AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: 21.5-3NP (Response Revision 1)

Original RAI Number(s): 440.164

Summary of Issue:

Core Level Swell

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

Information supplied by the applicant as part of the response to RAIs 440.164 and 440.171 suggests that level swell may not be adequately predicted for AP1000 and that the codes may not be predicting cladding heatup because of insufficient core nodalization and inadequate correlations used in predicting the level swell.

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

Westinghouse Response (Revision 1):

Revision 1 of this response provides detailed development of the equations used in the simple model described in the original response, and a sensitivity analysis relative to the homogeneous flow assumption in the simple model.

To address this DSER Open Item, Westinghouse has performed a series of analyses which are described herein. On one hand, the Cunningham-Yeh correlation, which is used to model the core void fraction distribution in NOTRUMP, was further validated against relevant full-scale rod bundle tests data. Independently a simplified AP1000 model was developed to analyze the AP1000 system behavior. The aim was to demonstrate that the liquid flow to the core is more than sufficient to remove the decay heat such that core heat-up is not expected to occur during the ADS-4/IRWST transition period following a SBLOCA event.

<u>Validation of Core Void Fraction Model Used in NOTRUMP Against Full-Scale Data</u>

NOTRUMP core level swell model is based on the use of the Cunningham-Yeh void fraction correlation (Ref. 1) implemented as a drift flux model. The scope of this study was to further

validate the correlation against a series of full-scale bundle experiments at conditions which are prototypical of the ADS4/IRWST transition phase of the AP1000.

In particular the following tests were considered:

FLECHT-SEASET: Runs 35114, 31504, 31805, 31203, 34006
FLECHT-Skewed: Runs 13404, 15606, 13609, 15713, 16022
G1: Runs 28, 35, 38, 42, 43, 58, 59, 61
G2: Runs 728, 729, 730, 732, 733
ACHILLES: Runs AIL066, AIL069
THETIS: Runs T2L101, T2L103, T2L098

Note that FLECHT-SEASET and FLECHT-Skewed are reflood tests. However data was considered soon after the bundle is quenched when the power level, pressure and bundle flow are more similar to the conditions expected in the AP1000 during the considered portion of the SBLOCA portion. All other tests are boil-off tests, which also have pressure and power conditions similar to the AP1000. On the other hand, in the boil-off tests, the liquid supply is insufficient to remove the power generated in the bundle. During the boil-off tests the mixture level drops below the top of the heated section. Once the heated rods are exposed to the steam, an almost adiabatic heat-up occurs because of the degraded heat transfer in the region above the mixture level.

For the boil-off tests, data was extracted at different times when the mixture level is located in the upper portion of the bundle (8–12 ft from the bottom of the heated length).

Table 1 shows the expected range of conditions in the AP1000 and conditions for the tests that were selected for the additional validation of the Cunningham-Yeh model:

Table 1: AP1000 and Full-Scale Tests Range of Conditions

Test	Pressure (psia)		Power (kW/ft)		Power Shape	Core/Assembly Flow (in/sec)		Inlet Subcooling (°F)	
AP1000									
FLECHT-SEASET									
FLECHT-Skewed									
G1									
G2									
ACHILLES									
THETIS									

a,b,c

Note that for THETIS and ACHILLES series the effect of subcooling was directly reported in terms of subcooled length (Z_{sub}) from the bottom of the heated length.

At a given time, for each test the vapor velocity was obtained as follows:

a,b,c

Similarly, the liquid superficial velocity was calculated from a quasi-steady state mass balance by knowing the inlet flow at the given time. Knowing phasic superficial velocities, the void fraction axial distribution was obtained from the Cunningham-Yeh model:

a,b,c

The collapsed liquid level Z_{CLL} in the bundle was then calculated from:

a,b,c

a,b,c

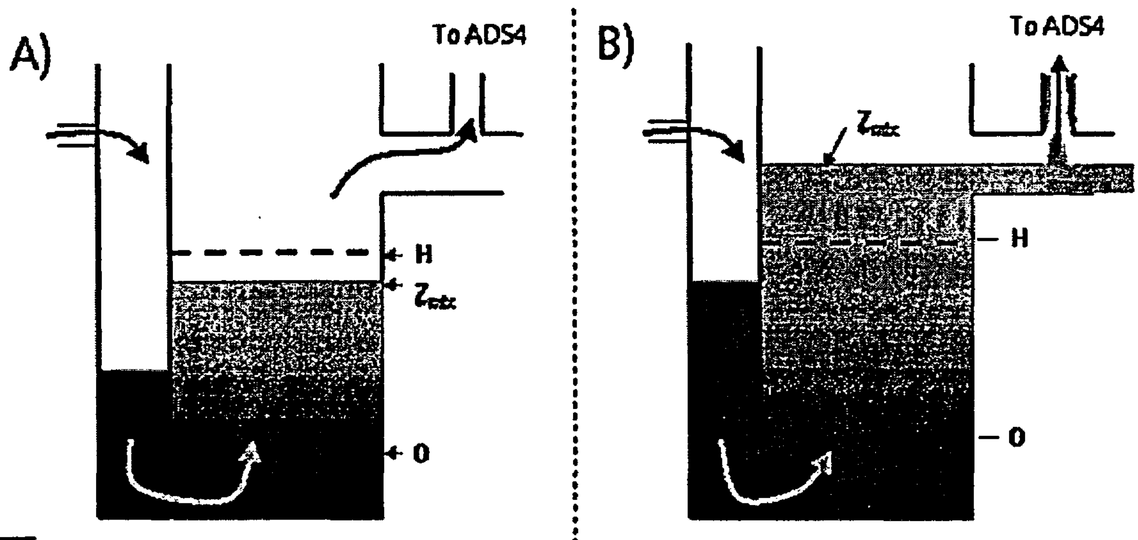
Figure 1: Calculated vs. Predicted Swell

The comparison shows a good agreement between the Cunningham-Yeh model and the test data. Most of the data is captured within a ±20% band. This result provides confidence that, for a given vessel mass inventory, the core average void fraction predicted by NOTRUMP during the ADS-4/IRWST transition period is acceptable.

<u>Comments to the NOTRUMP Base Model Analysis with Regard to Level Swell</u>

Regarding the level swell phenomenon, we considered what the level swell model will do in the following situations:

CASE A) The mixture level is within the core region
CASE B) The mixture level is above the core, in the upper plenum region



a,b,c

Assuming that the pressure in the upper plenum is the same as the pressure in the downcomer, an equilibrium is established where the collapsed liquid level in the downcomer Z_{DC} is equal to the integrated liquid fraction as shown in the equations above. The difference is the following:

- CASE A: The mixture level is a function of the level swell model used (similar to the boil-off tests). The supply of liquid is insufficient to remove the decay heat. The core exit quality is 100% and pure steam flows through the ADS-4 line.
- CASE B: The mixture level is determined by an equilibrium between the core exit quality (which is less than 100% in this case) and the supply of the safety injection system. If level is lower than the equilibrium the DP across ADS4 line decreases and as a result the injection increases until liquid content in ADS4 increases enough to match the increased supply from the injection. In this situation, the mixture level is virtually independent of the level swell model used within the core.

In other words, once the supply of liquid is enough to maintain a level in the upper plenum, the level swell model does not influence the system performance but only determines the core mass inventory (first term in R.H.S. of equation in case B).

The NOTRUMP base calculation (DEDVI) showed that adequate core cooling exists during the transient. The core inlet flow is more than sufficient to remove the decay heat. The inner vessel mixture level is predicted to be located significantly above the core plate through the transient, well into the upper plenum region. As shown above, under those conditions the effect of uncertainty on the core void fraction is insignificant on the overall system response.

To further support the argument that the core inlet supply of liquid during the ADS4/IRWST transition period is more than adequate to remove the decay heat and prevent core heatup from occurring (Case B), a simplified AP1000 model was developed and results are discussed in the following section.

AP1000 Simple Model

Westinghouse has developed a simplified model to provide a system level understanding of core region inventory behavior during ADS-IRWST period of limiting SBLOCA (DE DVI) using a simple, top-down type model. It supplements more detailed code results (i.e., NOTRUMP, WCOBRA/TRAC-AP, and RELAP5) and demonstrates conservative results when drift flux and bounding, homogeneous entrainment assumptions are employed. Although the Simple Model is steady state, the SBLOCA transient quickly becomes quasi-steady after ADS-4 actuation.

The Simple Model is first benchmarked against FLECHT SEASET test data and is then applied to APEX test data and AP1000. The results of the model provide core cooling mass flow demand relative to passive safety system supply. The APEX and AP1000 results show that the only solutions that satisfy the conservation equations require significant liquid flow into the upper plenum. This liquid flow is more than sufficient to remove decay heat and the excess liquid maintains core cooling and a two-phase mixture above the core.

Major features of this Simple Model include:

1. Drift flux void distribution in the core
2. ADS-4 two-phase pressure drop
3. Core decay heat
4. Bounding, homogeneous liquid entrainment from upper plenum, hot leg, and ADS-4 paths
5. Safety injection from CMT and IRWST

Description of the Simple Model

A general description of this model is provided in the paragraphs below. A detailed development of the equations is provided in Appendix 2 of this response.

The Simple Model consists of three sub-models:

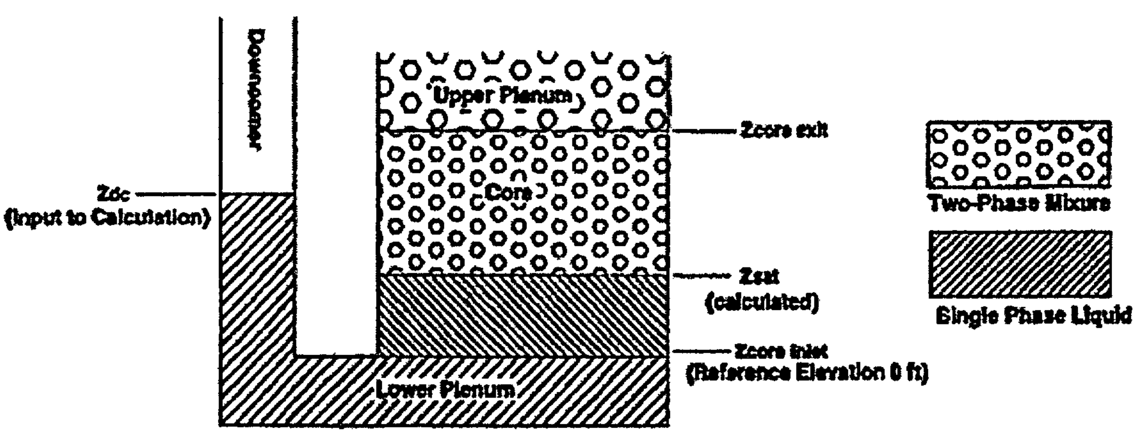
1. Core region (including the downcomer)
2. Core exit region (including the upper plenum, hot leg, ADS-4 paths and the ADS)
3. Safety injection from CMT and IRWST

The core region model accounts for slip between liquid and vapor phases via drift flux model to estimate liquid inventory in core region. The core exit region model accounts for ADS-4 pressure drop (subcritical flow) and maximizes entrainment of liquid exiting from core region by conservatively assuming homogeneous flow. The CMT/IRWST models account for gravity injection of liquid via DVI flow paths into reactor vessel downcomer.

Governing Equation Set for Core Region

The following illustration is a schematic diagram of the downcomer/core region modeled in the following conservation equations.

Downcomer/Core Region



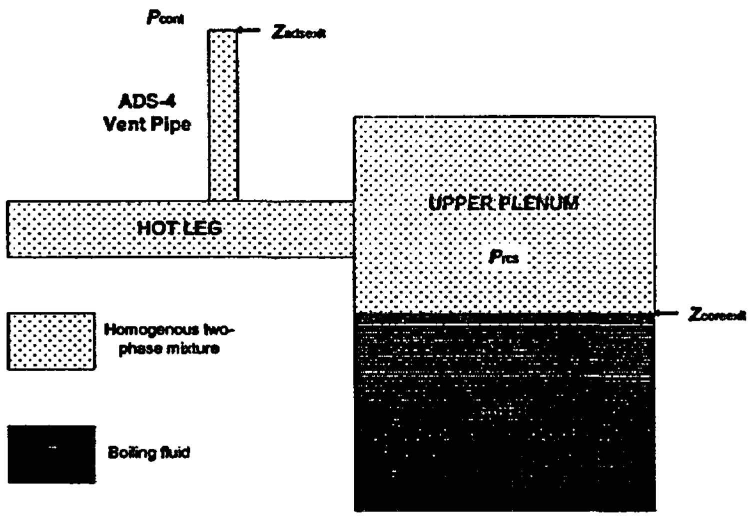
The conservation of mass equation for Steady State, 1-D, flow in a constant area channel is as follows:

a,b,c

a,b,c

a,b,c

Figure 2: Core Exit Region



a,b,c

The homogeneous two-phase multiplier from <u>One Dimensional Two-Phase Flow,</u> (G. B. Wallis) is used:

$$\Phi_{fo}^2 = \left(1 + x\frac{\Delta\rho}{\rho_g}\right)\left(1 + x\frac{\mu_{fg}}{\mu_g}\right)^{-1/4}$$

Application of the Simple Model to AP1000

Appendix 1 of this response provides the input to the Simple Model based on AP1000 parameters (Table A-1) and representative values of the core power (Qcore), downcomer level (Zdc), core inlet temperature (Tcin) and RCS pressure (Pdc) from the NOTRUMP analysis of the SBLOCA DEDVI break (Tables A-2 and A-3). The flow rate outputs from the simple model are used to generate the curves in Figure 3 through Figure 6.

Figure 3 provides the core-ADS region results for AP1000. The figure identifies the core flow required for decay heat removal as a function of back pressure from core exit region (ADS pressure drop). The core decay power range is representative of ADS-IRWST phase of DEDVI transient near initiation of IRWST injection.

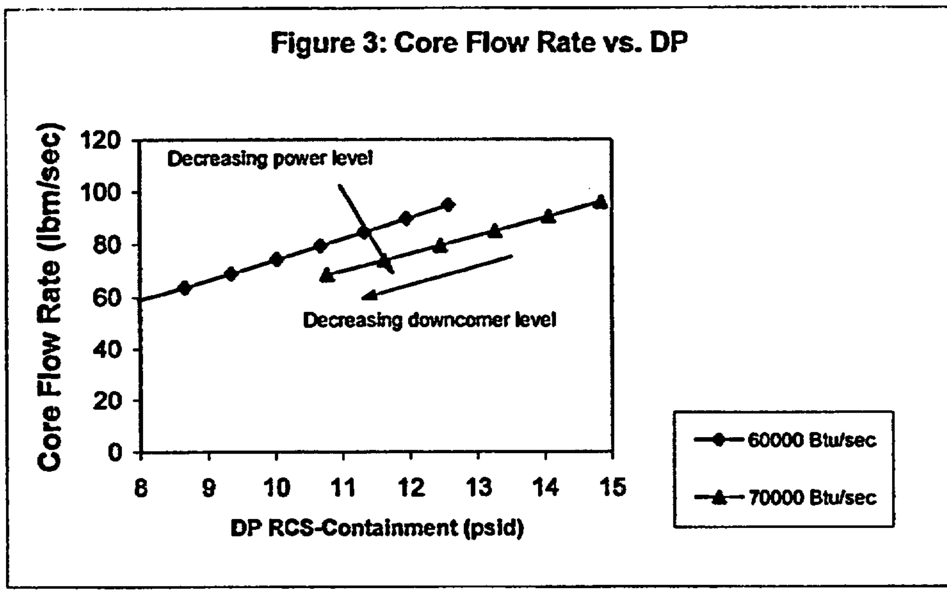


Figure 4 provides the calculated CMT flow rate results for AP1000. The CMT flow is calculated from steady state balance of CMT gravity head and DVI line resistance from CMT to reactor vessel. The results are based on flow from one CMT (DE DVI) at various liquid levels in CMT. Note that CMT flow is independent of downcomer pressure because the Δp is balanced via the pressure balance line from the cold leg to the CMT inlet.

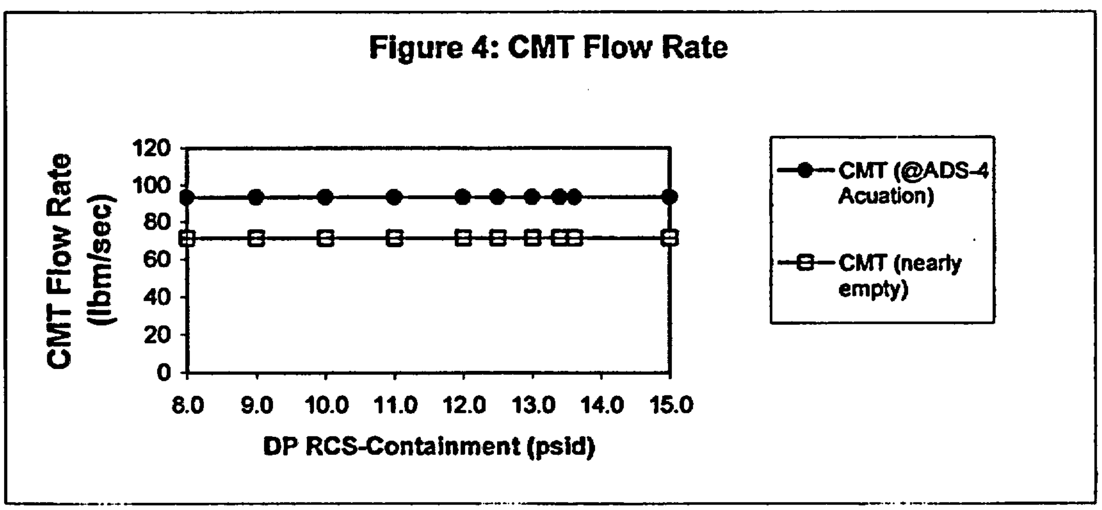


Figure 5 provides the calculated IRWST flow rate results for AP1000. The IRWST flow is calculated from steady state balance of IRWST gravity head, DVI line resistance from IRWST to reactor vessel, and Δp between downcomer and containment. The results are based on flow from 1 IRWST flow path (DE DVI). See Appendix 2 of this response for more detailed discussion of the CMT and IRWST flow equations.

Figure 5: IRWST Flow Rate vs. DP

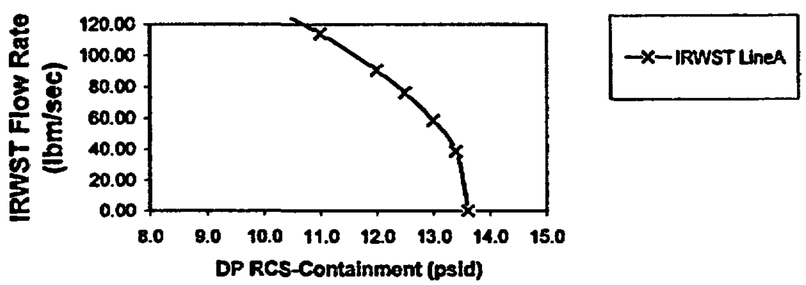


Figure 6 provides the composite results of applying the Simple Model to AP1000.

Figure 6: Flow Rate vs. DP

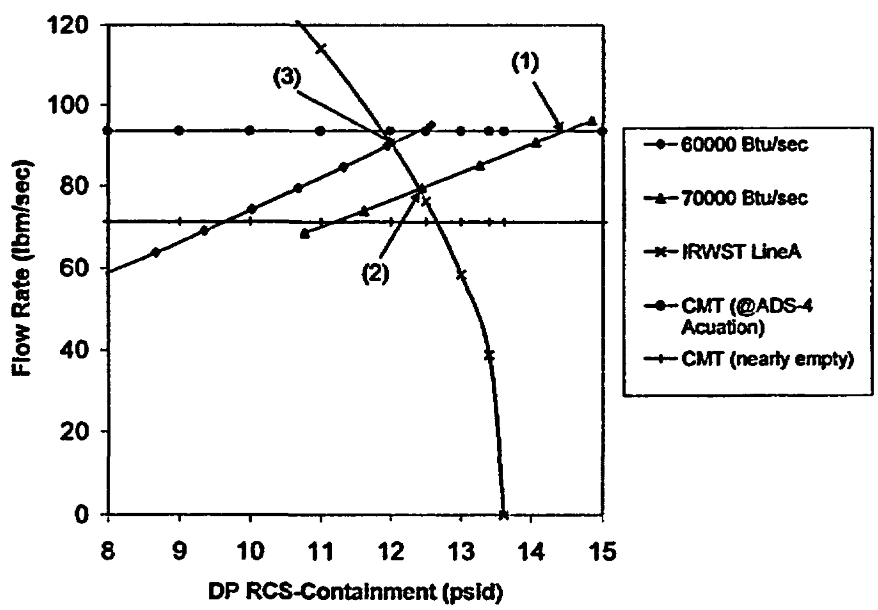


Figure 6 notes:

(1) Point of operation with CMT injection at higher core power
(2) Point of operation with IRWST injection at higher core power
(3) Point of operation with IRWST injection at lower core power

Following ADS-4 actuation, AP1000 would initially achieve stable operation at Point (1) on the higher power, core flow demand curve. At Point (1) core decay removal is met by CMT injection alone. As CMT injection decreases (with CMT liquid level), the point of operation moves from Point (1) toward Point (2). As the system moves in this direction, downcomer level, core collapsed level, and pressure decrease. When the operating point reaches the IRWST cut-in pressure at Point (2), IRWST injection initiates to supply downcomer level. Points of operation along the IRWST flow curve represent core decay removal met by IRWST injection as core decay power decreases from Point (2) to Point (3). As the system moves from Point 2 to Point 3 and beyond, the downcomer level and core collapsed level increase as shown in Table 2. The FLECHT-SEASET tests indicate that these conditions are sufficient to maintain adequate core cooling.

Table 2: Collapsed Level vs. Operating Point			
%CLL @ Intersection Point of Demand Curve w/CMT or IRWST Injection Supply Curve	Point of Intersection on Supply-Demand Curve		
	Point 1	Point 2	Point 3
	~45%	~43%	~46%

Table 3 provides the sensitivity of core inventory to variation in Co for Point 3 of the model. Increasing global slip parameter, Co, enhances phase separation. Therefore, less liquid is removed from the core region and %CLL increases. Conversely, decreasing Co reduces phase separation and therefore more liquid is removed from the core region. Therefore, as shown in the Table 3, the %CLL decreases with Co, however, the variation is within the range of %CLL for the full-scale rod bundle tests (i.e., 36.2% - 62.5%) which support adequate core cooling for AP1000.

Table 3: Sensitivity of Core Inventory to Variation in C			
%CLL @ Intersection Point of 60,000 Btu/sec Demand Curve w/IRWST Injection Supply Curve	Global Slip Parameter Co		
	Co=1.3	Co=1.4	Co=1.5
	~42%	~46%	~50%

Simple Model Comparison with APEX-AP1000 Test Data

Applying the Simple Model to APEX-AP1000 test DBA-02 shows (in Table 4) that the collapsed liquid level (%CLL) conservatively under-predicts measured %CLL (core plus upper plenum region) in the APEX-AP1000 test due to homogeneous treatment of core exit region. The APEX-AP1000 data shows that the effect of ADS4 is to draw liquid flow through the core that is more than sufficient to remove decay heat and results in a two-phase mixture above the core.

Table 4: Simple Model Comparison with APEX-AP1000 Test Data				
APEX-AP1000 Test Number	Measured %CLL	Predicted %CLL	Measured Massflow (lbm/sec)	Predicted Massflow (lbm/sec)
DBA-02 @ 400 sec.	~78%	~45%	~1.25	~1.36

For DBA-02 (DE DVI), 400 seconds represent a time after ADS-4 actuation with CMT injection only.

Sensitivity to Homogeneous Flow Assumption

A sensitivity analysis of the core exit region pressure drop for the simple model has been performed to evaluate the effect of slip between the gas and liquid phases. This sensitivity analysis is described in Appendix 3 and shows that the homogeneous assumption results in a conservatively high pressure drop relative to a model with slip ratio greater than one. The pressure drop analysis also shows that the acceleration pressure drop term dominates for flow quality above 0.1. This means that ADS4 exit flow area is the predominant factor in determining the ADS4 pressure drop during the ADS4-IRWST transition phase, as opposed to the irreversible form and friction losses that can have greater uncertainty for two-phase flow.

Conclusions from Simple Model

A Simple Model was developed that assumes homogeneous treatment of liquid entrainment in core exit region and provides conservative estimates of core inventory and collapsed liquid level. The model shows that AP1000 safety injection can meet demands of core cooling during ADS-IRWST injection phase of the limiting SBLOCA transient (DEDVI). The results of this model demonstrate that the only solutions that satisfy the conservation equations require significant liquid flow into the upper plenum and therefore adequate core cooling even with collapsed core levels well below 50%. This provides confidence that AP1000 core remains cooled during SBLOCA and LTC as predicted by the detailed analysis codes.

References:

1. Cunningham, J. P., Yeh, H. C., Experiments and Void Correlation for PWR Small-Break LOCA Conditions, Trans. Am. Nucl. Soc. 17 (1973) 369.

APPENDIX 1: TABLES OF INPUTS AND OUTPUTS FOR THE SIMPLE MODEL

The tables in this appendix provide the input to the Simple Model based on AP1000 parameters (Table A-1) and representative values of the core power (Qcore), downcomer level (Zdc), core inlet temperature (Tcin) and RCS pressure (Pdc) from the NOTRUMP analysis of the SBLOCA DEDVI break (Tables A-2 and A-3). The core flow rate outputs are used to generate the curves in Figure 3. Each row in Tables A-2 and A-3 corresponds to a point on the curves shown in Figure 3. The input and output data from Tables A-2 and A-3 is also used to provide a comparison between the FLECHT-SEASET tests used to benchmark the Simple Model and the Simple Model results.

a,b,c

a,b,c

APPENDIX 2: DEVELOPMENT OF EQUATIONS USED IN THE SIMPLE MODEL ANALYSIS

INTRODUCTION

The Simple Model consists of three submodels:

1. Core region (including the downcomer)
2. Core exit region (including the upper plenum, hot legs, and ADS-4 paths)
3. Safety injection from CMT and IRWST

Development of the equations for these submodels is described in the following sections.

CORE REGION

Conservation of Mass Equation in 2ϕ Region

a,c

Conservation of Mass Equation in 1ϕ Region

a,c

Conservation of Energy Equation for 1ϕ Region

a,c

Conservation of Energy Equation for 2ϕ Region

a,c

Void Fraction Model

a,c

a,c

a,c

a,c

a,c

a,c

CORE EXIT REGION

Conservation of Mass

a,c

a,c

Conservation of Energy

a,c

a,c

Conservation of Momentum

a,c

a,c

a,c

a,c

a,c

a,c

a,c

a,c

a,c

a,c

SAFETY INJECTION FROM CMT AND IRWST

Core Make-up Tank (CMT) SI Flow Rate

a,c

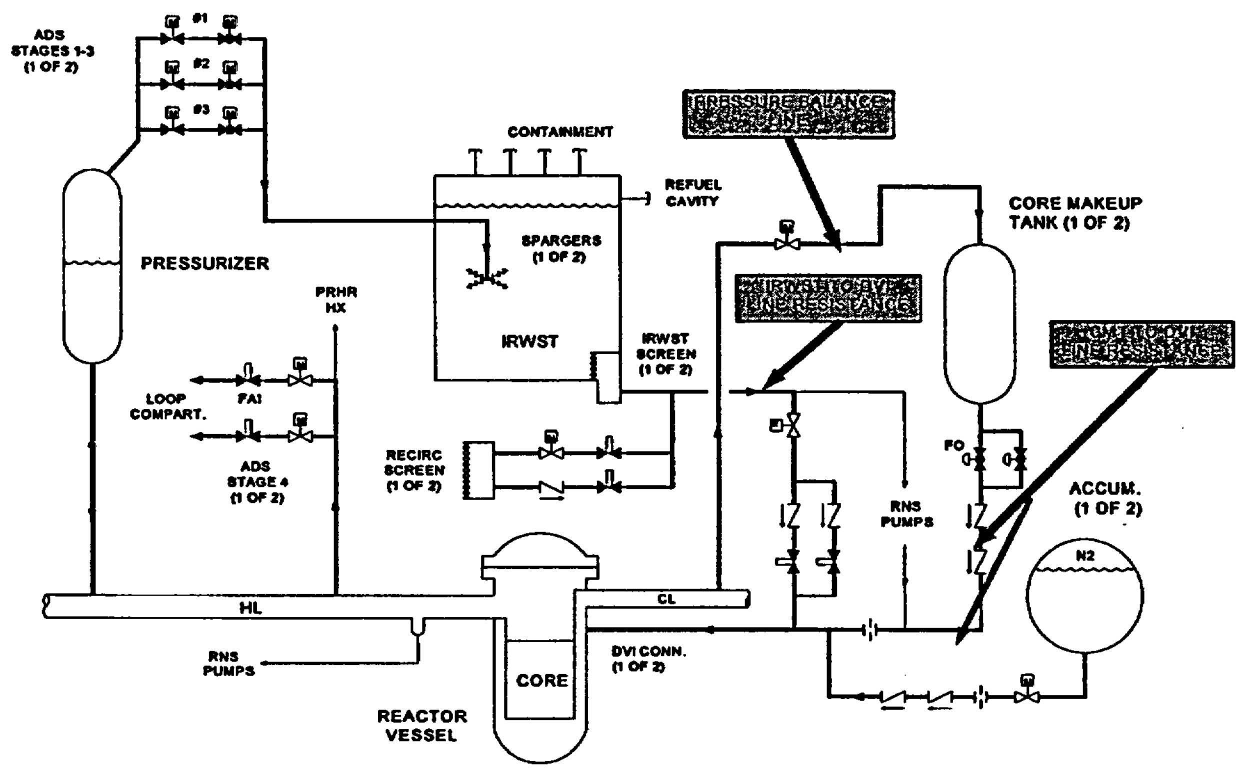


Figure A2-1 AP1000 Passive Safety Injection

a,c

a,c

IRWST SI Flow Rate

a,c

a,c

a,c

APPENDIX 3: SENSITIVITY OF CORE EXIT REGION PRESSURE DROP TO SLIP RATIO

The simple model shows that the pressure drop through the core exit region is important because it affects the pressure in the core region and core exit quality.

a,c

a,c

Results for Slip Ratio = 1 (That is, Homogeneous)

Pressure drop results for the S = 1 case are shown in Figure A3-1. As shown in the figure, acceleration pressure drop dominates except at extremely low quality. Gravity pressure drop is negligible except at low quality.

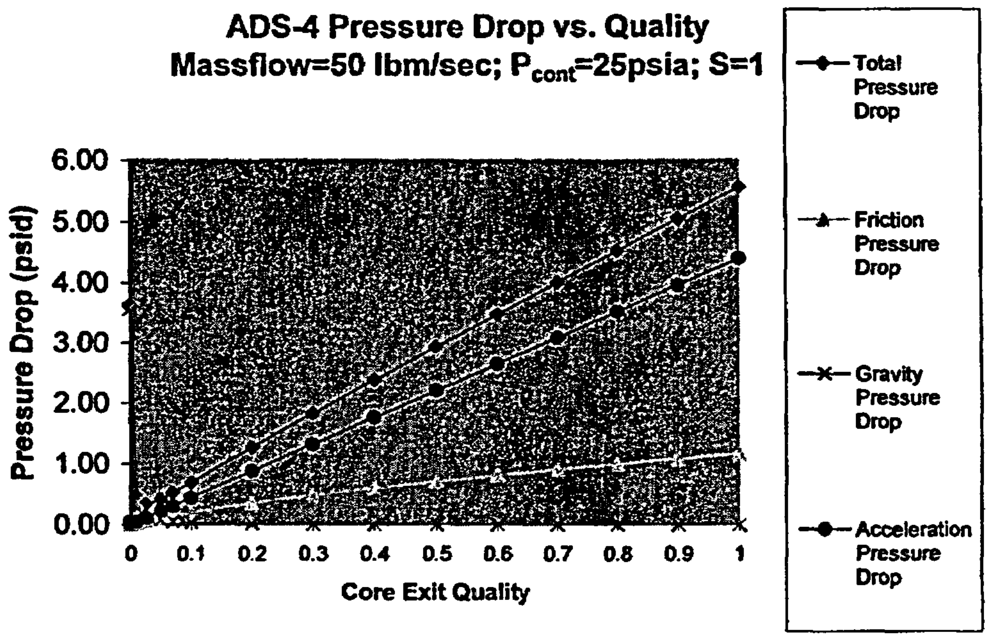


Figure A3-1

Results for Slip Ratio = 10 (That is, Nonhomogeneous)

Pressure drop results for the S = 10 case are shown in Figure A3-2. Similar to the homogeneous case, acceleration pressure drop dominates at high quality. However, gravity pressure drop becomes important at moderate quality and dominates below about 10-percent quality.

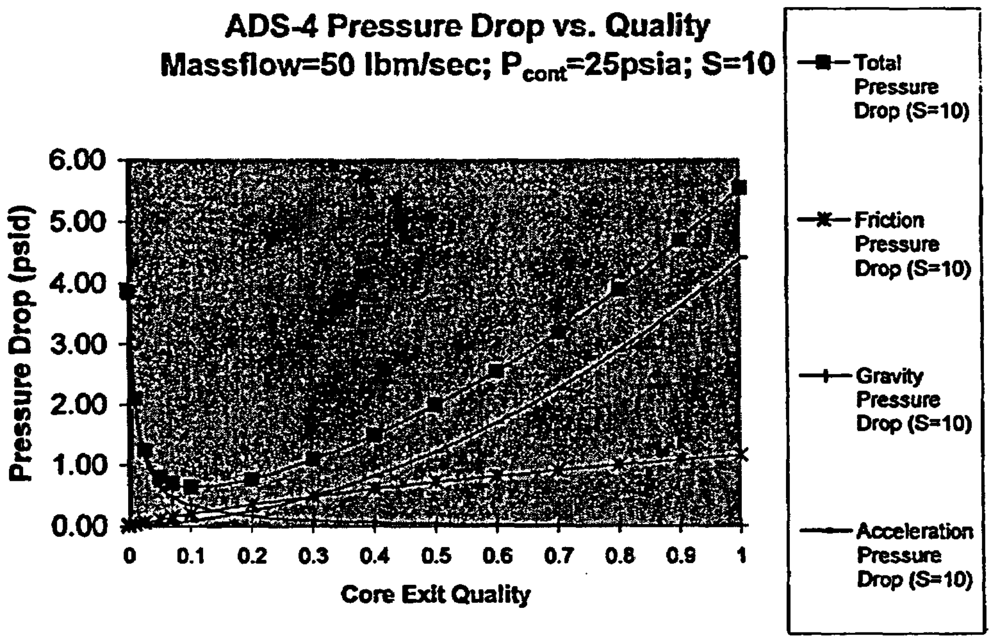


Figure A3-2

Overall Results/Conclusions

Comparing the two cases (Figure A3-3) shows that homogeneous treatment provides greater total pressure drop than nonhomogeneous, except at a quality less than 0.10. For most of the range of quality, acceleration pressure drop dominates; this is the range of interest. Gravity pressure drop dominates at low quality. Thus, the homogeneous treatment of ADS4 flow provides a conservative estimate of ADS4 pressure drop relative to a model with a slip ratio greater than one.

The pressure drop analysis also shows that the acceleration pressure drop term dominates for flow quality greater than 0.1. This means that the ADS4 exit flow area is the predominant factor in determining the ADS4 pressure drop during the ADS4-IRWST transition phase, as opposed to the irreversible form and friction losses, which can have greater uncertainty for two-phase flow.

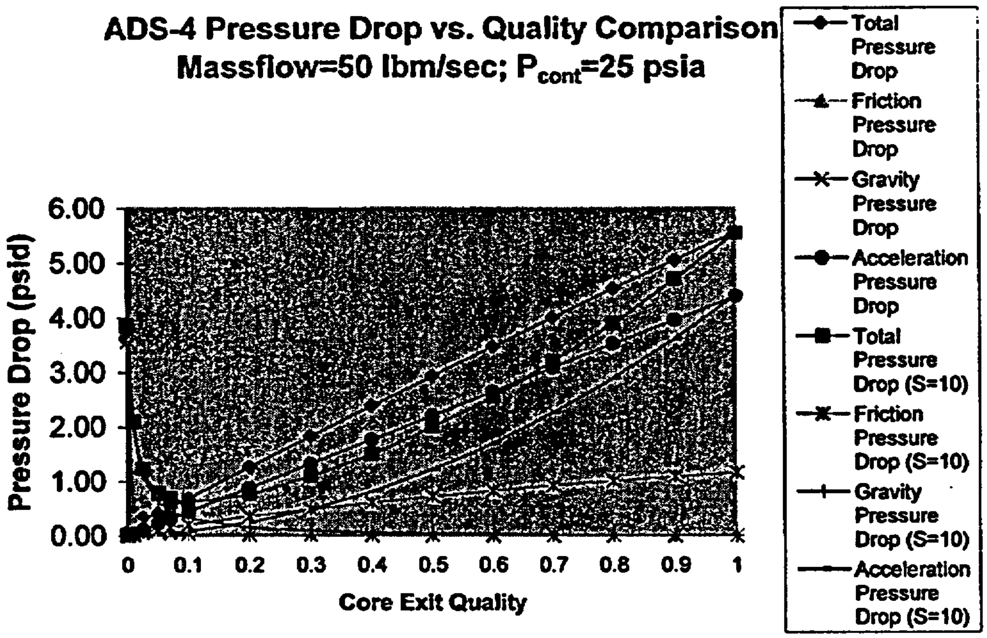


Figure A3-3

Design Control Document (DCD) Revision:

None

PRA Revision:

None