DCP/NRC1712
Docket No. 52-006

July 30, 2004

Attachment 3

AP1000 Design Certification Review
Draft Safety Evaluation Report Open Item Non-Proprietary Responses

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: 21.5-2 Item 19 (Response Revision 5)

Original RAI Number(s): None

Summary of Issue:

As mentioned in the ACRS Meeting in Monroeville in July, 2003, the APEX test facility contains an oversized downcomer. The oversized downcomer will produce high liquid inventories for extended periods of time which will maximize the liquid and two-phase levels in the core and upper plenum. This suggests the APEX facility cannot be used to simulate the minimum liquid and two-phase levels in the inner vessel that could occur following small breaks in the AP1000 plant. With a larger downcomer, more liquid mass will be retained in the vessel for small breaks. The statements in the Westinghouse August 13, 2003 letter (DCP/NRC1611) that the APEX-1000 facility is well scaled to AP1000 and the two-phase level remains in the upper plenum while the core remains covered for all phases of the simulated accident may not be appropriate and is misleading.

Please discuss the impact of the larger downcomer on the relevant APEX tests and explain why the facility test results can be used to demonstrate that significant amounts of inventory in this facility apply to the anticipated AP1000 response. Please also explain the statement that the APEX tests show the insensitivity of the AP1000 system behavior to entrainment is unaffected in lieu of the excessive amounts of liquid in the inner vessel during the tests referred to in the August 13, 2003 letter.

Westinghouse Response (Revision 5)

The incorrect proprietary markings in the previous response are corrected in the response below. This is the only change in Revision 5 of this response.

NRC Follow-on comment (12/17/03 meeting handout):

Westinghouse response to 'Item 19' concluded that the APEX test facility is adequately scaled for downcomer inventory depletion relative to AP1000 during a potential situation in an SBLOCA where only the liquid inventory in the downcomer is available for core cooling. This is inconsistent with OSU scaling report (OSU-APEX-03001 on page 6-7), which states that the APEX facility downcomer is oversized relative to AP1000. Westinghouse needs to explain the inconsistency.

NRC Follow-on comment (1/8/04 conference call):

In its December 22, 2003, submittal, Westinghouse provided Revision 2 of its response. Westinghouse concluded that the APEX facility is adequately scaled for downcomer inventory depletion relative to AP1000 during a potential situation in a SBLOCA where only the liquid inventory in the downcomer is available for cooling. This conclusion was based on its scaling analysis showing that the ratio of the downcomer drain time constant between the APEX test facility and the AP1000 to be approximated ½. However, this time constant ratio was based on a value of the core mass flow ratio between the APEX and AP1000, which the staff finds to be based on the results of the "Simple Model" as opposed to using the mass flow ratio for which the APEX-AP1000 facility was scaled. Using the core flow scale ratio of 1/96, the staff calculated the downcomer depletion time constant ratio to be close to a value of 1, which indicates that the APEX downcomer is oversized since the APEX facility was designed to operate with a ½ time scale. This conclusion is consistent with the report OSU-APEX-03001,"Scaling Assessment for the Design of the OSU APEX-1000 Test Facility," May 12, 2003, which indicated that the APEX downcomer is oversized.

1. Please provide an evaluation of the effect of oversized downcomer on the test DBA-2. That is, assuming the DBA-02 test was performed with the APEX facility having a properly sized downcomer, what would be the expected core collapsed liquid level compared to Figure 21.5-2.19 in the August 13, 2003, submittal.

2. Westinghouse needs to address the "APEX-AP1000 Scaling Report Questions" provided by the staff in the December 17, 2003 meeting.

NRC Follow-on comment (1/15/04) conference call):

Westinghouse should explain further why the oversized downcomer in the APEX-1000 facility is not a significant factor in use of the APEX-1000 data for code validation.

Westinghouse Response (Revision 4):

In theory, if the APEX-1000 were ideally scaled for every aspect of the plant geometry and transient phenomena, the APEX-1000 test results could be applied directly to the AP1000. In practice it is not possible to ideally scale every parameter and phenomena in a single test facility, and APEX-1000 test data cannot be used to directly infer AP1000 performance. Instead, the APEX-1000 test data, together with data from other test facilities with different scaling, is used to validate the computer models used in the AP1000 DCD safety analyses.

The oversized APEX-1000 downcomer volume does not significantly detract from the use of APEX-1000 data as part of the validation of the NOTRUMP safety analysis code. Application of test data to validate the analysis codes used for the AP1000 DCD safety analysis is discussed in WCAP-15644P Rev 1, AP1000 Code Applicability Report, September 2003. NOTRUMP compares well to APEX-1000 test data during the transition from CMT to IRWST injection when the downcomer volume is the source of cooling water for the core region. This transition from CMT to IRWST injection is the most limiting period of the small break LOCA transient. Since the thermal hydraulic phenomena in the AP1000 plant are the same as in the APEX-1000 the NOTRUMP code is able to conservatively model the AP1000 plant during this limiting phase of the small break LOCA transient.

Westinghouse Response (Revision 3):

1. The following discussion from Revision 2 of this response is revised as shown below to address item 1 of the 1/8/04 NRC comments:

The scaling report for the OSU APEX-1000 test facility (see OSU-APEX-03001) correctly notes in various portions of Section 6.3 that the actual downcomer volume scale (~1/100) in APEX-1000 is larger than the ideal test facility scaling ratio of 1/192. The scaling report indicates that although the downcomer area is distorted in APEX, the height of the downcomer is appropriately scaled to the ¼ ideal test facility height scaling ratio. Therefore, the gravity head associated with gravity drainage from the downcomer should be well scaled in APEX-1000.

The scaling evaluation presented in Section 6.3 addresses the early portion of the ADS-4 phase when the ADS-4 flow is in a choked condition and mass flow is scaled by the ideal test scaling ration of 1/96. However, it is possible that the ADS-4 flow becomes unchoked before IRWST injection occurs. Therefore, an assessment was made regarding the most important parameter(s) to scale regarding the downcomer under these conditions. This assessment concluded that preserving the scaling of the downcomer gravity head and associated downcomer liquid inventory depletion rate were more important in preserving the integral effect behavior of the test facility than preserving the ideal volume scale of the downcomer. As noted above, the downcomer gravity head is appropriately scaled in APEX-1000 due to the ¼ height scale. The discussion below addresses the scaling of the downcomer relative to liquid inventory depletion.

The appropriate parameters for assessing the scaling of the downcomer liquid inventory are obtained from the governing conservation equations. The situation of particular interest is the liquid inventory depletion in the downcomer during the ADS-IRWST transition phase of a limiting SBLOCA such as a DEDVI event where downcomer liquid inventory is most seriously challenged. Downcomer inventory depletion rate is the key scaling parameter, rather than downcomer volume, because the depletion rate determines the rate at which the core approaches a boiloff condition during the ADS-IRWST transition phase.

Derivation of Scaling Parameters

To obtain the appropriate scaling parameters, apply the conservation of mass equation to the downcomer region such that downcomer liquid inventory is depleted to satisfy core cooling and is not replenished via safety injection. The conservation of liquid mass in the downcomer region for this situation is as follows:

$$\frac{dM_{\substack{downcomer\\liquid}}}{dt} = -m_{out} = -m_{core}$$

The liquid inventory can be represented via the liquid volume and density such that:

$$\rho_f \frac{dV_{\substack{downcomer\\liquid}}}{dt} = -m_{core}$$

Variables in the above equation can be non-dimensionalized as follows:

$$m^{+}_{core} = \frac{m_{core}}{m_{core,ref}}$$

$$\rho^{+}_{f} = \frac{\rho_f}{\rho_{f,ref}}$$

$$V^{+}_{dc\ liquid} = \frac{V_{dc\ liquid}}{V_{dc\ liquid,ref}}$$

So,

$$dV^{+}_{dc\ liquid} = \frac{dV_{dc\ liquid}}{\Delta V_{dc,ref}}$$

Where the reference values are:

$m_{core,ref}$ = core massflow, where the core mass flow reflects that required to match core power.

$\rho_{f,ref}$ = liquid density

$\Delta V_{dc,ref}$ = downcomer volume

Substitution of the dimensionless variables results in the following:

$$(\rho_{f\ ref})\rho^{+}_{f}(\Delta V_{dc,ref})\frac{dV^{+}_{dc\ liquid}}{dt} = -(m_{core,ref})m^{+}_{core}$$

Dividing by the reference core mass-flow ($m_{core,ref}$) and collecting reference parameters, the following downcomer liquid inventory depletion rate scaling equation is obtained:

$$\left[\frac{\rho_f \Delta V_{dc}}{m_{core}}\right]_{ref} \rho^{+}_{f} \frac{dV^{+}_{downcomer\ liquid}}{dt} = -m^{+}_{core}$$

The above equation can be re-expressed in terms of a time constant (τ) that represents the time to drain or deplete the downcomer liquid inventory to satisfy core cooling in the absence of safety injection to replenish the downcomer:

$$[\tau]\rho_f^+ \frac{dV^+_{dc\,liquid}}{dt} = -m^+_{core}$$

Where the time constant represents the liquid inventory storage relative to the depletion rate:

$$\tau = \left[\frac{\rho_f \Delta V_{dc}}{m_{core}}\right]_{ref}$$

The appropriate scaling ratio for downcomer liquid inventory is therefore obtained by comparing the above time constant for the APEX-1000 test facility to AP1000:

$$\tau_{Ratio} = \frac{\left[\frac{\rho_f \Delta V_{dc}}{m_{core}}\right]_{ref,APEX-1000}}{\left[\frac{\rho_f \Delta V_{dc}}{m_{core}}\right]_{ref,AP1000}}$$

The ideal time scaling ratio for APEX-1000 relative to AP1000 is ½. Ratios less than ½ indicate that APEX liquid inventory is depleted faster than AP1000 on a scaled basis, and vice-versa.

Simple Model Inputs and Results

To obtain reference core mass flow values for the downcomer inventory scaling ratio derived above for APEX-1000 and AP1000, the Simple Model (see Open Item Response 21.5-3) was used with scaled gravity head and scaled core power for the test facility (see Table 1). Table 1 shows the primary differences in inputs to the Simple Model were core inlet temperature (~50 degrees additional subcooling for APEX) and backpressure where 14.7 psia is used for APEX-1000 (as only atmospheric backpressure has been tested at APEX) and 25 psia for AP1000.

Table 1 indicates a larger scaled mass-flow rate in APEX-1000 relative to AP1000. Table 1 also shows that the calculated core collapsed liquid level is somewhat higher in APEX-1000 relative to AP1000. This is acceptable as it is consistent with the larger scaled flow through the core and ADS-4 vent path and the integral effect behavior of APEX-1000 relative to AP1000 is preserved as shown below.

Numerical Evaluation of Scaling Parameters

The actual downcomer volume scaling ratio of APEX-1000 relative to AP1000 is about 1/112 as shown in Table 2 below. The mass flow scaling ratio associated with the actual APEX-1000 test conditions (pressure, density, etc.) relative to the AP1000 for a DEDVI event is about 1/58.

Applying these volume and massflow ratios (as liquid density ratio is about unity), it can be seen that the downcomer drain time ratio between APEX-1000 and AP1000 is about ½.

$$\tau_{Ratio} = \frac{\left[\frac{\rho_f \Delta V_{dc}}{m_{core}}\right]_{APEX}}{\left[\frac{\rho_f \Delta V_{dc}}{m_{core}}\right]_{AP1000}} = \frac{\left[\frac{\Delta V_{dc,APEX}}{\Delta V_{dc,AP1000}}\right]}{\left[\frac{m_{core,APEX}}{m_{core,AP1000}}\right]} = \frac{1/112}{1/58} = \frac{1}{1.93} \approx \frac{1}{2}$$

Impact of Downcomer Size on Scaling and Behavior of APEX-1000 Tests

The impact of downcomer size in APEX scaling is significantly reduced for simulating a potential safety injection gap period of an AP1000 DEDVI event as a lower containment pressure is actually simulated in the APEX-1000 test facility relative to that expected in the AP1000. Due to difference in pressure conditions, the mass flow ratio scale associated with the actual APEX-1000 test conditions is less than the mass flow scale ratio (1/96) which would be obtained if pressure was perfectly preserved. It is expected that if the downcomer were sized according to the volume ratio of 1/96, APEX-1000 test DBA-02 would exhibit a faster than ideal scaled downcomer drain time (~1/1 vs. ½). Based upon system behavior as exhibited by the "Simple Model", this would lead to reaching IRWST injection cut-in pressure sooner in the DEDVI transient in this hypothetical test configuration because system pressure reduces as downcomer/inner vessel level reduces.

In summary, the downcomer volume scale in APEX is distorted (oversized) for integral effect simulations of safety injection gap periods in which the containment pressure is to be preserved. However, due to the lower containment pressure actually simulated in APEX-1000, the test facility is adequately scaled to simulate downcomer inventory depletion in the context of the integral system effect behavior of AP1000 during a potential safety injection gap period in a DEDVI event.

Table 1: Inputs/Outputs to Simple Model

Variable (Units)	Qcore (Btu/sec)	Zdc (ft)	Tcin (F)	Pdc (psia)	Xcex (-)	Zsat (ft)	2Φ Rgn. Void (-)	CLL (ft)	CLL% (-)	Core Flow (lbm/sec)
APEX-1000	[									] a,b,c
AP1000	60000	6.5	180	37.2	0.595	1.83	0.617	6.49	46.3	93.5

Table 2: Reference Values

Reference Parameter	APEX-1000	AP1000
ΔV_{dc}	[ ] a,b,c	600.4 ft^3
ρ_f		58.5 lbm/ft^3
m_{core}		93.5 lbm/sec

2. Westinghouse response to the APEX-AP1000 Scaling Report Questions was provided by Westinghouse letter DCP/NRC 1667, January 9, 2004.

Design Control Document (DCD) Revision:

None

PRA Revision:

None

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: 21.5-2NP Item 29 Revision 2

Original RAI Number(s): None

Summary of Issue:

The Cunningham-Yeh correlation as described on OI 21.5-3 Page 3 has an error in the critical bubble radius term R_{bcr}.

Please confirm that it is only a typographic error and the correct Cunningham-Yeh correlation is used in the study.

Westinghouse Response (Revision 2):

The incorrect proprietary markings in the previous Revision 1 response are corrected in the response below. The only change in Revision 2 of this response is found on Page 1.

Westinghouse Response:

The Cunningham-Yeh correlation as described on OI 2.5-3 Page 3 did contain a typographical error as the item 29 asserts. The corrected equation is shown below:

$$\alpha(z) = 0.925\left(\frac{\rho_g}{\rho_l}\right)^{0.239}\left(\frac{j_g(z)}{V_{bcr}}\right)^{b}\left(\frac{j_g(z)}{j_g(z)+j_l(z)}\right)^{0.6}$$

Where:

$$V_{bcr} = \frac{2}{3}\left(gR_{bcr}\right)^{0.5}$$

$$R_{bcr} = \left(\frac{1.53}{2/3}\right)^{2}\left(\frac{\sigma}{g\rho_l}\right)^{0.5}$$

and

$$b = 0.67, \quad \text{if} \quad \frac{j_g}{V_{bcr}} \le 1.0$$

$$b = 0.47, \quad \text{if} \quad \frac{j_g}{V_{bcr}} > 1.0$$

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

NRC Comment from 12/17/03 Status meeting:

Revise WCAP-15644, Rev. 1, in the following areas (per Items 16, 17, and 29):

Correct Figure F-12 (i.e., Figure 21.5-1.12) for ADS-4 Liquid Discharge Comparison.

Correct text and Figure F-14 (i.e., Figure 21.5-1.14) to show Downcomer Pressure Comparison.

Correct the equation for critical bubble radius R-bcr of the Cunningham-Yeh correlation on Pp G-4.

Westinghouse Response (Revision 1):

WCAP-15644 Revision 1 will be revised as shown below and issued as WCAP-15644 Revision-2.

WCAP-15644 Revision:

The following pages include change bars to indicate the changes being incorporated in WCAP-15644 Revision. 2.

Figure F-12 and Figure F-13 present the ADS-4 Integrated liquid and vapor discharges for the two cases respectively. Again, the differences between these two cases are considered to be negligible.

a,c

Figure F-14 presents a comparison of the upper downcomer pressure between the base and sensitivity cases. As can be seen, the sensitivity case results in higher upper downcomer pressure and subsequently results in delayed IRWST injection (Figure F-15). This can also be observed in the intact DVI line flow, which comprises all intact injection flow components (i.e. Accumulator, CMT and IRWST) per Figure F-16. As expected, the initial ADS-4 liquid discharge is much higher (Figure F-17) until the inventory which resided in the upper plenum and hot leg regions was depleted (Figure F-18). The net effect is a decrease in the ADS-4 vapor discharge rate (Figure F-19) and subsequently higher RCS pressures.

Due to the elimination of the inventory stored in the upper plenum, the downcomer mass is also reduced (Figure F-20) and is caused by the displacement of the upper plenum mixture. Since the static head that existed in the upper plenum is eliminated when the model is made homogenous, the downcomer mixture is subsequently driven into the core as the static heads equilibrate. This results in the core region mass increasing initially due to the introduction of cold downcomer fluid to the core region (Figure F-21). The net effect of the sensitivity case is that the vessel inventory is substantially decreased over the base model simulation (Figure F-22); however, this inventory is sufficient for adequate core cooling because the ADS-4 continually draws liquid flow through the core (Figure F-17). Even though there is no liquid storage in the upper plenum for the homogenous case (Figure F-23), the coverage percentage (Figure F-24) is not impacted significantly.

The pressurizer mixture level response (Figure F-25) reflects the change in pressure response (Figure F-26) observed in the model as a result of the sensitivity study.

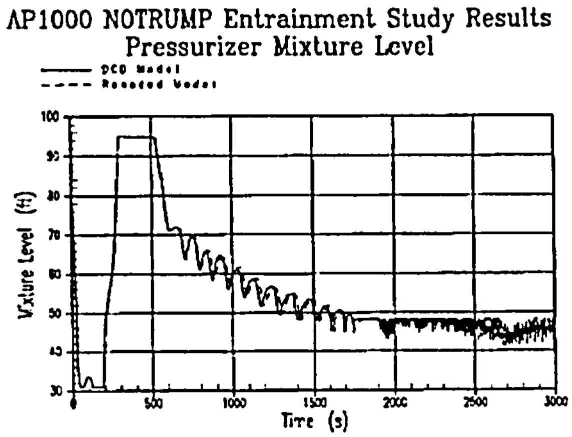


Figure F-11 Pressurizer Level Comparison

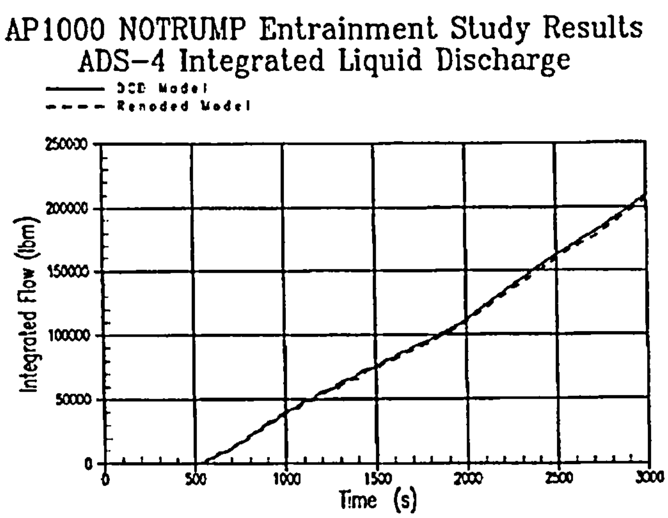


Figure F-12 ADS-4 Liquid Discharge Comparison

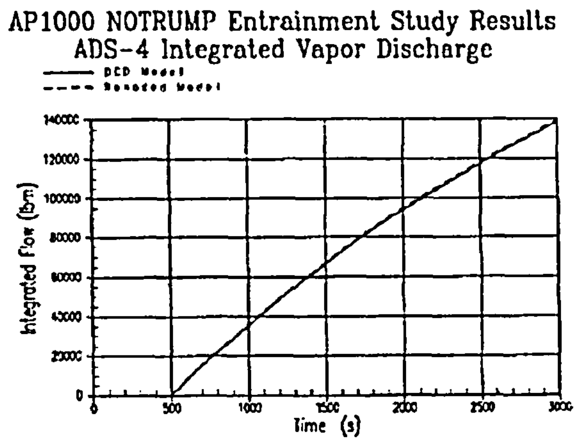


Figure F-13 ADS-4 Vapor Discharge Comparison

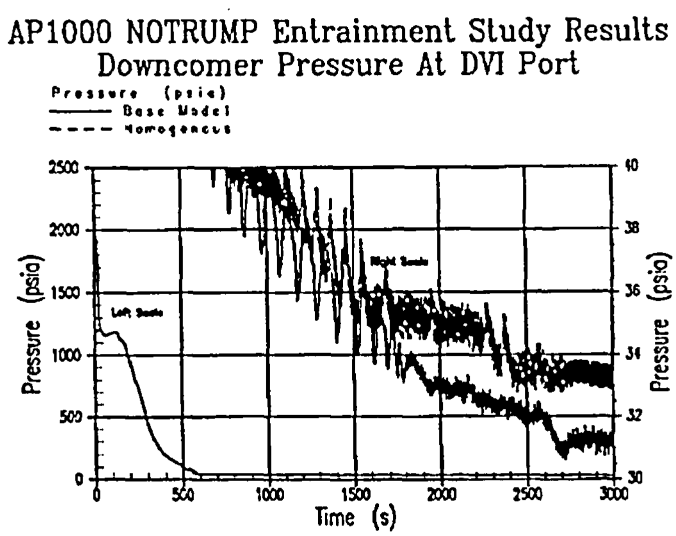


Figure F-14 Downcomer Pressure Comparison

where:

$$V_{bcr} = \frac{2}{3}(gR_{bcr})^{0.5}$$

$$R_{bcrr} = \left(\frac{1.53}{2/3}\right)^2 \left(\frac{\sigma}{g\rho_l}\right)^{0.5}$$

and

$$b = 0.67, \quad \text{if } \frac{j_g}{V_{bcr}} \le 1.0$$

$$b = 0.47, \quad \text{if } \frac{j_g}{V_{bcr}} > 1.0$$

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

$$Z_{CLL} = Z_{sub} + \int_{Z_{sub}}^{Z_{mix}} (1 - \alpha(z))\, dz$$

Where Z_{sub} and Z_{mix} were estimated from the test.

Finally the swell S was defined as follows:

$$S = \frac{Z_{mix} - Z_{sub}}{Z_{CLL} - Z_{sub}} = \frac{1}{1 - \overline{\alpha}}$$

The predicted swell S_c was then compared to the observed value S_m in Figure G-1.

Design Control Document (DCD) Revision:

None

PRA Revision:

None

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: 21.5-3NP (Response Revision 2)

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 2):

The incorrect proprietary markings in the previous Revision 1 response are corrected in the response below. The only change in Revision 2 of this response is found on Page 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.

Validation of Core Void Fraction Model Used in NOTRUMP Against Full-Scale Data

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:

$$\alpha(z) = 0.925\left(\frac{\rho_g}{\rho_l}\right)^{0.239}\left(\frac{j_g(z)}{V_{bcr}}\right)^{b}\left(\frac{j_g(z)}{j_g(z)+j_l(z)}\right)^{0.6}$$

where:

$$V_{bcr} = \frac{2}{3}(gR_{bcr})^{0.5}$$

$$R_{bcr} = \left(\frac{1.53}{2/3}\right)^{2}\left(\frac{g\sigma}{\rho_l}\right)^{0.25}$$

and

$$b = 0.67, \quad \text{if } \frac{j_g}{V_{bcr}} \le 1.0$$

$$b = 0.47, \quad \text{if } \frac{j_g}{V_{bcr}} > 1.0$$

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

a,b,c

a,b,c

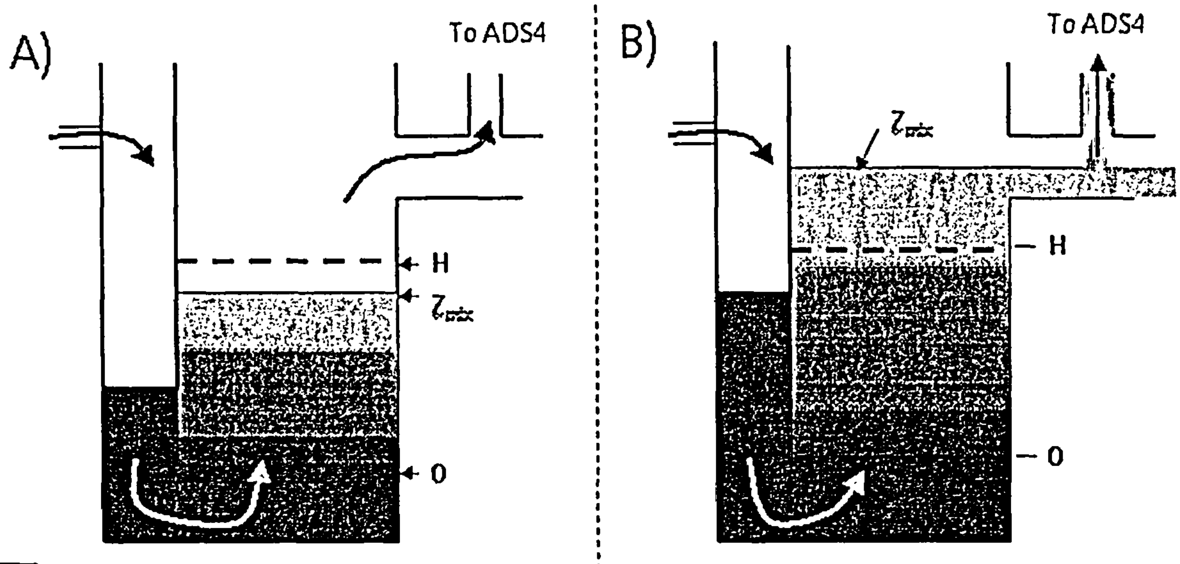
Figure 1: Calculated vs. Predicted Swell

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.

Comments to the NOTRUMP Base Model Analysis with Regard to Level Swell

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:

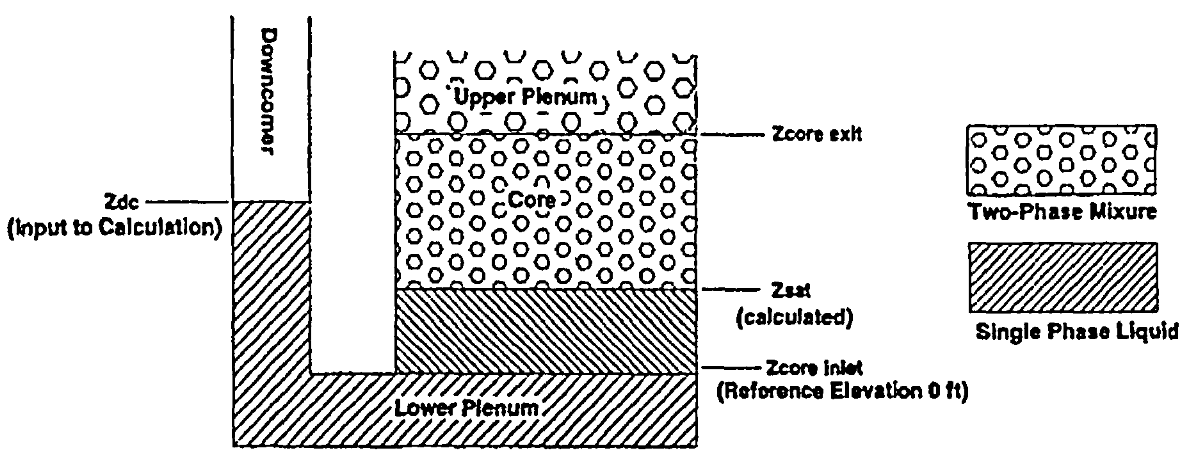
1. Core region (including the downcomer)
2. Core exit region (including the upper plenum, hot leg, ADS-4 paths and the ADS)
3. Safety injection from CMT and IRWST

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



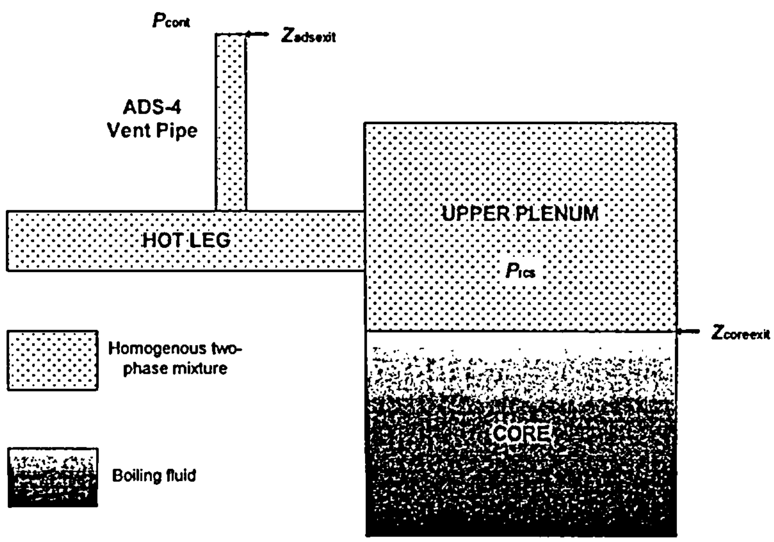
The conservation of mass equation for Steady State, 1-D, flow in a constant area channel is as follows:

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.

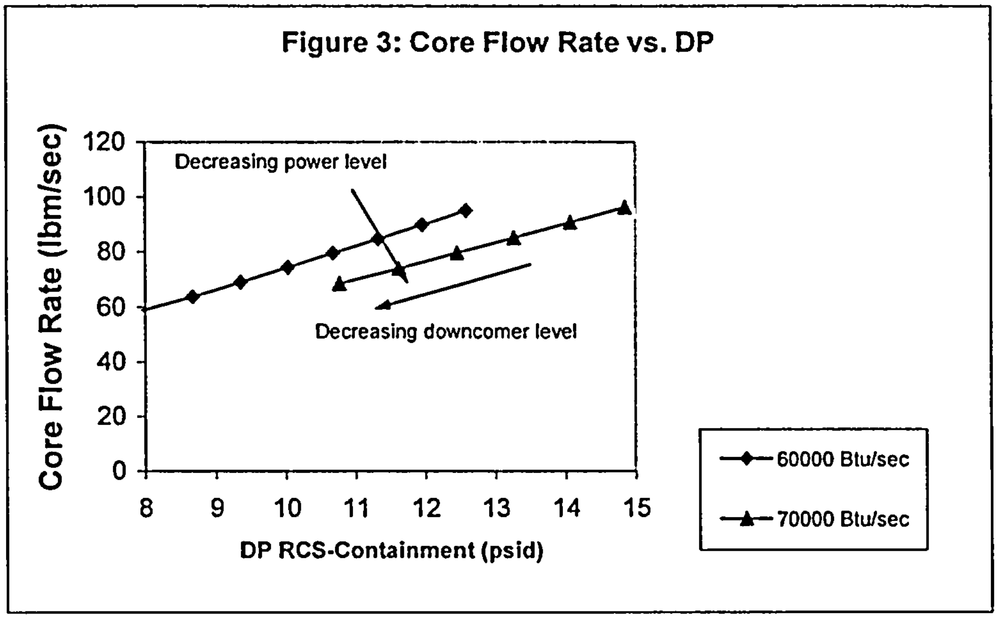


Figure 4 provides the calculated CMT flow rate results for AP1000. The CMT flow is calculated from steady state balance of CMT gravity head and DVI line resistance from CMT to reactor vessel. The results are based on flow from one CMT (DE DVI) at various liquid levels in CMT. Note that CMT flow is independent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

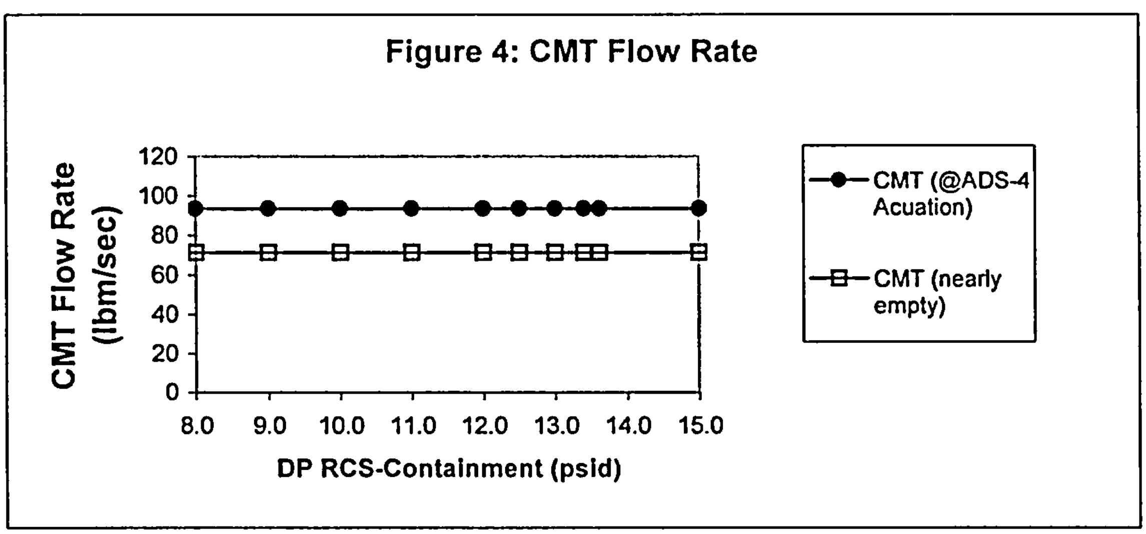


Figure 5 provides the calculated IRWST flow rate results for AP1000. The IRWST flow is calculated from steady state balance of IRWST gravity head, DVI line resistance from IRWST to reactor vessel, and Δp between downcomer and containment. The results are based on flow from 1 IRWST flow path (DE DVI).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

Figure 5: IRWST Flow Rate vs. DP

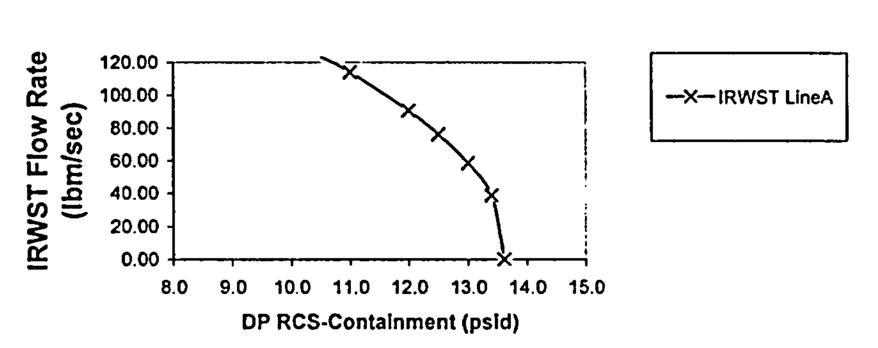


Figure 6 provides the composite results of applying the Simple Model to AP1000.

Figure 6: Flow Rate vs. DP

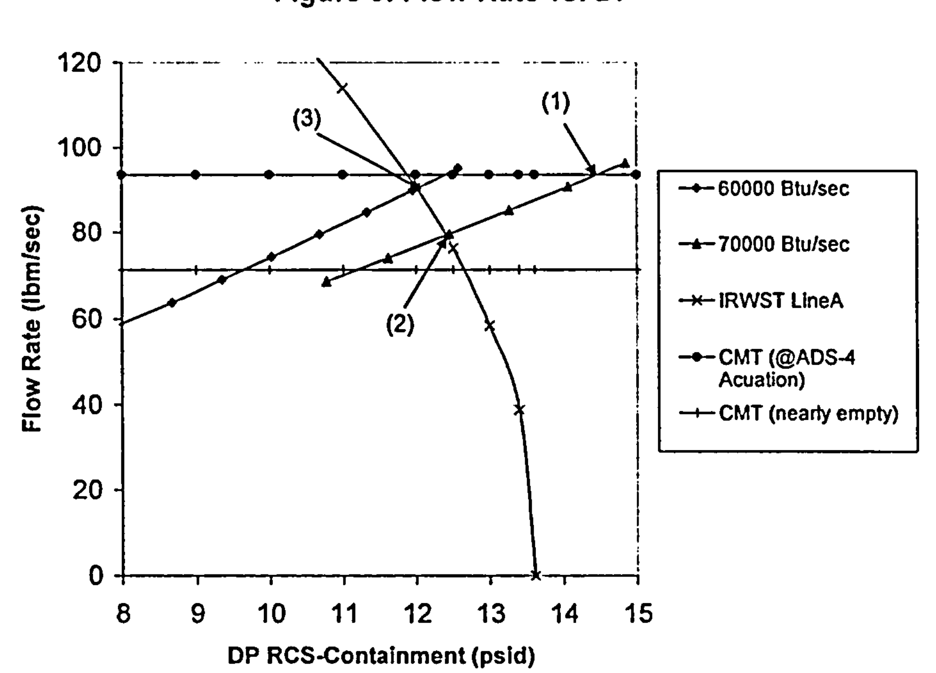


Figure 6 notes:

(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%

<u>Simple Model Comparison with APEX-AP1000 Test Data</u>

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

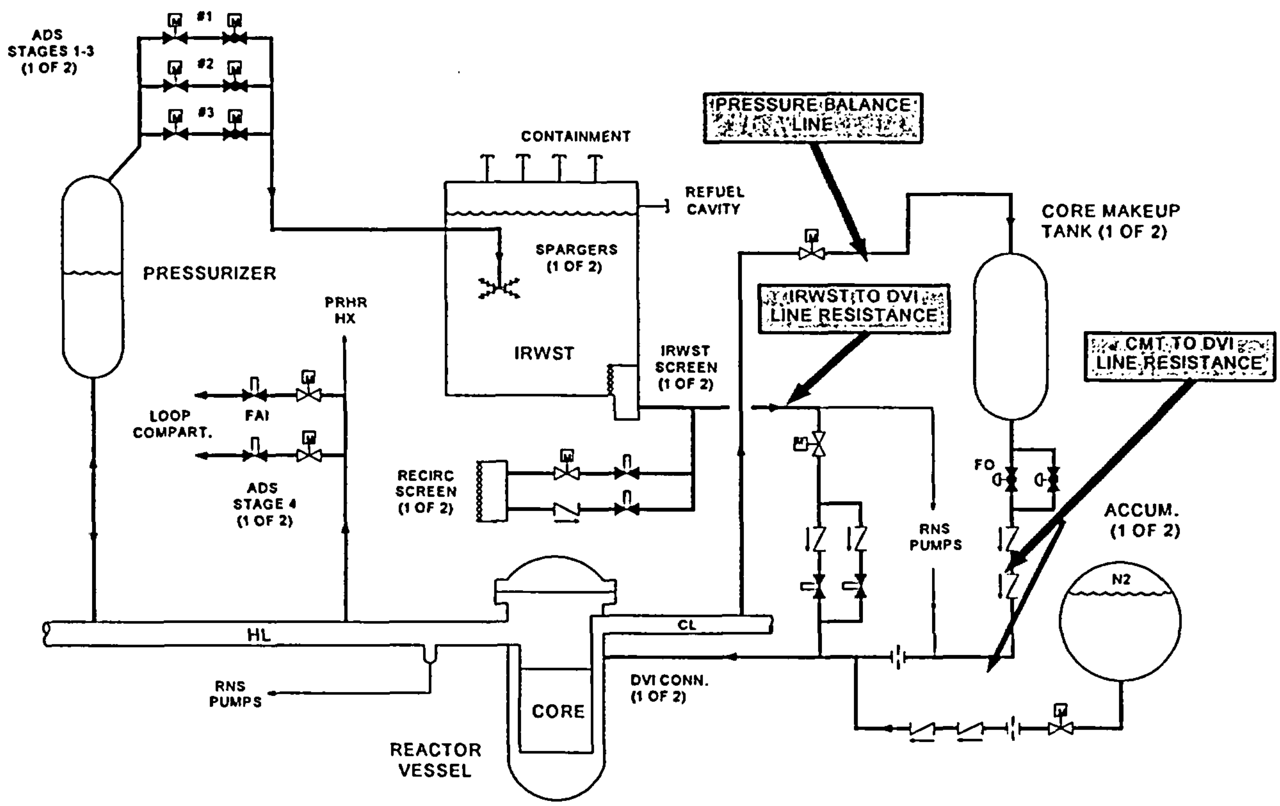


Figure A2-1 AP1000 Passive Safety Injection

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.

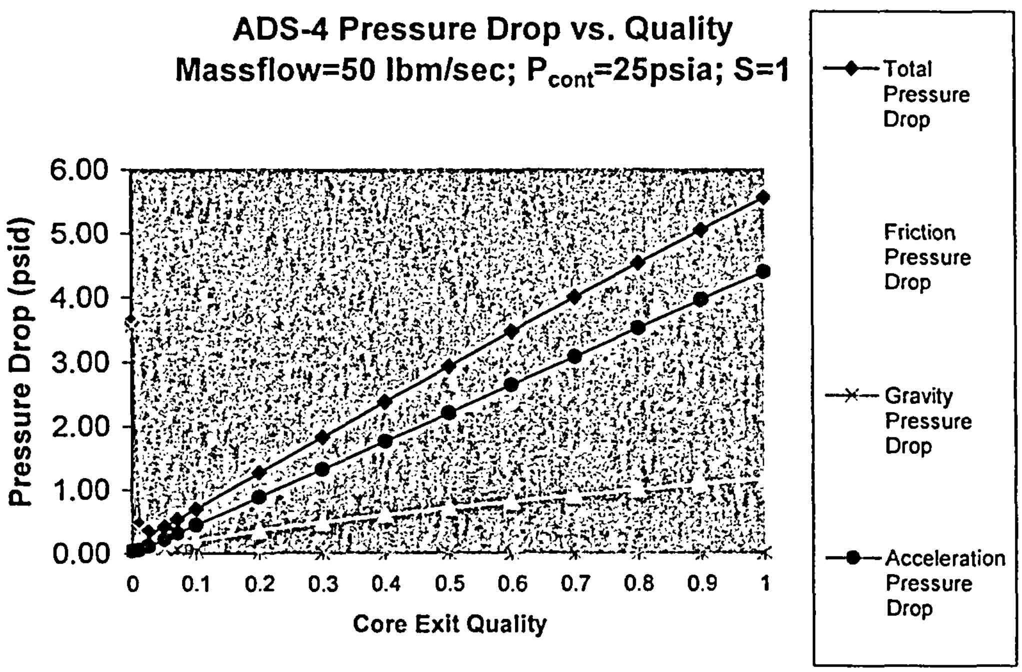


Figure A3-1

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.

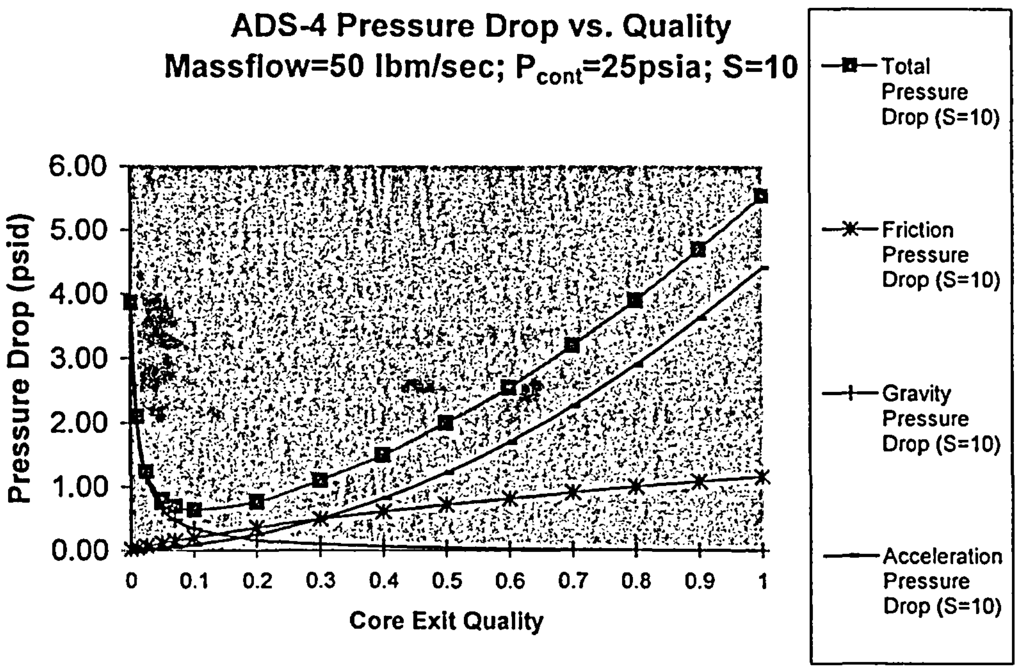


Figure A3-2

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.

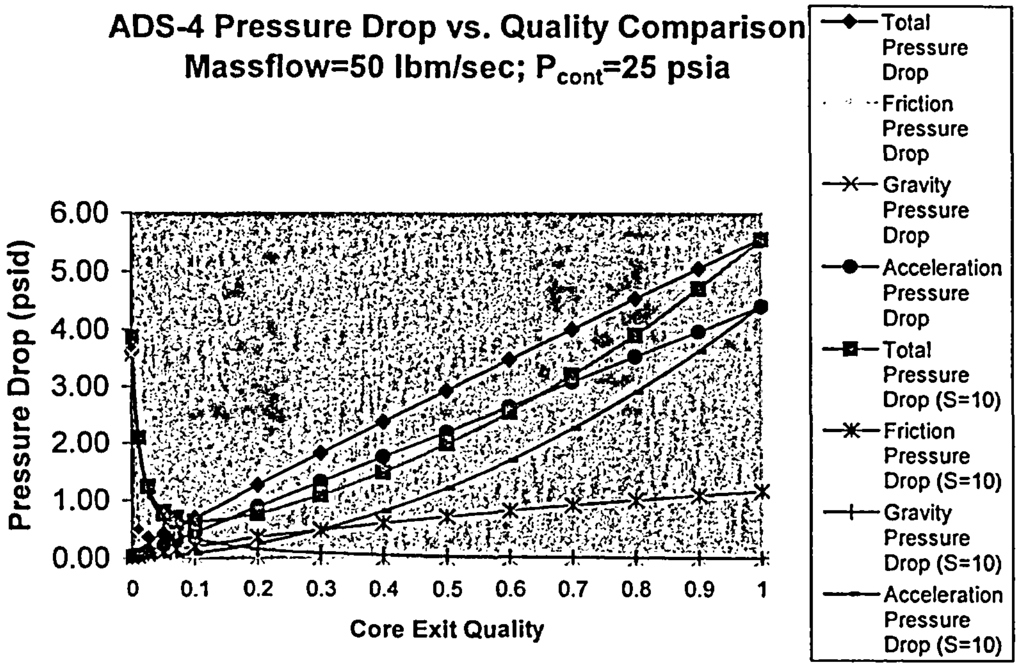


Figure A3-3

Design Control Document (DCD) Revision:

None

PRA Revision:

None