DCP/NRC1608
Docket No. 52-006

August 4, 2003

Attachment 1

List of

Proprietary and Non-Proprietary Responses

Table 1 "List of Westinghouse's Responses to DSER Open Items Transmitted in DCP/NRC1608"	
15.2.7-1P* **15.2.7-1** **15.3-2** **21.5-1P*** **21.5-1** **21.5-3P*** **21.5-3** * Westinghouse Proprietary	

DCP/NRC1608
Docket No. 52-006

August 4, 2003

Attachment 3

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

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: **15.2.7-1**

Original RAI Number(s): **None**

Summary of Issue:

Through analyses performed for the AP600, it was established that the evolution of the LTC is independent of the initiating transient and the determining parameters are the decay heat, cooling water flow and steam-water flow resistance. At the initiation of the LTC, the core has been quenched, the accumulators and the CMTs have emptied, and the IRWST injection has stabilized. At this stage the objective is to demonstrate that the passive system is capable of removing the decay heat. Therefore, the limiting case has the highest decay heat, the lowest cooling water flow, and the highest resistance to steam-water mixture exiting the vessel. As in the AP600 the parameters of the limiting case occur in the DEDVI line break. DCD Tier 2 Section 15.6.5.4C.2 presents a DEDVI line break with an ADS-4 single failure. Initial containment pressure was derived from the WGOTHIC code, and the transient was carried to 9,000 seconds until after a quasi-steady state sump recirculation was established. The results are presented in DCD Tier 2 Figures 15.6.5.4C-1 through 15.6.5.4C-28. The results show that the fuel PCT is low, and the water circulation is adequate to provide core cooling.

With regard to the boron precipitation issue, the results presented in DCD transient analysis (1) did not quantify the amount of water exiting the vessel; (2) there was no clear indication of void distribution in the core; (3) did not characterize the water-steam mixture flow regime in the ADS-4; and (4) did not minimize the steam velocity through the ADS-4. At the staff's request, the applicant presented a more conservative case by assuming that all ADS-4 valves are open and the containment pressure is at a maximum. In addition, the applicant presented a qualification of the WCOBRA/TRAC model regarding ADS-4 water-steam flow (RAI responses to 440.091, Revision 1). The staff reviewed this information and (as stated above) found that there is adequate justification for the WCOBRA/TRAC ADS-4 flow model. The applicant demonstrated that the flow regime is the same as in AP600 (annular flow) which would entrain fluid particles to expel water from the vessel as required to avoid boron concentration in the vessel and/or precipitation. The amount of water to be removed from the core was quantified. In addition, literature was cited regarding flow regimes applicable to the conditions of the ADS-4 which reinforced the credibility of the results.

However, the applicant did not present a detailed enough case regarding void distribution in the core. Persistent voiding in the core could result into adiabatic heating of the fuel. This is Open Item 15.2.7-1.

Westinghouse Response:

Summary

The original AP600/AP1000 WCOBRA/TRAC Long Term Cooling (LTC) model used in the DCD was based on a simplified noding. In particular, the core region was subdivided in [ ][a,c].

Questions have been raised about the adequacy of such modeling, and in particular the axial core noding was judged to be insufficient to correctly model the core axial void fraction distribution.

As a result, the AP1000 LTC model was extended/modified as follows:

1. The Core was subdivided in [ ][a,c].
2. The core region was subdivided axially in [ ][a,c] and is now consistent with nodalizations used to validate WCOBRA/TRAC against G1, G2 and FLECHT-SEASET tests.
3. The Upper Plenum explicitly models the CCFL region above the upper core plate and the nodalization is now equivalent to Westinghouse WCOBRA/TRAC LBLOCA model which was validated against full-scale UPTF tests.

Additional code validation was identified for the application of the revised WCOBRA/TRAC model to simulate the AP1000 LTC conditions. Selected G1 and G2 full-scale boil-off tests at pressure and power levels, which are prototypical of AP1000 conditions, were selected to validate the WCOBRA/TRAC core model. This validation included the determination, via sensitivity studies, of a corrective multiplier applied to the interfacial drag model such that the average core void fraction could be accurately predicted. Results from this validation are included in this response.

The validated model was then applied to simulate the LTC transient following a DEDVI break, which exhibits the most limiting relationship between core decay power (maximum) and available PXS liquid head (minimum).

The revised WCOBRA/TRAC analysis showed that adequate core cooling exists during the entire Long Term Cooling transient. The core inlet flow is more than sufficient to remove the decay heat and additional liquid is stored in the upper plenum and hot leg. No core temperature excursion is predicted to occur.

In addition a sensitivity study was performed where the interfacial drag coefficient was reduced by 20%. Results indicate that, under the AP1000 conditions, the core interfacial drag model has a negligible effect on the inner vessel mixture level. In both calculations (YDRAG=1.0 and YDRAG=0.8) mixture level is predicted in proximity of the hot leg centerline and the hot leg collapsed liquid level is almost identical in the two sensitivity cases.

These results are consistent with conclusions about the AP1000 system discussed in the response to Open Item 21.5-3. The analysis based on the simple AP1000 model showed that the system draws more flow through the core than is needed to remove decay heat. Under those circumstances the mixture level is above the top of core and is virtually independent of the level swell model used within the core. In the AP1000 DEDVI event, during the long term cooling, the average core exit quality is indicated to be always less than 50%. This flow regime is quite different than a boil-off scenario such as in the G1 and G2 tests. In the boil-off mode the exit

quality is approximately 1.0 and, once the two-phase mixture level drops below the top of the heated section, the rods are exposed to pure steam and can undergo an almost adiabatic heat-up. As a result, because of the sufficient liquid supply to the core, core heat-up does not occur during the AP1000 LTC phase following a LOCA event.

WCOBRA/TRAC Core Void Fraction Model Assessment Against G1 and G2 Low Pressure Boil-off Tests.

G1 test runs 28, 35, 38, 58 and 61 and G2 test runs 728, 729, 730, 732, 733, 734 were selected to validate the WCOBRA/TRAC core void fraction model used to perform the AP1000 long term cooling analysis. The following table shows the comparison between the test conditions and conditions expected in the AP1000 during the transient.

Test	Pressure (psia)		Power (kW/ft)		Core/Assembly Flow (in/sec)		Inlet Subcooling (F)	
AP1000	20	45	0.02	0.18	0.4	0.8	14	80
G1	[							][a,c]
G2	[							][a,c]

As discussed in the previous summary the AP1000 core is not to expected to be in a boil-off mode. Nevertheless, these experiments are useful to characterize the void fraction distribution and/or average void fraction within the core region when the mixture level is located above the top of the core.

G1 represents a prototypical [
][a,b,c] G2 represents a [
.][a,b,c]

For G1 the WCOBRA/TRAC Model includes the heated section, the lower plenum and the upper plenum and the downcomer region. The heated section is subdivided in [
.][a,b,c] The boil-off test is initiated by setting the liquid level in the heated section and in the downcomer region to a given value. The power is turned on at the beginning of the test. The liquid in the lower plenum [
.][a,b,c]

The WCOBRA/TRAC model for G2 is very similar. In this case [
][a,b,c]

At each given time, the location of the mixture level is defined by examining the rod temperature axial distribution. The rod surface temperature is close to saturation below the mixture level and suddenly increases significantly above the saturation temperature above the mixture level.

The average void fraction below the mixture level is related to a parameter called swell 'S' defined as follows:

a, b, c

Figure 1 shows the measured swell compared to the swell predicted by the nominal WCOBRA/TRAC interfacial drag model. The swell (or average void fraction) tends to be over-predicted by the code.

a, b, c

Figure 1

The G1 and G2 calculations were repeated by applying a multiplier (YDRAG=0.8) to the interfacial drag coefficient. Figure 2 shows the effect of a reduced interfacial drag. The predicted swell or void fraction is now in good agreement with the test data captured within ±20%. This

multiplier was selected to be used in the revised WCOBRA/TRAC LTC analysis presented herein.

a, b, c

Figure 2

Results from the revised WCOBRA/TRAC model for the AP1000 Long Term Cooling phase following a DEDVI Break in PXS Room B.

The method used to analyze the AP1000 Long Term Cooling with WCOBRA/TRAC is described in the DCD and in the AP1000 code applicability document. The transient begins from the end of DEDVI analysis of NOTRUMP at 3000 seconds, and continues with boundary conditions provided by WGOTHIC (containment analysis) predictions.

Main results from the revised WCOBRA/TRAC LTC calculation are presented here and will be included in the revised DCD. The DCD includes a more detailed description of the transient. Here the discussion is limited to address the level swell issue and to derive some conclusions about the vessel liquid inventory which demonstrates that adequate cooling exists during the LTC.

The time scale of the plots herein is adjusted to reflect DEDVI break transient time. Figure 3 shows the upper plenum pressure. The pressure decreases from its initial value to reach a quasi steady state value of 28 psia at about 7000 seconds.

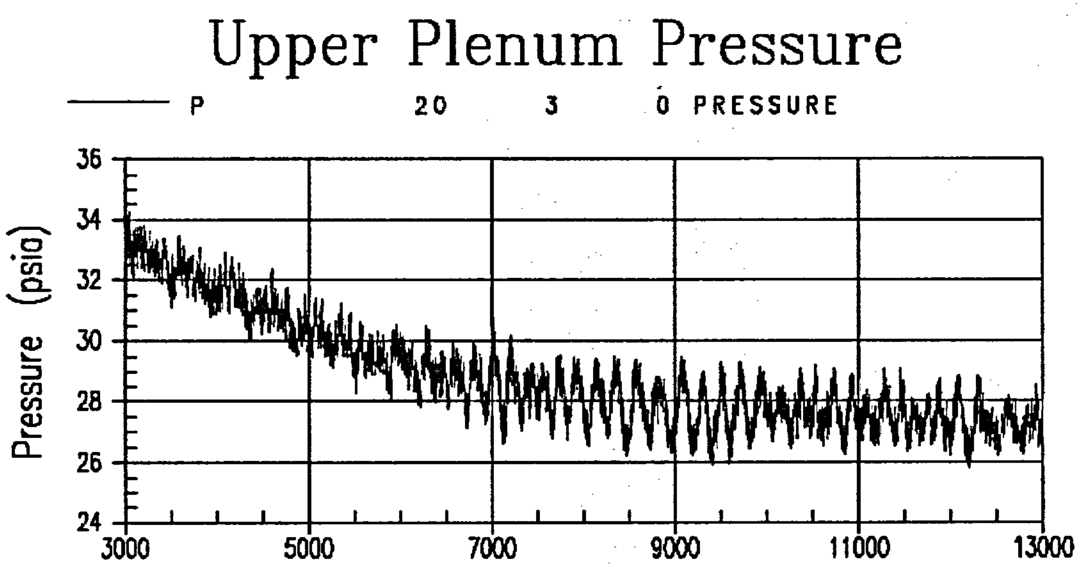


Figure 3

The next figures 4 and 5 show the ADS4 integrated flows and the integrated flows from the DVI nozzles:

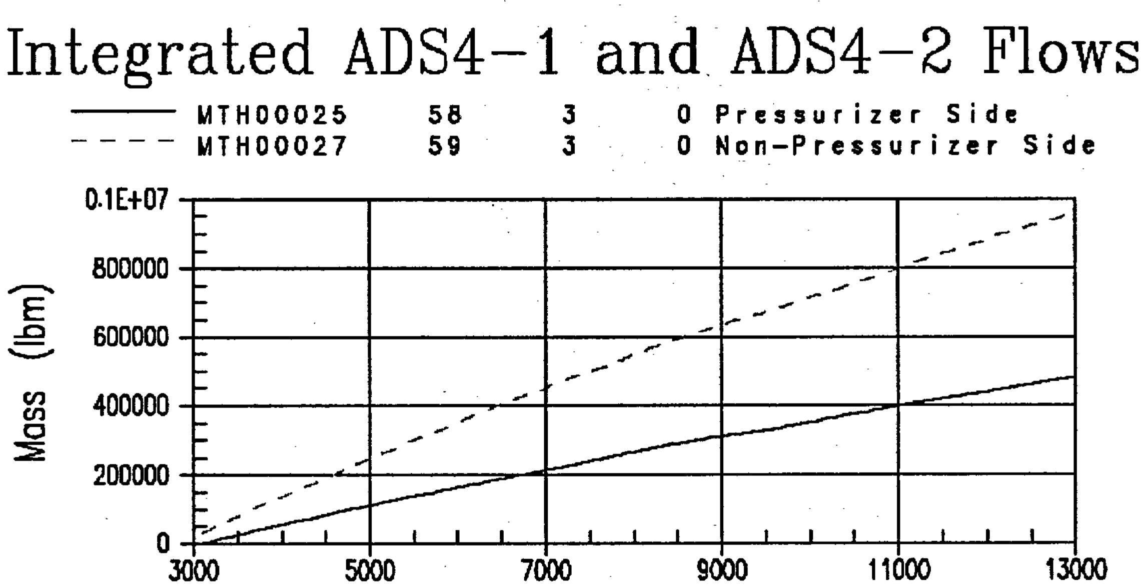


Figure 4

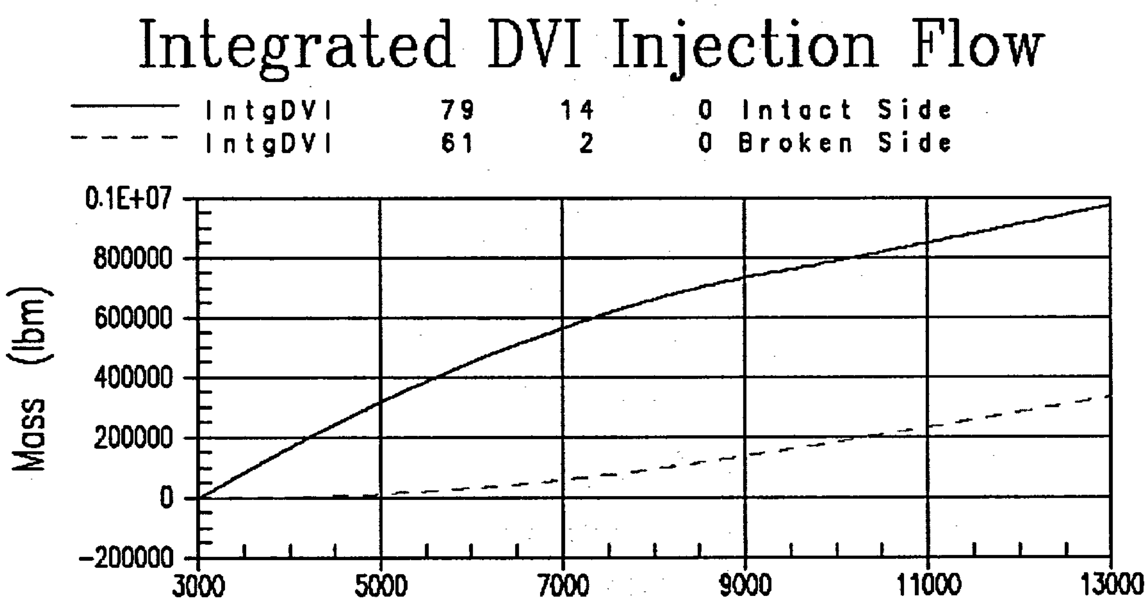


Figure 5

The inner vessel collapsed liquid level as well as the core region only collapsed liquid level are shown in Figures 6 and 7:

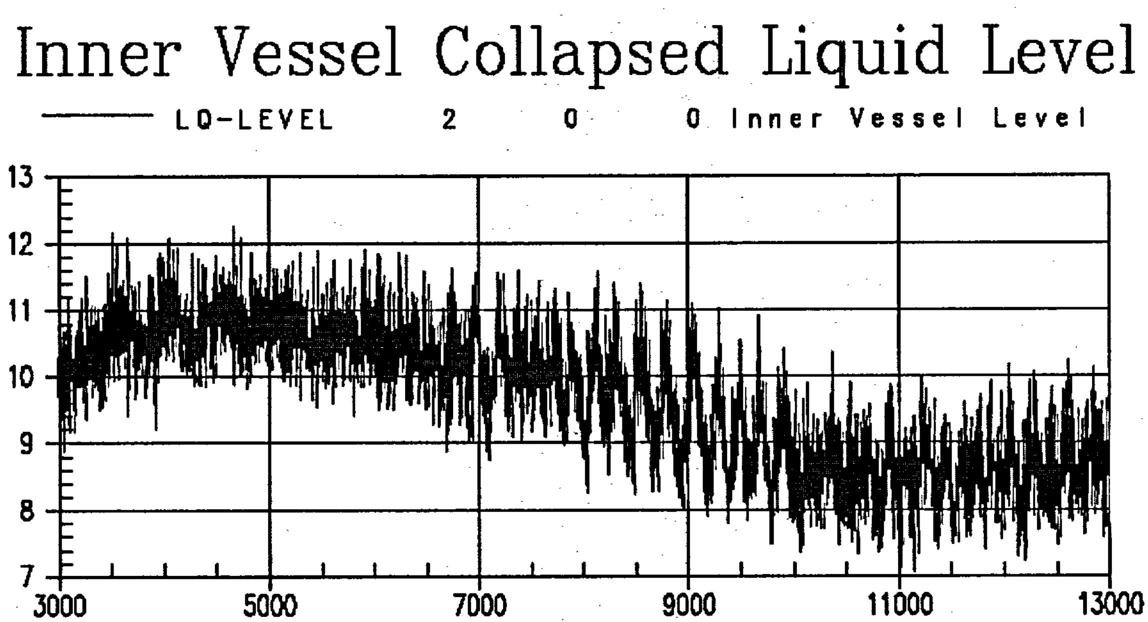


Figure 6

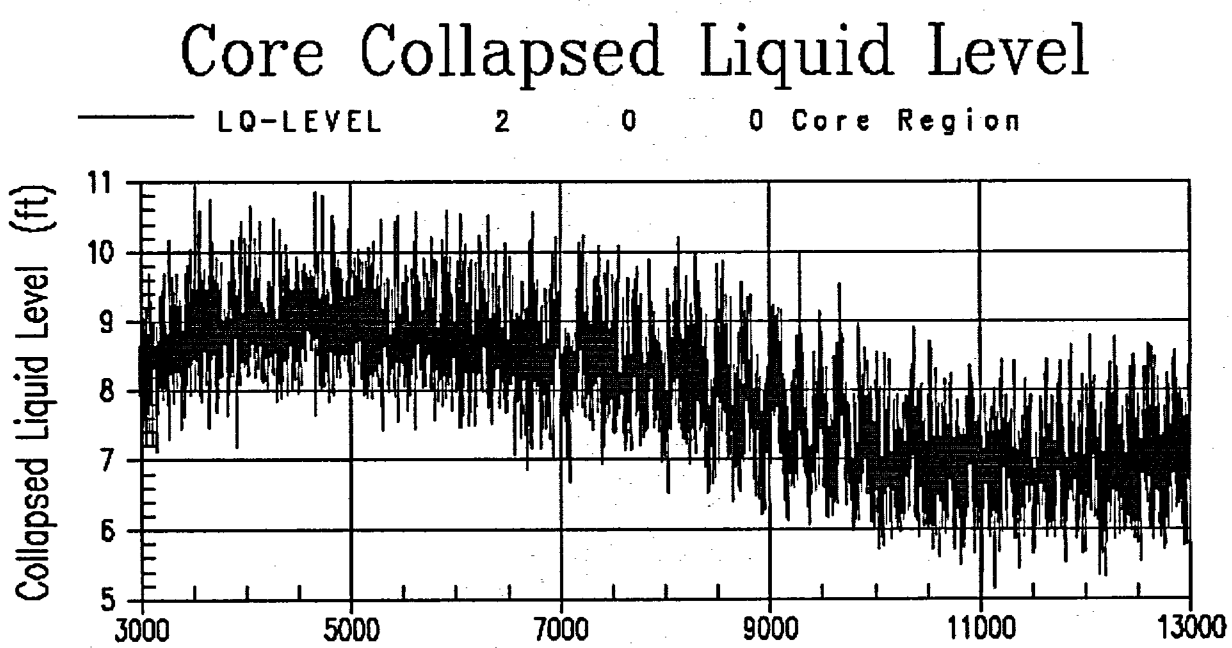


Figure 7

Figure 8 shows that the mixture level is located in proximity of the hot leg centerline.

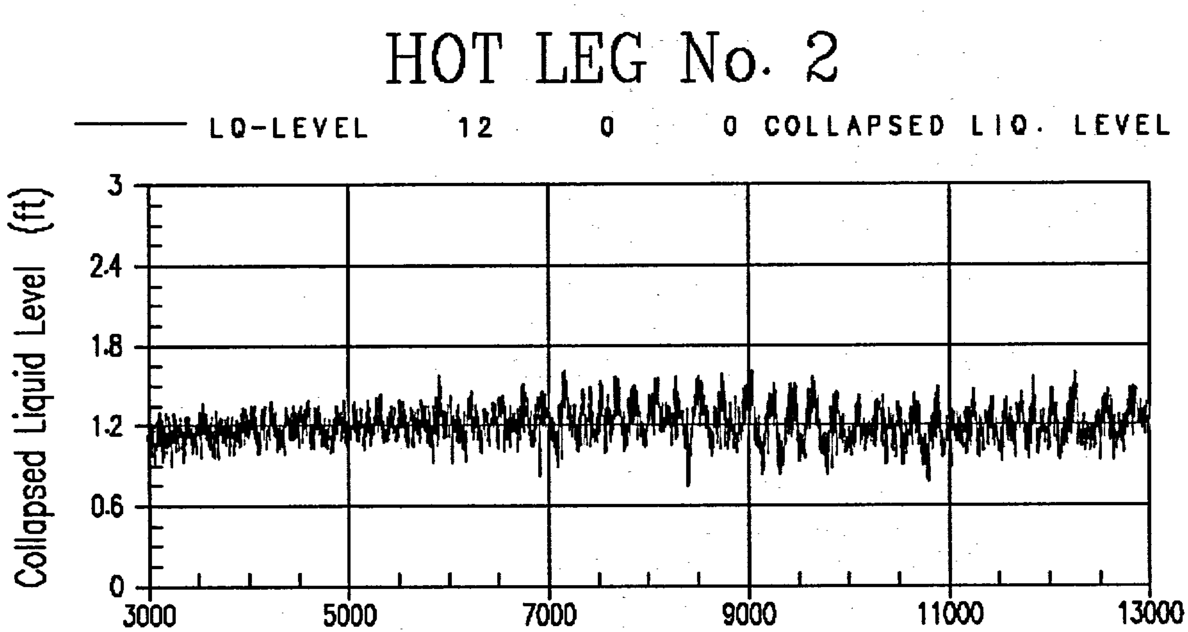


Figure 8

It is worth to note that the LTC case was analyzed with both nominal interfacial drag model and with 20% reduced interfacial drag model and it was observed that the hot leg levels from these calculations were nearly identical as shown in Figure 9.

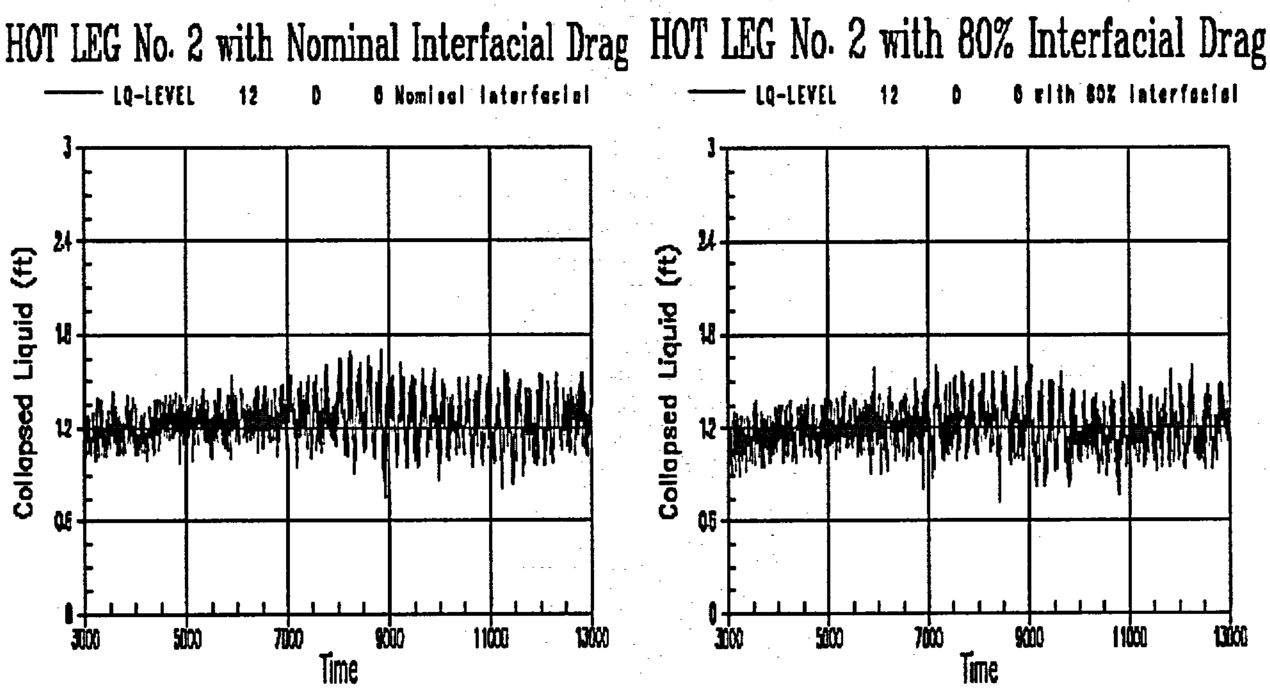


Figure 9

This result is an indication that once the mixture level is located above the top of the core and well into the upper plenum, the interfacial drag model or core swell model has a very small effect on the overall system behavior.

The liquid supply (core inlet liquid flow) is always sufficient to remove the decay heat. Additional liquid is stored in the upper plenum and discharged by the ADS-4. Figure 10 shows that the ADS-4 average exit quality float around 50% during the LTC transient.

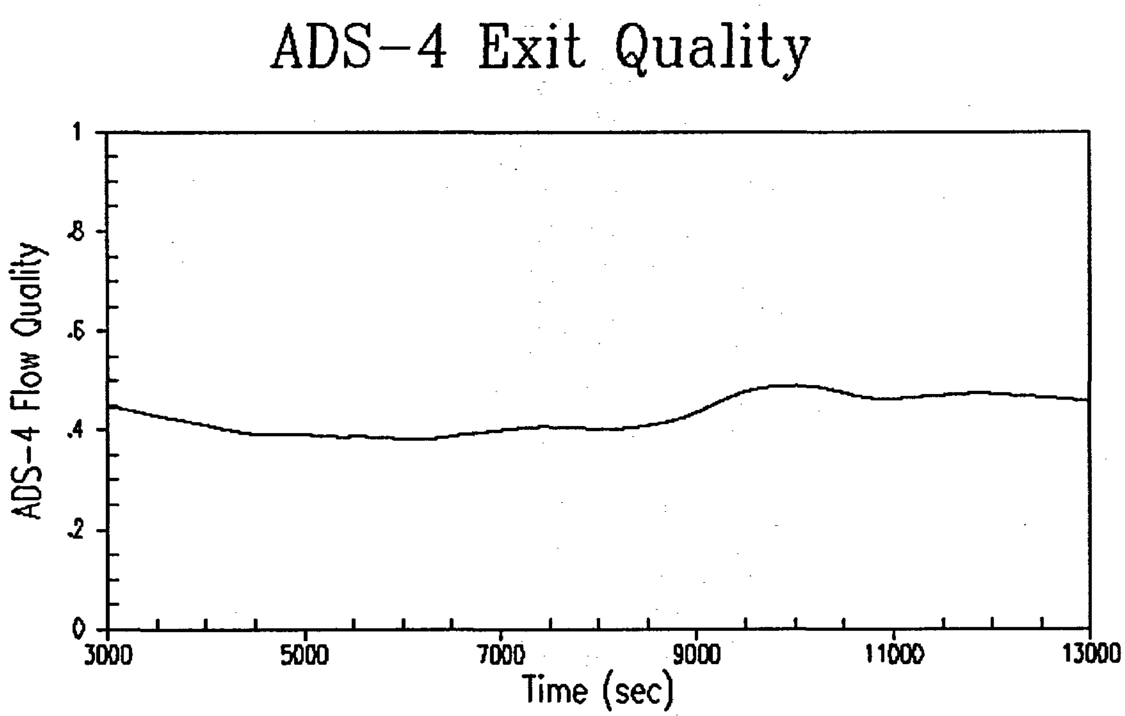


Figure 10

The predicted void fraction at the top of the core hot assembly is approximately 0.8 during the transient (Figure 11) which is another indication that sufficient liquid is provided at the top of the core preventing core heat-up from occurring.

Figure 12 shows that the clad temperature in the top region of the core is always close to the saturation temperature and no heat-up excursion is predicted to occur.

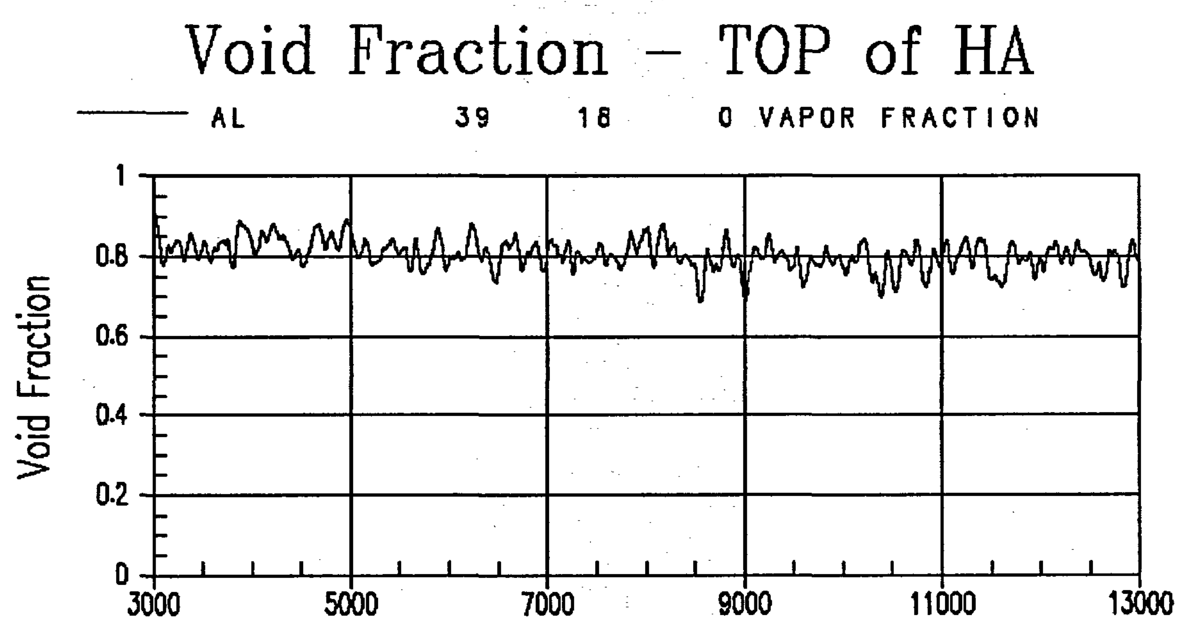


Figure 11

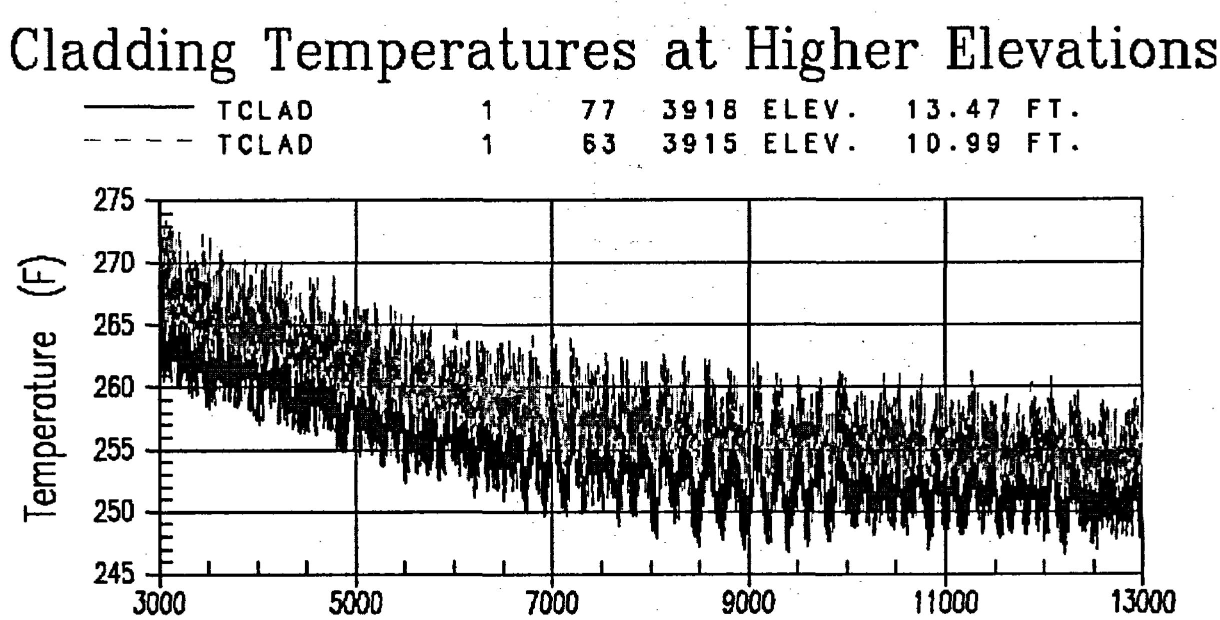


Figure 12

Additional Considerations

Further investigations were made to establish what flow regime should be expected in the top region of the core to further support that under the conditions expected during the LTC, adequate core cooling is provided to prevent core heat-up from occurring.

The expected flow regime at the top of the core is a churn or pulsated annular flow. The steam velocity is so low that entrainment of droplets is not expected to occur. Based on Ishii and Grolmes (1975) inception criteria for droplet entrainment in two-phase concurrent film (roll wave and liquid jet instabilities) the critical superficial velocity for droplet entrainment was estimated to be 77 ft/s (P=40 psia). Yonomoto et. al. (1987) (JAERI) established a criterion for entrainment onset based on reflood tests in rod bundle prototypical geometries and conditions. Based on Yonomoto model the onset is at about 20 ft/s at the same conditions. During the LTC, the vapor superficial velocity at the core exit is expected to be lower than 16 ft/s.

The possibility that the CHF could be exceeded, below the two-phase mixture level was also investigated. Schosse et. al. (1997) presented a review of CHF correlations applicable to low upward flows near atmospheric pressure. It was found that the AP1000 typical heat flux (the average heat flux is about 1.0 Btu/ft^2-s at 3000 sec.) is significantly less than the critical heat flux which can be predicted with their model.

References

1. Ishii, M. and Grolmes, M. A. (1975), Inception Criteria for Droplet Entrainment in Two-Phase Concurrent Film Flow, A.I.Ch.E. Jl 21, 308.

2. Yonomoto, T. et. al. (1987). Liquid Entrainment for Liquid Entrainment in Reflooding phase of LOCA. J. of Nuclear Science and Technology. Vol. 24 [10].

3. Schoesse, T. et. al. (1997), Critical Heat Flux in a Vertical Annulus under Low Upward Flow and near Atmospheric Pressure. J. of Nuclear Science and Technology. Vol. 34 [6].

Design Control Document (DCD) Revision:

Section 15.6.5.4C will be revised. A draft markup including the new DEDVI case is attached.

15.6.5.4C Post-LOCA Long-Term Cooling

15.6.5.4C.1 Long-Term Cooling Analysis Methodology

The AP1000 safety-related systems are designed to provide adequate cooling of the reactor indefinitely. Initially, this is achieved by discharging water from the IRWST into the vessel. When the low-3 level setpoint is reached in the IRWST, the containment recirculation subsystem isolation valves open and water from the containment reactor coolant system (RCS) compartment can flow into the vessel through the PXS piping. The water in containment rises in temperature toward the saturation temperature. Long-term heat removal from the reactor and containment is by heat transfer through the containment shell to atmosphere.

The purpose of the long-term cooling analysis is to demonstrate that the passive systems provide adequate emergency core cooling system performance during the IRWST injection/containment recirculation time scale. The long-term cooling analysis is performed using the WCOBRA/TRAC computer code to verify that the passive injection system is providing sufficient flow to the reactor vessel to cool the core and to preclude boron precipitation.

The AP1000 long-term cooling analysis is supported by the series of tests at the Oregon State University AP600 APEX Test Facility. This test facility is designed to represent the AP600 reactor safety-related systems and nonsafety-related systems at quarter-scale during long-term cooling. The data obtained during testing at this facility has been shown to apply to the AP1000 (Reference 25). These tests were modeled using WCOBRA/TRAC with an equivalent noding scheme to that used for AP600~~1000~~ (Reference 17~~23~~) in order to validate the code for long-term cooling analysis.

Reference ~~17~~24 provides details of the AP~~6~~1000 WCOBRA/TRAC modeling. **The coarse reactor vessel modeling used for AP600 has been replaced with a detailed noding like** ~~is much coarser than~~ that applied in the large-break LOCA analyses described in subsection 15.6.5.4A. ~~to permit faster computation and because less detail is required for the slowly changing parameters involved for the long-term transients.~~ The ~~equivalent~~ reactor vessel noding ~~is~~ used in the AP1000 long-term cooling analyses **in core and upper plenum regions is equivalent to that used in full-scale test simulations (see Reference 24).**

A DEDVI line break is analyzed because it is the most limiting long-term cooling case in the relationship between decay power and available liquid driving head. Because the IRWST spills ~~the transfer~~ directly onto the containment floor in a DEDVI break, this event has the highest core decay power ~~to sump injection~~ when **the transfer to sump** injection is initiated. In postulated DEDVI break cases, ~~before~~ the compartment water level exceeds the elevation at which the DVI line enters the reactor vessel, so water can flow from the containment into the reactor vessel through the broken DVI line; this in-flow of water through the broken DVI line assists in the heat removal from the core. The steam produced by boiling in the core vents to the containment through the ADS valves and condenses on the inner surface of the steel containment vessel. The condensate is collected and drains to the IRWST to become available for injection into the reactor coolant system. The WCOBRA/TRAC analysis presented analyzes the DEDVI small-break LOCA event from a time (3000 seconds) at which IRWST injection is fully established beyond ~~to~~ the time of containment recirculation. During this time, the head of water to drive the flow into the vessel for IRWST injection decreases from the initial level to its lowest value at the containment recirculation switchover time. **PXS Room B is** ~~T~~the location of the break in the DVI line. ~~is adjacent to the vessel nozzle.~~ At this location, ~~the in-flow through the broken DVI line is minimized as the IRWST drains~~ **liquid level in containment at the time of recirculation is a minimum.**

A continuous analysis of the post-LOCA long term cooling is provided from the time of stable IRWST injection through the time of sump recirculation for the DEDVI break. Maximum design resistances are applied in WCOBRA/TRAC for both the ADS Stage 4 flow paths and the IRWST injection and containment recirculation flow paths.

The break modeled is a double-ended guillotine rupture of one of the direct vessel injection lines. The long-term cooling phase begins after the simultaneous opening of the isolation valves in the IRWST DVI lines and the opening of ADS Stage 4 squib valves, when flow injection from the IRWST has been fully established. Initial conditions are taken from the NOTRUMP DEDVI case at 25 psia containment pressure reported in subsection 15.6.5.4B.

15.6.5.4C.2 DEDVI Line Break with ADS Stage 4 Single Failure, Passive Core Cooling System Only Case; Continuous Case

This subsection presents the results of a DEDVI line break analysis during IRWST injection phase continuing into sump recirculation. Initial conditions at the start of the case are prescribed based on the NOTRUMP DEDVI break results to allow a calculation to begin shortly after IRWST injection begins in the small break long-term cooling transient. The WCOBRA/TRAC calculation is then allowed to proceed until a quasi-steady-state is achieved. At this time, the predicted results are independent of the assumed initial conditions. This calculation uses boundary conditions taken from a WGOTHIC analysis of this event. During the calculation, which is carried out for ~~9000~~ 10,000 seconds until a quasi-steady-state sump recirculation condition has been established, the IRWST water level is decreased continuously until the sump recirculation setpoint is reached.

In the analysis, one of the two ADS Stage 4 valves in the PRHR loop is assumed to have failed. The initial reactor coolant system liquid inventory and temperatures are determined from the NOTRUMP calculation. ~~This equates to a full lower plenum and downcomer, a core collapsed liquid level of 9.5 feet (relative to the bottom of the heated length), and a collapsed level of 2.2 feet in the upper plenum.~~ The core makeup tanks do not contribute to the DVI injection. Steam generator secondary side conditions are taken from the NOTRUMP calculation (at the beginning of long-term cooling). The reactor coolant pumps are tripped and not rotating.

The levels and temperatures of the liquid in the containment sump and the containment pressure are based on ~~a~~ WGOTHIC calculations of the conservative minimum pressure during this long-term cooling transient, using the methodology described in Reference 17. Small changes in the RCS compartment level do not have a major effect on the predicted core collapsed liquid level or on the predicted flow rate through the core. ~~Sensitivity studies for this break scenario, which ranged level from 110 feet to 109.4 feet, predicted adequate core cooling during this time window.~~ The minimum compartment floodup level for this break scenario is ~~109.4~~107.8 feet or greater.

In this transient, the IRWST provides a hydraulic head sufficient to drive water into the downcomer through the intact DVI nozzle. Also, water flows into the downcomer from the RCS loop compartment through the broken DVI line once the liquid level is adequate to support flow. The water flows down the downcomer and up through the core, into the upper plenum. Steam produced in the core and liquid flow out of the reactor coolant system via the ADS Stage 4 valves. There is little flow out of ADS Stages 1, 2, and 3 even when the IRWST liquid level falls below the sparger elevation, so they are not modeled in this calculation. The venting provided by the ADS-4 paths enables the liquid flow through the core to maintain core cooling.

Approximately 500 seconds of WCOBRA/TRAC calculation are required to establish the quasi-steady-state condition associated with IRWST injection at the start of long-term cooling and so are ignored in the following discussion. The hot leg levels are such that during the IRWST injection phase the quality of the ADS Stage 4 mass flows varies as water is carried out of the hot legs. This periodically increases the pressure drop across the ADS Stage 4 valves and the upper plenum pressure. The higher pressure in the upper plenum reduces the injection flow. This cycle of pressure variations due to changing void fractions in the flow through ADS Stage 4 is consistent with test observations and is expected to recur often during long-term cooling.

The head of water in the IRWST causes a flow of subcooled water into the downcomer at an approximate rate of ~~180~~170 lbm/sec through the intact DVI nozzle at the start of long-term cooling. The downcomer level at the end of the code initiation (the start of long-term cooling) is about ~~19.5~~18.5 feet (Figure 15.6.5.4C-1). Note that the time

scale of this and other figures in subsection 15.6.5.4C.2 is offset by 2500 seconds; that is, a time of 500 seconds on the Figure 15.6.5.4C-1 axis equals 3000 seconds transient time for the DEDVI break. All of the injection water flows down the downcomer and up through the core. The accumulators have been fully discharged before the start of the time window and do not contribute to the DVI flow.

Boiling in the core produces steam and a two-phase mixture, which flows into the upper plenum. The core is 14 feet high, and the core average collapsed liquid level (Figure 15.6.5.4C-2) is ~~about 7.7 feet at~~**shown from the start of** long-term cooling. The boiling process causes a variable rate of steam production and resulting pressure changes, which in turn causes oscillations in the liquid flow rate at the bottom of the core and also variations in the core collapsed level and the flow rates of liquid and vapor out of the top of the core. In the WCOBRA/TRAC noding, the core is divided ~~into two axial levels, each of which is 7 feet high~~**both axially and radially as described in Reference 24.**. The void fractions in the top two ~~levels~~**cells of the hot assembly** are shown as Figures 15.6.5.4C-3 and -4. ~~The core void fraction is low for the bottom cell and has a mean void fraction less than 0.1 in the entire long-term cooling transient.~~ **The average void fraction of these upper core cells is about** ~~exceeds~~ 0.8 **during** ~~at the start of~~ long-term cooling, ~~decreases as the decay heat decreases, and levels out in the~~ **into** the containment recirculation period. ~~that begins at 6700 seconds on the figures.~~ There is a continuous flow of two-phase fluid into the hot legs, and mainly vapor flow toward the ADS Stage 4 valve occurs at the top of the pipe. The collapsed liquid level in the hot leg varies between ~~1.1~~0.9 feet to ~~1.7~~1.5 feet (Figure 15.6.5.4C-5). The hot legs on average are more than 50-percent full. Vapor and liquid flows at the top of the core are shown in Figures 15.6.5.4C-6 and 15.6.5.4C-7, the upper plenum collapsed liquid level in Figure 15.6.5.4C-8. Figures 15.6.5.4C-9 and 15.6.5.4C-10 are ADS stage 4 mass flowrates.

The pressure in the upper plenum is shown in Figure 15.6.5.4C-11. The upper plenum pressure fluctuation that occurs is due to the ADS Stage 4 water discharge. The ~~hot rod~~ PCT **at the top of the hot assembly rod** follows saturation temperature (Figure 15.6.5.4C-12) **which demonstrates that the calculated core collapsed liquid level is adequate to provide enough liquid at the top of the core that no uncovery and no cladding temperature excursion occurs.** A small pressure drop is calculated across the reactor vessel, and injection rates through the DVI lines into the vessel are presented in Figures 15.6.5.4C-13 and -14. Figure 15.6.5.4C-1~~3~~4 shows the flow is outward through the broken DVI line at the start of the long-term cooling period, and it increases to a maximum average value of about **52**~~90~~ lbm/s after the compartment water level has increased above the nozzle elevation to permit liquid injection into the reactor vessel. In contrast, the **intact DVI line** ~~DVI-B~~ flow falls from ~~180~~**170** lbm/s with a full IRWST to about ~~80~~**65** lbm/s flow from the containment at the end of the calculation. The recirculation core liquid throughput is more than adequate to preclude any boron buildup on the fuel.

15.6.5.4C.3 DEDVI Break and Wall-to-wall Floodup; Containment Recirculation

THIS SECTION TO BE REPLACED

~~This subsection presents a DEDVI line break analysis with wall-to-wall flooding due to leakage between compartments, using the window mode methodology. All containment free volume beneath the level of the liquid is assumed filled in this calculation to generate the minimum water level condition during containment recirculation. The time identified for this calculation is 28.5 days into the event, and the core power is calculated accordingly. The initial conditions at the start of the window are consistent with the analysis described in subsection 15.6.5.4C.2. Containment recirculation is simulated during the time window. The calculation is then carried out over 3000 seconds, which is a time period long enough to establish a quasi-steady state solution; after 1000 seconds, the flow dynamics are quasi-steady state and the predicted results~~

~~are independent of the assumed initial conditions. The liquid level is simulated constant at 28'-9" above the bottom inside surface of the reactor vessel (refer to Figure 15.0.3-2 for AP1000 reference plant elevations) during the time window while the liquid temperature in containment is set at the saturation condition at the identified containment pressure of 32.7 psia. The single failure of an ADS Stage 4 flow path is assumed as in the subsection 15.6.5.4C.2 case.~~

~~Focusing on the 1000-3000 second time interval of this case, the containment liquid provides a hydraulic head sufficient to drive water into the downcomer through the DVI nozzles. The water introduced into the downcomer flows down the downcomer and up through the core, into the upper plenum. Steam produced in the core entrains liquid and flows out of the reactor coolant system via the ADS Stage 4 valves. The DVI flow and the venting provided by the ADS paths provide a liquid flow through the core that enables the core to remain cool.~~

~~The downcomer collapsed liquid level (Figure 15.6.5.4C-15) is almost constant during the transient at about 25 feet, just below the lower lip of the cold leg nozzles. Pressure spikes produced by boiling in the core can cause the mass flow of the DVI flow rates shown in Figures 15.6.5.4C-27 and -28 into the vessel to stop momentarily, but the injection flow is quickly reestablished.~~

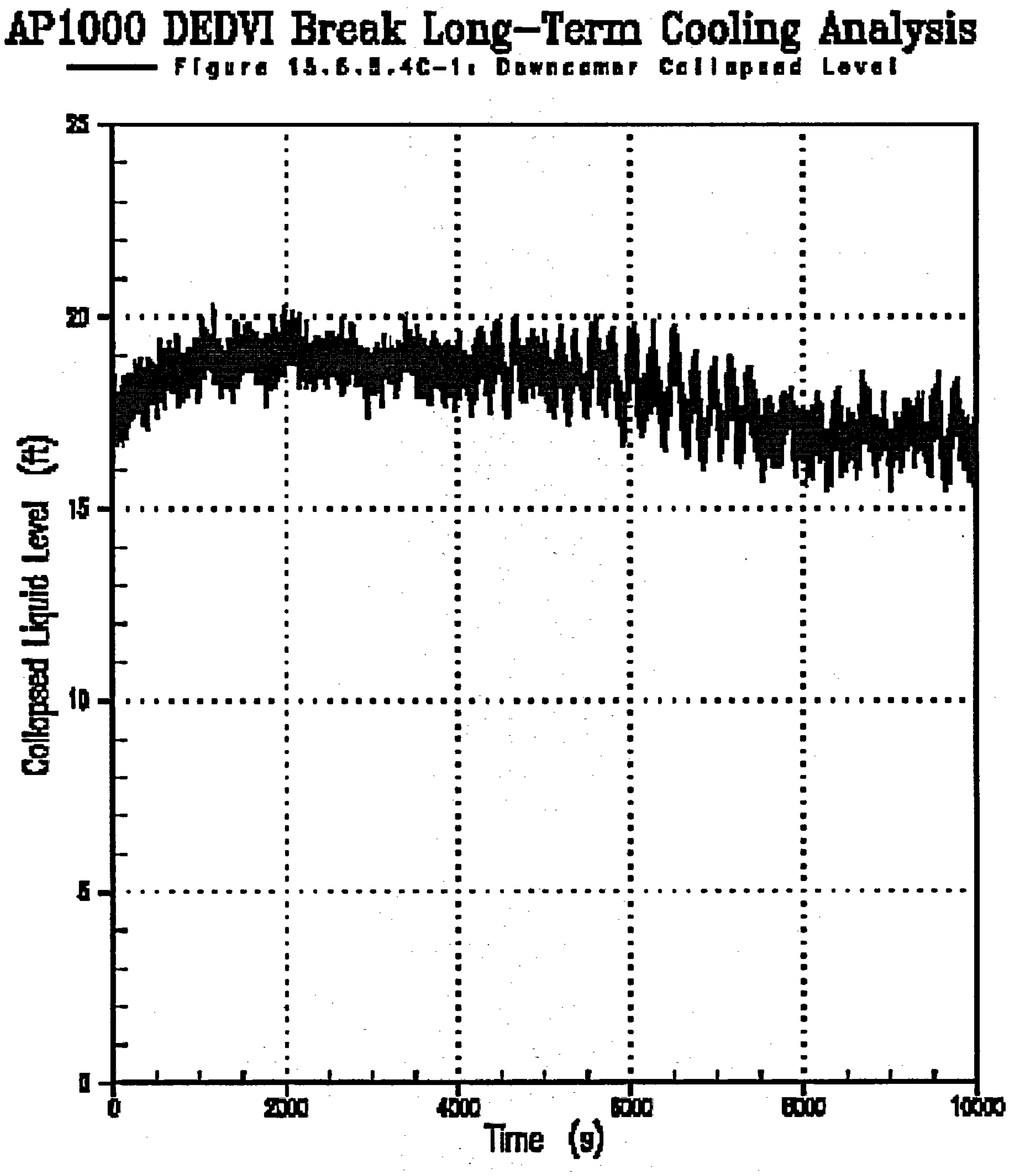
~~Boiling in the core produces steam and a two-phase mixture, which flows out of the core into the upper plenum. The core is 14 feet high, and the core collapsed liquid level (Figure 15.6.5.4C-16) maintains a mean level close to the top of the core. The boiling process causes pressure variations, which in turn, causes variations in the core collapsed level and the flow rates of liquid and vapor out of the top of the core. In the WCOBRA/TRAC noding, the core is divided into two axial levels, each 7 feet long. The void fraction in the top level is shown in Figure 15.6.5.4C-18, while Figure 15.6.5.4C-17 shows the small void fraction that exists at the bottom level. The PCT does not rise appreciably above the saturation temperature (Figure 15.6.5.4C.3-26). The flow through the core and out of the reactor coolant system is more than sufficient to provide adequate flushing to preclude concentration of the boric acid solution. Liquid collects above the upper core plate in the upper plenum, where the average collapsed liquid level is about 4.6 feet (Figure 15.6.5.4C-22). There is no significant flow through the cold legs into either the broken or the intact loops, and there is no significant quantity of liquid residing in any of the cold legs.~~

~~The pressure in the upper plenum is shown in Figure 15.6.5.4C-25. The upper plenum pressurization, which occurs periodically, is due to the ADS Stage 4 water discharge. The collapsed liquid level in the hot leg of the pressurizer loop varies between 0.0 feet to 2.0 feet, as shown in Figure 15.6.5.4C-19. Injection rates through the DVI lines into the vessel are presented in Figures 15.6.5.4C-27 and -28.~~

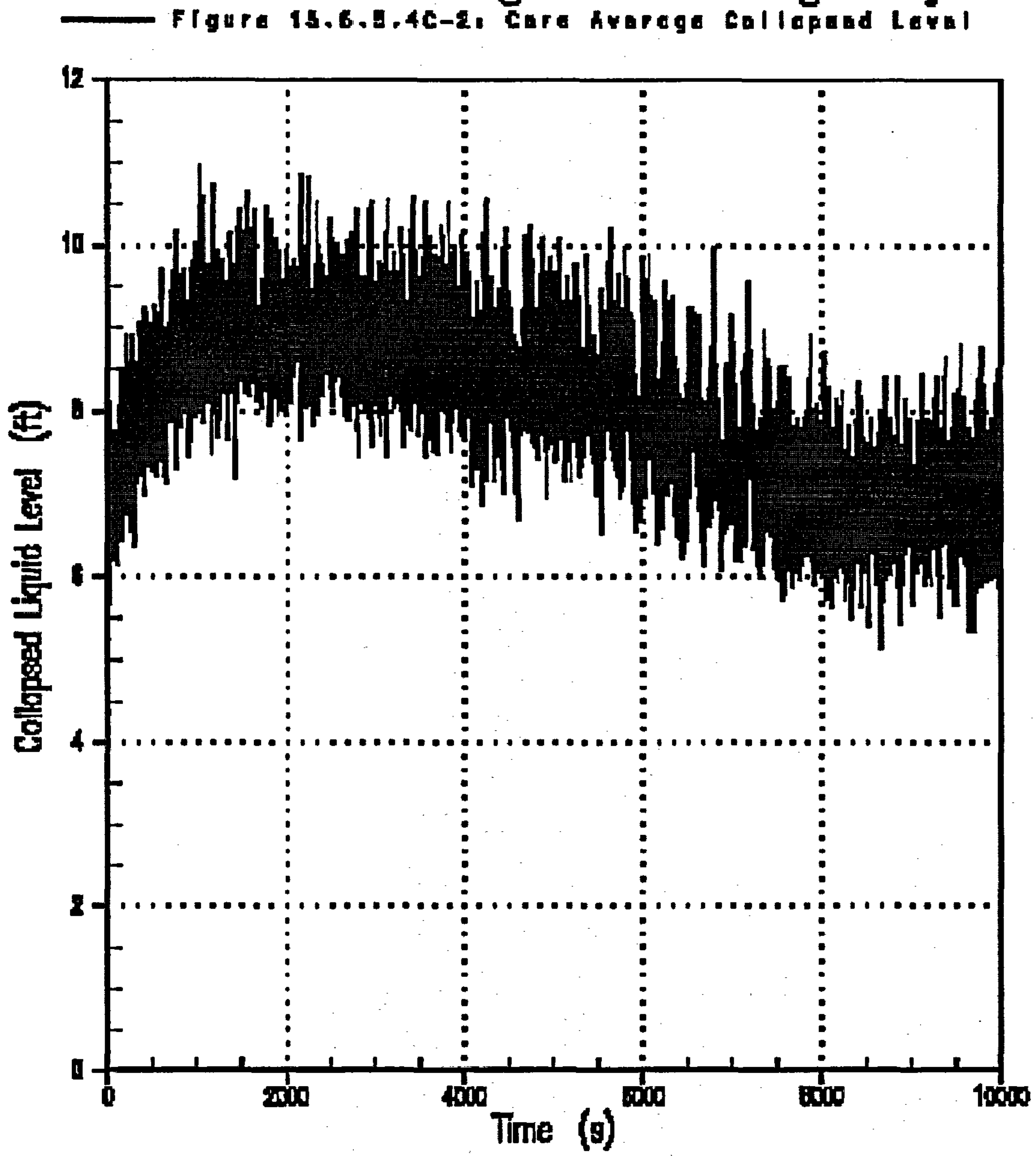
15.6.5.4C.4 Conclusions

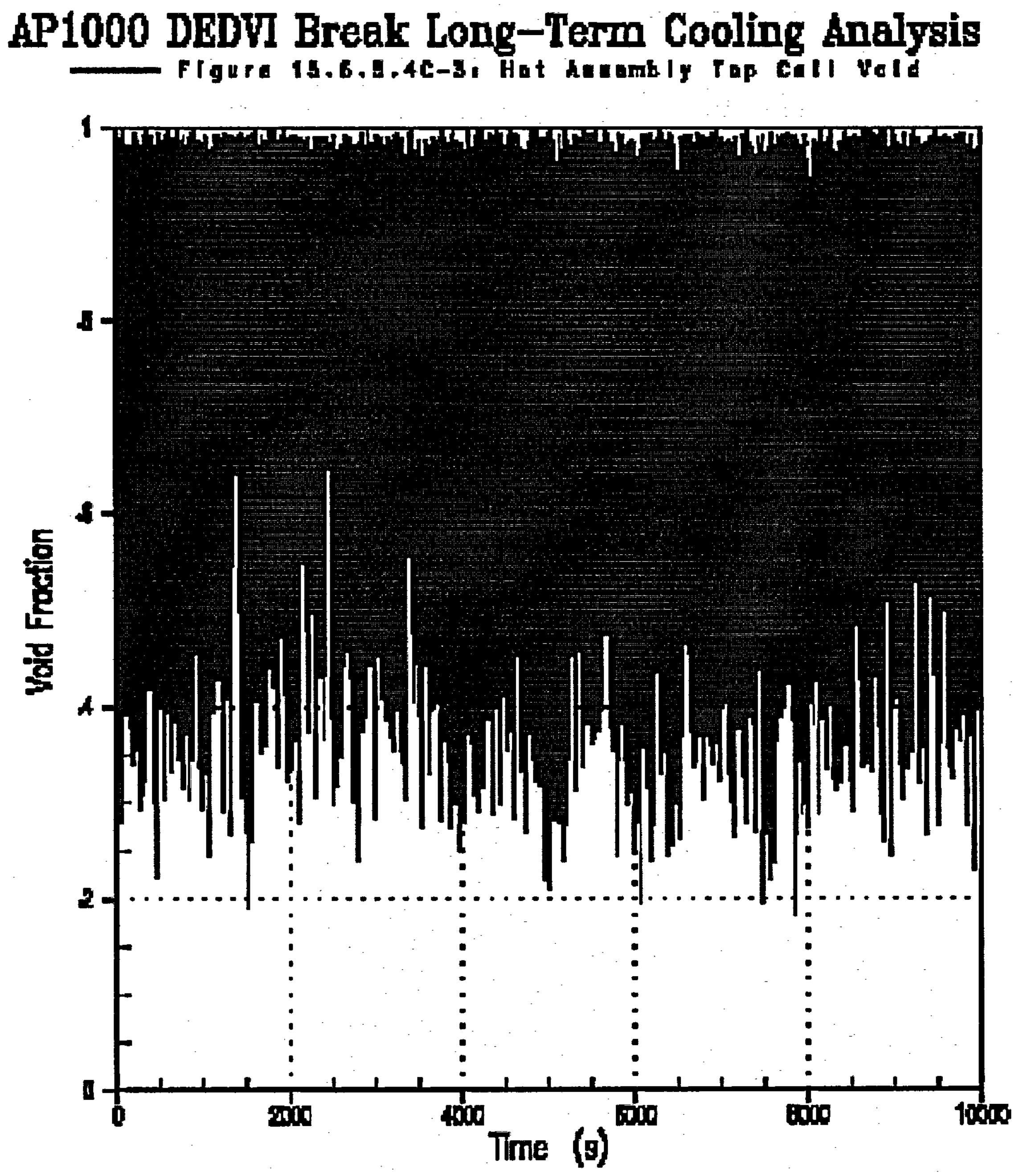
Calculations of AP1000 long-term cooling performance have been performed using the WCOBRA/TRAC model ~~approved for AP600~~**described in Reference 24.** The DEDVI case was chosen because it reaches sump recirculation at the earliest time (and highest decay heat). A window mode case at the minimum containment water level a month into long-term cooling was also performed.

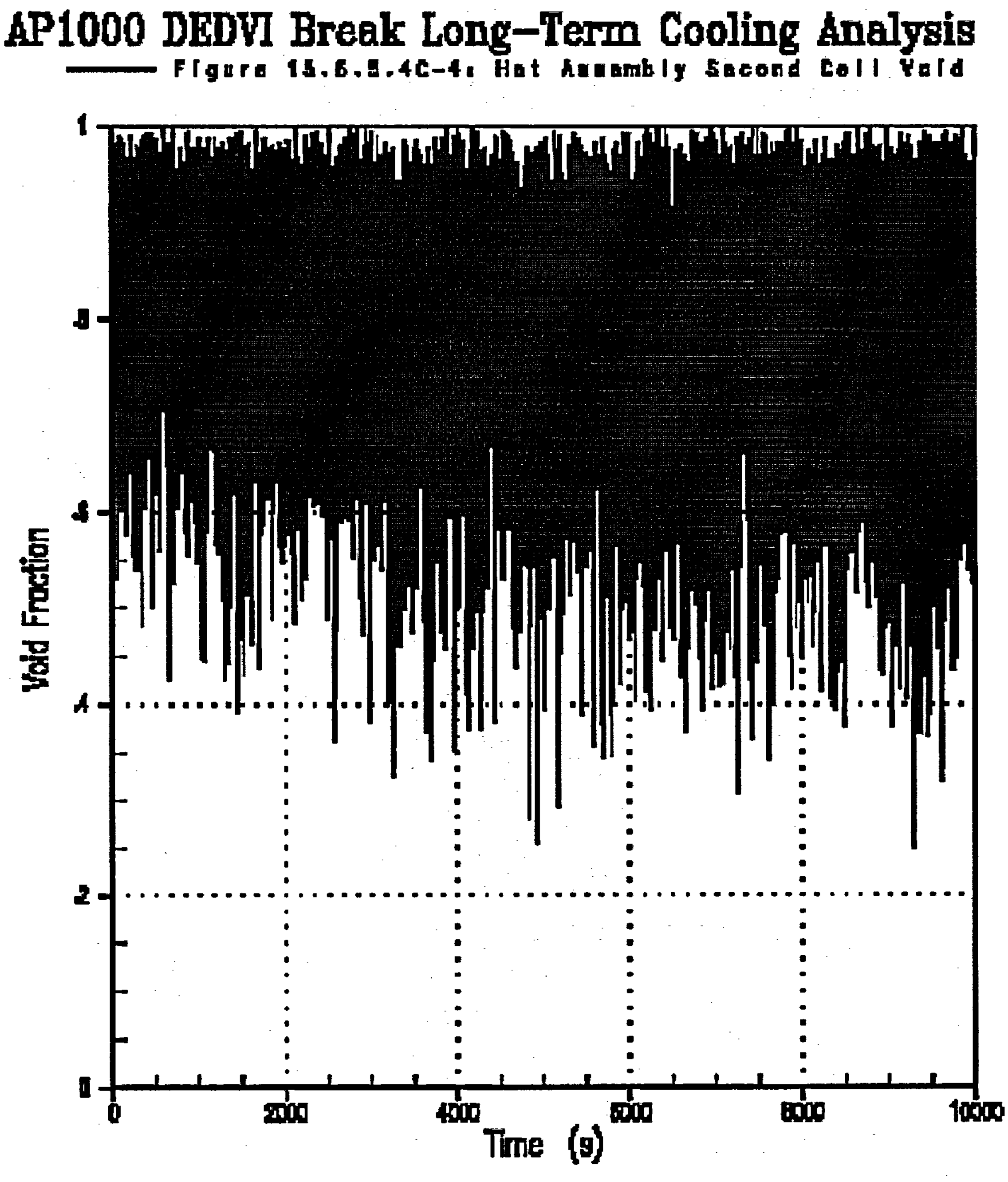
The DEDVI small break LOCA exhibits significant margin to core uncovery with a favorable reactor coolant system mass inventory condition during the long-term cooling phase from its initiation into containment recirculation. Adequate flow through the core is provided to maintaina low cladding temperature and to prevent any buildup of boric acid on the fuel rods. The wall-to-wall floodup case using the window mode technique demonstrates that effective core cooling is also provided at the minimum containment water level. The results of these cases demonstrate the capability of the AP1000 passive systems to provide long-term cooling for a limiting LOCA event.

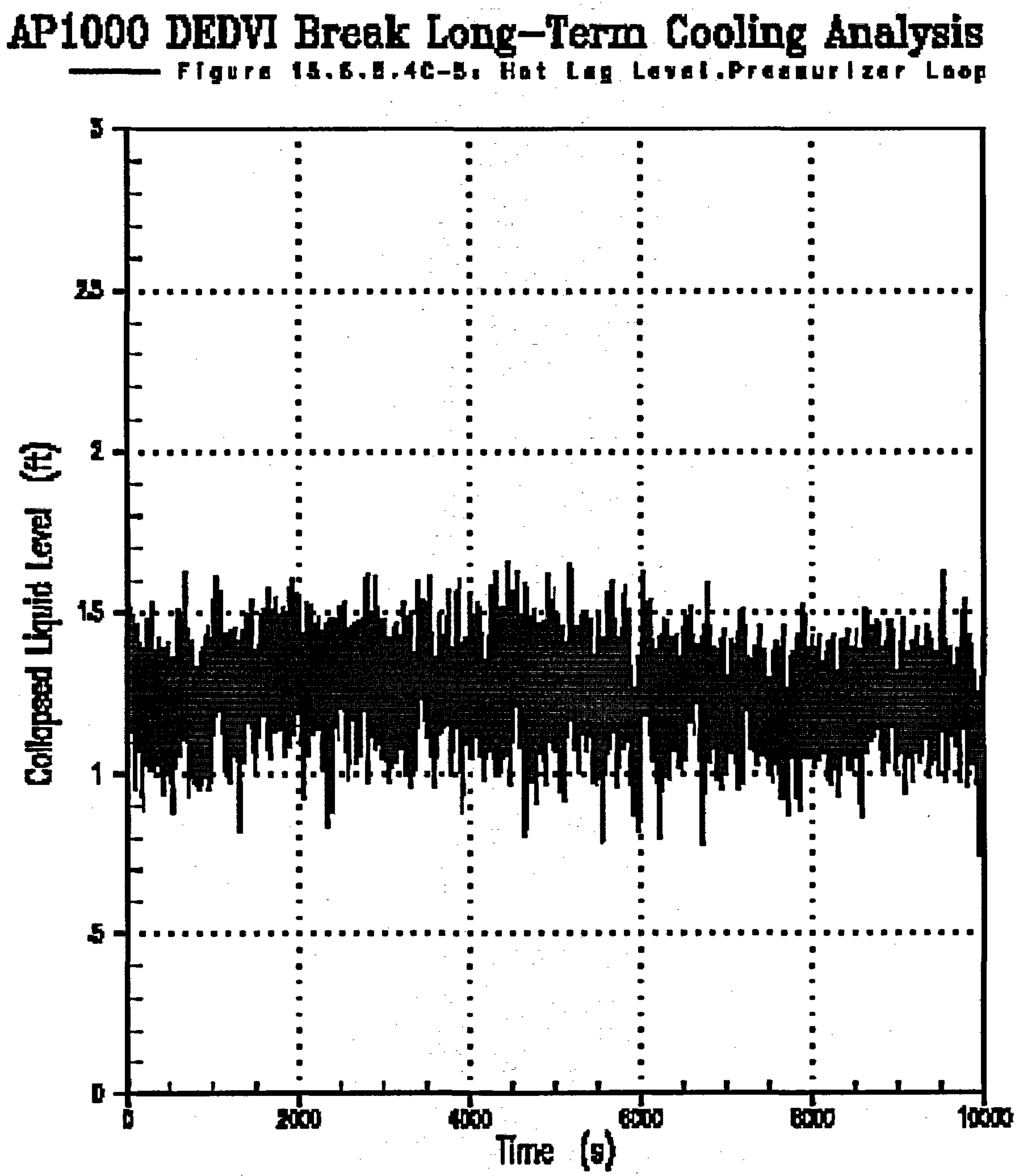

AP1000 DEDVI Break Long–Term Cooling Analysis
Figure 15.6.5.4C-1: Downcomer Collapsed Level
Collapsed Liquid Level (ft)
Time (s)
0
5
10
15
20
25
0
2000
4000
6000
8000
10000

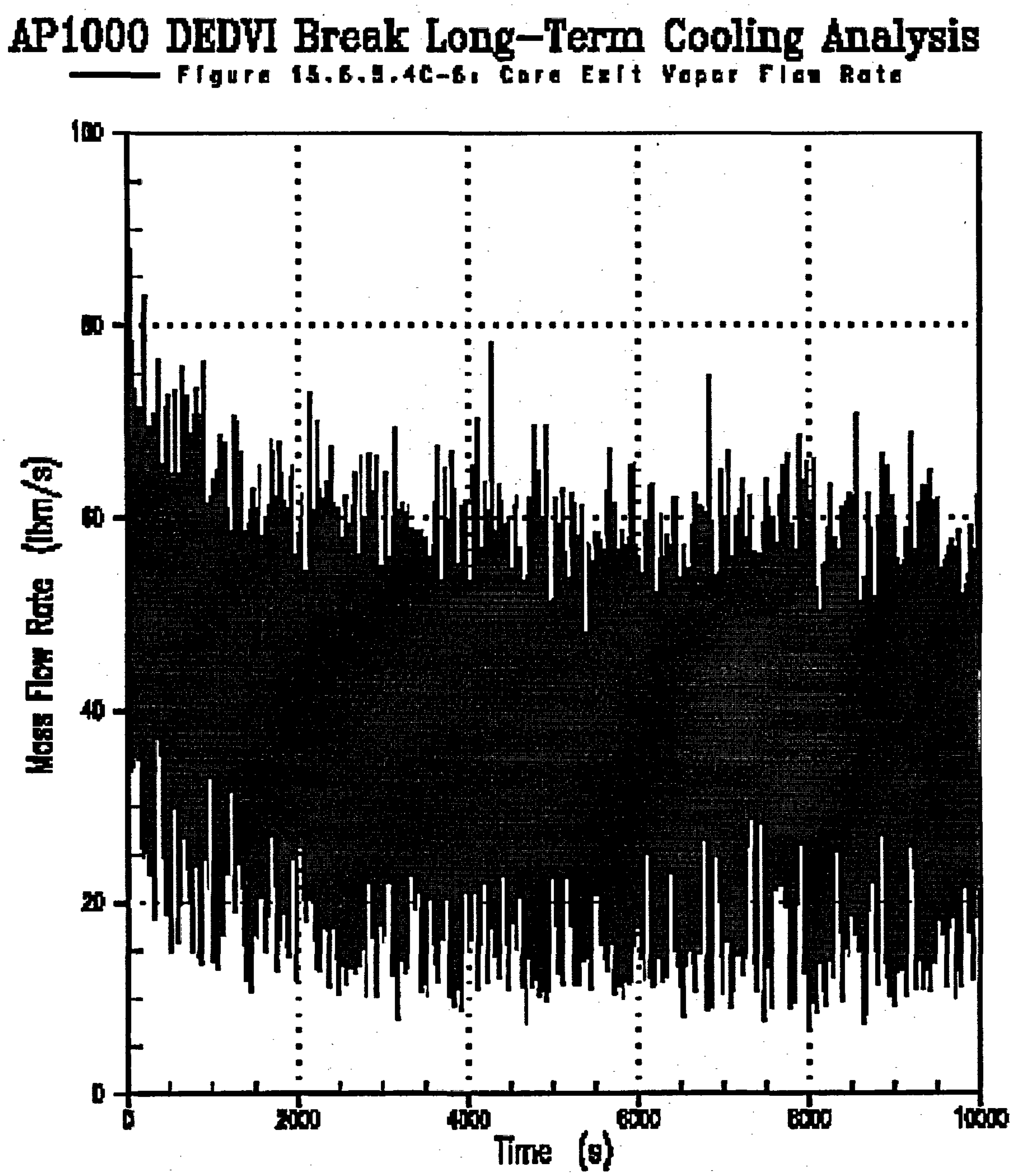
AP1000 DEDVI Break Long–Term Cooling Analysis

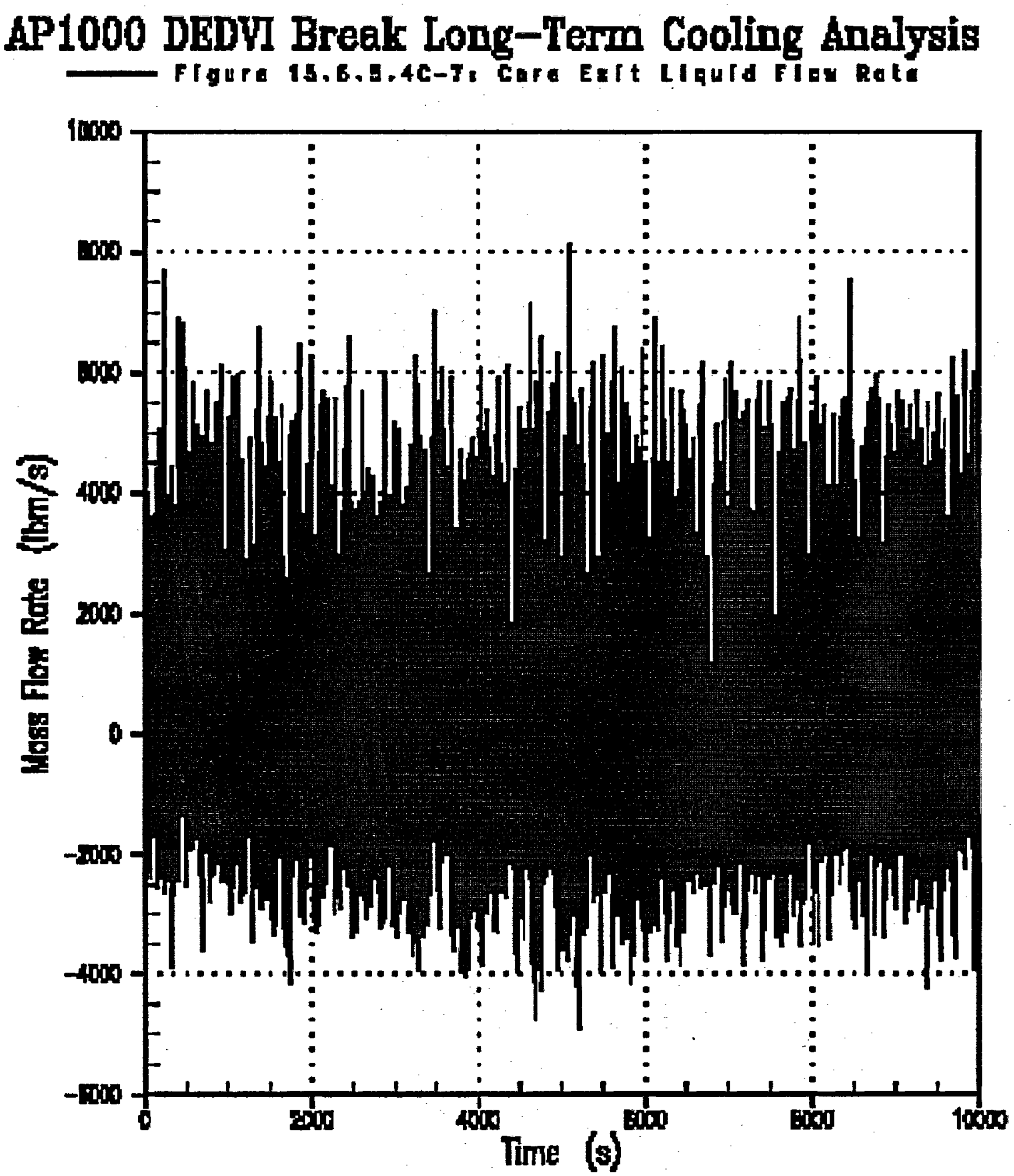


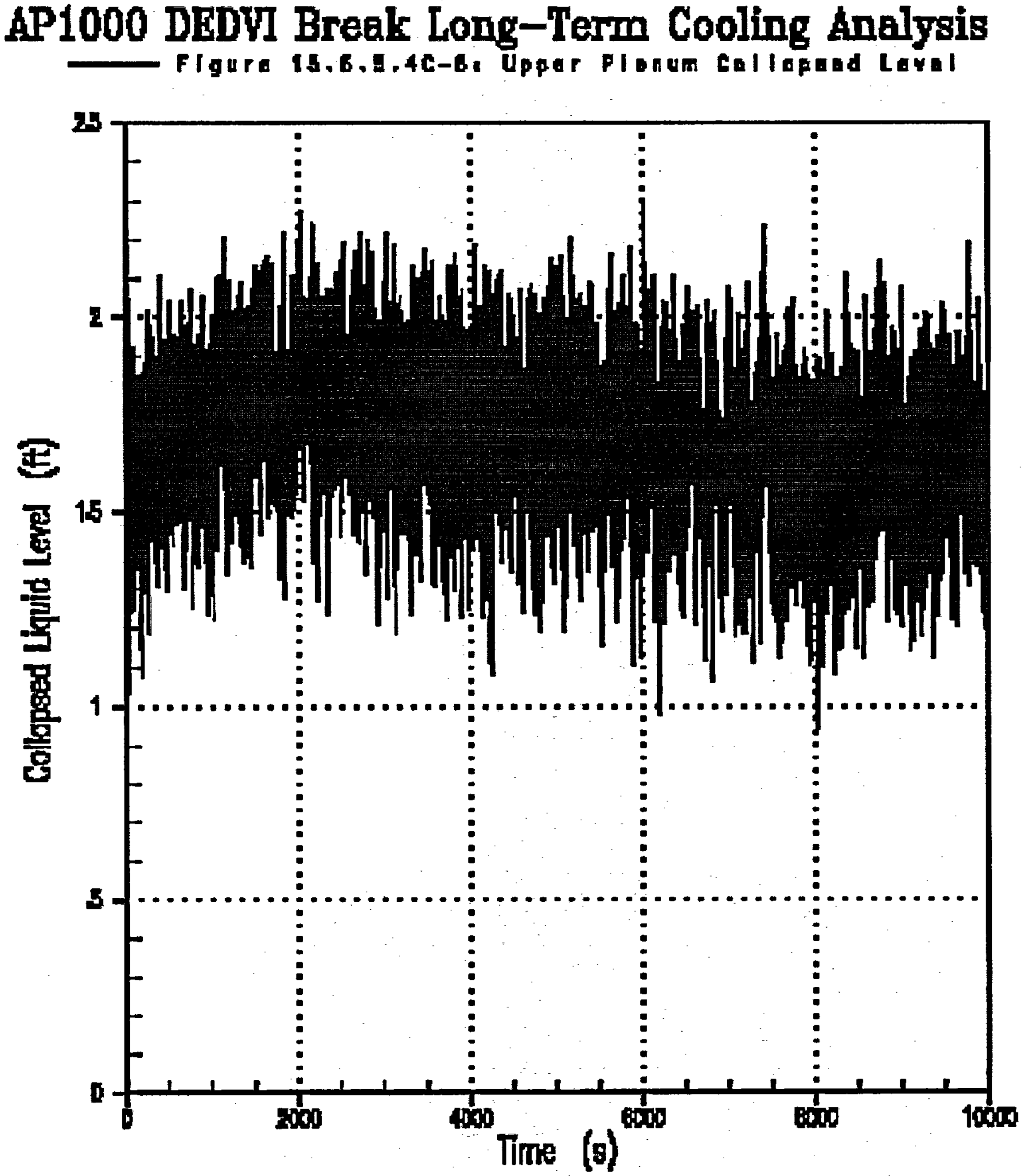

AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-3: Hot Assembly Top Cell Void
Void Fraction
Time (s)
0
.2
.4
.6
.8
1
0
2000
4000
6000
8000
10000


AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-4: Hot Assembly Second Cell Void
Void Fraction
1
.8
.6
.4
.2
0
0
2000
4000
6000
8000
10000
Time (s)

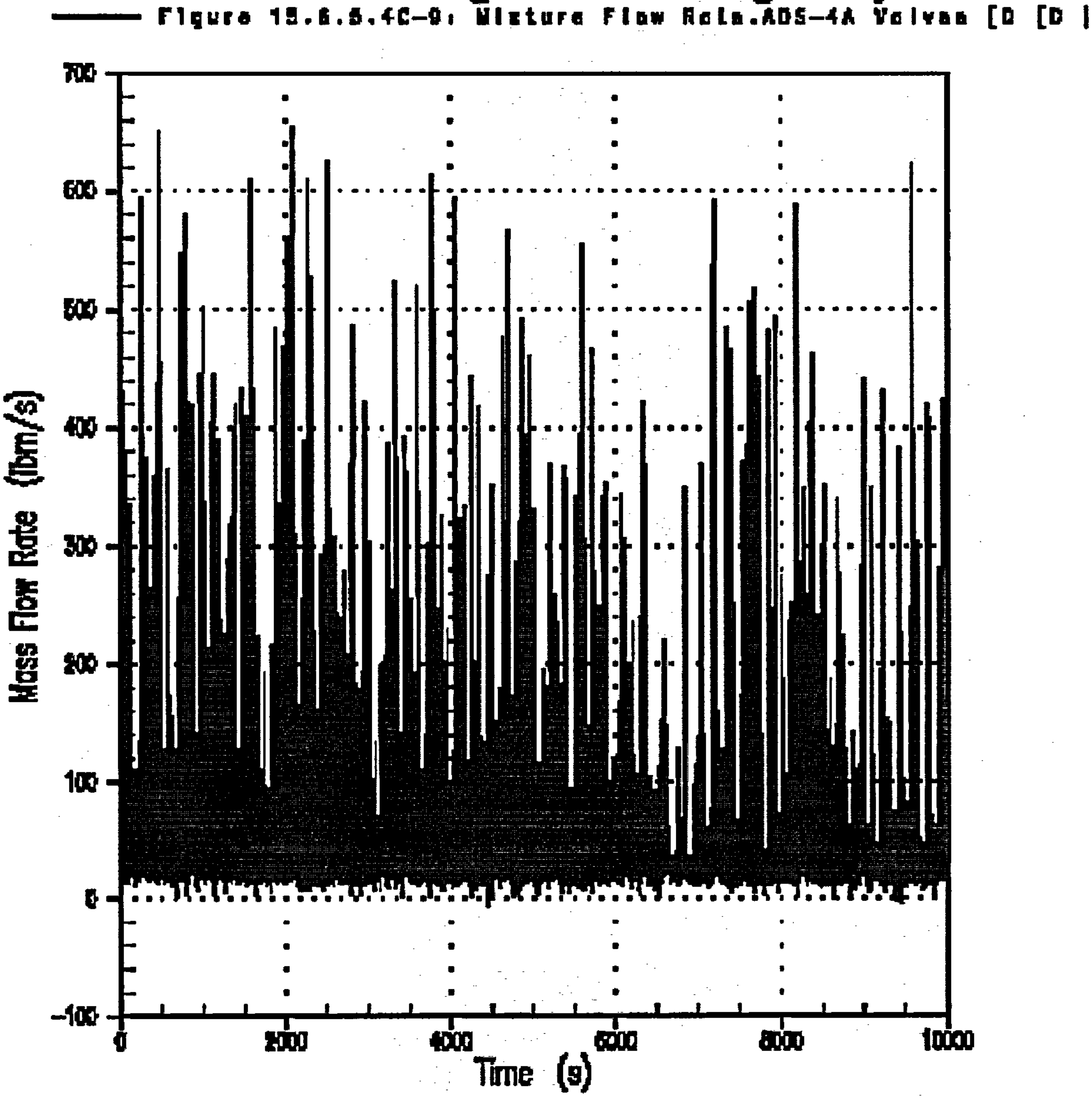

AP1000 DEDVI Break Long–Term Cooling Analysis
Figure 15.6.5.4C-5: Hot Leg Level.Pressurizer Loop
Collapsed Liquid Level (ft)
Time (s)
3
2.5
2
1.5
1
.5
0
0
2000
4000
6000
8000
10000

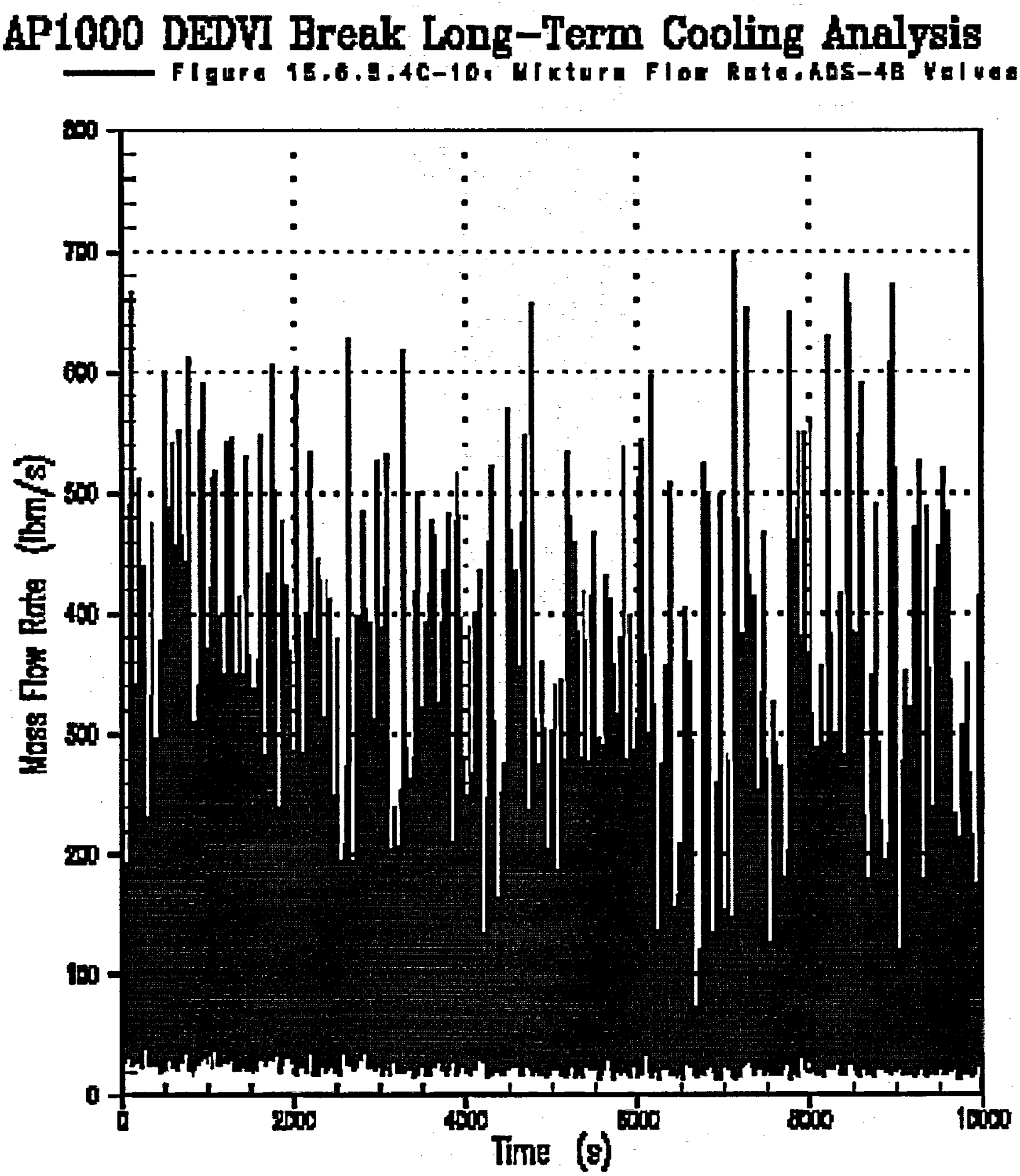

AP1000 DEDVI Break Long–Term Cooling Analysis
Figure 15.6.5.4C-6: Core Exit Vapor Flow Rate
Mass Flow Rate (lbm/s)
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
Time (s)


AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-7: Core Exit Liquid Flow Rate
Mass Flow Rate (lbm/s)
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
0
2000
4000
6000
8000
10000
Time (s)


AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-6: Upper Plenum Collapsed Level
2.5
2
1.5
1
.5
0
Collapsed Liquid Level (ft)
0
2000
4000
6000
8000
10000
Time (s)

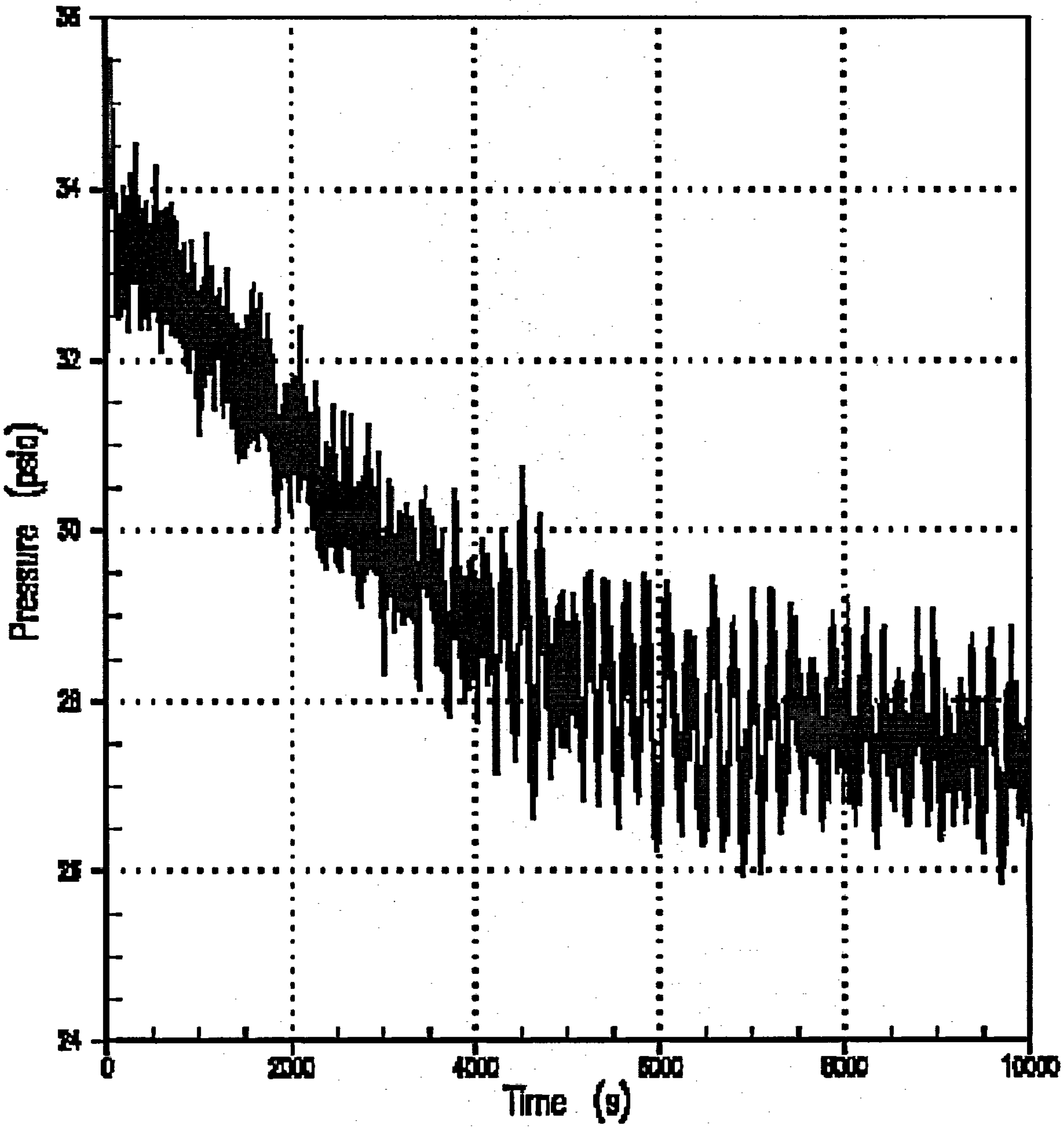
AP1000 DEDVI Break Long-Term Cooling Analysis

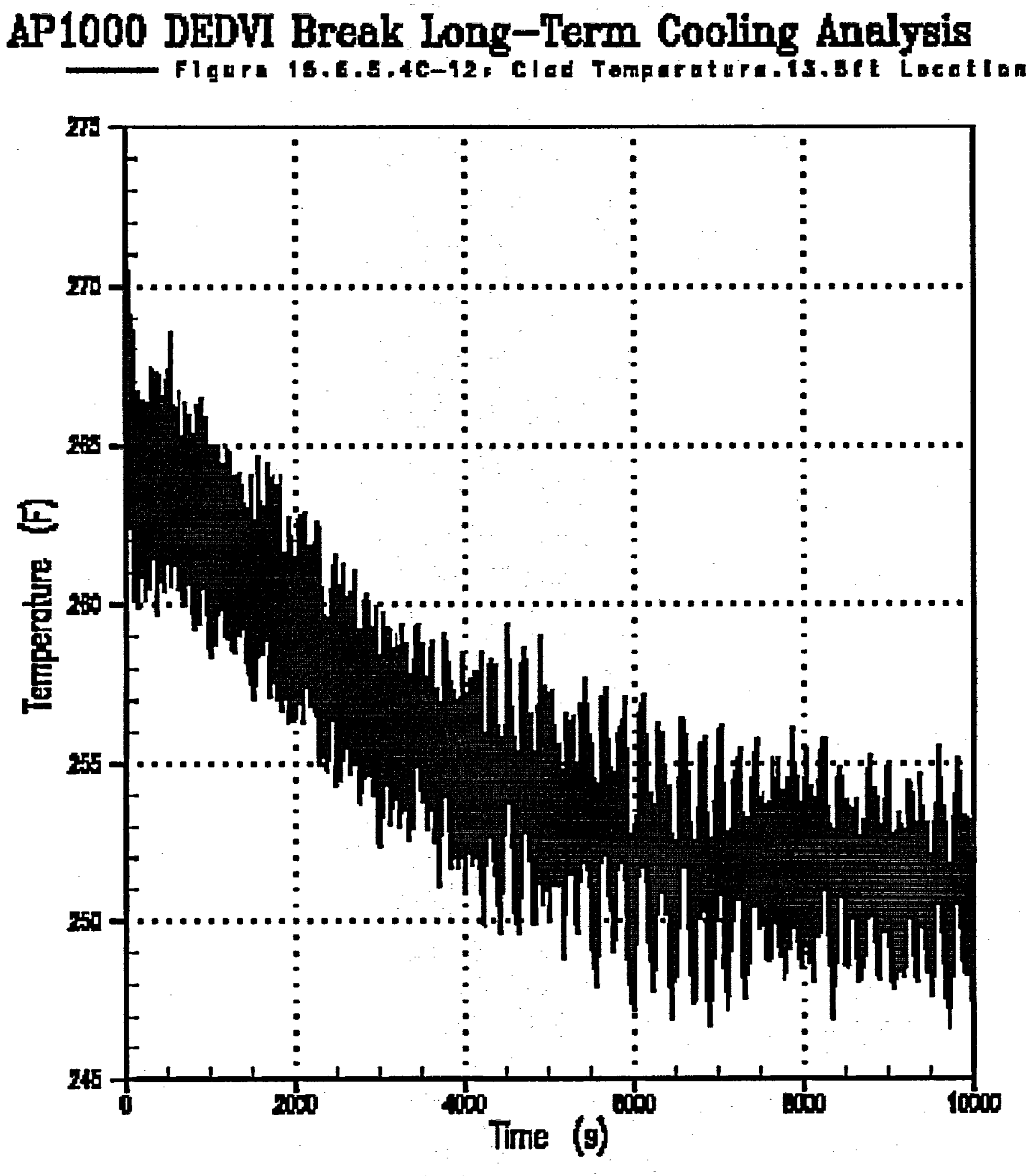


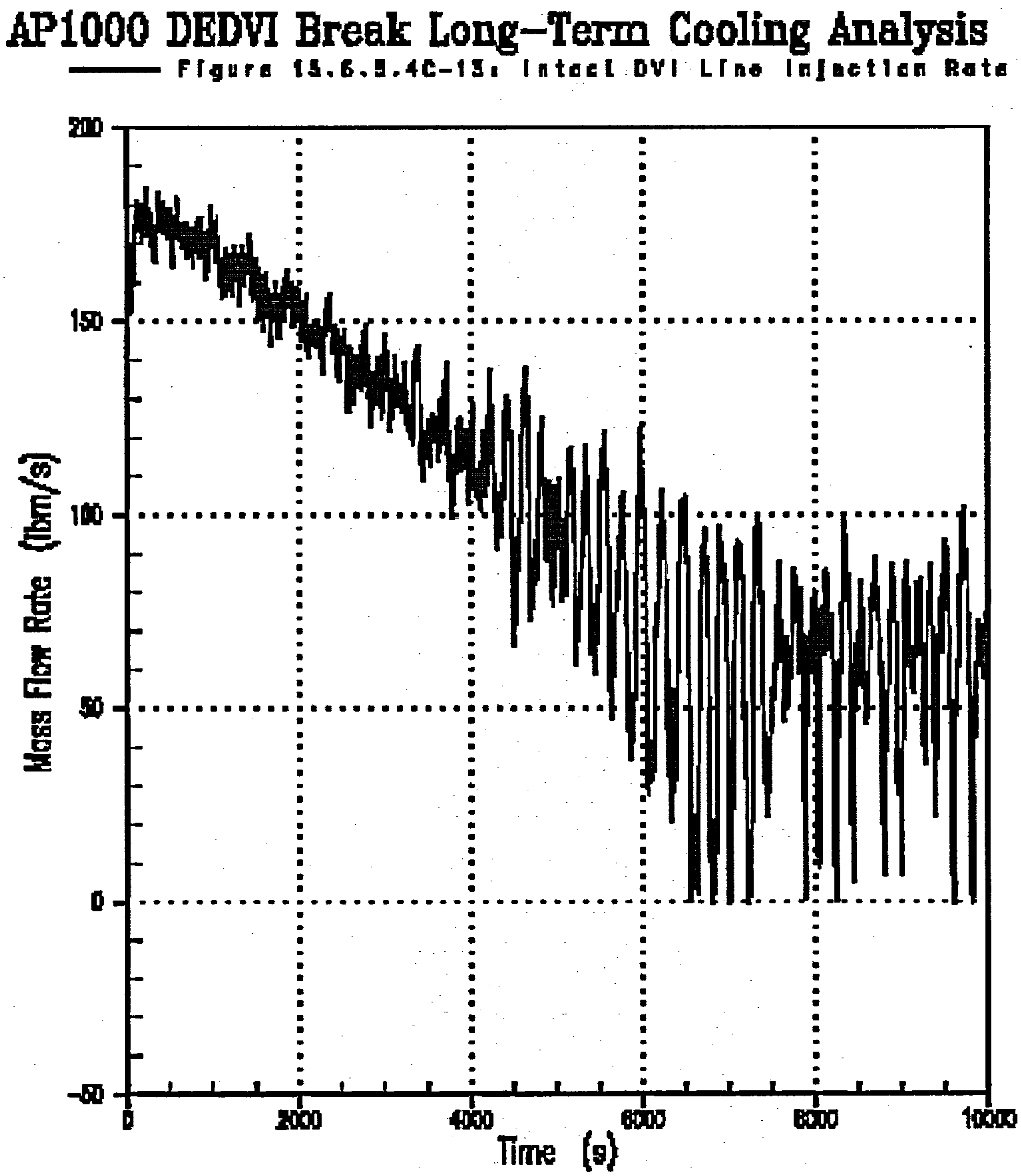

AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-10: Mixture Flow Rate,ADS-4B Valves
Mass Flow Rate (lbm/s)
800
700
600
500
400
300
200
100
0
0
2000
4000
6000
8000
10000
Time (s)

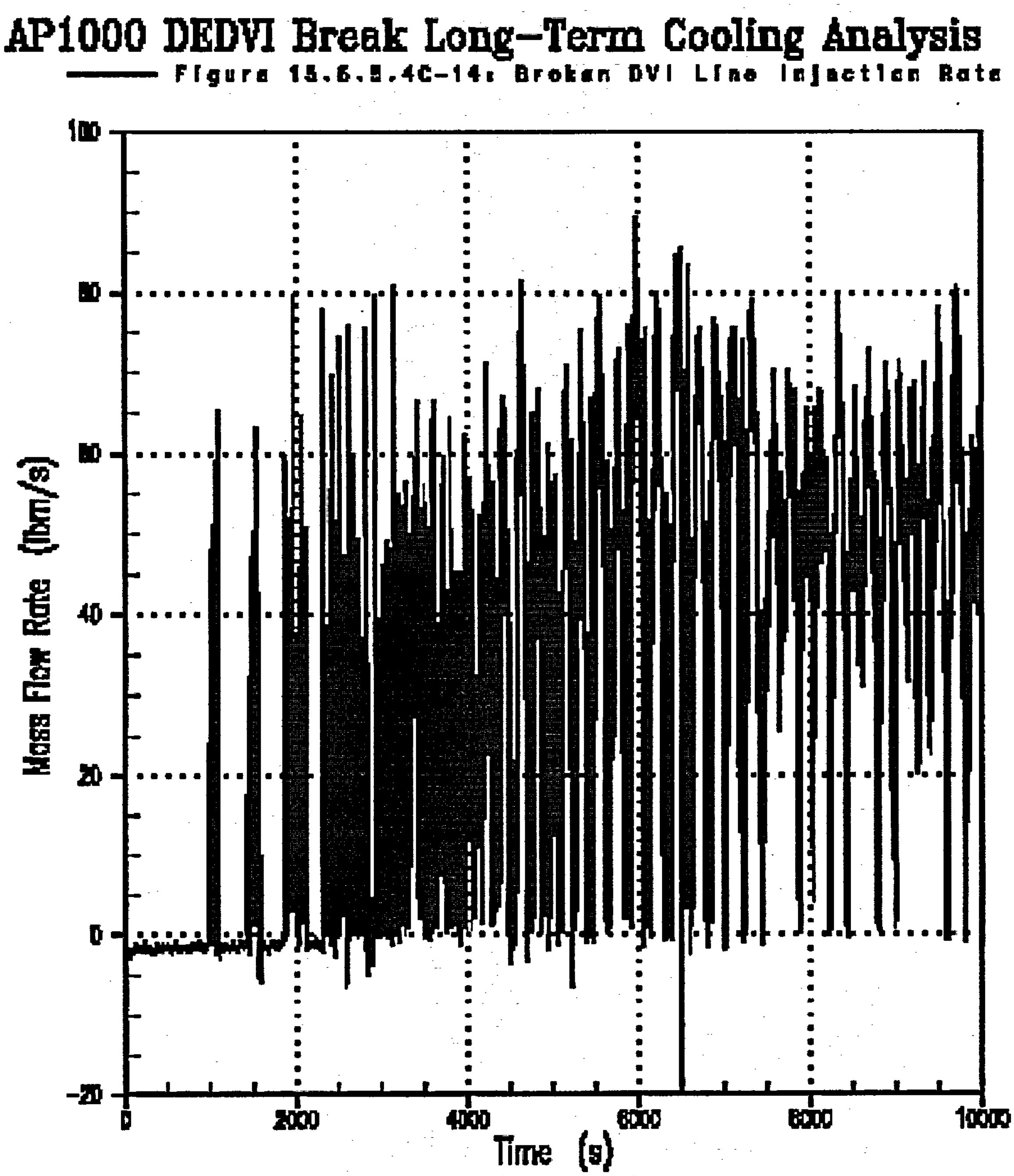
AP1000 DEDVI Break Long-Term Cooling Analysis

Figure 15.6.5.4C-11: Upper Plenum Pressure




AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-12: Clad Temperature.13.5ft Location
275
270
265
260
255
250
245
Temperature (F)
0
2000
4000
6000
8000
10000
Time (s)


AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-13: Intact DVI Line Injection Rate
200
150
100
50
0
-50
Mass Flow Rate (lbm/s)
0
2000
4000
6000
8000
10000
Time (s)


AP1000 DEDVI Break Long-Term Cooling Analysis
Figure 15.6.5.4C-14: Broken DVI Line Injection Rate
Mass Flow Rate (lbm/s)
100
80
60
40
20
0
-20
0
2000
4000
6000
8000
10000
Time (s)

PRA Revision:

None

WCAP Revision:

WCAP 15644 "AP1000 Code Applicability Report" will be revised to include the description and additional validation of the WCOBRA/TRAC long term cooling model discussed in this response.

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: **15.3-2**

Original RAI Number(s): **451.006, 451.006 Rev. 1**

Summary of Issue:

Staff review of the control room atmospheric dispersion factors is not complete (see Section 2.3.4 of this report). Pending resolution of staff's concerns with the hypothetical reference control room χ/Q values, review of the control room habitability radiological consequences analysis is also incomplete for each of the following design basis accidents. Inputs other than the assumed χ/Q values have been found acceptable. Using the control room χ/Q values provided in the AP1000 DCD, the staff has also preliminarily confirmed Westinghouse's control room doses for accidents other than the LOCA. Upon completion of the staff's review of the applicant's hypothetical reference control room χ/Q values, the staff will complete review of the control room habitability radiological consequences analyses. This is Open Item 15.3-2.

Westinghouse Response:

This item will be resolved through the resolution of DSER Open Item 2.3.4-1.

Design Control Document (DCD) Revision:

None

PRA Revision:

None

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: **21.5-1**

Original RAI Number(s): **440.151, 440.152, 440.154**

Summary of Issue:

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

Westinghouse Response:

In order to assess the potential impact of upper plenum and hot leg entrainment on the AP1000 plant design, a sensitivity study was performed with the Advanced Plant version of the NOTRUMP computer code. The AP1000 plant model, as defined for the DCD analysis effort, was modified as follows to perform this study:

- Insertion of fluid node [ ]^{a,c} in the core fluid-node stack that represents the [ ]^{a,c} and the [top of the core plate]. This node is inserted between fluid nodes [ ]^{a,c} and [ ]^{a,c} from the base DCD model. This results in the insertion of two additional flow links ([ ]^{a,c} and [ ]^{a,c}) for the added fluid node for the interior flow and reflux flow link types. In the base DCD model, this [ ]^{a,c} region is lumped into the [ ]^{a,c} stack. This modification was performed to improve the delineation between the [ ]^{a,c} regions. The base NOTRUMP noding diagram can be found in Figure 21.5-1.1 with the noding modifications performed shown in Figure 21.5-1.2.
- To account for a potential non-conservative pressure drop when modeling the fluid node/flow paths as homogenous, an additional pressure drop penalty, [ ]^{a,c}, is added to the ADS-4 discharge paths at the time when they become [ ]^{a,c}. This penalty corresponds to [ ]^{a,c}. This penalty is achieved via an [ ]^{a,c} as determined by the detailed momentum flux model (FLOAD4, Reference 21.5-1.1).

To confirm that the re-nodalization that was performed did not significantly impact the transient results, a comparison of the base DCD and the revised nodalization results will be presented first.

Figure 21.5-1.3 presents the core/upper plenum region two-phase mixture level comparison between the base DCD model and the revised noding model. As can be seen, the changes between the two cases are negligible. Figure 21.5-1.4 presents the two-phase downcomer mixture level comparison for the downcomer region between these same two cases. Again, the differences between the two cases are negligible.

Figure 21.5-1.5 presents a comparison of the upper downcomer pressure between the two cases. As can be seen, the pressure responses are nearly identical. As a result, the predicted intact DVI line IRWST injection flow (Figure 21.5-1.6) is also unchanged.

As can be observed from Figure 21.5-1.7, the vessel mixture masses are comparable between the two cases with the revised noding case having a slightly lower overall vessel inventory. This is due primarily to the improved resolution of the vessel mass in the [ ]^{a,c}. The revised noding reflects a more accurate depiction of the geometry and subsequently the void profile in this region. However, this does not impact the active fuel region of the vessel as can be seen in Figure 21.5-1.8 and Figure 21.5-1.9 respectively. Both the active region mass and void fraction profiles are approximately the same. As a result, the active fuel region collapsed mixture level (Figure 21.5-1.10) is also approximately the same.

Figure 21.5-1.11 presents the Pressurizer level response for the two cases. As can be seen, the responses are nearly the same for both cases.

Figure 21.5-1.12 and Figure 21.5-1.13 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.

Now that the baseline case has been established (i.e. re-noded core/upper plenum region), the sensitivity case can be described. The sensitivity case is performed to assess the effect of higher than expected entrainment in the upper plenum and hot legs on the overall system response and core cooling. The higher than expected entrainment is included in the analysis by assuming homogenous conditions in the upper plenum, hot legs and ADS-4 piping. The sensitivity involves the conversion of the fluid nodes representing the Upper Plenum [ ]^{a,c}, Hot Legs [ ]^{a,c}, the PRHR Inlet [ ]^{a,c} to homogenous following ADS-4 actuation (~500 seconds). This also involves making the hot leg inlet flow paths [ ]^{a,c}, PRHR Inlet [ ]^{a,c}, and ADS-4 Inlet [ ]^{a,c} homogenous as well. As a result of the noding modifications, the Upper Plenum fluid node must be removed from the core fluid-node stack. This will allow for the formation of a distinct two-phase mixture level below the core plate should the conditions support it's generation. If this modification is not performed, the NOTRUMP mixture level tracking model would not allow the region below the core plate to form a distinct mixture level and subsequently, core uncovery would not occur unless the fluid node void fractions in the region became 1.0 (i.e. all vapor). In addition, since the homogenous treatment of this region

will eliminate the pressure drop effect out of the fluid stored in the upper plenum, the NOTRUMP model was conservatively adjusted [ ]^{a,c}. This was accomplished by applying an additional [pressure drop penalty on the [ ]^{a,c} flow paths.

Figure 21.5-1.14 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 21.5-1.15). 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 21.5-1.16. As expected, the initial ADS-4 liquid discharge is much higher (Figure 21.5-1.17) until the inventory which resided in the upper plenum and hot leg regions was depleted (Figure 21.5-1.18). The net effect is a decrease in the ADS-4 vapor discharge rate (Figure 21.5-1.19) and subsequently higher RCS pressures.

Due to the elimination of the inventory stored in the upper plenum, the downcomer mass is also reduced (Figure 21.5-1.20) 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 21.5-1.21). The net effect of the sensitivity case is that the vessel inventory is substantially decreased over the base model simulation (Figure 21.5-1.22); however, this inventory is sufficient for adequate core cooling because the ADS-4 continually draws liquid flow through the core (Figure 21.5-1.17). Even though there is no liquid storage in the upper plenum for the homogenous case (Figure 21.5-1.23), the coverage percentage (Figure 21.5-1.24) is not impacted significantly.

The pressurizer mixture level response (Figure 21.5-1.25) reflects the change in pressure response (Figure 21.5-1.14) observed in the model as a result of the sensitivity study.

This sensitivity demonstrates that the AP1000 plant response is relatively insensitive to upper plenum and hot leg entrainment. Even with the assumption of homogenous fluid nodes above the core, adequate core cooling is demonstrated.

Design Control Document (DCD) Revision:

None

PRA Revision:

None

References:

21.5-1.1 WCAP-14807, Revision 5, NOTRUMP Final Validation Report for AP600, Volume 3, Appendix-A, RAI-440.796F, Part a, August 1998.

21.5-1.2 Response to DSER Open Item 25.1-3.

a,b,c

Figure 21.5-1.1 AP1000 NOTRUMP Noding Diagram

a.b,c

Figure 21.5-1.2 Vessel Noding Modifications

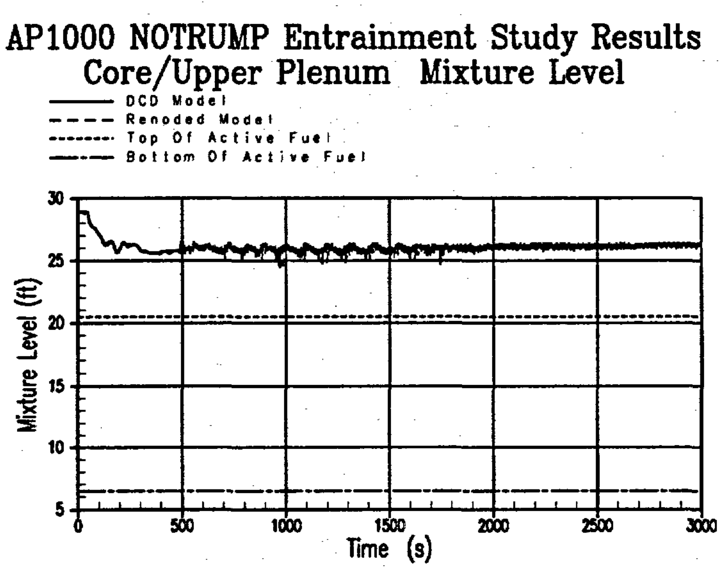


Figure 21.5-1.3 Core/Upper Plenum Mixture Level Comparison

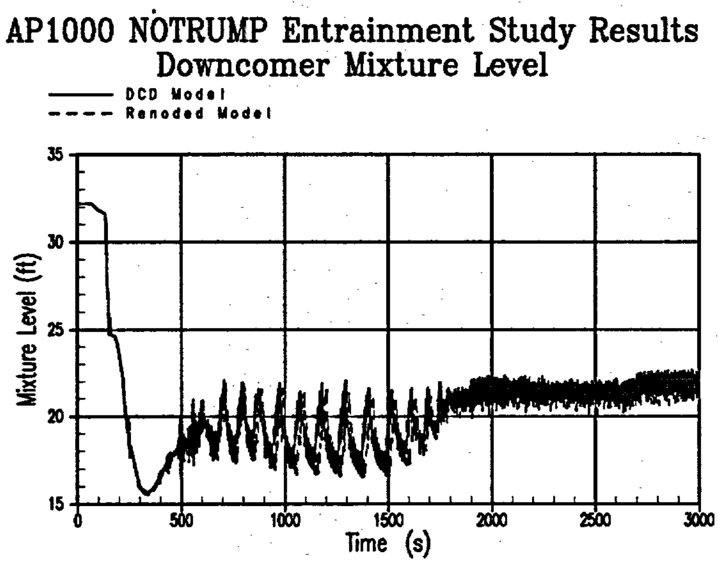


Figure 21.5-1.4 Downcomer Level Comparison

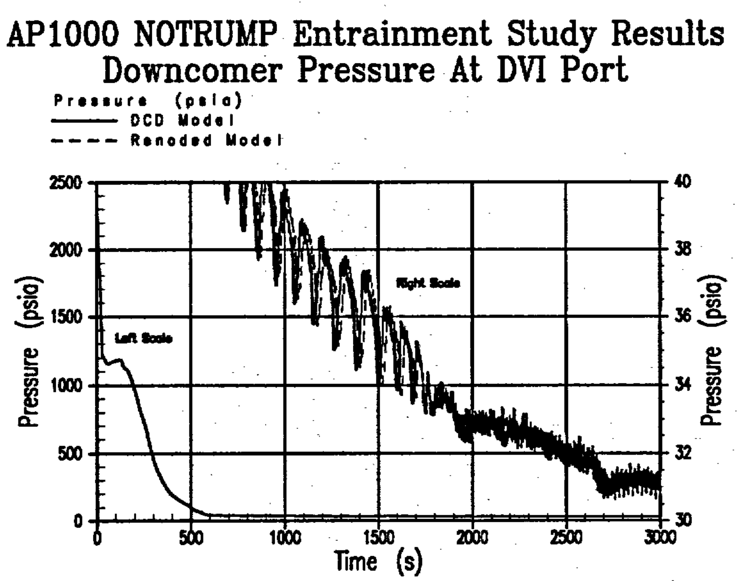


Figure 21.5-1.5 Downcomer Pressure Comparison

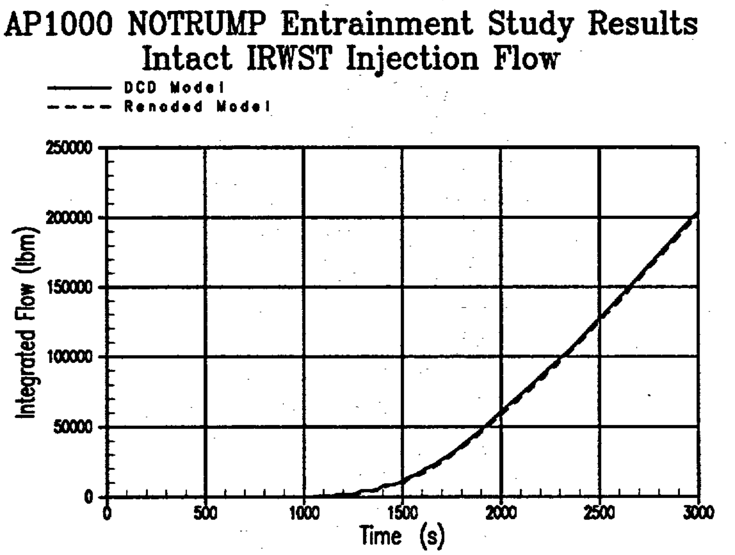


Figure 21.5-1.6 Intact IRWST Injection Comparison

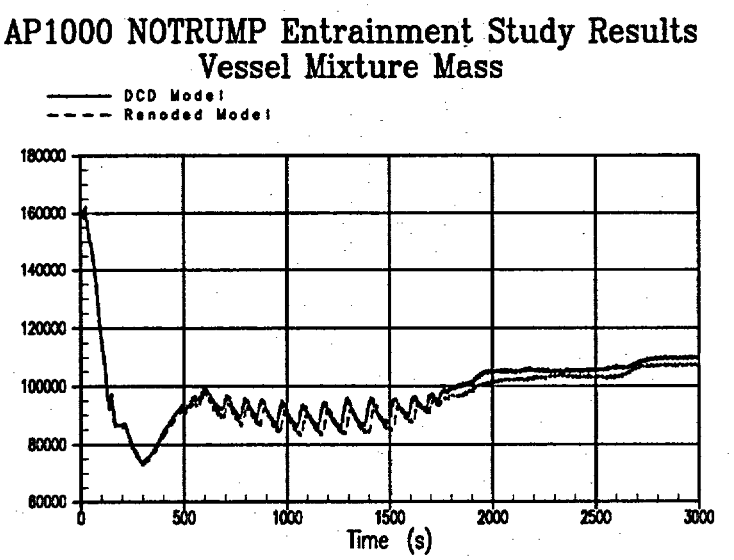


Figure 21.5-1.7 Vessel Mixture Mass Comparison

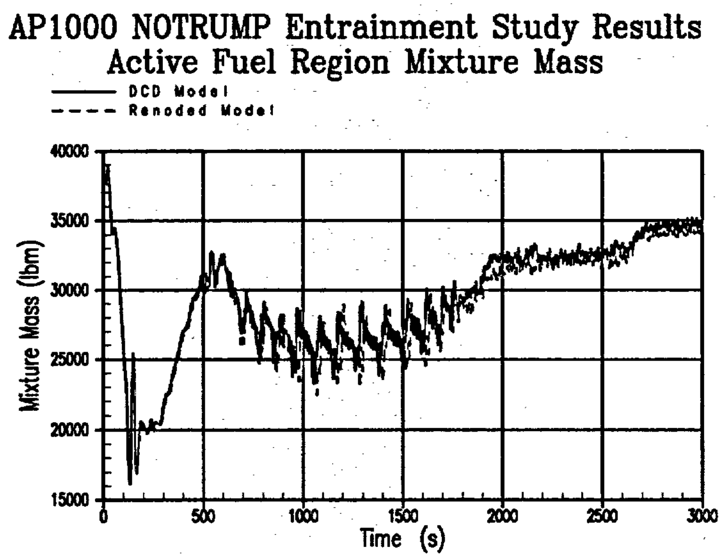


Figure 21.5-1.8 Active Fuel Region Mixture Mass Comparison

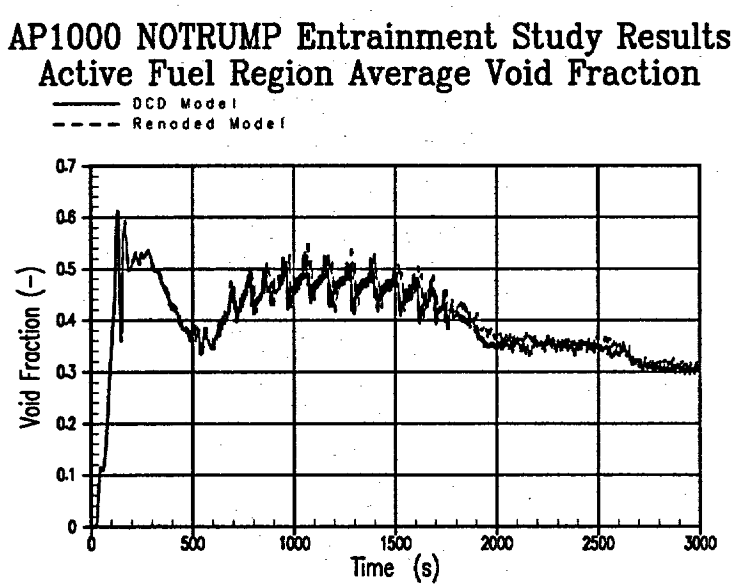


Figure 21.5-1.9 Active Fuel Region Core Average Void Fraction

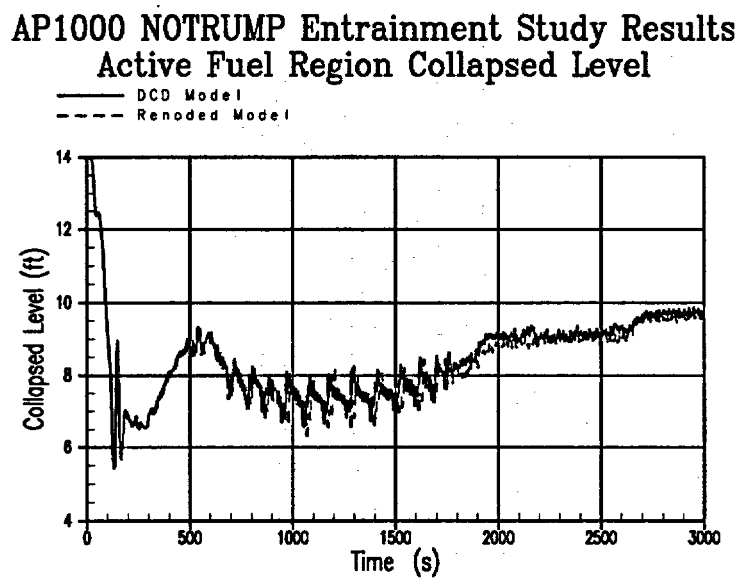


Figure 21.5-1.10 Active Fuel Region Core Collapsed Level

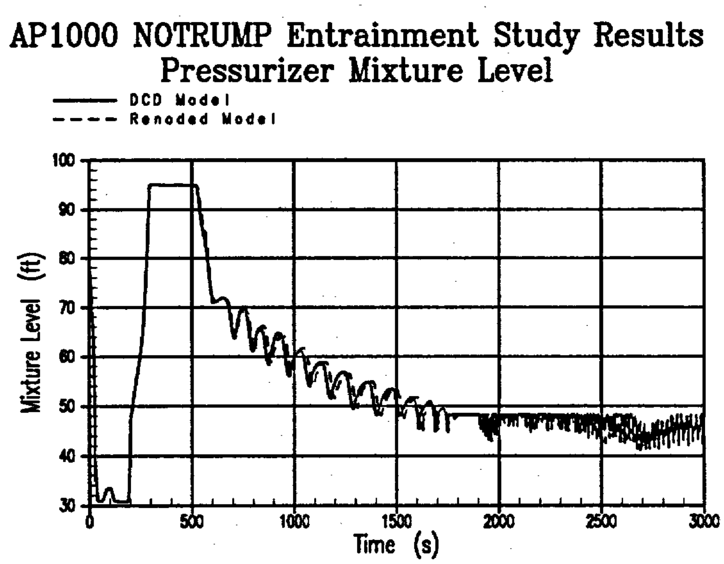


Figure 21.5-1.11 Pressurizer Level Comparison

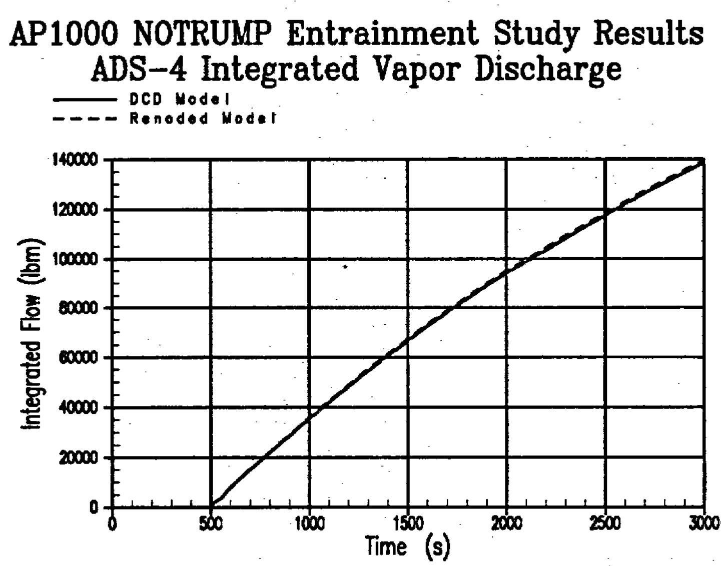


Figure 21.5-1.12 ADS-4 Liquid Discharge Comparison

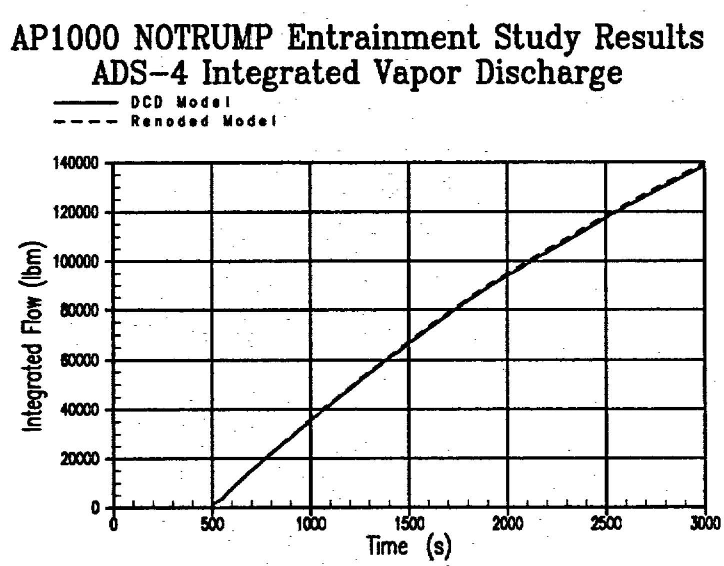


Figure 21.5-1.13 ADS-4 Vapor Discharge Comparison

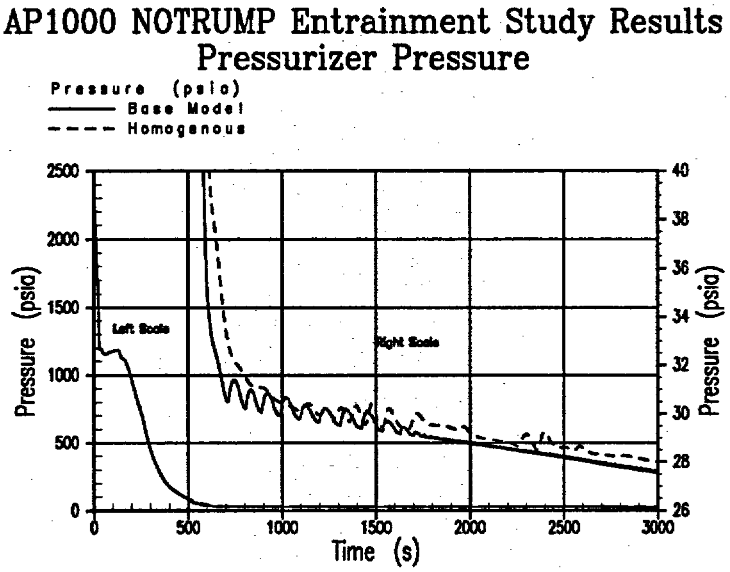


Figure 21.5-1.14 Downcomer Pressure Comparison

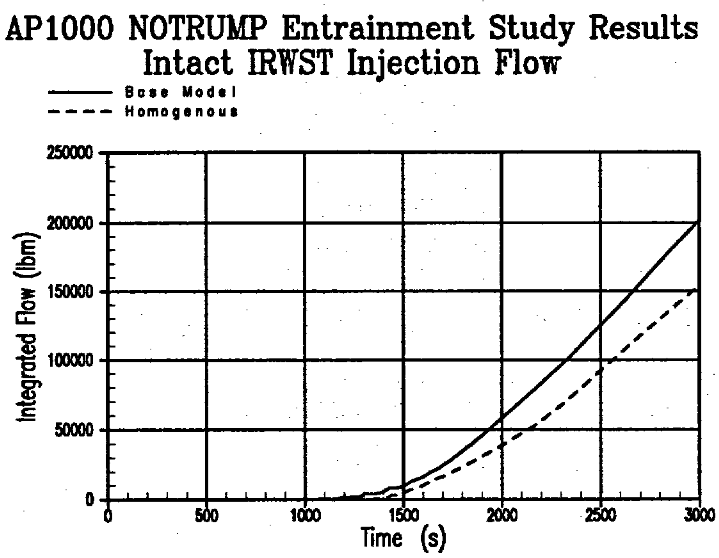


Figure 21.5-1.15 Intact IRWST Injection Flow

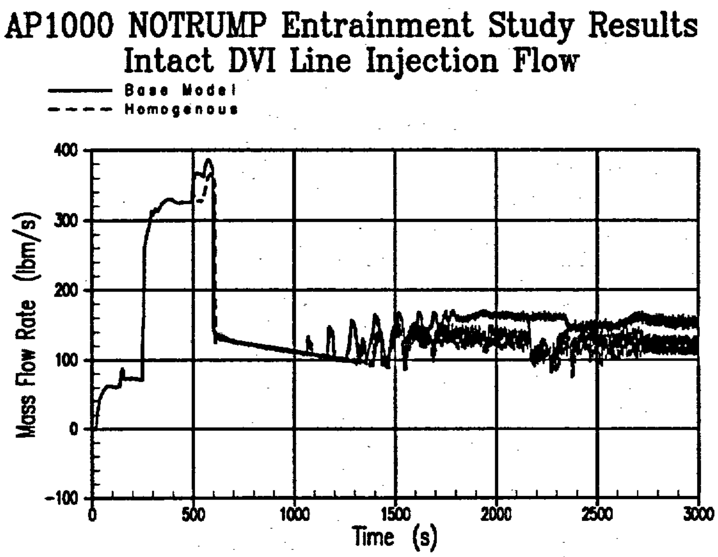


Figure 21.5-1.16 Intact DVI Line Injection Flow

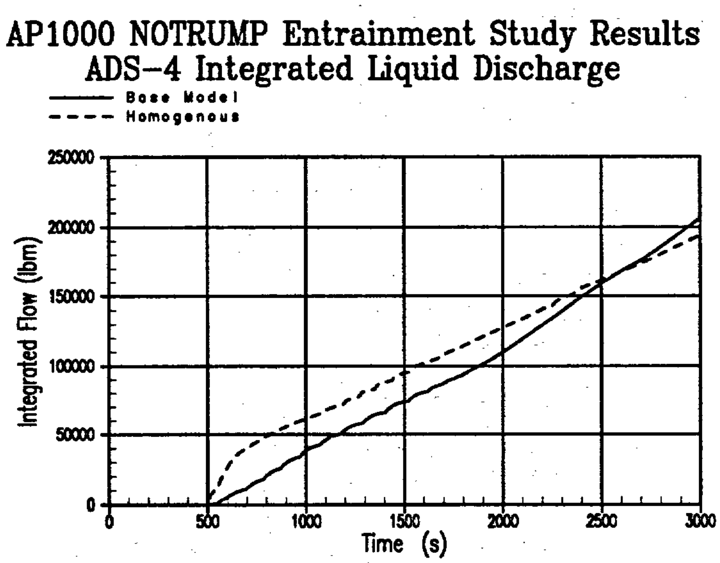


Figure 21.5-1.17 ADS-4 Integrated Liquid Discharge Comparison

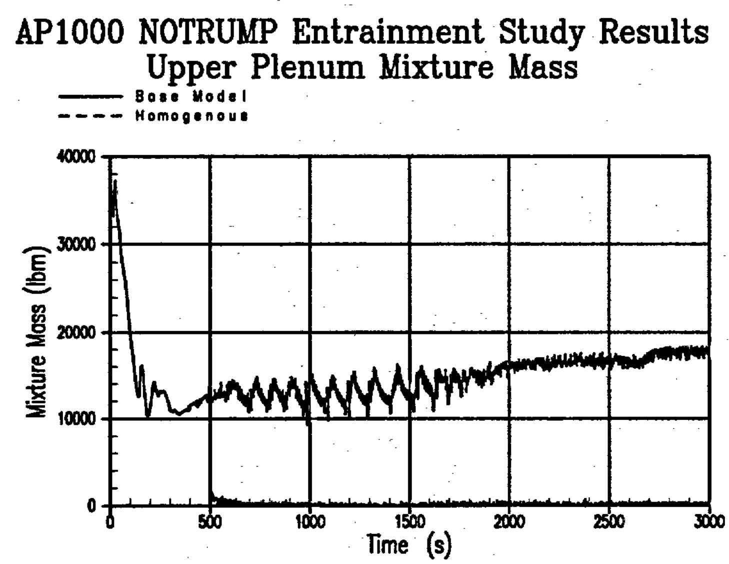


Figure 21.5-1.18 Upper Plenum Mixture Mass Comparison

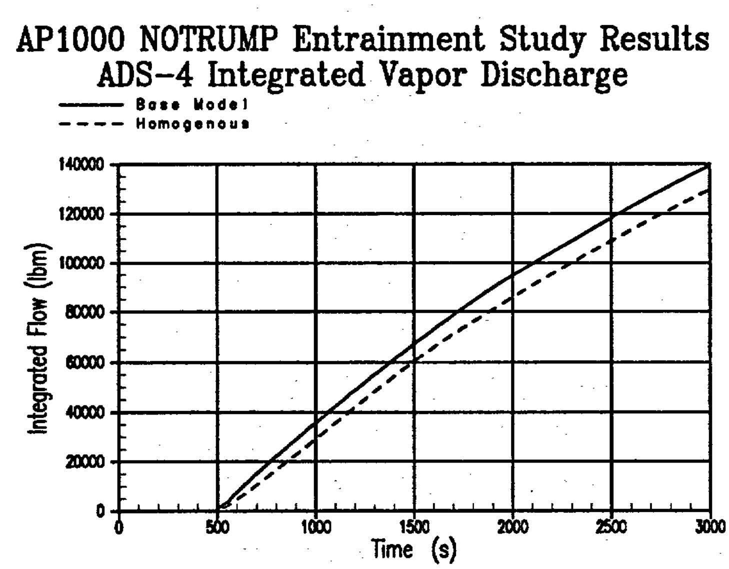


Figure 21.5-1.19 ADS-4 Integrated Vapor Discharge Comparison

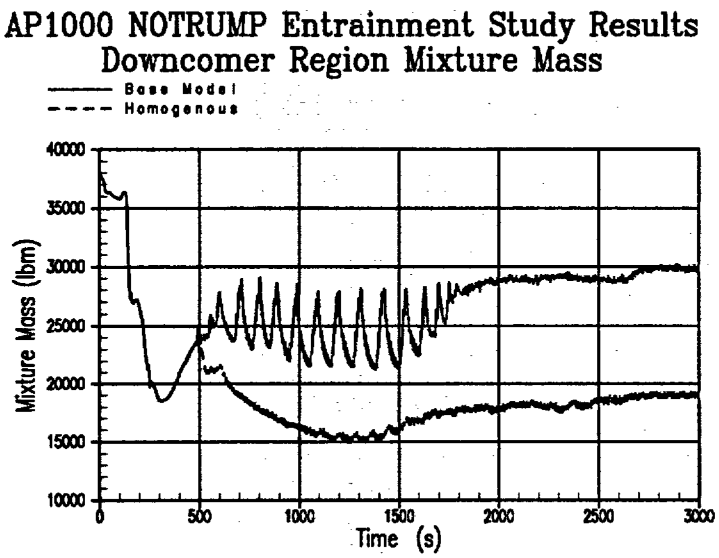


Figure 21.5-1.20 Downcomer Region Mass Comparison

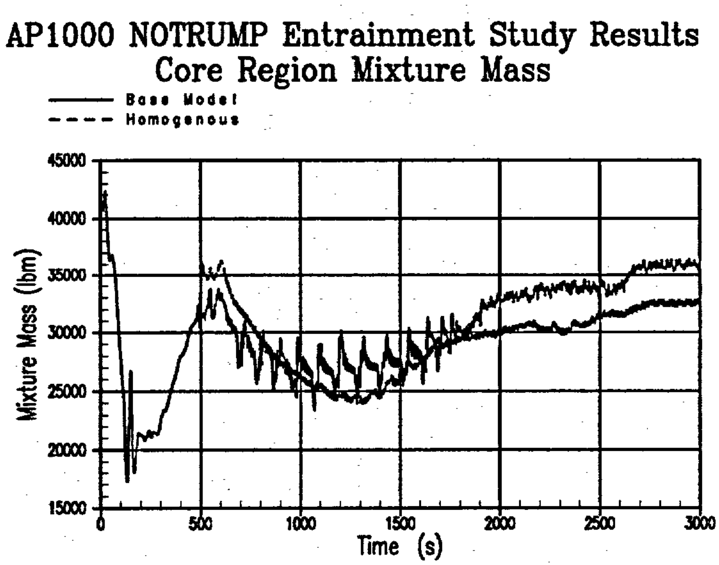


Figure 21.5-1.21 Core Region Mass Comparison

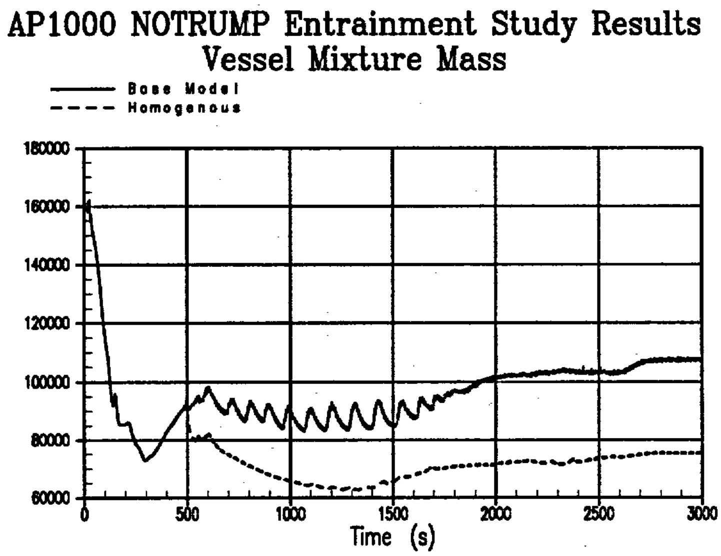


Figure 21.5-1.22 Vessel Mixture Mass Comparison

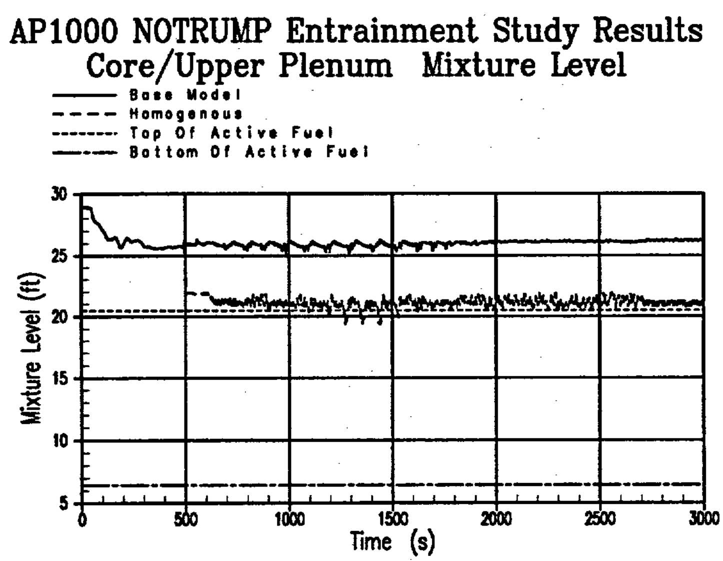


Figure 21.5-1.23 Core/Upper Plenum Mixture Level Comparison

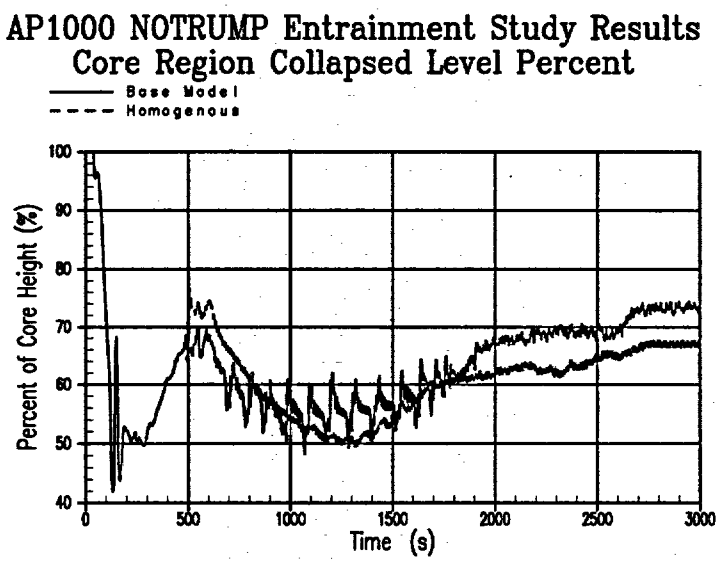


Figure 21.5-1.24 Core Coverage Percentage Comparison

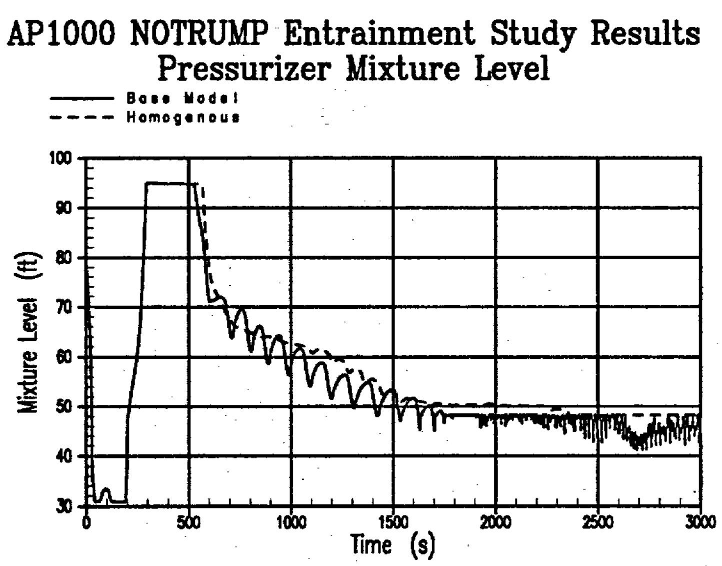


Figure 21.5-1.25 Pressurizer Mixture Level Comparison

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: 21.5-3

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:

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 (Zsub) from the bottom of the heated length.

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

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

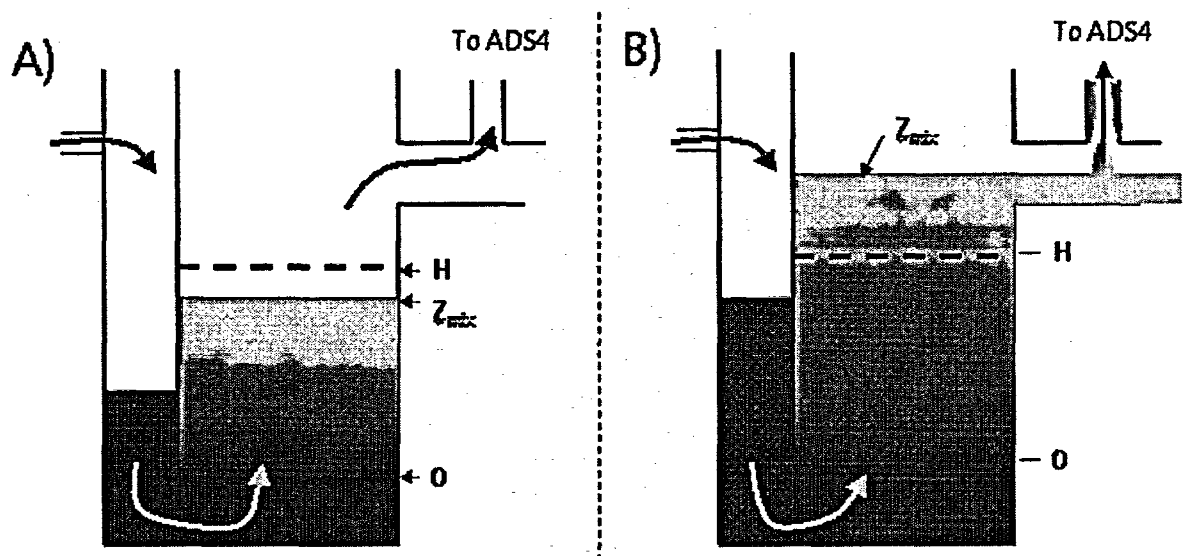
Figure 1 – Calculated vs. Predicted Swell

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

The Simple Model consists of three sub-models:

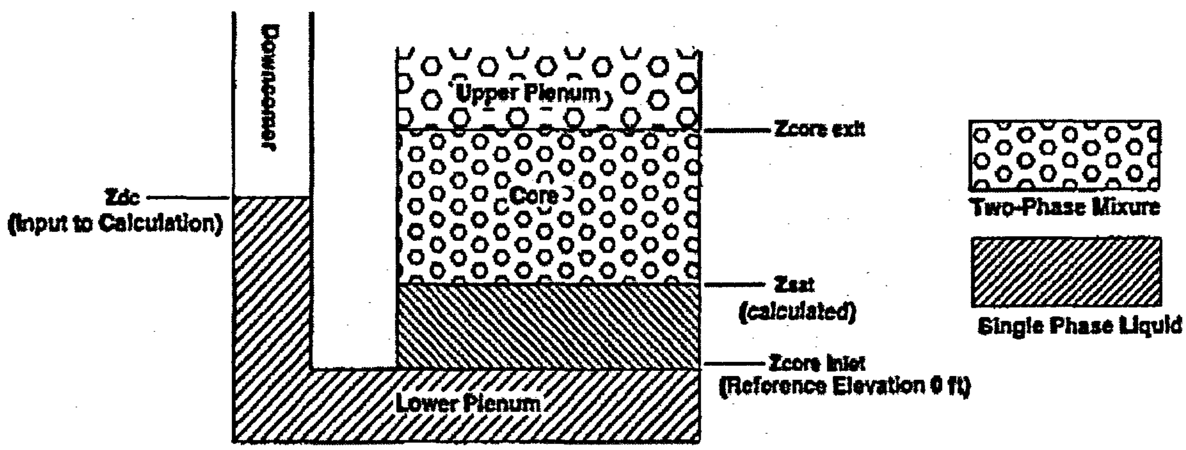
1. Core region (including the downcomer)
2. Core exit region (including the upper plenum, hot leg, ADS-4 paths and the ADS)
3. Safety injection from CMT and IRWST

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

Figure 1 provides a schematic diagram of the downcomer/core region modeled in the following conservation equations.

Figure 1: Downcomer/Core Region



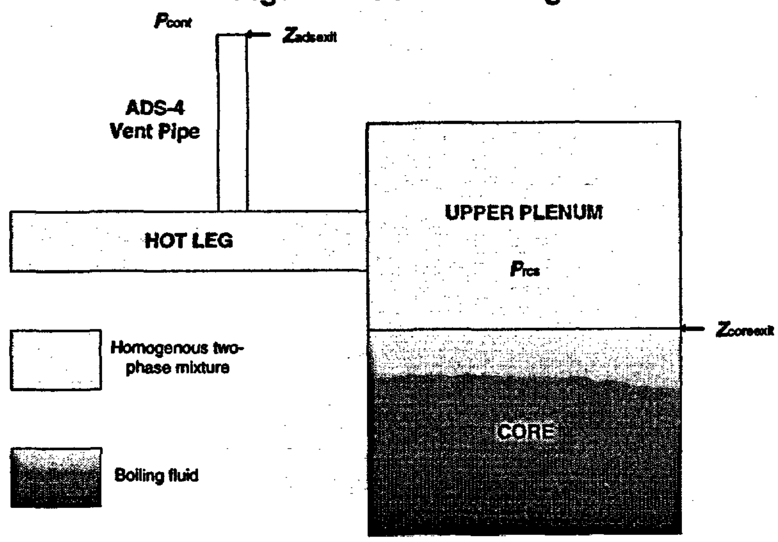
The conservation of mass equation for Steady State, 1-D, flow in a constant area channel is as follows:

a, b, c

a, b, c

a, b, c

Figure 2: Core Exit Region



a, b, c

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

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

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) form the NOTRUMP analysis of the SBLOCA DEDVI break (Tables A-2 ad 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.

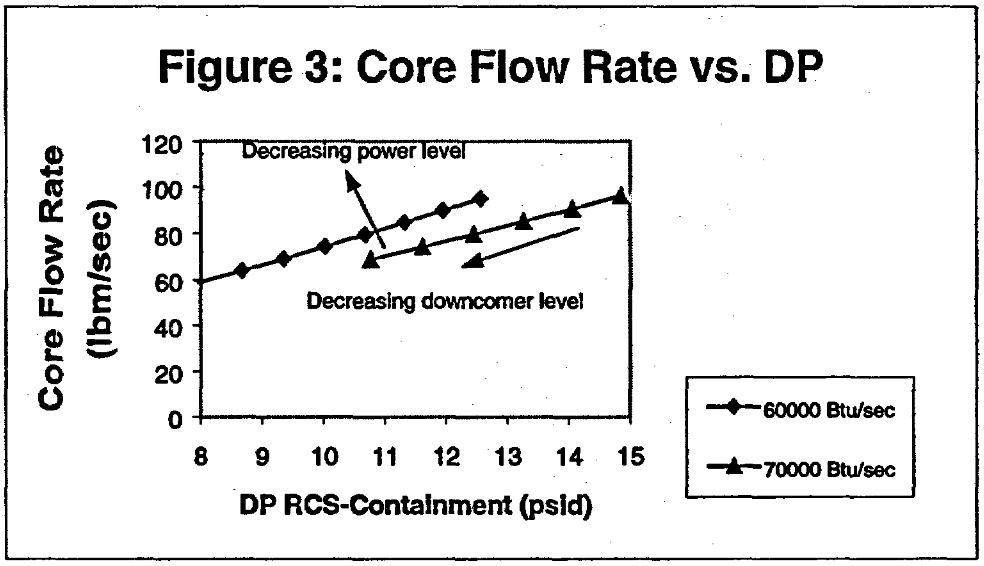


Figure 4 provides the calculated CMT flow rate results for AP1000. The CMT flow is calculated from steady state balance of CMT gravity head and DVI line resistance from CMT to reactor vessel. The results are based on flow from one CMT (DE DVI) at various liquid levels in CMT. Note that CMT flow is independent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

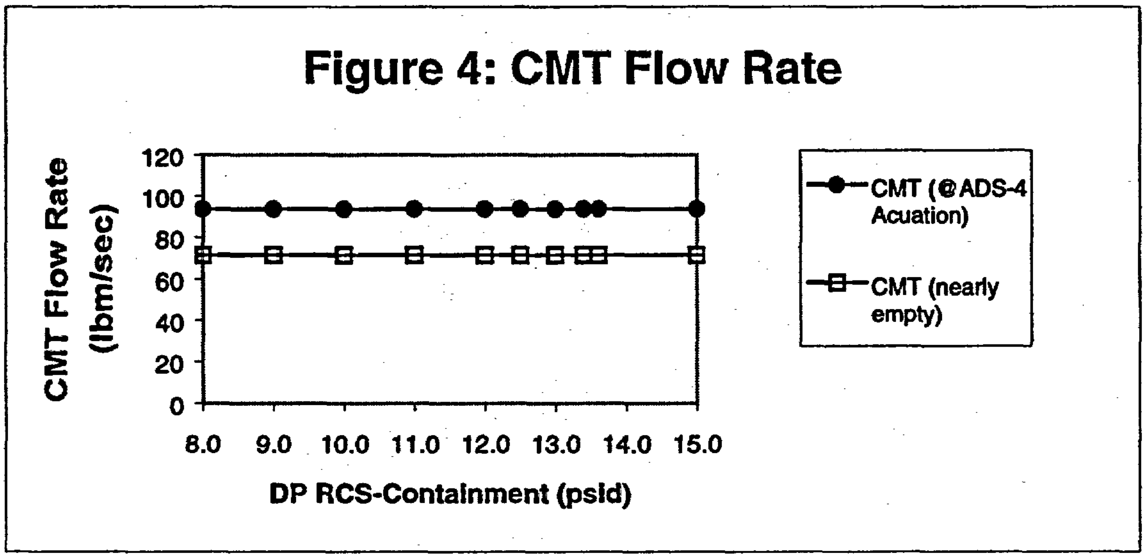


Figure 5 provides the calculated IRWST flow rate results for AP1000. The IRWST flow is calculated from steady state balance of IRWST gravity head, DVI line resistance from IRWST to reactor vessel, and Δp between downcomer and containment. The results are based on flow from 1 IRWST flow path (DE DVI).

Figure 5: IRWST Flow Rate vs. DP

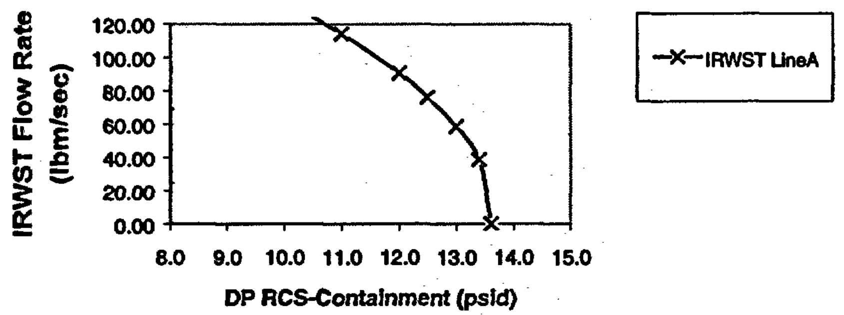


Figure 6 provides the composite results of applying the Simple Model to AP1000.

Figure 6: Flow Rate vs. DP

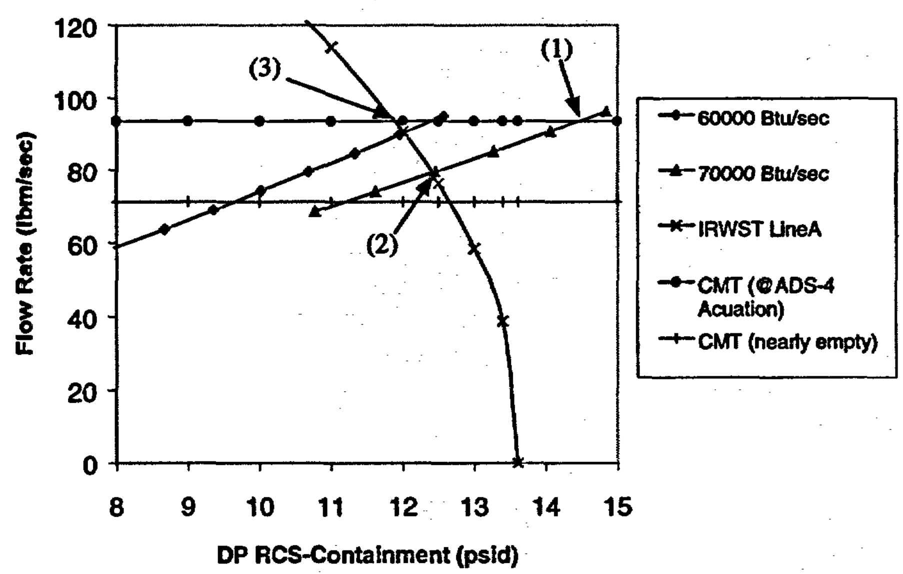


Figure 6 notes:

(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 second represents a time after ADS-4 actuation with CMT injection only.

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) form the NOTRUMP analysis of the SBLOCA DEDVI break (Tables A-2 ad A-3). The flow rate outputs from the simple model are used to generate the curves in Figure 3 through Figure 6. 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

Design Control Document (DCD) Revision:

None

PRA Revision:

None