FINAL SAFETY EVALUATION BY THE OFFICE OF NEW REACTORS
TOPICAL REPORT MUAP-07001, REVISION 5
"THE ADVANCED ACCUMULATOR"
MITSUBISHI HEAVY INDUSTRIES, Ltd
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1.0 INTRODUCTION

In support of the application for the design certification (DC) for the United States - Advanced Pressurized Water Reactor (US-APWR), Mitsubishi Heavy Industries, Ltd. (MHI), hereinafter referred to as the applicant, submitted Topical Report MUAP-07001-P, “The Advanced Accumulator,” (Reference 1). The US-APWR design uses advanced accumulators (ACC) as a part of the emergency core cooling system (ECCS) design. The US-APWR ACC design is built on the operating experience of a conventional accumulator used for mitigating the consequences of loss-of-coolant accidents (LOCAs) in pressurized water reactors (PWR). Similar to the conventional accumulators used in the operating PWR plants, the ACC is an accumulator tank partially filled with borated water and is pressurized with nitrogen. It is attached to the primary system with a series of check valves and an isolation valve, and is aligned during operation to allow flow into the primary coolant system if the primary system pressure drops below the pressure of the accumulator. The US-APWR ACC design differs from the conventional accumulators in that it incorporates a flow damper in the accumulator tank to provide a passive flow control. The flow damper is an inherently reliable passive fluidic device to achieve a desired reactor coolant injection flow profile without the need for any moving parts.

Emergency core cooling during a LOCA is one of the primary functions of the ECCS. In a conventional nuclear plant, the ECCS consists of accumulators, high-head safety injection system (SIS), and low-head SIS to accomplish these ECCS functions. During a large break LOCA (LBLOCA), the fuel cladding temperature increases due to the lack of liquid around the core. A LBLOCA generally includes blowdown, refill, reflood, and long-term cooling phases. After the initial blowdown, the ECCS is required to inject water into the core to limit the rise of fuel temperature in three steps. In the refill phase, the accumulators quickly inject water at a high flow rate to fill the lower plenum and downcomer of the reactor vessel. Subsequently, the core is reflooded by the water head in the downcomer, and the high-head and low-head SIS’ inject flow to keep high water level in the downcomer to reflood the core. In the long-term cooling phase after core reflood is completed, the low-head injection system provides water to remove decay heat and maintain the core in flooded state.

In the US-APWR ECCS design, the ACC switches its flow rate from large-flow injection to small-flow injection automatically and passively after the ACC injection reduces the water level in the tank below the top entrance of the large-flow standpipe. The combination of the ACC and the high-head injection system perform the function of the low-head injection system in the reflood and long-term cooling phases, and therefore, eliminate the need for the low-head injection system. Also, during a LBLOCA, it is necessary to start the ECCS pumps prior to the end of accumulator injection to the reactor vessel. The ACC injects water longer than a conventional accumulator, thereby allowing more time to start the ECCS pumps. This will allow the US-APWR to use gas turbine generators if needed.

The ACC design simplifies the ECCS design by the elimination of low-head safety injection (SI) pumps, and increases the amount of time available to start backup emergency power system. It is expected that the use of ACCs rather than the low-head SI pumps in the US-APWR design will reduce the net maintenance and testing workload at nuclear facilities.

Topical Report MUAP-07001-P describes the ACC design, the principles of operation and important design features of ACC, the empirical characteristic correlations of the ACC, and experimental programs to prove the concept and develop the correlations. Since the characteristic correlations were developed with a half-scale full-height test facility, the report also addresses the scalability of the half-scale tests to the full-size ACC application.

2.0 REGULATORY EVALUATION

The staff's review of MUAP-07001-P, Revision 5, is based on conformance with the following regulatory requirements:

General Design Criterion (GDC) 35, "Emergency Core Cooling," in Appendix A to Title 10 of the *Code of Federal Regulations* (10 CFR) as it relates to the requirement of a system that would provide abundant emergency core cooling to satisfy the ECCS safety function of transferring heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal-water reaction is limited to negligible amounts.

10 CFR 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," as it relates to the ECCS equipment being provided that refills the reactor vessel in a timely manner for a LOCA resulting from a spectrum of postulated piping breaks within the reactor coolant pressure boundary. The ECCS cooling performance following postulated LOCAs must be calculated in accordance with acceptable evaluation model to demonstrate conformance to the following acceptance criteria set forth in 10 CFR 50.46(b):

- The calculated maximum fuel element cladding temperature does not exceed 1200 ^{o}C (2200 ^{o}F).

- The calculated total local oxidation of the cladding does not exceed 17 percent of the total cladding thickness before oxidation. Total local oxidation includes pre-accident oxidation as well as oxidation that occur during the course of the accident.

- The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam does not exceed one percent of the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

- Calculated changes in core geometry are such that the core remains amenable to cooling.

- After any calculated successful initial operation of the ECCS, the calculated core temperature is maintained at an acceptably low value and decay heat is removed for the extended period of time required by the long-lived radioactivity remaining in the core.

10 CFR 50.46(a)(1)(i) also requires that for the realistic analysis of the ECCS cooling performance, the uncertainties in the analysis method and input must be identified and assessed so that the uncertainty in the calculated results can be estimated and accounted for.

The US-APWR ECCS design, including the ACCs, must comply with GDC 35, and the cooling performance will be evaluated through the safety analyses of LOCA for the full spectrum of break sizes (including LBLOCA and small-break LOCA (SBLOCA) to demonstrate that the above acceptance criteria are met.

The staff's evaluation of the ACC topical report includes the evaluation of the ACC characteristic equations, and uncertainties and applicability of the characteristic equations to US-APWR as part of the LOCA evaluation models for the calculation of the US-APWR ECCS capability, as required by 10 CFR 50.46 and GDC 35.

3.0 TECHNICAL EVALUATION

The US-APWR ECCS system configuration includes four ACCs connected to the reactor coolant system (RCS) cold legs. In addition, four high head injection subsystems inject directly into the reactor vessel downcomer following accumulator injection.

Each ACC consists of a tank partially filled with borated water and pressurized with nitrogen, and a flow damper inside the tank. The flow damper consists of a vortex chamber located near the bottom of the accumulator tank, a standpipe connected to a large-flow pipe attached radially to the vortex chamber, a side entry small-flow pipe tangentially connected to the vortex chamber, and a reducer-diffuser nozzle connected to the outlet port of the vortex chamber and the injection pipe. The standpipe and the small flow inlet pipe also include anti-vortex caps. The configuration and operation principle of the ACC design is shown in Figure 2.2.1-1, "Principle of Advanced Accumulator Operation," of the Topical Report MUAP-07001-P, Revision 5 (Reference 1).

When a LOCA occurs and pressure in the reactor vessel decreases below the ACC pressure, the check valves in the injection pipe open to permit the injection of the ACC cooling water into the reactor vessel. With the initial water level in the accumulator tank higher than the elevation of the inlet of the standpipe, water flows into the vortex chamber through both the large-flow rate and small-flow rate pipes. These flows collide with each other at a design facing angle between the large flow and small flow inlet pipes at the vortex chamber to cancel angular momentum, thus, preventing a vortex formation in the vortex chamber. Consequently, the flow resistance in the vortex chamber is small, resulting in a large flow rate. The flow through the flow damper is essentially the usual pipe flow without a strong vortex. The flow through the outlet nozzle dominantly experiences a pressure reduction in the reducer and a pressure recovery in the diffuser. The throat of the outlet nozzle is the critical section to determine the ACC flow rate.

The large-flow injection phase continues until the water level in the accumulator tank falls below the inlet level of the standpipe, and the flow in the standpipe almost comes to a stop. The flow from the small-flow pipe enters the vortex chamber tangentially, which creates a strong vortex in the vortex chamber. The vortex flow in the chamber creates a large pressure drop, and therefore, results in small-flow injection rate. The switching from the large-flow to small-flow injection phase is thus accomplished passively without any moving parts.

The US-APWR ACC is designed with two performance objectives: (1) immediately after the reactor coolant blowdown during a LBLOCA, the ACC injects water at a large flow rate for a limited duration to refill the reactor vessel lower plenum and downcomer, and (2) after the refill period, it injects water at a relatively small flow rate to establish the core reflooding condition by maintaining the downcomer water level. To achieve these performance objectives, Section 2.3.4, "Design Requirements for the ACC," of the report describes the determination of the design parameters for the large flow and small flow injection phases, respectively, based on a LBLOCA sensitivity analysis. The water volume above the top of the standpipe in the ACC is the large flow injection water volume needed to refill the reactor vessel lower plenum and downcomer during the refill phase of a LOCA. The injection flow rates for the large-flow and small-flow injection phases, respectively, are to refill the lower plenum and downcomer as rapidly as possible and to provide sufficient reflood rate to assure the peak cladding temperature is within the acceptance criteria during the worst case LOCA.

The flow resistance coefficient of the ACC injection flow path for the large flow phase is calculated based on the refill injection rate requirement and the ACC pressure and the RCS depressurization transient. The flow rate ratio at the flow-switching from large flow to small flow is used to determine the ratio of the flow resistance coefficients of the total ACC system injection line during the large-flow and small-flow injection phases. The flow damper flow resistance coefficients for the large-flow and small-flow phases, respectively, are obtained by subtracting the injection pipe resistance coefficient from the corresponding total ACC system injection line resistance coefficients. The ratio of the flow damper flow resistance coefficient for the small flow injection to the large flow injection is calculated to be about 50. The small flow injection water volume is determined based on the need for the duration of small flow injection from the ACC, followed by the injection from the SI pump, in the reflood phase to maintain the downcomer water level through the core quench. In all, the LBLOCA sensitivity study establishes the design requirements for the target flow damper flow resistance coefficients, and water injection volumes for the large-flow and small-flow injection phases, respectively. The design specifications of the ACC as summarized in Table 3.1-1, “Specifications for the ACC,” of the topical report include additional margins from the results of the sensitivity analysis. Section 3.1, “ACC Design Basis and Specifications,” of the topical report presents the detailed design of the “as installed” ACC with the structure of the flow damper depicted in Figure 3.3-1, “Overview of the Flow Damper,” and Figure 3.3-2, “Outline Drawing of the Flow Damper,” of the report.

It should be noted that the LBLOCA sensitivity analysis used in establishing the ACC design requirements was performed with the 10 CFR Part 50 Appendix K, “ECCS Evaluation Models,” with the Japanese decay heat model. The decay heat level of the Japanese model is different from that of the American Nuclear Society (ANS) 1971 decay heat model required in the Appendix K model, and therefore the core reflood rate would be different from the results if the ANS-1971 decay heat model was used. However, the sensitivity analysis was performed solely for the purpose of establishing the ACC design parameters. There are margins added to the final design specifications of the ACC. The applicant demonstrates compliance with the ECCS acceptance criteria in the LOCA safety analyses described in US-APWR Design Control Document Section 15.6.5, “Loss-of-Coolant Accidents Resulting from Spectrum of Postulated Piping Breaks within the Reactor Coolant Pressure Boundary.” The adequacy of the required injection flow rate will ultimately be confirmed by the ECCS performance analysis using the WCOBRA/TRAC code with ASTRUM methodology for the LBLOCA, and the M-RELAP5 code with the Appendix K requirements, including the ANS-1971 decay heat model, for the SBLOCA. The applicant used the Japanese decay heat model in the LOCA sensitivity analysis solely to establish the ACC design parameters. Since the Japanese decay heat model was not used in the safety analysis in the US-APWR DCD, its use in the sensitivity analysis is acceptable.

3.1 Evaluation of Accumulator Performance

The applicant conducted four sets of confirmatory tests to confirm the operational principles of the flow damper, and examine the flow characteristics of the ACC. The four sets of tests are of different scales with different objectives: 1/8.4, 1/3.5, 1/5 and 1/2 scales. The details of the test objectives, test apparatus, and test results for these tests are described in Section 4, "Confirmatory Testing Program for the ACC," of the topical report. The full-height, 1/2 scale tests were the tests that were used to develop the ACC flow characteristic equations. Other tests were conducted prior to the 1/2 scale tests to confirm expected performance from the operational principles of the ACC.

The 1/8.4 scale tests were flow visualization tests conducted to examine the basis of operation of the ACC and to understand the injection flow characteristics. The tests confirmed the basic operational characteristics of the flow damper in the ACC, and observe the flow switching from the large flow injection to small flow injection. The vortex chamber for this test was in an upright position, compared to a horizontal vortex chamber in the actual design.

The 1/3.5 scale tests were visualization tests conducted to confirm that the anti-vortex cap at the top of the standpipe prevent vortex formation at the standpipe inlet, and promote quick and smooth flow switching at the end of the large-flow injection. The anti-vortex cap that is at the top of the standpipe was made of transparent acrylate such that the flow can be observed at the standpipe inlet.

The 1/5 scale visualization tests were conducted to confirm the operational characteristics of the flow damper by observing the flow in the flow damper during large-flow injection, flow switching, and small-flow injection. The flow damper with a wall made of transparent acrylic resin was installed outside the test tank. The flow in the vortex chamber was recorded with a video camera. The characteristics in the vortex chamber were observed using blue ink as a flow tracer.

The full-height, 1/2 scale tests were full height and full pressure tests conducted to obtain flow characteristic data to develop the accumulator characteristic equations.

Overall, these tests were performed with the objective of confirming the following characteristics;

- Principle of flow damper.
- Performance of anti-vortex cap at the end of large flow injection.
- Water level transient in standpipe during flow switching.
- Performance of flow damper during large- and small-flow phases.
- Water level at flow switching from large- to small-flow.
- Effect of dissolved nitrogen.
- Dimensionless parameters (cavitation factor and flow rate coefficient) for ACC flow characteristics (Section 4.2.3, "1/5-Scale Test," of the report).
- Independence of ACC flow characteristics with scale. (Section 4.3.2.2, "Scalability of Flow Rate Characteristics," of the topical report).

3.1.1 Principle of Flow Damper

The flow damper is designed to act as a diode where flow decreases rapidly as the water level in the tank decreases below the standpipe entrance, leading to a vortex formation in the vortex chamber. The applicant performed tests at three scales, i.e., 1/8.4, 1/3.5 and 1/5, to demonstrate the intended operation.

As described in the topical report (Reference 1), the results of these tests showed that a vortex is not formed when the tank water level is above the standpipe; and, when the water level in the tank falls below the inlet of the standpipe, a vortex is formed in the vortex chamber, leading to a large pressure drop in the vortex chamber and a rapid decrease of flow rate. This is the intended characteristic of the ACC and these tests support the principle of passive flow switching from a large flow rate to a small flow rate.

3.1.2 Performance of Anti-Vortex Cap

An anti-vortex cap is installed at the entrance of the standpipe, as shown in Figure 3.3-1, "Overview of the Flow Damper," of the topical report. The purpose of the anti-vortex cap is to prevent any ingress of nitrogen from the top of the tank into standpipe. Without an anti-vortex cap at the entrance, it is possible to have a vortex formation at the level near the standpipe entrance that can entrain nitrogen as the level in the tank decreases. Anti-vortex cap will prevent this mechanism. There is an anti-vortex cap at the inlet of the small flow pipe, which is connected to the vortex chamber near the bottom of the ACC. However, by the time the water level approaches the level of the small flow pipe inlet, the ACC water is close to the dead volume, and the high head SI provides needed ECCS flow. Therefore, the effectiveness of the anti-vortex cap at the small flow entrance is not of particular interest.

The results of the tests at three test scales, 1/8.4, 1/3.5 and 1/5 scales, respectively, showed the effectiveness of anti-vortex cap in preventing ingress of nitrogen through the standpipe. The 1/3.5 scale test results showed that in the case of the standpipe inlet without an anti-vortex cap, there was a creation of vortex at the standpipe entrance as the water level decreases to the standpipe entrance, and subsequent entrainment of nitrogen as the water level further decreases. In the case of standpipe with the anti-vortex cap, a slight disturbance appeared on the water surface as the water level decreased from just above the upper end of the cap to the lower end of the cap. However, no vortex occurred, and the flow rate switched much more quickly than the case without the anti-vortex cap.

3.1.3 Water Level Transient in Standpipe during Flow Switching

During the switching of flow from the large-flow to the small-flow injection phase, the water level in the standpipe undergoes a transient due to inertial effects. Water level goes down and then recovers. If the level goes down too much, there is a possibility of entrainment of nitrogen from the standpipe to the vortex chamber. The data from the full-height, 1/2-scale tests (Section 4.2.4, "Full Height 1/2-Scale Test," of the topical report) showed that the water level in the standpipe at the time of flow-rate switching does not go down to the top of vortex chamber, but remains high enough to preclude any entrainment of nitrogen into the vortex chamber.

3.1.4 Performance of Flow Damper during Large Flow and Small Flow Phases

During a LOCA, there is initially large flow injection from the accumulator when the check valve in the injection pipe opens in response to the fall of the RCS pressure below the accumulator pressure. The flow decreases, as the water level in the accumulator tank decreases and the level reaches near the entrance to the standpipe. The large flow injection phase occurs as the combination of flow from the standpipe and the flow from the small-flow side entry. The net flow is radial in the vortex chamber, and there is no vortex so that the flow resistance is small. As the flow in the standpipe decreases, there is vortex formation in the vortex chamber with large increase in flow resistance and lower flow. This small-flow phase is equivalent to the low head injection pump in the ECCS of a conventional PWR. The requirement for the ACC design is a large flow injection phase for the first 40 or so seconds and then an order of magnitude less flow in the small-flow phase. The head losses in the small-flow phase should be about a factor of 50 (as discussed in Section 3.0, "Technical Evaluation," of this report) bigger than in the large-flow phase.

The full-height, 1/2-scale tests were used to confirm that the design requirements for the magnitude and timing of switching between the large flow and the small flow can be achieved. A total of seven test cases were conducted with various test accumulator tank pressures and exhaust tank pressures. The test conditions, including the injection pipe resistance, initial water level in the accumulator tank, and the initial accumulator pressure are comparable to the actual plant values. However, Test Case 7 was a low pressure test for assumed preoperational test conditions. Test Case 5 was conducted with water saturated with nitrogen to evaluate the effect of dissolved nitrogen gas. During the tests, water levels in the tank and the standpipe; pressures in the accumulator, injection pipe and exhaust tank; and water temperatures in the test tank were measured. These data, excluding data from Test Cases 5 and 7, were used to develop the flow characteristic equations. The applicant also conducted 1/5-scale low-pressure injection tests to obtain data to calculate flow rate coefficient and cavitation factor. The results showed similar characteristics as the 1/2 scale tests as shown in Figure 4.3.1-4, "Flow Rate Coefficient with Respect to Cavitation Factor of Flow Damper for Full Height 1/2-Scale and 1/5-Scale Models," of the topical report.

3.1.5 Water Level at Flow Switching

The ACC is designed such that the flow switching from the large-flow rate to the small-flow rate takes place when the water level drops to the lower end of the anti-vortex cap at the entrance of the standpipe. For the full-height, 1/2-scale tests, the accumulator flow rates and the accumulator water level for each test were plotted as a function of time. The water level at the switching of flow rates from large-flow to small-flow was defined as the intersecting point of two curves of water levels for large flow injection and small flow injection. As shown in Table 4.2.4-2, "Flow Switching Water Level," of the topical report, the data from the 1/2 -scale tests showed that the water level for the flow rate switching is within a small range of uncertainty of [ ] from the expected flow-switching water level at the lower end of the anti-vortex cap installed at the inlet of the standpipe. The concept of flow switching is confirmed with the tests.

The uncertainty in the switching level and its treatment in the safety analysis are described in Section 5.2, "Estimation of Potential Uncertainties of Water Level for Switching Flow Rates," of the topical report and in Section 3.3.3, "Uncertainty in Switching Level," of this report.

3.1.6 Effect of Dissolved Nitrogen

Fluid in the accumulator is in contact with nitrogen and overtime nitrogen will dissolve and diffuse throughout the liquid phase. In the limiting case, water could be saturated with nitrogen and there could be equilibrium between gas phase and liquid phase. There could be a potential impact of dissolved gas on the performance of the flow damper. As the fluid particles move through the flow damper, subject to decreasing pressure, the dissolved nitrogen gases will emerge and potentially affect the flow resistance of the flow damper.

To evaluate the effect of dissolved nitrogen gas in the accumulator water, the applicant conducted a test (Test 5) with nitrogen-saturated water in the full-height, 1/2-scale facility. In Test Case 5, water in the ACC tank was forced to be saturated with nitrogen by compulsorily bubbling and showering with nitrogen. This nitrogen-saturated water test case was conducted with similar boundary conditions of Test Case 1 in which nitrogen gas was passively charged so that it was not in equilibrium. A comparison of the test results between Test Cases 1 and 5, as shown in Figure 4.2.4-9 of the topical report, showed lower cavitation factor and flow coefficient for the large flow phase and a delay of about [ ] in the switchover from the large-flow rate to small-flow rate phase for Test Case 5. Lower flow coefficient, or higher flow resistance, during the large flow injection phase due to the effect of the dissolved nitrogen resulted in a lower accumulator flow rate, and a longer period of the large flow injection phase.

The applicant did not consider the flow coefficient data points from Test 5 in developing the accumulator characteristic equations as documented in Section 5.1, "Flow Rate Characteristics for Safety Analysis," of the topical report. This is because the test condition in Test Case 5 with saturated nitrogen is much more critical than the actual accumulators, and therefore, using the Test Case 5 data will result in evaluating flow coefficient smaller than that of the actual accumulator. Rather, Test Case 5 result of a [ ] of flow rate switching was used to address the effect of the dissolved nitrogen. As discussed in Section 3.3.3 of this report, the applicant will incorporate an increase in the accumulator injection pipe flow resistance coefficient in the LOCA analyses.

<u>Summary</u>

In summary, the staff's review of the four sets of different scale tests conducted by the applicant finds that the tests demonstrated the ACC performance principles. The tests confirm the principle of the flow damper performance to switch the ACC flow from large flow injection to small flow injection caused by a vortex formation in the vortex chamber during the small flow injection phase. The tests demonstrated that installation of an anti-vortex cap at the standpipe inlet prevents nitrogen ingress through the standpipe at the end of large-flow injection phase, and that, at the time of flow rate switching, the water level in the standpipe remains high enough above the vortex chamber to preclude any entrainment of nitrogen into the vortex chamber. The tests also showed that the flow rate switch water level is within a small uncertainty range of the standpipe inlet, and that the dissolved nitrogen has minimal effect on the ACC flow injection. Both the uncertainties of the flow rate switching water level and dissolved nitrogen effect will be accounted for in the safety analysis. The full-height, 1/2 scale tests results are used to develop the ACC characteristic equations for the large-flow and small flow injection phase as will be discussed the in following section.

3.2 Characteristics Equations for Advanced Accumulator (ACC)

The ACC provides SI in response to pressure drop in the primary system. For the calculation of the ACC flow rate, the applicant developed two ACC flow characteristic equations 5-1 and 5-2 for the large-flow and the small-flow injection phases, respectively, as described in Section 5.1.1, "Characteristic Equations of Flow Rates for the Safety Analysis," of the topical report. These characteristic equations describe the flow coefficient, C_v, as a function of cavitation factor, σ_v, which are defined below. The transition from the large-flow characteristic equation to the small-flow characteristic equation takes place based on the water level in the accumulator. When the water level decreases below the inlet of the standpipe, no flow enters the large flow standpipe and a vortex is formed in the vortex chamber thereby decreasing flow rate.

These characteristic equations along with switching criteria between two equations are developed based on data from the full-height, half-scale ACC tests. As described in Section 4.2.4, "Full Height 1/2-Scale Test," of the topical report, the applicant conducted seven tests and used data from 5 tests, Test Cases1 through 4 and the 6th test, to derive the equations. Test Case 5 was not considered as it was done with water saturated with nitrogen and was not considered to be a representative test. Test Case 7 was conducted with lower tank pressure of [ ] and was not representative of reactor operating conditions. The water temperature varied from [ ] to [ ] as stated in request for additional information (RAI) 89 (UAP-HF-12065, Reference 8). The temperature effect was considered through density and vapor pressure. It is assumed that density does not change significantly but vapor pressure in cavitation factor was affected.

The flow rate coefficient, C_v, and the cavitation factor, σ_v, as defined below, for each test are obtained from the test data.

$$K_D = \frac{(P_A + \rho g H) - (P_D + \rho V_D^2/2 + \rho g H')}{\rho V_D^2/2}$$

$$C_v = \frac{1}{\sqrt{K_D}}$$

$$\sigma_v = \frac{P_D + P_{atm} - P_v}{(P_A + \rho g H) - (P_D + \rho V_D^2 + \rho g H')} = \frac{P_D + P_{atm} - P}{\Delta P_{damper}}$$

Where,

C_v	Flow rate coefficient.
σ_v	Cavitation factor.
K_D	Resistance coefficient of flow damper.
V_D	Velocity in the flow damper outlet piping.
P_A	Tank pressure (gauge).
P_D	Injection pipe outlet pressure (gauge).
P_v	Vapor pressure of water.
P_{atm}	Atmospheric pressure.
H	Height of water level from vortex chamber.
H'	Height of injection pipe exit from vortex chamber.

The test data had been plotted in log-log curve between flow rate coefficient and cavitation factor. The data for the large-flow and small-flow phases collapse into two distinct curves as shown in Figure 5.1-1, “The Flow Characteristics of the Flow Damper,” of the topical report. The ACC characteristic equations shown in Equations 5-1 and 5-2 of the topical report for the large-flow and small-flow phases, respectively, are obtained by least square fits of the test data.

The flow switches from low resistance to high resistance flow path when the level in accumulator reaches the entrance of the standpipe. The ACC characteristic equation changes from the large-flow to the small-flow equation.

Since the characteristic equations were developed based on data from full-height, 1/2-scale test facilities, there are two issues related to application of this correlation, i.e., applicability and uncertainty. These issues have been addressed in the topical report in Sections 4.3, “Validity and Scalability of Flow Rate Characteristics,” Section 5.1.2, “Estimation of Uncertainty of the Characteristic Equations of Flow Rates,” and Section 5.4, “Estimation of Scaling Effect for Characteristic Equations.”

These are evaluated in Sections 3.2.1 and 3.3 below.

3.2.1 Applicability of the Characteristic Equations

There are two issues pertaining to the ACC characteristic equations as shown in Equations 5-1 and 5-2 of the topical report: (1) whether the two non-dimensional groups (C_v and σ_v) without any reference to the test facility size and viscosity effect are sufficient, and (2) whether the characteristic equations are applicable to the full size accumulator. The topical report addressed these concerns in Section 4.3.1, “Large Flow Injection,” for the large flow phase and Section 4.3.2, “Small Flow Injection,” for the small flow phase. These were addressed separately as the flow phenomena for the large-flow and small-flow injection phases are very different.

As discussed Section 3.2, “Characteristics Equations for Advanced Accumulator (ACC),” of this report, the plots of flow rate coefficient versus cavitation factor of the data for the large flow and small flow phases collapse into two distinct curves. This indicates that for the 1/2-scale facility, the data can be correlated with flow rate coefficient and cavitation factor for large and small flow phases, respectively.

The review here will consider the contributors of pressure losses in the flow path from the entrance of the vortex chamber to the exit of outlet nozzle. The large contributors will be identified for applicability assessment. There are three ways to assess the applicability of the 1/2-scale facility tests to the full scale ACC: scaling study, tests at full scale, and computational fluid dynamics (CFD) analyses. The applicant has relied on the results from CFD analyses to justify the applicability of the characteristic equations and quantitative estimate of scaling bias. The staff’s evaluation of the CFD analysis will be discussed in Section 3.3.2, “Scaling Effect - CFD Analysis,” of this report. In the following two sections, a qualitative assessment of applicability of the characteristic equations will be made.

3.2.1.1 Large Flow Phase

Section 4.3.1 of the topical report discusses the applicability of the characteristics equation for the large-flow phase to the full scale accumulator.

The large-flow test data and corresponding characteristic equation indicate that with the increase in pressure drop, both flow rate coefficient and cavitation factor decrease, probably due to cavitation. If the total loss coefficient was a constant, the flow rate coefficient should be independent of cavitation parameter. However, the flow rate coefficient does decrease (from 0.8 to 0.4) with the decrease in cavitation factor as shown in Figure 5.1-1 of the topical report. This indicates that loss coefficients are changing with flow rate and most likely due to cavitation.

[

] The losses will depend on the geometry and Reynolds number, as indicated in the Handbook of Hydraulic Resistance (Idelchek, Reference 10). For large Reynolds number (> 10^4) the loss coefficient is independent of Reynolds number (Page 217, Reference 16) for the junction from the vortex chamber to the outlet nozzle, and the loss coefficient in the injection pipe is also almost independent of Reynolds number (Page 81, Reference 16) for turbulent regime with wall roughness.

Loss coefficient, K_{Junc}, for the junction from the vortex chamber to the outlet nozzle is as follows:

$$K_{Junc} = 0.5(1 - \frac{A_{Inj}}{A_{vort}})^{0.75}$$

Where A_{Inj} and A_{vort} are areas of entrance to the outlet nozzle and vortex chamber, respectively. As the area ratios for the test and the full scale facilities are the same, the loss coefficients will also be the same.

For turbulent flow in smooth pipe the friction factor is estimated as follows (Reference 15):

$$f = {}^{1}/_{(1.8Log(Re) - 1.64)^2}$$

$$\frac{df}{dRe} = \frac{-1.56}{Re * (1.8Log(Re) - 1.64)^3}$$

The friction factor is very insensitive to Reynolds number, (df/dRe) = 10^{-8} (for large Reynolds number, 10^5), and for rough pipes it is even less dependent and friction factor is almost independent of Reynolds number. Therefore, the effect of scale will be minimal for this part of the pressure loss.

Section 4.3.1.2, “Scalability of Flow Rate Characteristics,” of the topical report provides a qualitative investigation on scaling effects for the large flow injection phase. A comparison of the primary dimensions between the 1/2 scale and full scale model shows that the scaling is geometrically consistent for both models with the exception of the standpipe height. There could be some scaling effects on total friction loss. There are some scaling effects due to size differences that will be captured with detailed CFD analyses described in the CFD Technical Report MUAP-09025-P, “CFD Analysis for Advanced Accumulator,” (Reference 9) as reported in Section 5.4 of the topical report and Section 3.3.2 of this report. The scaling effects estimated through the CFD analysis will be used as a bias correction on the flow rate coefficient.

3.2.1.2 Small Flow Phase

Section 4.3.2, “Small Flow Injection,” of the topical report describes the applicability of the characteristic equation for small flow phase.

The flow field in this regime is more complicated with vortex region in the vortex chamber, swirl flow and counter current flow in the outlet nozzle. As the standpipe flow decreases, the flow from the small flow pipe initiates a vortex in the vortex chamber. The vortex in the peripheral region is a free vortex and in the center is a forced vortex. Most of the pressure drop occurs in the forced vortex region. There is also a possibility of cavitation in the center of vortex chamber and in the center of the outlet nozzle.

[

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The Swirl Number is defined as follows:

$$Sw = \frac{\int_0^R uwr^2 dr}{R\int_0^R u^2\, rdr}$$

Where u is axial velocity, w tangential velocity and R is the radius of the pipe.

The swirl number is a measure of intensity of swirl as it is the ratio of angular momentum to axial momentum. The larger the value is, the stronger the vortex. Table 4.3.2-2, “Swirl Number Comparison between 1/2-Scale and Full-Scale,” of the topical report provides values of average swirl numbers based on the CFD analyses for the 1/2-scale full-height model and full-scale ACC, respectively, at different locations. [

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[

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Based on the above observation, the staff concludes that the flow coefficient and cavitation factor can be used to define the characteristic equation for the small flow phase. However, the flow coefficient is almost constant with very insignificant dependence on the cavitation factor as shown in Figure 4.3.1-4, "Flow Rate Coefficient with Respect to Cavitation Factor of Flow Damper for Full Height 1/2-Scale and 1/5-Scale Models," of the topical report, [
]

The characteristic equations will be similar for the full scale accumulator and half scale facility. However, there will be quantitative differences, which will be discussed later in the Section 3.3.2 of this report and the details are provided in the CFD report.

Summary

Based on qualitative assessment discussed above, the staff concludes that the characteristic equations shown in Equations 5-1 and 5-2 of the topical report adequately describe the ACC flow characteristics during the large-flow rate and small-flow rate phases, respectively. For the large flow phase, the non-dimensional groups (C_v and σ) used to develop the characteristic equation are sufficient to represent the flow conditions. The viscous effects on the wall are not significant as Reynolds numbers are very large. Therefore, the Reynolds number is not needed in the characteristic equation. There could be some scaling effects on the total friction loss, which will be estimated through the CFD analysis.

For the small flow phase, the flow rate coefficient is almost independent of the cavitation factor. The CFD studies also indicated that not only the flow rate coefficients have very little variation with the cavitation factor but are close for two facilities (1/2-scale and full-scale ACC). CFD analyses also indicated that the flow fields were qualitatively similar in 1/2 scale and full scale model of ACC. In addition, it was shown that the Reynolds numbers are very large leading to small effect of wall friction. Therefore, Reynolds number is not included in the equation. The correction for size will be estimated through CFD analyses.

The applicability of the 1/2-scale tests to the full scale ACC and the quantitative estimate of the scale effects or biases are addressed through CFD analyses described in the CFD technical report as described in Section 3.3.2, "Scaling Effect – CFD Analysis," of this report.

3.3 Uncertainty in ACC Characteristic Equations

The characteristic equations developed from the full-height, 1/2-scale test data will be used in the safety analyses. There are uncertainties in the characteristics equations that have to be factored in the safety analyses either as conservative bias or as a distribution in statistical analyses for determining overall uncertainty.

The overall uncertainties of the ACC characteristic equations are attributed to experimental uncertainty, and the scaling uncertainty as the underlying data was from the full-height, 1/2-scale test model.

The experimental uncertainty includes the manufacturing error of the test model, instrumentation uncertainty for data acquisition, and the dispersion uncertainty of the least-square fit equation to the test data. Section 5.1.2, "Estimation of Uncertainty of the Characteristic Equations of Flow Rates," of the topical report provides an analysis of the scale test characteristic equation uncertainties, and the staff evaluation is described in Section 3.3.1, "Experimental Uncertainty in Characteristic Equations," of this report. The scaling uncertainty is obtained separately and treated differently from the experimental equation uncertainties. The applicant calculated the scaling uncertainty via CFD analysis, and applied the scaling uncertainty as a bias in the ACC flow coefficient in the LOCA analysis. The CFD analysis is described in the CFD technical report (Reference 9). A summary estimate of the scaling effect of the characteristic equations is described in Section 3.5.3, "Evaluation of Scale Effect Between 1/2 Scale and 1/1 Scale," of the CFD technical report and in Section 5.4 of the topical report, the staff evaluation is described in Section 3.3.2 of this report.

The US-APWR LBLOCA analysis is performed with the best-estimate evaluation model described in the Realistic LBLOCA Evaluation Methodology Using Automated Statistical Treatment of Uncertainty Method (ASTRUM), WCAP-16009-P-A (Reference 3). A model of ACC, including the characteristic equations, has been incorporated in the system code WCOBRA-TRAC (Reference 2). The scaling uncertainties are applied as bias by reducing the flow coefficients calculated from the characteristic equations for the large-flow and small-flow injection phases, respectively.

SBLOCA is analyzed with the M-RELAP5 code with Appendix-K of 10CFR50 approach (Reference 4). A model of ACC, including the characteristic equations, has been incorporated in the in M-RELAP5 (Reference 4). For SBLOCA analyses the scale test characteristic equation uncertainty and scaling uncertainty are accounted by taking 95 percent negative uncertainties as bounding biases, as there is no statistical approach for the SBLOCA analyses.

There are additional uncertainties in the modeling parameters such as water level for the switchover from the large-flow to small-flow injection phase, and the dissolved nitrogen effects. The uncertainties of the ACC water level for switching flow rates is described in Section 5.2, "Estimation of Potential Uncertainties of Water Level for Switching Flow Rates," of the topical report, and the staff evaluation is described in Section 3.3.3, "Uncertainty in Switching Level," of this report. The treatment of the dissolved nitrogen effect is discussed in Section 5.3, "Treatment of Dissolved Nitrogen Gas Effect in the Safety Analysis," of the topical report, and the staff's evaluation is described in Section 3.3.4, "Uncertainty due to Dissolved Nitrogen Effect," of this report.

3.3.1 Experimental Uncertainty in Characteristic Equations

As discussed above, the ACC flow rate coefficient is predicted using two characteristic equations: one for the early large flow phase when the water level is above entrance of the standpipe, and the other for the small flow phase when the water level is below the standpipe entrance. These two characteristic equations were derived from the data obtained from the full-height, half diameter test facility. In addition, information about the water level in the tank at the time of switch is also obtained from these tests. This section describes the evaluation of the uncertainties associated with the 1/2 scale test characteristic equations.

3.3.1.1 Estimate of Experimental Uncertainty

There are three sources of uncertainty. The first source of uncertainty is dispersion deviation, which is the uncertainty due to curve fitting the data to obtain the characteristic equations. The second is instrument uncertainty, which is the uncertainty in the measurement of different parameters that are used to compute flow rate coefficients and cavitation factors. The third is the manufacturing error in different components of the test setup.

Section 5.1.2, “Estimation of Uncertainty of the Characteristic Equations of Flow Rates,” of the topical report, identifies these sources of uncertainties and the values associated with dispersion deviations, instrument uncertainties, and manufacturing errors. The details of the calculation of the uncertainties are provided in the response to the staff’s RAI. In its response to RAI 17 (UAP-HF-07086, Reference 5), dated July 20, 2007, and RAI 42 (UAP-HF-09453, Reference 7), dated September 16, 2009, the applicant provided the detailed calculations of the instrumentation uncertainties for various injection stages of the large-flow injection and small-flow injection phases. The response to RAI 42 also provides a detailed description on how the bias limits of six parameters (i.e., test tank diameter, specific weight of water, flow rate, height of injection pipe, injection pipe diameter, and flow rate coefficient) are obtained. In its response to RAI 18 (Reference 5) dated July 20, 2007, and RAI 44 (UAP-HF-09239, Reference 6), dated May 20, 2009, the applicant provided detailed calculations of the manufacturing errors. In its response to RAI 43 (Reference 7), dated September 16, 2009, the applicant provides justification of [

]. These are elaborated here.

The dispersion deviation is computed by estimating departure of the characteristic equation from the measurement as described in Section 5.1.2 of the topical report. For each data point in a 1/2 scale test, the relative difference between the flow coefficients from the test data and the flow coefficient calculated with characteristic equation is made, and the dispersion deviation of the test is the standard deviation of the relative differences of the data points in the tests. Equation 5-4 of the topical report is used to calculate the dispersion deviation of all 1/2-scale tests used in the development of the flow characteristic equation. Table 5.1-1, “Dispersion of the Data from the Experimental Equations,” summarizes the standard deviation of the relative differences of the flow rate coefficient calculated from the test data and the characteristic equations, respectively of individual tests and combined over all the five tests. [

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The staff finds this to be a standard curve fitting procedure and acceptable.

The instrument uncertainty relates to the uncertainties associated with the measurement of those parameters in the experiment pertaining to the determination of the flow characteristics of the accumulator. A detailed description of the calculation of the instrument uncertainty is provided in MHI’s response to RAI 17-B (Reference 5). The staff requested that the applicant provide a description of (1) instrument string for each parameter measured in the tests, (2) the accuracy or allowance associated with each instrument component, (3) the methodology for combining the uncertainties, allowances, or errors of the instrument components associated with each parameter to arrive at the overall uncertainty of each measured parameter, and (4) the methodology used to arrive at the total uncertainty for the flow rate coefficient. In its response, dated July 20, 2007, the applicant provides the measuring system of the full height 1/2 scale tests and the instrument strings for the flow rate coefficient and cavitation factor. The equation of calculating the flow rate coefficient C_v is used to show the parameters measured in the tests. [

.] The overall instrument uncertainty is the combination of the relative bias limit (B_r) and relative precision index (S_r) using the square root of the sum of the squares method. The method of combining the two is standard industry approach described in American Society of Mechanical Engineers (ASME) PTC 19.1, "Test Uncertainty" (Reference 11), and based on 95 percent value of precision index of the average based Student t distribution and degrees of freedom, N. The expression is as follows:

$$U_{RSS} = \sqrt{B_r^2 + \left(t\, S_r / \sqrt{N}\right)^2}$$

As there are at least seven data points and the degree of freedom is six or more.
[

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The staff finds that this simplified estimate of uncertainty is conservative and is therefore acceptable.

In its response to RAI 17-B (Reference 5), the applicant provides a sample calculation for the uncertainty of the flow rate coefficient of the large flow phase of Test Case 1. The staff reviewed the instrument uncertainty calculation methodology and the sample calculation, and found them acceptable. The overall instrumentation uncertainties at the large-flow phase and the small-flow phase for each test are summarized in Table 5.1-2 (1/2), "Instrumental Uncertainties at Large Flow," and Table 5.1-2 (2/2), "Instrumental Uncertainties at Small Flow," of the topical report. These tables show that the instrument uncertainties increase as the accumulator injection progresses through different stages of the injection. [

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The third source of uncertainty is due to manufacturing tolerance of the flow damper dimensions. In its response to RAI 18 (Reference 5), the applicant described that the effect for flow rate coefficient due to manufacturing error is considered separately for the large-flow and small-flow injection phases. For the large-flow injection phase, the parameters with dominant effect on the flow rate coefficient are the vortex chamber outlet nozzle throat diameter and the facing angle between the large-flow and small-flow inlet pipe at the vortex chamber. The outlet nozzle throat has the minimum flow area in the flow damper and is therefore the dominant dimension to the flow damper performance. The facing angle of the large and small flow inlet pipe is the angle that flows from the large and small flow inlet pipe collide together and vanishes the angular momentum to eliminate vortex in the vortex chamber, and therefore the error in this collision angle would cause vortex during large-flow injection and affect the flow damper performance. [

]

There is an additional uncertainty that is due to scale effect as the characteristic equations are based on full height 1/2 scale data. The applicant has addressed this through simulation of ½ and full scale facilities and estimating the differences between flow rate coefficients for same cavitation parameters. A bounding bias was estimated to be used to correct the characteristic equations for application to full scale facility. A summary estimate of the scaling effect of the characteristic equations is described in Section 5.4 of the topical report, and the staff's evaluation is described in Section 3.3.2 of this report.

3.3.1.2 Combining Uncertainties

The characteristic equations are incorporated in the computer codes such as WCOBRA-TRAC as best estimate values. However, there is need for estimate of aggregate of all uncertainties as bias and distribution. This is described in Section 5.1.2 of Topical Report MUAP-07001.

[

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The total experimental uncertainty in the characteristic equation is expressed in terms of standard deviation for the flow rate coefficient and is summarized in Table 5.1-3, “Total Uncertainty of Flow Rate Coefficient (Experimental Equations) for Safety Analysis of US-APWR,” of MUAP-07001. In the LBLOCA analysis (Reference 2), the total uncertainty is treated as a statistical parameter in the ASTRUM analysis and the value is randomly sampled from the normal distribution within four standard deviations. In the SBLOCA analysis (Reference 4) and the mass and energy release analyses, the total uncertainty is treated as a negative bias of one-sided 95 percent confidence level. The staff finds this uncertainty treatment approach acceptable because it is a conservative method of accounting for uncertainties.

3.3.2 Scaling Effect – CFD Analysis

Section 3.2.1, “Applicability of the Characteristic Equations,” of this report described that the phenomena are similar between the 1/2-scale test facility and the full size accumulator. The characteristic equations for the large-flow and small-flow phases will be close for both the 1/2 scale and 1/1 scale accumulators. However, as these equations will be used in LOCA analysis, a quantitative value of correction for the scaling effect is needed. Since there is no test data for full scale facility, the applicant has undertaken CFD analysis to estimate the scaling effect. This is done by modeling both the 1/2 scale and 1/1 scale ACC with CFD and determining the differences in flow rate coefficients for given cavitation factors. The applicant prepared Technical Report MUAP-09025, Revision 3, “CFD Analysis for Advanced Accumulator,” (Reference 9) to describe the CFD analysis, scale effect and uncertainty in CFD results.

The Office of Nuclear Regulatory Research conducted an independent CFD scaling analysis of the ACC in 2009. In this study (Reference 12), the staff found that CFD is an appropriate tool to evaluate scaling, and concluded that the behavior seen in the 1/2 scale test facility is appropriately representative of the 1/1 scale (as-designed) component.

3.3.2.1 Review of CFD Analyses

The applicant conducted a CFD analysis to better understand the flow structure and the cavitation phenomena in the ACC, and to further validate the extrapolation from the 1/2 to the 1/1 scale ACC. The analysis was conducted to meet the following four objectives:

- Evaluate the flow behavior at quasi-steady-states for both small-flow rate and large-flow rate conditions,

- validate the CFD model using the 1/2 scale experimental data,

- evaluate the significance of the CFD-evaluated scale effect by computing the difference in flow coefficient results from the 1/2 scale and 1/1 scale CFD analyses (i.e., CFD-evaluated bias), and

- quantify the CFD-evaluated scale effect, including the uncertainty in CFD calculations for application to the 1/2 scale and 1/1 scale ACC hydraulic performance.

The applicant conducted the CFD analysis using a general-purpose thermal-hydraulics simulation software package, ANSYS FLUENT, Version 12 (Reference 13).

The applicant developed two separate analysis models to simulate the two different flow injection modes, large flow injection and small flow injection. The geometric configurations are described in Figure 3.2-1, "Analysis Models for 1/1 Scale," and Figure 3.2-2, "Analysis Models for 1/2 Scale," of the CFD report (Reference 9). These two models were first constructed using a 1/2 scale geometry to validate the results against the experimental data, then for a 1/1 scale geometry to check the validity of scaling analysis. The applicant also consulted and followed various CFD best practice guidelines (BPG) (Reference 14) when setting up and analyzing their models. Dimensionless distance from the wall, y^+, was used to test the quality of the grids. The y+ values were also used to judge the adequacy of the turbulence model used in the analysis. The ranges of the y^+ values were within an acceptable range for the type of turbulence model chosen for the analysis. Additional information on y^+ values can be found in Appendix G, "Y+ Profile," of the CFD report (Reference 9). The CFD results showing the experimental observations for both small and large flow rates for the 1/2 scale and the comparison with the 1/1 scale results, are shown in Appendix E, "Flow structure for Large Flow," and Appendix F, "Flow structure for Small Flow," of the CFD report. To verify the model, the applicant used the Grid Convergence Index (GCI) according the ASME V&V 20 (Reference 15) standard to evaluate the uncertainty of the model. Detailed information about the method is in Appendix A, "Calculation of GCI," of the CFD report.

Section 3.2.3, "Specification of the CFD Analysis," of the CFD report (Reference 9) describes the specifications to setup the CFD analysis, which are summarized in Table 1 below:

[

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The following boundary conditions were used to analyze the small and large flow rate conditions shown in Figure 3.2-1 and Figure 3.2-2 of the CFD report:

- For Large Flow Injection Case:
  - Inlet Boundary Condition: Tank Pressure.
  - Outlet Boundary Condition: Outlet Pressure.

- For Small Flow Injection Case:
  - Inlet Boundary Condition: Velocity Inlet (Standpipe).
  - Inlet Boundary Condition: Velocity Inlet (Small Flow Pipe).
  - Outlet Boundary Condition: Outlet Pressure.

Pressure boundary conditions are preferred at the inlet and outlet of pressure driven flow in a CFD model. When using a velocity inlet at the boundary, uniform velocity will be prescribed, which may or may not resemble reality. Also, in this analysis, the objective of the 1/2 scale CFD model was to use the test data pressure values as boundaries and validate the CFD predicted mass flow rate with the obtained experimental mass flow rate. Concerns such as these were raised by the staff and resulted in a number of sensitivity studies conducted by the applicant.

<u>Sensitivity Analysis of CFD models</u>:

To check the CFD model response to various modeling options, the following three major sensitivities involving turbulence model, inlet boundary conditions and the cavitation model were performed:

- Turbulence model.

The applicant used the Reynolds Stress Model (RSM) to model turbulence in the flow. RSM solves the continuity equations of the Reynolds stresses in all three directions in addition to the dissipation of turbulent kinetic energy equation. Details of the model can be found in FLUENT theory manual (Reference 13). The dissipation of turbulent kinetic energy equation uses coefficients that are not valid for highly complicated flows as in the case of small flow rate conditions in the ACC. The applicant performed sensitivity calculations to tune the $C_{1\varepsilon}$ coefficient of the turbulent kinetic energy dissipation equation as explained in Appendix B, "Scale up Capability of Turbulence Model," of the CFD report (Reference 9) to match the experimental data for small flow rate cases. The calibration was only needed for small flow rate conditions, as high rotational flow persisted in the vortex chamber and the outlet nozzle. The default coefficients in the dissipation equation are highly dissipative, thus miss-predict the flow variables and overall flow rate when compared to the experimental data. When the default value of [ ] was used, the tank inlet pressure was [ ] As such, the applicant performed analysis using lower values for $C_{1\varepsilon}$ to match the predictions to the experimental data. Appendix B of the CFD report lists references of other published analysis that used a similar approach.

[ ] The applicant cited other works where authors changed the dissipation coefficient to accommodate complex flows, as predicted in the ACC during small flow rate conditions, and listed these prior studies in Table B2-1, "Examples of Tuning the ε Equation," of the CFD report. All the authors in that table used additional functional terms in addition to changing the value of $C_{1\varepsilon}$ constant as shown in the table. These additional functions take into account the dependence of dissipation on strain and velocity gradient in the flow. Changing $C_{1\varepsilon}$-from one constant value to another constant value may not be the most accurate way to model complex flows as in small flow rate cases. As a result, the applicant was not able to match all 1/2 scale experimental data for small flow rate conditions found in Test Cases 3 and 6.

Despite the simplified approach chosen by the applicant, the staff finds the applicant's tuning acceptable because the results fit within the instrumental uncertainty of the test data for those bounding flow cases (as shown in Table 1).

- Boundary conditions

[

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- Cavitation model

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3.3.2.2 GCI Method:

There are two kinds of verification. The first is code verification which is used to demonstrate that the computerized model is consistent with the CFD code as stated above, i.e., that there are no programming errors or inconsistencies in the solution algorithm. This is normally done by the code developers. The second kind of verification is solution verification which is the estimation of the numerical error or uncertainty of a specific simulation result and is to be done by the code user. Solution verification is also known as numerical error estimation.

Both kinds of verification need to quantify the discretization error which results from the fact that a system of partial differential equations is solved with finite discretization in space and time. The most general method for estimating the discretization error is the Richardson Extrapolation, which is used in code verification and solution verification. The application of the Richardson extrapolation method to quantify the discretization error is called the GCI which can be found in more detail in ASME V&V 20 (Reference 15) and References 17 and 18, as well as in Appendix A of the CFD report (Reference 9).

According to the ASME V&V 20 (Reference 15), GCI can be understood as:

- Uncertainty of the solutions is derived from discretized equations by a numerical and analytical approach.
- Its uncertainty is at 95 percent confidence level.
- Numerical uncertainty (Umesh) is evaluated using GCI.
- No assumption on the form of error distribution was made for these empirical studies. Specifically, the common statistical distribution of a Gaussian distribution is not used (i.e., Umesh = GCI).

To use the GCI method, the following criteria should be met:

- The solution displays monotonic convergence.
- The solution on the mesh should be in the asymptotic range.

These criteria can be met only if the following conditions are satisfied:

- A minimum of three grids is required to perform the GCI calculations. According to ASME V&V 20 standards, a minimum of four grids is needed to demonstrate that the observed order of accuracy is constant for a simulation series. In fact, it may require more than four grids to convincingly demonstrate asymptotic response in difficult problems, possibly five or six grid resolutions in cases where the convergence is noisy (Reference 15).
- The observed order of accuracy has to be comparable to the expected order of accuracy of the analysis method.
- There are some advantages to using integer grid refinement but it is not necessary. It is desirable that the grid refinement factor, $r = h_{coarse}/h_{fine}$, should be greater than 1.3 for most practical problems. This value of 1.3 is based on experience and not on a formal derivation. The grid refinement should, however, be made systematically; that is, the refinement itself should be structured even if

the grid is unstructured. Geometrically similar cells in the grid sequence are required to avoid noisy and erroneous observed p values. It is highly recommended not to use different grid refinement factors in different directions (e.g., r_x =1.3 in x direction and r_y = 1.6 in y direction), because erroneous observed p values are produced. (The computational solutions still converge to the correct answers with $r_x \neq r_y$, but the observed rate of convergence p is affected.)

[

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Additionally, the grid refinement ratio "r" as explained in Appendix A (Reference 9) is not as large as the ASME V&V 20 guidelines (Reference 15). V&V 20 suggests a value of at least 1.3 for the grid refinement ratio. The values used by the applicant are less than 1.3 except for the values used in small flow rate conditions with a 1/2 scale model. Additionally, the refinement was not consistent and systematic in all the directions as explained above.

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In summary, the applicant's GCI calculations deviated from the BPG in the following ways:

- Grid size ratios for all the GCI cases except for the small flow rate condition with 1/2 scale were calculated to be below 1.3 (when the guidelines recommend a value of least 1.3).

- Only three grids were used for each GCI calculation point, instead of four. The fourth grid is necessary to test and compare the order of accuracy. Each set of three grids will produce an order of accuracy value (one p value). A combination of four grids will give three values for the order of accuracy to be used for comparison. Additionally, the results from fourth grid will be used to test if the results are in the asymptotic range.

- Different grid refinement factors were used in different directions. This was the main reason why erroneous observed order of accuracy (p values) were produced as shown in Table A-2 of the CFD report.

- Grid resolutions of 4 out of 16 studied cases are not in the asymptotic region.

3.3.2.3 Evaluation of Scale Effect on Characteristic Equations

The applicant analyzed various flow situations with the CFD code, FLUENT (Reference 13). The analysis accounted for the effects of nodalization, turbulent models and cavitation models. The CFD methodology was first validated with the 1/2 scale test data. The analyses were repeated for the full scale facility with similar boundary conditions for the large-flow and small flow phases.

These analyses met two objectives. First, it showed that the flow field for the 1/2 scale and full scale facilities are similar for both large flow and small flow phases. This indicates that facilities qualitatively will have similar performance. It should be noted that they are not the same.

Therefore, the application of these characteristic equations to plant calculations will require an estimate of scale effect. Section 3.5.3, “Evaluation of Scale Effect between 1/2 and 1/1 scale,” of the CFD report (Reference 9) provides an estimate of scaling biases as a bounding value that will be applied directly to flow rate parameters obtained from the characteristic equations to predict the full scale ACC performance. This bounding value includes the effects of facility differences (size) and nodalization effect through the GCI. These biases are listed in Section 5.4 of the ACC topical report.

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3.3.2.4 Conclusions from Reviewing MHI's CFD Analysis

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However, the staff does not agree with the applicant for the use of an order of accuracy [ ] and the assumption of [ ]

Additionally, the following concerns were expressed to the applicant by the staff to reduce the uncertainty in their analysis:

[

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Overall, the staff concludes that the applicant has done an acceptable job in conducting its scaling analysis using CFD. However, the applicant must address the order of accuracy and GCI distribution treatment, as detailed below, to properly quantify the uncertainty in the scaling analysis.

- The applicant's GCI methods are questionable due to the high obtained degree of accuracy values (p). The high values of p are likely due to the non-systematic approach that the applicant took when developing their grid convergence study. Also, an additional mesh (a total of four) for the GCI calculations would be helpful to check and assess the order of accuracy. Additionally, grid resolutions of 4 out of 16 studied cases are not in the asymptotic region. Thus, to evaluate the CFD numerical error, the applicant should use an order of accuracy (p) = 1.0 and should not assume [ ]

3.3.2.5 Evaluation of Estimate of Scaling Bias

The calculation of GCI is described in Appendix A of the CFD technical report (Reference 9) and ASME V&V 20 Guidance (Reference 15). In the calculation of GCI for the large-flow and small-flow injection phases, respectively, the applicant proposed in Appendix A, Item (6), "Modification of the GCI Calculation," and in response to RAI 94(a) (Reference 19), dated May 29, 2013, to use [

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However, as discussed in Section 3.3.2.4, "Conclusions from Reviewing MHI's CFD Analysis," of this report, the staff's evaluation of the CFD grid refinement analysis concluded [

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The staff concludes that the scaling biases of [ ] should be applied to the ACC flow coefficients of the large-flow and small-flow injection phases, respectively. The applicant's use of the scaling biases of [ ] and [ ] of the large-flow and small-flow injection phases, respectively, in the LOCA analyses is not acceptable. The applicant should apply the scaling biases of [ ] to the flow coefficient of the large-flow and small-flow injection phases, respectively.

3.3.3 Uncertainty in Switching Level

The ACC model implementation requires the logic of switching from the large flow characteristic equation to the small flow characteristic equation. The uncertainty in this model is described in Section 5.2 of the topical report. The data from the full height, 1/2 scale tests, excluding Test Case 5, indicate that switching level deviation with respect to the standpipe entrance varies from [ ] to [ ] Test Case 5 with coolant saturated with nitrogen showed maximum deviation of [ ] which implies that switching occurred when level was [ ] above the standpipe entrance. The applicant conservatively chose the bounding value of Case 5 as the flow switch level uncertainty to provide additional margin. With addition of instrument uncertainty, the uncertainty in the switchover water level is [ ] to [ ]

The water level uncertainty is accounted for in the safety analyses by converting it into the initial ACC water volume uncertainty, i.e., decreasing the initial water volume in the accumulator by the "+" side error of the water level uncertainty range. This will result in earlier switching to the small flow phase, and will result in shorter duration of the large flow injection phase. Since the important function of the ACC is to fill up the reactor vessel lower plenum promptly during the refill period, and then simultaneously raise the water level in the downcomer, the shorter duration of the large flow injection phase will result in the slower increase in the downcomer water level. Thus it is conservative and acceptable to treat the switchover water level uncertainty by reducing the initial water level in the accumulator.

For the LBLOCA analysis, which uses the realistic analysis with the ASTRUM statistical treatment of uncertainties methodology, the flow rate switching water level uncertainty is included in the initial ACC water volume uncertainty ł and used in the ASTRUM analysis, as described in Section 3.5.1.4, "Uncertainty," of Topical Report MUAP-07011-P, "Large Break LOCA Code Applicability Report for US-APWR," (Reference 2). For the SBLOCA analysis, which uses the Appendix K to 10 CFR 50 approach, the switching water level uncertainty will be treated as a bounded value to reduce the initial water volume in the accumulator, as described in Section D.4, "Treatment of Uncertainty," of Topical Report MUAP-07013-P, "Small Break LOCA Methodology for US-APWR," (Reference 4). The staff finds the treatment of the switching water level uncertainty by reducing the initial accumulator water volume in the LOCA safety analyses acceptable.

3.3.4 Uncertainty due to Dissolved Nitrogen Effect

As stated in Section 3.2 of this report, the characteristic equations were developed from the full-height, 1/2 scale test data. The data from Test Case 5 was not included in the database for the characteristic equations because it was performed with accumulator water forced saturated with nitrogen. Section 3.1.6, "Effect of Dissolved Nitrogen," of this report described the effect of dissolve nitrogen on the ACC performance. The liquid in the actual accumulators will have dissolved nitrogen, which may be less than the saturated nitrogen in Test Case 5. However, as a conservative approach, the applicant proposed to increase the accumulator injection line piping resistance to compensate for the dissolved nitrogen effect.

In its response to RAI 34 (UAP-HF-09453-P, Reference 7), the applicant performed a sensitivity analysis of LBLOCA with the accumulator injection line resistance varied within [ ]. The results showed that a change of the injection pipe loss coefficient from [ ] to [ ] will delay the onset of transition from the large-flow injection phase to the small-flow phase by [ ], which encompasses the [ ] observed in Test Case 5. In Section 5.3 of the topical report, it is stated that although the dissolved nitrogen in Test Case 5 greatly exceeds that expected in the actual accumulator tank, the [ ] flow switching delay due to the dissolved nitrogen effect is included in all the LOCA safety analysis by increasing the injection piping resistance by [ ]. The staff finds that the increase of the ACC injection line piping resistance in the LOCA analysis adequately account for the two seconds flow switching delay caused by the dissolved nitrogen effect, and is, therefore, acceptable.

3.4 Pre-Operational Test of Accumulator Performance

Section 6.0, "Characteristic Equations in the Pre-Operational Test," of the topical report provides the calculation for acceptable ranges of the flow resistances of the flow damper. The accumulator flow resistance is the inverse of the square of the flow damper flow coefficient. The acceptable flow resistance ranges for the large flow and small flow injection phases, respectively, are therefore based on the flow coefficients calculated from the characteristic equations, and the uncertainties associated with the flow characteristic equations, including the scaling bias. (The staff evaluation of the uncertainties in the characteristic equations is described in Section 3.3 of this report.)

In the US-APWR design certification (DC) application DCD Tier 1 information, Section 2.4.4, “Emergency Core Cooling System (ECCS),” Table 2.4.4-5, “Emergency Core Cooling System Inspections, Tests, Analyses, and Acceptance Criteria [ITAAC],” lists ITAAC items for the ECCS system. Item 7.b.i.b requires that tests and analyses of the as-built accumulator system be performed for the as-built accumulator system to calculate and demonstrate the resistance coefficient of the as-built accumulator system meet the acceptance criteria shown in Table 2.4.4-6, “Requirement for Accumulator System Resistance Criteria.” The acceptance criteria specified in Table 2.4.4-6 are consistent with the acceptable resistance ranges of the large flow and small flow injection modes of the accumulator flow damper described in Section 6.0 of the topical report. Therefore, the staff finds that the ITAAC test provides acceptable verification that the performance of the as-built advanced accumulator system is consistent with the ACC flow characteristic equations within the acceptable uncertainty range.

4.0 SUMMARY OF EVALUATION

The staff reviewed US-APWR Topical Report MUAP-07001, Revision 5, “The Advanced Accumulator,” (Reference 1) along with the CFD analysis report MUAP-09025-P (Reference 9, as well as the responses to the staff’s requests for additional information. As a result of its review, the staff reached the following conclusions.

a) The concept of a vortex damper to passively switch the accumulator injection flow from a large flow to a small flow injection works.

b) An anti-vortex cap will prevent formation of vortex at the entrance of the standpipe.

c) The accumulator flow rate coefficient can be estimated from two characteristic equations that correlate flow rate coefficient with cavitation factor for the large flow and small flow injection phases.

d) The characteristic equations developed from the 1/2 scale facility are applicable to the full scale accumulator with additional uncertainties and bias, which are described in Section 3.3.1 and 3.3.2 of this report.

e) Cavitation is expected in the outlet nozzle for both large and small flow phases. The location and impact of losses have been correctly addressed.

f) Dissolved nitrogen effect will be accounted for through an increase in loss coefficient by [ ] in the accumulator discharge pipe. This will be additional loss to already existing loess coefficient for accumulator injection pipe.

5.0 LIMITATIONS

As stated in Section 3.3.2.5, “Evaluation of Estimate of Scaling Bias,” of this report, the staff concludes that the scaling biases of [ ] should be applied to the ACC flow coefficients of the large-flow and small-flow injection phases, respectively. The applicant’s use of the scaling biases of [ ] to the flow coefficients of the large-flow and small-flow injection phases, respectively, in the LOCA analyses is not acceptable. The applicant should apply the scaling biases of [ ] to the flow coefficients of the large-flow and small-flow injection phases, respectively.

6.0 REFERENCES

1. “The Advanced Accumulator”, MUAP-07001-P, Revision 5, July 2013 (ADAMS Accession Number ML131960302).

2. “Large Break LOCA Code Applicability Report for US-APWR”, MUAP-07011-P, Revision 3, December 2011.

3. “Realistic Large Break LOCA Evaluation Methodology Using the Automated Statistical Treatment of Uncertainty Method (ASTRUM)”, WCAP-16009-P-A, Revision 0, January 2005.

4. “Small Break LOCA Methodology for US-APWR,” MUAP-07013, Revision 2, October 2010.

5. “Response to NRC’s Questions for Topical Report MUAP-07001-P, Revision 1, “The Advanced Accumulator (Proprietary)”, UAP-HF-07086, July 20, 2007 (ADAMS Accession Number ML072080355, ML072080359).

6. “MHI’s Responses to NRC’s Requests for Additional Information on Advanced Accumulator for US-APWR Topical Report MUAP-07001-P, Revision 2,” UAP-HF-09239, May 20, 2009 (ADAMS Accession Number ML091420548, ML091420549).

7. “Amended MHI’s Responses to NRC’s Requests for Additional Information on Advanced Accumulator for US-APWR Topical Report MUAP-07001-P, Revision 2,” UAP-HF-09453, September 16, 2009 (ADAMS Accession Number ML092650198, ML092650170).

8. “Amended MHI’s Responses to NRC’s Request for Additional Information Topical Report, the Advanced Accumulator, MUAP-07001, Revision 4”, UAP-HF-12065, March 13, 2012 (ADAMS Accession Number ML12074A234, ML12074A235).

9. “CFD Analysis for Advanced Accumulator”, MUAP-09025-P, Revision 3, June 2013 (ADAMS Accession Number ML13198A023).

10. “Handbook of Hydraulic Resistance”, 3rd Edition, Idelchik, 1994.

11. “Test Uncertainty”, ASME PTC 19.1-2005.

12. Armstrong K, Zigh G. “US-APWR Advanced Accumulator Test Data and Scalability Review Using Computational Fluid Dynamics,” May 2009 (ADAMS Accession Number ML090930211) (OUO).

13. ANSYS FLUENT, FLUENT 12.0 Documentation, User Guide and Validation Guide.

14. NEA/CSNI/R(2007)5, “Best Practice Guidelines for the Uses of CFD in Nuclear Reactor Safety Applications,” May 15, 2007.

15. ASME V&V 20-2009, “Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer.”

16. “MHI’s Response to NRC’s Request for Additional Information Topical Report, the Advanced Accumulator, MUAP-07001, Revision 4 – Question 92,” UAP-HF-13026, February 2, 2013 (ADAMS Accession Number ML13046A095, ML13046A096).

17. Roache P. J.(1998), “Fundamental of Computational Fluid Dynamics.”

18. Roache P. J. (1998), “Verification and Validation in Computational Science and Engineering.”

19. “MHI’s Amended Response to NRC’s Request for Additional Information Topical Report, the Advanced Accumulator, MUAP-07001, Revision 4 – Question 94,” UAP-HF-13107, May 29, 2013 (ADAMS Accession Number ML13151A266).

7.0 **LIST OF ACRONYMS**

ACC	Advanced Accumulator
ANS	American Nuclear Society
ASTRUM	Realistic Large Break LOCA Evaluation Methodology Using Automated Statistical Treatment of Uncertainty Method
BLC	Boundary Layer Coefficient
BPG	Best Practice Guidelines
CFR	Code of Federal Regulations
DCD	Design Control Document
ECCS	Emergency Core Cooling System
GCI	Grid Convergence Index
GDC	General Design Criteria
LOCA	Loss-of-Coolant Accident
MHI	Mitsubishi Heavy Industries, LTD
NRC	U. S. Nuclear Regulatory Commission
PCT	Peak Cladding Temperature
PWR	Pressurized Water Reactor
RAI	Request for Additional Information
RCS	Reactor Coolant System
RSM	Reynolds Stress Model
SRSS	Square-Root-Sum-of Square
SS	Schnerr and Sauer
US-APWR	United States-Advanced Pressurized Water Reactor
ZGB	Zwart-Gerber-Belamri