THE ADVANCED ACCUMULATOR

Non-Proprietary Version

June 2013

Revision History

Revision	Page	Description
0	All	Original issued
1		The followings items are revised in accordance with the revision of the proprietary scopes;
		Flow diagram of 1/3.5 Scale Test Apparatus is deleted.
	4.2.2-2	In accordance with the deletion above, the information of test components is added to Outline Drawing of 1/3.5 Scale Test Apparatus (Fig.4.2.2-1).
		The photograph of 1/3.5 Scale Test Apparatus is deleted
		Overview of 1/5-Scale Test Apparatus and Block Diagram is deleted.
	4.2.3-2	In accordance with the deletion above, the information of test components is added to Outline Drawing of the Visualization Test Apparatus (Fig. 4.2.3-1).
		The photograph of 1/5-Scale Test Apparatus is deleted.
	4.2.3-8	The photographs of 1/5-scale test results are changed with non-proprietary photographs.
		The photograph of Full-Height 1/2-Scale Confirmation Test Facility is deleted.
		In accordance with these revisions from item 1 to 8 above, figure numbers, photo numbers, lists of figures and photos, and relevant descriptions are revised.
2	ABSTRACT	The name of part “vortex damper” is fixed to the correct name “vortex chamber.”
	3-2 (Table 3.1-1)	Maximum design pressure of ACC is fixed correctly [ ], and Maximum design temperature of ACC is fixed correctly [ ].
	3-6 (Fig.3.3-2)	The position of leader line for (7) width of small flow pipe is fixed to correct position.

Revision History (Cont.)

Revision	Page	Description
2	3-6	The distance between the center of vortex chamber and the center line of small flow pipe, which is in parenthesis in inches [ ], is fixed to the correct value [ ]. The height of standpipe (the distance between the bottom of anti-vortex cap and the top of vortex chamber), which is in parenthesis in inches [ ], is fixed to the correct value [ ].
	4.2.2-3	“(standpipe’s diameter)” is deleted from explain of “L” reflecting the response to RAI 15 of “MHI’s Response to NRC’s RAI on Advanced Accumulator for US-APWR Topical Report MUAP-07001-P (R1), UAP-HF-08174-P/NP (R0).”
	4.2.4-3 (Fig.4.2.4-2)	The height of test tank [ ] mm is converted to [ ] inches and added.
	4.2.4-4 (Fig.4.2.4-3)	The distance between the center line of injection pipe and the top of vortex chamber, which is in parenthesis in inches [ ], is fixed to the correct value [ ].
	4.2.4-5 (Fig.4.2.4-4)	The distance between the center of standpipe inner section and the center of vortex chamber of actual flow damper, which is in parenthesis in inches [ ], is fixed to the correct value [ ]. The distance between the throat and diffuser end of actual flow damper, which is in parenthesis in inches [ ] is fixed to the correct value [ ]. The inner diameter of outlet port of test flow damper, which is in parenthesis in inches [ ], is fixed to the correct value [ ]. The radius value at the top of standpipe of test flow damper; [ ] mm is converted to [ ] inch and added.

Revision History (Cont.)

Revision	Page	Description
2	5.3 Instrument Uncertainties	The title, text, and Table 5.2-2 are corrected appropriately reflecting the response to Question 17-C in “Response to NRC’s Questions for Topical Report MUAP-07001-P(R1) ADVANCED ACCUMULATOR, UAP-HF-07086-P/NP(R0).” And other scribal errors are corrected in whole report.
3	1.0	Description is corrected because the DCD has already been submitted.
	2.4	Equation (2-8) is corrected because of typographical error.
	4.3-1 through 4	Section 4.3 is revised to reflect based on the discussion with the NRC.
	7.0 REFERENCES	7.0 REFERENCES is added
	Appendix A	Appendix A is added to reflect the modification of Section 4.3.
4	General	Editorial Collections and modifications for readability
	4.3 Validity and Scalability of Flow Rate Characteristics	Section 4.3 and Appendix A is revised to reflect based on the discussion with the NRC.
	5.0 Concept of the Safety Analysis Model	Chapter 5 is revised to describe the total uncertainty of the advanced accumulator used for the safety analyses.
	7.0 References	Reference document is revised in Chapter 7.0
5	General	Editorial Collections and modifications for readability.
	3.0 Detailed Design of the as-installed ACC	Fig. 3.2-1 and Fig. 3.3-2 are revised to incorporate DCD RAI 941 response
	4.3 Validity and Scalability of Flow Rate Characteristics	Section 4.3 is revised to incorporate RAI 84 and 85 discussions.

Revision History (Cont.)

Revision	Page	Description
5	5.0 Concept of the Safety Analysis Model	Chapter 5 is revised to incorporate RAI 94 discussion. Discussion regarding combination of uncertainty is removed.
	6.0 Characteristic Equations in the Pre-operational Test	Discussion regarding pre-operational test is added. The numbers of Chapters are changed due to new Chapter 6 addition.

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List of Acronyms

ACC	Advanced Accumulator
A/D converter	Analog to Digital Converter
ANSI	American National Standards Institute
APWR	Advanced Pressurized Water Reactor
ASME	American Society of Mechanical Engineers
CD	Discharge Coefficient
CFR	Code of Federal Regulations
COL	Combined Operation License
CRT	Cathode-Ray Tube
CS/RHRS	Containment Spray / Residual Heat Removal System
ECCS	Emergency Core Cooling System
GT/G	Gas Turbine Generator
HHSI	High Head Safety Injection
LOCA	Loss-of-Coolant Accident
MHI	Mitsubishi Heavy Industries, Ltd
NQA	Quality Assurance Program Requirements for Nuclear Facilities
PCT	Peak Clad Temperature
PC	Personal Computer
PRZ	Pressurizer
PWR	Pressurized Water Reactor
QA	Quality Assurance
RCS	Reactor Coolant System
R/V (RV)	Reactor Vessel
RWSP	Refueling Water Storage Pit
S/G	Steam Generator
SI	Safety Injection
SIP	Safety Injection Pump
USNRC	United States Nuclear Regulatory Commission

ABSTRACT

The US-APWR Advanced Accumulator (ACC) simplifies the emergency core cooling system (ECCS) design by integrating the short term large flow rate design requirements currently satisfied by conventional accumulators and the low head safety injection pumps of a conventional pressurized water reactor (PWR) into a single passive device, the ACC. Upon initiation of a loss of coolant accident (LOCA) event, all low head injection requirements are satisfied by the ACC. Following depletion of the ACC's water volume, the long-term ECCS flow requirements are met by the high head safety injection pumps thus eliminating the need for low head injection pumps. Furthermore, the immediate availability of low head flow provided by the ACC upon loss of electrical power provides additional time to permit activation of the emergency backup power supplies.

Characteristics of the passive ACC, the detailed design of the ACC, the scaled testing program for the ACC, and the concept of the safety analysis model are discussed in this report.

The ACC has a flow damper which primarily consists of the stand pipe and vortex chamber. When the ACC water level is above the top of the standpipe, water enters the vortex chamber through both inlets at the top of the standpipe and at the side of the vortex chamber injecting water with a large flow rate. When the water level drops below the top of the standpipe, the water enters the vortex chamber only through the side inlet and vortex formation in the vortex chamber achieves the small flow rate injection.

In the first stage of injection, the ACC provides large flow injection to refill the reactor vessel then automatically reduces the flow as the water level decreases. This small flow stage of injection in conjunction with the high head safety injection pumps provides for core reflooding thereby eliminating the conventional low-head safety injection system.

In order to verify this unique design for the US-APWR, four types of scaled tests were performed: 1/8.4, 1/3.5, 1/5, and full height 1/2-scale model tests. These tests used visualization to confirm flow rate switching, vortex formation, and the prevention of gas entrainment into the vortex chamber at the end of the large flow stage of injection. The injection test provides the performance data required for quantitative evaluation of ACC flow.

Major results of the tests include:

(1) From the results of the 1/8.4 scale test, it was confirmed that switching from large flow to small flow occurs smoothly and a stable level was maintained in the stand pipe.
(2) From the results of the 1/3.5 scale test, it was confirmed that a sharp flow rate switching without gas entrainment was achieved.
(3) From the results of the 1/5-scale test, it was confirmed that no vortex was observed during the large flow injection stage, and a stable vortex was formed in the vortex chamber during the small flow injection stage.
(4) From the results of the full height 1/2-scale tests, it was confirmed that the flow characteristics of the flow damper can be represented by dimensionless numbers and are independent of the scaling. Therefore the similarity law that evaluates the actual flow damper can be applied.

The ACC design will improve the overall safety of pressurized water reactors by the innovative application of the flow damper which assures the early stage of LOCA injection flow is satisfied by a highly reliable passive system. This innovation reduces the necessity of relying on

maintenance sensitive components, such as low head safety injection pumps, for assuring LOCA safety injection flow. This provides sufficient relief from the need for rapid start emergency diesel generator backup power and permits use of highly reliable gas turbine generators.

The flow characteristics of the ACC have been verified by thorough testing and can be fully described as a function of dimensionless numbers. Empirical flow rate coefficients have been developed from the test results and will be used in an integrated thermal hydraulic model of the US-APWR Reactor Coolant and ECCS systems to assure the US-APWR meets or exceeds all US safety standards.

1.0 INTRODUCTION

This report describes the Mitsubishi Heavy Industries, Ltd. (MHI) Advanced Accumulator (ACC) design that will be used in MHI's Advanced Pressurized Water Reactor (APWR), and MHI's US-Advanced Pressurized Water Reactor (US-APWR). MHI intends to seek certification of the US-APWR design from the United States Nuclear Regulatory Commission (USNRC) and offer the design to utility companies for installation in the United States. The purpose of this document is to provide the design details and confirmatory testing results of the ACC to the USNRC in order to facilitate the review of this innovation in support of the US-APWR Design Certification Application. Review and approval of this Topical Report should increase the efficiency of the US-APWR Design Certification process and any subsequent Combined Operating Licenses (COLs) which reference the US-APWR design.

The ACC is an accumulator tank with a flow damper inside the tank. The tank is partially filled with borated water and pressurized with nitrogen. It is attached to the primary system by an injection pipe fitted with a series of two check valves plus an isolation valve which 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 ACC design combines the known advantages and extensive operating experience of a conventional accumulator used for loss of coolant accident (LOCA) mitigation in pressurized water reactors with the inherent reliability of a passive fluidic device to achieve a desired reactor coolant injection flow profile without the need for any active moving parts.

Incorporation of the ACC into the US-APWR design and LOCA mitigation strategy simplifies a critically important safety system by integrating an inherently reliable passive safety component into an otherwise conventional Emergency Core Cooling System (ECCS). This design improvement will allow the elimination of the low head safety injection pumps, and increases the amount of time available for the installed backup emergency power system to actuate. It is expected that the use of ACCs rather than low head safety injection pumps in the US-APWR design will reduce the net maintenance and testing workload while maintaining a very high level of safety.

This Topical Report describes the principles of operation, the important design features, and the extensive analysis and confirmatory testing program conducted to assure that the performance of the ACC is well understood.

2.0 CHARACTERISTICS OF THE ADVANCED ACCUMULATOR (ACC)

2.1 ECCS Performance During a LOCA

Emergency core cooling during a Loss-of-Coolant Accident (LOCA) is one of the primary functions of the ECCS. During a large break LOCA, the fuel cladding temperature increases due to the significant loss of reactor coolant from the primary system. The ECCS is required to inject water into the core to limit the rise of fuel temperature as follows:

Step 1: Inject water at a high flow rate to rapidly refill the lower plenum and downcomer of the reactor vessel. (Reactor Vessel Refilling)

Step 2: Recover the core water level using the water level head in the downcomer. Small ACC flow to the reactor vessel keeps the water level in the downcomer high and quickly re-floods the core. (Core Reflooding)

Step 3: After core reflooding is completed, safety injection flow is continued in order to remove decay heat and maintain the core flooded. (Long-Term Cooling)

The performance requirements for the ECCS in a conventional nuclear plant during a large break LOCA is fulfilled using the following subsystems.

Step 1: Accumulator System
Step 2: Low Head Safety Injection System and High Head Safety Injection System
Step 3: Low Head Safety Injection System and High Head Safety Injection System

Thus, in a conventional nuclear plant, the functions of the ECCS during a LOCA are assigned to three subsystems: the Accumulator System, the Low Head Safety Injection System, and the High Head Safety Injection System.

In the US-APWR, the ACC, which automatically shifts its flow rate from large to small, is incorporated into the safety system design. The function of the Low Head Safety Injection System is accomplished by the Accumulator System and the High Head Safety Injection System; therefore, the Low Head Safety Injection System can be eliminated to simplify the configuration of the ECCS.

The performance requirements are fulfilled by the US-APWR ECCS subsystems during a large break LOCA as described below and as shown in Fig. 2.1-1.

Step 1: Accumulator System
Step 2: Accumulator System and High Head Safety Injection System
Step 3: High Head Safety Injection System

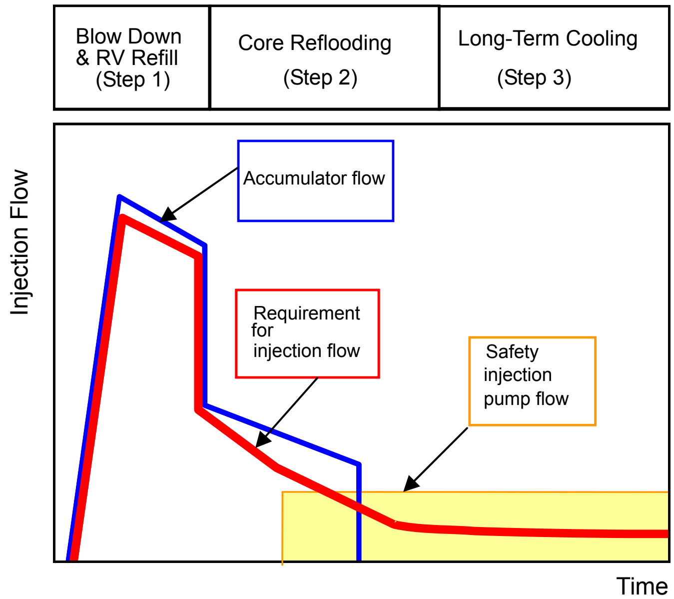
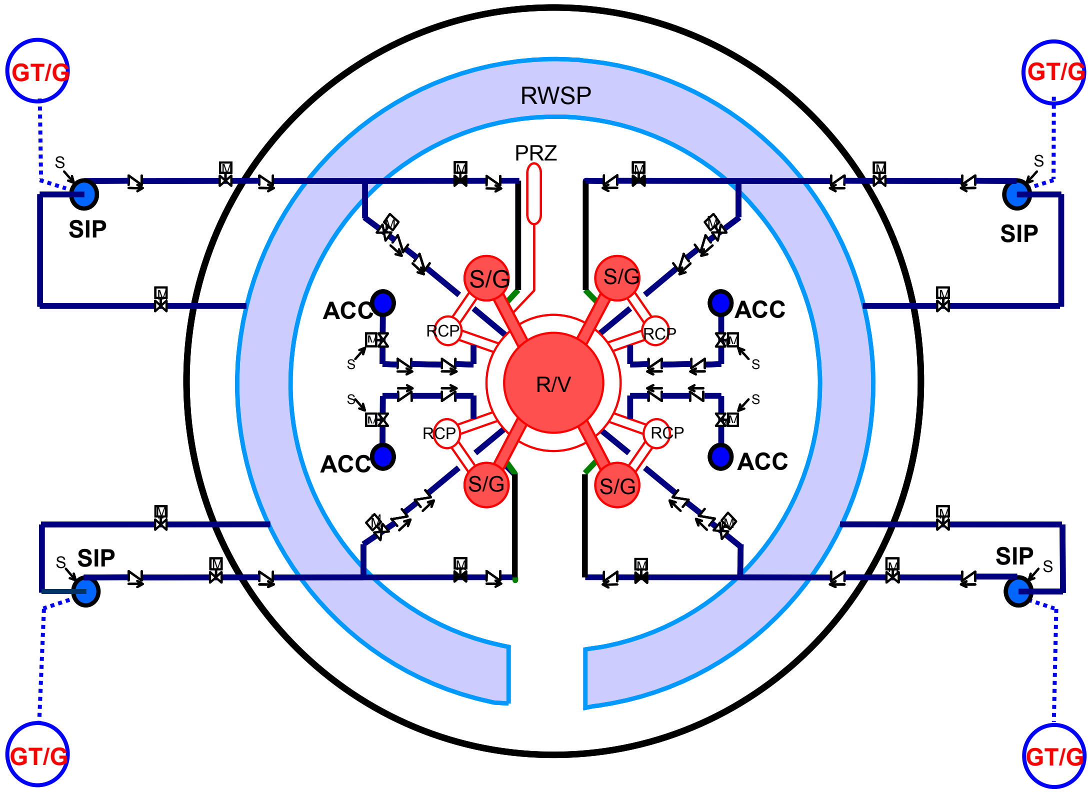


Fig. 2.1-1 ECCS Performance During a Large LOCA

During a large break LOCA, it is necessary to start the safety injection pumps prior to the end of accumulator injection to continuously inject water to the core. The ACC injects water longer than a conventional accumulator, thereby allowing more time for the safety injection pumps to start. This additional time margin allows the US-APWR to use gas turbine generators for the emergency power source if needed.

The system configuration of the US-APWR ECCS is shown in Fig.2.1-2. Four accumulators are installed and each ACC is connected to a Reactor Coolant System (RCS) cold leg. Four High Head Safety Injection Subsystems are installed and inject directly into the vessel downcomer following accumulator injection. Low Head Safety Injection subsystems are not installed.



R/V: Reactor Vessel
S/G: Steam Generator
PRZ: Pressurizer
RWSP: Refueling Water Storage Pit

ACC: Advanced Accumulator
SIP: Safety Injection Pump
GT/G : Gas Turbine Generator
S: Safety Injection Signal

Fig. 2.1-2 System Configuration of the US-APWR ECCS

2.2 Principles of ACC Operation

2.2.1 Concept and Principle of Flow Switching

The ACC is a water storage tank containing a flow damper that automatically switches the flow rate of cooling water injected into the reactor vessel from a large to a small flow rate.

The conceptual drawing of the ACC is shown in Fig. 2.2.1-1.

The ACC is a simple device with no moving parts consisting of a large tank containing a flow damper. In essence, the "flow damper" consists of the standpipe, the large flow pipe, the small flow pipe, the vortex chamber, and their corresponding connections. The outlet of the flow damper is connected to the injection pipe. There is a vortex chamber with its outlet connected to the injection piping exiting the accumulator. The small flow pipe is tangentially attached to the vortex chamber. The large flow pipe connects the bottom of the standpipe radially to the vortex chamber. The height of the standpipe inlet port is located at a tank level that corresponds to the interface between the volume of water needed for the large flow rate injection stage and the volume needed for the small flow rate injection stage.

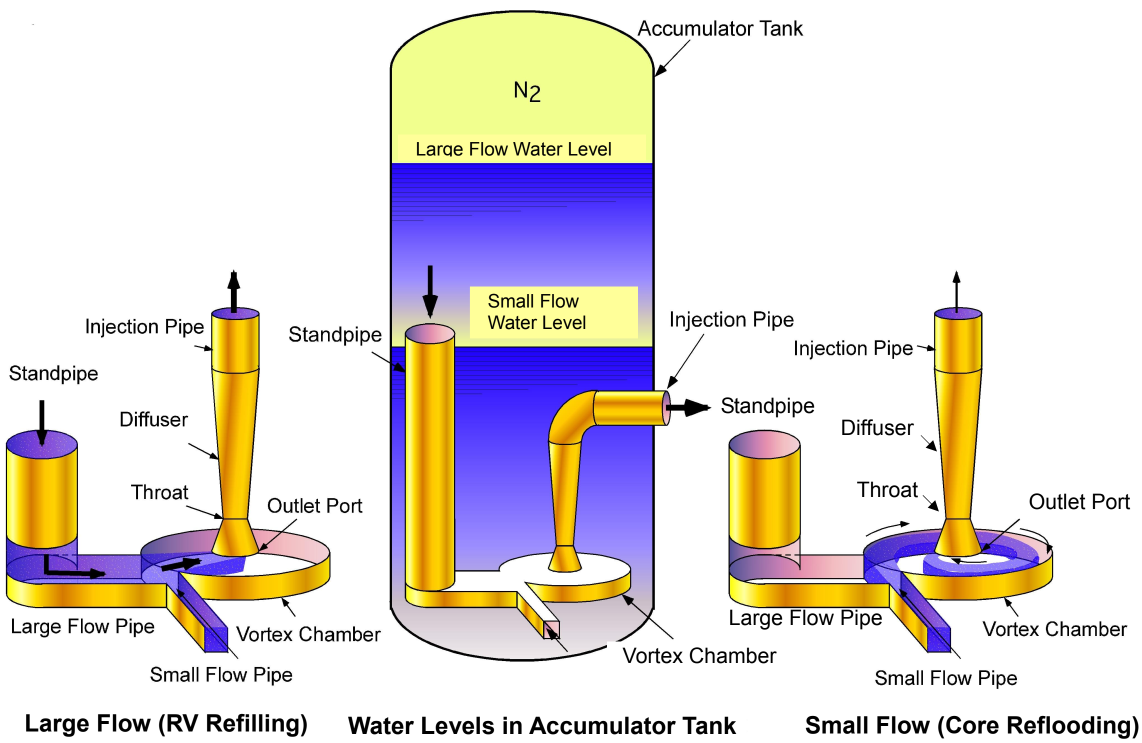


Fig. 2.2.1-1 Principle of Advanced Accumulator Operation

When a Loss of Coolant Accident (LOCA) occurs and pressure in the reactor coolant system decreases, the check valves along the injection pipe open to permit injection of ACC water into the reactor vessel. Since the water level in the accumulator is initially higher than the elevation of the inlet of the standpipe, water flows through both the large and small flowrate pipes. These flows collide with each other so that no vortex is formed in the vortex chamber. The angle of collision, θ, is determined so that the flow from the large flowrate pipe cancels out the angular momentum of the flow from the small flowrate pipe. Consequently, the overall flow resistance of the flow damper is small resulting in a large flow. Fig. 2.2.1-2 shows additional details of the flow damper.

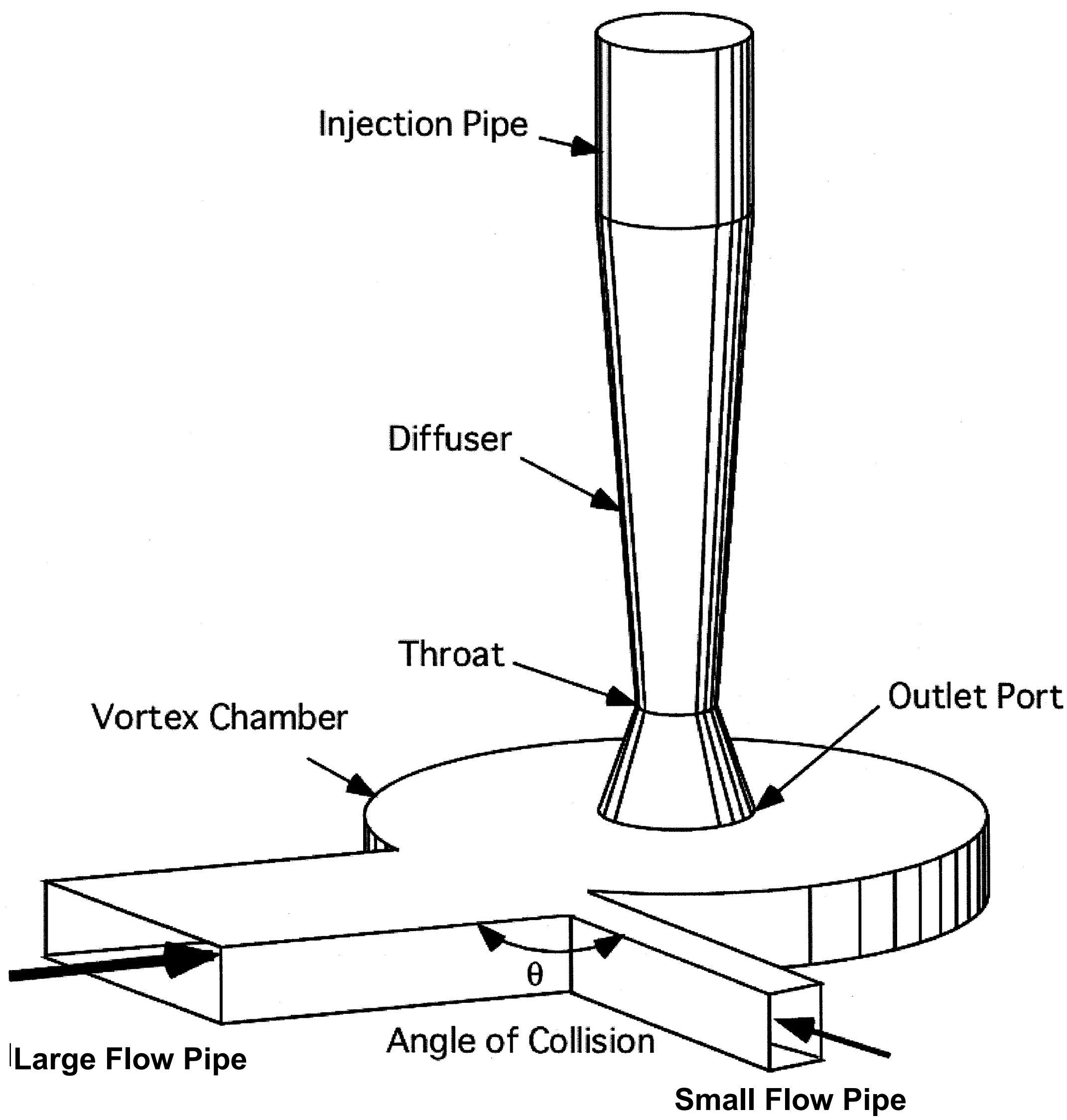


Fig. 2.2.1-2 Flow Damper

High flow continues until the water level in the accumulator decreases to the inlet level of the standpipe, and the flow into the standpipe stops. The flow in the large flowrate pipe comes to a near-stop. Without this flow from the large flow pipe, the continued flow from the small flowrate pipe forms a strong vortex in the vortex chamber. As a result of centripetal force, a large pressure drop (and the equivalent of a high flow resistance) occurs along the radius of the vortex chamber between the small flow pipe and the outlet port. Therefore, a small flow rate is achieved with a vortex rather than with moving parts.

The strength of the vortex in the chamber depends on the ratio of the diameter of the vortex chamber, D, and that of the outlet port, d. The ACC design objective was to make the ratio, D/d, as large as possible. The diameter of the vortex chamber, D, is determined by the accumulator diameter, while that of the outlet port, d, is limited by the required flow rate at large flowrate conditions. In order to satisfy these design requirements and achieve a larger ratio of large to small flow rates, a throat followed by a diffuser is employed at the outlet port of the vortex chamber.

2.2.2 Expected Phenomena

1) During Large Flow Rate Stage

Since there is no vortex in the vortex chamber at large flowrates, the resistance of the flow damper is similar to that of a conventional pipe. The form resistance (that is, the resistance resulting from the piping geometry) is larger than the flow friction in the flow damper because the flow is required to make high velocity direction changes within a short distance. Therefore, the pressure loss of the flow damper will be primarily due to form resistance and secondarily due to flow friction. The latter can be evaluated by its Reynolds number. The form resistance is independent of Reynolds number.

The diffuser recovers pressure after the throat in order to reduce the losses, and the pressure at the throat is lower than that in the injection pipe at large flow rates. If the pressure at the throat drops below the critical pressure of cavitation inception, cavitation may occur. If cavitation occurs at the throat of the outlet port, the existence of bubbles may reduce the flow rate. Hence, the cavitation factor will be the main parameter affecting the flow rate coefficient if the effect of friction is neglected.

The pressure in the accumulator is over 580 psig (4 MPa [gage]) at the beginning of injection and comes down to about 145 psig (1 MPa [gage]) at the end of large flowrate injection stage. Dissolved nitrogen gas in the stored water will separate out due to the pressure drop and may affect the flow rate. However, the effects of the dissolved nitrogen were simulated in full height and full pressure experiments to verify that dissolved gases will not significantly affect the ACC flow rate. The details of the test will be provided later in this report.

Additional details for the flow phenomena are provided in Section 4.3.

2) During Flow Rate Switching

At the end of the large flowrate injection stage, water stops flowing into the standpipe. A water surface is formed within the stand pipe and the water column in the standpipe still has momentum at that time. The inertia of the water column makes the water surface undershoot below the ACC water level that balances with the pressure difference inside and outside of the standpipe. The water level recovers to its balanced level thereafter. Fig. 2.2.1-3 shows a schematic chart of the water level transient in the standpipe. The standpipe must be designed to ensure that nitrogen gas in the tank does not flow into the injection pipe during undershoot. This effect was evaluated in the testing described later in this report.

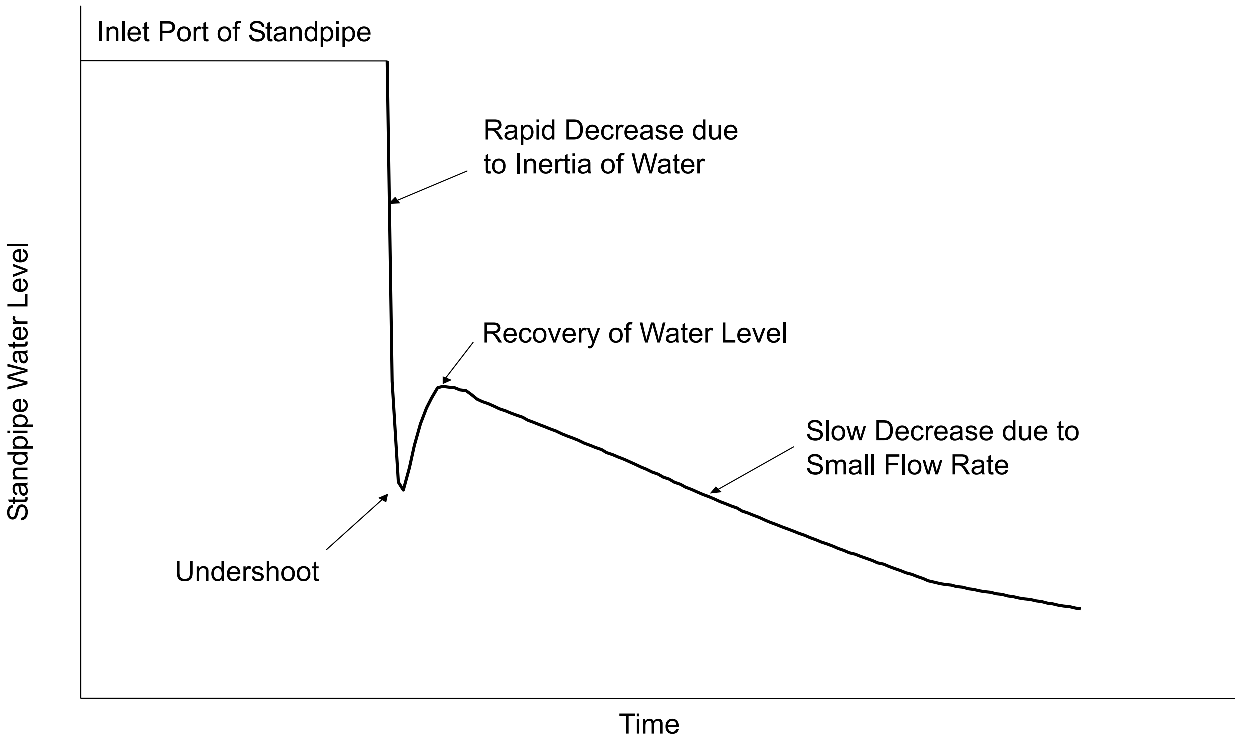


Fig.2.2.1-3 Example of Water Level Transient in Standpipe (Schematic Chart)

3) During Small Flow Rate Stage

After flow in the standpipe is almost stopped, a strong and steady vortex flow is formed in the vortex chamber by flow from the small flow pipe. Since the pressure loss in the small flowrate pipe is negligible, the static pressure at the exit of the small flowrate pipe equals the static pressure in the accumulator minus the dynamic pressure in the small flowrate pipe. In other words, the difference between the water level in the tank and in the standpipe is equal to the dynamic pressure in the small flowrate pipe, which is much smaller than the pressure drop due to a vortex in the chamber. This is the main feature of the flow damper that prevents gas leakage during the small flow rate stage.

Pressure drop through the flow damper is due to the development of strong vortex at small flow rates. Pressure recovery in the diffuser after the throat is negligible during small flow rate, and most of the dynamic pressure developed in the vortex is lost in the diffuser. The scaled test results indicate that the flow performance is independent of any potential cavitation at the center of the vortex.

If the influence of friction is negligible, the flow rate coefficients will be similar for any size of flow damper.

Additional details for the flow phenomena are provided in Section 4.3.

2.3 Performance Requirements for the ACC

The functions of the ACC during a large break LOCA, as described in Section 2.1, are refilling the lower plenum and downcomer immediately following the reactor coolant blow down (Step 1), and establishing the core reflooding condition by maintaining the downcomer water level after refilling the core (Step 2). In this section, these functional requirements are quantified as performance requirements and design requirements.

2.3.1 Performance Requirements for Large Flow Injection

The lower plenum and downcomer of the reactor vessel shall be filled by large flow injection. Since the time required for accomplishing large flow injection is the dominant factor for the Peak Clad Temperature (PCT), the performance requirement is that the lower plenum and the downcomer are filled with water as rapidly as possible during the refilling period.

2.3.2 Performance Requirements for Small Flow Injection

1) Basic concept

It is important to keep the downcomer filled with ECCS water, in order to ensure that a water-head is maintained to force ECCS water flow into the core through the lower plenum of the reactor vessel to provide core cooling (See Fig. 2.3.2-1).

2) Required injection flow rate

The required injection flowrate during the core re-flood period is determined as follows.

The required flow rate is obtained from the core reflooding flow rate calculated by the hypothetical LOCA analysis, which assumes that the downcomer is filled with sufficient water to adequately achieve safety injection flow. The conventional 4-loop plant approach of a double-ended cold leg break (with a discharge coefficient of 0.6) causing the worst-case PCT is assumed for the analysis.

The required flowrate is obtained as the sum of the injection flowrate and the product of flow area times the reflooding rate for each of the following three regions (See Fig.2.3.2-1).

(1) Core region
(2) Neutron reflector cooling-holes region
(3) Neutron reflector back side region

The required injection flowrate obtained by this analysis is shown in Fig.2.3.2-2. According to the progression of core reflooding, the difference of water-head between the downcomer and the core is reduced gradually, and the required injection flowrate also decreases gradually.

This analysis was performed using the Appendix K ECCS model with the Japanese decay heat model. Since the decay heat level of the Japanese model is lower than that of the Appendix K model, the core reflooding rate is larger. Therefore, the Japanese decay heat model was used to obtain the conservative (larger) reflooding rate requirement.

The adequacy of the required injection flowrate will ultimately be confirmed by the ECCS performance analysis using the WCOBRA/TRAC code with ASTRUM methodology.

3) Required injection flow rate margin

The required flowrate for the small flow injection stage will be supplied solely by the ACC as described in Fig. 2.1-1 (Section 2.1). The Safety Injection pumps will provide additional ECCS flow rate margin.

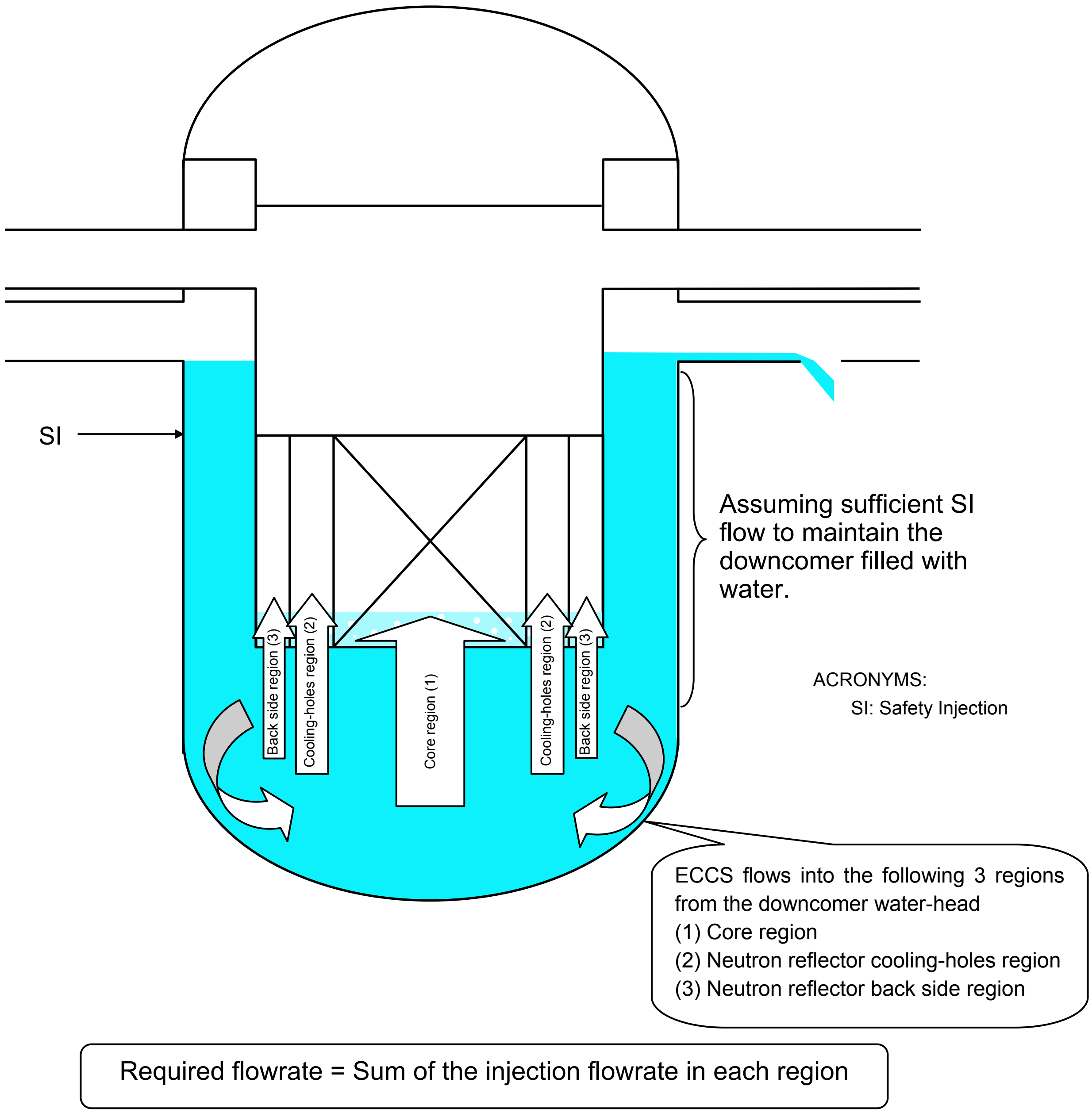


Fig. 2.3.2-1 Basic Concept for Calculation of the Required ECCS Injection Flow Rate
(Core Reflooding Phase)

Note: According to progression of core reflooding, the difference of water-head between the downcomer and the core is gradually reduced. The required flowrate also decreases gradually.

Fig. 2.3.2-2 Required ECCS Injection Flow Rate

2.3.3 Expected ECCS Function for Various Break Sizes

In general, high PCT is postulated to occur in two break-size ranges. One is for a large-break LOCA and the other is for a small-break LOCA.

Fig. 2.3.3-1 shows the RCS pressure transient and ECCS flow injections for various break sizes.

- **Large-break size**:

  Because of large break flow, the core would be uncovered and fuel-cladding temperature would rise. The ECCS injection capability requires core water level to be recovered quickly. Therefore, the prompt injection during the refill period is required to be performed by the large flow rate stage of the accumulators. (See Fig. 2.3.3-1(a))

  When the accumulators inject water for medium break sizes (that is, less severe large break LOCAs) the fuel-cladding temperature does not reach high values because of the lower decay heat level at the time of ACC injection and relatively quick core reflooding due to the slow accident transition compared to larger break-sizes. (See Fig. 2.3.3-1(b))

- **Small-break size**:

  Because of the loop seal and boil-off phenomena, the core would be uncovered and the fuel-cladding temperature would rise. In this case, the accumulators do not inject water for the core reflooding. The required ECCS function is the injection capability to supply the evaporated coolant in the long-term after core reflooding. Therefore, the high head safety injection pumps provide this function. (See Fig. 2.3.3-1(c))

The ECCS design will be validated by the ECCS performance evaluation analysis.

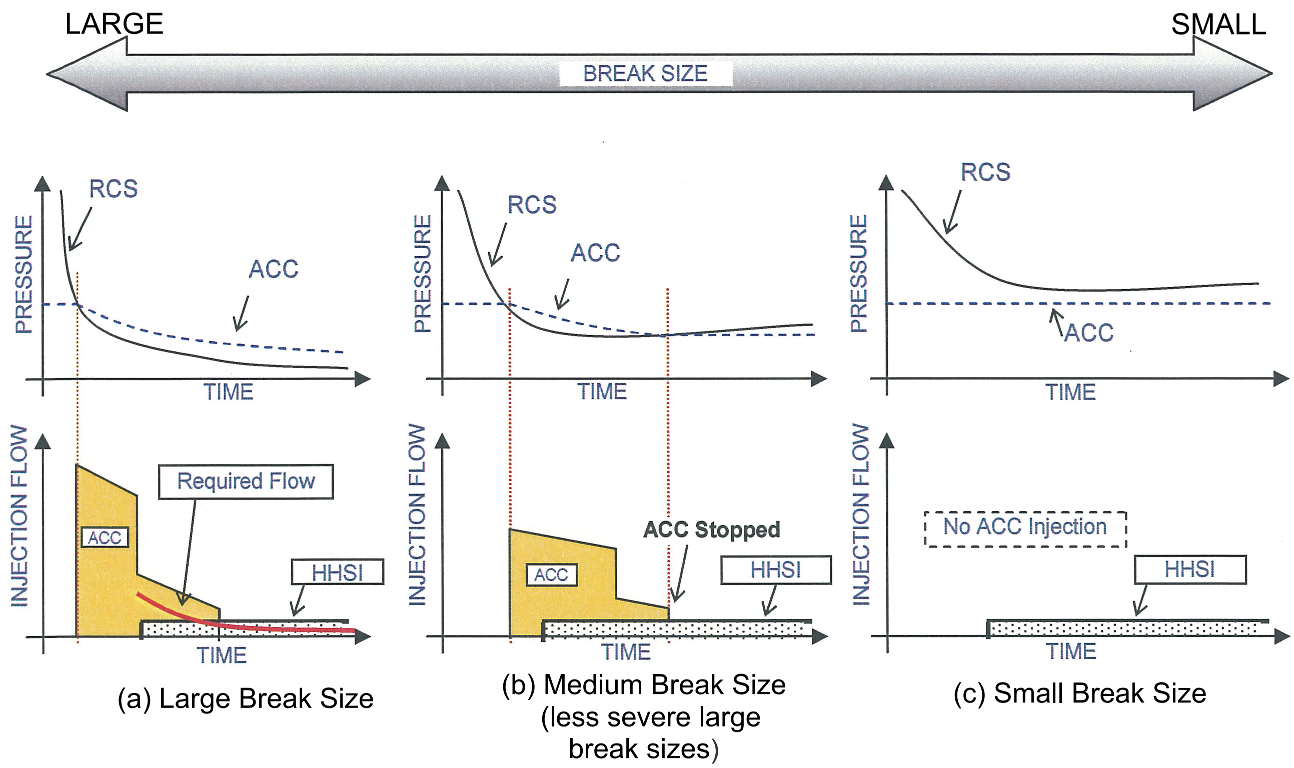


Fig. 2.3.3-1 RCS Pressure Transients and ECCS Injection Flow for Various Break Sizes

2.3.4 Design Requirements for the ACC

This subsection describes specific design requirements based on the performance requirements specified in Subsections 2.3.1 and 2.3.2.

1) Design Requirements for Large Flow Injection

The performance requirements for the large flow injection stage discussed in Section 2.3.1 are as follows:

Requirement

The lower plenum and the downcomer are filled with water as rapidly as possible during the refilling period.

Major parameters affecting the duration of large flow injection are specified to meet this requirement as follows.

- Large flow injection water volume: [ ]
- Initial gas volume: [ ]
- Initial gas pressure: [ ]
- Resistance coefficient of the accumulator injection line in large flow injection: [ ]

The RCS pressure transient during a large break LOCA is assumed to be as shown in Fig. 2.3.4-1[Note1], and the injection flow rate transient for large flow that is calculated based on the above parameters is shown in Fig. 2.3.4-2.

Note1: It is assumed that RCS pressure is reduced to [ ] in [ ] seconds after initiation of accumulator injection based on the result of the APWR LOCA analysis.

The injection flow rate transient shown in Fig. 2.3.4-2 is obtained using the following equations. The concept is similar to that used in conventional nuclear safety analyses.

$$Pgas - Pinj = \frac{\rho K U^2}{2} - \rho g (Ht - Hp) \tag{2-1}$$

$$Pgas = \left(\frac{Vgaso}{Vgas} \right)^{\kappa} Pgaso \tag{2-2}$$

$$\frac{dVgas}{dt} = A \cdot U \tag{2-3}$$

where:

$Pgas$	:	Accumulator gas pressure
$Pgaso$	:	Initial accumulator gas pressure
$Vgas$	:	Accumulator gas volume
$Vgaso$	:	Initial accumulator gas volume
$Pinj$	:	Pressure at the injection point
K	:	Overall resistance coefficient of accumulator injection system during large flow
Ht	:	Water level elevation of accumulator
Hp	:	Elevation of the injection point
U	:	Velocity in the injection pipe
A	:	Cross section inside of the injection pipe
ρ	:	Density of water
g	:	Gravitational acceleration constant
t	:	Time
κ	:	Adiabatic exponent

Each parameter is shown in Fig. 2.3.4-3 which provides an overall view of the Advanced Accumulator System.

The PCT results were confirmed to be below [ ] in the APWR design stage by using these parameters for large flow injection (assuming the resistance coefficient of the accumulator injection system is [ ]). Since the resistance coefficient of the planned accumulator injection piping and valves (K_p) is approximately [ ], the resistance coefficient of the flow damper during large flow (K_D) was determined to be [ ] using the following design requirement:

$K_D = K - K_p$
= [ ]
= [ ] (2-4)

The resistance coefficient of the flow damper during large flow changes is based on the cavitation factor as described in Section 2.2. The design requirement above is specified as a target for the resistance coefficient of the flow damper at the end of RCS depressurization ([ ] seconds after initiation of accumulator injection), which is where the cavitation factor becomes smallest.

2) Design Requirements for Small Flow Injection

The performance requirements for small flow injection during large break LOCA are described in Section 2.3.2. The required small injection flow rate following the flow transition is [ ] as shown in Fig. 2.3.2-2. Assuming 3 of the 4 accumulators are available, the required flow rate is [ ] per tank. The expected flow rate at the end of large flow injection from each accumulator is [ ], as shown in Fig. 2.3.4-2. The flow-shifting ratio from large flow to small flow necessary to meet the performance requirement is as follows:

R = [ ]
= [ ] (2-5)

Therefore, the flow-shifting ratio of [ ], which is within the required flow-shifting ratio [ ] from large flow to small flow, is specified as a design requirement.

Fig. 2.3.4-1 RCS Pressure Transient during Large Break LOCA

Fig. 2.3.4-2 Large Flow Injection Transient during Large Break LOCA

Fig. 2.3.4-3 Overall View of the Accumulator System

Note
Refer to Section 3.1

2.4 Expected Performance of the ACC

The major design parameters for the ACC, specified to meet the performance requirements in Section 2.3.4, are as follows:

- Large flow injection water volume: [ ]
- Initial gas volume: [ ]
- Initial gas pressure: [ ]
- Injection pipe inner diameter: [ ]
- Resistance coefficient of the accumulator injection line in large flow injection: [ ]
- Resistance coefficient of the flow damper in large flow injection: [ ]
- Flow-shifting ratio: [ ]

The expected injection flow characteristics based on the parameters listed above are shown in Fig.2.4-1.

The calculation method used for this calculation is the same as described in Section 2.3.4. However, the resistance coefficient of the flow damper (K_D) is changed from [ ] to [ ] at the point where the water volume for large flow injection becomes zero. The rationale for the K_D value of [ ] in the small flow injection stage is shown as follows:

$$R = \frac{Q_L}{Q_S} \qquad (2\text{-}6)$$

$$\frac{K_{DL} + Kp}{K_{DS} + Kp} = \left(\frac{Q_S}{Q_L}\right)^2 = R^{-2} \qquad (2\text{-}7)$$

$$K_{DS} = \frac{K_{DL} + Kp}{R^{-2}} - Kp$$

$$= \left[(5 + 6.5)/5^{-2} - 6.5 = 281 \approx 250\right] \qquad (2\text{-}8)$$

where

R	:	Flow-shifting ratio
Q_L	:	Large injection flow rate
Q_S	:	Small injection flow rate
K_{DL}	:	Resistance coefficient of flow damper during large flow injection
K_{DS}	:	Resistance coefficient of flow damper during small flow injection
Kp	:	Resistance coefficient of injection pipe

Fig. 2.4-1 Expected Performance of the ACC

3.0 DETAILED DESIGN OF THE AS-INSTALLED ACC

3.1 ACC Design Basis and Specifications

The performance and the design requirements for the Advanced Accumulator (ACC) were described in Section 2.3. This section describes the design basis and specifications of the ACC.

Each ACC connects to a corresponding RCS cold leg (4 ACCs in all) and has the function of injecting water into the core during the reactor vessel (RV) refilling process and also injecting water at a lower flow rate during the core reflooding process.

The goals of the above stated functions are as follows:

- **Refilling process (large flow injection):**

  Rapidly inject 2,613 ft^3(74 m^3) [Note1] of water (equivalent to the volume of the downcomer and lower plenum of the RV) to initiate reflooding.

- **Reflooding process (small flow injection):**

  Continue injecting water for approximately 180 seconds[Note2] following the refilling process to maintain downcomer water level through core quench.

  Note1: The planned volume of the downcomer and lower plenum of US-APWR is approximately 2,295 ft^3 (65 m^3). The required value (2,613 ft^3 (74 m^3)) is selected to provide additional margin.

  Note2: It is assumed that the duration of small flow injection from the accumulator is 180 seconds followed by the injection from the Safety Injection (SI) pumps. The duration of small flow injection is related to with the SI pump capacity. If the duration of small flow injection is short then a correspondingly larger volumetric flow rate is required from the SI pumps.

Since the water from an ACC installed on the broken loop is assumed to spill into the containment and does not contribute to core injection, only the water injected from the remaining three accumulators is available for core injection. Thus, the required volume of ACC is specified as follows:

- **Refilling process (large flow injection)**

$$2{,}613\ ft^{3(a)} / (2/3)^{(b)} / 3^{(c)} = 1{,}307\ ft^3/ACC \quad (3\text{-}1)$$

The volume of an ACC is specified to be 1,342 ft^3 (38 m^3), which is the required 1,307 ft^3 (37 m^3) plus margin.

(a) Total volume of the downcomer and the lower plenum (ft^3)
(b) Assumption based on the experience that 1/3 of injection flow is spilled from the broken loop to the containment
(c) Number of ACCs assumed to inject into the core

- **Reflooding process (small flow injection)**

The relationship between the amount of small injection flow and the duration of small flow injection with regard to the expected performance of the ACC defined in Section 2.4 is shown in Fig. 3.1-1. The expected duration of the small flow injection from the ACC is 180 seconds. Therefore, 724 ft^3 (20.5 m^3) of injection water is required per ACC. Thus, 784 ft^3 (22.2 m^3) of injection water volume is specified giving a margin above approximately 8%. Considering the total water volume, 2,126 ft^3 (60.2 m^3), and adding the volume of gas space and dead water volume, the required volume of a single ACC is 3,180 ft^3 (90 m^3). The validity of this volume will be confirmed in the ECCS performance analysis. Specifications for the ACC are summarized in Table 3.1-1.

Table 3.1-1 Specifications for the ACC

Type:	Vertical cylindrical
Number:	4
Volume:	3,180 ft^3 (90 m^3)
Maximum design pressure:	700 psig (4.83 MPa [gage])
Maximum design temperature:	300 deg F (149 deg C)
Large flow injection volume:	1,342 ft^3 (38 m^3)
Small flow injection volume:	784 ft^3 (22.2 m^3)

Fig. 3.1-1 Basis of the Small Flow Injection Water Volume

3.2 ACC Dimensions and Structure

An outline drawing of the ACC is shown in Fig. 3.2-1. The inner diameter of the tank is [ ] ft [ ] and total height is [ ]. The tank inner structure includes the flow damper and the standpipe. Because the outlet piping is above the flow damper, the un-available "dead" water is less than that for an ACC design that has its outlet piping attached under the flow damper due to the need for increased installation space. The ACC main dimensions are shown in Fig. 3.2-1.

Fig. 3.2-1 Outline Drawing of Advanced Accumulator

3.3 Structure of the Flow Damper

The structure of the flow damper is shown in Fig. 3.3-1 and Fig. 3.3-2. The flow damper consists of an anti-vortex cap, standpipe, vortex chamber, small flow pipe, and outlet pipe. The inlet of the standpipe is set at the water level at which the flow rate switches from large flow to small flow. The anti-vortex cap installed on the standpipe inlet prevents gas entrainment just before the flow switching and improves the flow-switching characteristics. The small flow piping is connected to the vortex chamber tangentially. An anti-vortex plate is also provided at the inlet of the small flow pipe and prevents the gas in the ACC gas space from being sucked into the standpipe when the water level is reduced to the small flow inlet. During large flow injection, the flows from the standpipe and the small flow pipe collide in the vortex chamber and the resulting water stream flows out of the chamber directly without forming a vortex. The throat portion and diffuser are provided on the outlet pipe to increase the flow resistance during small flow, recover the pressure during large flow, and provide a smooth transition for the pipe. The detailed dimensions, such as the inner diameters of the throat, and the vortex chamber, are determined from the tests using the ratio of Zobel diode. The basis for determining the dimensions is shown in Table 3.3-1.

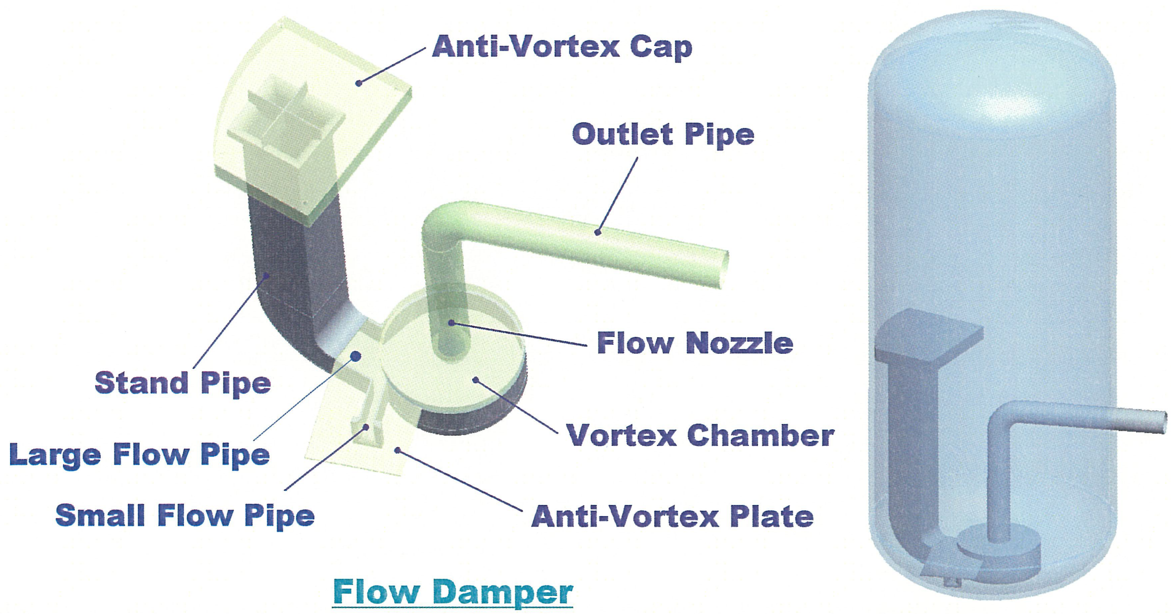


Fig. 3.3-1 Overview of the Flow Damper

Fig. 3.3-2 Outline Drawing of the Flow Damper

Table 3.3-1 The Basis for the Flow Damper Dimension

Regions	The bases of dimension
(1) Standpipe height	Specified to assure the required injection water volume during small flow injection is maintained between the inlet of the standpipe and the upper end of the vortex chamber, and to prevent the water level from reducing below the upper end of the vortex chamber.
(2) Height of standpipe inner section	Specified to be consistent with the width of the large flow pipe connecting to the vortex chamber to assure the smooth flow from the standpipe to the vortex chamber.
(3) Width of standpipe inner section	Specified to limit the flow velocity just before the flow switching to prevent entrainment of gas during the water level transient in the standpipe.
(4) Inner diameter of the throat	The inner diameter of the throat is the dominant factor of the resistance of the flow damper during large flow. The inner diameter of the throat is specified to meet the required resistance of large flow.
(5) Inner diameter of the vortex chamber	The inner diameter of the vortex chamber is determined by tests using the ratio of Zobel diode.
(6) Height of the vortex chamber	The inner height of the vortex chamber is determined by tests using the ratio of Zobel diode.
(7) Width of small flow pipe	It is preferable that the width of the small flow pipe be as small as possible to increase the flow damper resistance during small flow. However, if the aspect ratio of the small flow pipe (height/width) is large, a stable jet flow is not formed. It is necessary that a stable jet flow is induced from the small flow pipe to the vortex chamber in order to form the stable vortex. Thus, the width of the small flow inlet pipe is specified with an aspect ratio of [ ] [Note]. Note: Max. aspect ratio for a stable jet flow is acquired from experience.
(8) Width of large flow pipe	It is preferable that the width of the large flow pipe is as large as possible to reduce the flow damper resistance during large flow. Therefore, the width of the large flow pipe is specified to make it as large as practical according to the structure considering the facing angle of the large flow and small flow pipe.
(9) Facing angle of large flow pipe and small flow pipe	The facing angle of the large flow and small flow pipe is specified to balance the angular momentum of each other so that no vortex is formed in the chamber during large flow considering the width of large flow pipe.
(10) Expansion angle of the throat	It is preferable that the flow area from the throat to outlet pipe increases gradually in order to return the kinetic pressure to the static pressure during large flow. However, if the expansion angle is too large, the flow may strip off the pipe and cause an energy loss. Therefore, the expansion angle is specified as [ ] degrees which is less than [ ] degrees, which prevents flow stripping based on experience.