THE ADVANCED ACCUMULATOR

September 2008

Revision History

Revision	Page	Description
0	All	Original issued
1	 4.2.2-2 4.2.3-2 4.2.3-8	The followings items are revised in accordance with the revision of the proprietary scopes; 1. Flow diagram of 1/3.5 Scale Test Apparatus is deleted. 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). 3. The photograph of 1/3.5 Scale Test Apparatus is deleted 4. Overview of 1/5 Scale Test Apparatus and Block Diagram is deleted. 5. 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). 6. The photograph of 1/5 Scale Test Apparatus is deleted. 7. The photographs of 1/5 scale test results are changed with non-proprietary photographs. 8. The photograph of Full-Height 1/2 Scale Confirmation Test Facility is deleted. 9. 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 3-2 (Table 3.1-1) 3-6 (Fig.3.3-2)	1. The name of part “vortex damper” is fixed to the correct name “vortex chamber.” 2. Maximum design pressure of ACC is fixed correctly [711psig (4.9MPa)→700psig(4.83MPa)], and Maximum design temperature of ACC is fixed correctly [(150 deg C) →(149deg C)]. 3. 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	4. 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[ ].
		5. 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	6. "(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)	7. The height of test tank [ ]mm is converted to[ ]inches and added.
	4.2.4-4 (Fig.4.2.4-3)	8. 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)	9. 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[ ].
		10. The distance between the throat and diffuser end of actual flow damper, which is in parenthesis in inches[ ]is fixed to the correct value[ ] .
		11. The inner diameter of outlet port of test flow damper, which is in parenthesis in inches[ ], is fixed to the correct value [ ].
		12. 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	13. 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.

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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
P/C	Personal Computer
PRZ	Pressurerizer
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) design simplifies the emergency core cooling system (ECCS) design by integrating the short term large flow rate design requirements currently satisfied by the accumulators and the low head safety injection pumps of a conventional nuclear pressurized water reactor (PWR) design 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 longer term ECCS flow requirements are met by the high head safety injection pumps thus eliminating the need for low head injection pumps. Further, the immediate availability of low head flow provided by the ACC upon loss of electrical power provides the additional time to permit activate emergency backup power supplies.

Characteristics of the passive ACC, detail design of the as-installed ACC, confirmation testing program for the ACC and concept of the safety analysis model are discussed in this report.

The ACC has flow damper, primarily consisting of the stand pipe and vortex chamber. When the ACC water level is high and 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 and thus it injects 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 thus vortex formation in the vortex chamber achieves the small flow injection.

The ACC injects large flow to refill the reactor vessel in the first stage and then the injection flow is automatically reduced by the flow damper.
The ACC performs the large flow injection to refill the reactor vessel and later contributes to the small flow injection during core reflooding in addition to the safety injection pump, thereby eliminating the conventional low-head injection system.

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

Major results of the tests are;

(1) From the results of 1/8.4 scale test, it was confirmed that switching from large flow to small flow could done smoothly and a stable level was kept in the stand pipe.
(2) From the results of 1/3.5 scale test, it was confirmed that the sharp flow rate switching without gas entrainment was achieved.
(3) From the results of 1/5 scale test, it was confirmed that no vortex was found during large flow, and a stable vortex was formed during small flow in vortex chamber.
(4) From the results of 1/5 and full height 1/2 scale tests, it was confirmed the flow characteristics of flow damper can be represented dimensionless number and were independent with 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 to assure 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 injection flow, and provides sufficient relief from the need for rapid start emergency diesel generator backup power to permit use of highly reliable gas turbine generators. The operating characteristics of the ACC have been validated by testing.

The flow characteristics of the ACC have been verified by thorough testing and can be fully described as a function of dimensionless numbers independent of the effects of scale. Empirical flow rate coefficients were 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 Reactors (APWR), and MHI's 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 advance of the submission 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 (COL) which reference the US-APWR Design.

The ACC is an accumulator tank with the flow damper that is 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 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 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 the conventional Emergency Core Cooling System (ECCS). This design improvement will allow the elimination of 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 at nuclear facilities while maintaining a very high level of safety.

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

2.0 CHARACTERISTICS OF THE ADVANCED ACCUMULATOR (ACC)

2.1 ECCS Performance during 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 since the liquid around the core is carried away by a 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 fill the lower plenum and downcomer of the reactor vessel quickly (Core Refilling)

Step 2: Recovery of the core water level using the water head in the downcomer. Large ACC flow to the core keeps the high water level in the downcomer and quickly re-floods the core. (Core Reflooding)

Step 3: After core reflooding is completed, water is injected to accommodate the reduction due to decay heat and to maintain the core flooded. (Long Term Cooling)

The performance requirement for the ECCS in a conventional nuclear plant during a large LOCA is fulfilled using the following subsystems;

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

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

The assigning of the function of the US-APWR ECCS subsystems during a large LOCA is shown as follows in Fig.2.1-1.

Step 1: Accumulator System (ACC)
Step 2: Accumulator System (ACC) and High Head Injection System
Step 3: High Head Injection System

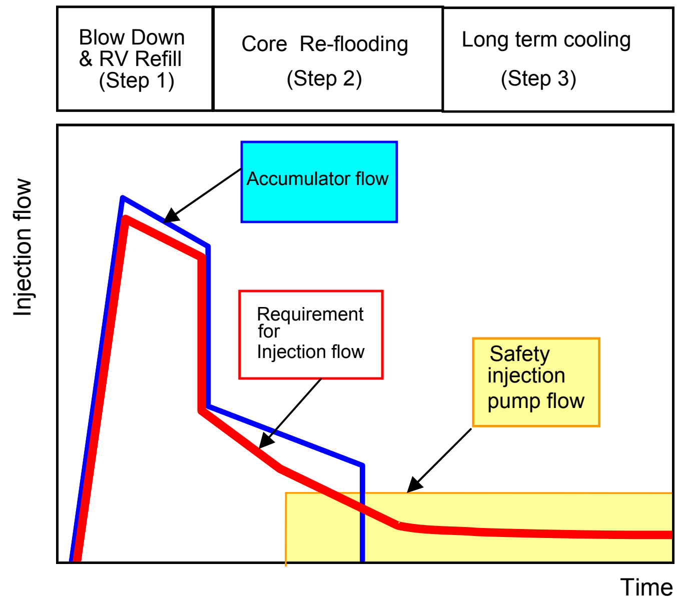
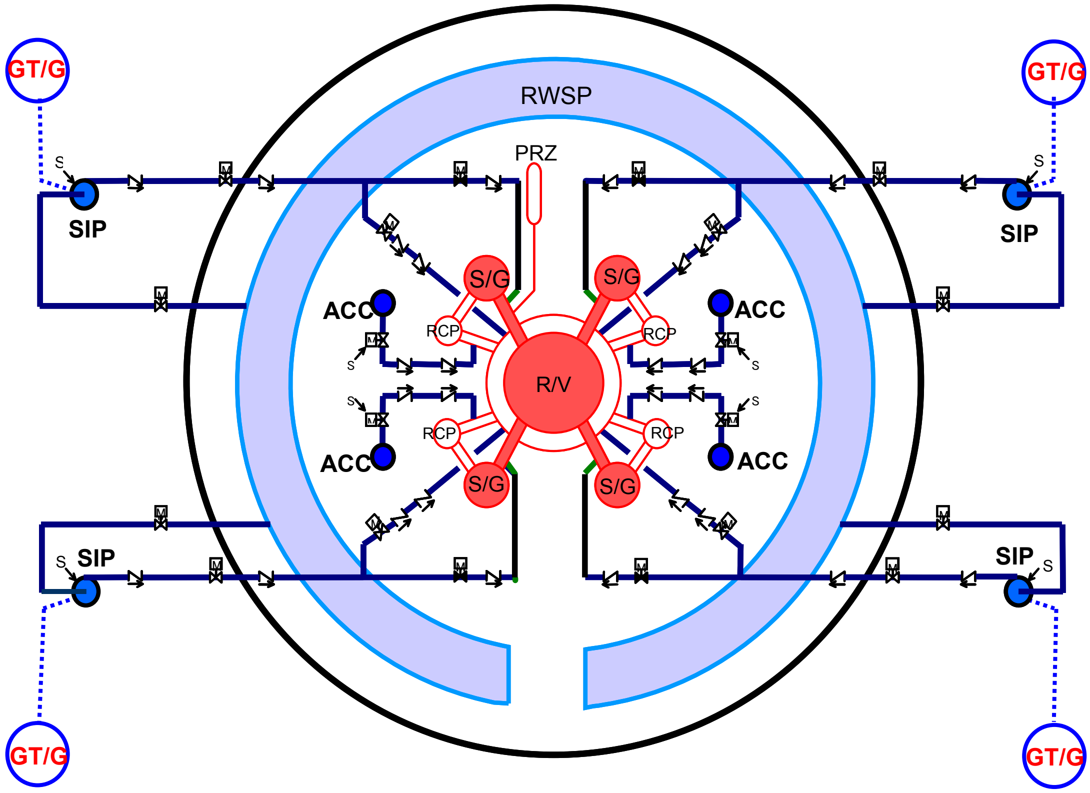


Fig. 2.1-1 ECCS Performance during Large LOCA

During a large LOCA, it is necessary to start the ECCS pumps prior to end of accumulator injection to inject water to the core continuously. The ACC injects water longer than a conventional accumulator, thereby allowing more time for ECCS pumps to start. Therefore, in the US-APWR, gas turbine generators can be used for the emergency power source, if needed.

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

A more detailed description of the ACC will be provided later.



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 ECCS of the US-APWR

2.2 The Principles of the ACC Performance

2.2.1 Concepts of Flow Switching Principle

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

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

There is a vortex chamber at the inlet of the injection pipe in the accumulator tank. The small flow rate pipe is tangentially attached to the vortex chamber. The large flow rate pipe is radially attached to the vortex chamber on one end and connected to the standpipe on the other end. The inlet port of the standpipe is located on the level of the interface between the volume of water for the large flow rate injection and that for the small flow rate injection in the tank. The outlet port of the flow damper is connected to the injection pipe. The ACC is thus a simple device with no moving parts.

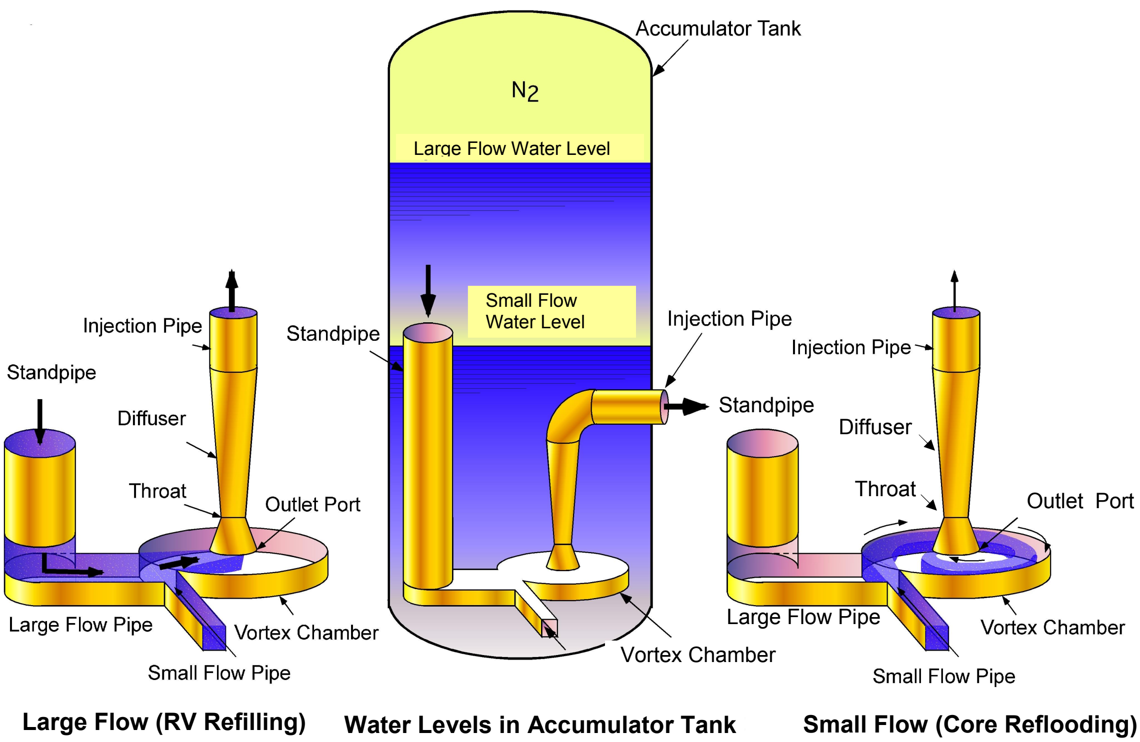


Fig.2.2.1-1 Principle of Advanced Accumulator

When a Loss of Coolant Accident (LOCA) occurs and pressure in the reactor vessel decreases, the check valves in the injection pipe open to permit injection of cooling water into the vessel. Since the water level in the accumulator tank is at first higher than the elevation of the inlet of the standpipe, water flows through both the large and small flow rate 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 flow rate pipe cancels the angular momentum of the flow from the small flow rate pipe. Consequently, the flow resistance is small resulting in a large flow. Fig. 2.2.1-2 shows additional details of flow damper.

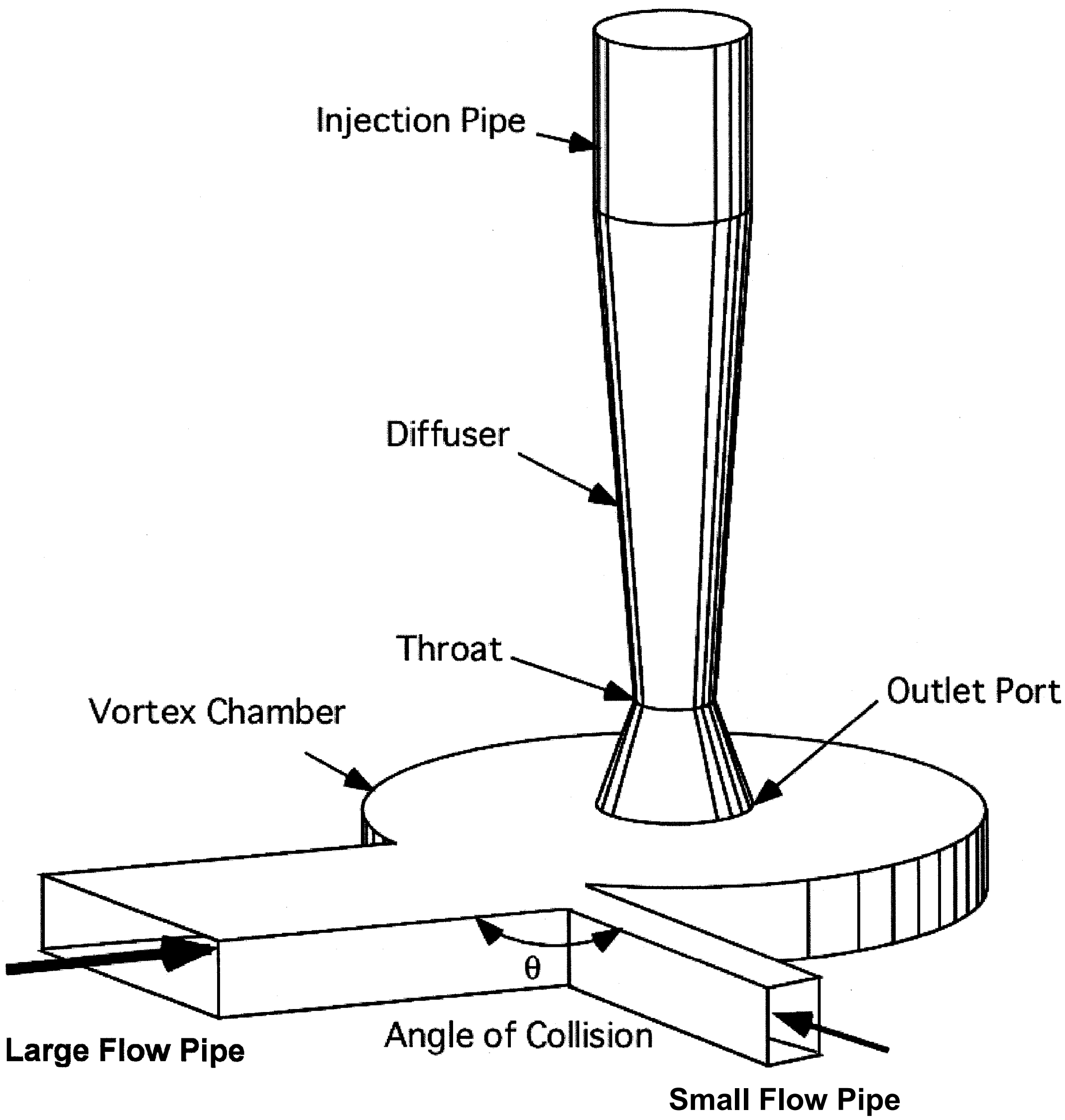


Fig.2.2.1-2 Flow Damper

High flow continues until the water level in the accumulator tank comes down to the inlet level of the standpipe, and the flow into the standpipe stops. The flow in the large flow rate pipe almost comes to stop and the flow from the small flow rate pipe forms a strong vortex in the vortex chamber. As a result of centripetal force, a large pressure drop occurs along the radius of the vortex chamber between the small flow rate pipe and the output 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 tank, while that of the outlet port, d, is limited by the required flow rate at large flow rate condition. In order to satisfy these requirements and to 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) At Large Flow Rate

Since there is no vortex in the vortex chamber at large flow rates, flow resistance of the flow damper must be similar to that of a conventional pipe. The form resistance is larger than flow friction in the flow damper because the flow has high velocity direction changes within a short distance. Therefore pressure loss of the flow damper will be primarily due to form resistance, and secondarily due to a 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 rate. If the pressure at the throat goes 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 flow rate. Hence, a cavitation factor will be a parameter of a flow rate coefficient, if the effect of friction is neglected.

The pressure in the accumulator tank is over 580psig (4MPa [gage]) at the beginning of injection and comes down to about 145psig (1MPa[gage])at the end of large flow rate injection. 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, full pressure experiments to verify that dissolved das will not significantly affect the ACC flow rate. The detail of the test will be show later in this report.

2) At Switching Flow Rate

At the end of large flow rate injection, water stops flowing into the standpipe but a water surface is formed in the standpipe. 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 between inside and outside of the standpipe. The water level recovers to its balanced level thereafter. Fig. 2.2.1-3 shows schematic chart of transient of a water level 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 will be evaluated in the testing described later.

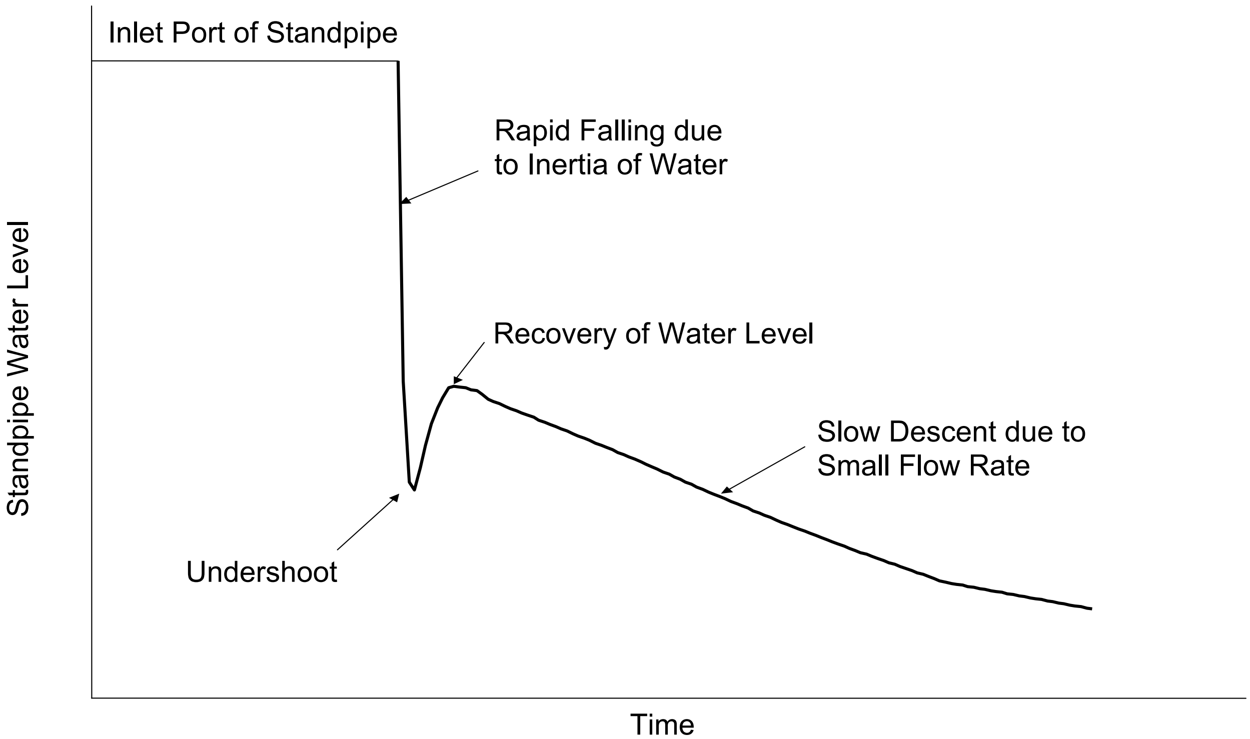


Fig.2.2.1-3 Example of Water Level Transient in Standpipe (Schematic Chart)

3) At Small Flow Rate

After flow in the standpipe is almost stopped, a strong and steady vortex flow is formed in the vortex chamber. Since the pressure loss in the small flow rate pipe is negligible, the static pressure at the exit of the small flow rate pipe equals the static pressure in the accumulator tank minus the dynamic pressure in the small flow rate 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 flow rate pipe, which is much smaller than the pressure drop due to a vortex in the chamber. This is a main feature of the flow damper which prevents gas leakage during the small flow rate.

Pressure losses of the flow damper are due to a strong vortex at small flow rates. Pressure recovery in the diffuser after the throat is negligible during small flow rate, and pressure at the center of the vortex is almost equal to that in the injection pipe. This indicates that the minimum pressure is much higher than the vapor pressure of the water. Consequently, cavitation will not occur at the throat during small flow rate.

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

2.3 Performance Requirements for the ACC

The functions of the ACC during a large break LOCA are, as described in Section 2.1, 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 refilling period.”

2.3.2 Performance Requirements for Small Flow Injection

1) Basic concept

It is important for core cooling 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 (See Fig.2.3.2-1).

2) The required injection flow rate

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

The required flow rate is obtained from the core re-flooding flow rate calculated by the hypothetical LOCA analysis, which assumes that the downcomer is filled with sufficient water to adequate safety injection flow. A double-ended, Cold-Leg break (CD (Discharge Coefficient) =0.6), which makes the PCT worst conventionally for 4-loop plants, is assumed for the analysis condition.

The required flow rate is obtained as the sum of the injection flow rate and the product of flow area times the re-flooding 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

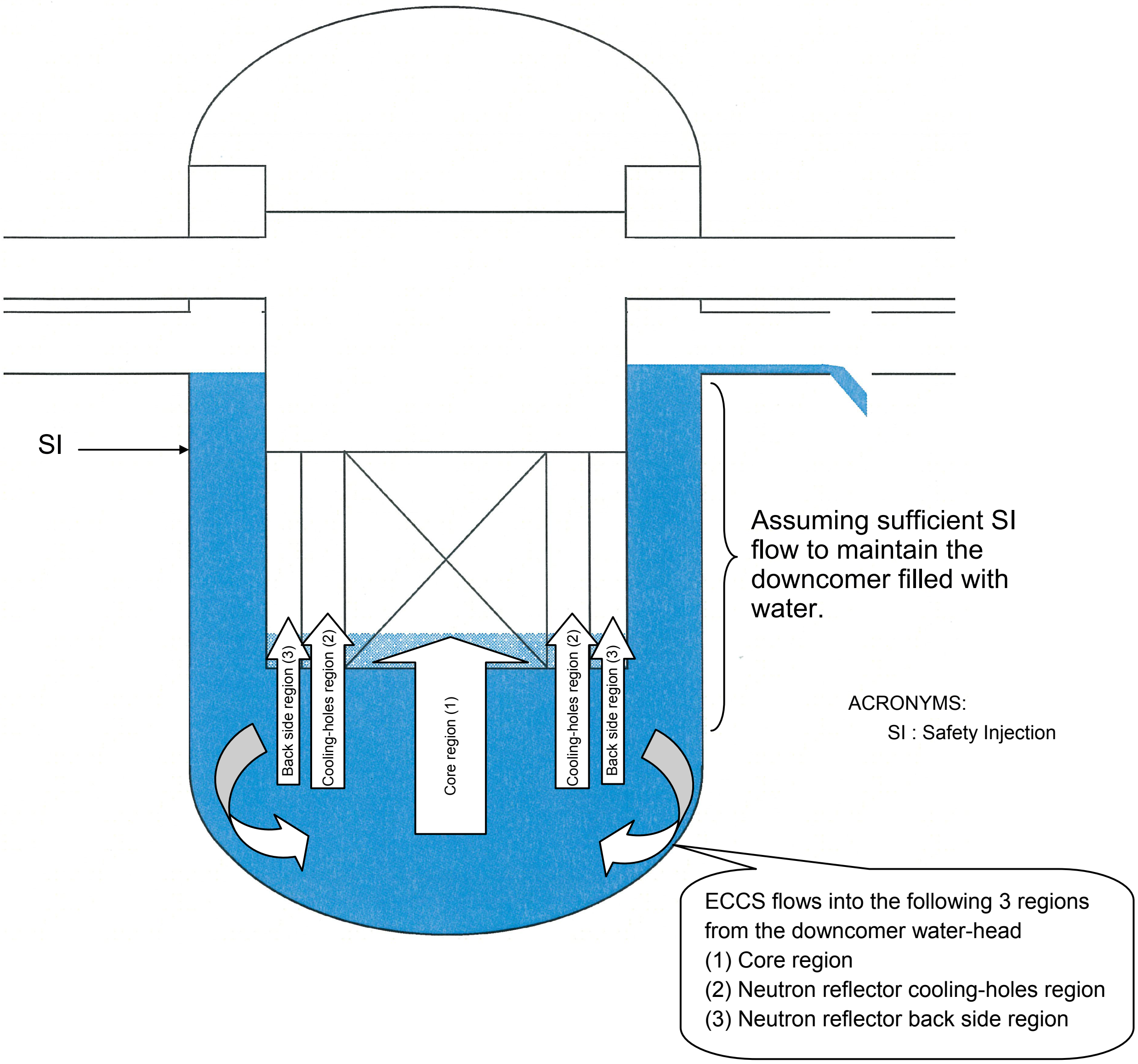
The required injection flow rate obtained by this analysis, is shown in Fig.2.3.2-2. According to the progress of core re-flooding, the difference of water-head between the downcomer and the core is reduced gradually, and the required injection flow rate decreases gradually.

This analysis was calculated 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, core re-flooding rate becomes larger. Therefore, we used the Japanese decay heat model to obtain the conservative (larger) flooding rate requirement.

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.

3) Required injection flow rate Margin

The required flow rate for small flow 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.



Required flow rate = Sum of the injection flow rate in each region

Fig.2.3.2-1 Basic Concept for Calculation of the Required ECCS Injection Flow Rate
(Core re-flooding phase)

Note: According to progress of core re-flooding, the difference of water-head between the downcomer and the core is gradually reduced. The required flow rate 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 calculated 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 deeply and fuel-cladding temperature would rise. The injection capability to recover the core water level quickly is needed as the ECCS function. Therefore, the prompt injection during the refill period would be performed by large flow of accumulators. (See Fig.2.3.3-1(a))

  When the accumulators inject water for smaller break-sizes, the fuel-cladding temperature do not reach high values because of the lower decay heat level 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 uncover and fuel-cladding temperature would rise. In this case, the accumulators would not start injecting water for the core reflooding. The injection capability to supply the evaporated coolant in the long-term after core reflooding is the required ECCS function. Therefore, the safety injection pumps are in charge of this function. (See Fig.2.3.3-1(c))

The validity of ECCS design will be confirmed by the ECCS performance evaluation analysis.

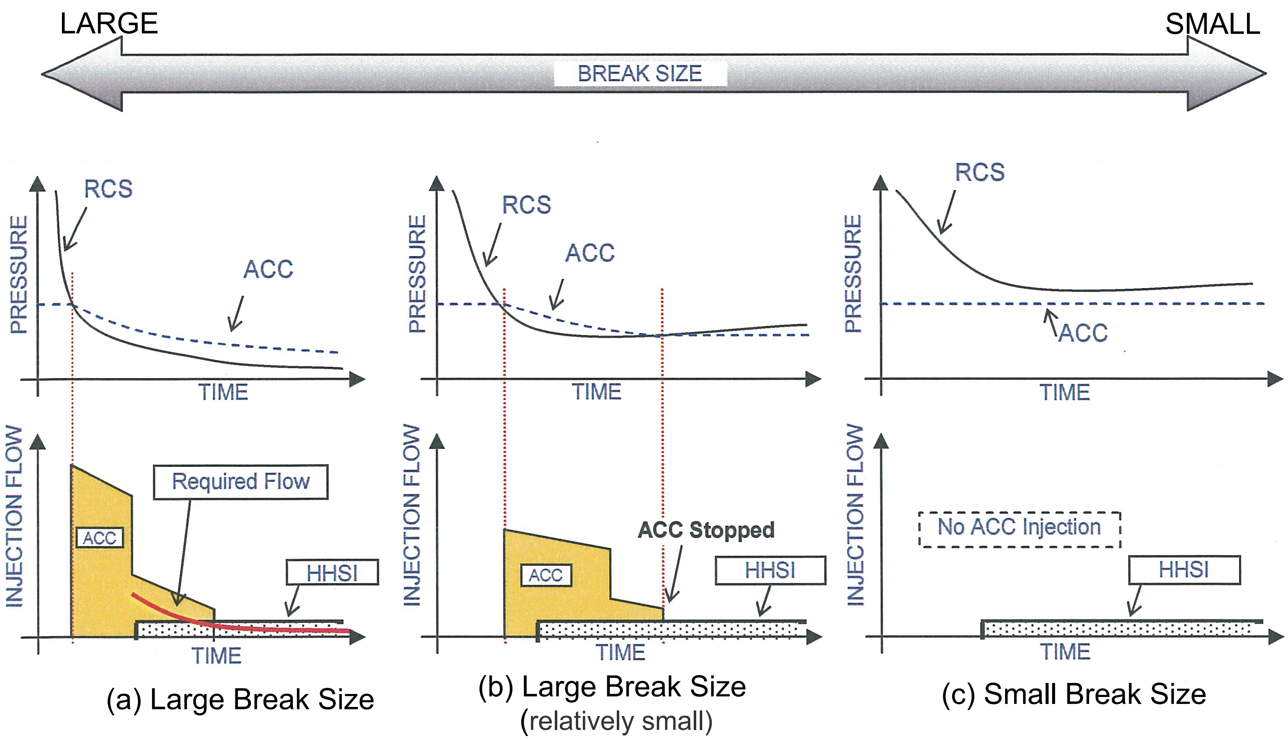


Fig.2.3.3-1 RCS Pressure Transients and ECCS Injection Flow for Various Break Sizes

2.3.4 Design Requirements for the ACC

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

1) Design Requirements for Large Flow Injection

The performance requirements for the large flow injection 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 refilling period.

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

- 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 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 APWR LOCA analysis.

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

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

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

$$\frac{dVgas}{dt} = A \cdot U \qquad (2\text{-}3)$$

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 tank
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	:	Gravity acceleration
t	:	Time
κ	:	Adiabatic exponent

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

The PCT results were confirmed in the APWR design stage by using these parameters for large flow injection (assuming the resistance coefficient of the accumulator injection system is [ ] to be below [ ]. 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 to the design requirement as follows:

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

The resistance coefficient of the flow damper during large flow changes 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), where the cavitation factor becomes smallest.

2) Design Requirements for Small Flow Injection

The performance requirements for small flow injection during large LOCA are described in Section 2.3.2. The required small injection flow rate following the shift of flow 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[ ], which exceeds the required (smallest) flow-shifting ratio [ ] from large flow to small flow, is specified as the 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 Injection System

Note
Refer Section 3.1

2.4 Expected Performance of the ACC

The major design parameters specified in Section 2.3.4 to meet the performance requirements for the ACC 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.

Although the calculation method is the same as described in Section 2.3.4, for this calculation, 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 of the value[ ]of K_D in the small flow injection is shown as follows:

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

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

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

$$= [\quad] \qquad (2\text{-}8)$$

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 The Design Basis and Specifications of the ACC

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

Each ACC connects to a corresponding RCS cold leg (4 accumulators 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):**

  Inject 2,613ft^3(74m^3) [Note1] of water rapidly (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 2,295ft^3(65m^3). The required value (2,613ft^3(74m^3)) is set 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 associated with the SI pump capacity. If the duration of small flow injection is short then a 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 to the containment and does not contribute to core injection, 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)**

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

The volume of an ACC is specified to be 1,342ft^3(38m^3), which is the required 1,307ft^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 spilt from the broken loop to the containment.
(c) The number of ACC assumed to inject to the core injection

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

The relation 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, 724ft^3(20.5m^3) of injection water is required per ACC. Thus, 784ft^3 (22.2m^3) of injection water volume is specified giving a margin above approximately 8%. Considering the total water volume , 2,126ft^3(60.2m^3), and adding the volume of gas space and dead water volume, the required volume of a single ACC is 3,180ft^3(90m^3). The validity of the volume will be confirmed in ECCS performance analysis. Specifications for the ACC are shown in Table 3.1-1.

Table 3.1-1 Specifications for the ACC

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

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

3.2 The Structure of the ACC

An outline drawing of the ACC is shown in Fig. 3.2-1. The inner diameter of the tank is [ ] [ ] 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 space for installation. The ACC main dimensions are shown in Fig.3.2-1.

Fig. 3.2-1 Outline Drawing of Advanced Accumulator

3.3 The 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 flow 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 and to recover the pressure during large flow and to provide a smooth transition for the pipe. The detailed dimensions, 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.

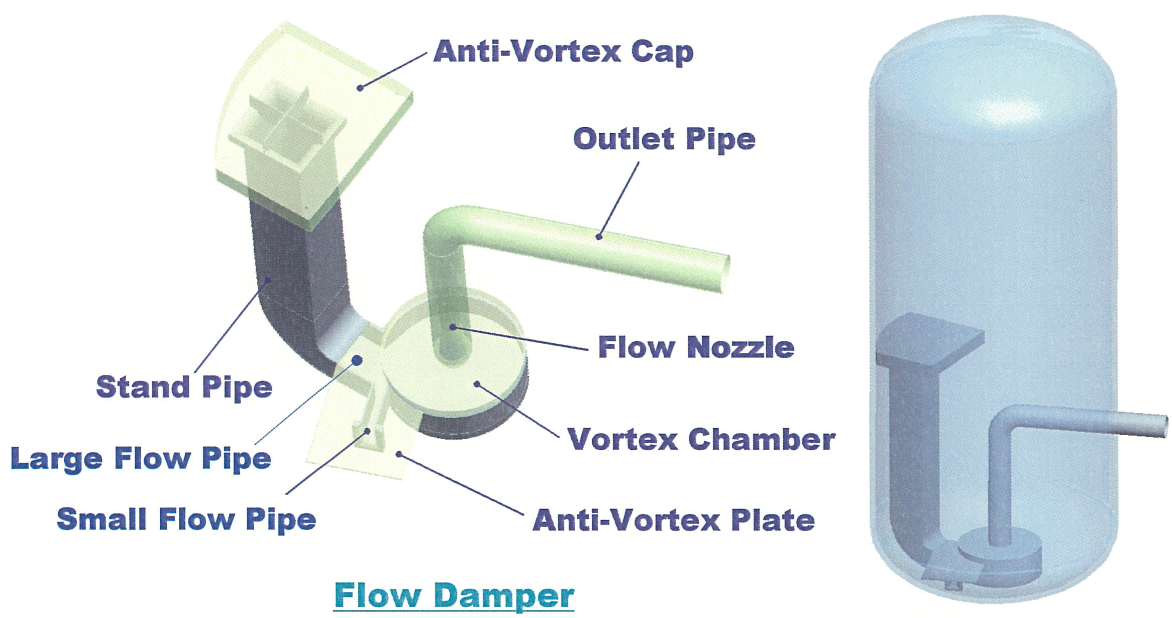


Fig. 3.3-1 Overview of the Flow Damper

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 enlarge 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 which 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.

4.0 CONFIRMATORY TESTING PROGRAM FOR THE ACC

The design requirements and specifications of the ACC for the US-APWR that were discussed in section 2 and 3 are the same as that for the APWR. The core output and the size of the reactor vessel are the main parameters used to determine the design requirements and the specifications of the ACC are common to both the APWR and the US-APWR. Therefore, the confirmation test program of the ACC previously been done for the APWR is applicable to the US-APWR. This test program was conducted as a joint study among five utilities [Note] and MHI, from September 1994 to September 1996.

Note: Japan Atomic Power Co., Hokkaido Electric Power Co., Kansai Electric Power Co., Shikoku Electric Power Co., and Kyushu Electric Power Company.

This Section of the Topical Report (1) describes the purposes and objectives of the confirmatory test program; (2) provides a detailed description of the tests and the test results; (3) provides demonstration of the validity and scalability of the test results for the design of the US-APWR; and (4) sets forth, the quality assurance performed to re-verify and confirm that the results of the test program are reliable and accurate for use in the design of the US-APWR.

4.1 Purpose of the ACC Scale Testing

Confirmatory tests were conducted to determine whether expected performance could be achieved from the operational principles of the ACC. The following items were tested to verify the principles and characteristics of the flow damper:

(1) Confirmation of the principles of the flow damper:

Tests were conducted to observe the behavior of the flow in the vortex chamber of the flow damper during large flow injection, large/small flow switching, and small flow injection and to confirm that their behavior was as expected.

(2) Confirmation of the anti-vortex function at the end of large flow injection:

As water level in the accumulator decreases after initiation of accumulator injection, it may be possible to form a vortex at the entrance to the standpipe and nitrogen gas in ACC gas space can be sucked into the standpipe when the water level is low. Therefore, an anti-vortex cap was designed for the large flow inlet. The tests were conducted to confirm that the anti-vortex cap prevented the vortex from forming at the standpipe inlet and gas was not sucked into the stand pipe.

(3) Confirmation of the standpipe water level transient during flow switching:

During flow switching from large flow to small flow, the standpipe water level is temporarily decreased by inertial force, and then recovers due to the differential of the water level between the tank and the standpipe. When the standpipe water level decreases to the top of the flow damper, gas can be entrained the flow damper and carried to RCS.
However, the ACC was designed so that gas entrainment will be precluded.
The test was conducted and confirmed that gas was not entrained into the flow damper by measuring the water level transient during the flow switching.

(4) Confirmation of performance during large flow:

A test was conducted to confirm that the performance of the flow damper during large flow met the design requirement (i.e. Resistance coefficient for large flow injection)

(5) Confirmation of performance during small flow:

A test was conducted to confirm that the performance of the flow damper during small flow met the design requirement (i.e., flow switching ratio).

(6) Confirmation of flow switching water level:

It is assumed that the injection flow rate shifts from large flow to small flow when the tank water level decreases to the lower edge of the standpipe anti-vortex cap. However, in the actual tank, the flow switching level may have some variations. Therefore, the actual switching level was confirmed through testing.

(7) Confirmation of the effect of dissolved nitrogen gas:

Since the accumulator tank is compressed by nitrogen gas, it is possible that nitrogen gas will dissolve in the water. If the water in the accumulator tank contains nitrogen gas, it is assumed that the gas comes out of solution and affects the flow characteristics of the flow damper. Therefore, the test was conducted with nitrogen-rich water to confirm that the effect of nitrogen gas was negligible with ACC design.

(8) Confirmation that the ACC flow characteristics are represented by dimensionless numbers (cavitation factor and flow rate coefficient):

The throat portion of the ACC is located at the outlet of the vortex chamber to form a strong vortex in the vortex chamber during small flow. Therefore, it is assumed that cavitation could occur and affect the flow characteristics during large flow. The cavitation phenomenon can be evaluated by utilizing a cavitation factor. The tests were conducted to confirm that the flow characteristics obtained through the tests were a function of the cavitation factor.

The cavitation factor σ_v is defined by the following equations.

$$\sigma_v = \frac{P_D + P_{at} - P_v}{\Delta P} \tag{4-1}$$

where P_{at} : Atmospheric pressure

P_D : Outlet pressure of flow damper [gage]

P_v : Vapor pressure of the water

ΔP : Pressure drop of flow damper

(9) Confirmation that flow characteristics (cavitation factor and flow rate coefficient) are independent of scaling:

To confirm the validity of applying the similarity law that evaluates the actual flow damper by the test results using scale model of the flow damper and to acquire the data required.

These test items are summarized in Fig.4.1-1.

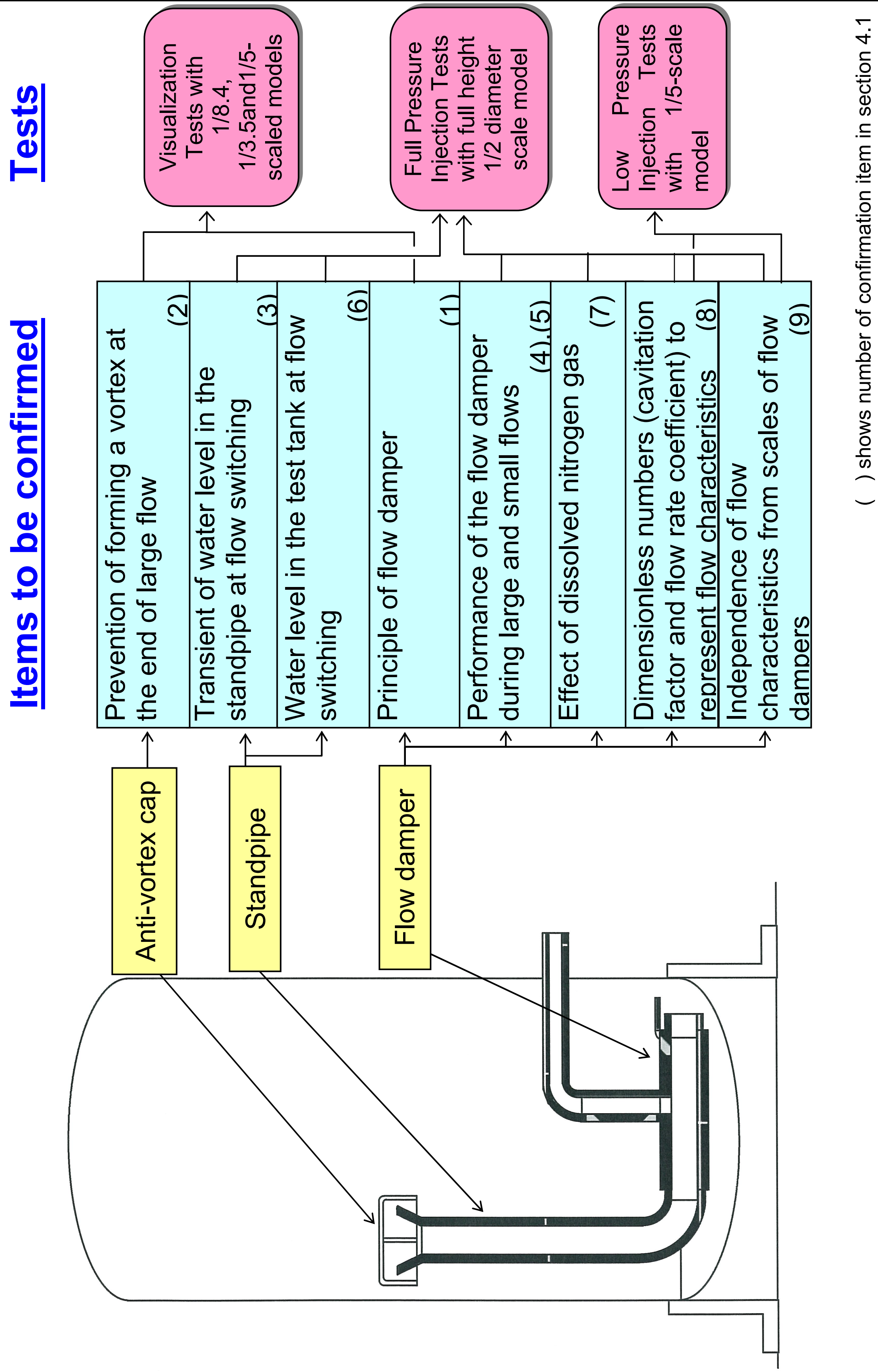


Fig. 4.1-1 Confirmation Items by Test

4.2 Detailed Description of the Test and Results

4.2.1 1/8.4 Scale Test

1) Objectives

To examine the basis of operation of the ACC and to understand the injection flow characteristics and 1/8.4 scaled flow visualization experiment was designed. Items to be confirmed in this test are as follows;

- **Confirmation of operating principles of the flow damper**

  To visualize the behavior of flow in the flow damper and the standpipe during large flow injection, large/small flow switching, and small flow injection, and confirm the behavior and stability of the flow in the vortex chamber and flow switching. From this test, it was confirmed that: (1) A vortex was not formed in the vortex chamber during large flow, (2) A vortex was formed and flow rate was decreased during small flow, and (3) injection flow rate was shifted sharply from large flow to small flow.

- **Confirmation of behavior of the water level in the standpipe at flow-switching**

  To visualize the behavior of the water level in the standpipe at flow-switching and confirm the behavior of the flow.

2) Test apparatus

The visualization test of operating principles of the flow damper was conducted using the test apparatus shown in Fig. 4.2.1-1 and Photo. 4.2.1-1. The test apparatus consists of an ACC model, exhaust tank and injection pipe. The scale of the flow damper is 1/8.4 and the vortex chamber is upright. One side of the vortex chamber and the standpipe is integrated into the front of ACC model, which is made of transparent acrylate so that the flow behavior inside of the ACC, the standpipe and the flow damper can be observed. (The shape of each part of the apparatus was simplified while assuring the operating principles of the flow damper was not affected.)

Fig. 4.2.1-1 1/8.4 Scale Test Apparatus

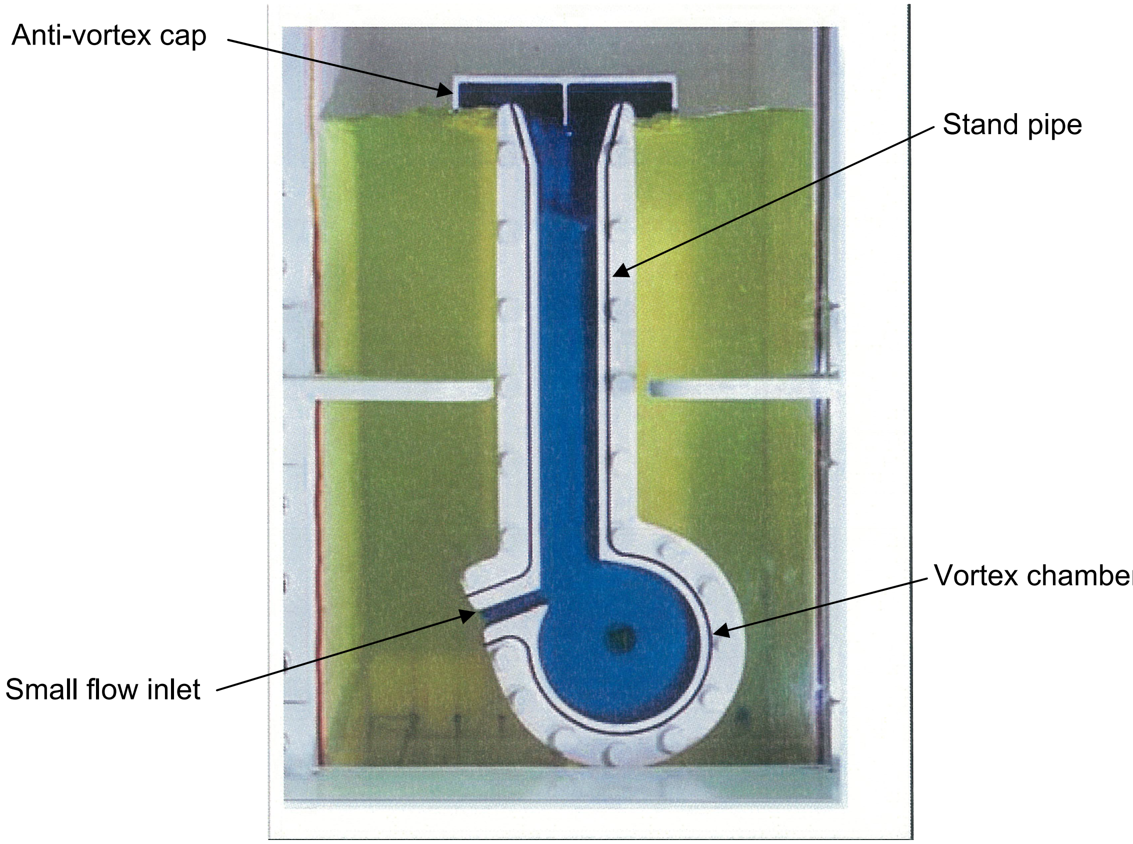


Photo. 4.2.1-1 1/8.4 Scale Test Apparatus

The major specifications of the test facility are as follows:

(1) ACC Model

Design Pressure :
Width :
Length :
Height :
Volume :

(2) Flow Damper and Standpipe

Dimensions : 1/8.4 of actual tank
(Flow damper inner diameter :) Simplified shape

(3) Injection Piping

Diameter :