ADVANCED SAFETY EVALUATION BY THE OFFICE OF NEW REACTORS
TOPICAL REPORT MUAP-07011-P, REVISION 3
"LARGE BREAK LOCA CODE APPLICABILITY REPORT FOR US-APWR"
MITSUBISHI HEAVY INDUSTRIES, Ltd
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# 1 INTRODUCTION

By letter dated July 20, 2007, Mitsubishi Heavy Industries, Ltd. (MHI), hereinafter referred to as the applicant, submitted Topical Report MUAP-07011-P(R0), "Large Break LOCA, Code Applicability Report for the US-APWR," [Ref. 1] prepared in connection with its request to the U.S. Nuclear Regulatory Commission (NRC), hereinafter referred to as the staff, for a pre-application review of the United States - Advanced Pressurized Water Reactor (US-APWR).

This report provides the staff's safety evaluation (SE) of Topical Report MUAP-07011-P(R3) [Ref. 28]. The evaluation focused on: (1) the differences between the US-APWR and currently operating plants considered in Reference 2, and (2) the applicability of the code assessment and validation described in Reference 3 to the US-APWR.

The applicant's Best Estimate Large Break Loss of Coolant Accident (BELBLOCA) methodology is based upon the Automated Statistical Treatment of Uncertainty Method (ASTRUM) methodology [Ref. 2] which has been approved by the NRC for the Westinghouse 2, 3 and 4 loop pressurized-water reactor (PWR) designs, the Combustion Engineering (CE) PWR design, and the Westinghouse AP600 and AP1000 advanced reactors. The methodology uses WCOBRA/TRAC(M1.0), hereinafter referred to as WCT-M1, as its thermal-hydraulic modeling engine. WCT-M1 is based upon the WCOBRA/TRAC computer program. The code qualification document for WCOBRA/TRAC has been approved by the NRC for the frozen code version WCOBRA/TRAC MOD7A Revision 1 [Ref. 3]. ASTRUM methodology with the frozen code version WCOBRA/TRAC MOD7A Revision 6 [Ref.2] has been also approved by the NRC. WCT-M1 is based on WCOBRA/TRAC MOD7A Revision 6. Significant differences between WCT-M1 and WCOBRA/TRAC are described and evaluated in Section 4.1.2 of this report.

# 2 SYSTEM DESCRIPTION

The US-APWR is a 4-loop plant with a core rated output of 4451 megawatts thermal (MWt). The reactor core consists of 257 fuel assemblies each containing 264 fuel rods, 24 guide tubes, and 1 incore instrument tube, all arranged in a 17x17 square lattice. The active fuel height is 4.201 m (13.78 ft). The core average linear heat generation rate is 15.2 kW/m (4.6 kW/ft). Local power peaking factor values in the US-APWR are similar to those in currently operating plants.

Unique design features of the US-APWR relative to currently operating PWRs are core length, a neutron reflector (NR) surrounding the core, omission of the low head safety injection (LHSI) system, an advanced accumulator, and direct vessel injection (DVI) of the high head safety injection (HHSI) system.

The NR assembly, which surrounds the core, consists of a ring of stacked stainless steel blocks perforated with vertical cooling holes. Its purpose is to improve neutron economy and reduce the fluence to the reactor pressure vessel. Because of its size, the NR may represent a significant heat source during the reflood period of a Large Break Loss of Coolant Accident (LBLOCA).

The advanced accumulators, one per reactor loop, are unique in that each contains an internal flow damper. The flow damper, a passive device, is designed to deliver a large flow rate during the refill of the reactor vessel following a LBLOCA, and then to automatically switch to a low flow rate as the accumulator water level drops. The accumulators' sustained delivery period at a low flow rate eliminates the need for a LHSI system.

There are four independent HHSI trains. Each train consists of a high pressure pump and the associated valves and piping.

The HHSI pumps are automatically started by an S-signal and supply borated water (approximately 4,000 ppm boron) from the Refueling Water Storage Pit (RWSP) to the reactor vessel. Each train is connected to a dedicated DVI nozzle for injection into the reactor downcomer. The DVI nozzles are located slightly below the centerline elevation of the reactor coolant hot and cold leg nozzles. A safety injection pad is attached to the outside of the core barrel opposite each DVI nozzle. The pad directs the injected flow downward. The HHSI pumps are sized so that two of the four systems can supply adequate flow to keep the core cooled following the 180 second time period of accumulator injection.

## 3 REGULATORY BASIS

Title 10 of the *Code of Federal Regulations* (10 CFR), Part 50, Section 46, Paragraph (a) specifies that each boiling or pressurized light-water nuclear power reactor fueled with uranium oxide pellets within cylindrical Zircaloy or ZIRLO$^{TM}$ cladding must be provided with an Emergency Core Cooling System (ECCS) designed so that the calculated cooling performance following a postulated loss-of-coolant accident (LOCA) conforms to the criteria set forth in 10 CFR 50.46(b). 10 CFR 50.46(a) also stipulates that the requirement can be met through an evaluation model for which an uncertainty analysis has been performed as follows:

> *...the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that, when the calculated ECCS cooling performance is compared to the criteria set forth in paragraph (b) of this section, there is a high level of probability that the criteria would not be exceeded.*

10 CFR 50.46(b) specifies that: (1) the Peak Cladding Temperature (PCT) must not be calculated to exceed 1204°C (2200°F), (2) the maximum Local Cladding Oxidation (LCO) must not exceed 0.17 times the total cladding thickness before oxidation, (3) the maximum hydrogen generation from Core Wide Oxidation (CWO) must not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding surrounding the fuel pellets were to react, and (4) the core must remain in a coolable geometry. Also, the core temperature shall be maintained at an acceptably low level and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

The NRC has provided guidance on how the above regulatory criteria can be met. Regulatory Guide (RG) 1.157 [Ref. 4] and NUREG/CR-5249 [Ref. 5] describe acceptable approaches to determine the calculated uncertainty in the 10 CFR 50.46(b) parameters.

## 4 TECHNICAL EVALUATION

Prediction of the 10 CFR 50.46(a)(1)(i) key safety parameters (PCT, LCO, and CWO) with a high level of probability requires that distribution of uncertainty in the models and correlations be determined. The first step in this process is to identify the important phenomena via construction of a Phenomena Identification and Ranking Table (PIRT).

The applicant's BELBLOCA methodology is based on the NRC Code, Scaling, Applicability, and Uncertainty (CSAU) methodology [Ref. 5] as applied and approved for Westinghouse PWRs [Refs. 2 and 3].

The methodology consists of two best estimate codes, WCT-M1 for simulating reactor system response, and HOTSPOT for hot rod analysis. A third component of the methodology is ASTRUM, an automated method of conducting a set of LBLOCA calculations and extracting the uncertainty and confidence limits of the key safety parameters. The staff's review of the applicant's BELBLOCA methodology focuses on whether the CSAU methodology has been properly applied, in particular CSAU Steps 3, 6, 10, and 11 through 14.

CSAU Step 1, scenario specification, is clearly the LBLOCA for this application. Step 2, nuclear power plant selection, is the US-APWR. For CSAU Step 3, the construction of a PIRT, the applicant has relied heavily on Reference 3. This is acceptable to the staff because of the similarities between a Westinghouse 4-loop PWR and the US-APWR. In those areas where the plants are different the applicant has augmented the Reference 3 PIRT. The applicant's PIRT is evaluated in Section 4.1.1 below.

The CSAU methodology (Step 4) requires the use and identification of a frozen code. The applicant's response to the first LBLOCA Request for Additional Information (RAI) set, Question 1 [Ref. 9] noted that its system code, WCT-M1, is based on a previously approved code, WCOBRA/TRAC MOD7A Revision 6 [Ref. 3]. WCT-M1 has three significant changes from the approved code version: The incorporation of models for the advanced accumulator, allowing the neutron reflector component to use existing hot wall flow regime models, and replacement of the fuel thermal conductivity model. These changes are described in Section 3.5 of References 1 and 28. The applicant's version of HOTSPOT was properly modified to the version already approved by the staff and is therefore acceptable.

CSAU Step 5 requires proper documentation of the computer programs being used, including user manuals, assessment reports, and a demonstration of the applicability of the computer models to the US-APWR. In its response to the second LBLOCA RAI set, Question 37 [Ref. 11], the applicant noted that it fulfilled CSAU Step 5 by supplying the staff with the WCT-M1 code input manuals [Refs. 26 and 27], the subject topical report (TR), and References 2 and 3, which document the applicability of WCOBRA/TRAC and the ASTRUM methodology to the US-APWR. The staff agrees that CSAU Step 5 has been fulfilled.

Determination of code applicability, CSAU Step 6, is addressed in Section 3.5 of the subject TR. The applicant has relied on Reference 3 as proof of the applicability of WCT-M1 to simulate non-unique features of the US-APWR during a LBLOCA. The code's applicability to simulate the unique features of the US-APWR is addressed in Section 3.5 of the subject TR, and evaluated in Section 4.1.2 of this report.

CSAU Step 7 calls for the establishment of an assessment matrix for the applicant's computer program. The applicant has fulfilled this step for the US-APWR NR and advanced accumulator [Refs. 7 and 8] and has referenced the WCOBRA/TRAC assessment matrix [Ref. 3] for all other features.

Step 8 of the CSAU methodology concerns plant model nodalization. The subject TR (Section 3.6.1, "Nodalization of Plant Analysis") discusses the nodalization used in the WCT-M1 model of the US-APWR. The staff's review of the TR and its evaluation of the applicant's responses to numerous RAIs (Section 4.2 below) have led it to conclude that the applicant has satisfactorily fulfilled the requirements of CSAU Step 8.

The applicant has addressed CSAU Step 9, definition of code and experimental accuracy, in two ways. For the non-unique features of the US-APWR, the applicant has relied on [Ref. 3].

For the NR and the advanced accumulator, the applicant has conducted experiments and assessed WCT-M1 against those experiments. Uncertainty parameters have been developed for the advanced accumulator model. The staff's evaluation of the NR and advanced accumulator modeling are given in Section 4.1.2 below.

Determination of the effects of scale, CSAU Step 10, is discussed briefly in Section 3.5 of the subject TR. The most significant issue in this regard is the scalability of the advanced accumulator test results. The staff's review of this issue is not addressed here, but rather in its review of the MUAP-07001-P(R4), "The Advanced Accumulator [Ref. 29]." A limitation has been placed in this SE regarding the accumulator scaling effect as the review of MUAP-07001-P (R4) [Ref. 29] is ongoing.

Steps 11 through 14 of the CSAU process all relate to determination of code sensitivity and uncertainty. These steps are addressed in Section 3.7 of the TR. The staff's review is in Section 4.1.3 of this report.

## 4.1 <u>CSAU Issues Addressed in MUAP-07011-P(R3)</u>

The previous section has identified four main CSAU review areas for the staff: The applicant's PIRT (CSAU Step 3), the applicability of WCT-M1 (CSAU Step 6), scaling (CSAU Step 10), and the evaluation of uncertainty (CSAU Steps 11-14). The following subsections present the staff's review of these areas.

### 4.1.1 <u>The US-APWR PIRT</u>

For the purpose of PIRT and uncertainty analyses, the LBLOCA transient is subdivided into three phases. These phases are blowdown, refill, and reflood (Table 3.3-1 of MUAP-07011-P). There is a PIRT for each phase of the transient and the content of each PIRT depends upon the definition of the phases. In the CSAU and Westinghouse LBLOCA PIRT descriptions, the refilling phase starts when accumulator flow begins and ends when the lower plenum is full.

The applicant's responses to the first LBLOCA RAI set, Question 3.1 [Ref. 9] and follow-up second LBLOCA RAI set, Question 1.1 [Ref. 11] clarified the definitions of the LBLOCA phases. When describing the LBLOCA scenario, the applicant described the blowdown phase ending and the refill phase beginning when the Reactor Coolant System (RCS) pressure equaled the containment pressure. However, for the US-APWR PIRT, the definitions of the blowdown, refill, and reflood phases are identical to those used in previous PWR LBLOCA PIRTs: The blowdown phase ends and the refill phase begins when accumulator injection begins; the reflood phase begins when the lower plenum is full of liquid. The applicant's responses have provided the clarification the staff requested and assured the staff that the applicant's PIRT definitions of the LBLOCA phases are consistent with the NRC PIRT. They are therefore acceptable.

The response to the second LBLOCA RAI set, Question 22 [Ref. 11] addressed apparent inconsistencies between the description of coolant injection through the DVI nozzles and the figures and tables in Section 3.3.3. The response explained that HHSI can occur either during the refill phase or the reflood phase of a LBLOCA, depending upon whether or not offsite power is lost. The description and illustration of HHSI timing assumed no loss of offsite power (LOOP) while the sequence of events table assumed a LOOP. The staff finds the explanation of the differences between the text and tables acceptable.

The sequence of events table in Section 3.3.3 also indicated that the ECCS start signal ("S" signal) is generated by high containment pressure. The applicant explained that (in response to the second LBLOCA RAI set, Question 23 [Ref. 11]), in the plant, the "S" signal can be generated by either high containment pressure or low-low pressurizer pressure; however, in the safety analysis only the low-low pressurizer pressure signal is credited because it occurs later than the high containment pressure signal. Ignoring the high containment pressure signal conservatively delays the ECCS start signal and is therefore acceptable to the staff.

In Section 3.4 of the TR, a PIRT for the US-APWR is developed, using the same process that is described in the Westinghouse PIRT for a conventional 4-loop plant [Ref. 3]. The following phenomena were highly ranked:

(1) critical flow
(2) broken loop resistance
(3) fuel rod modeling
(4) core heat transfer
(5) ECC bypass
(6) entrainment/steam binding
(7) accumulator nitrogen
(8) condensation

There are some differences in phenomena ranking between the applicant's PIRT and the staff's CSAU PIRT [Ref. 5]. Those differences received special consideration from the staff.

The applicant's PIRT process was conducted as follows: Physical components of the RCS were considered individually and the thermal hydraulic processes related to each component were ranked in importance. The subsequent paragraphs in this section present the staff's review of each component considered by the applicant.

<u>In Subsection 3.4.1.1 "Fuel Rod,"</u> the applicant's rankings for stored energy, decay heat, and cladding oxidation are consistent with the staff's PIRT [Ref. 5] and are therefore acceptable.

The applicant's PIRT ranked gap conductance low for all three LBLOCA phases. The CSAU PIRT [Ref. 5] had ranked it low during the blowdown and refill phases but high during the reflood phase. However, the CSAU report was documenting the PIRT process as it evolved. Subsequent analysis indicated that gap conductance was important in the blowdown phase and should be considered in the uncertainty estimate. During the blowdown phase, the stored energy is released to the clad, and is more important than the decay heat. Stored energy is rated high and the process of heat transfer from the fuel to the clad should also be rated high.

The CSAU (Ref. 5, Table 16) showed that the effect of gap conductance on the blowdown PCT was large.

The first LBLOCA RAI set, Question 3.2 asked the applicant to justify the basis for rating gap conductance low in both the blowdown and the reflood phases. The response to Question 3.2 [Ref. 9] noted that the ranking of gap conductance is consistent with that of Reference 3 and the ASTRUM methodology that has been previously approved by the staff. It also noted that gap conductance is an uncertainty parameter in the US-APWR BELBLOCA analyses; therefore, even though its ranking is different from Reference 5, its impact is included in the analyses. The response to Question 3.2 is acceptable. It shows that although gap conductance is ranked low, it is treated as if it were ranked high; i.e., it is treated as an uncertainty parameter in the analysis.

In Subsection 3.4.1.2, "Core," Departure from Nucleate Boiling (DNB), post critical heat flux (CHF) heat transfer, 3-D flow, void generation, and flow reversal were all highly ranked phenomena for the blowdown phase. Only post CHF heat transfer was ranked high for the refill phase, and only reflood heat transfer and entrainment/de-entrainment were ranked high for the reflood phase. These rankings are the same as those in Reference 3. This is to be expected since the US-APWR fuel is the same, except for length, as that used in Westinghouse 4-loop plants. WCT-M1 has the same core heat transfer models as the approved WCOBRA/TRAC code; therefore, it is reasonable to conclude that it can adequately simulate all of the highly ranked phenomena in the core region. The applicant's methodology has six uncertainty parameters related to core heat transfer.

The staff has noted that DNB has been ranked high in the applicant's PIRT but it is not treated as an uncertainty parameter in the WCT-M1 model. Rather, the uncertainty is treated indirectly by modifying the blowdown heat transfer coefficient in HOTSPOT. The staff's evaluation of this methodology is given in Section 4.2 of this report.

The effect of the NR on core thermal hydraulics was ranked moderate. The NR is cooled by water flowing upward through a series of holes drilled through the structure. During reflood the NR will reflood in a manner similar to the core. Steam will be generated and entrainment of liquid into the upper plenum will occur. The flow area of the NR is very small to the core's flow area, so the effect of NR reflood on the overall reflood process is small in comparison to the core. In spite of the moderate ranking of the NR, the applicant has expended considerable effort ensuring that the reflood of the NR is adequately modeled [Ref. 8]. The staff's evaluation of the modeling of the NR is in Section 4.1.2.3 of this report.

In Subsection 3.4.1.3, "Upper Plenum," only the position of the hot assembly was ranked high; it was ranked high for blowdown only. The reason for the high ranking is that the flow draining from the upper plenum into the hot assembly during blowdown can be influenced by whether or not a guide tube sits atop the hot assembly. The staff notes that the position of the hot assembly is treated conservatively and therefore acceptably in the applicant's WCT-M1 analysis.

The entrainment/de-entrainment phenomenon was rated as moderate. It was rated high in CSAU (Ref. 5, Table 1) as it could lead to steam binding when the droplets evaporate in the steam generator (SG). In response to the first LBLOCA RAI set, Question 3.4 [Ref. 9], the applicant explained that best-estimate computer codes are less sensitive to upper plenum entrainment because they better simulate the phenomena than older conservative simulation models. The ranking of the phenomena for the US-APWR was therefore set to moderate. The staff notes that the ranking of the phenomenon is not as important as having a good simulation of the phenomenon. The ability of WCOBRA/TRAC to adequately simulate the phenomenon has been verified by comparisons to test data [Ref. 3]. The applicant's explanation for a moderate ranking for entrainment/de-entrainment is acceptable. This issue is resolved.

In Subsection 3.4.1.4, "Hot Leg," there were no highly ranked phenomena for the hot leg. The phenomenon of entrainment/de-entrainment was rated as moderate in the reflood phase. However, if the two-phase level is at hot leg elevation then there will be a two phase mixture in the hot leg. The staff's CSAU [Ref. 5] rated it high as a continuation of upper plenum phenomenon. The first LBLOCA RAI set, Question 3.5 requested an explanation for the moderate ranking for the US-APWR. In response to LBLOCA RAI set, Question 3.5 [Ref. 9], the applicant stated that the hot leg has a small volume and any water swept into the hot leg would be entrained into the SG. It further noted that when the upper plenum two phase level reaches the hot leg elevation the core hot spot region has already quenched. The staff finds this explanation of the moderate ranking to be reasonable and acceptable.

In Subsection 3.4.1.5, "Pressurizer," the pressurizer provides coolant to the remainder of the RCS during the blowdown phase and the pressurizer pressure is the control parameter that leads to reactor trip and the safety injection signal. The first LBLOCA RAI set, Question 3.6 asked how the ranking of moderate for pressurizer phenomena was determined. In its response to LBLOCA RAI set, Question 3.6 [Ref. 9], the applicant noted that, since reactor scram is not modeled in the BELBLOCA analysis for the US-APWR, the low pressurizer pressure reactor trip signal is not needed in the analysis. The safety injection (SI) signal is modeled with a conservative delay. Therefore, the pressurizer pressure is not identified as a significant phenomenon. In its response to the second LBLOCA RAI set, Question 1.3 [Ref. 11], dated, the applicant noted that a SI signal delay time of 118 seconds is assumed. The responses to Question 3.6 and follow-up Question 1.3 are acceptable. The explanation of a moderate ranking for pressurizer pressure is reasonable. The applicant's BELBLOCA methodology places the pressurizer on the loop (intact or broken) where it is most limiting on calculated PCT. This location is determined by a sensitivity study. This placement of the pressurizer is conservative and therefore acceptable to the staff.

In Subsection 3.4.1.6, "Steam Generator," steam binding during reflood is the only highly ranked phenomenon. There is a general agreement [Refs.3 and 5] with this finding, and the ranking is acceptable to the staff.

In Subsection 3.4.1.7, "Pump," the two phase pump performance in the blowdown phase was rated as moderate. It was rated high in the staff's CSAU [Ref. 5]. The first LBLOCA RAI set, Question 3.7 asked how the ranking of moderate was determined. In its response to Question 3.7 [Ref. 9], the applicant acknowledged that the pump's two-phase behavior is important since it determines when the pumps lose their pumping capability which, in turn, determines when the flow reverses in the core. The response further noted that the most important element is the broken-loop pump resistance compared to the flow resistance through the core, downcomer, and broken loop cold leg nozzle to the break. The difference in the flow resistance between the two flow paths to the break, which is treated as an uncertainty parameter, determines the amount of down flow through the core and, accordingly, the degree of core cooling during the blowdown phase. The applicant concluded that the two-phase pump performance is less important than flow split between the two paths to the break; therefore, a moderate ranking was assigned to two-phase pump performance. The staff finds this response both reasonable and acceptable. Regardless of its ranking, two phase pump performance is modeled in WCT-M1.

In its response to the second LBLOCA RAI set, Question 1.4 [Ref. 11], the applicant discussed why the uncertainty of two-phase multipliers for the Reactor Coolant Pump (RCP) homologous curves is not included as an uncertainty parameter in the BELBLOCA methodology. First, it was noted that there is very little scatter in two-phase data when the pump is in the pumping mode, but a large scatter in the data when the RCP is in a dissipation mode of operation. Only the pumping mode data is used to develop the two-phase multiplier used in WCT-M1. For large breaks the broken loop, the RCP may transition to the dissipation mode, but the intact loop RCPs remain in the pumping mode. In this case, the broken loop's RCP void fraction increases rapidly and the RCP becomes fully degraded. Therefore, the time spent in the two-phase regime is short. A sensitivity study was conducted in which a lower bound two-phase multiplier curve based on the dissipation mode data was used instead of the curve based on the pumping mode data. The applicant concluded that the study demonstrated that the calculated plant response was insensitive to which multiplier curve was used and it was therefore not necessary to treat the RCP two-phase multiplier as an uncertainty parameter. The staff agrees with the applicant's conclusion. This issue is resolved.

<u>In Subsection 3.4.1.8, "Cold Leg and Accumulator,"</u> the accumulator flow mixes with the two-phase mixture in the cold leg. There will be condensation of steam during both the refill and reflood phases. The condensation is retarded if there is a non-condensable in the gas phase. The applicant ranked condensation high in the refill phase, in agreement with previous rankings [Refs. 3 and 5].

The staff's CSAU [Ref. 5] ranked the effect of non-condensable gas as high during reflood, while the applicant ranked it low. In its response to the first LBLOCA RAI set, Question 3.8 [Ref. 9], the applicant explained that the effect of non-condensable gas is ranked low during reflood because nitrogen is not released from the advanced accumulator until well after the peak cladding temperature has occurred. Based upon the applicant's response, the staff believes a ranking of low is reasonable and acceptable.

Accumulator flow was ranked high for the refill phase. This is reasonable because the accumulator flow is the main contributor to refill of the reactor pressure vessel (RPV). In the case of a LOOP, it is the only contributor during the refill phase. The accumulator flow was also ranked high during reflood, because it serves as a low pressure safety injection system until the core is nearly all quenched. The uncertainty in accumulator flow during both the high flow and low flow regimes is treated by assigning nominal values and uncertainty bands to the accumulator lines resistance coefficient. The staff agrees with the high ranking of accumulator flow.

<u>In Subsection 3.4.1.9, "Downcomer,"</u> flashing of the fluid was rated low during the blowdown phase. In response to the first LBLOCA RAI set, Question 3.9 [Ref. 9], the applicant explained that flashing of the downcomer fluid during blowdown was ranked low because it has a very small effect on core cooling. Flashing of the downcomer fluid occurs concurrently with flashing of the lower plenum fluid. Lower plenum flashing may affect core cooling by driving fluid into the core, but downcomer flashing will not. The staff finds the applicant's explanation to be reasonable and acceptable.

Entrainment, condensation, countercurrent flow, and 3-D effects were all ranked high for the refill phase. All these rankings are consistent with the rankings for a Westinghouse 4-loop plant [Ref. 3]. This is expected because the US-APWR downcomer width is very similar to that of the Westinghouse plant, although the RPV has a larger diameter.

The effect of DVI on phenomena in the downcomer was ranked low. Steam condensation by the injected liquid is minimal because DVI is not initiated (assuming a LOOP) until after the DVI nozzles are covered with liquid that is injected by the accumulators.

Downcomer hot wall effects were ranked high for the reflood period. If the temperature of the fluid in the downcomer approaches the saturation temperature, boiling may occur, resulting in a loss of downcomer driving head and possible entrainment of downcomer fluid out the break. The staff concurs with the applicant's high ranking.

<u>In Subsection 3.4.1.0, "Lower Plenum,"</u> the only phenomenon ranked high was the hot wall effect during reflood. The lower plenum metal structures give up their heat to the reflood liquid, thereby reducing its subcooling. This, in turn, means that more of the core will be in nucleate boiling during reflood and more steam will have to be vented through the loops. The ranking is therefore reasonable.

<u>In Subsection 3.4.1.11, "Break,"</u> critical flow is ranked high for the blowdown phase. Break size and break discharge multipliers are both treated as uncertainty parameters in the applicant's methodology. Containment pressure is ranked high for the reflood phase.

The applicant's methodology uses a conservatively low containment pressure, an approach which is acceptable to the staff in lieu of treating it as an uncertainty parameter.

<u>In Subsection 3.4.1.12, "Loop,"</u> only the hot leg/cold leg flow split received a high ranking. This flow split is treated as an uncertainty parameter in the applicant's methodology.

In the first LBLOCA RAI set, Question 3.11, the staff asked why the stored energy from passive heat structures was not considered in the PIRT. In response to Question 3.11 [Ref. 10], the applicant noted that it was considered under the phenomenon 'Hot Wall' for each RCS component. The response provides the clarification needed and is acceptable.

The staff requested that all of the highly ranked PIRT items be discussed, noting that several items in PIRT Table 3.4.1 were not. The information requested was provided in the response to the second LBLOCA RAI set, Question 25 [Ref. 11]. In its response, the applicant noted that fuel rod oxidation is ranked high because it can provide an additional heat source to the cladding at high temperatures. Core 3-D coolant behavior is ranked high because it directly affects cladding heat transfer. RCP head and flow losses are ranked high during reflood because they affect loop flow resistance and thereby affect core reflood. Entrainment/De-entrainment in the downcomer during the refill period is ranked high because these phenomena affect the rate at which emergency core cooling flows into the lower plenum. The foregoing response is acceptable because it makes the discussion in Section 3.4.1 address all of the highly ranked phenomena. The issue is resolved.

### 4.1.2 WCT-M1 Code Applicability

Step 6 in CSAU is to establish the applicability of the code to the plant and the intended transient. WCOBRA/TRAC has been approved for application to Westinghouse 3 and 4 loop plants and the AP-1000. Most of the components and the expected phenomena during LBLOCA are expected to be similar between the US-APWR and Westinghouse PWRs. Therefore, the applicability of WCT-M1 to the US-APWR reduces to an assessment of models for four components unique to the US-APWR. These are: the longer core, the advanced accumulator, an NR, and DVI.

#### 4.1.2.1 Core Length

The 4.2-m (13.8 ft) core is about 17 percent longer than current PWR cores. The main effect of the longer core is the introduction of additional grid spacers in the fuel assembly. These additional spacers are modeled by adding additional frictional loss coefficients to the WCT-M1 model. The applicant's BELBLOCA methodology is based on a code that has been validated [Ref. 3] against the Loss-Of-Fluid Test (LOFT), which used a 1.7-m (5.6-ft) core, and against cylindrical core test facility (CCTF) and slab core test facility (SCTF) tests, which used 3.6-m (11.8-ft) cores. The validation at two different core lengths indicates the methodology is scalable to a 4.2-m (13.8-ft) core. Based on the above information, the staff finds that the methodology is applicable to the US-APWR core.

#### 4.1.2.2 Advanced Accumulator

Subsection 3.5.1 and Appendix B of the TR describe the advanced accumulator. The advanced accumulator is a new component in the US-APWR. To properly model it, new models were added to WCT-M1. During the review of these models, 21 RAI questions were generated. Its responses are discussed in the following paragraphs. The questions are related to the effect of dissolved nitrogen, applicability of the characteristic equations derived from a full-height, ½ scale test facility, and the uncertainties associated with the characteristic equations that are implemented in the code.

The applicability of the advanced accumulator correlations to full scale is addressed in the staff's review of the topical report on the advanced accumulator (MUAP-07001-P(R4)) [Ref. 29].

In response to the first LBLOCA RAI set, Question 3.12.1 [Ref. 9], the applicant stated that nitrogen will not be released from the advanced accumulator tank until well after the peak cladding temperature has occurred. The full-height ½-scale tests of the advanced accumulator have confirmed that there is no possibility of nitrogen ingress into the standpipe during the switching from the high to low flow mode. The response also stated that the effect of dissolved nitrogen on core cooling is not significant. As part of the Advance Accumulator Topical Report review, the staff asked a similar question, under the Advanced Accumulator RAI set, Question 63 [Ref. 30], regarding the effect of dissolved nitrogen on accumulator performance. In the Advanced Accumulator Topical Report the applicant presented a ½ scale test (Test Number 5) with water-saturated nitrogen. This test indicated that switchover from large-flow to small-flow injection was delayed by up to few seconds. This switchover delay could be the effect of the dissolved nitrogen causing an increased flow resistance and a reduced flow rate. As discussed in Section 5.3 of MUAP-07001 [Ref. 29], the accumulator injection pipe loss coefficient is increased to account for any possible dissolved nitrogen effect. The basis for increase in loss coefficient is described in the Advance Accumulator Topical Report SE. To take the increase in accumulator injection pipe loss coefficient into account for the LOCA analysis is part of the

LBLOCA methodology and shall be used for licensing calculations. As the dissolved nitrogen effect has been conservatively addressed, the staff finds the response to Question 3.12.1 acceptable.

The verification of the implementation of the advanced accumulator model into WCT-M1 was done by comparing WCT-M1 simulations to the full-height ½-scale tests. In response to Question 3.12.2 [Ref. 9], the applicant noted that the correlations implemented are independent of scale and are therefore valid when applied to US-APWR accident simulations. As part of the Advanced Accumulator Topical Report review the staff asked in the Advanced Accumulator RAI set, Question 66 [Ref. 30], if there was any scaling effect on the flow coefficients. The Advanced Accumulator Topical Report review staff determined that a negative scaling bias shall be applied to the accumulator flow coefficients. The Advanced Accumulator Topical review is ongoing therefore; the applicant assumed bounding scaling biases as part of the LBLOCA Topical Report methodology. The assumed bounding large and small flow scaling biases to the flow rate coefficients are given in Table 3.5-7 [Ref. 28]. Therefore, a limitation exists that the final scaling biases determined in the Advanced Accumulator Topical Report are more positive than the values given in Table 3.5-7 [Ref. 28].

In its responses to the first LBLOCA RAI set, Questions 3.12.3 and 3.12.5 [Ref. 9], the applicant addressed instrument and manufacturing uncertainties. The responses noted that these uncertainties are addressed in MUAP-07001-P and the responses to the staff RAIs issued in the review of that document. The staff's Advanced Accumulator Topical report review is ongoing; therefore, a limitation exists that the final instrument and manufacturing uncertainties as determined in the Advanced Accumulator Topical Report bound those values given in Table 3.5-6 [Ref. 28].

Because the accumulator characteristics equations are least square curve fits of the test data, a dispersion uncertainty is calculated for the dispersion deviation of the flow coefficient fit. The original method of splitting the flow coefficient dispersion deviation data into two groups was clarified in the response to the first LBLOCA RAI set, Question 3.12.4 [Ref. 9]. In Advanced Accumulator Topical Report Revisions 1 through 3, the data is divided into two groups: one with values greater than the equation's values, and one with values less than the equation's value.

Separate standard deviations were than determined for data greater than (+) and less than (-) the equation values. In MUAP-07001-P (R4) [Ref. 29], the dispersion error was performed for all data points and an equal, positive and negative standard deviation determined. The revised data dispersion standard deviation is given in Table 3.5-6 [Ref. 28]. Therefore, Question 3.12.4 is no longer relevant and the dispersion standard deviation acceptability will be addressed in the review of Advanced Accumulator Topical Report. As the review of the Advanced Accumulator Topical Report is ongoing, a limitation exists that the final dispersion standard deviations in MUAP-07001 are bounded by the Table 3.5-6 [Ref. 29] values.

In its responses to the first LBLOCA RAI set, Question 3.12.6 [Ref. 9], and follow-up second LBLOCA RAI set, Question 1.7 [Ref. 11], the applicant addressed the distributions applicable for instrument error, dispersion deviation, manufacturing error, and the combination of these three distributions to form the distribution of the flow coefficient. The experimental data distribution (dispersion deviation) is assumed to be normal based upon the observed distribution of the data points. Standard engineering practice is to assume a normal distribution for the total manufacturing error, which is due to several factors; e.g., diameter of the tank, diameter of the injection pipe, height of the standpipe, etc. Finally, according to the central limit theorem, the distribution of the uncertainty made by combining independent uncertainty distributions will be a normal distribution. Hence, the uncertainty in the flow coefficient is a normal distribution. The staff finds that the procedure followed by the applicant to obtain the uncertainty in the flow coefficient is reasonable and the assumption of a normal distribution is acceptable. The staff conducted WCT-M1 simulations to examine the sensitivity of calculated results to the flow coefficient uncertainty and determined that calculated results are relatively insensitive to the uncertainty value of the flow coefficient. Using a flow coefficient value of nominal minus one standard deviation and then nominal plus one standard deviation only changed computed PCT by 22 °F.

The flow coefficient is treated as a statistical parameter in the applicant's ASTRUM analysis. In response to the first LBLOCA RAI set, Question 3.12.9 [Ref. 9], the applicant provided a proprietary discussion of how it is implemented in ASTRUM, the type and range for the probability density function (PDF), and how the PDF is sampled. The staff reviewed the information provided in the response and found it to be technically sound, and therefore acceptable. In response to follow-up second LBLOCA RAI set, Question 1.8 [Ref. 11], the applicant clarified that there is no bias applied to the flow coefficient, and that the PDF is symmetrical about the mean value. Based on Section 5.4 of MUAP-07001-P (R4) [Ref. 29], a negative scaling bias has been added to the flow coefficient after (outside of) the ASTRUM determined value (see the discussion of Question 3.12.11 below). Therefore, the response to Question 1.8 [Ref. 11] is superseded by MUAP-07001-P (R4). The symmetry occurs as a single total (instrument, dispersion and manufacturing) standard deviation value is used for the PDF (see the discussion of Question 3.12.4 above).

The advanced accumulator switches from a high (large) flow mode to a low (small) flow mode when the top of the stand pipe uncovers. To address the uncertainty in switchover time, the accumulator water level is set conservatively low; so the high flow period is conservatively short (response to Question 3.12.10 [Ref. 9]). In response to Question 3.12.10, the applicant demonstrates a conservative treatment of switchover time and is acceptable. The response to follow-up second LBLOCA RAI set, Question 1.9 [Ref. 11], clarified that switchover time is not an uncertainty parameter; the low accumulator water level is a fixed input in WCT-M1. The clarification is acceptable; there is no need to apply uncertainty to a conservative input.

In response to the first LBLOCA RAI set, Question 3.12.11 [Ref. 9], the applicant stated that the flow coefficient uncertainty derived from the full-height ½-scale tests is applicable to the US-APWR, i.e., the uncertainty is independent of scale.

Follow-up scaling RAIs were asked as part of the Advanced Accumulator Topical Report review. Based on the applicant's response to the Advanced Accumulator RAI set, Question 66 [Ref. 30], and Advanced Accumulator Topical Report, Revision 4 [Ref. 29], the applicant assumed conservative large and small flow coefficient scaling biases in the LBLOCA methodology. Therefore, Question 66 [Ref. 30] supersedes the applicant's response to Question 3.12.11 [Ref. 9]. The staff's review of the Advanced Accumulator Topical Report is ongoing; therefore, a limitation exists that the final scaling biases determined in the Advanced Accumulator Topical Report are more positive than the values given in Table 3.5-7 [Ref. 28].

Equation B-1 of the subject TR implies that the flow damper outlet pressure must be greater than the vapor pressure if the value of the cavitation factor is to be meaningful (i.e., positive). In response to the first LBLOCA RAI set, Question 3.12.12 [Ref. 9], the applicant provided material which demonstrated that this was always the case in the full-height ½-scale tests. Therefore, equation B-1 will always yield a positive value of the cavitation factor. The staff finds this response acceptable, pending approval of MUAP-07001-P (R4), which will address the issue of the applicability of the full-height ½-scale tests to the US-APWR.

Appendix B Equations B-4 and B-5 state that the flow coefficient becomes constant when the flow through the flow damper is small. In response to the first LBLOCA RAI set, Question 3.12.13 [Ref. 9], the applicant notes that for low flow velocities the cavitation factor becomes very large (large values are associated with little occurrence of cavitation). For large values of the cavitation factor, the exponential term in Equation B-2 and B-3 goes to zero and the equation for the flow coefficient is reduced to the first term only, which is a constant. The response properly explains how Equation B-4 and B-5 are derived and is acceptable.

The flow coefficient is converted to a form loss coefficient and then to a friction factor value for use by WCT-M1 at the outlet of the accumulator component. In response to the first LBLOCA RAI set, Question 3.12.14 [Ref. 9], the applicant explained how the loss coefficient is derived from the experimentally determined flow coefficient. The explanation is technically sound and therefore acceptable. The staff notes that the adequacy of the final FRIC values used in WCT-M1 have been verified by comparisons of WCT-M1 calculated flows to the experimental flows from the advanced accumulator tests.

In response to the first LBLOCA RAI set, Question 3.12.15 [Ref. 9], the applicant explains the apparent factor of two discrepancy between the friction factor values given in TR Appendix B, Equations B-9 and B-10, and those derived by the reviewer from Equations 4-197 and 4-256 in Reference 2. The response demonstrates that Equations B-9 and B-10 are correct and is therefore acceptable.

As explained in Appendix B of TR MUAP-07011(R0), the switch between the high and low flow modes in the advanced accumulator is modeled by changing the loss coefficient at the accumulator exit junction. Because the change in loss coefficient is large and sudden, there is a chance it may introduce numerical instability. To prevent this, Equation B-11, which slows the rate of change of the loss coefficient, is applied for ten seconds after mode switching is calculated to occur. In response to the first LBLOCA RAI set, Question 3.12.16 [Ref. 10], the applicant explains how the loss factor damping affected the results of one of the cases presented in Section 3.5 of the subject report. The explanation noted that the damping logic is active for ten seconds after mode switching, but the rate of change of the flow coefficient is determined by the rate change parameter named DKSWDT. Typically, this parameter has a large value, so the switch between flow modes is complete within three seconds. The response also demonstrated that the flow damping did not significantly alter the calculated flow being discharged by the accumulator. For this reason, the RAI response is acceptable.

In response to the first LBLOCA RAI set, Question 3.12.17 [Ref. 9], the applicant provided the values (proprietary) for parameters named QLTMIN and VDMIN. QLTMIN is the amount of water that remains in the accumulator due to the dead volume below the flow control device. VDMIN is the minimum discharge velocity used in the calculation of the cavitation factor. The discharge velocity appears in the denominator of the cavitation factor equation, so a minimum value is needed to prevent a divide by zero. The response is acceptable; it provided the requested information and justified the values used.

Heat transfer between the accumulator wall and the nitrogen gas within the accumulator is not simulated in the WCT-M1 model of the US-APWR according to the response to the second LBLOCA RAI set, Question 9 [Ref. 11]. During accumulator injection the nitrogen gas falls below the accumulator wall temperature. Simulating the wall heat transfer would result in a slight increase in the pressure of the nitrogen gas and a slightly faster discharge of the accumulator liquid into the RCS. Ignoring this heat transfer in the US-APWR LBLOCA simulation is acceptable to the staff because it has no significant impact on the calculated core response.

Nitrogen, which is dissolved in the accumulator fluid, will not affect the operation of the advanced accumulator flow damper (response to the second LBLOCA RAI set, Question 10 [Ref. 11]). The diffusion coefficient of nitrogen is small; therefore, no significant bubble formation can occur during the short time (< 1 s) it takes fluid to traverse the flow damper. As part of the Advance Accumulator Topical Report review, the staff asked a similar question, the Advanced Accumulator RAI set, Question 63 [Ref. 30], regarding the effect of dissolved nitrogen on accumulator performance. In the Advanced Accumulator Topical Report the applicant presented a ½ scale test (Test Number 5) with water-saturated nitrogen. This test indicated that the accumulator injection large (high flow) injection phase could be extended by up to two seconds. Based on this test, the applicant agreed to increase the accumulator injection pipe loss coefficient by 20 percent to account for any possible dissolved nitrogen effect. The basis for the 20 percent increase in injection pipe loss coefficient is described in the Advance Accumulator Topical Report SE. The 20 percent increase in accumulator loss coefficient is part of the LBLOCA methodology and shall be used for licensing calculations. Therefore, the applicant's response to Question 10 is superseded by the response to Question 63 [Ref. 30].

In response to the second LBLOCA RAI set, Question 11 [Ref. 11], the applicant explained how the uncertainty in the cavitation factor was covered by the assumed uncertainty in the flow coefficient. For large values of the cavitation factor the effect of cavitation factor uncertainty on the flow coefficient is negligibly small. For small values of the cavitation factor, the instrument uncertainties are quite small, less than half of the value assumed in the ASTRUM methodology. Therefore, the assumed instrument uncertainty for the flow coefficient already covers any uncertainty associated with the measurement of the cavitation factor. The applicant also noted that the cavitation factor is independent of scale. The staff agrees with the applicant's conclusion that the uncertainty in the cavitation factor is covered by the assumed uncertainty in the flow coefficient. The response is acceptable. The effect of scaling is being addressed in the Advanced Accumulator, MUAP-07001-P (R4) review. The Conclusion and Limitations section of this SE lists the limitations associated with the effects of accumulator scaling on the LBLOCA analyses.

The applicant was asked why N instead of N-1 was used when calculating the standard deviation of the flow coefficient equations. In response to the second LBLOCA RAI set, Question 12, [Ref. 11], the applicant replied that the size of the statistical population was large (>2500); therefore, the difference between N and N-1 is negligible. The staff agrees and accepts the applicant's response.

In its response to the second LBLOCA RAI set, Question 13 [Ref. 11], the applicant addressed the effect of surface roughness on the inception of cavitation in the throat of the flow damper's outlet nozzle. Surface roughness of the flow damper device in the full scale advance accumulator will be the same as the roughness in the ½ scale device. Hence, the effect of surface roughness has already been accounted for in the determination of the overall uncertainty of the full-height ½ scale tests. The staff agrees that it is reasonable to conclude that the effects of surface roughness on cavitation are covered by the uncertainty that has been assigned to the advanced accumulator flow coefficient. The applicant's response is therefore accepted.

#### 4.1.2.3 <u>Neutron Reflector</u>

TR Section 3.5.3, “Neutron Reflector,” describes the modeling of a new component of the US-APWR. The report did not provide any specific information about the cooling holes and stored energy of the neutron reflector. The applicant subsequently provided this information in its response to the first LBLOCA RAI set, Question 3.13.1 [Ref. 9], which partially resolved this question.

In the base version of WCOBRA/TRAC, structures in the RPV, except the fuel rods, are modeled as unheated conductors with wetted walls. This was not considered appropriate for the cooling holes in the NR. Therefore, WCT-M1 was modified to allow inverted annular flow and entrainment to be simulated in the cooling holes. This change was implemented by allowing the NR cooling channels to use the flow regime models that were previously only used by the fuel rods. These flow regimes are used whenever the local wall surface temperature is greater than the local critical heat flux temperature. Several RAI questions were issued to aid the staff in judging the applicability of the WCT-M1 model for the NR and the verification of the model. The RAIs were issued in two groups. The following discussion first addresses the responses to the first set of LBLOCA RAI Questions 3.13-1 through 3.13-4, and then the second set of LBLOCA RAI Questions 1 through 8.

In response to the first LBLOCA RAI set, Question 3.13.2 [Ref. 10], the applicant discussed the NR confirmatory tests [Ref. 8] and the WCT-M1 simulations of those tests. It was demonstrated that the switching of flow regimes in WCT-M1 correlated reasonably well with the progression of the experimental quench front, thus demonstrating the validity of the switching criterion ($T<T_{chf}$). This response satisfactorily addressed the issue raised by Question 3.13.2 and is therefore acceptable. Follow-up to the second LBLOCA RAI set, Question 1.10 [Ref. 11] asked what caused the rapid drop in the measured temperatures shortly after reflood began in the NR tests. In its response the applicant stated that sudden drop in the measured surface temperatures at the higher elevations was likely caused by entrained droplets impinging upon the heated wall. It noted that even thermocouples at the same elevation but on opposite sides of the flow channel showed different temperature responses, indicating that the cause of the rapid cooling was very localized. WCT-M1 cannot predict such localized, asymmetric behavior because, by design, it simulates only one-dimensional axi-symmetric flow within each control volume representing the flow channel. The applicant’s response is reasonable and acceptable.

Modeling of the flow in the NR cooling holes requires predicting the flow regimes in the holes. One parameter required is the void fraction, $\alpha_{critical}$, above which entrainment can occur. The applicant’s response to the first LBLOCA RAI set, Question 3.13.3 [Ref. 9], provided the derivation of $\alpha_{critical}$. The response is acceptable because it clarifies how the onset of entrainment is calculated in WCT-M1.

In order to judge the importance of the stored energy in the NR, the staff requested a comparison of the release of energy from the NR to core decay heat for the reference LBLOCA presented in Section 3.6 of MUAP-07011(R0). In response to the first LBLOCA RAI set, Question 3.13.4 [Ref. 10], the applicant provided the requested information, which is therefore acceptable. The response showed that the NR heat release is about 10 percent of the decay heat release at the time of PCT, and less than 20 percent thereafter.

The effect of the NR regarding reflood behavior and the applicability of WCT-M1 to model the relevant thermal hydraulic phenomena were further discussed in the response to the second LBLOCA RAI set, Questions 1 through 8 of Reference 11. Adequate simulation of the NR is needed because of the large amount of stored energy in the NR. During the reflood phase of a LBLOCA the heat release from the NR will cause vapor generation in the NR cooling holes and entrainment and carryout of liquid droplets into the upper plenum. This carryout of liquid droplets to the steam generators may increase the effect of steam binding on core reflooding.

In response to the second LBLOCA RAI set, Question 1 [Ref. 11], the applicant noted that calculated reflood rates in the US-APWR are between 2 and 6 cm/s, which is well within the range of reflood rates of the experimental data base used for the assessment of WCT-M1 [Ref. 3]. The code has also been assessed against the NR reflood tests [Ref. 8], which had reflood rates ranging from 5 to 15 cm/s. The latter assessments show that WCT-M1 overpredicted the amount of entrainment at the 5 cm/s reflood rate test and agreed very well with measured wall temperatures at all elevations. For the higher reflood rate tests, WCT-M1 underpredicted entrainment and the rate of heat transfer from the wall to the fluid; however, these tests are not representative of the long term reflood rates expected during an LBLOCA in the US-APWR. The staff has reviewed the WCT-M1 simulations of the NR reflooding tests and has concluded that the code can adequately simulate the thermal hydraulic phenomena occurring in the NR during reflood. Therefore, the WCT-M1 model of the NR is acceptable.

In responses to the second LBLOCA RAI set, Questions 2 and 3 [Ref. 11], the applicant provided a detailed description of how the NR is represented in the WCT-M1 model. These responses confirmed that the noding used in the US-APWR model was the same as that used in the assessment of the NR reflood tests. This modeling issue is therefore resolved.

Responses to the second LBLOCA RAI set, Questions 4, 5, and 6 [Ref. 11], all addressed the conservatisms inherent in the treatment of the NR for LBLOCA simulations. At the beginning of each transient simulation, the temperature of the NR is set artificially high in order to maximize the heat release during the simulation. The amount of flow through the NR cooling holes is set to the minimum expected value. Heat release to the core peripheral region and the NR/core barrel region is neglected in the simulation, maximizing the heat release to the cooling holes. The staff finds all of the foregoing modeling techniques to be appropriate conservatisms in that they maximize the stored energy of the NR and result in an overprediction of the liquid entrainment in the NR holes.

The code modifications needed to activate the hot wall flow regime model for the NR were given in the response to the second LBLOCA RAI set, Question 7 [Ref. 11]; WCT-M1 simulations of one of the NR reflood tests were presented to show better agreement with the test data obtained when the hot wall model was used instead of the wetted wall model. The comparison demonstrates the appropriateness of using the hot wall flow regime model. This modeling issue is therefore closed.

MHI noted (response to the second LBLOCA RAI set, Question 8 [Ref. 11]) that the applicability of WCOBRA/TRAC to simulate an LBLOCA in the AP600 was approved by the staff [Ref. 12]. The AP600 has an NR similar to that in the US-APWR and WCT-M1 is largely the same as WCOBRA/TRAC.

Based upon its review of all of the information supplied by MHI, the staff concludes that WCT-M1 can adequately simulate the thermal-hydraulic phenomena occurring in the NR cooling holes during an LBLOCA.

In order to confirm that releasing the NR stored energy to only the NR coolant holes was conservative the staff requested the applicant to provide the results of an LBLOCA simulation in which the NR had heat transfer to both the coolant holes and its outer surface. In response to the fourth LBLOCA RAI set, Question 5 [Ref. 19], the applicant provided a comparison of the base case (heat transfer to coolant holes only) to a case with heat transfer from all of the NR surfaces. The sensitivity case resulted in more heat being released during the early reflood period, as expected. However, because the sensitivity case released much of its heat during blowdown, the overall heat released from the NR during reflood was lower than the base case heat release. The PCT of the sensitivity case was 9 °F lower than the base case PCT, demonstrating that the heat transfer modeling technique in the base case is slightly conservative. That modeling technique is therefore acceptable to the staff.

#### 4.1.2.4 Direct Vessel Injection (DVI)

DVI in the US-APWR differs from the AP600 and AP1000 designs in that it has only the HHSI flow injected into the vessel downcomer while the others have all SI flow injected into the downcomer. In response to the second LBLOCA RAI set, Question 20 [Ref. 11], the applicant noted that the NRC approved WCOBRA/TRAC for simulating DVI in the AP600 [Ref. 12] and AP1000 [Ref. 13] because WCOBRA/TRAC conservatively predicted the experimental data obtained in CCTF Run 58 and Upper Plenum Test Facility (UPTF) 21 [Ref. 3], experiments which had DVI. Since WCT-M1 is nearly identical to WCOBRA/TRAC it is reasonable to believe it also can satisfactorily simulate DVI. The response to Question 20 is therefore accepted. The US-APWR contains safety injection pads on the outside of the core barrel opposite each of the DVI nozzles. The purpose of the pads is to direct the HHSI flow downward. The effect of these pads is ignored in WCT-M1, where the DVI is connected horizontally to the vessel (response to Question 21 [Ref. 11]). The staff notes that this treatment of DVI is conservative treatment of the momentum of the injected fluid (downward momentum is ignored) and is acceptable.

### 4.1.3 Scaling Effects

Conformance with NUREG/CR-5249 CSAU Step 10 requires an applicant to address the ability of a best-estimate code to scale-up the phenomena and processes. The effects of scaling are not addressed in the subject technical report. Scaling was addressed in Reference 3, which considers the base code for WCT-M1. That report addressed conventional 3 and 4 loop Westinghouse plants. The US-APWR power is some 30 percent larger than those plants and may have a different power-to-volume ratio. The staff therefore requested the applicant to evaluate scaling effects with regard to emergency core cooling (ECC) bypass, liquid entrainment, and steam binding in the SG tubes in the second LBLOCA RAI set, Question 39 [Ref. 11].

In response to Question 39, the applicant noted that the ratio of the core power for the US-APWR to a conventional 4-loop Westinghouse plant is 1.3, while the ratio of the RCS liquid volume between the two plants is 1.37. Therefore, the power to volume ratio for the US-APWR is 95 percent of the power to volume ratio of a conventional PWR. It is generally accepted [Refs. 3 and 5] that full-height, power-to-volume scaling is appropriate for LBLOCA phenomena in the blowdown and reflood phases. Since the power-to-volume ratio for the US-APWR is similar to that of a conventional PWR, it is reasonable to believe that the assessment of applicability of WCOBRA/TRAC presented in Reference 3 can be used to justify the application of WCT-M1 to the US-APWR.

Scale effects were observed for some phenomena (ECC bypass, de-entrainment in the upper plenum, and entrainment in the hot legs) in the scaling assessment of WCOBRA/TRAC. Assessments of WCOBRA/TRAC [Ref. 3] against full scale UPTF data showed that it conservatively underpredicted ECC delivery to the lower plenum.

The downcomer gap in the US-APWR is the same size as in a Westinghouse 4-loop plant, while the downcomer flow area, and the core barrel and RPV diameters are 20 percent larger. Thus, one would expect ECC delivered to the core to be smaller in the US-APWR compared to the conventional plant. It is reasonable to believe, therefore, that WCT-M1 will conservatively underpredict the delivery of ECC to the lower plenum for an LBLOCA in the US-APWR.

The applicant's response to Question 39, stated that de-entrainment in the upper plenum of the US-APWR can be expected to be greater than in a conventional PWR while entrainment into the hot legs can be expected to be smaller. A comparison of the upper plenum internals shows that there are many more surfaces upon which to de-entrain liquid in the US-APWR. Also, since the diameter of the US-APWR vessel is 20 percent greater than that of a conventional plant there will be less entrainment of liquid into the hot legs due to the longer transverse path from the core to the hot legs. Therefore, the WCT-M1 prediction liquid flow into the hot legs can be reasonably expected to be less in the US-APWR than in a conventional plant, but WCOBRA/TRAC has already been demonstrated to conservatively predict this phenomenon for a conventional plant [Ref. 3]. The foregoing observations indicate that WCT-M1 can be applied without bias to the modeling of upper plenum de-entrainment and hot leg entrainment in the US-APWR.

In response to the second LBLOCA RAI set, Question 42 [Ref. 11], the applicant noted that while the core power in the US-APWR is 30 percent greater than that of a conventional plant, the flow area of the hot leg is only 14 percent greater. For similar core steaming rates in the two plants, the velocity of the steam in the hot legs would be greater (about 15 percent) in the US-APWR. Hence, any droplets which make it to the hot leg would have a greater probability of reaching the SG tubes. This is not particularly significant, however, because the WCT-M1 simulations show that all the droplets reaching the hot legs are swept into the SG tubes until well after the time of maximum PCT.

The staff finds the analysis and arguments provided in the responses to Questions 39 and 42 form a reasonable basis for concluding WCT-M1 can adequately simulate the entrainment/de-entrainment phenomena in the upper plenum and hot legs during an LBLOCA in the US-APWR. The applicant's responses are accepted.

The staff's review of scaling issues for the advanced accumulator is considered elsewhere – they are part of the staff's review of the Advanced Accumulator Topical Report, MUAP-07001-P(R4). The dynamics of reflood in the NR have already been evaluated at full scale in Reference 8.

### 4.1.4 ASTRUM Methodology Applied to US-APWR

Per NRC guidelines (RG 1.157 and the CSAU methodology), any best estimate LBLOCA analysis must be accompanied by an estimate of the uncertainty of the key safety parameters: PCT, LCO, and CWO.

In TR Section 3.7, the application of the ASTRUM methodology to the US-APWR is described. ASTRUM is based on the non-parametric approach described by Wilks [Ref. 17] and later on by

Guba et al. [Ref. 18]. This step is consistent with CSAU Step 13 but differs from the CSAU demonstration in Reference 5, where a response surface method was used. In the non-parametric approach, the plant and model parameters are randomly sampled and a set of 124 calculations are performed to achieve 95/95 values for the three safety parameters. The 95/95 value means that there is a 95 percent probability at the 95 percent confidence level that the actual value of a safety parameter is less than the maximum value produced by the analysis.

ASTRUM consists of a set of computer programs and PERL scripts. The calculation of the RCS response for a set of pipe breaks is accomplished using WCT-M1. The calculation of local response for the limiting rod is accomplished using HOTSPOT. HOTSPOT takes boundary conditions (local power, heat transfer coefficient, etc.) from the WCT-M1 calculation and calculates the thermal response of the hot assembly fuel rods.

The ASTRUM methodology calls for the calculation of a WCT-M1 Reference Case. This calculation is a double-ended guillotine break (DEGB) of the cold leg which uses the best estimate values for some, and conservative values of other, uncertainty parameters used in ASTRUM. All subsequent 124 WCT-M1 and HOTSPOT calculations are perturbations to the Reference Case – uncertainty parameters are randomly changed for each run. The output from all 124 cases is sorted to identify the case that has the highest PCT, the case that has the highest LCO, and the case which gives the highest CWO. These three parameters are then compared to the corresponding safety limits, and the results are reported in Section 15.6.5 of the Design Control Document (DCD) for the US-APWR.

The applicant's ASTRUM methodology has 42 uncertainty parameters, which address the highly ranked phenomena identified in its PIRT. These parameters are either sampled or treated in a conservative fashion. Of the 42 uncertainty parameters, 38 are the same as those in Reference 2, although the PDF may differ. The other four parameters are associated with uncertainty of the advanced accumulator discharge flow coefficient, one each for the high flow and low flow regimes with either a large or small cavitation factor.

In response to the first LBLOCA RAI set, Question 3.16.1 [Ref. 9], the applicant demonstrated that the value for any uncertainty parameter is obtained by sampling the full range of the parameter's uncertainty range. The response provided the demonstration requested and is therefore acceptable.

Editorial corrections requested by the staff were made in response to the first LBLOCA RAI set, Question 3.16.2 [Ref. 9] and the second LBLOCA RAI set, Questions 32 [Ref. 11].

TR Subsection 3.16.3 describes the parameters used in the uncertainty analysis, but does not provide the connection between processes ranked high in the PIRT and the uncertainty parameters. Nor does it provide any information regarding the distribution type, range, and basis for the uncertainty parameters. The first LBLOCA RAI set, Questions 3.16.3 and 3.16.4 [Ref. 9], as well as the follow-up second LBLOCA RAI set, Questions 1.12, 30, and 31 [Ref. 11], all address this lack of information. In its responses to these RAIs, the applicant stated that the connection between important PIRT parameters and uncertainty parameters are described in the ASTRUM methodology report [Ref. 2], which is the core of the applicant's approach. It was also noted that the uncertainty distribution types and ranges are also given in that report and, for most parameters, are the same as those used for the US-APWR. Four tables were provided to show those parameters that were treated differently in the US-APWR than they were in the ASTRUM report. Since the responses to the foregoing RAIs provided the nominal value, distribution type, and distribution range for the uncertainty parameters, they are acceptable.

In response to the fourth LBLOCA RAI set, Question 2 [Ref. 19], the applicant provided justification for the nominal value, range, and distribution type for several uncertainty parameters about which the staff requested additional information. The response indicated that core power level would not be sampled below the nominal value of 100 percent. The nominal value for the cold leg nozzle coefficient was derived for the US-APWR, thus providing assurance that the value was unique to the US-APWR and not a carry-over from Reference 3. The nominal value of $F_q$ is obtained by subtracting the uncertainties in $F_q$ from the technical specifications (TS) limiting value.

The limiting value is then conservatively assumed to be the 95 percent value for a normal distribution centered about the nominal value. This procedure can be shown to yield values of $F_q$ that are higher than the values expected during normal operation, and therefore conservative. Because it provided the clarifications sought, the response to Question 2 is acceptable with respect to all parameters except the accumulator temperature and the fuel burnup. The staff's concerns with those parameters are addressed elsewhere in this SE.

The applicant confirmed, in its response to the second LBLOCA RAI set, Question 14 [Ref. 11], that the accumulator nominal pressure in the ASTRUM analysis is the midpoint of the TS minimum and maximum allowed values. The range of these values is sampled uniformly. The response confirmed that a reasonable nominal value and PDF are used for the accumulator pressure; it is therefore acceptable.

The temperature of the water in the accumulator and the temperature of the high pressure SI water are both uncertainty parameters in the ASTRUM analysis. The second LBLOCA RAI set, Questions 16 and 19[Ref. 11], requested justification of the lower bound values being used for these parameters. The response to Question 16 [Ref. 11] stated that the lower bound for the accumulator temperature was 21 °C (70 °F), which is at the lower end of the anticipated containment temperatures for normal operation. The upper bound was the maximum TS limit of 49 °C (120 °F). The liquid temperature distribution is assumed to be uniform over this range. The applicant did not supply any information justifying its choice of a lower limit. The staff therefore issued the fourth LBLOCA RAI set, Question 2 which requested further justification of the lower limit value, or a demonstration that the calculated PCT for the LBLOCA analysis is not sensitive to the value chosen for the lower bound. In an amended response to Question 2 [Ref. 23], the applicant noted that the lower bound value of 21 °C (70 °F) was chosen to be consistent with the analysis for minimum containment temperature. In addition, the response presented an evaluation of the effect of the accumulator temperature lower bound value upon computed ASTRUM results. Three ASTRUM calculations (124 cases each) were run: Case 1 had an accumulator temperature range of 21 °C – 49 °C (70 °F – 120 °F); Case 2 used a 38 °C – 49 °C (100 °F – 120 °F); and Case 3 used a fixed temperature of 49 °C (120 °F). Only the accumulator temperature was varied in the three sets of runs; the values of other uncertainty parameters were the same in each set of 124 runs. The limiting run for each of the three ASTRUM cases was run 103 and the three PCTs were all within 19 °F of one another. The PCT for Cases 1 and 2 were the same and the PCT for Case 3 was 19 °F lower. Comparison of the top five highest PCT runs from Case 1 and Case 2 revealed that the range of PCTs was the same and the average PCT was somewhat higher for Case 1, the case with the largest sampling range for the accumulator temperature. The applicant concluded that the ASTRUM results demonstrate that the choice of the lower bound temperature has little effect on the final PCT obtained by ASTRUM as applied to the US-APWR. In order to cover a wider range of possible accumulator temperature values the applicant elected to use a lower bound of 21 °C (70 °F). The staff believes it is fairly unlikely that the accumulator temperature will be near 21

°C during normal reactor operation. However, because of the low sensitivity of PCT to the lower bound choice and because the case with the larger sampling range gave a higher average PCT for the top five runs, the staff finds the applicant's choice reasonable and accepts its response to Question 2.

In response to the second LBLOCA RAI set, Question 19 [Ref. 11], the applicant stated that the RWSP water temperature was represented as a uniform distribution over the range 7 °C (45 °F) to 49 °C (120 °F), with a nominal value of 35 °C (95 °F). However, in the response to the fourth LBLOCA RAI set, Question 2 [Ref. 19], the applicant revised the lower bound to 21 °C (70 °F). The staff finds the assumed range and distribution to be reasonable and therefore acceptable. The assumed RWSP temperature will not affect the limiting PCT calculated in the applicant's ASTRUM analysis because HPSI always starts after the time of PCT for the limiting breaks.

The liquid temperatures in the US-APWR accumulator may be as high as 49 °C and is slightly out of the full-height ½ scale advanced accumulator tests range. The second LBLOCA RAI set, Question 17 requested the applicant to address the effect of higher temperatures upon the flow coefficient correlations derived from the full-height ½ scale tests. In its response [Ref. 11], the applicant observed that a water temperature difference will affect water viscosity and density and nitrogen solubility. The effect of viscosity is negligible because of the high Reynolds numbers associated with accumulator injection. The effect of fluid density is included in the calculation of the flow coefficient. The solubility of $N_2$ at 49 °C is about 70 percent of what it is at 20 °C. In its review, the staff has concluded that the effect of temperature upon the flow coefficient equations is encompassed by the uncertainties assigned to those equations. Therefore, the response to Question 17 is accepted.

The nominal value and sampling range of the accumulator liquid volume were verified to be in compliance with the staff's expectations in the response to the second LBLOCA RAI set, Question 18 [Ref. 11], closing that issue.

In response to the second LBLOCA RAI set, Question 36 [Ref. 11], the applicant noted that fuel manufacturing uncertainties are not treated directly in the uncertainty analysis; rather, they are included in the uncertainty of the fuel rod gap conductance. This approach is standard industry practice and acceptable to the staff.

The responses to the second LBLOCA RAI set, Questions 34, 43, and 44 [Ref. 11], address initial fuel rod stored energy issues that were raised by the staff. The fuel rod temperature at any burnup is determined using the FINE computer code. Although the fuel thermal conductivity model in WCT-M1 is the same as that in FINE, the fuel gap model is not. Therefore, the gap size is adjusted in the WCT-M1 initialization process so that the average initial pellet average temperature agrees with that calculated by FINE. All fuel rods in the WCT-M1 model are initialized at a burnup of 2.4 GWD/MTU. Fuel rod gap conductance and fuel pellet thermal conductivity are uncertainty parameters in the HOTSPOT calculation. The response to Question 43 compared the nominal fuel pellet temperature from FINE plus its maximum uncertainty to the 95/95 value computed by HOTSPOT. The comparison showed that HOTSPOT always produced the higher pellet average temperature. The applicant's responses to the forgoing RAI questions regarding stored energy have provided assurance that its uncertainty is being treated reasonably. The responses are therefore acceptable.

The response to the fourth LBLOCA RAI set, Question 3 [Ref. 19], was an attempt to demonstrate that the initial fuel stored energy in the WCT-M1 simulations was conservatively high. The response showed that for a given fuel rod the stored energy peaks at a burnup of 2.4

GWD/MTU. Therefore, the applicant uses that burnup to initialize all fuel in the core. The staff was not convinced that this procedure gives a conservative initial stored energy. The periphery fuel is low power (~3 kW/m) but high burnup (~ 45 – 62 GWD/MTU over a cycle). The applicant's response to the second LBLOCA RAI set, Question 43 [Ref. 11], shows that, for a fixed rod power, fuel average temperature at 42 GWD/MTU exceeds the fuel average temperature at 2.4 GWD/MTU and steadily increases as exposure increases. A plausible makeup of an equilibrium core is 40 percent fresh fuel, 40 percent once-burnt fuel, and 20 percent twice-burnt fuel. It is not obvious that the stored energy of this fuel combination is bounded by fuel having an exposure of 2.4 GWD/MTU. In an April 5 and 6, 2011, meeting between the staff and the applicant, the staff explained its concern with the stored energy in WCT-M1. The applicant committed to providing a supplemental response to the fourth LBLOCA RAI set, Question 3 to address the staff's concerns.

In the supplemental response to RAI-3 [Ref. 24], the applicant presented the results for the following WCT-M1 cases:

**Table 1 WCT-M1 Cases for RAI-3**

| | Hot Assm. | Avg. Assm. | Periphery Assm. | PCT °C (°F) |
|---|---|---|---|---|
| Base Case[a] | BOL[b] | BOL | BOL | 909 (1669) |
| Case 1-1 | BOL | EOL[c] | EOL | 902 (1656) |
| Case 1-2 | BOL | BOL | EOL | 903 (1657) |
| Case 1-3 | BOL | EOL | BOL | 902 (1656) |

[a] Reference Case in Chapter 15.6.5 of the US-APWR DCD Revision 3
[b] 2.4 GWD/MTU
[c] 62 GWD/MTU

The lower PCT in Case 1-1 was shown to be a result of an increase in lateral flow from the average core region into the hot assembly.

The applicant's results demonstrate that using a beginning of life burnup distribution for all the assemblies in the core results in the highest PCT. Therefore, the staff finds the use of that distribution in WCT-M1 to be acceptable. The initial stored energy issue is resolved.

The uncertainty in the ANSI/ANS 5.1-1979 decay heat standard is ±3 percent for time less than 20 seconds after shutdown and ±2 percent thereafter. The former uncertainty value is used for all times in the applicant's ASTRUM methodology (response to the second LBLOCA RAI set, Question 40 [Ref. 11]). This uncertainty value was previously approved by the staff in its review of ASTRUM and is therefore acceptable for the US-APWR application. The response is acceptable.

The process of running ASTRUM for the US-APWR was described in the response to the second LBLOCA RAI set, Question 45 [Ref. 11]. All of the PERL scripts (PERL is a scripting language) which control the running of the computer codes for 124 LBLOCA cases were provided to the staff. The description of how the various scripts are used is acceptable.

In response to the second LBLOCA RAI set, Question 47 [Ref. 11], the applicant confirmed that the same seed was used to generate the values of uncertainty parameters for the LBLOCA results in Revisions 1 and 2 of the US-APWR DCD. This response allows the staff to confirm that the changes in the LBLOCA results were not due to use of different uncertainty parameters. Therefore, the result is acceptable.

### 4.2 Sample Plant Analysis

TR Section 3.6 describes the nodalization used in WCT-M1 for the analysis of an LBLOCA in the US-APWR. The results of a sample calculation are also presented.

The first LBLOCA RAI set, Questions 3.3 and 3.15.1 [Ref. 9] and the second LBLOCA RAI set, Questions 1.2, and 1.11 [Ref. 11], all pertained to calculated core heat transfer during the blowdown period. The response to Question 3.3 [Ref. 9] explained the early, brief reversal of the temperature rise at the hot spot is due to fluid flashing at the break causing a reduction in break flow, thus allowing for a brief re-establishment of positive core flow by the RCPs. The Question 3.15.1 response [Ref. 9] explained how the cladding temperature rise during blowdown was terminated by a surge of reverse flow through the core. The response to Question 1.2 [Ref. 11] provided plots showing cladding temperature and local mass flow rate during blowdown and the response to Question 1.11 [Ref. 11] provided plots of RCP flow and void fractions. The aforementioned RAI responses have provided an adequate explanation of the blowdown core heat transfer mechanisms and are therefore acceptable.

In the second LBLOCA RAI set, Question 35 [Ref. 11], the staff requested additional information about the DNB correlation used in WCT-M1, and its applicability to the US-APWR 4.2 m long core. The response to Question 35 noted WCT-M1 uses a combination of the Biasi CHF correlation and the modified Zuber CHF correlation. Both correlations are local-condition correlations and do not depend directly on heated length. Plots of DNB time and fluid conditions at DNB occurrence for the DCD LBLOCA Reference Case were given to demonstrate that the local fluid conditions were within the experimental range of the Biasi correlation. Finally the response noted that the WCT-M1 DNB model had been validated against Oak Ridge National Laboratory (ORNL) Thermal Hydraulic Test Facility (THTF) and Loss of Fluid Test (LOFT). Those validations showed DNB locations were adequately predicted in the THTF tests and DNB occurrence times were well predicted in LOFT.

In the WCT-M1 sample plant analysis DNB occurred on the hot rod at 0.4 seconds (response to Question 35 [Ref.11]). The staff conducted an independent WCT-M1 calculation using a 0.7 multiplier on the calculated CHF value. This WCT-M1 simulation calculated DNB to occur at 0.24 seconds and gave a PCT that was about 28 °C (50 °F) higher than the applicant's sample plant analysis value. Thus, the time of DNB is a significant parameter in the determination of PCT. The applicant has ranked DNB as a significant parameter in its PIRT, but the applicant's methodology does not treat the uncertainty in DNB in its WCT-M1 calculation. Rather, the methodology claims to account for the uncertainty in the DNB calculation via application of a blowdown heat transfer multiplier in the HOTSPOT computer code. In the ASTRUM methodology, the HOTSPOT code, not WCT-M1, yields the PCT.

The staff investigated the nature of the blowdown heat transfer multiplier distribution and its derivation. It found that the multiplier's PDF was such that in a random sampling there would be only a 5 percent chance of obtaining a value greater than unity. It was much more likely to obtain a value considerably less than unity. Therefore, the most probable effect of the multiplier is to increase the HOTSPOT PCT relative to the WCT-M1 hot spot cladding temperature. The staff's investigation found the blowdown PCT calculated by HOTSPOT was 86 °C (155 °F) greater than the WCT-M1 hot spot cladding temperature for the limiting PCT case (Case 48) reported in Revision 2 of the US-APWR DCD. This is considerably larger than the increase in PCT obtained by modifying the CHF correlation in WCT-M1 as discussed in the previous paragraph. In light of these results, the staff believes the ASTRUM method of addressing uncertainty in blowdown heat transfer is reasonable and acceptably accounts for the DNB calculation uncertainty. Therefore, the response to Question 35 is accepted and the issue closed

TR Sections 3.6.1 to 3.6.3 describe the nodalization, calculation process, and specific models of the NR, pump, and containment. Five questions (the first LBLOCA RAI set, Questions 3.14.1 to 3.14.5) were originally issued pertaining to these sections. These are general questions and requests for better documentation. They are related to three dimensional nodalization, flow losses in azimuthal and axial direction, the friction option, and nodalization in the fuel rods.

The response to Question 3.14.1 [Ref. 9], explained how WCT-M1 calculates frictional losses in the vessel. The response demonstrated that frictional losses in the radial, azimuthal, and axial directions are properly treated; therefore, the response is acceptable. In response to RAI 3.14.2 [Ref. 9], the applicant demonstrated that the nodalization used in the model of heat conduction in the fuel rods was the same as that used in the NRC approved version of WCOBRA/TRAC. Since the US-APWR fuel rods are similar to existing fuel rods, the staff agrees that the nodalization being used is adequate and this issue is closed. The modeling of the DVI in the WCT-M1 model was described to the staff's satisfaction in the response to Question 3.14.3 [Ref. 9].

Prior to running a transient, the WCT-M1 model must be brought to steady-state. In its response to Question 3.14.4 [Ref. 9], the applicant described its steady-state acceptance criteria which determine when a satisfactory steady-state condition has been achieved. The criteria require the simulated value of each of eleven parameters be within the measurement uncertainty of the desired value of that parameter. The staff finds this to be a reasonable definition of steady state; therefore, the response is acceptable.

The two-phase performance (fully degraded homologous curves and the two-phase multiplier curve) of the US-APWR pump model in WCT-M1 is based upon 1/3 scale pump tests at low pressures. In its response to Question 3.14.5 [Ref. 10], the applicant discussed the applicability of the 1/3 scale pump data to the full scale US-APWR pump. The staff finds the arguments advanced by the applicant to be reasonable and the response acceptable. Although there is some uncertainty associated with using the 1/3 scale derived performance curves, it is conservative to do so. This is because pump degradation and its uncertainty decrease with increasing pressure and increasing pump size [Ref. 5].

An editorial change was made in response to the first LBLOCA RAI set, Question 3.15.2 [Ref. 9]: the definition of the end-of-refill was corrected to be the time at which the lower plenum refills, not the time when the downcomer is full.

The staff's request for a comparison of the plant and safety analysis logic for reactor trip, RCP trip, and main steam isolation was satisfied by the response to the second LBLOCA RAI set, Question 24 [Ref. 11], confirming that all were modeled conservatively.

The applicant uses a single containment pressure curve as the break boundary condition, regardless of break size. The applicant enumerated all the conservatisms that are in its calculation of containment pressure in its response to the second LBLOCA RAI set, Question 26 [Ref. 11]. It compared a best-estimate containment pressure calculation with the conservative one used in the LBLOCA analysis and concluded that the best estimate containment pressure response is up to 40 percent higher than the curve used in the LBLOCA analysis. The staff also conducted containment pressure response calculations which showed that the curve being used is lower than a best-estimate calculation over the range of break sizes being used in the applicant's BELBLOCA methodology. The staff is therefore confident that the containment pressure curve used in the LBLOCA analysis is conservatively low.

Table 3.6-5, "Analysis Conditions," states that the pressurizer is on an intact loop, but Figure 3.3-3 shows it on the broken loop. This discrepancy was explained in the response to the second LBLOCA RAI set, Question 27 [Ref. 11]. As part of the BELBLOCA methodology a sensitivity study is done using the Reference Case input to determine which pressurizer location, intact or broken loop, gives the highest PCT. The pressurizer location corresponding to the highest PCT is then used in all subsequent analyses. The staff accepts this technique as a reasonable approach to establishing the location of the pressurizer for the LBLOCA analysis.

The hot rod power peaking factor, $F_{\Delta H}$, is assigned a value of 1.78, while the value of 1.73 is used for the US-APWR design (response to the second LBLOCA RAI set, Question 28 [Ref. 11]). The use of a conservative value in the BELBLOCA analysis is acceptable to the staff.

The BELBLOCA methodology does not credit control rod insertion. The large amount of voiding early in the LBLOCA simulation is sufficient to quickly shut down the fission process.

In response to the second LBLOCA RAI set, Question 29 [Ref. 11], the applicant addressed an apparent discrepancy between Section 15.6.5 of the DCD and the topical report. The time of reactor trip given in the DCD only refers to the time the reactor trip signal was generated. It does not imply rod insertion. The clarification is acceptable.

Proof of temporal convergence of the WCT-M1 calculations was provided in the response to the second LBLOCA RAI set, Question 33 [Ref. 11], where it was demonstrated that essentially the same PCT was obtained when the time step sizes used in the LBLOCA simulations were cut in half. This is the usual way of demonstrating temporal convergence and is acceptable to the staff.

The noding scheme used in the WCT-M1 for the US-APWR model is the same as that used in Westinghouse's approved model for 3 and 4 loop plants. Therefore, the applicant addressed only spatial convergence for those features of the US-APWR that are unique (response to the second LBLOCA RAI set, Question38 [Ref. 11]). The adequacy of the model of the neutron reflector was demonstrated by comparisons of WCT-M1 to the NR reflood tests. The plant model uses the same nodalization as was used in those tests. The results of the nodalization sensitivity studies for the advanced accumulator, break, and DVI region of the vessel were presented. The studies showed that doubling the number of spatial nodes in the broken cold leg, and at the ECC injection points, and near the DVI nozzles did not significantly change computed results. These results satisfactorily demonstrate that the noding in these regions is adequate to resolve the thermal-hydraulics associated with the unique features of the US-APWR. The responses to Questions 33 and 38 demonstrate fulfillment of CSAU Step 8 and are therefore acceptable.

The staff noted that Figure 3.6-18, "Downcomer Liquid Level," showed an oscillatory behavior. The first LBLOCA RAI set, Question 3.10 requested an explanation of the oscillatory behavior, in particular the role of condensation due to direct vessel injection, a phenomenon which is ranked as not applicable. The response to Question 3.10 [Ref. 10] stated that DVI related condensation was rated as not applicable because it occurred after the hot spot in the core had quenched. When DVI was initiated (125 s) the downcomer level was high enough to cover the DVI nozzles, so no steam condensation was occurring due to DVI. Only after the accumulators emptied did the downcomer level drop below the DVI nozzles, but by this time the core had been quenched. The staff finds the applicant's response acceptable in that it explained the role of DVI-induced condensation. However, the applicant did not address the part of the RAI that requested an explanation of the downcomer oscillations. Therefore, follow-up second LBLOCA RAI set, Questions 1.5 and 41 were issued, both requesting an explanation of source of the downcomer level oscillations that occur between 40 and 125 seconds and an explanation of how the uncertainty in the prediction of the oscillations is treated.

In response to Question 1.5 [Ref. 11], the applicant stated that the ASTRUM analysis accounts for the effect of core flow oscillations on PCT through its treatment of the uncertainty in parameters that affect system behavior. It provided no information about how this is done. The response to Question 41 [Ref. 11] noted that in comparisons of WCOBRA/TRAC, the base code of WCT-M1, to integral tests it also exhibited oscillations not seen in the data. Nevertheless, the code showed adequate prediction of cladding temperatures, indicating that the oscillations did not unduly enhance the core heat transfer calculation [Ref. 3]. The response to Question 41 also presented a sensitivity study which, it claimed, showed that reducing the magnitude of the oscillations did not significantly change the calculated PCT for the WCT-M1 sample calculation presented in the LBLOCA Topical Report [Ref. 1]. The staff agrees with the applicant's conclusion; however, the applicant did not present enough information for the staff to conclude that its sensitivity study was meaningful. The applicant's response indicated that oscillations were suppressed by modifying WCT-M1. In order to judge the efficacy of the modifications the staff requested more information about the code modifications and any input modifications.

In its response to the fourth LBLOCA RAI set, Question 4 [Ref. 19], the applicant provided a discussion of the temporary changes that were made to the WCT-M1 source code and input to dampen the core flow oscillations. The applicant also provided an explanation of how the temporary code modifications led to a PCT that was slightly lower than the base case. The modifications resulted in more liquid accumulation in the bottom of the core, which led to an increased vapor generation rate and increased entrainment flow rate at the hot channel PCT location.

The response to Question 4 also noted that in the assessment of WCOBRA/TRAC against CCTF run 62 fairly large oscillations were observed in the calculation, yet the calculated PCT agreed well with the measured value, indicating that calculated core flow oscillations are benign with respect to their effect on PCT calculations.

The staff evaluated the temporary changes made to WCT-M1 and judged them to be a reasonable approach to dampen the core flow oscillations. The changes essentially introduced a dynamic loss coefficient at the core inlet. By increasing the loss when the core flow increased the magnitude of the oscillations was reduced. Based on the applicant's response to Question 4, the staff believes it is reasonable to conclude that the reflood flow oscillations in the WCT-M1 simulations do not have a large effect on the calculated PCT. The response to Question 4 is therefore acceptable.

During the staff's evaluation of Question 4, it discovered a coding error in HOTSPOT. In an April 5–6, 2011, meeting with the applicant, the staff discussed the possible impact of the error and asked the applicant to address the impact in a supplementary response to Question 4. The supplementary response to Question 4 [Ref. 24] confirmed that HOTSPOT did not correctly impose the maximum limit (HMAX) on the local heat transfer coefficient as described in the HOTSPOT documentation. The applicant corrected the coding and reran the four cases with the highest PCTs in the ASTRUM analysis for DCD Revision 3. Comparison of these four cases with their original results showed that the PCT was unaffected for all cases. The only difference in hot spot cladding temperature response was that the new cases had a slightly higher cladding temperature just prior to cladding quench. Plots of the local cladding heat transfer coefficients showed that this was the time where the HMAX limit had been exceeded in the unmodified version of HOTSPOT. The staff is satisfied that HOTSPOT has been modified so that it properly imposes HMAX and that the code modification has no impact upon the current values of PCT reported in the DCD. Therefore, the staff accepts the supplementary response to Question 4 as it pertains to HOTSPOT.

In an April 5 – 6, 2011, meeting with the applicant, the staff discussed the need for the applicant to demonstrate the WCT-M1 model noding was adequate to address potential downcomer boiling. The hot wall effect, which could cause downcomer boiling, was ranked high during reflood in the applicant's PIRT. The staff requested the applicant to address downcomer boiling as part of its supplementary response to Question 4.

To assess the treatment of DC boiling the applicant provided the following WCT-M1 simulations:

**Table 2 WCT-M1 Cases to Address DC boiling**

| Parameter | Base Case | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| Accum . Temp. | Nominal | Maximum | Maximum | Maximum | Maximum |
| Accum. Flow | Nominal | Minimum | Minimum | Minimum | Minimum |
| SI Temp. | Nominal | Maximum | Maximum | Maximum | Maximum |
| SI Flow | Minimum | Minimum | Minimum | Minimum | Minimum |
| Azimuthal Nodes | 4 | 4 | 8 | 4 | 4 |
| Azimuthal loss coefficients | 0.0 | 0.0 | 0.0 | 0.5 | 0.0 |
| Timestep Size / DTMAX in the reflood phase | 0.001/0.002 | 0.001/0.002 | 0.001/0.002 | 0.001/0.002 | 0.0005/0.002 |

The base case is the Reference Case in DCD Revision 3. All cases were run to 1000 seconds to see if significant downcomer boiling occurred and resulted in a second reflood heatup. All cases used the minimum containment back pressure curve used in the ASTRUM analysis. The break was a DEGB with a discharge coefficient of 1.0 for all cases. The response showed that this break type results in PCTs occurring during reflood, while split breaks generally result in blowdown PCTs. Thus, the DEGB break type is more likely to be affected by downcomer boiling.

No significant boiling of the downcomer fluid occurred in any of the five WCT-M1 simulations. The average collapsed level in the downcomer was as much as 30 cm (1 ft.) lower in the sensitivity cases because of the limiting boundary conditions used in those simulations. However, since the average collapsed downcomer level for all simulations was greater than 4.2 m, all the simulations had sufficient driving head to keep coolant flowing into the core throughout the 1000 seconds of simulation time. Thus, there was no second reflood heatup in any of the simulations.

The staff reviewed the axial noding used in the WCT-M1 model and the radial and axial noding used for the heat structures attached to the downcomer channels and found them sufficient to accurately capture the thermal hydraulic phenomena occurring during core reflood and the long term cooling phases of the LBLOCA. Based upon this finding and the results presented in the foregoing paragraph, the staff finds the WCT-M1 model of the downcomer to be adequate and acceptable for LBLOCA analysis. The applicant's response is therefore accepted and the issue is resolved.

The staff noticed that the LBLOCA sample problem's upper head temperature was equal to the cold leg temperature. It requested a justification of that value. The applicant responded as a supplementary response to the fourth LBLOCA RAI set, Question 2 [Ref. 23], stating that the US-APWR is designed so that the upper head fluid remains at the temperature of the cold leg fluid. The response provided the design calculations that were made to determine what downcomer to upper head bypass flow is required to guarantee downward flow in all the Rod Cluster Control Assembly (RCCA) guide tubes, the only flow paths between the upper plenum and upper head. The staff reviewed the design calculations and concurs that the designed bypass flow from downcomer to upper head is sufficient to keep the upper head fluid temperature the same as the cold leg fluid temperature. The design calculation has considered all appropriate uncertainties.

## 4.3 Independent Analyses

Confirmatory calculations were conducted by the staff to provide a basis for evaluating whether the applicant's LBLOCA analysis results are reasonable, and to inform the staff of the influence of uncertainty parameters upon computed results.

### 4.3.1 RELAP5/MOD3.3 Simulations

The RELAP5/MOD3.3 (R5M33) US-APWR plant model employed for the small break LOCA (SBLOCA) confirmatory analyses [Ref. 14] was used as the starting point for developing a R5M33 US-APWR model for the LBLOCA confirmatory calculations.

Overall the R5M33 confirmatory calculation was in good agreement with the WCT-M results for the LBLOCA Reference Case [Ref. 15]. The calculated PCT is 940 °C (1,723 °F) with R5M33 and 970 °C (1,665 °F) with WCT-M1. Therefore, neither the R5M33 nor WCT-M1 calculations indicate a significant challenge to the 1,204 °C (2,200 °F) PCT acceptance limit. The R5M33 calculation showed the PCT occurred during blowdown while WCT-M1 calculated it to occur during the reflood period. An investigation into this discrepancy revealed the lower blowdown peak temperature in WCT-M1 was due to both a model difference and a code difference.

The model difference is that the WCT-M1 model had a large loss coefficient at the broken cold leg nozzle. The R5M33 model, being based on the applicant's SBLOCA model, did not. The LBLOCA WCT-M1 model's cold leg loss coefficient is one of the ASTRUM uncertainty parameters. When the same loss was added to the R5M33 model, its calculated blowdown PCT was in much better agreement with WCT-M1.

R5M33 does not apply any relaxation technique to either heat transfer coefficients or critical heat flux. Consequently, the R5M33 LBLOCA simulation calculated DNB to occur within 20 ms of the break opening. WCT-M1 applies an exponential relaxation to both heat transfer coefficients and the critical heat flux [Ref. 3]. DNB was calculated to occur at about 0.25 seconds in the WCT-M1 simulation. The quarter-second longer period of nucleate boiling in the WCT-M1 simulation allowed the removal of a significant amount of stored energy from the fuel rods relative to the R5M33 simulation.

The R5M33 PCT response was found to be insensitive to a 15 percent variation in the peak break flow rate, which is the magnitude of the difference between peak break flows in the WCT Reference Case and R5M33 calculations.

Fuel rod gap conductance is modeled differently in WCT-M1 than in R5M33. WCT-M1 has a dynamic gap conductance model in which the conductance varies during the LOCA transient. On the other hand, gap conductance was constant throughout the transient in the R5M33 simulations. A R5M33 gap conductance sensitivity study was conducted to see how much of the codes' difference in PCT results could be attributed to the different gap conductance models. A R5M33 gap conductance sensitivity evaluation indicated that a significantly-reduced constant gap conductance (to about 20 percent of the constant gap conductance used in the R5M33 base calculation) provided the best match to the WCT-M1 PCT results. However, this value is unrealistically low, indicating that differences in gap conductance models in the two codes could not be responsible for all of the differences in calculated PCTs in the two codes.

The R5M33 blowdown/reflood period fuel temperature response was found to be insensitive to variations in the axial location of the fuel rod peak power density. This finding indicates that effects related to the elevation of core flow stagnation are likely not major contributors to the blowdown-period PCT behavior differences between R5M33 and WCT-M1 Reference Case calculations.

### 4.3.2 <u>WCT-M1 Simulations</u>

Confirmatory WCT-M1 and HOTSPOT calculations were performed to:

- Independently verify the results reported by the applicant.
- Better understand the ASTRUM methodology.
- Identify PCT sensitivities to uncertainty parameters.
- Examine calculation details not reported by the applicant.

The Reference and limiting PCT cases reported in the DCD (Section 15.6.5, Ref. 15) were run using input files and code executables supplied by the applicant. The results of that staff's calculations were in excellent agreement with the DCD results, verifying that the files provided to the staff were those used for the DCD analysis. The results also showed that for the limiting PCT case, the PCT calculated by HOTSPOT was 68 °C (123 °F) higher that the PCT calculated by WCT-M1. The fuel rod uncertainty parameters associated with HOTSPOT are responsible for the increase. The results also showed that the hot spot cladding temperature from the WCT-M1 Reference Case was 17 °C higher than the limiting case's value. This is because the Reference Case uses the TS maximum $F_q$ value, while the hot spot cladding temperature limiting case samples $F_q$ from a PDF with the TS maximum as a 95 percent probability.

A WCT-M1 run was made to verify that the gravitational heads around the RCS coolant loops summed to zero. This was done by specifying the RCP speeds, core power, main feedwater flows, and steam flows as zero in the model and running a 1,500-s transient calculation under those conditions. The result of this calculation revealed that instead of decaying to zero, the flow in each coolant loop reached a steady value of 300 kg/s. This result indicates an input error in the model. The second LBLOCA RAI set, Question 46 was issued asking the applicant to address the issue.

In response to Question 46 [Ref. 11], and in response to the fourth LBLOCA RAI set, Question 1 [Ref. 19], the applicant acknowledged the WCT-M1 result obtained by the staff. The responses demonstrated that WCT-M1 would predict zero loop flow if the elevation difference terms were set to zero for each loop. The responses do not address the relevant issue. WCT-M1 is calculating a residual flow in each loop even when the fluid density is the constant around the loop. This indicates an error in WCT-M1's treatment of the gravity head. The staff's position is that if WCT-M1 has an error in its treatment of the gravity head, it should be addressed by the applicant. In a revised response to Question 1 [Ref. 20], the applicant acknowledged that an error in the momentum source calculation in the pump component of WCT-M1 was the cause of the residual loop flow identified by the staff. The coding error was fixed and the applicant demonstrated that now the residual flow disappeared after the RCPs coasted down. The applicant then presented the results of the Reference Case and the limiting PCT case (Case 48) in the DCD using the new code version. The PCT for the Reference Case decreased 3°C and the case 48 WCT-M1 and HOTSPOT PCTs increased 2 °C and 8 °C, respectively. The staff accepts the revised response to RAI-1 because it corrects a code error and demonstrates that the error had only a small impact upon computed PCT.

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The set of independent calculations showed that the dominant uncertainty parameters in the WCT-M1 are break size, break discharge coefficient, and the cold leg nozzle factor (influences the flow split in the broken loop). They also demonstrated that the uncertainty in the advanced accumulator flow coefficient had little impact on PCT. Varying the flow coefficient from nominal minus one standard deviation to nominal plus one standard deviation only changed the PCT by 12 °C (22 °F).

The results of the staff's calculations are presented in more detail in Reference 14.

# 5 CONCLUSIONS AND LIMITATIONS

The US-APWR is an advanced PWR design that retains many functional similarities to conventional PWRs with respect to the system response during an LBLOCA accident. The advanced features of this design will not introduce any new phenomena. The codes and methodologies that were reviewed were WCT-M1, HOTSPOT, and ASTRUM. These codes and methodologies are based on NRC-approved versions of these codes and methodology, for LBLOCA analyses of Westinghouse 3 and 4 Loop plants, and the AP1000. The applicant has described and justified the changes made to WCOBRA/TRAC and ASTRUM to be applicable to US-APWR. The US-APWR unique features are an advanced accumulator, a neutron reflector, direct vessel injection, and a longer core.

The staff finds that the applicant's use of WCT-M1, HOTSPOT, and the ASTRUM methodology for the US-APWR, as described in MUAP-07011-P (R3), is acceptable for meeting the regulatory requirements of 10 CFR 50.46 based on the following limitations:

1. The final large and small scaling biases in the Advanced Accumulator Topical Report MUAP-07001 are equal to or more positive than those given in Table 3.5.7 [Ref. 28].

2. The final dispersion standard deviation values in the Advanced Accumulator Topical Report MUAP-07001 bound (smaller absolute values) or equal those

given in Table 3.5.6 [Ref. 28].

3. The final instrument uncertainly and manufacturing error standard deviation values in the Advanced Accumulator Topical Report MUAP-07001, bound (smaller absolute values) or equal those given in Table 3.5.6 [Ref. 28].

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## 7 LIST OF ACRONYMS

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| ANS | American Nuclear Society |
| ANSI | American National Standards Institute |
| AP600 | Advanced Passive 600 MW plant |
| AP1000 | Advanced Passive 1000 MW plant |
| APWR | Advanced Pressurized Water Reactor |
| ASTRUM | Automated Statistical Treatment of Uncertainty Method |
| BELBLOCA | Best Estimate Large Break Loss of Coolant Accident |
| CCTF | Cylindrical Core Test Facility |
| CE | Combustion Engineering |
| CFR | Code of Federal Regulations |
| CHF | Critical Heat Flux |
| CSAU | Code, Scaling, Applicability, and Uncertainty |
| CWO | Core Wide Oxidation |
| DCD | Design Control Document |
| DEGB | Double-Ended Guillotine Break |
| DNB | Departure from Nucleate Boiling |
| DVI | Direct Vessel Injection |
| ECC | Emergency Core Cooling (or Coolant) |
| ECCS | Emergency Core Cooling System |
| HHIS | High-Head Injection System |
| HHSI | High Head Safety Injection |
| LBLOCA | Large Break Loss of Coolant Accident |
| LCO | Local Cladding Oxidation |
| LHSI | Low Head Safety Injection |
| LOCA | Loss of Coolant Accident |
| LOFT | Loss of Fluid Test |
| MHI | Mitsubishi Heavy Industries, LTD |
| MWt | Megawatts thermal |
| NR | Neutron Reflector |
| NRC | U. S. Nuclear Regulatory Commission |
| NUREG/CR | Nuclear Regulatory Commission Regulation/Contractor Report |
| ORNL | Oak Ridge National Laboratory |
| PCT | Peak Cladding Temperature |
| PDF | Probability Density Function |
| PIRT | Phenomena Identification and Ranking Table |
| PWR | Pressurized Water Reactor |
| RAI | Request for Additional Information |
| RCCA | Rod Cluster Control Assembly |
| RCP | Reactor Coolant Pump |
| RCS | Reactor Coolant System |
| RG | Regulatory Guide |
| RPV | Reactor Pressure Vessel |
| RWSP | Refueling Water Storage Pit |
| R5M33 | RELAP5/MOD3.3 |
| SBLOCA | Small Break Loss of Coolant Accident |

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|---|---|
| SCTF | Slab Core Test Facility |
| SE | Safety Evaluation |
| SER | Safety Evaluation Report |
| SG | Steam Generator |
| SI | Safety Injection |
| THTF | Thermal Hydraulic Test Facility |
| TR | Topical Report |
| UPTF | Upper Plenum Test Facility |
| US-APWR | United States Advanced Pressurized Water Reactor |
| WCT-M1 | WCOBRA/TRAC(M1.0) |