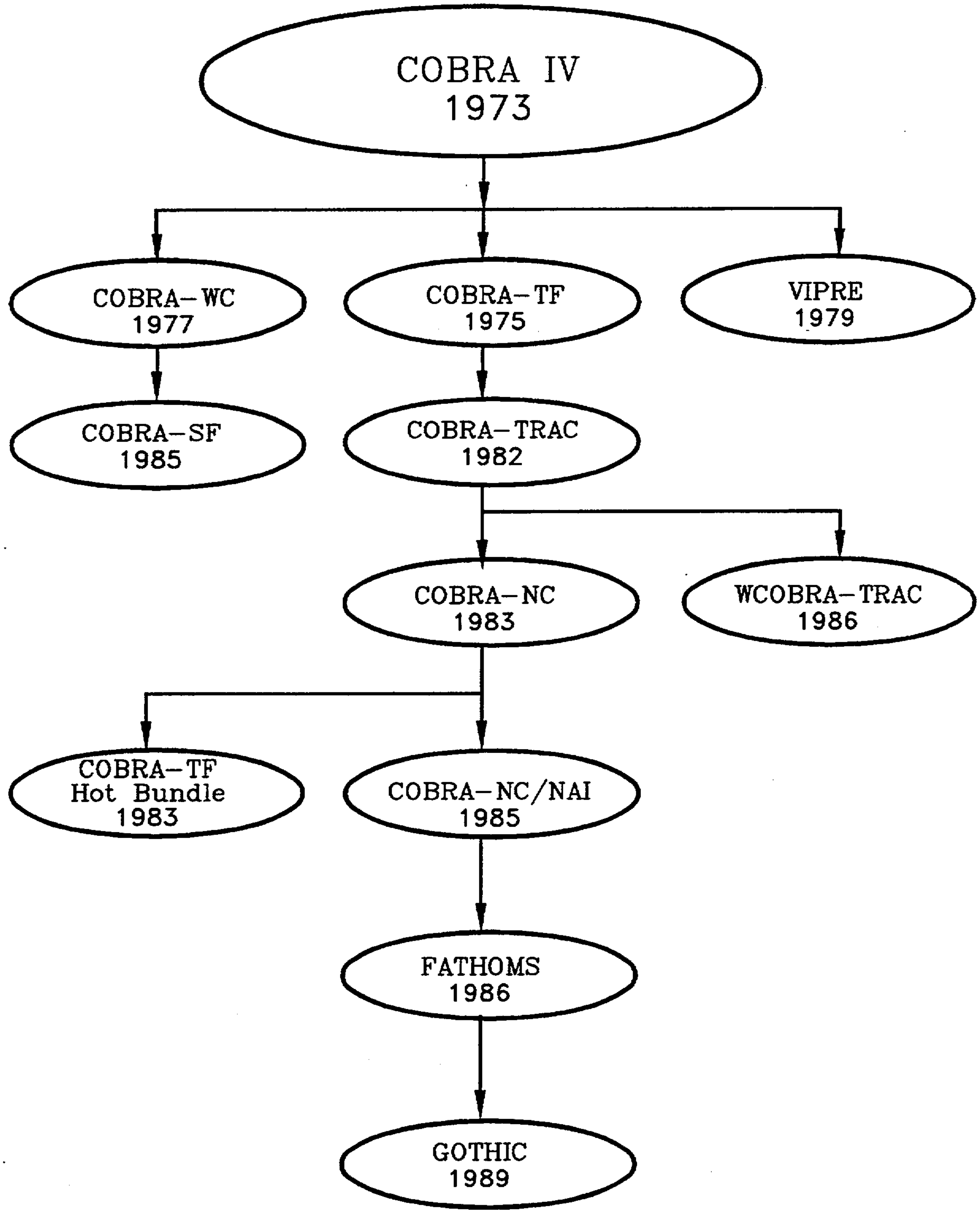

Figure 5-1 Summary of GOTHIC Historical Development

6.0 CONCLUSIONS

This report provides an assessment of the analysis codes that were developed and approved for the AP600 Design Certification to determine their applicability and use for Design Certification of an AP1000. The analysis codes that were approved for the purposes of performing safety analyses of the AP600 passive plant are:

- LOFTRAN – transient analyses
- NOTRUMP – small-break LOCA analysis
- WCOBRA/TRAC – large break LOCA and long-term cooling analysis
- WGOTHIC – containment analysis

This report describes a plan to use these safety analysis codes approved for a plant design with passive safety features for a Design Certification of an AP1000. For each of the thermal-hydraulic analysis codes, the report discusses the basis for that approval as described in NUREG-1512, Final Safety Evaluation Report (FSER) Related to Certification of the AP600 Standard Design (AP600 FSER, Reference 1). This report discusses the basis for their approval for AP600, and provides an assessment as to how that basis can be applied to AP1000. In addition, the main attributes associated with the graded approach to assessment and application of an evaluation model outlined in Draft Regulatory Guide DG-1096 are addressed for each analysis code.

In this report, our plan for the use of the analysis codes (previously validated and approved for AP600) is described. For each of the thermal-hydraulic analysis codes that were developed and approved as part of AP600 Design Certification, LOFTRAN, NOTRUMP, WCOBRA/TRAC, and WGOTHIC, the report discusses the basis for that approval as described in the AP600 FSER. A summary of the major issues for each code is provided with a discussion of the applicability of the AP600 code approval basis to the AP1000. This provides the justification for the continued use of these approved codes for AP1000.

The following summarizes the conclusions of this report specific to each code:

1. The LOFTRAN-AP code that was approved for AP600 can be used for the purposes of performing conservative analysis of the transient events presented in Chapter 15 for AP1000. The basis for this conclusion is that when considering transient events, no new phenomenon is identified for AP1000 (when compared to AP600). Analysis show that passive plants behave similarly to operating plants with regards to transient events. The test database that supported validation of this code for AP600 is applicable to AP1000. The means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000.

   The main code-related issues identified during the AP600 Design Certification review include:

   - Modeling of asymmetric flow conditions

- ADS flow for event involving inadvertant opening of ADS valves
- Impact of flashing or steam in the CMT balance line on CMT flow
- Impact of thermal stratification in IRWST on PRHR heat transfer

Modeling of asymmetric flow conditions is accomplished through a methodology which employed the use of auxiliary calculations approved for AP600. This methodology can be applied for AP1000. Therefore, the means for resolution is applicable to AP1000.

The ADS flow for inadvertant ADS actuation events was treated in the same manner as an open PORV for which LOFTRAN was found acceptable. This same approach will be used for AP1000. The means for resolution is applicable to AP1000.

The LOFTRAN CMT model is not written for simulation of two-phase flow transients. The possibility of flashing or steam in the CMT balance line was resolved by inclusion of a penalty on the CMT gravity head such that natural circulation flow the CMT flow is terminated. This penalty can be applied to AP1000. Therefore, the means of resolution is applicable to AP1000.

The LOFTRAN IRWST model consisted of a single homogeneous fluid node and therefore did not account for the effects of stratification. Sensitivity studies showed that homogeneous treatment of IRWST fluid temperature produced conservative results for non-LOCA transients. The same treatment can be applied to AP1000. Therefore, the means for resolution is applicable to AP1000.

Assessments indicate that the AP1000 passive safety systems operate the same as the AP600, and that large margins to the regulatory limits exist for the transient events analyzed. It is expected that large margins will exist for the final accident analysis events analyzed with LOFTRAN.

2. The NOTRUMP code that was approved for AP600 can be used for the purposes of performing conservative (Appendix K) analysis of the small break LOCA events presented in Chapter 15 for AP1000. The basis for this conclusion is that for small break LOCA events, no new phenomenon is identified for AP1000 (when compared to AP600), and the test database that supported validation of this code for AP600 is applicable to AP1000. The means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000.

   It was noted in the AP1000 PIRT and Scaling Assessment (Reference 2) that some phenomena previously addressed for AP600 could be judged to be of higher importance for AP1000 (i.e., entrainment in the hot leg during the transition from ADS to IRWST injection of the SBLOCA event). To better address this phenomena, as well as to address the importance of momentum flux during this same phase, a supplemental analysis using WCOBRA/TRAC will be used to demonstrate the conservative results using NOTRUMP analysis methods employed for AP1000. This supplemental analysis, including validation of WCOBRA/TRAC against relevant test data, will be provided to the NRC for their review, during the review of the AP1000 application for Design

Certification. This AP1000 supplemental analysis will be performed to support the assessment of conservative results for the Chapter 15 NOTRUMP accident analyses.

The use of WCOBRA/TRAC to analyze the IRWST injection phase of small break LOCA events addresses the most significant concerns identified by the NRC staff in the AP600 FSER. It also applies Westinghouse's most advanced robust analysis code to the analysis of the portion of the event that has the minimum core inventory and is therefore of the most interest in the safety assessment of the AP1000.

Assessments indicate that the AP1000 passive safety systems provide large margins to the regulatory limits for the small break LOCA events analyzed. It is expected that large margins will exist for the final accident analysis events analyzed with NOTRUMP.

3. The WCOBRA/TRAC code that was approved for AP600 large break LOCA analysis can be used for the purposes of performing best-estimate analysis for AP1000. The basis for this conclusion is that for large break LOCA events, no new phenomena are identified for AP1000 (when compared to AP600) and the test database that supported validation of this code is applicable to AP1000. The means of resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000.

   The main code-related issue identified during the AP600 Design Certification review was the validation of WCOBRA/TRAC to address uniqueness of the passive safety system direct vessel injection (DVI). Westinghouse performed the validation and the NRC approved the code for AP600. As the AP1000 DVI configuration and location are the same as AP600, this validation is applicable to AP1000 as well. Therefore, the means of resolution applies to AP1000.

   The WCOBRA/TRAC computer code and large break LOCA methodology and approved by the NRC for AP600 are applicable to the 10CFR50.46 ECCS performance analysis of the AP1000 for 95th percentile calculated PCT values up to the 2200°F licensing limit.

4. The WCOBRA/TRAC code that was approved for AP600 long-term cooling analysis can be used for the purposes of performing conservative (Appendix K) analysis of long-term cooling for LOCA events presented in Chapter 15 for AP1000. The basis for this conclusion is that for LOCA events, no new phenomenon are identified for AP1000 (when compared to AP600), and the test database that supported validation of this code for AP600 is applicable to AP1000. The means for resolution of issues identified during the AP600 Design Certification review are applicable to the AP1000.

   The main code-related issues identified during the AP600 Design Certification Review included:

   - Application of WCOBRA/TRAC within the range of the OSU experimental validation, including the nodalization scheme used to perform the validation.

- The use of "window" mode calculations of segments of the long-term cooling transient

AP1000 scaling analysis demonstrates that the OSU test facility is sufficiently scaled to AP1000, so that the experimental validation is applicable to AP1000. The nodalization scheme for AP1000 will be consistent with the OSU experimental validation. Therefore the means of resolution applies to AP1000.

In Reference 1, the use of WCOBRA/TRAC for long-term cooling in the "window" mode (as approved for AP600) was compared to analysis using a "continuous" mode for the limiting long-term cooling event. Results of that analysis demonstrated good agreement between the "window" mode analysis and the continuous mode analysis. Westinghouse will perform the limiting long-term cooling analysis using the continuous mode methodology presented in Reference 1, but will retain the "windows" mode methodology for the less limiting events to minimize the resources expended to perform this analysis. Comparison of the results of the "continuous" mode to the "window" mode supports the assessment of conservative results for the "window" mode analyses. The means of resolution are therefore applicable to AP1000 and enhanced expanded use of continuous mode analysis.

Assessments indicate that the AP1000 passive safety systems provided large margins to the regulatory limits for the long term cooling analysis, and it is expected that large margins will exist for the final accident analysis events analyzed with WCOBRA/TRAC for long-term cooling.

5. The WGOTHIC code that was approved for AP600 can be used for the purposes of performing conservative containment analysis of the events presented in Chapter 6 for AP1000. The basis for this conclusion is supported by the results of the AP1000 PIRT and Scaling assessment (Reference 2) and the assessment provided in this report that the means for resolution of code-related issues identified during the AP600 Design Certification review are applicable to AP1000.

The PIRT assessment found that for events that challenge containment integrity (i.e., large LOCA and large steam line break), no new phenomena are identified for AP1000 (when compared to AP600). The scaling assessment demonstrated that the range of important phenomena for AP1000 containment heat and mass transfer and liquid film coverage are sufficiently covered by the AP600 test database. Therefore, the extensive validation performed for use of the WGOTHIC code for AP600 is applicable to AP1000.

The main code-related issues identified during the AP600 Design Certification review included:

- Modeling circulation and mixing within containment
- Modeling PCS condensation and evaporation heat removal
- Validation of WGOTHIC evaluation model

The means of resolution of issues associated with modeling circulation and mixing within containment included applying results from experimental test facilities such as LST and HDR which showed that mixing circulation and mixing where enhanced when water is applied externally to the containment shell. In addition, conservative analysis code treatments such as eliminating heat transfer to floors and terminating heat transfer to conductors within dead-ended compartments after the blowdown phase is complete. Applying the LST and HDR tests for purposes of circulation and mixing behavior are as valid to AP1000 and they were to AP600 as the PCS design is the same. This is further confirmed by the CFD analysis presented in the AP1000 PIRT and Scaling Assessment. The conservative treatments will be used for AP1000. Therefore, these means of resolution are still valid for AP1000.

The means of resolution of issues associated with modeling PCS condensation and evaporation heat removal included use of correlations with conservatively biased multipliers validated against separate effect heat and mass transfer tests. Initial PCS water coverage fraction was established from full-scale containment dome test data. The time dependent PCS water flow applied to the containment shell was the smaller of the PCS flow rate obtained assuming as single failure of one of two valves to open, or the estimated transient evaporation rate. Scaling analysis showed that the heat and mass transfer correlation ranges cover the range for AP1000 and the PCS dome test facility is fully applicable to AP1000. The conservative treatment of PCS flow rate will be used for AP1000. Therefore, these means of resolution are still valid for AP1000.

The means of resolution associated with validation of the WGOTHIC evaluation model included comparison against LST data. The scaling of the LST limited this comparison to the quasi-steady state portion of the transient as insufficient steam input distorted the rapid blowdown portion of the transient. However, it was determined that the blowdown phase was not different than conventional plants for which there was ample validation for WGOTHIC. Therefore, the quasi-steady long-term cooling phase which relies on the passive safety features was well represented for AP600 and AP1000. Therefore, the means of resolution is still valid for AP1000.

Assessments indicate the AP1000 has sufficient margin to the containment design pressure when bounding-type analyses are performed using WGOTHIC.

The following overall conclusions are reached supporting the applicability of the analysis codes to AP1000:

- The analysis codes were reviewed and approved by the NRC as part of the AP600 Design Certification process. The in-depth review conducted by the NRC staff included key elements of Draft Regulatory Guide DG-1096. Therefore, the analysis codes should be approved for use on AP1000 without extensive incremental review and subject to the proposed stipulations outlined in this report.

- PIRT assessment confirms that while there are a few phenomena that have been re-ranked, there are no new phenomena associated with the AP1000. Therefore, there are no models or features that must be added to the analysis codes and reviewed to account for any new phenomena.

- Scaling demonstrates that elements of the AP600 test database needed to validate the analysis codes for AP600 are applicable to AP1000. Therefore, as the extensive AP600 test program and code validation is applicable, the analysis codes do not need to be re-validated for AP1000.

- Selected analysis and evaluation of key plant parameters and accidents indicate that similar plant safety margins exist between AP600 and AP1000 and that AP600 and AP1000 behave similarly. Where margins were used in evaluating the acceptability of the AP600 safety analysis, sufficient margins have been established for the AP1000.

References

1. NUREG-1512, "Final Safety Evaluation Report Related to Certification of the AP600 Standard Design," September 1998.

2. WCAP-15613, "AP1000 PIRT and Scaling Assessment," February 2001.

APPENDIX A

DISCRETIONARY AND NON-DISCRETIONARY CHANGES MADE TO WCOBRA/TRAC-AP

The AP600 large break LOCA DCD analysis reports a calculated peak cladding temperature (PCT) at the 95th percentile of 1676°F, which occurs during the blowdown phase. In the 10CFR50.46 model assessments for 1998 an increase of 11°F was allocated to the AP600 PCT value. This permanent margin allocation considered the impact of the WCOBRA/TRAC Vessel Channel DX error. This, the licensing basis PCT for AP600 was re-established as 1687°F.

Subsequent to this assessment, further discretionary and non-discretionary changes to the WCOBRA/TRAC computer code were reported by Westinghouse for 1999 and 2000 in reference A-1 and Reference A-2, respectively. A description of each change relevant to the WCOBRA/TRAC version and/or the analysis methodology used in the AP600 CDC analyses is presented on the following pages. The conclusion is that the 1999 and 2000 changes have a 0°F impact on the AP600 LBLOCA and LTC analyses, and they also have no impact on the applicability of WCOBRA/TRAC-AP to the AP1000 DCD LBLOCA and LTC analyses.

References

3. NSBU-NRC-00-5970, "1999 Annual Notification of Changes to the Westinghouse Small Break LOCA and Large Break LOCA ECCS Evaluation Models, Pursuant to 10CFR50.46," Sepp, Westinghouse to J. S. Wermiel, May 12, 2000.

4. LTR-NRC-01-6, "10CFR50.46 Annual Notification and Reporting for 2000," Sepp, Westinghouse to J. S. Wermiel, March 13, 2001.

INCONSISTENT GUIDANCE FOR HOTSPOT OUTPUTS IN BE LBLOCA METHODOLOGY

Background

The BE LBLOCA methodology described in WCAP-12945-P-A contains inconsistent guidance on the selection of HOTSPOT outputs to be used as inputs for the 95th percentile PCT calculation. As a result, the published material does not always reflect the intended definition of late reflood, resulting in misrepresentation of the second reflood PCT time, magnitude and elevation for some transients which have low or non-existent second reflood PCTs. This issue was determined to be a non-discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

The impact of the inconsistent guidance for selection of HOTSPOT outputs was evaluated on a plant specific basis for all plants currently licensed with BE LBLOCA Evaluation Model. Only second reflood PCTs are affected by this inconsistency. The AP600 LBLOCA analysis exhibits no second PCT during reflood and therefore is unaffected.

DECAY HEAT UNCERTAINTY ERROR IN MONTE CARLO CALCULATIONS

Background

It was determined that an error existed in the calculation of decay heat uncertainty in the Monte Carlo code used for calculation of the 95th percentile PCT for Best Estimate LBLOCA. This issue was determined to be a Non-Discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

Plant specific PCT calculations were performed to assess the impact of this error for all analyses using the affected EMs. The correction for the AP600 LBLOCA analysis is calculated to be 0°F.

WCOBRA/TRAC GAP INPUT ERROR IN SECY UPI/BELOCA EM ANALYSES

Background

A survey of current SECY UPI, Best Estimate LBLOCA analyses and LBLOCA test simulations utilizing WCOBRA/TRAC identified an error in the application of the affected evaluation models. The error was in the specification of horizontal channel connections (gaps), which should be from lower numbered to higher numbered channel. The survey showed that only a few analyses contained this error. This error was determined to be a non-discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Potentially Affected Evaluation Models

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

For the AP600 Best Estimate LBLOCA analyses, no errors were found.

For the Oregon State APEX facility no errors were found

The survey found no errors in the AP600 LTC analysis.

GEDM INTERFACE ERROR

Background

A discrepancy between the inputs for the neutronics model and the way the code used the inputs was discovered that impacted the calculated gamma redistribution factors. This issue was determined to be a Non-Discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

It was determined that the error only concerns the neutronic input, which is not used in the code uncertainty/bias calculations, but only in plant calculations. A typical value of error in terms of the relative power is 0.001% or less than 0.01°F in peak average fuel temperature. This is well within the steady state tolerance criteria, such that estimated impact of the effect of this error on all plant calculations is 0°F, including AP600.

DROP DIAMETER PLOT TAPE STORAGE ERROR

Background

It was discovered the droplet diameter variable stored in the plot file contained a wrong value. This issue was determined to be a non-discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

There is no impact on analysis results, since the drop diameter edit output is not used in the calculation of PCT. A work around is available for old versions of the code. The WCOBRA/TRAC-AP code version corrects this error, and there is no PCT impact as a result of this error.

CLADDING OXIDATION EDIT ERROR

Background

It was determined that the hot rod fuel clad oxidation printouts after the end of fuel rod edits were incorrect. This issue was determined to be a Non-Discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

There is no impact on analysis results, since the guidance for the oxidation calculation uses the data in the plot file, which are correct. The WCOBRA/TRAC-AP code version corrects this error, and there is no PCT impact as a result of this error.

OUTPUT EDIT ERROR FOR SI UNITS

Background

It was determined that the fuel rod and 1D component edits were incorrect if the SI output option is selected. This issue was determined to be a Non-Discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

There is no impact on analysis results, since the reported PCT was not affected by this error. Users of older code versions have been advised to use English units for all WCOBRA/TRAC calculations. The current code version corrects this error. There is no PCT impact as a result of this error.

RADIATION HEAT TRANSFER TO VAPOR PHASE ERROR

Background

It was determined that the radiation heat transfer was set to zero when the void fraction in a channel exceeded 0.9999. This issue was determined to be a non-discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

Evaluations indicate that the single phase vapor heat transfer regime can occur during blowdown heatup, refill, and reflood. This error has negligible impact on existing analyses during the blowdown heatup and refill phases, since the single phase vapor heat transfer mode occurs only briefly in the blowdown heatup and refill. In reflood, single phase vapor conditions occur primarily during the downcomer boiling period for plants with late reflood PCTs. Under those conditions, the radiation heat transfer can account for approximately 20% of the total clad-to-vapor heat transfer. However, these conditions are nearly adiabatic, and the effect can be considered negligible for AP600, where the PCT occurs during blowdown. The WCOBRA/TRAC-AP code version corrects this error, and there is no PCT impact as a result of this error.

GRID HEAT TRANSFER ERROR

Background

It was determined that the grid's turbulence enhancement to heat transfer coefficient is erroneously applied to Radiation Heat Transfer to vapor phase. The enhancement from these grids should only be applied to the convective single phase heat transfer coefficient. This issue was determined to be a Non-Discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

The heat transfer multipliers used in the BE LBLOCA process include data from rod bundles with grids. Therefore, the effect of the error is compensated for by the multipliers, resulting in no impact on the analysis. The WCOBRA/TRAC-AP code version corrects this error, and there is no PCT impact as a result of this error.

PRESSURE DROP ERROR FOR 1D CONNECTIONS TO 3D VESSEL

Background

It was determined that the pressure drop was overestimated in the vertical momentum cell when the vessel vertical momentum flux is convected by the 1D component velocity. This issue was determined to be a non-discretionary change in accordance with Section 4.1.2 of WCAP-13451.

Affected Evaluation Models

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

In the AP600 large break LOCA simulation, the DVI ID component is connected to the downcomer vessel channel with a vertical connection. The impact of the pressure drop overestimation has been investigated and shown to be negligible on the AP600 large break LOCA transient.

During the AP600 long-term cooling transient fluid velocities are low in the vessel channels, so the pressure drop overestimation is negligible and does not impact the results predicted by the code.

There is no PCT impact on AP600 as a result of this error, which is corrected in the WCOBRA/TRAC-AP code version.

PAD 4.0 IMPLEMENTATION

Background

The Westinghouse Performance Analysis and Design Model (PAD) is used to generate fuel-related input data for use in LOCA licensing calculations. As documented in Reference 1, the Safety Evaluation Report for Version 4.0 of the PAD model was issued by the US NRC on April 24, 2000. Use of PAD Version 4.0 is considered to represent a Discretionary Change and will be implemented on a forward-fit basis, in accordance with Section 4.1.1 of WCAP-13451.

Affected Evaluation Models

1981 Westinghouse Large Break LOCA Evaluation Model

1981 Westinghouse Large Break LOCA Evaluation Model with BART

1981 Westinghouse Large Break LOCA Evaluation Model with BASH

1985 Westinghouse Small Break LOCA Evaluation Model with NOTRUMP

SECY UPI WCOBRA/TRAC Large Break LOCA Evaluation Model

1996 Westinghouse Best Estimate Large Break LOCA Evaluation Model

1999 Westinghouse Best Estimate Large Break LOCA Evaluation Model, Application to PWRs with Upper Plenum Injection

Estimated Effect

The implementation of PAD Version 4.0 with respect to Appendix K Large Break LOCA and Small Break LOCA analyses will be handled on a forward-fit basis and is assigned a PCT estimate of 0°F for 10CFR50.46 reporting purposes.

References

1. WCAP-15063-P-A Revision 1, with Errata, "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)", J. P. Foster and S. Sidener, July 2000.

APPENDIX B

WCOBRA/TRAC-AP APPLICATION TO THE ADS-4 IRWST INITIATION PHASE

B-1 INTRODUCTION

The Automatic Depressurization System (ADS) Stage 4 In-containment Refueling Water Storage Tank (IRWST) initiation phase of the small break LOCA event for AP1000 is characterized by the following phenomena: significant momentum flux pressure drop in the ADS-4 flowpaths, entrainment in the reactor vessel and hot legs, and draining of the pressurizer and surge line mass. To account for these phenomena, a modified version of WCOBRA/TRAC-MOD7A designated as "WCOBRA/TRAC-AP" is used to supplement NOTRUMP. In comparison to the NOTRUMP code, WCOBRA/TRAC provides a more detailed model of the physical processes encountered during these conditions as follows:

The momentum equation as solved in the TRAC components used for ADS Stage 4 (ADS-4) piping contains all significant terms, including the momentum flux terms, as discussed in Section 2-5 of Reference 3, Volume 1.

[ ]^{a,b,c}

Within the hot legs, horizontal flow regimes are identified using the Taitel-Dukler flow map (Reference 1). The Ishii-Grolmes (Reference 2) criteria are used to predict the onset of entrainment off the horizontal surface. Entrainment into the ADS Stage 4 offtake piping atop the hot legs is determined using a Froude-number relationship. In the event that entrainment is predicted to occur, the quality in the ADS-4 pipe is calculated using a correlation for a vertical upward branch connection.

Prediction of the mixture level in a WCOBRA/TRAC channel depends on interfacial drag between the vapor and liquid phases. Models and correlations are available that calculate interfacial shear in both vertical and horizontal flows. Models for flow regime transition and bubble rise in the code allow for phase separation and entrainment.

This appendix is intended to describe the models and correlations that have been included in the WCOBRA/TRAC-AP code to enable it to compute the important phenomena during the ADS-4 IRWST initiation phase of a small break LOCA in AP1000. The appendix presents the code features for modeling horizontal flow behaviors and for calculating the entrainment into the branch line at a "TEE" vertical connection, such as the ADS-4 offtake piping atop the hot legs in the AP1000 design. The performance of the code in predicting the horizontal flow behaviors observed in a separate effect test conducted at atmospheric pressure is presented in Section B-9. To facilitate the review by the NRC staff, the level of detail in this appendix is consistent with that provided in Reference 3.

B-2 HORIZONTAL FLOW REGIME PROCESSES

Horizontal stratification, counter-current flow and counter-current flow limitations (CCFL), and transition between flow regimes in WCOBRA/TRAC depend on interfacial drag between phases in lateral flow. WCOBRA/TRAC-AP allows for horizontal flow regime modeling using correlations for drag to allow stratification. Section 15 of Volume 3 of WCAP-12945-P-A (Reference 3) reported an assessment and calculations of flow in horizontal pipes represented by COBRA channels. The evaluation showed that WCOBRA/TRAC has the capability to predict counterflow and CCFL at horizontal locations within the reactor coolant system. A further assessment of WCOBRA/TRAC-AP presented in Section B-9 shows it capable of predicting horizontal stratified flow behaviors with the accuracy necessary for the ADS-4 IRWST initiation phase of small break LOCA analyses for AP1000.

Horizontal flow regimes and the transition criteria from one regime to another have been the subjects of several studies. The most notable result is the Taitel-Dukler flow regime map for horizontal flows (Reference 1), which takes into account both pipe diameters and fluid properties on each of the flow pattern transitions. The Taitel-Dukler flow regime map and transition criteria include a dependence on pipe diameter. This provides a means of examining the scale diameter dependence of the WCOBRA/TRAC models for horizontal flow.

Section B-9 presents the results of WCOBRA/TRAC simulations of tests reported in Lim (Reference 4) investigating the horizontal two-phase flow in a channel. The wavy or stratified flow regime condensation and pressure drop data were obtained, together with steam flowrate and water layer thickness data at various locations in a four-foot long experimental channel.

The carry out of droplets from the upper plenum into the hot legs by the flow of steam above the mixture level is assigned a medium (M) ranking for the ADS-4 operation time period in the AP1000 small break LOCA PIRT in WCAP-15613 (Reference 5). Entrainment in the flow from the hot legs into the ADS-4 piping is assigned a high (H) ranking for AP1000, increased from the medium (M) ranking of AP600. This carryover by drops entrained in the steam is modeled in detail in WCOBRA/TRAC-AP.

B-3 LIQUID ENTRAINMENT ONSET CORRELATIONS

General Form of Entrainment Onset Correlations Into Branch Pipes

The general form of most entrainment onset correlations for offtake pipes found in the literature is as follows:

$$Fr_g\left(\frac{\rho_g}{\rho_l-\rho_g}\right)^{0.5}=C_1\left[\frac{z_b}{d}\right]^{C_2} \qquad \text{(B-3-1)}$$

The key elements of this correlation form consist of the Froude number (Fr), density ratio ($\rho/\Delta\rho$), and a geometric ratio (z/d) of entrainment onset height (z) to offtake diameter (d). The coefficient C_1 and exponent C_2 are functions of the orientation and geometry of the offtake.

Side Offtake Orientation

Craya (Reference 6) developed a theoretical onset of liquid entrainment for discharge from a side offtake neglecting viscosity and surface tension effects. Craya's theoretical result was obtained by treating the offtake as a potential flow point sink. From this he arrived at onset correlations for orifice-type offtakes and slot-type offtakes as follows:

$$Fr_g\left(\frac{\rho_g}{\rho_l-\rho_g}\right)^{0.5}=C_1\left[\frac{z_b}{d}\right]^{2.5}\qquad \text{for orifice}\qquad\text{(B-3-2)}$$

$$Fr_g\left(\frac{\rho_g}{\rho_l-\rho_g}\right)^{0.5}=C_1\left[\frac{z_b}{d}\right]^{1.5}\qquad \text{for slot}\qquad\text{(B-3-3)}$$

Note that the form is similar for orifice and slot, however, the exponents for the geometric ratio (z/d) are 2.5 and 1.5 respectively.

Top Offtake Orientation

Rouse (Reference 7) developed a correlation for onset of liquid entrainment for top offtake configurations as follows:

$$Fr_g\left(\frac{\rho_g}{\rho_l-\rho_g}\right)^{0.5}=C_1\left[\frac{z_b}{d}\right]^{2}\qquad\text{(B-3-4)}$$

It is important to note here that the exponent for the geometric ratio is 2.0, which is different from those obtained by Craya for side offtake orientations. Ardron and Bryce (Reference 8) provide a summary of exponents and coefficients recommended for use in Froude number type correlations in the open literature. For the top offtake orientation, Ardon and Bryce propose the vertical upward branch correlation of Schrock et al (Reference 9) to compute the discharge flow quality in the offtake branch when entrainment occurs as presented in Section B-7.

Issues with General Correlation Form for Entrainment

While it appears from several data sets that the general correlation form for entrainment onset provides reasonable agreement or representation, there is room for improvement in several areas:

1. Viscous effects are neglected. Interfacial shear stress between the gas and liquid phases would be expected to play some role in liquid entrainment such as found in the work of Ishii and Grolmes (Reference 2). However, there is no viscosity term or viscosity-related non-dimensional parameter in the general correlation.

2. Liquid surface tension and intermolecular force effects are neglected. It is expected that surface tension is important in resisting the onset of entrainment. Intermolecular liquid forces are probably involved in a liquid siphoning-type effect that is seen in experiments once entrainment onset is reached.

3. The offtake branch, orifice, or slot is treated in most cases (with the exception of the work by Soliman and Sims [Reference 10]) as a point sink. This treatment may be

appropriate for very large tanks or reservoirs with relatively small diameter offtakes, but may not be so good for reactor coolant piping connected to a branch pipe.

4. The potential flow solution treatment such as that of Craya and others neglects liquid velocity in liquid phase streamlines and even neglects the very presence of the liquid phase itself in obtaining a potential flow solution for the flowing gas field. Again, neglecting liquid velocity in large reservoirs or tanks may be reasonable, but it would be a more difficult case to make for reactor coolant piping connected to a breakflow path.

A liquid entrainment correlation for flow into branch pipes using a more realistic potential flow, Bernoulli type solution which addresses the concerns outlined earlier (i.e. viscosity, surface tension, etc.) has not been developed and correlated against data sets. Therefore, [

]a,b,c

B-4 HORIZONTAL FLOW REGIME MAP

Model Basis

Predicting the flow regime for two-phase flow in horizontal pipes is important in an accurate representation of the ADS-4 IRWST initiation phase of a small break LOCA transient for AP1000; the realistic, mechanistic model of Taitel and Dukler (Reference 1) for predicting flow regime transitions provides this capability in WCOBRA/TRAC-AP. This physically based, semi-theoretical model provides an unambiguous analytical prediction of the transition between horizontal flow regimes. It is a preferred approach because it takes into account the different influences of pipe diameter and fluid properties on each flow pattern transition.

Five flow regimes (Reference 1) are considered in this model: intermittent (slug and plug), stratified smooth, stratified wavy, dispersed bubble, and annular/annular dispersed liquid flow. Transitions between horizontal pipe flow regimes are determined using the following dimensionless groups:

$$X = \left[\frac{(dP/dx)_\ell^S}{(dP/dx)_v^S} \right]^{1/2} \tag{B-4-1}$$

$$T = \left[\frac{|(dP/dx)_\ell^S|}{(\rho_\ell - \rho_v) g \cos\delta} \right]^{1/2} \tag{B-4-2}$$

$$F = \sqrt{\frac{\rho_v}{(\rho_\ell - \rho_v)}} \frac{U_v^S}{\sqrt{Dg\cos\delta}} \tag{B-4-3}$$

$$K = \left[\frac{\rho_v U_v^{S^2} U_\ell^S}{(\rho_\ell - \rho_v)\, g_\ell\, \nu_\ell \cos\delta} \right]^{1/2} \tag{B-4-4}$$

Each quantity in the above groups is available from the prevailing flow conditions.

The horizontal tube flow regime flow transition boundaries are shown in Figure B-1. Specific transitions are controlled by the dimensionless groups as follows:

Stratified to annular	X, F
Stratified to intermittent	X, F
Intermittent to dispersed bubble	X, T
Stratified smooth to stratified wavy	X, K
Annular dispersed liquid to intermittent and to dispersed bubble	X

where

X	is the phasic pressure drop ratio (Lockhart and Martinelli, 1949) where $\|(dP/dx)^S\|$ designates the pressure drop of one phase flowing alone
T	considers the ratio of turbulent to gravity forces acting on the gas
F	is the Froude number times the square root of the density ratio
K	is the product of F and the square root of the superficial Reynolds number of the liquid
δ	is the angle at which the pipe is inclined to the horizontal

In Reference 1, Taitel-Dukler show that predictions from this model agree very well with data.

Model as Coded

Flowrates, fluid conditions and properties, pressures, and diameter are available from WCOBRA/TRAC input and output for a given timestep. The VESSEL channel formulation calculates the flow between two cells for three separate fields: continuous liquid, continuous vapor, and entrained liquid droplets.

The fluid properties [

]^{a,b,c}

[

]a,b,c

Next, the equilibrium liquid level $\left(\frac{h_L}{D}\right)$ is calculated for the $\delta = 0$ case from the Taitel-Dukler function that is graphically represented in Figure B-2.

Referring to Figure B-1, X = 1.6 is the limit line B.

For Curve A, Froude number (F) is calculated [

]a,b,c

[

]a,b,c

Lastly, curve D is defined.

On curve D, parameter T, which is the ratio of turbulent force to the gravity force acting on gas, is calculated from:

$$T = \left[\frac{8\tilde{A}_G}{\tilde{S}_i \tilde{U}_L^2 \left(\tilde{U}_L \tilde{D}_L\right)^{-0.2}} \right]^{1/2} \quad \text{(B-4-8)}$$

Where, [

]a,b,c

By equating

$$T = \left[\frac{\frac{4C_{FF}}{D}\left(\mathrm{Re}_f^{-0.2}\right)\frac{\left(\rho_\ell U_L^S\right)^2}{2\rho_\ell}}{\left(\rho_\ell - \rho_v\right)g} \right]^{1/2} \quad \text{(B-4-9)}$$

and solving for, U_L^S as,

$$U_L^S = \frac{1}{\rho_\ell}\left[\frac{T^2 \bullet \left(\rho_\ell - \rho_v\right) g}{\frac{2\,C_{FF}}{D\,\rho_\ell}\,Re_f^{-0.2}}\right]^{1/2} \qquad \text{(B-4-10)}$$

The gap superficial velocities are compared against X = 1.6, Equations B-4-9 and B-4-10, to determine the flow regime. Currently, four flow regimes, namely, stratified, annular dispersed liquid, dispersed bubble, and intermittent are recognized.

Scaling Considerations

Pipe diameter is one of the parameters that affects the flow regime transitions in the Taitel-Dukler horizontal flow regime map, through its presence in the "F" term. Therefore, the method is general, and may be used with confidence to predict flow regimes at various scales of operation; at larger diameters the regime boundaries are displaced relative to their location with a small pipe diameter.

Likewise, the use of prevailing fluid properties in this model considers variations in pressure, temperature, and quality such as those that occur during the ADS-4 IRWST initiation phase of a small break LOCA transient.

Conclusions

The Taitel-Dukler method for determining flow regime transitions in horizontal two-phase flow has been incorporated into WCOBRA/TRAC-AP. This method provides a mechanistic prediction of flow regime based on realistic theoretical considerations. The agreement with data is judged to be very good in Reference 1.

B-5 HORIZONTAL STRATIFIED INTERFACIAL DRAG

Model Basis

This model is based on stratified flow steam-water data in a rectangular channel (Jensen, Reference 11). The model is mechanistically based on the turbulent motion of the liquid near the interface. In addition, the interfacial shear and interfacial heat transfer are consistent with each other.

The interfacial friction factor K is computed according to Equations 5.5 and 5.6 of Jensen (Reference 11):

$$K_{ix,vl,HS} = 0.5 \bullet f_i \bullet \left| W_{vl} \right| \bullet A_{HS} / \Delta Z \qquad \text{(B-5-1)}$$

Where

A_{HS} is the vapor/liquid stratified interface area

$$f_i = 0.01 \qquad \text{if } U' < 17.6 \tag{B-5-2}$$

$$= 14.6 \times 10^{-6}(U')^{1.8} \quad \text{if } U' \geq 17.6 \tag{B-5-3}$$

Where

$$U' = \frac{U_V - U_\ell}{1.414\left(\frac{\sigma(\rho_\ell - \rho_V)g}{\rho_\ell^2}\right)^{1/4}} \tag{B-5-4}$$

U_v and U_ℓ are the vapor and liquid velocities, respectively.

Model as Coded

Note that the friction factors are discontinuous at $U' = 17.6$ and also between developed and undeveloped flows.

The horizontal stratification is checked only [

]^{a,b,c} to identify the flow regime according to the Taitel-Dukler (Reference 1) flow regime map. The parameters used in the determination of the horizontal flow regime are the total liquid superficial velocity, total vapor superficial velocity, gap average vapor density, gap average liquid density, the vapor viscosity, liquid viscosity, total gap void fraction, hydraulic diameter of flow channel, and mixture level.

The drag term for the horizontally stratified flow is modified in [

]^{a,b,c}

Conclusions

Horizontal stratified flow regime behaviors are important during the ADS-4 IRWST initiation phase of AP1000 small break LOCA events. The ability to identify horizontal stratified flow regimes has been implemented in WCOBRA/TRAC-AP, together with a method for calculating the interfacial drag for two-phase flow in these regimes.

B-6 ENTRAINMENT IN HORIZONTAL STRATIFIED FLOW

Model Basis

When horizontal stratification is identified, the Ishii - Grolmes (Reference 2) criteria are checked; if the criteria are satisfied, the calculation of entrainment off of the horizontal surface is enabled.

Ishii and Grolmes describe entrainment in horizontal cocurrent flow as the stripping of drops from the top of waves. They describe four mechanisms, but the shearing off of the top of roll waves by turbulent gas flow is expected to be significant for the ADS-4 IRWST initiation. Ishii and Grolmes state that this mechanism is valid for liquid Re>160 in horizontal cocurrent flow. For roll wave entrainment,.Ishii and Grolmes provide two correlations based upon Re:

For Re>1635:

$$\frac{\mu_\ell U_g}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} \geq N_\mu^{0.8} \ \mathit{for}\ N_\mu < \frac{1}{15}$$

$$\frac{\mu_\ell U_g}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} \geq 0.1146 \ \mathit{for}\ N_\mu < \frac{1}{15}$$

For Re<1635:

$$\frac{\mu_\ell U_g}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} \geq 11.78 N_\mu^{0.8}\, \mathrm{Re}_\ell^{-1/3} \ \mathit{for}\ N_\mu < \frac{1}{15}$$

$$\frac{\mu_\ell U_g}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} \geq 1.35\, \mathrm{Re}_\ell^{-1/3} \ \mathit{for}\ N_\mu > \frac{1}{15}$$

Re is based upon liquid film thickness, U_g is the minimum gas velocity for entrainment to occur, and N_μ represents viscosity number.

The entrainment source term in the continuity cell is evaluated when the Ishii - Grolmes criteria are satisfied for gap flow connections according to the model used by Hanratty (Reference 12):

$$R_e = K_a U_v \sqrt{\rho_v \rho_\ell}\ (\mathrm{lb/s\text{-}ft^2}) \qquad \text{(B-6-1)}$$

Where

$K_a = 0.2$ is currently used.

The size of the entrained droplets is determined by Tatterson's (Reference 13) model:

$$D_e = 0.0112\left(\frac{D_g \sigma}{0.5 f_i \rho_v U_v^2}\right)^{1/2} \qquad \text{(B-6-2)}$$

This correlation is for vertical annular flow, and the characteristic length is the pipe diameter. It will be implemented here by assuming that the characteristic length is the hydraulic diameter (D_g) of the gap above the mixture elevation.

De-entrainment onto the interface is assumed to be dominated by the terminal velocity of the droplets. The settling velocity (V_s) is the minimum of the Stokes flow solution Equation 9.13 (Wallis, Reference 14):

$$V_{s,1} = \frac{1}{18}\frac{D_e^2 g\,(\rho_\ell - \rho_v)}{\mu_\ell} \qquad \text{(B-6-3)}$$

and the turbulent flow solution Equation 12.29 (Wallis):

$$V_{s,2}\sqrt{\frac{D_e\,(\rho_\ell - \rho_v)\,g}{\rho_v}} \qquad \text{(B-6-4)}$$

Where

D_e is the average diameter of the entrained drops in the vapor above the mixture. The net flux of droplets into the mixture is:

$$R_{de} = \rho_\ell \alpha_e \left(V_s - U_{v,ver}\right) \qquad \text{(B-6-5)}$$

Where

$U_{v,ver}$ is the average vertical vapor velocity above the mixture and $V_s = \min(V_{s,1}, V_{s,2})$.

Model as Coded

As previously described in Section B-4, the horizontal stratified flow model is activated for
[

]^{a,b,c} to identify the flow regime according to the Taitel-Dukler flow regime map. The parameters used in the determination of the horizontal flow regime are the total liquid superficial velocity, total vapor superficial velocity, gap average vapor density, gap average liquid density, the vapor viscosity, liquid viscosity, total gap void fraction, hydraulic diameter of flow channel, and mixture level.

Within the structure of WCOBRA/TRAC, entrainment must be treated [

]^{a,b,c} The entrainment and de-entrainment source calculations are then performed using the techniques described earlier in this section.

Scaling Considerations

In WCOBRA/TRAC-AP, entrainment [

]^{a,b,c} The entrainment from stratified surfaces in the hot leg pipes may be important in the ADS-4 IRWST initiation phase of small break LOCA transients for AP1000. The ability of WCOBRA/TRAC-AP to predict accurately behavior in the stratified horizontal two-phase flow regimes is demonstrated by calculations shown in Section B-9.

Conclusions

Horizontal stratified flow regime behaviors are important during the ADS-4 IRWST initiation phase of AP1000 small break LOCA events. The ability to identify horizontal stratified flow regimes has been implemented in WCOBRA/TRAC-AP, together with the calculation of entrainment at the vapor-liquid stratified interface for two-phase flow in these regimes.

B-7 FLOW REGIME CONDITIONS UPSTREAM OF THE ADS-4 DELIVERY PIPING (ENTRAINMENT/VAPOR PULL-THROUGH MODEL)

Model Basis

During the ADS-4 IRWST initiation phase of a small break LOCA event, flow in the hot leg pipes will eventually become two-phase and stratify. A stratified flow regime near or upstream of the ADS-4 valves may lead to liquid entrainment in the hot legs and in the ADS-4 delivery piping depending upon local characteristics such as the velocity of the gas phase and the height of liquid in the pipe relative to the ADS-4 branch elevation.

Nearly all entrainment onset correlations found in the literature were developed from stratified, potential flow, Bernoulli-type solutions. In these correlations, the Froude number (ratio of inertia to gravity forces) is usually a predominant term.

The general form of most entrainment onset correlations found in the literature is as follows:

$$Fr_k = \frac{U_k}{\sqrt{d \bullet g \dfrac{\Delta\rho}{\rho_k}}} = C_1 \left[\frac{Z_b}{d}\right]^{C_2} \qquad \text{(B-7-1)}$$

Where

k indicates the continuous phase.

The key elements of this correlation form consist of the Froude number (Fr), density ratio $\Delta\rho/\rho_k$, and a geometric ratio (Z_b/d) of entrainment onset height (Z_b) to offtake diameter (d). The coefficient C_1 and exponent C_2 are functions of the orientation and geometry of the offtake.

Different offtake orientations lead to different values of C_1 and C_2 in the equation B-7-1 for the flow.

The following exponent and multiplier values in the correlation form for entrainment are provided by Anderson (Reference 15):

$C_1 = 0.35$, $C_2 = 2.50$ for liquid entrainment into a top branch

The above values, or modified values which predict the AP600 integral effects tests during the ADS-4 IRWST initiation phase, will be used in WCOBRA/TRAC-AP.

When entrainment is predicted to occur, the quality in the offtake will differ from that in the donor cell. In WCOBRA/TRAC-AP, the discharge flow quality in the offtake branch is calculated by the following correlation as proposed by Ardron and Bryce (Reference 8):

Vertical upward branch, from Schrock et al, (Reference 9):

$$x = R^{3.25(1-R)^2} \qquad \text{(B-7-2)}$$

Where

$R = |h / Z_b|$

And h is the distance between the branch pipe and the liquid surface,

Z_b is the critical distance at which the entrainment begins.

Model as Coded

The model as coded proceeds through a sequence of calculational steps to determine the entrainment from a channel in the hot leg pipes. [

]^{a,b,c}

[

]a,b,c

Scaling Considerations

Ardron and Bryce (Reference 8) based their selections of correlations from a review of several series of tests carried out to study two-phase flow in offtake branches at top, bottom and central position connections to a larger diameter horizontal pipe containing stratified flow. In these experiments, pressures ranged from 0.2-6.2MPa. Ardron and Bryce concluded that this data base was adequate to assess the modeling of horizontal stratification entrainment to a PWR RCS loop pipe break.

Conclusions

Appropriate correlations are included in WCOBRA/TRAC-AP to provide the capability to calculate: (1) the onset of entrainment from the hot legs into the ADS-4 pipes and (2) the flow quality in the ADS-4 pipes during the ADS-4 IRWST initiation phase for a postulated AP1000 small break LOCA event.

B-8 INTERFACIAL HEAT TRANSFER IN THE HORIZONTAL STRATIFIED REGIME

The horizontal stratified heat transfer model will be utilized in a continuity cell where the horizontal stratified flow is identified in the connecting gap according to the Taitel-Dukler (Reference 1) flow regime map.

If the flow regime is determined to be annular-dispersed or dispersed bubble according to the Taitel-Dukler flow regime map, the appropriate interfacial heat/mass transfer is used.

Model Basis

The interfacial heat transfer model developed by Jensen (Reference 11) is mechanistically based on the turbulent motion of the liquid near the interface, and is consistent with the interfacial drag model. Equation 5.11 (Jensen) states:

$$\frac{Nu_x}{Pr_l^{0.5}} = 0.0405 \bullet \left(\frac{u^* \bullet x}{\nu} \right)^{1.1} \tag{B-8-1}$$

Where:

$$Nu_x = \frac{h_{i\ell} \bullet x}{k_l}$$

$$u^* = \sqrt{\frac{\tau}{\rho_l}} = \sqrt{\frac{f_i \bullet \rho_v \bullet U_r^2}{2 \bullet \rho_l}} \tag{B-8-2}$$

where, x is the lateral distance, τ is the interfacial sheer stress, U_r is the relative velocity, and ν is the kinematic viscosity. Note that while this is not the final recommended correlation, it is not very different from the final version (Figure 5.24 of Jensen). The interfacial friction is obtained from the value without condensation (Section B-5), but needs to be adjusted to account for condensation. This is done by applying Equation 2.31 (Jensen, Reference 11) as follows:

$$\tau_c = \tau + \frac{\Gamma_c \bullet U_v}{144 \bullet g_c} \tag{B-8-3}$$

Where the τ is in psia and the condensation rate (Γ_c) is in lb/ft²/s.

Rearranging Equation B-8-1 yields,

$$h_{il} = 0.0405 \bullet k_l \bullet Pr_l^{0.5} \bullet \left(\frac{u^*}{\nu} \right)^{1.1} \bullet x^{0.1} \tag{B-8-4}$$

Model as Coded

Since h_{il} is a very weak function of the lateral distance x, the [

]^{a,b,c} (B-8-5)

The heat transfer coefficient h_{il} is then multiplied by the appropriate interfacial area to yield the condensation heat transfer coefficient (HASCL) as:

$$HASCL = h_{il} \bullet Area$$

Where Area = continuity cell area as seen in Figure B-3.

Conclusions

Horizontal stratified flow regime behaviors are important during the ADS-4 IRWST initiation phase of small break LOCA events for AP1000. The ability to identify horizontal stratified flow regimes has been implemented in WCOBRA/TRAC-AP, together with a method for calculating the interfacial heat transfer for two-phase flow in these regimes. The capability of WCOBRA/TRAC-AP to predict the thermal conditions in the stratified horizontal two-phase flow regime is demonstrated by the test simulations shown in Section B-9, of this report.

B-9 HORIZONTAL STRATIFIED FLOW VALIDATION

The predicted performance of AP1000 during the ADS-4 IRWST initiation phase of a small break LOCA transient is influenced by the two-phase flow regime present in the horizontal hot leg pipes. In the WCOBRA/TRAC-AP computer code, the Taitel and Dukler flow regime map (Reference 1) is used to define the horizontal pipe flow regime. At the relatively low flowrates associated with ADS-4 operation during a small break LOCA, the horizontal two-phase flow is in the stratified wavy and/or stratified smooth flow regimes most of the time. Therefore, the stratified flow regimes are of central importance for the prediction of the ADS-4 IRWST initiation phase.

Within WCOBRA/TRAC-AP logic, the horizontal flow regime is identified [ ]^{a,b,c} using the Taitel and Dukler regime map. If the path is determined to be stratified, the Jensen and Yuen model (Reference 11) is applied to calculate the interfacial drag and condensation that occurs; entrainment at the interface between gas and liquid is calculated according to the Kataoka and Ishii model (Reference 16). Because the interfacial drag and entrainment modeling for horizontal stratified flow are basic processes that are directly related to high-ranked items in the AP1000 small break LOCA PIRT given in WCAP-15613 (Reference 5), individual validation of each of these models is needed to confirm their accuracy. This is accomplished using the experimental WCOBRA/TRAC-AP simulations presented in the following sections.

Physical Processes

In the condition of a smooth, equilibrium-stratified flow, the wall resistance of the liquid is similar to that for open-channel flow and that of the gas is similar to closed-duct flow. Because the gas phase velocity is much larger than the velocity at the gas-liquid interface, the gas side interfacial shear stress is evaluated using the equation for gas wall shear. The interfacial drag is thus easily defined theoretically.

Entrainment from the liquid film at the stratified flow two-phase interface is important in determining the mass inventory of the RCS during the ADS-4 IRWST initiation phase of a small break LOCA in AP1000.

WCOBRA/TRAC-AP Models

Phenomena associated with the ADS-4 IRWST initiation phase of a small break LOCA - the interfacial drag, entrainment, and condensation - are discussed in this section.

Interfacial Drag

The models and correlations used to calculate interfacial drag in horizontal stratified flow are described in Section B-5. In particular, the work reported by Jensen and Yuen (Reference 11) is used.

Entrainment

Section B-6 describes the models and correlations in WCOBRA/TRAC-AP that are used to calculate the horizontal flow processes.

In general, entrainment is the result of interfacial shear between vapor and liquid film. In WCOBRA/TRAC-AP, liquid is moved from the continuous liquid field to the entrained field when the interfacial shear forces acting on the liquid are sufficient. In de-entrainment, liquid is moved from the entrained field to the continuous liquid field. A summary of the applicable models in WCOBRA/TRAC-AP is as follows:

- Entrainment in Film Flow

  WCOBRA/TRAC determines film entrainment rates by comparing the entrainment rate based on a stable film flow to an empirical entrainment rate based on the work of Walley (Reference 17).

- Entrainment in Bottom Reflood

  The model for entrainment in the core near the quench front is based on a model by Kataoka and Ishii (Reference 16) assuming vapor bubbling through a liquid pool.

- Entrainment at a Horizontally Stratified Surface

  In the ADS-4 IRWST initiation phase of small break LOCA events, if the vapor velocity is sufficient, entrainment can occur from a horizontal interface of vapor and liquid. Refer to Section B-6.

- De-entrainment in Film Flow

  The model to estimate the de-entrainment of entrained drops into the continuous liquid field uses an empirical model by Cousins (Reference 18).

- Crossflow De-entrainment

  Entrained liquid in the upper plenum can de-entrain on structures there as the two-phase mixture flows from the vessel into the hot legs. WCOBRA/TRAC uses a model based on experiments by Dallman and Kirchner (Reference 19) to determine the amount of de-entrainment in the upper plenum and other regions of the reactor vessel.

- De-entrainment at Area Changes

  De-entrainment occurs as a two-phase mixture encounters a flow restriction such as a tie plate. WCOBRA/TRAC uses a simple area ratio to de-entrain a fraction of the droplet field where an area reduction occurs in the reactor vessel.

- De-entrainment at Solid Surfaces and Liquid Pools

  Drops are assumed to de-entrain when the drops flow into a cell with a solid surface at the opposite face or when the drops flow into a cell which is in a bubbly flow regime.

Condensation

WCOBRA/TRAC-AP uses a model for interfacial heat and mass transfer similar to other best estimate codes. As described in Section 5 of WCAP-12945 (Reference 3), four components are evaluated to calculate interfacial heat and mass transfer; they may be described as:

$$\begin{aligned}
\Gamma_{SCL} &= \frac{HA_{SCL}(T_\ell - T_i)}{H_v - H_f} \\
\Gamma_{SHL} &= \frac{HA_{SHL}(T_\ell - T_i)}{H_g - H_\ell} \\
\Gamma_{SCV} &= \frac{HA_{SCV}(T_v - T_i)}{H_v - H_f} \\
\Gamma_{SHV} &= \frac{HA_{SHV}(T_v - T_i)}{H_g - H_\ell}
\end{aligned} \qquad \text{(B-9-1)}$$

Where:

Γ_{SCL} = condensation to subcooled liquid

Γ_{SHL} = evaporation from superheated liquid

Γ_{SCV} = condensation from subcooled vapor

Γ_{SHV} = evaporation to superheated vapor

Figure B-4 provides a pictorial representation of the WCOBRA/TRAC-AP approach. [

]^{a,b,c}

Assessment of WCOBRA/TRAC-AP Horizontal Stratified Flow Models

The performance of the horizontal stratified flow models in WCOBRA/TRAC-AP are established in predicting a pertinent separate effect test to demonstrate that the models are adequate for the ADS-4 IRWST initiation phase of AP1000 small break LOCA applications. The interfacial drag predictive capability is validated against relevant experimental data (Reference 4); these data are also used to validate the interfacial condensation heat transfer.

Test Facility Description and Modeling

The test facility of Lim (Reference 4) used a rectangular channel to measure condensation of steam in cocurrent, horizontal flow. The channel was constructed of stainless steel with pyrex glass windows; its dimensions were 160.1 cm long, 6.35 cm high, and 30.48 cm wide. Data were taken in the course of 35 runs. Controlled parameters in the experiments included water and steam inlet temperatures, mass flowrates, and water layer thickness at the inlet. The range of steam (maximum velocity 18 m/s) and water (maximum velocity 41 cm/s) flowrates were restricted by either the initiation of bridging phenomena or the occurrence of a hydraulic jump. Inlet steam pressure was approximately 1 atmosphere. Steam velocity, static pressure (for some experiments), and water layer thicknesses were measured at five locations along the channel. The water inlet temperature was also measured. Figure B-5 is a schematic diagram of the experimental system.

Figure B-6 presents the WCOBRA/TRAC noding of the test facility. [

]^{a,b,c}

As shown in Figure B-6, the experimental channel is modeled axially [

]^{a,b,c} This was considered sufficient to provide enough resolution to compare with experimental measurements, which are available at only five axial locations.

The experimental channel is divided [

]^{a,b,c}

The experimental report (Lim, et al., 1981) offers no data on liquid level in the discharge tank during the experiments and on the tank dimensions. Because it is impractical to simulate a constant liquid level in the tank due to condensation in the channel, the liquid level in the tank was allowed to rise during the simulation, but it was always kept below the liquid level in the channel. Condensation was turned off [ ]a,b,c to minimize the effect of the discharge tank on the channel flow.

[ ]a,b,c

The liquid level at the channel inlet [ ]a,b,c As shown in Figures B-7 and B-8, the liquid profile away from the channel inlet is determined only by the steam and water flowrates. The "line" in Figure B-8 is a linear correlation plane oriented in parallel to the reader's line of sight. Because essentially all of the variation in the liquid water thickness in the experimental channel can be attributed to the variations in steam and water flowrates, the effect of the initial water layer thickness on the flow pattern away from the inlet can be ignored.

The experimental results used in this analysis are reported to be at steady-state. That is, the water level, pressure, temperature, and steam flow in the channel were stable and not varying significantly.

The WCOBRA/TRAC-AP simulations were run [ ]a,b,c

Calculational Results

A total of 35 tests are reported in Lim (Reference 4). Those tests in which the horizontal two-phase flow is fully within the wavy or stratified flow regimes (32 in number) were simulated. The experimental results and test conditions for the tests simulated with WCOBRA/TRAC-AP are shown in Table B-1. Steam density and steam and water velocities were input as boundary conditions in the model's steam and liquid fill components, respectively.

In Table B-1, steam flowrate and water layer thickness data at locations 1, 2, 3, 4, and 5 correspond to 6.18, 12.05, 23.08, 34.18, and 48.14 inches from the experimental channel inlet. Static pressure difference measurements at 4.88, 10.75, 21.77, 32.87, and 47.24 inches are listed as being at locations 1 through 5. Nomenclature is provided on the table.

Steam density input is calculated using NIST/ASME steam properties for given values of the steam inlet temperature and constant pressure of 16 psi. Due to small variations in the liquid temperature and density among the tests and along the experimental channel, a constant liquid density corresponding to the average liquid temperature of 148.6°F is assumed. Steam and water inlet velocities in the model fill components (Figure B-6) are calculated using a constant flow area of 0.2083 ft^2.

Figures B-9 through B-14 provide, for a typical case (run 275), the predicted results and the comparison between experimental data and the WCOBRA/TRAC-AP predictions. For calculated quantities, stable or periodic (at one or two axial locations) behavior is observed over the duration of the test (Figures B-9, B-11, and B-13). There is a reasonably good agreement between the measured and predicted average values of liquid level and pressure drop[1] in the channel as seen in Figures B-10 and B-12. While the liquid level at 47.27 inches is significantly underpredicted, the observed trend of the liquid level to recover toward the channel outlet is well reproduced by WCOBRA/TRAC-AP (Figure B-10). WCOBRA/TRAC-AP overpredicted the steam flowrate axially as seen in Figure B-14; underpredicting the steam condensation rate is the cause. This matter was investigated further; condensation heat transfer correlations used in WCOBRA/TRAC-AP (Reference 11), and one derived from the experimental data, were compared to each other for typical flow conditions in the channel. This comparison is presented in Figure B-15.

The alternative correlation for a smooth interface based on this test data (Lim, et al., 1981) is given by:

$$Nu_{x\_As} := 0.631 \bullet (Re_g)^{0.58} \bullet (Re_l)^{0.09} \bullet (Pr_l)^{0.3} \qquad (18\text{-}1)$$

Where:

Nu_{x_As} = is the Nusselt number (Nu), equals 1344 for case 275

The principal difference between the correlations is that the Nu value in WCOBRA/TRAC-AP
[

]^{a,b,c}

The cumulative results of all tests simulated are shown in Figures B-16 through B-19, which show scatter plots of predicted versus measured quantities of the liquid level, steam mass flowrate, liquid temperature at the channel exit, and the pressure drop in the channel, respectively. For most of the cases, liquid level predictions are within ± 0.2 inches of the measurements. The steam flowrate is overestimated almost everywhere in the test section,

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[1] Note that the pressure actually increases as the steam flow proceeds through the channel.

particularly near the channel exit. As a result, the liquid temperature at the channel exit is underpredicted by 20° to 40° F. The large majority (approximately 80 percent) of the pressure drop predictions is within ± 33 percent of the experimental data, as shown in Figure B-19.

Conclusions

WCOBRA/TRAC-AP predictions of two-phase flow in a horizontal channel were verified against data for a rectangular channel with cocurrent water flow at atmospheric pressure. A model of the experimental channel, consisting of [ ]^{a,b,c} was developed. The pertinent cases among the 35 test cases reported in Lim (Reference 4) were simulated. For most of the cases, liquid level predictions are within ± 0.2 inches of the measurements. Depending on the axial position, steam flowrate can be overestimated by a factor of 2 or more (near the channel exit). As a result, the liquid temperature at the channel exit is underpredicted by 20 to 40°F. To address this, values of the condensation heat transfer coefficient calculated by the code were compared with those given by the correlation used in WCOBRA/TRAC-AP and one derived from the experimental data. The difference in the condensation heat transfer coefficient is determined to be due to the correlation used in the code. Condensation heat transfer in AP1000 hot leg horizontal stratified flow is a minor effect during the ADS-4 IRWST initiation phase.

Most of the pressure drop predictions are within ± 33 percent of the experimental data, and the number of points for which the pressure drop is underpredicted is approximately the same as the number for which it is overpredicted. Inasmuch as hot leg steam velocities are low when horizontal stratified flow conditions exist in the AP1000 hot legs during the ADS-4 IRWST initiation phase of a small break LOCA event, the hot leg pressure drop prediction is not of major importance in predicting ADS-4 performance.

B-10 REFERENCES

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EQUATION NOMENCLATURE

A	Area
d	Offtake diameter
D	Pipe diameter
D_H	Hydraulic diameter
F_r	Froude Number
g	Gravitational acceleration
h_L	Mixture level
H	Heat Transfer coefficient
i	Interfacial
k	Thermal conductivity
K	Interfacial friction factor
N_μ	Viscosity number
P	Pressure
P_r	Prandtl number
R_e	Reynolds number
T	Temperature
V_s	Settling velocity
x	Vertical direction, Cartesian coordinates
X	Phasic pressure drop ratio in two-phase flow
U	Vertical velocity component, Subchannel coordinates
z	Transverse direction, Cartesian coordinates
Z	Transverse direction, Subchannel Coordinates

Greek

ρ	Density
δ	Angle
ν	Kinematic viscosity
α	Void fraction
σ	Surface tension
μ	Viscosity
τ	Interfacial sheer stress

Subscripts

b	Bubble
g	Saturated vapor
ℓ	Liquid field
v	Vapor field
f	Saturated liquid

Superscripts

e	Entrained field
k	Continuous phase
x	Vertical direction, Cartesian Coordinate
S	Superficial

Table B-1 Test Matrix Parameters

No.	Units(a)	Location						W_L^{in} (lb/s)	T_G^{in} (°F)	T_L^{in} (°F)	T_L^{ex} (°F)
		Inlet	1	2	3	4	5				
211	W_G (lb/s)	0.09	0.083	0.077	0.069	0.065	0.064	0.866	281	76.7	160
	δ_L (in)	0.623	0.534	0.393	0.223	0.222	0.241				
	ΔP(psi)	0	7E-05	1E-04	2E-04	3E-04	3E-04				
231	W_G (lb/s)	0.09	0.082	0.074	0.063	0.06	0.059	0.896	271	33.8	118
	δ_L (in)	0.623	0.626	0.487	0.317	0.293	0.317				
	ΔP(psi)	0	1E-04	2E-04	3E-04	4E-04	5E-04				
251	W_G (lb/s)	0.09	0.077	0.072	0.06	0.055	0.054	1.17	272	33.8	98.1
	δ_L (in)	0.623	0.624	0.55	0.349	0.403	0.436				
	ΔP(psi)	0	3E-04	5E-04	7E-04	7E-04	7E-04				
253	W_G (lb/s)	0.143	0.129	0.12	0.086	0.063	0.039	1.447	281	70.88	156
	δ_L (in)	0.623	0.569	0.444	0.3	0.417	0.484				
	ΔP(psi)	0	7E-04	1E-03	0.002	0.002	0.002				
255	W_G (lb/s)	0.204	0.188	0.167	0.113	0.081	0.061	1.57	278	72.68	175
	δ_L (in)	0.623	0.411	0.291	0.208	0.218	0.433				
	ΔP(psi)	0	0.001	0.002	0.004	0.004	0.004				
257	W_G (lb/s)	0.275	0.248	0.222	0.163	0.128	0.101	1.573	287	72.86	190
	δ_L (in)	0.623	0.298	0.208	0.173	0.178	0.23				
	ΔP(psi)	0	0.002	0.004	0.006	0.007	0.007				
273	WG (lb/s)	0.144	0.119	0.096	0.061	0.042	0.025	2.253	280	77.54	144
	δL (in)	0.623	0.783	0.643	0.525	0.591	0.642				
	ΔP(psi)	0	7E-04	0.001	0.002	0.002	0.002				
275	WG (lb/s)	0.202	0.169	0.14	0.097	0.069	0.047	2.244	285	79.7	163
	δL (in)	0.623	0.623	0.51	0.403	0.352	0.622				
	ΔP(psi)	0	0.001	0.002	0.004	0.004	0.005				

a. Definitions for all units are listed at the end of this table.

Table B-1 Test Matrix Parameters (cont.)

No.	Units	Location						W_L^{in} (lb/s)	T_G^{in} (°F)	T_L^{in} (°F)	T_L^{ex} (°F)
		Inlet	1	2	3	4	5				
277	W_G (lb/s)	0.277	0.24	0.212	0.156	0.117	0.08	2.289	287	76.1	175
	δ_L (in)	0.623	0.427	0.334	0.307	0.283	0.314				
	ΔP(psi)	0	0.002	0.004	0.006	0.007	0.008				
293	W_G (lb/s)	0.144	0.106	0.084	0.05	0.033	0.019	3.17	279	76.82	126
	δ_L (in)	0.623	0.956	0.819	0.658	0.702	0.754				
	ΔP(psi)	0	7E-04	0.002	0.002	0.002	0.003				
295	W_G (lb/s)	0.199	0.155	0.127	0.08	0.055	0.034	3.148	284	78.44	144
	δ_L (in)	0.623	0.869	0.693	0.551	0.652	0.726				
	ΔP(psi)	0	5E-04	0.002	0.004	0.004	0.005				
297	W_G (lb/s)	0.276	0.224	0.193	0.141	0.101	0.064	3.165	287	79.34	161
	δ_L (in)	0.623	0.605	0.444	0.446	0.389	0.419				
	ΔP(psi)	0	0.001	0.004	0.006	0.007	0.008				
353	W_G (lb/s)	0.144	0.132	0.127	0.09	0.067	0.043	1.5	281	76.73	160
	δ_L (in)	0.873	0.653	0.528	0.309	0.242	0.451				
357	W_G (lb/s)	0.274	0.255	0.231	0.173	0.138	0.109	1.489	288	77	192
	δ_L (in)	0.873	0.493	0.303	0.203	0.173	0.213				
373	W_G (lb/s)	0.141	0.125	0.114	0.077	0.049	0.03	2.233	281	75.92	139
	δ_L (in)	0.873	0.828	0.665	0.453	0.363	0.585				
377	W_G (lb/s)	0.272	0.246	0.218	0.155	0.112	0.074	2.236	288	76.1	175
	δ_L (in)	0.873	0.653	0.456	0.316	0.282	0.302				
393	W_G (lb/s)	0.141	0.118	0.102	0.06	0.042	0.024	3.143	280	78.62	127
	δ_L (in)	0.873	0.931	0.776	0.562	0.606	0.711				
397	W_G (lb/s)	0.277	0.233	0.201	0.144	0.104	0.067	3.095	288	77.36	161
	δ_L (in)	0.873	0.688	0.638	0.441	0.367	0.393				
153	W_G (lb/s)	0.146	0.13	0.117	0.071	0.05	0.031	1.5	221	73.04	165
	δ_L (in)	0.375	0.568	0.524	0.414	0.541	0.573				
157	W_G (lb/s)	0.285	0.254	0.227	0.169	0.135	0.124	1.463	241	75.74	194
	δ_L (in)	0.375	0.306	0.279	0.196	0.241	0.484				
173	W_G (lb/s)	0.147	0.128	0.105	0.063	0.043	0.041	2.311	220	73.4	144
	δ_L (in)	0.375	0.779	0.71	0.546	0.663	0.681				

Table B-1 (cont.) **Test Matrix Parameters**

No.	Units	Location						W_L^{in} (lb/s)	T_G^{in} (°F)	T_L^{in} (°F)	T_L^{ex} (°F)
		Inlet	1	2	3	4	5				
177	W_G (lb/s)	0.285	0.262	0.217	0.159	0.115	0.086	2.315	241	80.06	177
	δ_L (in)	0.375	0.503	0.438	0.335	0.36	0.381				
453	W_G (lb/s)	0.142	0.131	0.123	0.099	0.08	0.063	1.504	280	122.2	182
	δ_L (in)	0.623	0.6	0.544	0.43	0.535	0.567				
455	W_G (lb/s)	0.207	0.193	0.176	0.138	0.119	0.108	1.5	284	119.5	190
	δ_L (in)	0.623	0.445	0.361	0.299	0.305	0.507				
457	W_G (lb/s)	0.282	0.261	0.238	0.199	0.179	0.165	1.496	287	118.4	197
	δ_L (in)	0.623	0.407	0.293	0.257	0.252	0.263				
459	W_G (lb/s)	0.344	0.315	0.294	0.254	0.236	0.223	1.562	288	125.8	201
	δ_L (in)	0.623	0.329	0.257	0.227	0.214	0.249				
473	W_G (lb/s)	0.141	0.125	0.112	0.084	0.064	0.045	2.344	280	123.8	172
	δ_L (in)	0.623	0.766	0.663	0.526	0.61	0.675				
475	W_G (lb/s)	0.199	0.176	0.156	0.119	0.094	0.079	2.286	284	119.5	180
	δ_L (in)	0.623	0.635	0.53	0.444	0.367	0.632				
477	W_G (lb/s)	0.285	0.256	0.233	0.187	0.158	0.132	2.337	287	117.9	189
	δ_L (in)	0.623	0.491	0.367	0.336	0.298	0.333				
493	W_G (lb/s)	0.143	0.118	0.102	0.072	0.056	0.037	3.002	278	119.7	164
	δ_L (in)	0.623	0.906	0.825	0.665	0.728	0.77				
495	W_G (lb/s)	0.2	0.17	0.149	0.109	0.083	0.064	3.007	285	119.8	172
	δ_L (in)	0.623	0.812	0.735	0.546	0.451	0.721				
497	W_G (lb/s)	0.282	0.252	0.225	0.178	0.142	0.11	3.156	287	119.3	181
	δ_L (in)	0.623	0.622	0.458	0.426	0.392	0.426				

W_G = steam mass flowrate
δ_L = water layer thickness
ΔP = differential pressure
W_L^{in} = inlet liquid mass flowrate
T_G^{in} = inlet vapor temperature
T_L^{in} = inlet liquid temperature
TL^{ex} = outlet liquid temperature

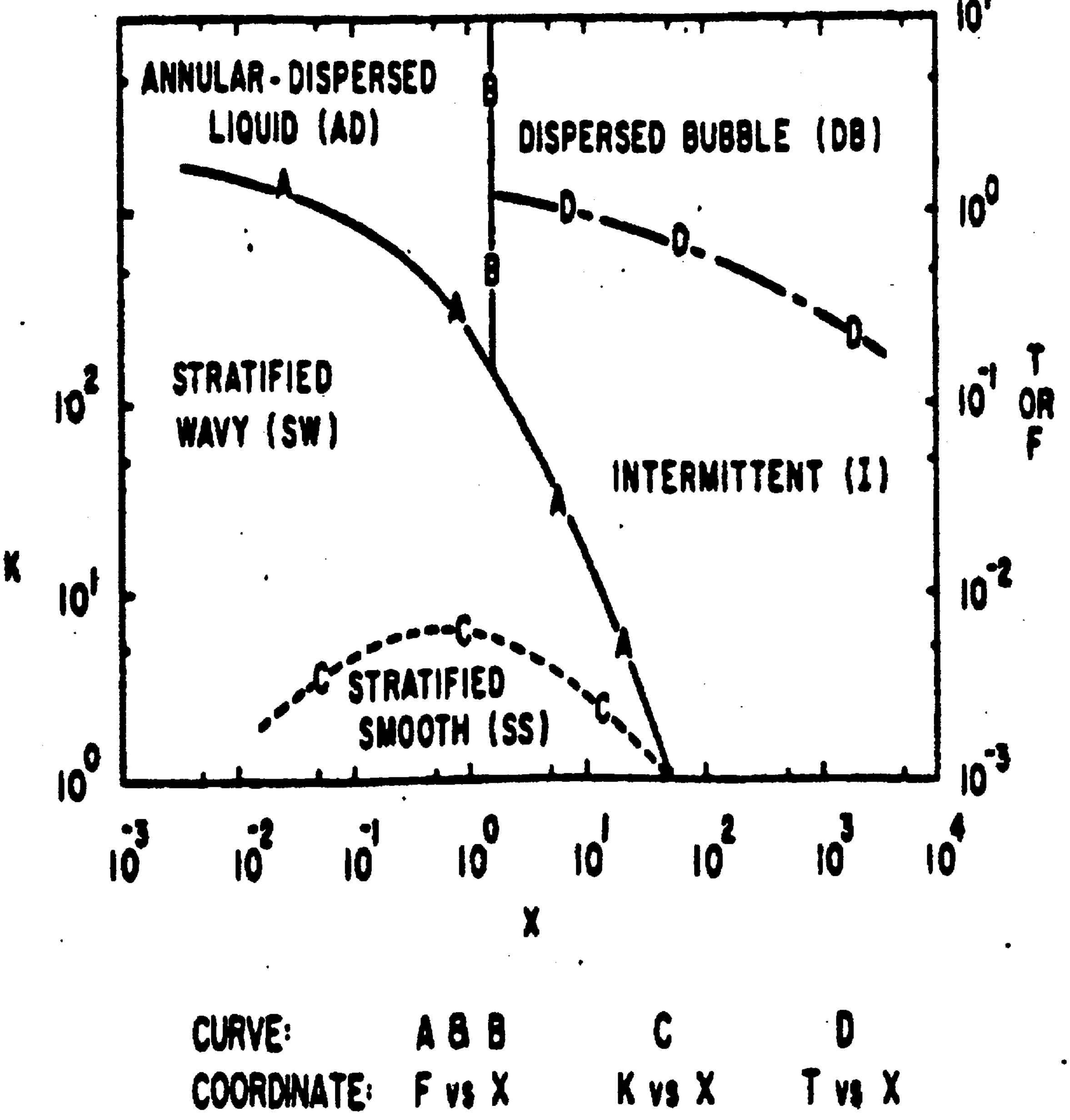


Figure B-1 Generalized Flow Regime Map for Horizontal Two-Phase Flow

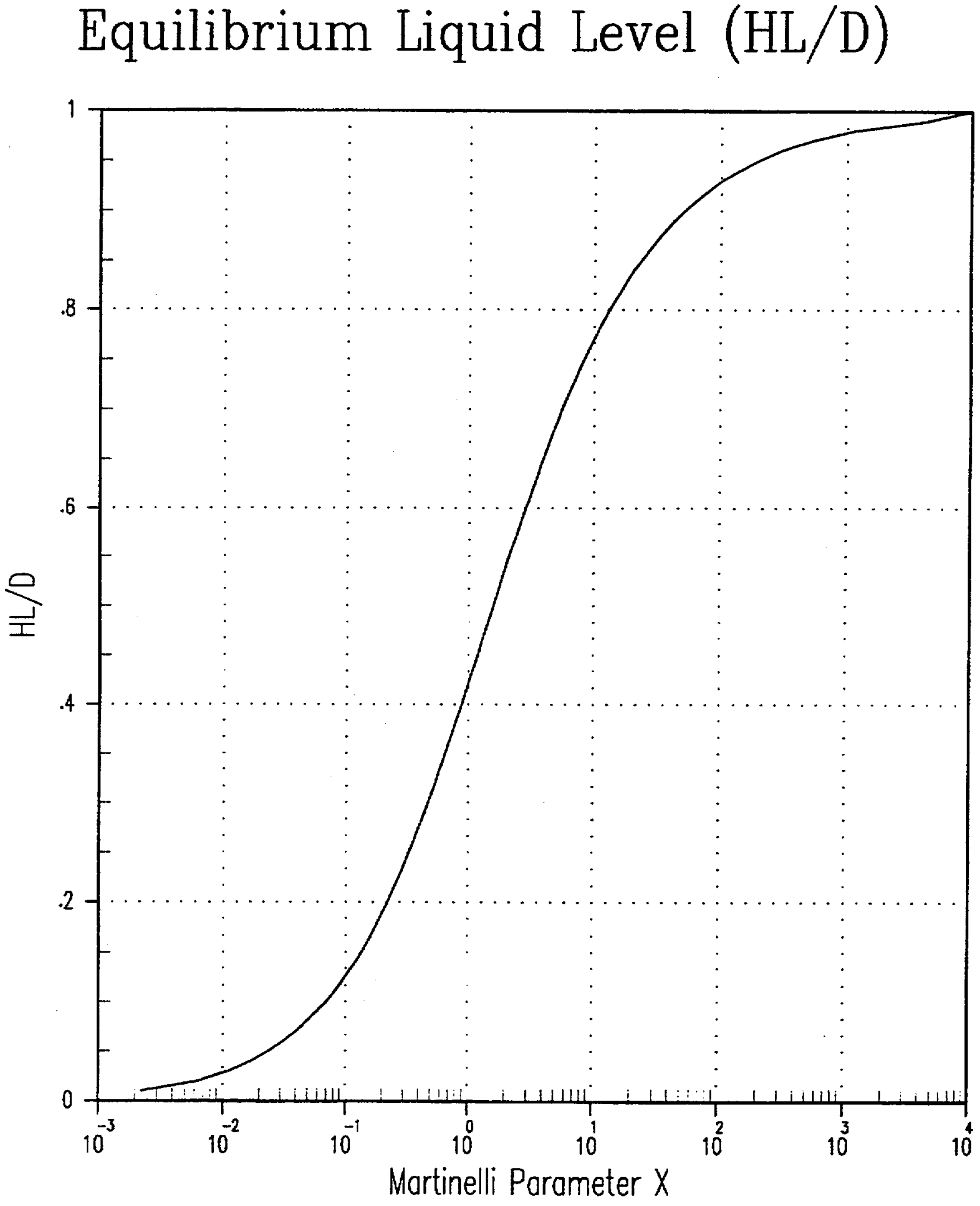


Figure B-2 Equilibrium Liquid Level vs. Martinelli Parameter, X

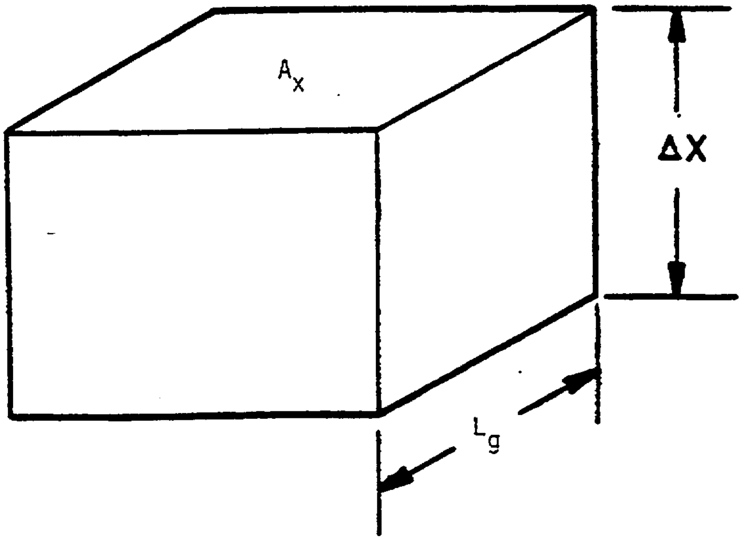


Figure B-3 Basic Mesh Cell

a,b,c

Figure B-4 WCOBRA/TRAC-AP Representation of Interfacial Heat Transfer

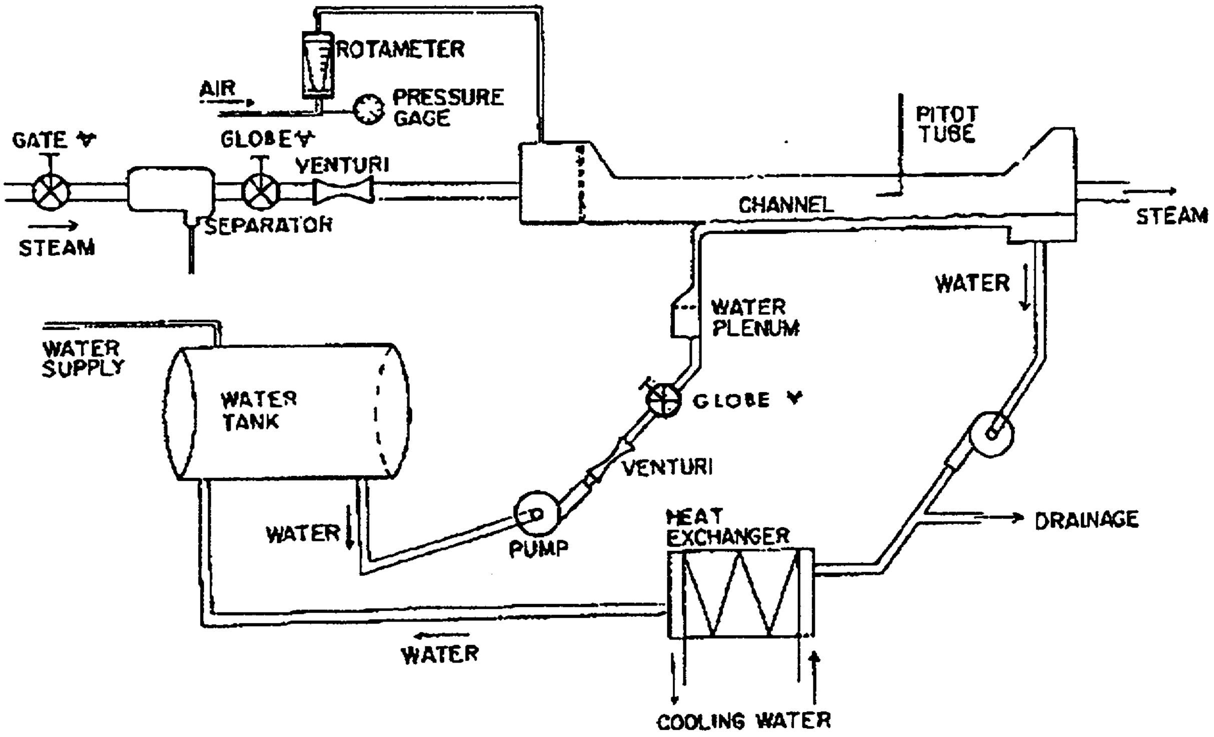


Figure B-5 Schematic Diagram of the Experimental System (Lim, et al., 1981)

a,b,c

Figure B-6 WCOBRA/TRAC Noding

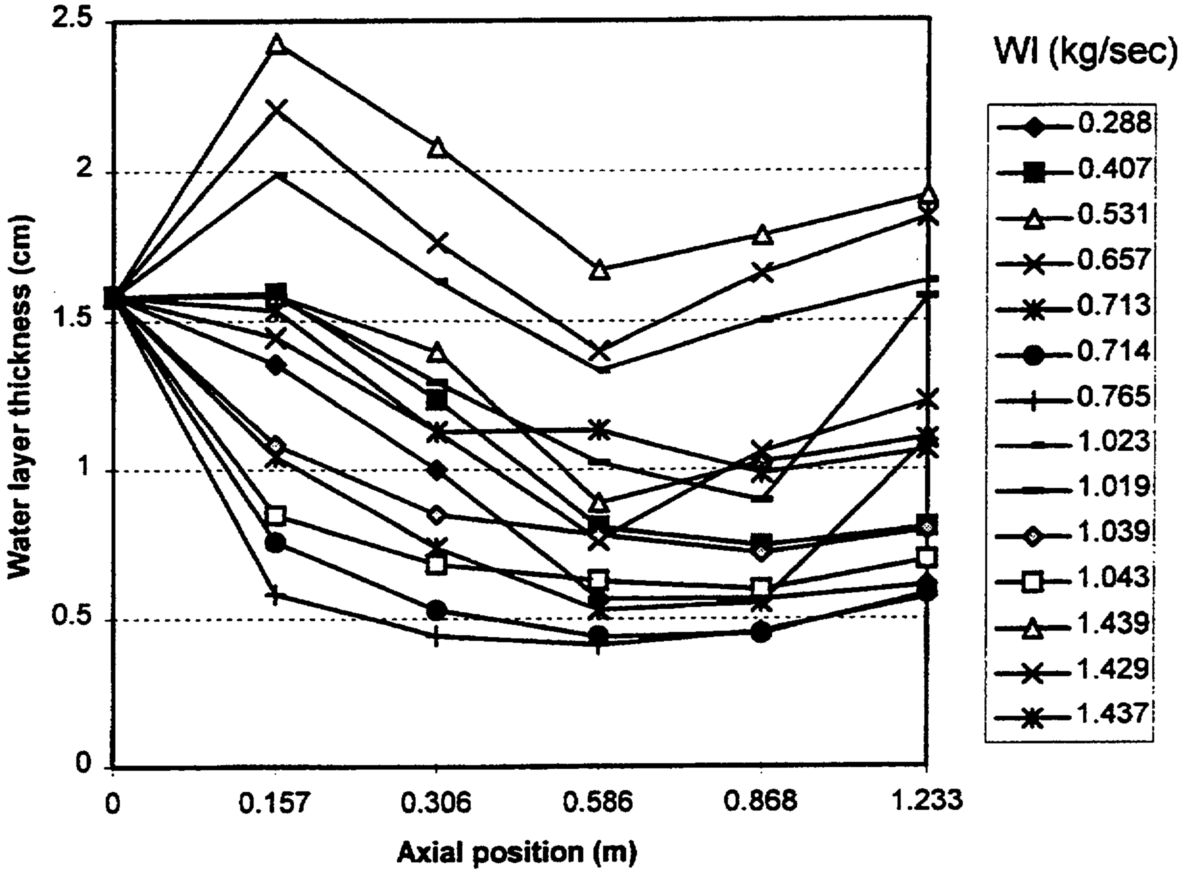


Figure B-7 Measured Water Thickness versus Axial Position for Various Liquid (WI) Flowrates and Inlet Water Layer Thickness of 1.583 cm

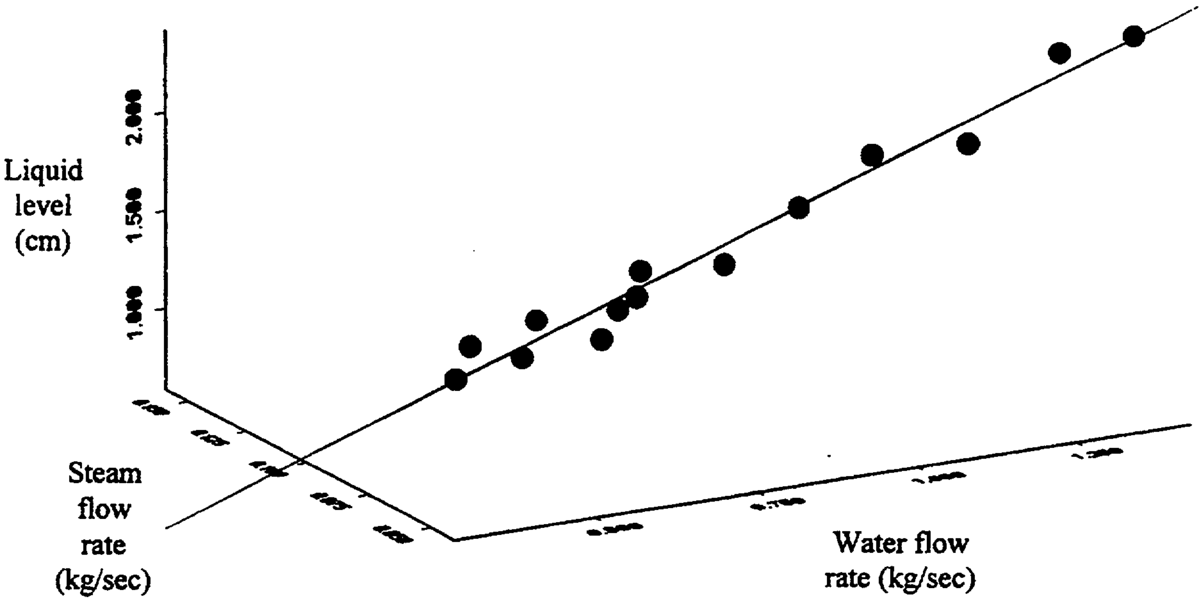


Figure B-8 Measured Water Thickness at 0.157 m From the Channel Inlet versus Liquid and Steam Flowrates

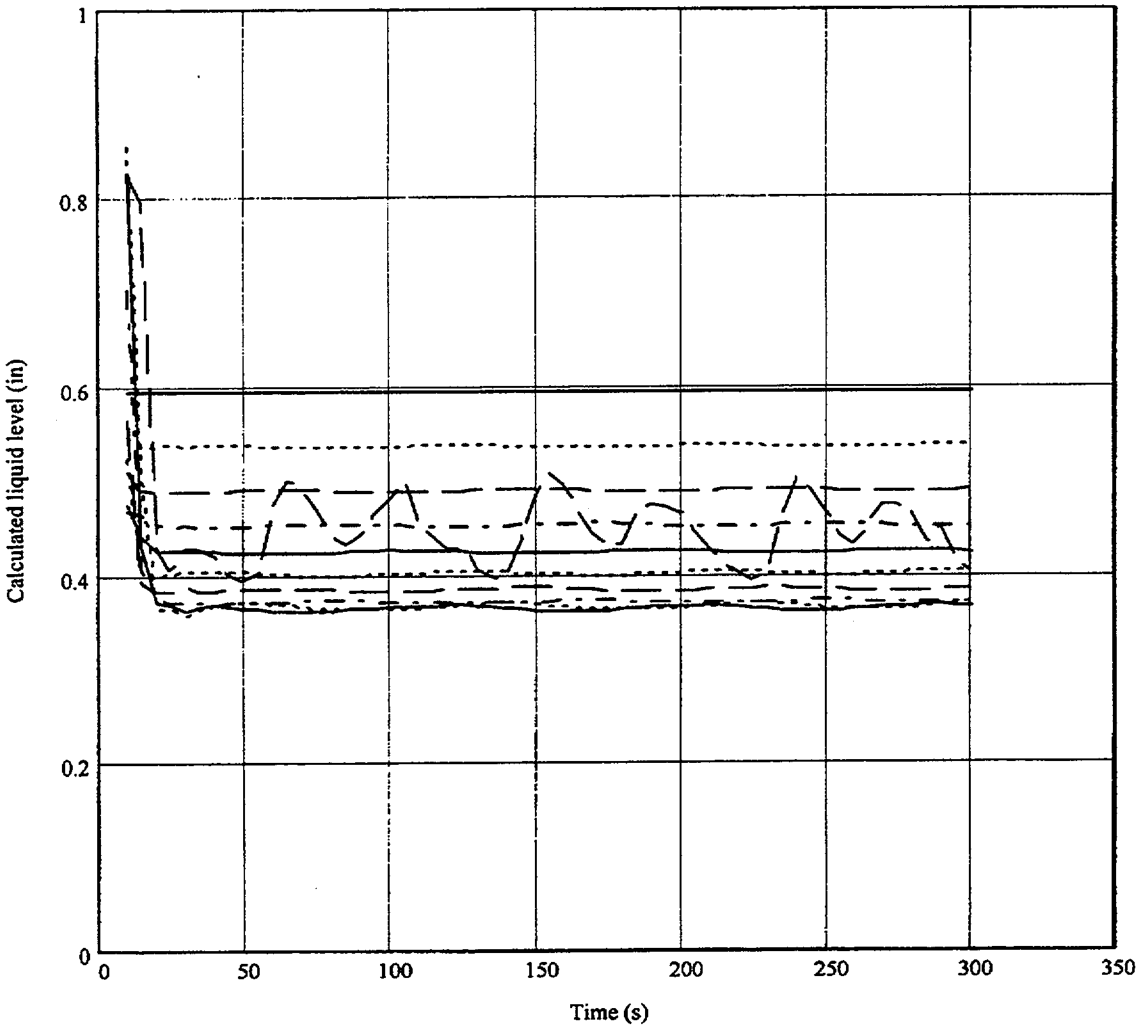


Figure B-9 Calculated Liquid Level (Run 275)

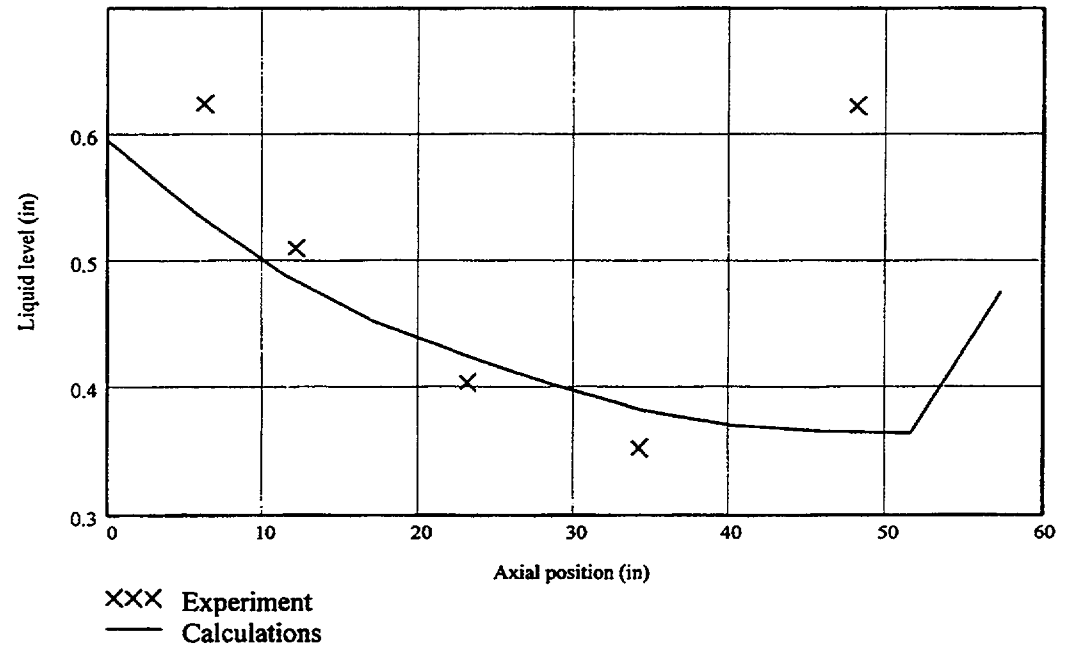


Figure B-10 Calculated and Measured Liquid Levels Versus Axial Position (Run 275)

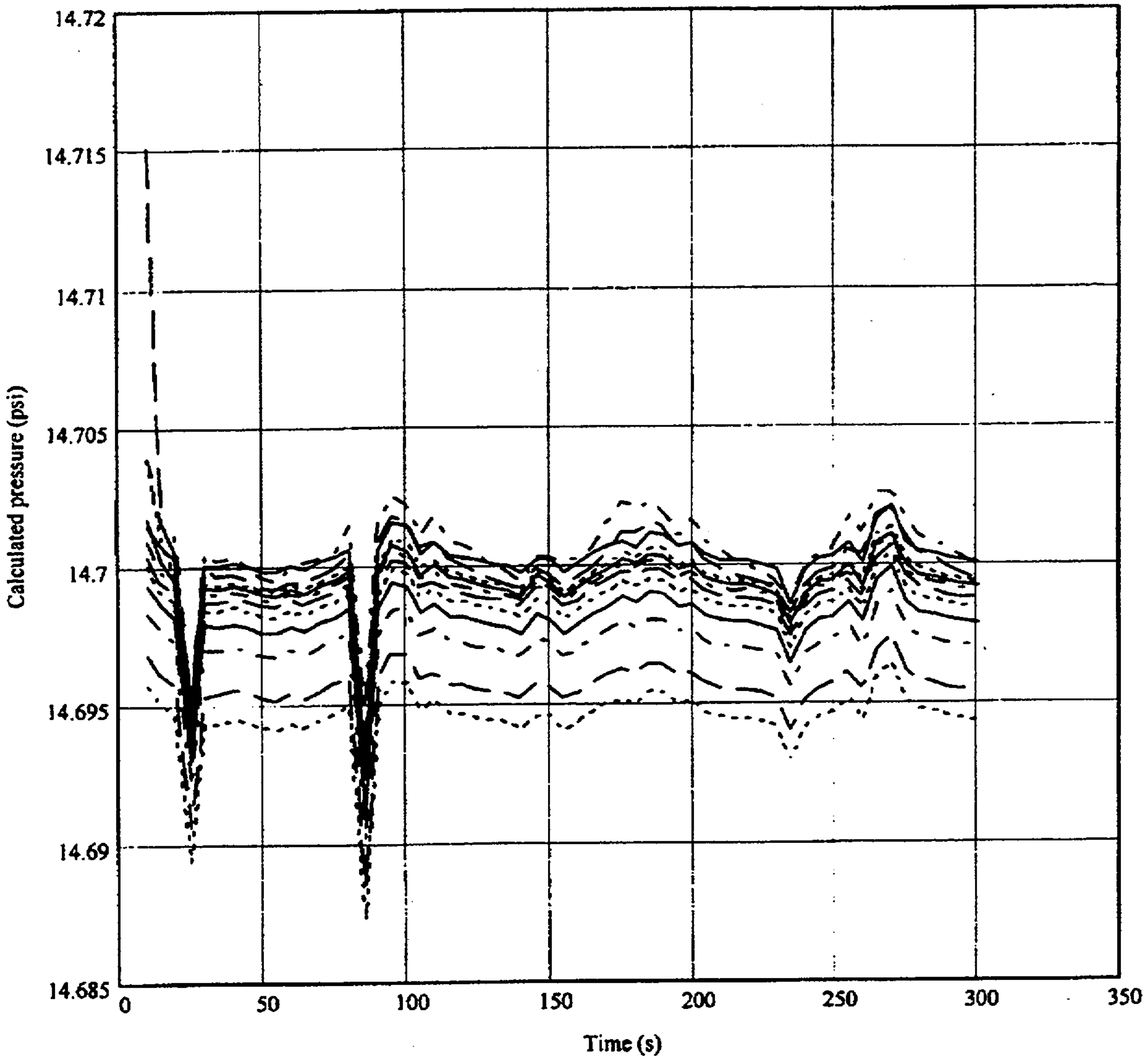


Figure B-11 Calculated Steam Pressure (Run 275)

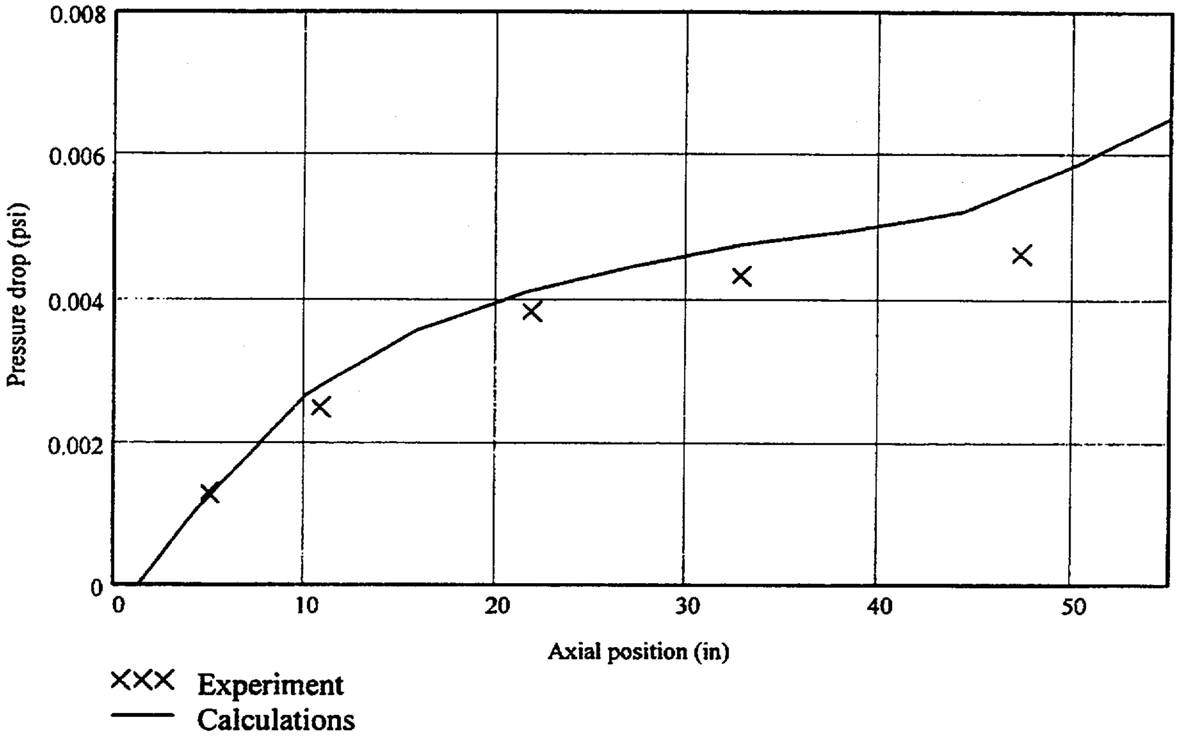


Figure B-12 Calculated and Measured Steam Pressure Versus Axial Position (Run 275)

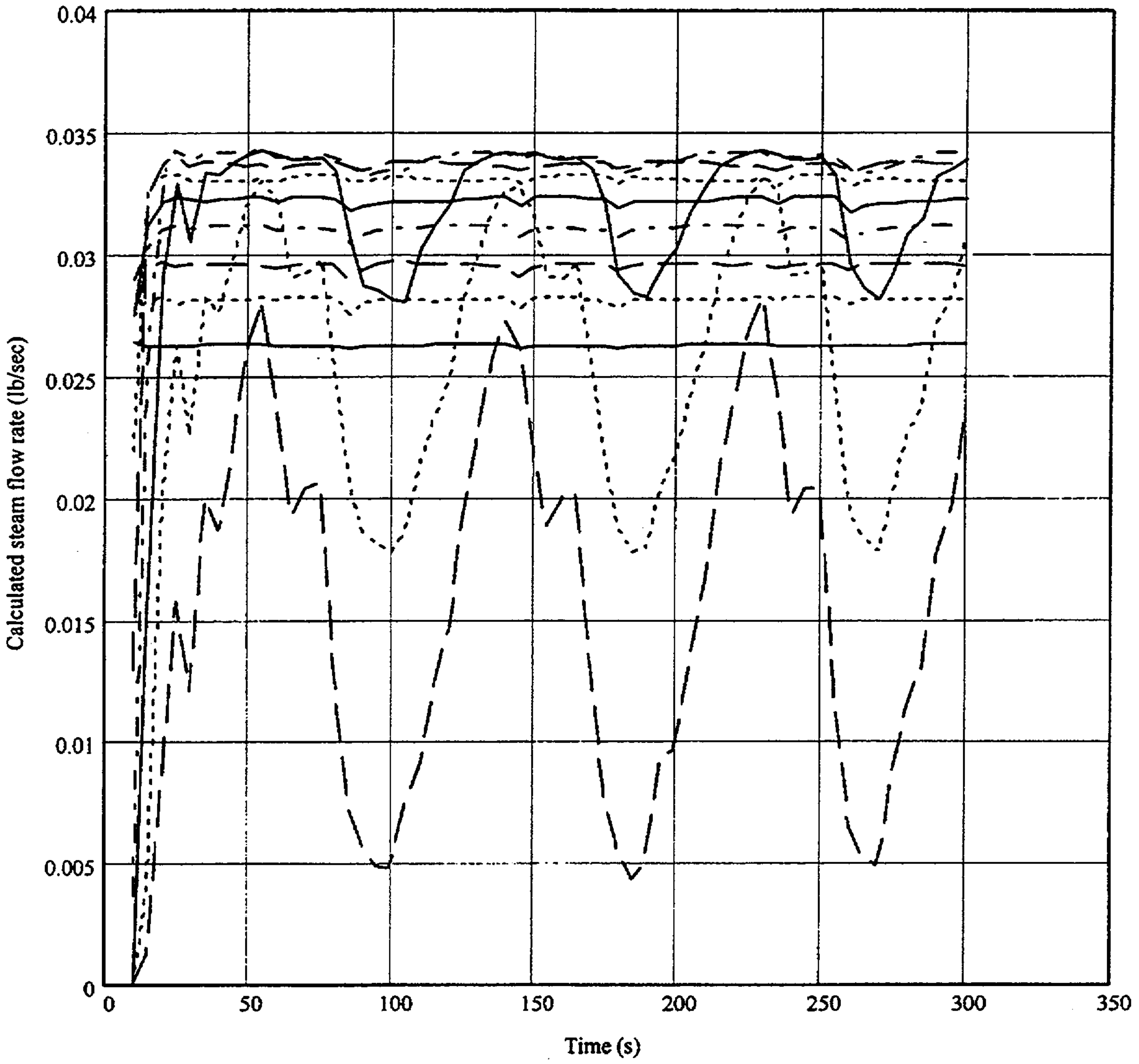


Figure B-13 Calculated Steam Flowrate (Run 275)

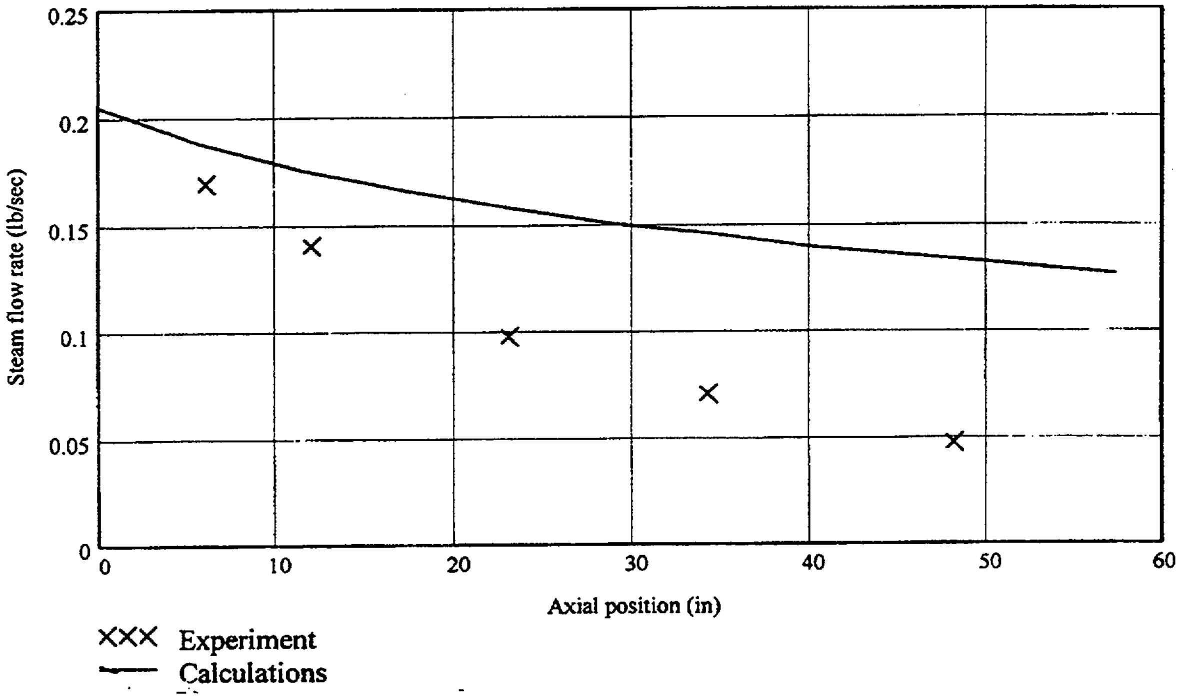


Figure B-14 Calculated and Measured Steam Flowrate Versus Axial Position (Run 275)

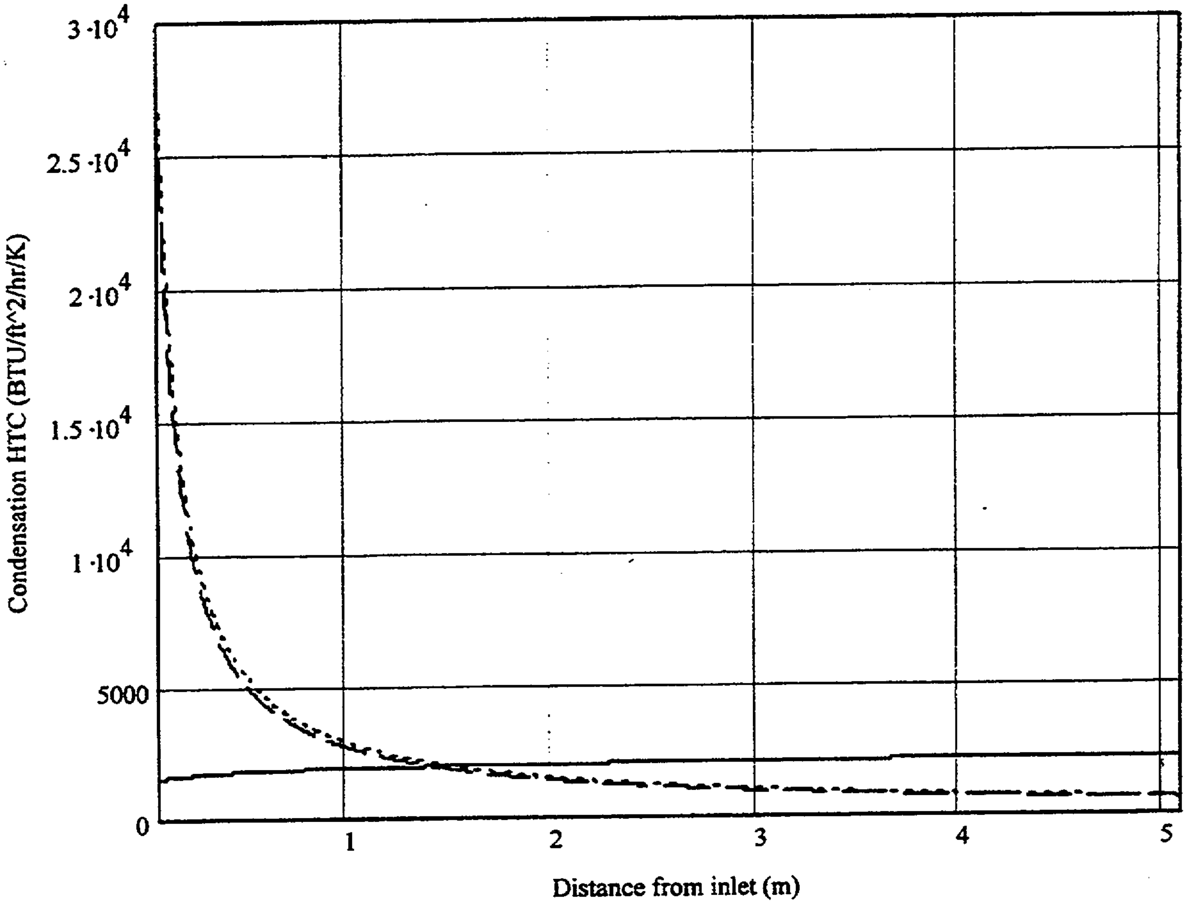


Figure B-15 Comparison of Condensation Heat Transfer Correlations

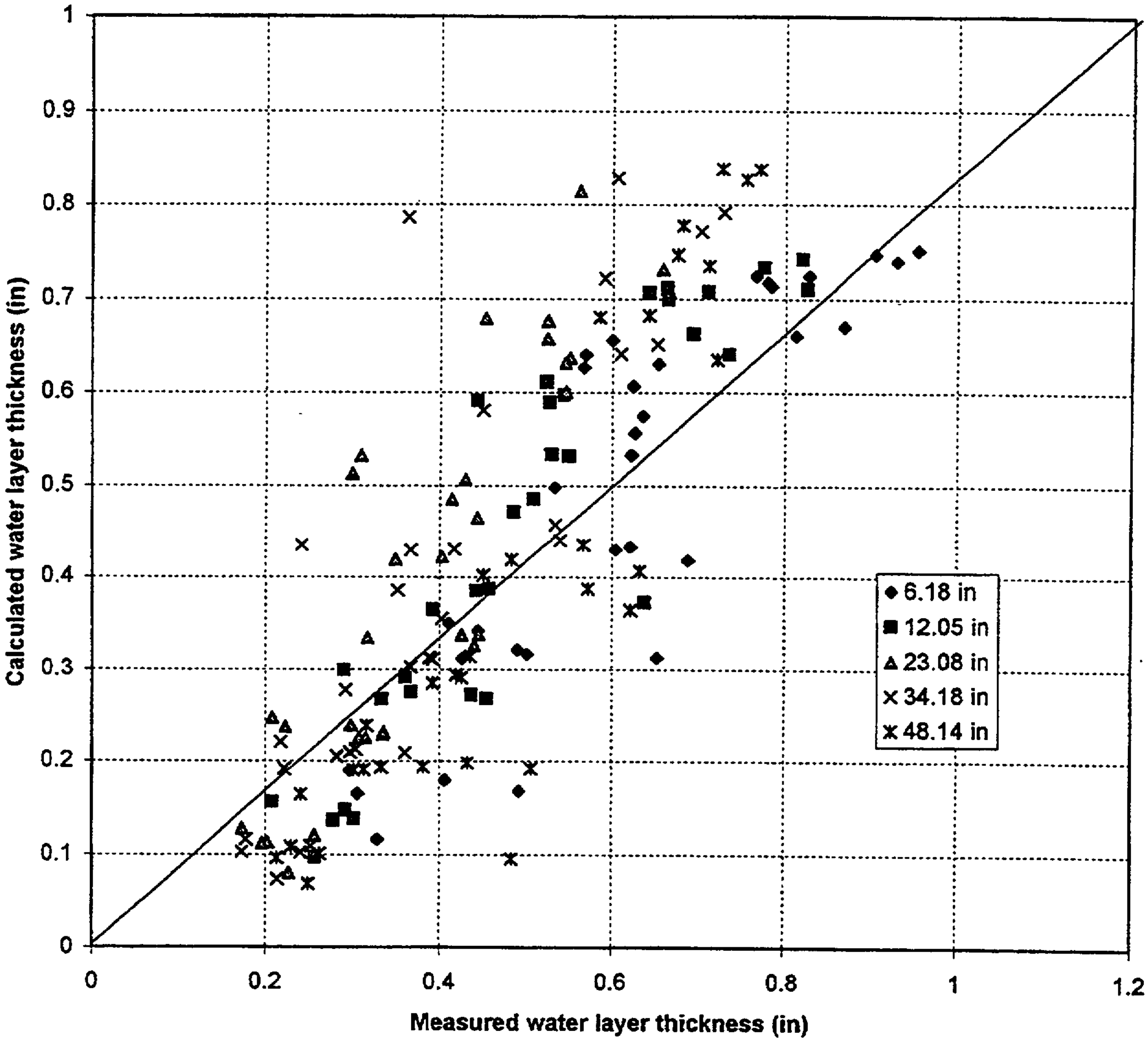


Figure B-16 Predicted Versus Measured Liquid Level at Various Axial Locations

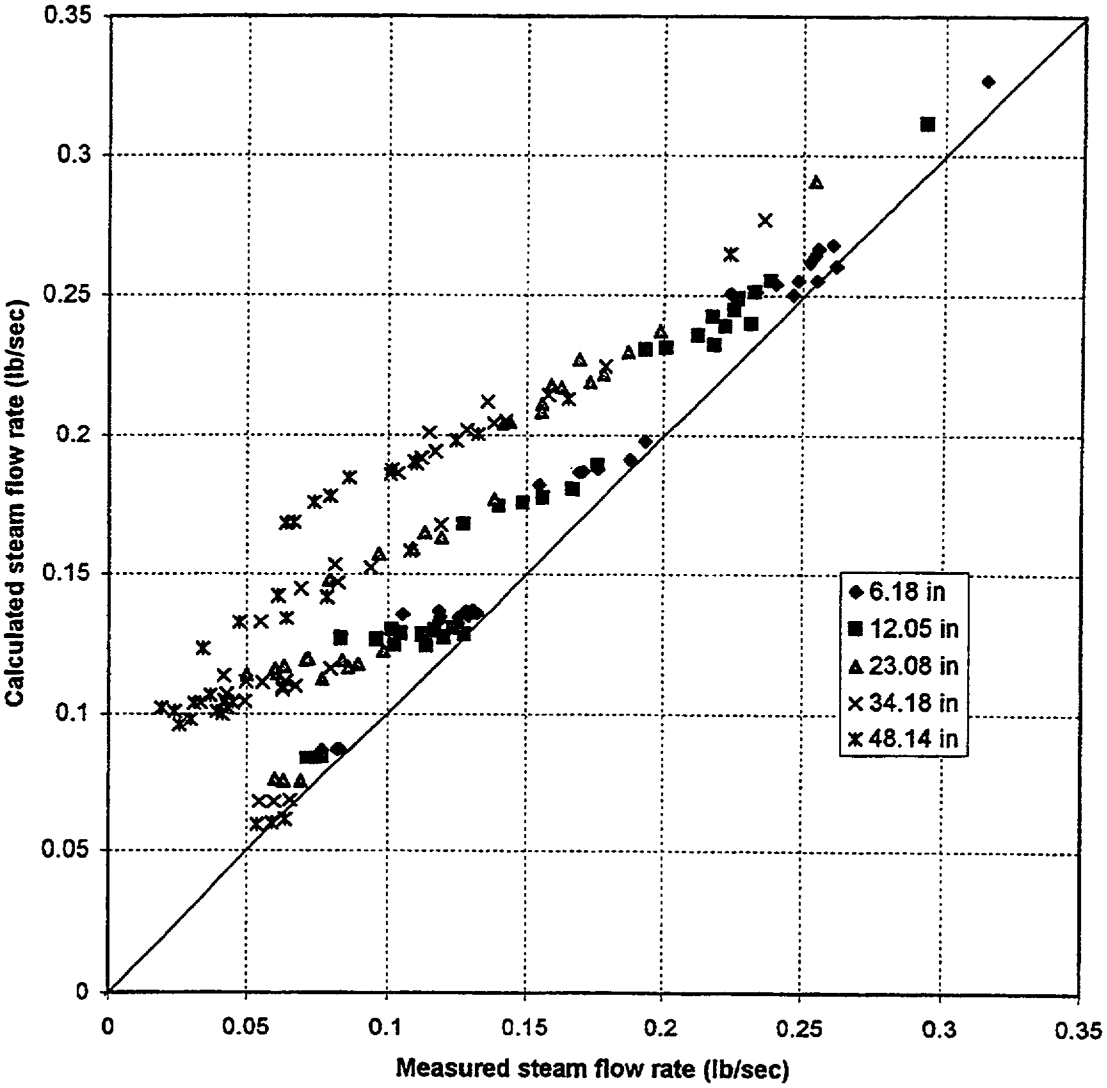


Figure B-17 Predicted Versus Measured Steam Flowrate at Various Axial Locations

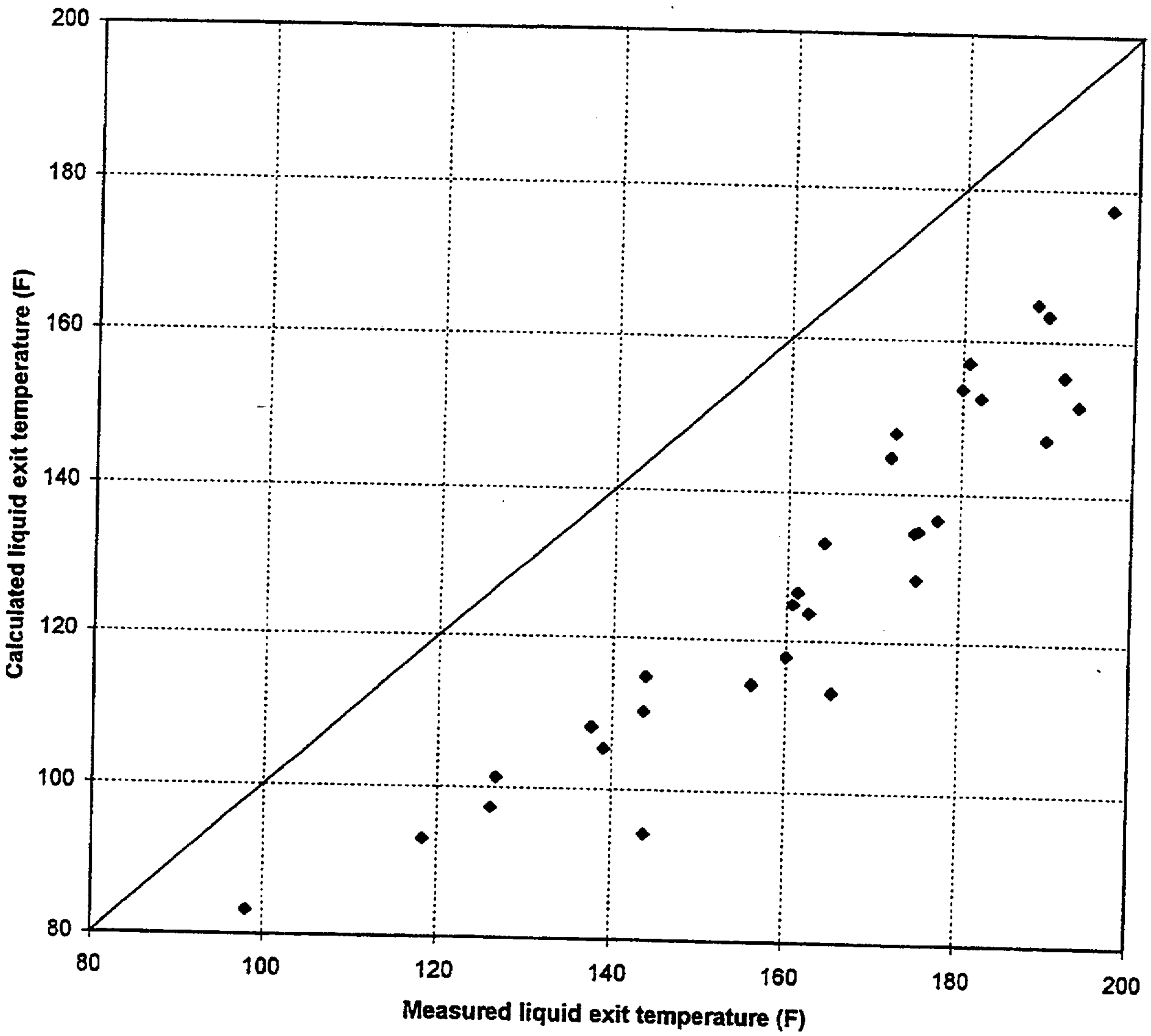
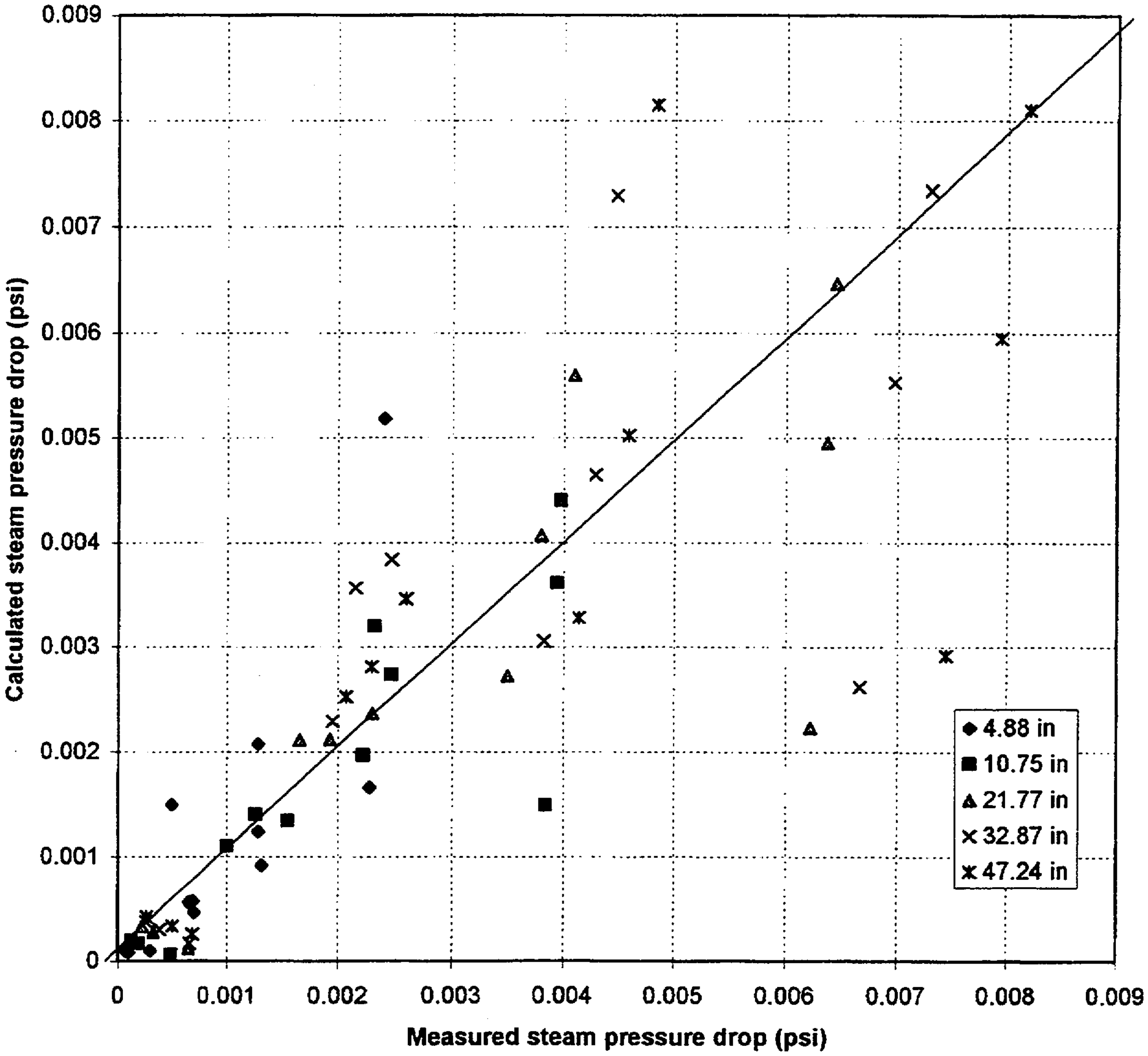


Figure B-18 Predicted Versus Measured Liquid Temperature at the Channel Exit



(Measurements were taken only during the following runs: 211, 231, 251, 253, 255, 257, 273, 275, 277, 293, 295, and 297)

Figure B-19 Predicted Versus Measured Steam Pressure Drop at Various Axial Locations

APPENDIX C

ASSESSMENT OF NOTRUMP CODE ERRORS ON AP600 DSER ANALYSIS RESULTS

To provide evidence that the errors discovered in the AP600 NOTRUMP code do not invalidate the AP600 DSER results or the applicability of the revised code to the AP600/AP1000 designs, information for AP600 2-Inch Cold Leg break simulations was generated. A synopsis of the results is provided below. Note that NOTRUMP Version 36.0, which was released after the AP600 SSAR analysis was performed, contains discretionary changes applicable to all Westinghouse plant designs as well as the gravitational head error correction.

The assessment of the impact of errors associated with implicit fluid node gravitational head, droplet fall models and volumetric flow link variable updating can be shown to have a negligible impact on the AP600 2-Inch Cold Leg break when compared to the AP600 DSER results. Figures C-1 through C-3 present comparisons of the Pressurizer pressure (Figure C-1), Core/Upper plenum mixture level (Figure C-2) and RCS system inventory (Figure C-3) responses associated with the correction of the fluid node gravitational head in Version 36.0 and the droplet fall model errors respectively. Figures C-4 through C-6 present the same figures associated with the responses when the volumetric flow link variable updating error is corrected in NOTRUMP Version 37.0. As can be seen by reviewing these figures and the sequence of events summary in Table C-1, the conclusion that the impact of these errors on the code and the simulation results is negligible can be readily supported.

The errors associated with the region depletion model logic can not be directly assessed since AP600 plant specific transient simulations have not been performed with a corrected code version. As a result, only the impact established from traditional PWR designs can be utilized to make this determination. The documentation supporting correction of this error contains the following synopsis.

"Although this is a code correction, the impact is expected to be minimal since the interior metal node temperature updates performed in the old code version were only out-of-phase by one time step with respect to the interior fluid node central variable adjustments. In addition, the interior fluid node central variable adjustments are expected to be small and to occur infrequently during a typical transient. As such it is expected that the internal metal node temperatures are considered to have an insignificant impact on analysis results, since the temperature differences between un-heated conductors and adjacent fluid channels are typically small."

To further substantiate this conclusion, plot results for three key parameters (Core mixture level, core exit vapor temperature and core exit vapor flow) were generated for several Westinghouse plant cases. The results of these cases demonstrate the benign nature of this code error correction and support the conclusion that small break LOCA transient simulations are negligibly impacted by this change. In addition, since the AP600/AP1000 plant results obtained do not indicate the existence of core uncovery, it is expected that the AP600/AP1000 designs will also exhibit no impact from this change.

Table C-1 Sequence of Events Summary

Event	SSAR Results (Seconds)	Version 36.0 Results (Seconds)	Revised Droplet Fall Results (Seconds)	Version 37.0 Results (Seconds)
Break Opens	0.0	0.0	0.0	0.0
Reactor Trip Signal	33.5	33.5	33.5	33.5
"S" Signal	39.7	39.7	39.7	39.7
ADS Stage 1	1032	1036	1036	1036
ADS Stage 2	1102	1106	1106	1106
ADS Stage 3	1222	1226	1226	1226
Accumulators Empty	1470	1468	1467	1467
ADS Stage 4	2422	2414	2418	2401
Core Makeup Tank Empty	2820	2790	2790	2772
IRWST Injection Starts	3544	3548	3561	3562

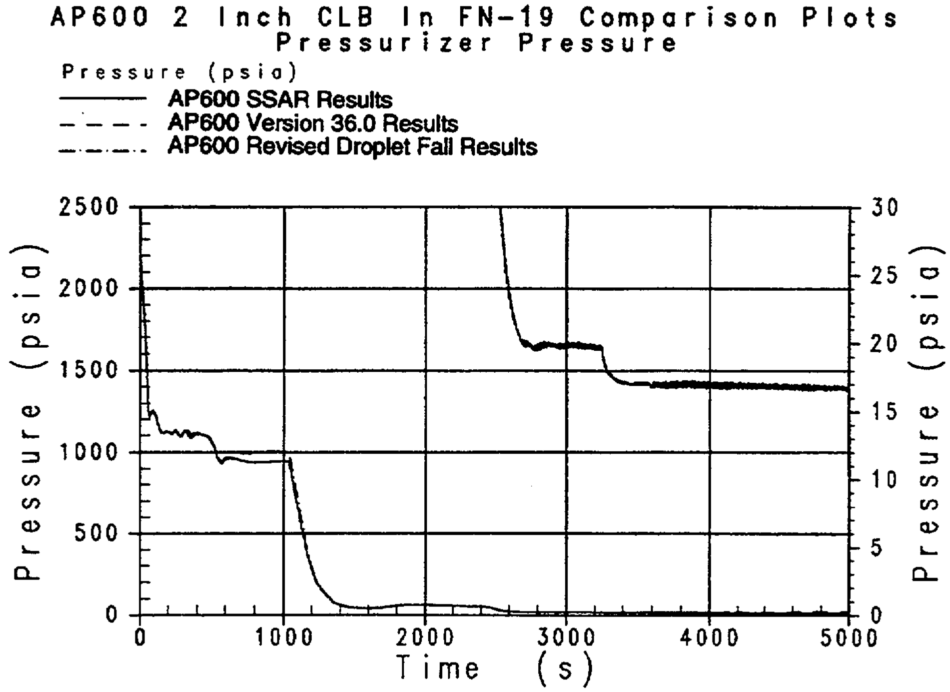


Figure C-1 Pressurizer Pressure

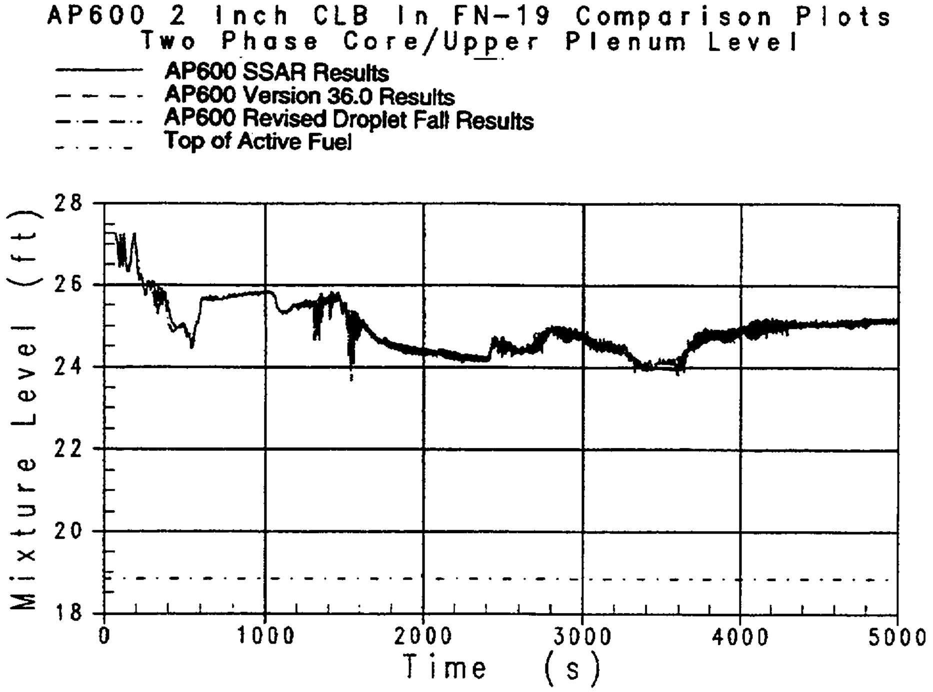


Figure C-2 Core/Upper Plenum Mixture Level

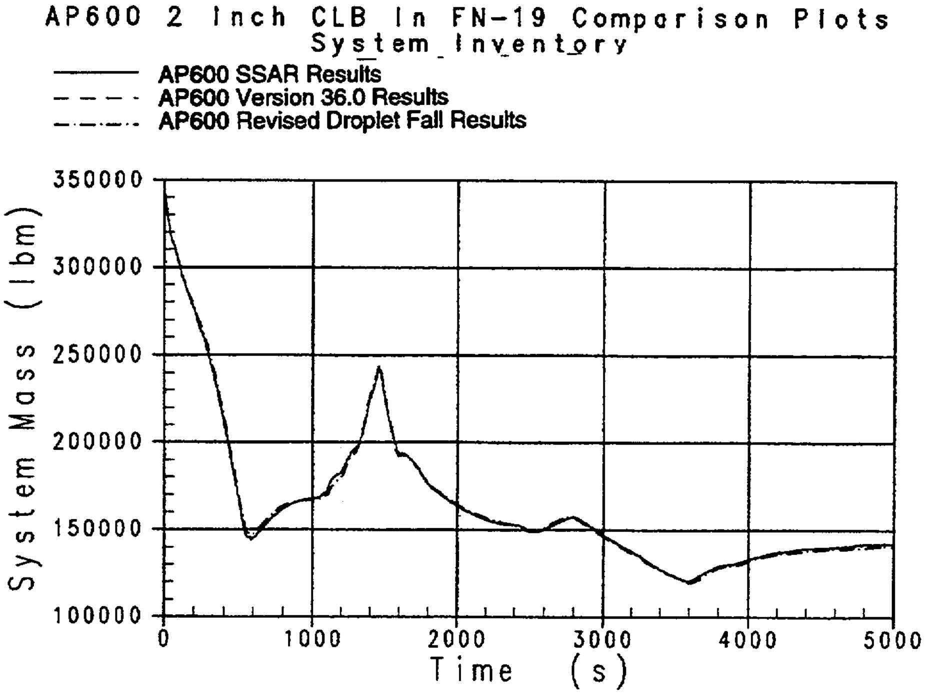


Figure C-3 RCS System Inventory

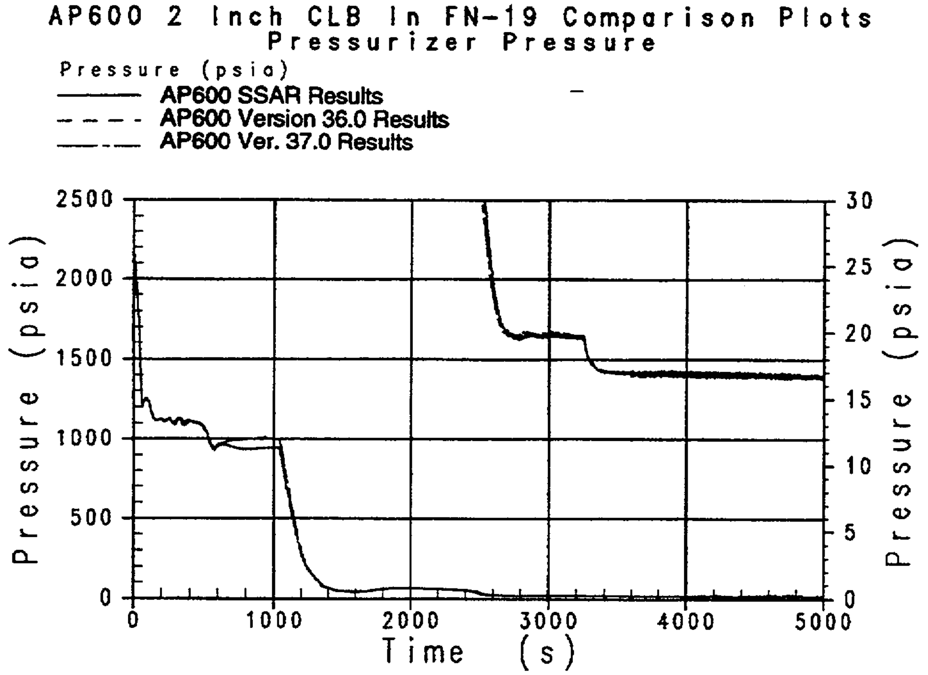


Figure C-4 Pressurizer Pressure

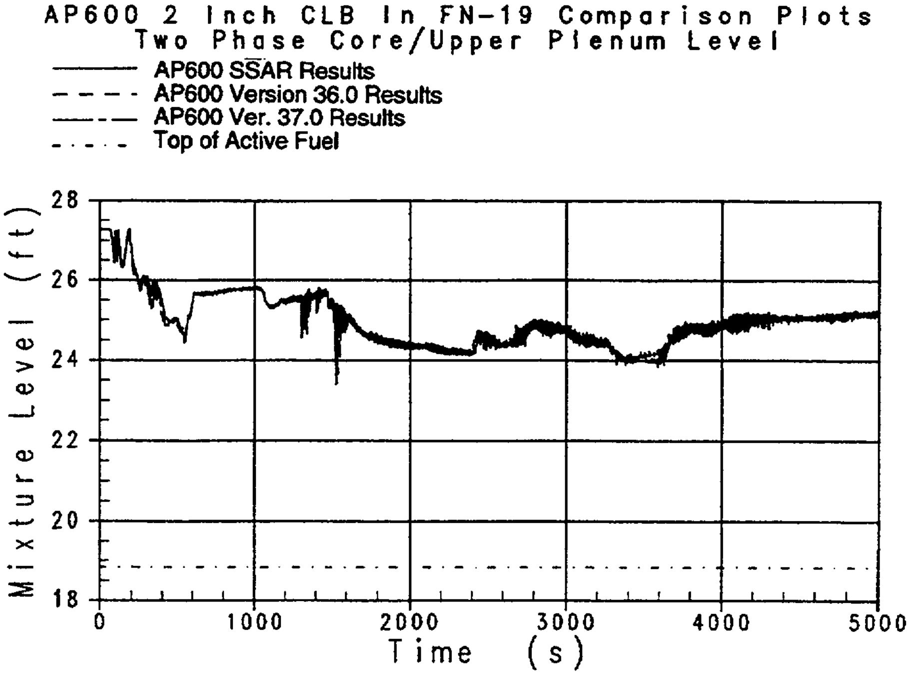


Figure C-5 Core/Upper Plenum Mixture Level

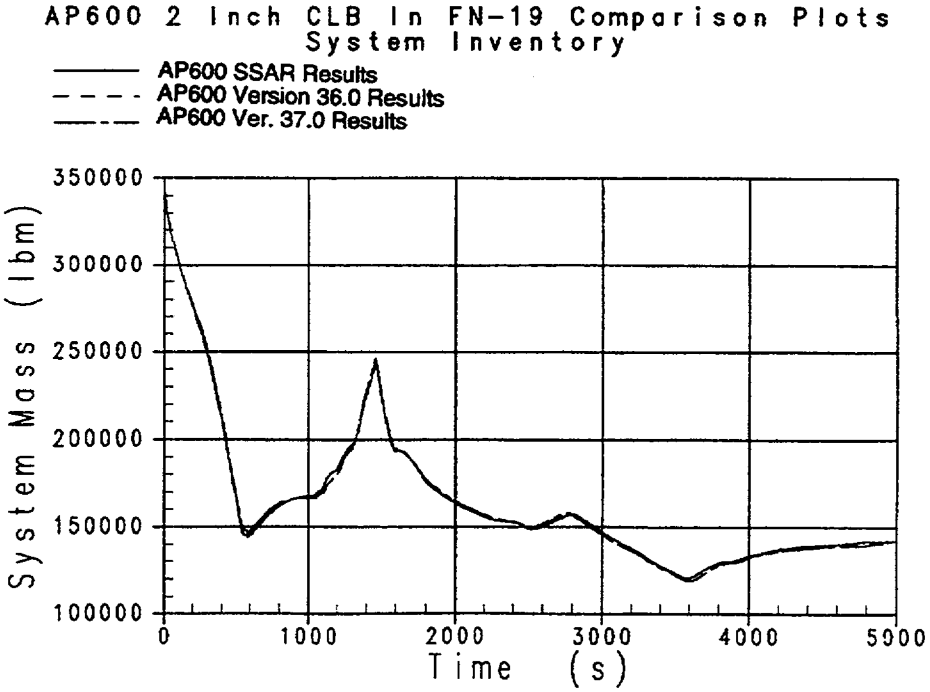


Figure C-6 RCS System Inventory