THE ADVANCED ACCUMULATOR

February 2007

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Revision History

Revision	Page	Description
0	All	Original issued
1		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.
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	4.2.3-2	
	4.2.3-8	

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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 damper through both inlets at the top of the standpipe and at the side of the vortex damper 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 damper 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

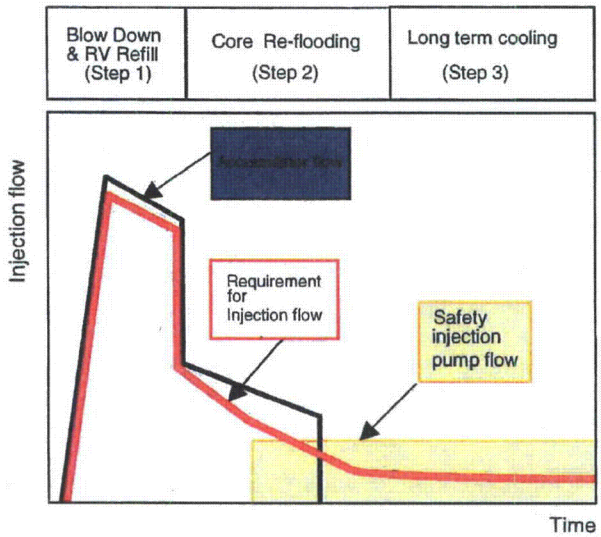
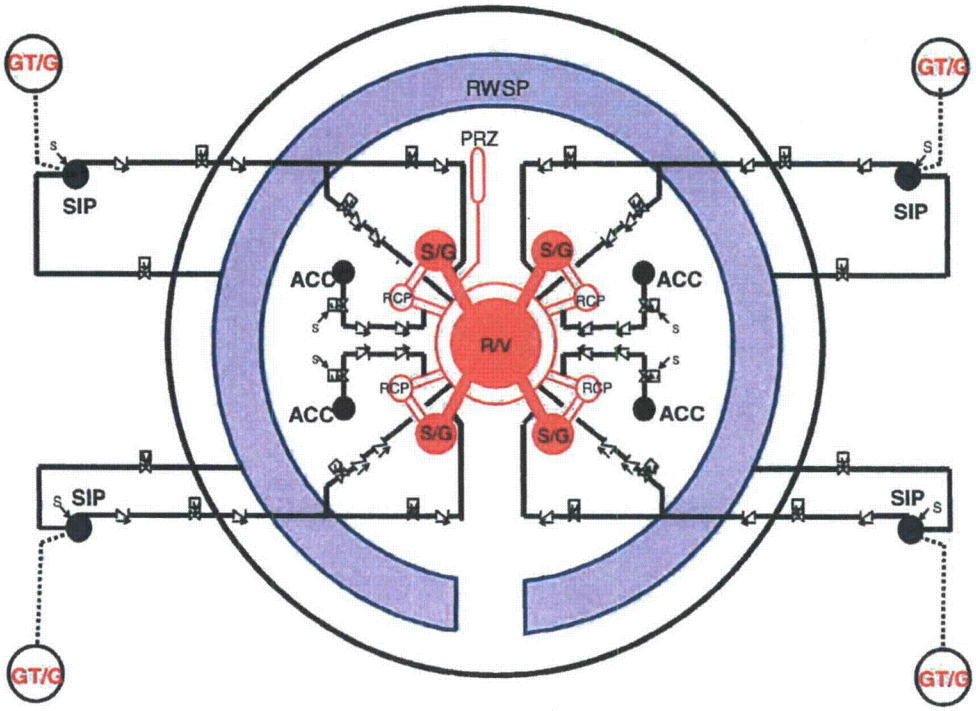


Fig. 2.1-1 ECCS Performance during Large LOCA

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 Principal

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 for 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.

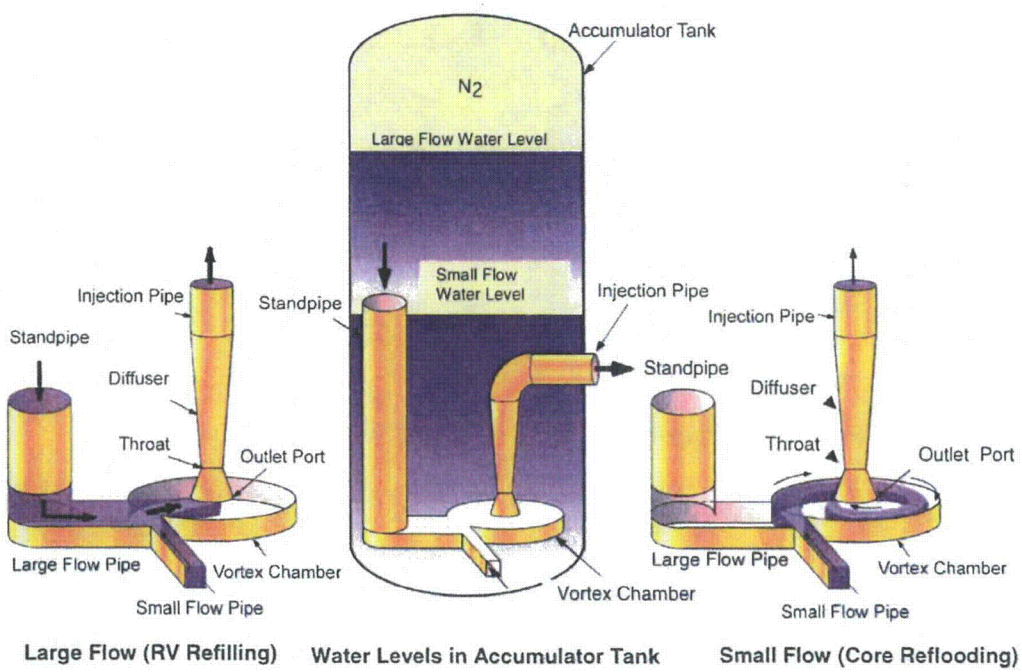


Fig.2.2.1-1 Principle of Advanced Accumulator

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.

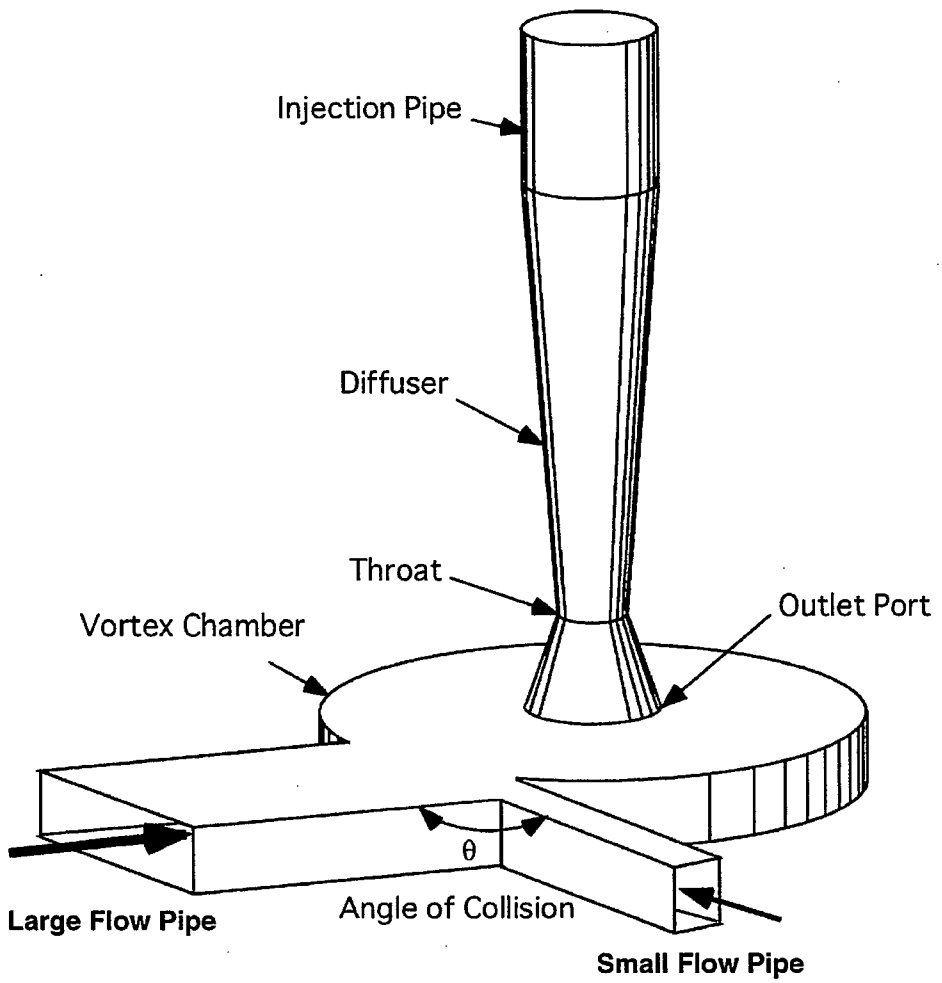


Fig.2.2.1-2 Flow Damper

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.

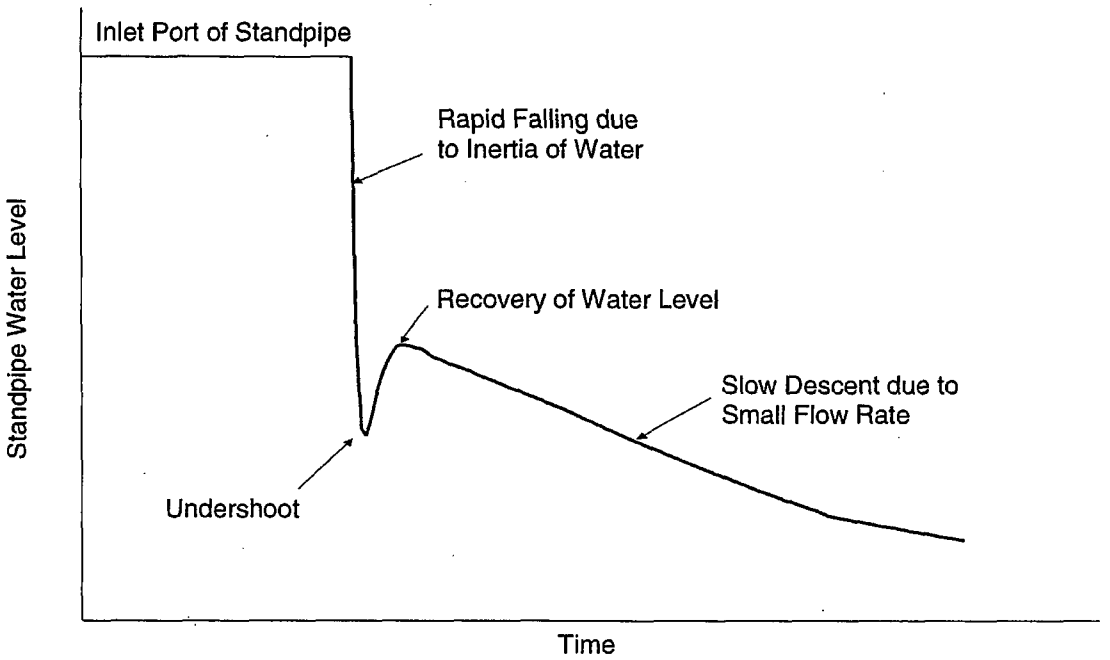


Fig.2.2.1-3 Example of Water Level Transient in Standpipe (Schematic Chart)

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 approximately 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.

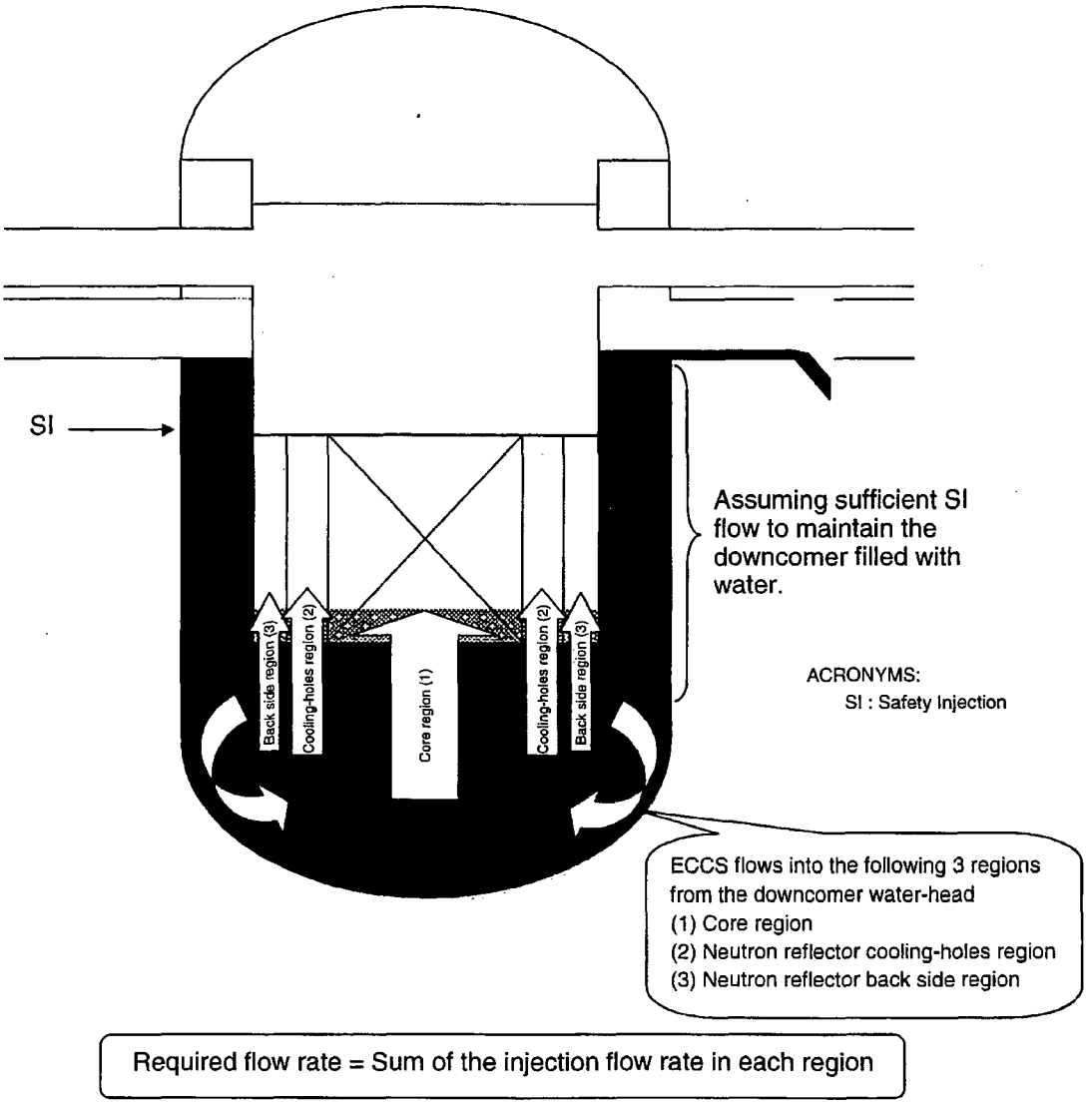


Fig.2.3.2-1 Basic Concept for Calculation of the Required ECCS Injection Flow Rate
(Core re-flooding phase)

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.

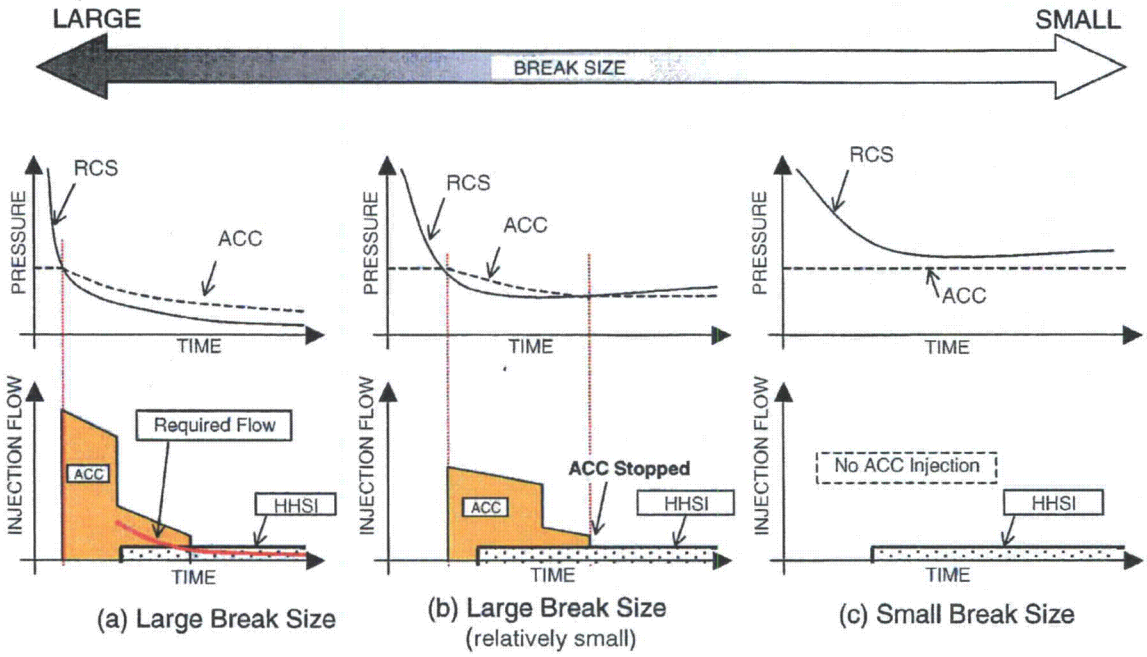


Fig.2.3.3-1 RCS Pressure Transients and ECCS Injection Flow for Various Break Sizes

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:

$$K_D = K - K_p$$
$$= [\quad]$$
$$= [\quad] \qquad (2\text{-}4)$$

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:

$$R = [\quad]$$
$$= [\quad] \qquad (2\text{-}5)$$

Therefore, the flow-shifting ratio[ ], which exceeds the required (smallest) flow-shifting ratio [8.3]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:

$$R = \frac{Q_L}{Q_S} \tag{2-6}$$

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

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

$$= [\quad] \tag{2-8}$$

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[ ]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[ ]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[ ]. The required value[ ]is set to provide additional margin.

  Note2: It is assumed that the duration of small flow injection from the accumulator is[ ] 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)**

$$[\quad]^{(a)} / (2/3)^{(b)} / 3^{(c)} = [\quad] / \mathrm{ACC} \qquad (3\text{-}1)$$

The volume of an ACC is specified to be[ ], which is the required[ ] 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[ ] seconds. Therefore,[ ]of injection water is required per ACC. Thus,[ ] [ ]of injection water volume is specified giving a margin above approximately[ ]%. Considering the total water volume ,[ ] and adding the volume of gas space and dead water volume, the required volume of a single ACC is[ ] 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:	[ ]
Maximum design temperature:	
Large flow injection volume:	
Small flow injection volume:	

[ ]

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 low 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.

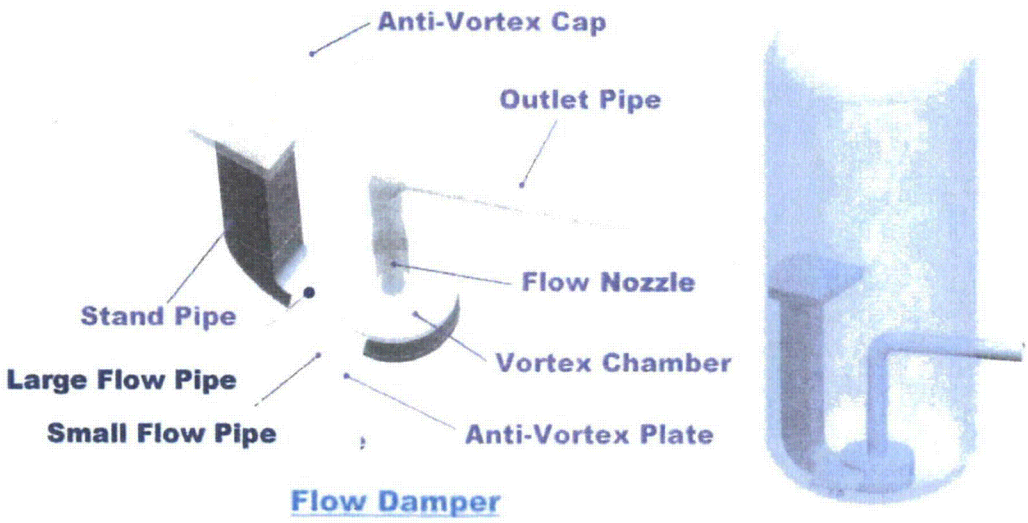


Fig. 3.3-1 Overview of the Flow Damper

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.

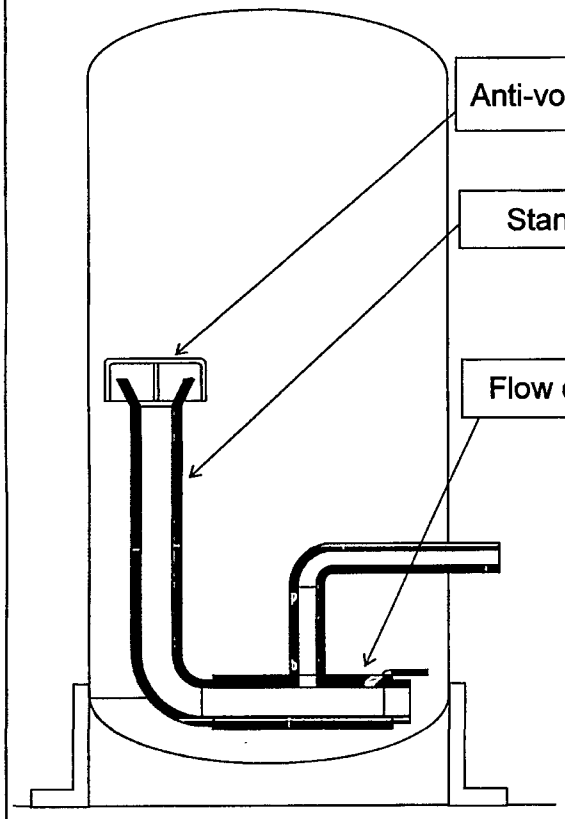
$$\sigma_v = \frac{P_D + P_{at} - P_v}{\Delta P} \qquad (4\text{-}1)$$

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.



Anti-vortex cap

Standpipe

Flow damper

Items to be confirmed

- Prevention of forming a vortex at the end of large flow (2)
- Transient of water level in the standpipe at flow switching (3)
- Water level in the test tank at flow switching (6)
- Principle of flow damper (1)
- Performance of the flow damper during large and small flows (4),(5)
- Effect of dissolved nitrogen gas (7)
- Dimensionless numbers (cavitation factor and flow rate coefficient) to represent flow characteristics (8)
- Independence of flow characteristics from scales of flow dampers (9)

Tests

- Visualization Tests with 1/8.4, 1/3.5and1/5-scaled models
- Full Pressure Injection Tests with full height 1/2 diameter scale model
- Low Pressure Injection Tests with 1/5-scale model

( ) shows number of confirmation item in section 4.1

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

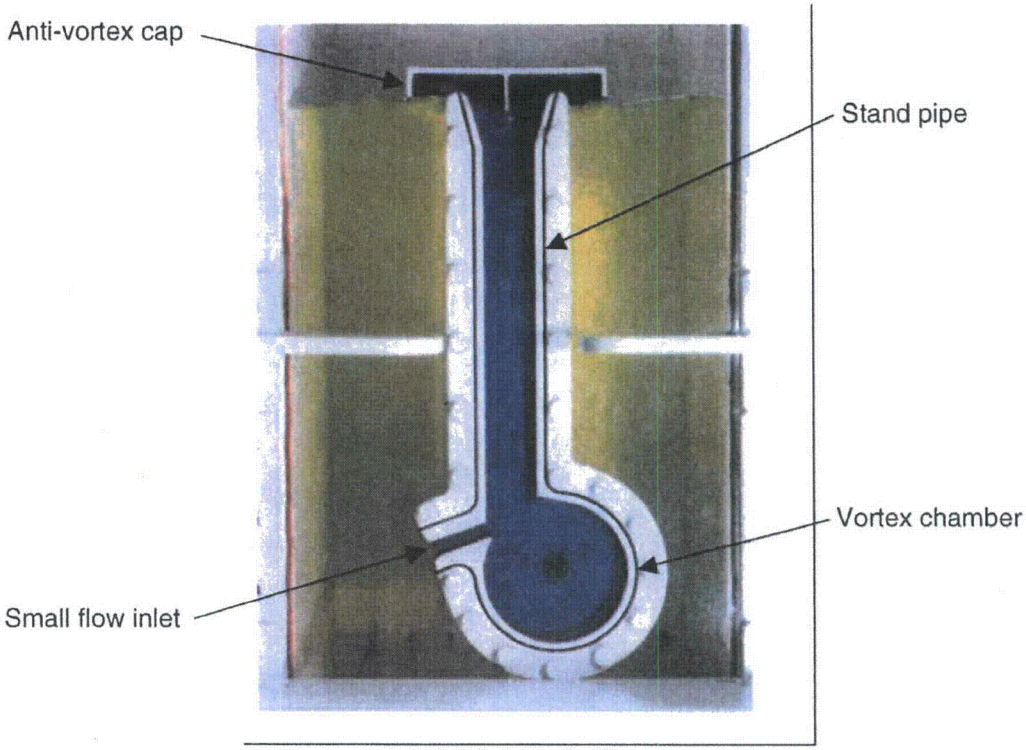


Photo. 4.2.1-1 1/8.4 Scale Test Apparatus

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 : ( )

(4) Exhaust Tank

Design Pressure	:	( )
Width	:	
Length	:	
Height	:	
Volume	:	

3) Test condition

The pressure of the gas space is ( ) (Max pressure of test facility)

4) Parameter to be measured

The behavior of flow in the standpipe and the flow damper was observed. Also, flow-switching was observed on a CRT as shown in Fig. 4.2.1-1.

5) Measuring equipment

The behavior of flow in the standpipe and the flow damper was confirmed by visual inspection. Flow switching was confirmed by visual tracking of flow rate using the flow meter as shown in Fig. 4.2.1-1.

6) Test results and consideration

The behavior of the flow and the flow transient in the standpipe and the vortex chamber at flow switching are shown in Photos. 4.2.1-2 to 4.2.1-7, respectively. The following items were confirmed from the test:

(1) The behavior of the flow in the vortex chamber during large flow conditions is shown in Photo. 4.2.1-3. It was confirmed that a vortex was not formed in the vortex chamber since the air, which was injected as a flow tracer, directly drifted from the point where the flow from the inlet of standpipe and the flow from small flow pipe collided to the outlet.

(2) By comparing the water level in the standpipe at shortly after the flow switching (Photo. 4.2.1-5) and during small flow condition (Photo. 4.2.1-6), it was found that the water level during small flow is higher than the water level at flow switching. Thereby confirming that the water level in the standpipe was temporarily reduced, and then recovered.

(3) It was confirmed that the flow switched sharply from large flow to small flow in a short time as shown in Photo. 4.2.1-6.

(4) It was confirmed that following the initiation of small flow, the stable vortex was formed since the air that was injected as a flow tracer was swirling into the outlet as shown in Photo. 4.2.1-7 .

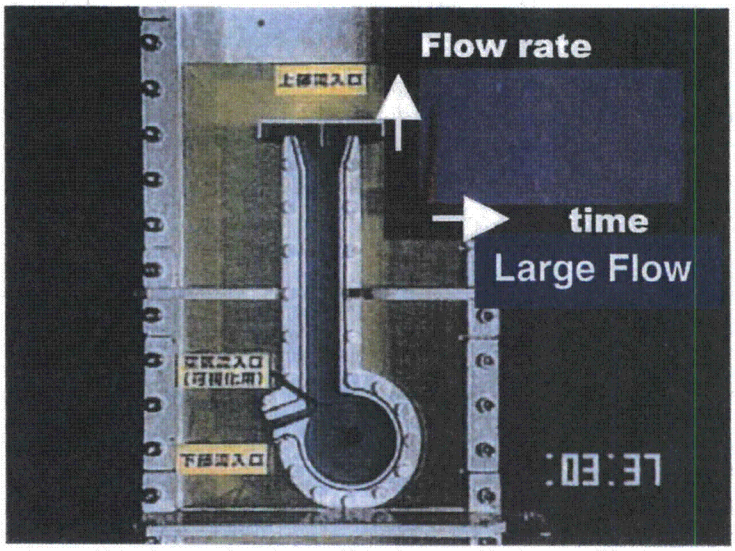
From the test results above, the basic principle of the flow damper was confirmed as follows:

(1) When the water level in the accumulator tank is above the upper end of the standpipe, the flow from standpipe and the small flow inlet collide in the vortex chamber and flow directly to the outlet, and a vortex is not formed in the vortex chamber. Therefore, the resistance is small and the large flow rate is available.

(2) When the water level in the tank is reduced below the upper end of the standpipe, the flow from the standpipe almost stops and only the flow from the small inlet flows into the vortex chamber, forming a strong vortex. Therefore, the flow resistance is large and the injection flow rate becomes small.

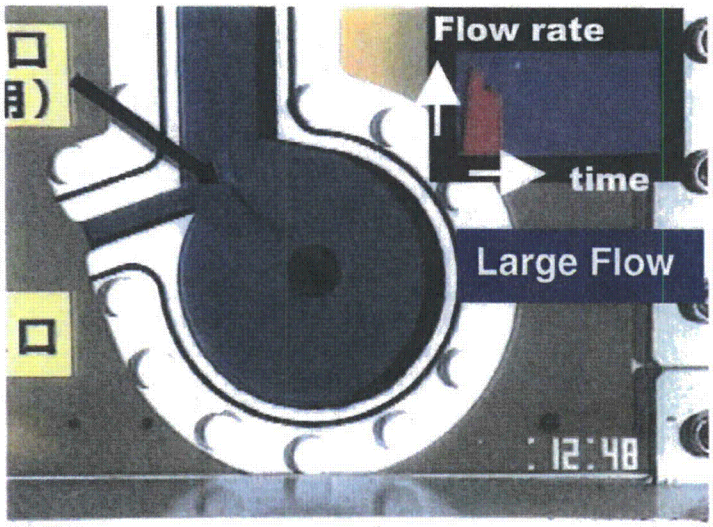
(3) When the water level is close to the flow switching level, it was confirmed that the anti-vortex cap on the standpipe prevents a vortex from being drawn into the standpipe. The lower end of the anti-vortex cap is almost at the same level as the upper end of the standpipe. If the water level in the tank is reduced below the lower end of the anti-vortex cap, the flow from the standpipe almost stops very quickly.

(4) During the flow switching, the water level in the standpipe is temporarily reduced by inertial force. However the water level recovers quickly and the flow in the standpipe almost stops and the water level in the standpipe is maintained. Therefore, gas does not enter into the vortex chamber from the standpipe.



- 3.37 seconds after initiation of the test

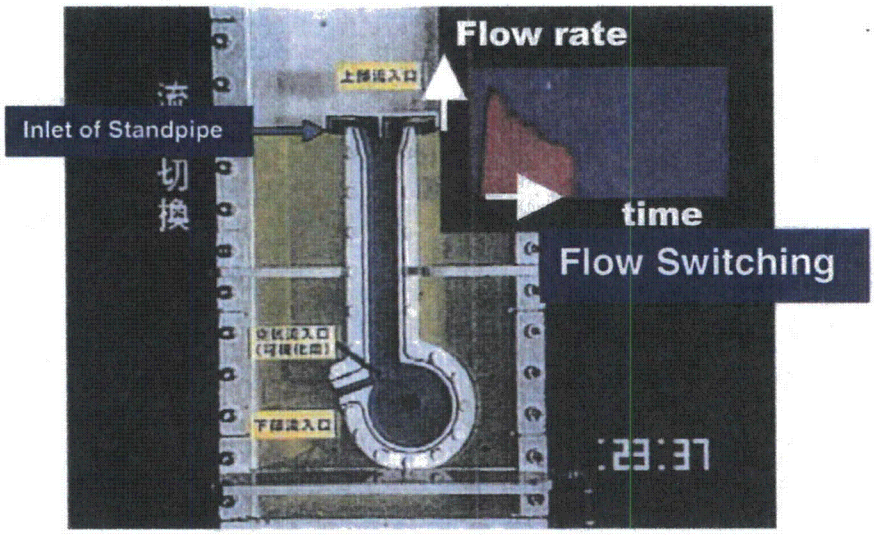
Photo. 4.2.1-2 Flow in the Standpipe and the Vortex Chamber during Large Flow



- 12.48 seconds after initiation of the test
- Air injection into the vortex chamber

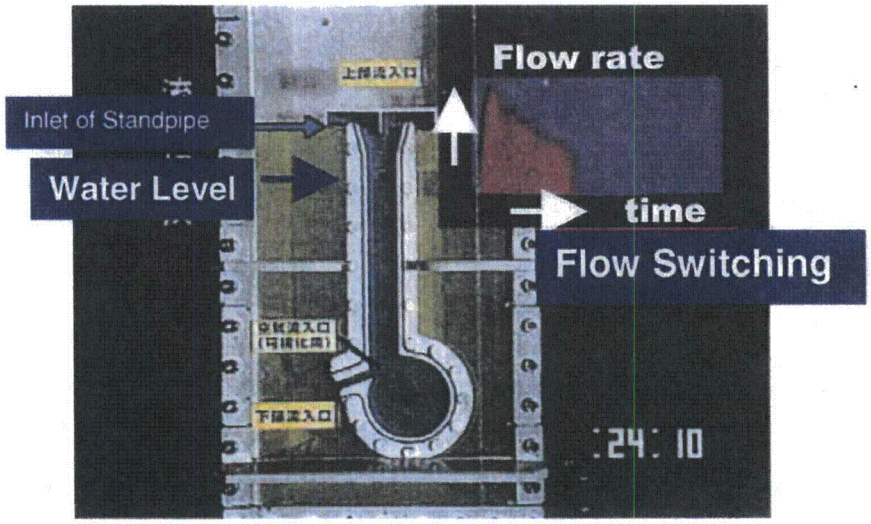
(This Photo. shows that the vortex is not formed in the vortex chamber.)

Photo. 4.2.1-3 Flow in the Vortex Chamber during Large Flow



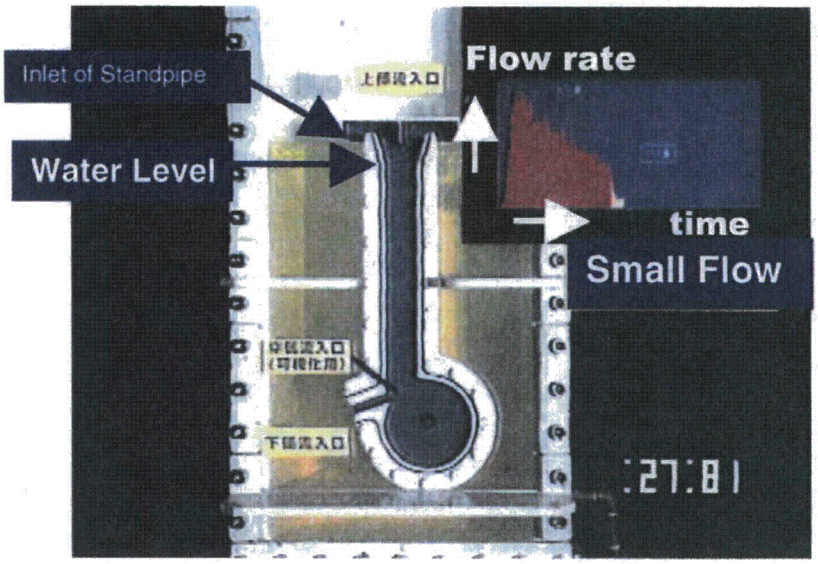
- 23.37 seconds after initiation of the test

Photo. 4.2.1-4 Flow Just before Large/Small Flow Switching



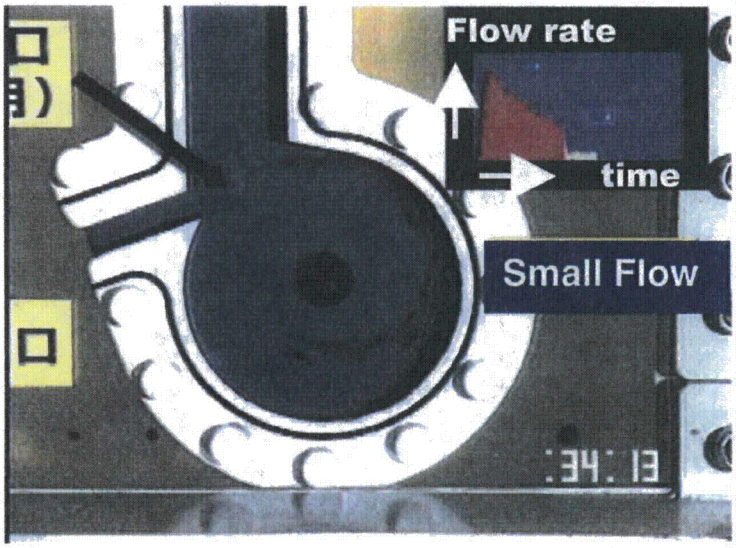
- 24.10 seconds after initiation of the test

Photo. 4.2.1-5 Flow Shortly after Large/Small Flow Switching



- 27.81 seconds after initiation of the test

Photo. 4.2.1-6 Flow during Small Flow



- 34.13 seconds after initiation of the test
- Air injection into the vortex chamber

(This Photo. shows that the vortex is formed in the vortex chamber.)

Photo. 4.2.1-7 Flow in the Vortex Chamber during Small Flow

4.2.2 1/3.5 Scale Test

1) Objectives

The ACC design uses an anti-vortex cap at the top of the standpipe to prevent the formation of a vortex as the flow drains from the tank such that the flow will only switch from a high flow to a lower flow when the level in the ACC tank drops below the top of the standpipe.

Without the anti-vortex cap, as the water level is reduced close to the upper end of the standpipe, it is possible for supercritical flow to form at the inlet of the standpipe and gas could be entrained, and the flow rate would not shift smoothly. The purpose of the experiments was to demonstrate that with the vortex cap design, a smooth flow switching behavior from the high flow to the lower flow as the tank level would decrease would occur.

The test was conducted to confirm the behavior of flow and potential for vortex formation in the ACC tank and confirming the effect of the anti-vortex cap.

2) Test apparatus

The outline drawing of the test facility is shown in Fig. 4.2.2-1. The test apparatus consists of the standpipe, test tank, pump and piping. The anti-vortex cap that is installed at the top of the standpipe was made of transparent acrylate such that the flow can be observed at the standpipe inlet. The scale of the standpipe inlet is 1/3.5 of the actual standpipe.

Fig. 4.2.2-1 Outline Drawing of 1/3.5 Scale Test Apparatus

3) Testing Method

(1) The experiment was scaled using the Froude Number as a basis since there was an open tank with a fluid surface. The relationship between the model tank (m) and the actual accumulator (p) is given below assuming the Froude Number is defined as

$$Fr = \frac{V}{(g \cdot L)^{0.5}} \tag{4-2}$$

And $$Fr_p = Fr_m \tag{4-3}$$

$$Q_p = \left(\frac{L_p}{L_m}\right)^{2.5} \cdot Q_m \tag{4-4}$$

$$V_p = \left(\frac{L_p}{L_m}\right)^{0.5} \cdot V_m \tag{4-5}$$

$$t_p = \left(\frac{L_p}{L_m}\right)^{0.5} \cdot t_m \tag{4-6}$$

where

Fr	:	Froude number
L	:	Typical dimension (standpipe's diameter)
Q	:	Typical flow rate
V	:	Typical velocity
t	:	Time
p	:	Subscript of the actual ACC tank
m	:	Subscript of the 1/3.5 scale model

(2) The flow rate was measured by ultrasonic flow meter, and the tank water level was measured by the level marking on the sidewall of the tank.

4) Test condition

The test conditions are shown in Table 4.2.2-1. Two types of standpipe inlet (with the anti-vortex cap and without it) were tested. The tests were performed using two flow rates in which the test and actual ACC Froude numbers were preserved. The flow rates were [ ]and[ ] that covers the flow rates at flow switching at minimum initial gas pressure and at maximum initial gas pressure, respectively. The injection characteristics with test flow rates are shown in Fig. 4.2.2-2 to 4.2.2-5.

Table 4.2.2-1 Test Condition

Test Number	Test Condition			Remarks	Corresponding Actual Condition	
	Anti-vortex Cap	Flow Characteristics	Flow Rate just before switching (gpm (l/sec))		Initial Gas Pressure (psig (MPa(g)))	Flow Rate just before switching (gpm (m^3/h))
1-1	No	Fig. 4.2.2-2	[ ]	Froude number is preserved.	[ ]	[ ]
1-2	Yes	Fig. 4.2.2-3				
2-1	No	Fig. 4.2.2-4			[ ]	
2-2	Yes	Fig. 4.2.2-5				

5) Parameters and measuring equipment

Flow rate and water level were measured to confirm the conditions during flow switching. The flow rate was measured by ultrasonic flow meter, and the tank water level was measured by the level marking on the sidewall of the tank.

6) Test results and consideration

Test results are listed in Table 4.2.2-2. The flow at the inlet for various conditions is shown in Photos. 4.2.2-1(1/2), (2/2) through 4.2.2-2(1/2), (2/2). The observations included.

(1) In the case of the standpipe inlet without the anti-vortex cap, when the water level is slightly decreased, a slight surface dimple appeared above the inlet and the initiation of supercritical flow developed. When the water level decreased further, the supercritical flow condition was apparent and the surface dimple reached into the standpipe, and gas entrainment occurred. (Photo. 4.2.2-1(1/2), (2/2))

(2) Below the water level where the supercritical flow condition becomes apparent, the critical depth became smaller consistent with the water level reduction. This resulted in lower flow rate and a slower reduction of the water level.

(3) The condition described in (2) above is apparent in the wave pattern. For example, in Fig. 4.2.2-2, supercritical flow was apparent and gas entrainment started at 26 seconds after initiation of the test, and the variation of the flow rate became bigger. As the flow rate became smaller, it took as long as 5 seconds until the flow rate into the standpipe became zero.

(4) This qualitative condition appeared in the case of both the minimum initial gas pressure of [ ] and the maximum initial gas pressure of [ ] [ ] without any significant differences.

(5) In the case of the standpipe inlet with the anti-vortex cap, a slight disturbance appeared on the water surface as the water level decreased from just above the upper end of the cap to the lower end of the cap. However, neither a vortex nor supercritical flow occurred, and the flow rate switched sharply in a short time. (Photos. 4.2.2-2(1/2), (2/2))
This condition is apparent in the wave pattern. For example, in Fig. 4.2.2-3, the flow rate into the standpipe became zero in approximately 1 second. The flow rate switched much

more quickly than the case without the anti-vortex cap (approximately 5 seconds, Fig.4.2.2-2).

(6) Based on the data and visual observation above, the desired effects of the anti-vortex cap were confirmed.

Table 4.2.2-2 List of Test Results

Test Number (T. No)	Test condition		Test Results		
	Flow Characteristics	Anti-vortex Cap	Vortex Formation	Finishing Transition time (sec)	Remark
1-1	Fig. 4.2.2-2	No	Yes	Approx. 5	Photo. 4.2.2-1(1/2), (2/2)
1-2	Fig. 4.2.2-3	Yes	No	Approx. 1	Photo. 4.2.2-2(1/2), (2/2)
2-1	Fig. 4.2.2-4	No	Yes	[ ]	-
2-2	Fig. 4.2.2-5	Yes	No	[ ]	-

Photo. 4.2.2-1 (1/2) Aspect of Flow without Anti-Vortex Cap (T. No. 1-1) 1/2

Photo. 4.2.2-1 (2/2) Aspect of Flow without Anti-Vortex Cap (T. No. 1-1) 2/2

Photo. 4.2.2-2 (1/2) Aspect of Flow with Anti-Vortex Cap (T. No. 1-2) 1/2

Photo 4.2.2-2(2/2) Aspect of Flow with Anti-Vortex Cap (T. No. 1-2) 2/2

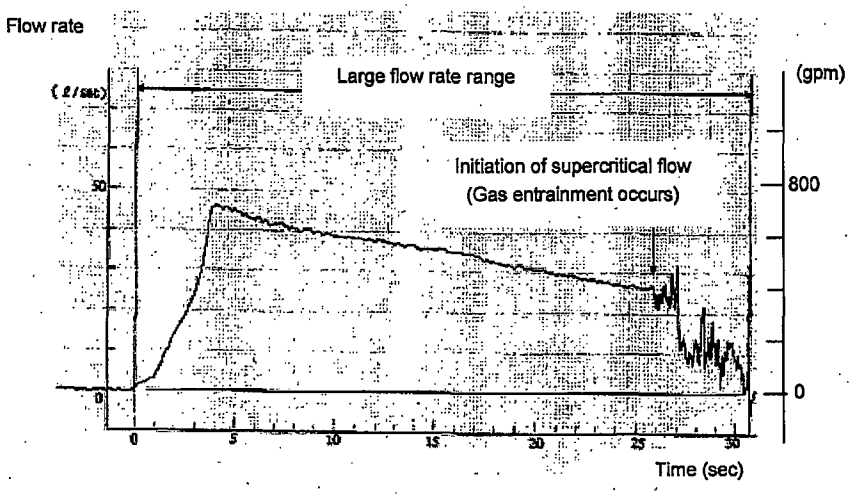


Fig 4.2.2-2 Test Flow Characteristics without Anti-Vortex Cap (T. No. 1-1)

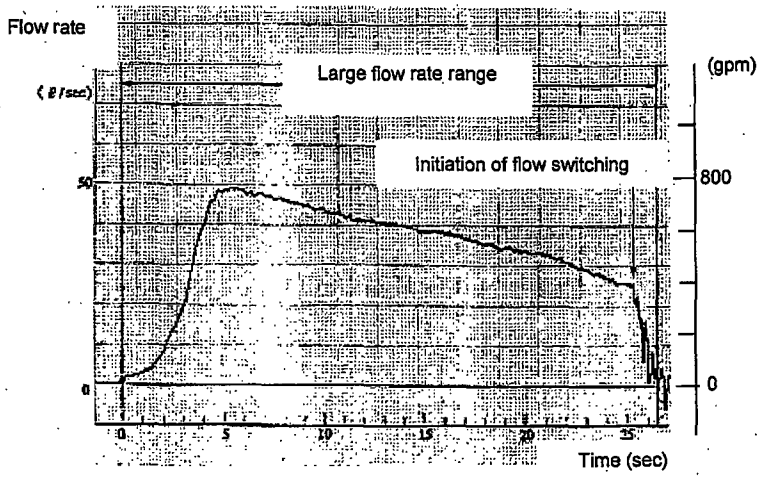


Fig 4.2.2-3 Test Flow Characteristics with Anti-Vortex Cap (T. No. 1-2)

Fig 4.2.2-4 Test Flow Characteristics without Anti-Vortex Cap (T. No. 2-1)

Fig 4.2.2-5 Test Flow Characteristics with Anti-Vortex Cap (T. No. 2-2)

4.2.3 1/5 Scale Test

1) Objectives

(1) Confirm the operational characteristics of the flow damper

Observation of the flow in the flow damper during large and small flow, large/small flow switching, and confirmation of the expected behavior of the flow

(2) Confirm the performance characteristics during large and small flow by measurement

The cavitation factor and flow rate coefficient during both flow conditions were measured, and confirm the flow characteristics are similar to the expected ACC performance. The flow characteristics obtained by the test were compared with the results of the full height 1/2 scale test later in this report and are used to confirm the validity of applying the scaling basis for these experiments.

2) Test apparatus

The outline drawings of the test apparatus is shown in Fig. 4.2.3-1. The test facility consists of a test tank, flow damper, standpipe, injection piping and exhaust tank. The flow damper made of transparent acrylate was installed outside of the test tank, thereby allowing fluid characteristics in the flow damper to be observed. A ball valve (nominal diameter is [ ] [ ] is provided on the injection line as the isolation valve and a gate valve (nominal diameter is [ ] is also provided on the injection line to control the flow resistance.

Fig. 4.2.3-1 Outline Drawing of the Visualization Test Apparatus

The specifications of the test facility are as follows:

(1) Test tank

Design Pressure : [ ]
Diameter :
Height :
Volume :

(2) Flow damper and standpipe (1/5 scale of the Actual size)

Diameter of vortex chamber : [ ]
Height of vortex chamber :
Shape of standpipe :

(3) Injection piping

Inner diameter : [ ]
(Simulating the pressure drop)

(4) Exhaust tank

Design Pressure : [ ]
Diameter :
Height :
Volume :

3) Testing method

(a) Visualization test method

(1) Visualization tests were conducted for three cases: (i) examining flow characteristics during large flow injection and flow switching, setting the initial pressure at [ ], which is the maximum design pressure of the test tank; (ii) examining flow characteristics during small flow injection, setting the initial pressure at [ ] for a long small flow injection time, and (iii) examining flow characteristics during flow switching, setting the initial pressure at [ ] which has the same Froude number as that of the actual plant condition.

(2) The flow characteristics in the flow damper were recorded and observed using a video camera, shown in Fig.4.2.3-1.

(3) The characteristics of the flow in the vortex chamber were observed using blue ink as a flow tracer.

(b) Low pressure injection testing method

(1) The test tank pressure, test tank water level, damper outlet pressure, and exhaust tank pressure were measured and input into a PC to calculate the flow rate coefficient and the cavitation factor.

(2) Flow rate coefficient and cavitation factor were obtained by the following equations:

Flow rate coefficient C_V

$$C_V = \frac{1}{\sqrt{K_D}} \tag{4-7}$$

$$K_D = \frac{(P_A + \rho g H) - (P_D + \rho V_D{}^2/2 + \rho g H')}{\rho V_D^2/2} \tag{4-8}$$

Cavitation factor σ_v

$$\sigma_v = \frac{P_D + P_{at} - P_v}{(P_A + \rho g H) - (P_D + \rho V_D^2/2 + \rho g H')} \tag{4-9}$$

Where

K_D	:	Resistance coefficient of flow damper
P_A	:	Test tank pressure [gage]
ρ	:	Density of water
g	:	Acceleration of gravity
H	:	Distance between test tank water level and vortex chamber
H'	:	Distance between outlet pipe and vortex chamber
P_{at}	:	Atmospheric pressure
P_v	:	Vapor pressure of water
P_D	:	Static pressure of flow damper outlet piping [gage] Note
V_D	:	Velocity in the flow damper outlet piping Note

Note: These parameters were the values converted to the scale of the actual ACC

(3) Data Processing

Data smoothing techniques were utilized to eliminate noises from data of the ACC water level, the ACC pressure and the flow damper outlet pressure data processing and is discussed.

The water level data as a function of time is shown here, and a polynomial equation is made by the least square method.

(a) Data of the ACC water level

The pressure data is shown as a function of time. a polynomial equation is made by the least square method.

(b) Data of the ACC pressure

The pressure data is shown as a function of time, and the polynomial equation is made by the least square method.

(c) Data of the Flow Damper outlet pressure

4) Test Conditions

Visualization Test Conditions

Visualization test conditions are shown in Table 4.2.3-1.

Low Pressure Injection Test Conditions

Low pressure test conditions are shown in Table 4.2.3-2.
The purpose of this test was to confirm the flow characteristics of the flow damper during large flow with wide variations of cavitation factors. The initial pressure conditions for the test tank and the exhaust tank were set at values that facilitated the testing.

Table 4.2.3-1 Visualization Test Conditions

Table 4.2.3-2 Low Pressure Injection Test Conditions

5) Parameters and Measuring Equipment

Pressure, water level and temperature were measured to calculate cavitation factors and flow rate coefficients. The differential pressure transducer measuring water level in tank and the attachments of pressure transducer are shown in Fig. 4.2.3-1.

6) Test Results and Consideration

a) The Visualization Test Results

The visualization test results are listed in Table 4.2.3-3 and the flow in the vortex chamber during large, large/small switching and small flow are shown in Photos. 4.2.3-1 to 4.2.3-3. The white lines are added in the photos to show the tracer trajectories clearly.

(1) The characteristic of the large flow is shown in Photo. 4.2.3-1. Since the flow tracer traveled from the point of the flow from the standpipe directly to the flow damper exit following collision with the water from the small flow inlet, it was confirmed that a vortex was not formed in the vortex chamber during large flow injection.

(2) The characteristic of the large/small flow switching is shown in Photo. 4.2.3-2. It shows transient status forming vortex under flow rate switching. It was also confirmed that gas entrainment from the standpipe did not occur and the flow rate switched smoothly in a short time.

(3) The characteristic of small flow is shown in Photo. 4.2.3-3. It was confirmed that the flow tracer swirled to the outlet, and a stable vortex was formed in the vortex chamber.

Table 4.2.3-3 Visualization Test Results

Test Number (T. No.)	Initial pressure [Test Tank]	Large flow	Flow rate switching	Small flow
1/5- 1-1		A vortex was not formed in the vortex chamber during large flow.	The flow rate switched smoothly in a short time.	-
1/5- 1-2		-	-	A stable vortex was formed in the vortex chamber.
1/5-1-3		-	The flow rate switched smoothly in a short time.	-

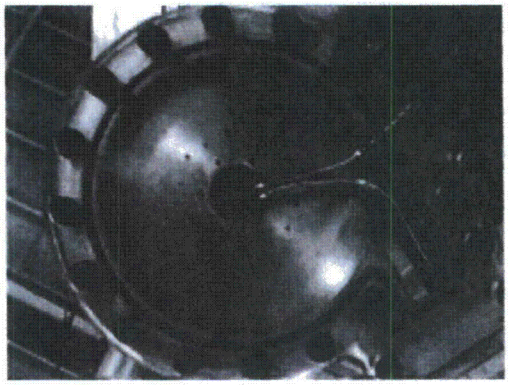


Photo. 4.2.3-1 Large Flow

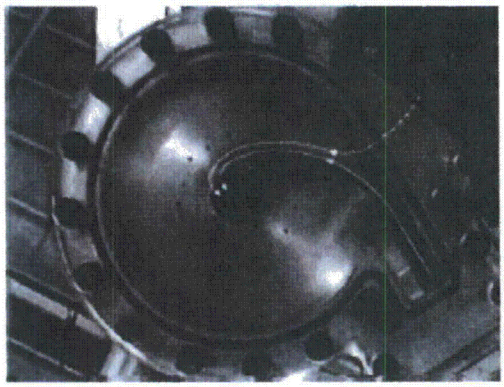


Photo. 4.2.3-2 Switching Flow Rate

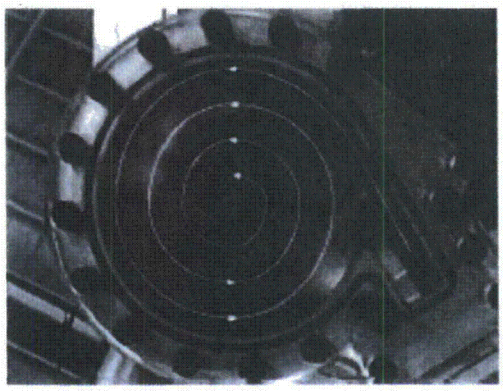


Photo. 4.2.3-3 Small Flow

b) Low Pressure Injection Test Results

This test was conducted at low pressure using a 1/5 scale model and the following results were obtained.

(1) The test tank pressure and water level and the outlet pressure of the flow damper as a function of time are shown in Figs. 4.2.3-2(1/2),(2/2) to 4.2.3-4(1/2),(2/2). It was confirmed that the test tank water level decreased steeply during large flow and decreased gently after the flow rate switching to small flow.

(2) The relation between the flow rate coefficient and cavitation factor in the flow damper is shown in Figs. 4.2.3-2 (2/2) to 4.2.3-4(2/2)[Note]. The behavior of large flow injection shows that the flow rate coefficient increased when the cavitation factor increased and became almost constant when the cavitation factor was greater than[ ].

Note: The data during almost steady condition were plotted.

(3) The relation between the flow rate coefficient and cavitation factor in the flow damper during small flow is also shown. It is shown that the flow rate coefficient during small flow was constant and independent of the cavitation factor.

Fig. 4.2.3-2 (1/2) Low Pressure Injection Test Results (T. No. 1/5-2-1) 1/2

Fig. 4.2.3-2 (2/2) Low Pressure Injection Test Results (T. No. 1/5-2-1) 2/2

Fig. 4.2.3-3(1/2) Low Pressure Injection Test Results (T. No. 1/5-2-2) 1/2

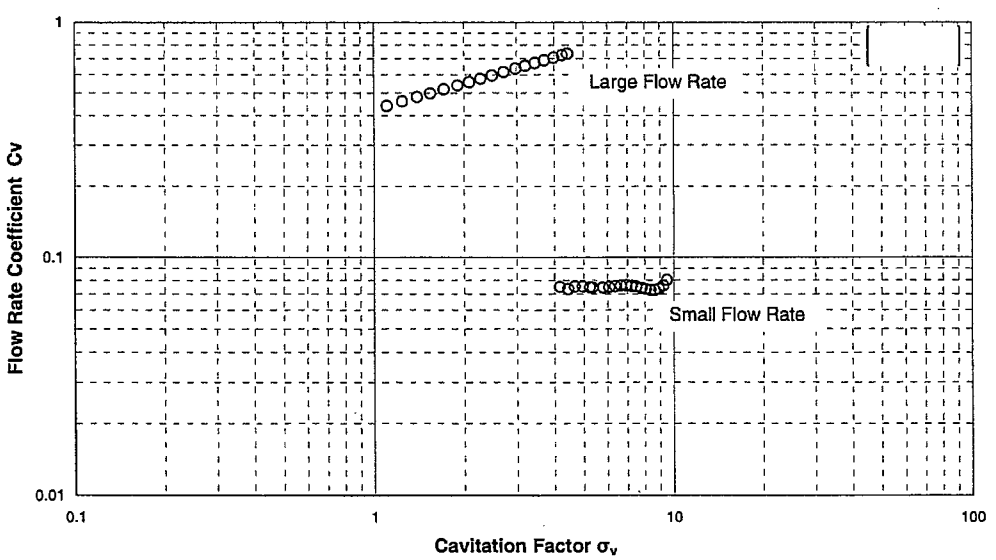


Fig. 4.2.3-3 (2/2) Low Pressure Injection Test Results (T. No. 1/5-2-2) 2/2

Fig. 4.2.3-4 (1/2) Low Pressure Injection Test Results (T. No. 1/5-2-3) 1/2

Fig. 4.2.3-4(2/2) Low Pressure Injection Test Results (T. No. 1/5-2-3) 2/2

4.2.4 Full Height 1/2 Scale Test

1) Objectives

(1) Obtainment of the flow characteristic data and confirmation of no gas entrainment
The test was conducted to obtain the flow characteristic data in the flow damper and to confirm that gas entrainment through the standpipe is prevented during flow switching and small flow injection.

(2) Confirmation that the flow characteristics can be characterized by dimensionless numbers (cavitation factor and flow rate coefficient)
Since a throat was added at the vortex chamber outlet to form strong vortex, it was assumed that cavitation might occur at the throat. The cavitation phenomenon is characterized by the cavitation factor which can be evaluated. It was confirmed by test that the flow rate coefficient is characterized by cavitation factor.

(3) Confirmation of the flow switching water level
The flow rate, as expected, switched from large flow to small flow when the water level decreased to the lower end of the standpipe cap. However, it is assumed that the water switching level may vary in the actual accumulator. Therefore, the actual switching water level was confirmed.

(4) Confirmation of the effect of dissolved nitrogen gas
Since the accumulator tank is pressurized by nitrogen gas, it is assumed that nitrogen gas dissolves into the water. If the water contains dissolved nitrogen gas, the dissolved gas may come out of solution during injection and affect the flow characteristics of the flow damper. Therefore, the test was conducted to evaluate the effect of dissolved gas on the injection flow.

2) Test Facility

The schematic and outline drawing of the test facility and the general flow path are shown in Fig. 4.2.4-1 and Fig. 4.2.4-2. The test facility consists of a test tank, flow damper, injection piping and exhaust tank. The flow damper is installed in the test tank. The height of the test tank and the standpipe is the full scale height and the inner diameter of the test tank is 1/2 scale (Fig. 4.2.4-3 and Fig. 4.2.4-4). Therefore, the water volume is 1/4 scale and the flow rate is also 1/4 scale. The test was conducted simulating the actual time. In addition, the water level transient during flow switching in the standpipe can be observed to represent the level transient in the actual standpipe. A ball valve is provided on the injection line as the isolation valve and a gate valve is provided on the injection line to control flow resistance. A pressure control valve is provided on the upper side of the test tank to control the tank pressure during the test.

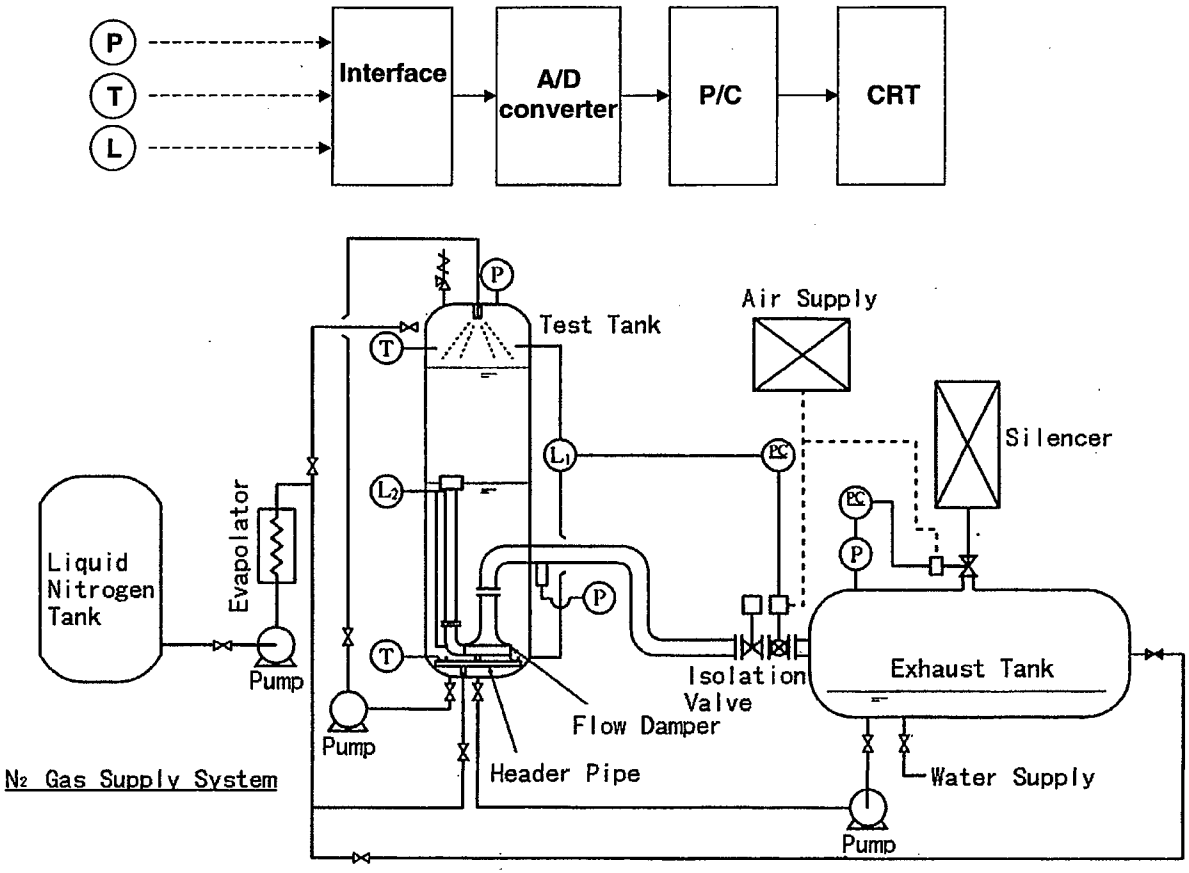


Fig. 4.2.4-1 Schematic Drawing of the Full Height 1/2 Scale Test Facility

Fig. 4.2.4-2 Outline Drawing of the Full Height 1/2 Scale Test Facility

Fig. 4.2.4-3 Schematic Comparison of Actual Tank and Test Tank

Fig. 4.2.4-4 Outline Drawings of the Actual Flow Damper and the Test Flow Damper

3) Test Conditions

Full height 1/2 scale test conditions are shown in Table 4.2.4-1. The following seven cases were tested on initial tank pressure that reflects the ACC operating conditions. And the pressure of the exhaust tank corresponds to RCS pressure.

- Case 1: The initial test tank pressure was 586psig (4.04MPa [gage]) simulating the condition for ECCS performance during a large LOCA.
- Case 2: The initial test tank pressure was 657psig (4.53MPa [gage]) to obtain data for high pressure design.
- Case 3: The initial tank pressure was 758psig (5.23MPa [gage]) to obtain data for high pressure design.
- The pressure in the exhaust tank was 14psig (0.098MPa [gage]) for Case 1, 2, and 3. Since the pressure of the exhaust tank becomes the same as the pressure of the containment vessel (C/V) after the blow down phase during a large LOCA, and ECCS performance analysis uses approximately 14psig(0.098MPa [gage]), the pressure of the backpressure was set at 14psig (0.098MPa [gage]).
- Case 4: The initial tank pressure was the same as Case 1. However, the pressure in the exhaust tank was maintained at 71psig (0.49MPa [gage]) to obtain data for high back pressure.
- Case 5: The test was conducted with water containing dissolved nitrogen to confirm the effect of dissolved nitrogen gas on flow characteristics.
- Case 6: The test was conducted with a small differential pressure between the test tank and the exhaust tank to take into account large cavitation factors.
- Case 7: The injection test was conducted with the initial tank pressure was[ ] [ ]assuming the pre-operational test condition.
- The valve opening speed was set at[ ]seconds which is faster than the depressurization time during a LOCA in order to assure smaller cavitation factors.
- The resistance coefficient of the piping was controlled at the actual design condition[ ] in order to confirm the injection time during the large flow injection period.

Table 4.2.4-1 Test Conditions of Full Height 1/2 Scale Test

	Test Tank Pressure	Exhaust Tank Pressure	Initial Gas Volume	Injection Water Volume		Objective
				Large Flow	Small Flow	
	psig [MPa [gage]]	psig [MPa [gage]]	ft^3 [m^3]	ft^3 [m^3]	ft^3 [m^3]	
Case 1	586 (4.04)	14 (0.098)				Obtain flow characteristics for ECCS performance evaluation during a large LOCA
Case 2	657 (4.53)	14 (0.098)				Obtain flow characteristics for high pressure design
Case 3	758 (5.23)	14 (0.098)				Obtain flow characteristics for large differential pressure
Case 4	586 (4.04)	71 (0.49)				Obtain flow characteristics for small differential pressure
Case 5						Obtain flow characteristics to confirm the effect of dissolved nitrogen gas
Case 6						Obtain flow characteristics in large cavitation factors
Case 7						Obtain flow characteristics for the assumed pre-operational test condition

4) Parameters and Measuring Equipment

Pressure, water level, and temperature were measured by the instruments shown in Fig.4.2.4-1 for all test cases and used to calculate the cavitation factor and the flow rate coefficient.

5) Test Results and Conditions

The test results are shown in Figs. 4.2.4-5 to 4.2.4-11. The test results, such as injection flow rate, test tank pressure, test tank water level and the flow rate coefficients [Note] during both large and small flow for each test case, are shown in these figures. The conclusions for each test are shown as follows.

Note: Where possible steady conditions were plotted.

[Case 1]

- It was confirmed that the injection flow rate was switched from large flow to small flow smoothly, and small injection began after large flow injection.[Refer to Fig.4.2.4-5(1/2)]
- It was confirmed that the test tank pressure dropped quickly after initiating the test and dropped gradually, after the flow rate switching at about approximately 114psig (0.8MPa [gage]). [Refer to Fig.4.2.4-5(2/2)]
- It was confirmed that when the test tank water level was reduced to the flow switching level, the standpipe water level temporarily dropped to its low point level in about 1.7 seconds and then recovered and continued to drop gradually during the small flow injection period. [Refer to Fig.4.2.4-5(1/2)]
- It was confirmed that the standpipe water level did not decrease to the top of the flow damper during flow switching. [Refer to Fig.4.2.4-5(1/2)]

[Case 2]

- Although the initial test tank pressure was 71psi (0.49MPa) higher than in Case 1, it was confirmed that the injection flow rate, test tank pressure and water level as a function of time were the same as in Case 1. [Refer to Fig.4.2.4-6(1/2), (2/2)]
- Since the initial test tank pressure was 71psi (0.49MPa) higher than in Case 1, the range of the cavitation factor during large flow shifted slightly to lower side. However, the flow rate coefficient was the same as in Case 1 in the region where the cavitation factor was the same as in Case 1. Therefore, it was confirmed that the characteristics of the flow rate coefficient and the cavitation factor are the same even if the tank pressure was increased 71psi (0.49MPa). [Refer to Fig.4.2.4-6(2/2)]
- It was confirmed that the characteristics of the flow rate coefficient and the cavitation factor during small flow were the same as in Case 1. [Refer to Fig.4.2.4-6 (2/2)]

[Case 3]

- Although the initial test tank pressure was 172psi (1.19MPa) higher than in Case 1, it was confirmed that the injection flow rate, test tank pressure and water level as a function of time were the same as in Case 1. [Refer to Fig.4.2.4-7(1/2), (2/2)]
- The flow rate coefficient was the same as in Case 1 in the performance range where the cavitation factor was the same as in Case 1. Therefore, it was confirmed that the characteristics of the flow rate coefficient and the cavitation factor are the same even if the tank pressure is increased by 172psi (1.19MPa). [Refer to Fig.4.2.4-7(2/2)]

- It was confirmed that the characteristics of the flow rate coefficient and the cavitation factor during small flow were the same as in Case 1. [Refer to Fig.4.2.4-7(2/2)]

[Case 4]

- Although the pressure of the exhaust tank was 71psig (0.49MPa [gage]) as opposed to 14psig (0.098MPa [gage]) in Case 1, it was confirmed that the injection flow rate, test tank pressure, and water level as a function of time were the same as in Case 1. [Refer to Fig.4.2.4-8(1/2), (2/2)]
- The flow characteristics data was obtained over a larger range of cavitation factors than Case 1 because of higher backpressure tank pressure. [Refer to Fig.4.2.4-8(2/2)]

[Case 5]

- For this case, Nitrogen gas was dissolved into the water. It was confirmed that the flow rate coefficient during large flow was smaller than that of the case where nitrogen was not dissolved. [Refer to Fig.4.2.4-9 (2/2)]
- It was confirmed that the flow rate coefficient during small flow was essentially the same as in Case 1 and no change was caused by the dissolved nitrogen gas. [Refer to Fig.4.2.4-9(2/2)]

[Case 6]

- It was confirmed that the injection flow rate was switched from large flow to small flow smoothly, and small injection began after large flow injection. [Refer to Fig.4.2.4-10(1/2)]
- The flow characteristics data was obtained for a larger range of cavitation factors than in Case 1 since the initial test tank pressure was reduced. [Refer to Fig.4.2.4-10(2/2)]

[Case 7]

- Although Case 7 was a low-pressure injection test, it was confirmed that the test tank pressure and water level were reduced rapidly during large flow and that the flow rate switching to small flow reduced gradually, as in Case 1. [Refer to Fig.4.2.4-11(1/2)]
- It was confirmed that the flow characteristics of the flow damper during both large and small flow were consistent with those in other cases. [Refer to Fig.4.2.4-11 (2/2)]

Performance Confirmation during Large Flow

In the case that simulates LOCA conditions, the resistance coefficient during large flow injection is less than[ ]. These results are generally consistent with the performance requirements.

Performance Confirmation during Small Flow

Measurements from the test results of Case 1 show that the flow rate before and after the flow switching was approximately 3170gpm (approximately 720m3/h) and approximately 652gpm (approximately 148m3/h), respectively. Therefore, the flow-switching ratio (3170/652=4.9) was less than[ ] and was consistent with the performance requirements.

Flow Switching Water Level

The measured flow-switching water level in each test case is shown in Table 4.2.4-2. The expected flow-switching water level was set at the lower end of the anti-vortex cap installed at the inlet of the standpipe. The actual flow-switching water levels were within the range from[ ]to[ ]of the expected flow switching water level.

Based on above test results, it was confirmed that the variation of flow-switching water level was limited to a sufficiently small range by the anti-vortex cap at the inlet of the standpipe.

Table 4.2.4-2 Flow Switching Water Level

	Initial tank pressure [psig (MPa [gage])]	Exhaust tank pressure [psig (MPa [gage])]	Flow switching water level [in (mm)][Note]
Case 1	586 (4.04)	14 (0.098)	
Case 2	657 (4.53)	14 (0.098)	
Case 3	758 (5.23)	14 (0.098)	
Case 4	586 (4.04)	71 (0.49)	
Case 5			
Case 6			
Case 7			

Note: Reference point is bottom of anti-vortex cap. The upper is '+', and the lower is '-'.

Water Level Reduction in Switching Flow Rate

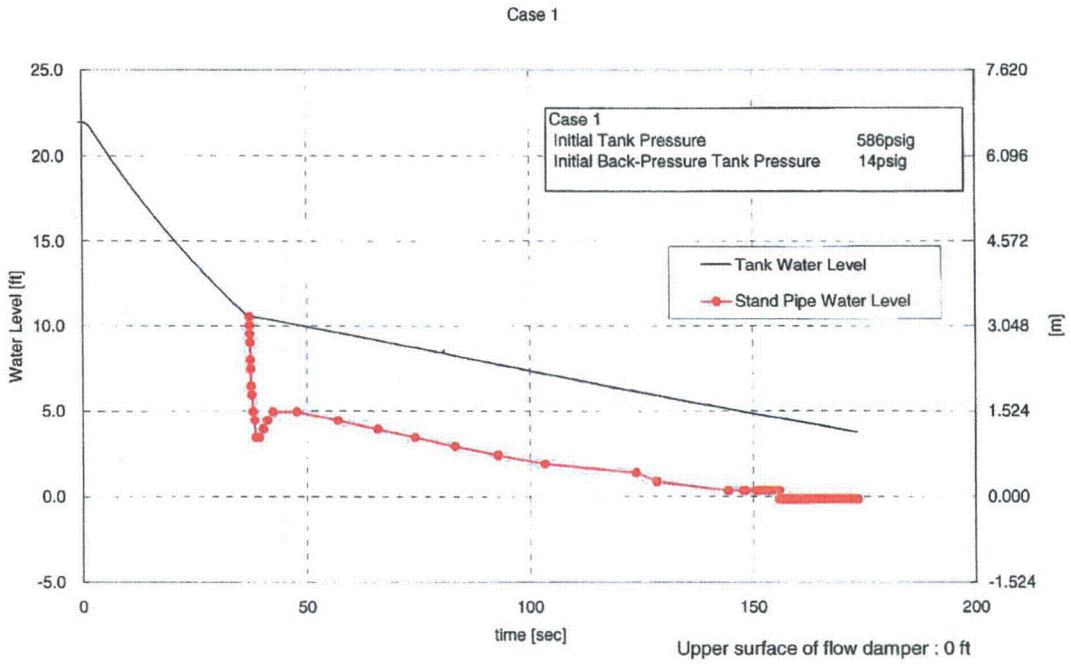
It was confirmed that the reduction of the water level in each test during flow switching was smaller than the height of the standpipe and sufficient margin was provided to prevent gas entrainment. [Refer to Fig. 4.2.4-12]

Effect of Dissolved Nitrogen Gas

It was confirmed that, in the test with nitrogen saturated water (Case 5), the duration of large flow injection was slightly longer (approximately[ ]) than in Case 1. Since Case 5 was conducted with nitrogen-saturated water, and this condition was not applicable in the actual accumulator tank, it is assumed that dissolved nitrogen is less effective in the actual tank. [Refer to Fig.4.2.4-9(2/2)]

Result of the Test Assuming Pre-operational Test Condition

The comparison between the characteristics of cavitation factor vs. flow rate coefficient measured in a LOCA simulation test (Case 1) and in this test is shown in Fig. 4.2.4-11. This comparison shows that the cavitation factor over a wide range can be obtained from this test and beyond the results of LOCA simulation test (Case 1). [Refer to Fig.4.2.4-11(2/2)]



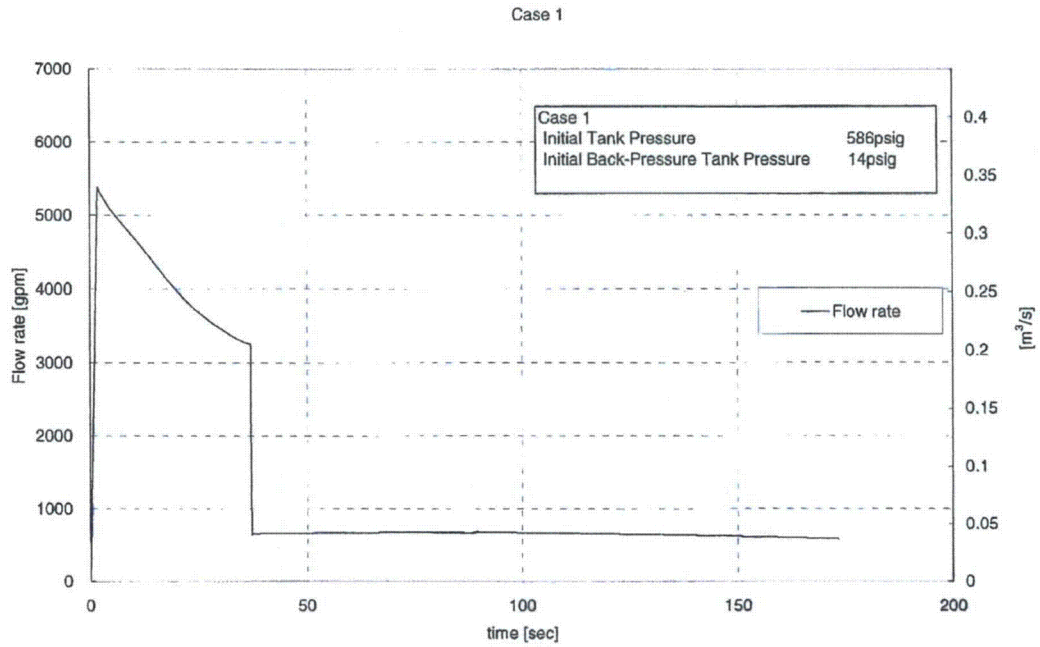
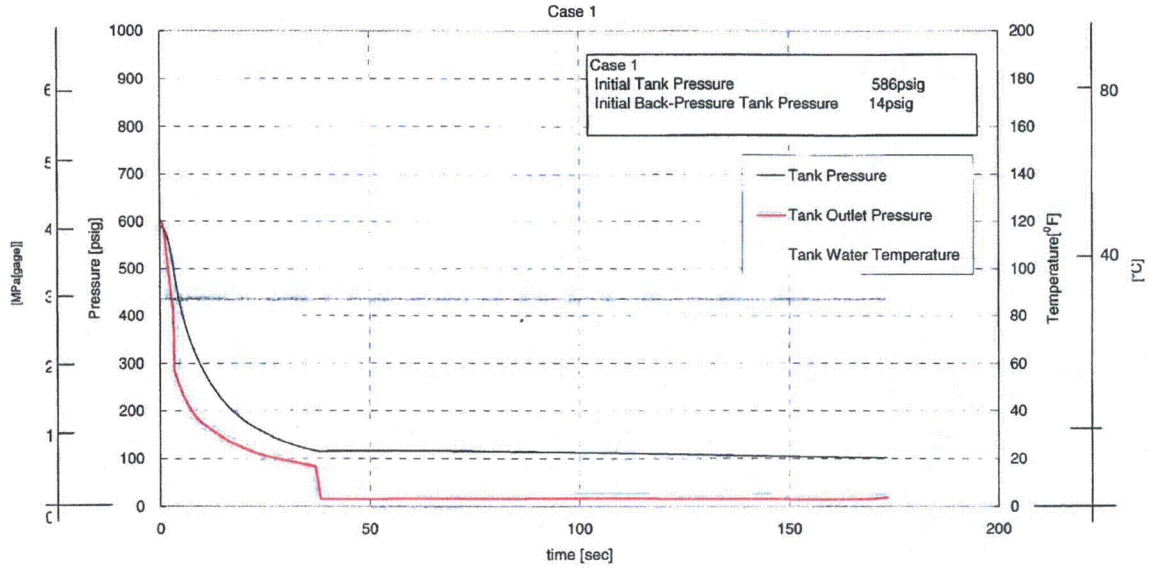


Fig. 4.2.4-5 (1/2) Full Height 1/2 Scale Test Results (Case 1) 1/2



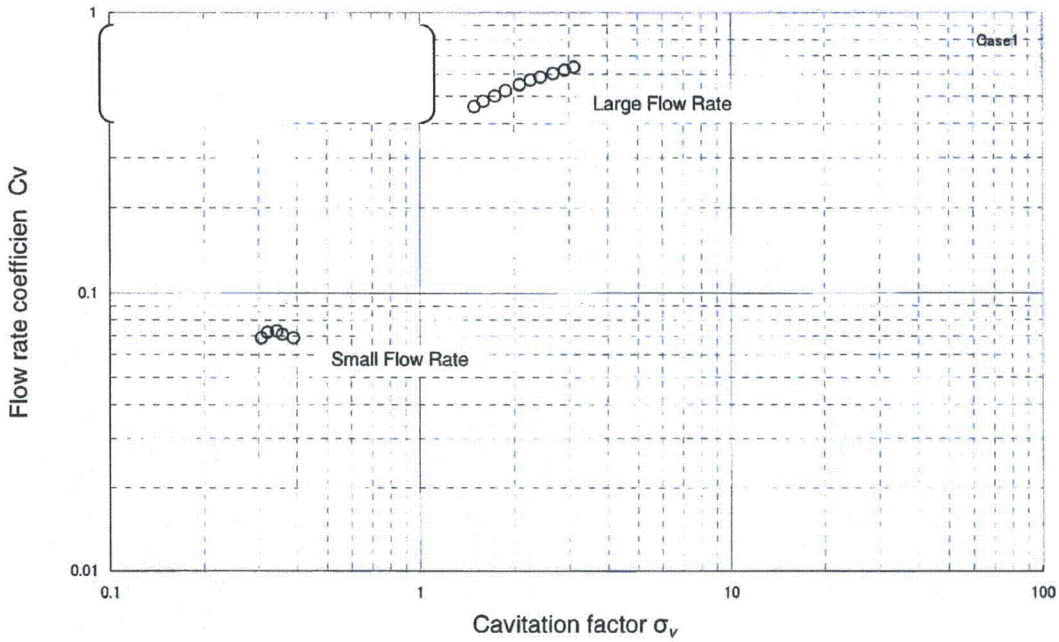


Fig. 4.2.4-5 (2/2) Full Height 1/2 Scale Test Results (Case 1) 2/2

Fig. 4.2.4-6 (1/2) Full Height 1/2 Scale Test Results (Case 2) 1/2

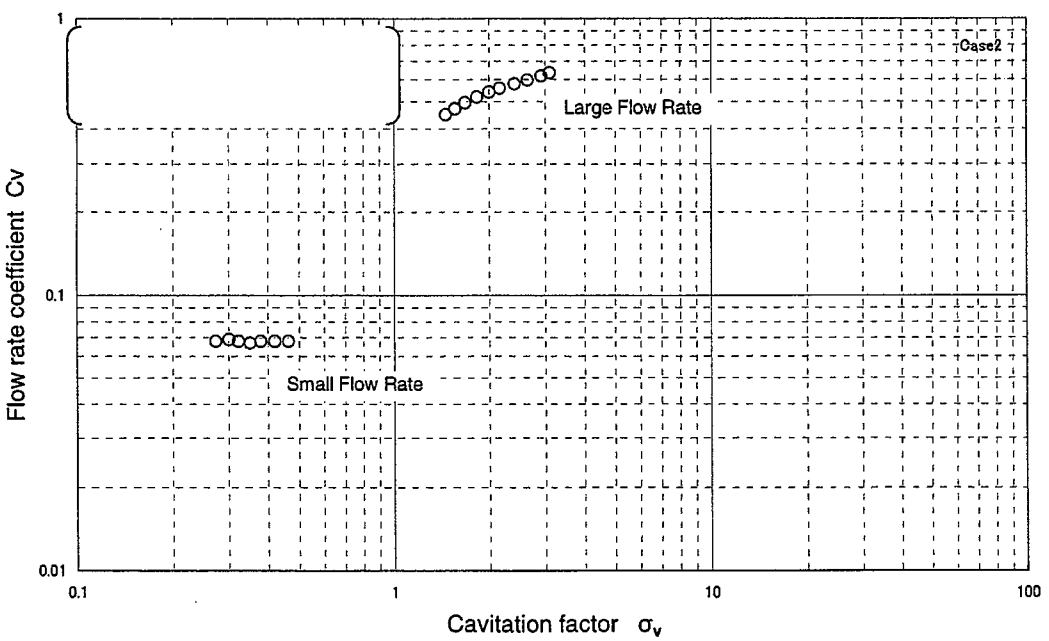


Fig. 4.2.4-6 (2/2) Full Height 1/2 Scale Test Results (Case 2) 2/2

Fig. 4.2.4-7 (1/2) Full Height 1/2 Scale Test Results (Case 3) 1/2

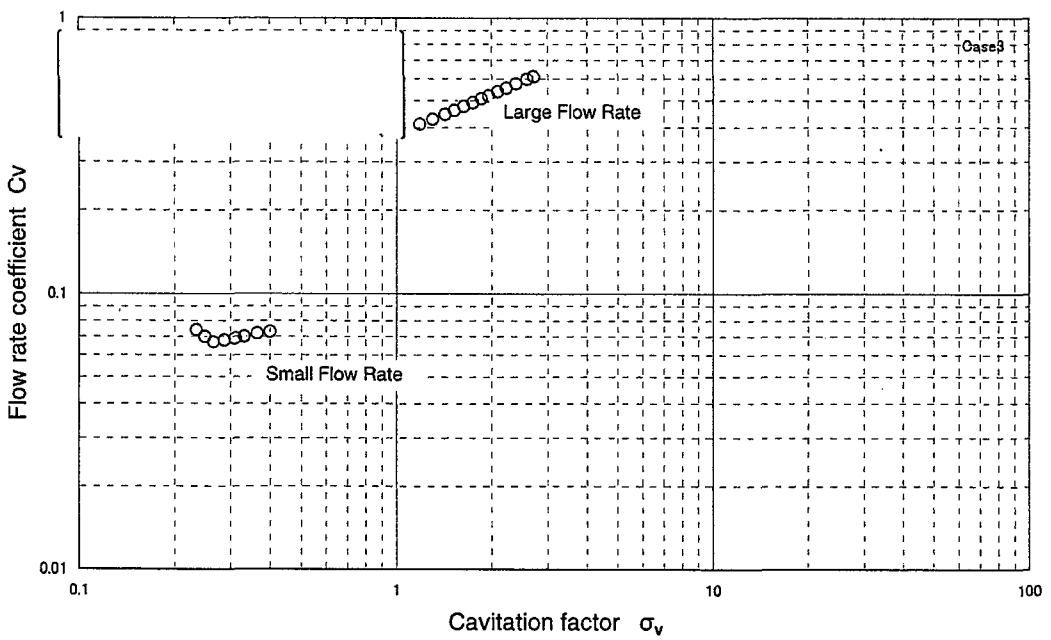


Fig. 4.2.4-7(2/2) Full Height 1/2 Scale Test Results (Case 3) 2/2

Fig. 4.2.4-8 (1/2) Full Height 1/2 Scale Test Results (Case 4) 1/2

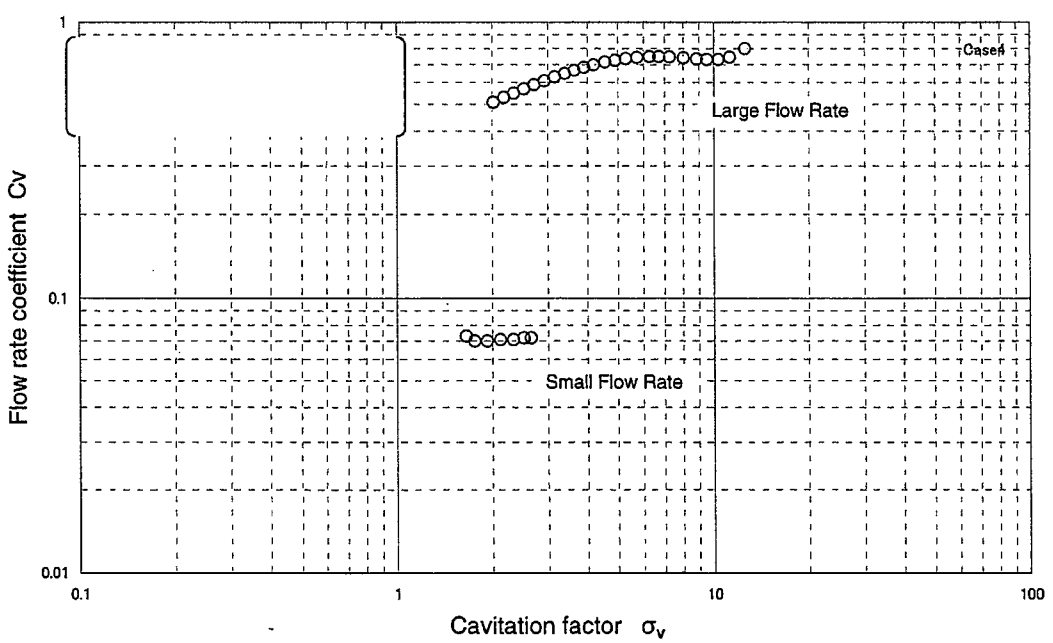


Fig. 4.2.4-8 (2/2) Full Height 1/2 Scale Test Results (Case 4) 2/2

Fig. 4.2.4-9 (1/2) Full Height 1/2 Scale Test Results (Case 5) 1/2

Fig. 4.2.4-9 (2/2) Full Height 1/2 Scale Test Results (Case 5) 2/2

Fig. 4.2.4-10 (1/2) Full Height 1/2 Scale Test Results (Case 6) 1/2

Fig. 4.2.4-10 (2/2) Full Height 1/2 Scale Test Results (Case 6) 2/2

Fig. 4.2.4-11(1/2) Full Height 1/2 Scale Test Results (Case 7) 1/2

Fig. 4.2.4-11(2/2) Full Height 1/2 Scale Test Results (Case 7) 2/2

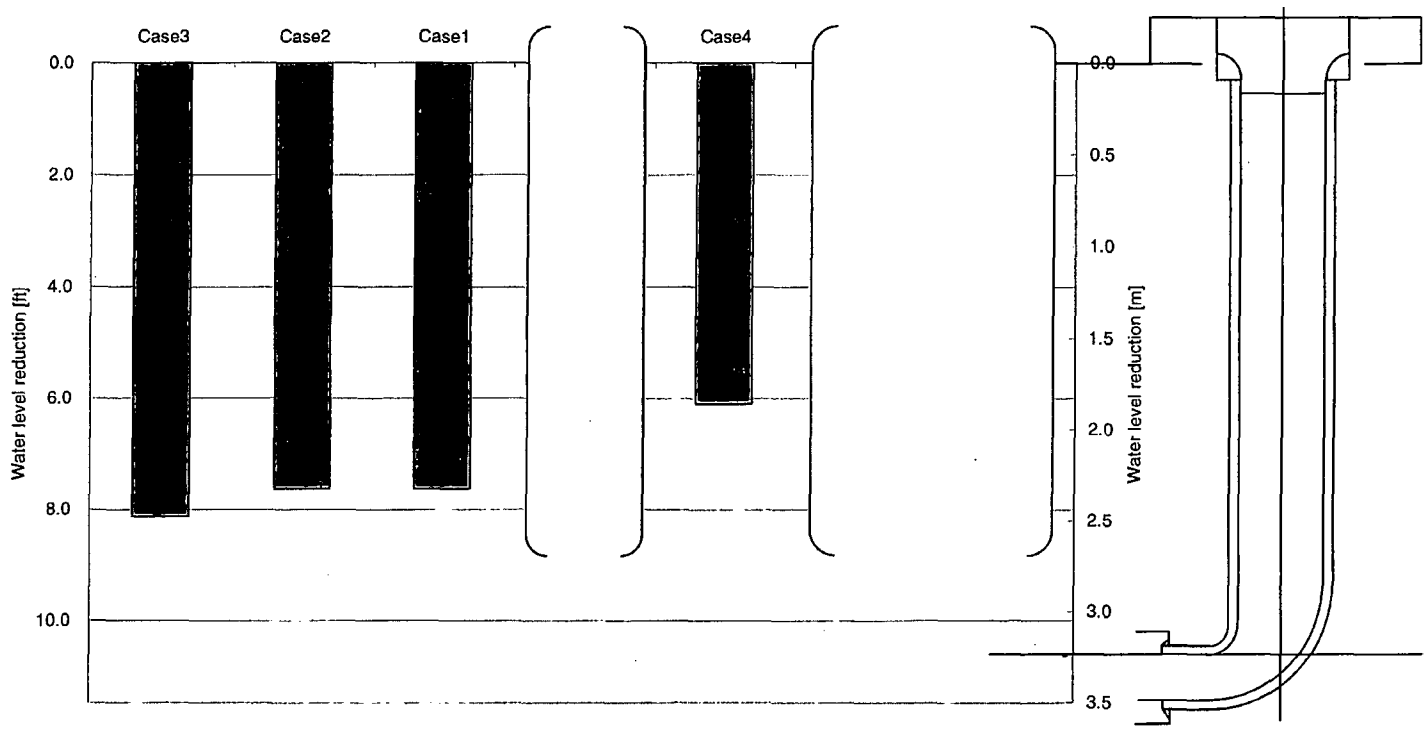


Fig. 4.2.4-12 The Test Results of Water Level Reduction in Switching Flow Rate

4.3 Validity and Scalability of Flow Rate Characteristics

The governing equations of flow in the flow damper are the equation of continuity and the Navier-Stokes equation for incompressible flow. The dimensionless forms of these equations and the boundary conditions of the flow damper give two dimensionless numbers: a Reynolds number for internal flow and a Froude number for a free surface. Therefore, a Reynolds number will affect the resistance of the internal flow in the flow damper without cavitation, while a Froude number will affect the behavior of the free surfaces in the accumulator tank and the standpipe.

Since cavitation bubbles may reduce the flow rate, a cavitation factor is another parameter that affects the flow resistance of the flow damper in addition to the Reynolds number. Generally speaking, friction coefficients come to a constant as the Reynolds number gets larger. If the effect of friction can be neglected at a large Reynolds number, cavitation factor will be the only parameter of the flow rate coefficient.

Table 4.3-1 shows the Reynolds numbers for the 1/5-scale model, the full height 1/2-scale model and the actual plant. This table shows that each the Reynolds number is generally large enough that the effect of friction can be neglected.

Fig.4.3-1 shows the flow rate coefficient with respect to cavitation factors obtained by the 1/5-scale and full height 1/2-scale models of the flow damper. There are two lines: one for the large flow rate injection and the other for the small flow rate injection. The data for both 1/5-scale and full height 1/2-scale models collapsed into the same lines for large and small flow rates from which in fact.

Consequently, the flow rate characteristics with respect to cavitation factor shown in Fig. 4.3-1 are the flow characteristics applicable to the actual ACC.

Table 4.3-1 Comparison with Reynolds number

	Reynolds Number
Actual Plant	
Full height 1/2-scale model	
1/5-scale model	

Note: Reynolds numbers are calculated with respect to the throat.

Fig. 4.3-1 Flow Rate Coefficient with Respect to Cavitation Factor of the Flow Damper for Full Height 1/2 Scale and 1/5 Scale Models

The trend that the flow rate coefficient lessens as the cavitation factor gets smaller for the large flow rate injection is reasonable, because cavitation is stronger for a smaller cavitation factor. And the flow rate coefficient approaches a constant value as the cavitation factor gets larger, because cavitation is reduced and vanishes for larger cavitation factors.

Since there is no cavitation at the throat for the small flow rate injection, the flow rate coefficient for small flow should be independent of a cavitation parameter as shown in Fig. 4.3-1.

In case of the full height 1/2 scale model, the accumulator tank with the same height and the same nitrogen-gas pressure as those of the actual ACC gives the same Froude number as that of the actual ACC for a given backpressure, or RCS pressure. It simulates the same transients of injection velocity, water level in the standpipe, and pressures in the test apparatus as those of the actual ACC. We can thus confirm the injection of cooling water at the actual conditions with that of the full height 1/2 scale model.

The performance of the actual accumulator will be confirmed in a pre-operational test.

4.4 Quality Assurance of the ACC Test Program

1) General

The results of the ACC test program, performed from June 1994 to August 1996, are applicable to the US-APWR. These results were reviewed and MHI confirmed that the requirements of the Japanese QA Guideline and QA activities at that time met the requirements of 10 CFR 50 Appendix B and ASME NQA-1-1994, by comparing the requirements of the Japanese QA Guideline to those of 10 CFR 50 Appendix B and ASME NQA-1-1994.

2) Procedure of Re-verification

The ACC test program was re-verified and confirmed to be reliable and accurate for use in the US-APWR. This re-verification was performed by evaluating the following items in accordance with a written procedure.

(1) Confirmation of Test Procedure
(2) Evaluation of Test Personnel
(3) Evaluation of Test Equipment
(4) Evaluation of Test Procedure (execution)
(5) Evaluation of test results
(6) Evaluation of design Personnel Concerning to the Test

3) Results

It was confirmed that the reliability and accuracy for the ACC test program satisfied the requirements of 10 CFR 50 Appendix B and ASME NQA-1-1994.

The following sets out the re-verification results of the above six items.

(1) Confirmation of Test Procedure

The ACC test program can be applied to the US-APWR by comparing the test conditions as follows:

- MHI established test conditions for the ACC of the US-APWR consistent with the design requirements for the ACC of the US-APWR.
- MHI compared the previous APWR test conditions with the test conditions established for the US-APWR and confirmed that the previous test conditions are applicable to the US-APWR.
- The test conditions that were compared and confirmed were the following prerequisite conditions for the test:
- Prerequisites: - Adverse conditions (considering operating modes and environments)
  - Configuration
  - Test scope addressed applicable design features

(2) Evaluation of Test Personnel

It was confirmed that the test personnel who had conducted the previous tests satisfied the current necessary qualifications as follows:

- MHI reviewed the qualifications of the test personnel who had conducted the previous tests against current qualification requirements (NQA-1-1994 2S-1).
- MHI established records documenting this re-verification of the qualifications of the testing personnel.

(3) Evaluation of Test Equipment

It was confirmed that the condition and the accuracy of the test equipment and measurements used during the testing met current requirements taking into account the test objectives for the US-APWR. The results of this validation were as follows:

- MHI documented the test objectives and test results required for the US-APWR based on the design conditions for the ACC of the APWR.
- Based on this document, MHI established the requirements for the accuracy of test equipment and measurements for the US-APWR.
- MHI determined that the accuracy of the test equipment and measurements used in the ACC test program at that time satisfied the requirements for the US-APWR.

(4) Evaluation of Test Procedure (execution)

It was confirmed that the test procedure used for conducting the ACC tests at that time meets the current requirements as follows:

- MHI documented the design requirements for the US-APWR (i.e., items that must be verified in the test) based on the design conditions for the ACC as used in the US-APWR.
- MHI confirmed that the test procedure used at that time the tests were conducted meets the present requirements and are appropriate by comparing the items that were to be verified by those tests with the above identified design requirements for the US-APWR to be verified by test.

(5) Evaluation of Test Results

Test results were evaluated by the responsible design organization and it was confirmed that the test results obtained could be applied to the US-APWR.

- MHI documented this evaluation of the applicability of the past test results to the US-APWR.

(6) Evaluation of Design Personnel Concerning to the Test

Design personnel responsible for the test at that time had participated in the test process from the commencement of test preparations (e.g. test plan, test procedure, test equipments) to the completion of the tests and had both witnessed and evaluated the test results. MHI also confirmed that design test program was independently reviewed by experienced engineers and the tests were witnessed by representatives of the funding the design personnel of utilities and MHI. Therefore, the test at that time was objective. MHI confirmed that the design personnel had participated in the design of the test plan, test procedure, and test equipment and also in the evaluation of test results from evidence such as meeting minutes, trip reports and document review reports etc.

- MHI confirmed based on meeting minutes, trip reports, etc. that meetings concerning the test plan, test procedure, and test equipment had been held with the utilities and that the designs had been reviewed by the utilities and their comments had been incorporated.
- MHI confirmed that the design personnel of utilities and MHI had witnessed the actual test.
- MHI confirmed that the design review (e.g. Design Review Board) for the overall review of the test, including the test plan, test procedure, test equipment, and test results, was conducted by independent experienced engineers.

5.0 CONCEPT OF THE SAFETY ANALYSIS MODEL

5.1 Characteristic Equations of Flow Rates for the Safety Analysis

The flow rate coefficient is a function of the cavitation factor as shown in Fig.5.1-1. Experimental formulae of the flow rate characteristics of the flow damper were derived with respect to a cavitation factor separately for the large and small flow rate injections each by curve fitting using the data of the full height 1/2-scale tests. The curve fitting is based on the least-squares method. An exponential function was chosen as the form of the fitting curves to give the best fitting of the data. The resultant experimental equations are:

$$C_v = 0.7787 - 0.6889\,exp(-0.5238\sigma_v) \quad \text{For Large Flow Rate Injection,} \qquad (5\text{-}1)$$

and

$$C_v = 0.07197 - 0.01904\,exp(-6.818\sigma_v) \quad \text{For Small Flow Rate Injection} \qquad (5\text{-}2)$$

The flow resistance coefficient of the flow damper (K_D) is given by

$$K_D = \frac{1}{C_v^{\,2}} \qquad (5\text{-}3)$$

Fig. 5.1-1 The Flow Characteristics of the Flow Damper

5.2 Estimation of Uncertainty of the Characteristic Equations of Flow Rates

The data from the full-height, full pressure, 1/2 diameter experiment was used to develop the characteristic equations for the ACC performance. Errors of measured values consist of experimental errors, instrument errors and manufacturing errors. The causes of experiment errors may be turbulence, unsteadiness of flow, structural vibration, noises, etc. The causes of instrument errors may be sensitivities of sensors, linearity of instruments, etc. The causes of manufacturing errors may come from machining and assembling accuracies.

The total error of a measured value was, however, divided into a bias error and a random error according to ANSI/ASME PTC19.1-1985 as described below. In LOCA analysis, uncertainty of characteristic equation will be considered conservatively to evaluate fuel cladding temperature using these errors.

Random Errors

Pressures and water levels were measured as a function of time. The raw data generally scatter and form a band with time. For LOCA analysis, it is necessary to use the reduced data without dispersion that represent the flow rate characteristics of the flow damper. These reduced data were taken by curve fitting of the raw data to make a curve that lies at the middle of the data band. The experimental equations were derived from the curves. The standard deviation of the dispersion of the data from the experimental equations was evaluated as random errors for each test case as shown in Table 5.2-1.

Table 5.2-1 Dispersion of the Data from the Experimental Equations

Bias Errors

A true value may be different from the experimental equations. This difference is defined as a bias error. However, the true value is not known and needs to be estimated. The dominant cause of the bias error may be the instrument errors. Each sensor and amplifier pair was calibrated one by one. Instrument error consists of calibration error and resolution capability. Consequently, the bias error can be represented by the instrument error. The instrument error associated with flow rate coefficients is shown for each test case in Table 5.2-2.

Table 5.2-2 (1/2) The Instrument Error (Large Flow)

Table 5.2-2 (2/2) The instrument Error (Small Flow)

Manufacturing Errors

The manufacturing error of the flow damper associated with the flow rate coefficient is determined based on the dimensions and manufacturing tolerance of the following parts that affect the performance of the flow damper.

- The inner diameter of the throat
- The facing angle (collision angle) of the large flow inlet pipe and the small flow inlet pipe
- The inner diameter of the vortex chamber
- The width of the small flow pipe
- The height of the small flow pipe

Consequently, the manufacturing error associated with the flow rate coefficient will be less than[ ].

5.3 Estimation of Potential Uncertainties of Water Level for Switching Flow Rates

The uncertainty in the switching levels as function of the water level in the test tank was taken from elevation data of the inlet port of standpipe in full height, full pressure, 1/2 diameter experiments. A water level at switching of flow rates was defined as an intersecting point of two curves of water levels for large flow rate injection and small flow rate injection. The instrument errors were also counted in the estimation of the uncertainties.

Uncertainty of water level for switching flow rates in each test case is shown in Table 5.3-1.

Table 5.3-1 Uncertainty of Water Level for Switching Flow Rates

5.4 LOCA Analytical Model and Computational Procedure

The resistance coefficient of the flow damper varies over time depending on the flow condition. The resistance coefficient is calculated by the correlation equations between cavitation factor and flow rate coefficient.

The correlation equations are incorporated into the LOCA analysis computer code and resistance coefficient of the flow damper is calculated at each time-step in the LOCA analysis. Compared with the ACC, the resistance coefficient of a conventional nuclear plant accumulator does not vary for conditions such as pressure and flow rate.

The computational procedure for determining the resistance coefficient of the ACC is determined as follows;

1) Calculate cavitation factor σ_v from the flow condition at the flow damper.

$$\sigma_v = \frac{P_D + P_{at} - P_v}{(P_A + \rho g H) - \left(P_D + \frac{\rho V_D^2}{2} + \rho g H'\right)} \qquad (5\text{-}4)$$

Where,

σ_v	:	Cavitation factor
P_{at}	:	Atmospheric pressure
P_D	:	Flow damper outlet pressure [gage]
P_A	:	Gas pressure in accumulator
P_v	:	Vapor pressure
ρ	:	Density of water
g	:	Acceleration of gravity
H	:	Distance between ACC water level and vortex chamber
H'	:	Distance between outlet pipe and vortex chamber
V_D	:	Velocity of injection pipe

2) Calculate the flow rate coefficient Cv using the following correlations.

For large flow rate: C_v=0.7787-0.6889 exp(-0.5238 σ_v) (5-5)

For small flow rate: C_v=0.07197-0.01904 exp(-6.818 σ_v) (5-6)

The injection flow rate switches to small flow rate when the calculated accumulator water volume becomes less than the volume below the standpipe inlet level.

Uncertainty of characteristics equations is considered conservatively to evaluate fuel cladding temperature in LOCA analysis.

3) Convert flow rate coefficient C_v to resistance coefficient of the flow damper K_D.

$$K_D = \frac{1}{C_v^2} \qquad (5\text{-}7)$$

4) Calculate total resistance coefficient by summing up resistance coefficient of the flow damper and that of injection piping.

$$K_{acc} = K_D + K_{pipe} \tag{5-8}$$

Where,

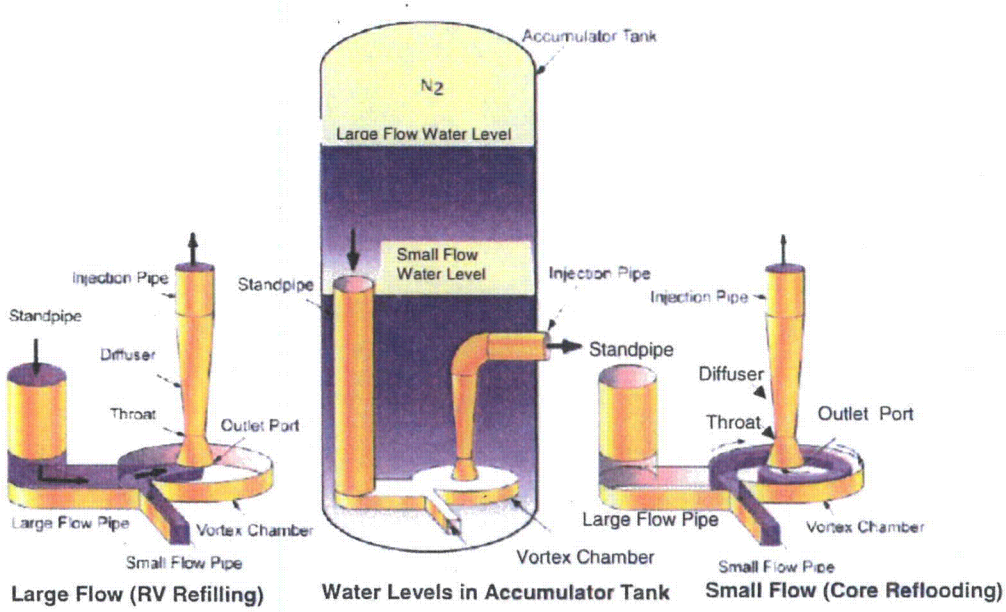
K_{acc} : Total resistance coefficient of the flow damper and injection piping

K_{pipe} : Total resistance coefficient of injection piping

6.0 SUMMARY

The Mitsubishi Heavy Industries, Ltd. Advanced Accumulator (ACC) design will be used in MHI's Advanced Pressurized Water Reactors. The ACC design simplifies the emergency core cooling system design by integrating the short term large flow rate design requirements currently satisfied in conventional pressurized water reactor designs by the combined injection capabilities of the primary system accumulator and the low head safety injection pump into a single passive device, the ACC.

The ACC is a borated water storage tank with a fluidic device that throttles the flow rate of cooling water injected into a reactor vessel from a large to a small flow rate. A conceptual drawing of the ACC is shown below.



The vortex chamber at the inlet of the injection pipe in the accumulator tank accomplishes the flow rate throttling from large flow to small flow by establishing a vortex (and thus a large pressure drop) at a predetermined accumulator tank level. The inlet of the standpipe is located at the ACC volume level at which the transition from large to small flow is desired to occur. The ACC is a simple device that achieves precise throttling from a large injection flow rate to a small injection flow rate with no moving parts.

Upon initiation of a large break loss of coolant accident, all short term low head primary coolant injection flow requirements are satisfied by the ACC. Following depletion of the ACC water volume, the longer term ECCS flow requirements are met by the safety injection pumps thus eliminating the need for low head injection pumps. The immediate availability of low head flow provided by the ACC upon loss of electrical power coincident with a large break loss of coolant accident provides additional time for actuation of the backup emergency power source.

The design requirements and specifications of the ACC for the US-APWR are the same as that for the APWR. The confirmatory test program for the APWR was successfully conducted as a joint study among five utilities (Japan Atomic Power Co., Hokkaido Electric Power Co., Kansai Electric Power Co., Shikoku Electric Power Co., and Kyushu Electric Power Company) and MHI, from September 1994 to September 1996. The tests confirmed the principles of operation of the flow damper and successfully established the ACC flow characteristics. Specifically, the testing confirmed that:

1. No vortex was formed during large flow and a stable vortex was formed during low flow in the vortex chamber
2. Sharp flow rate switching occurred without gas entrainment.
3. The flow characteristics of the flow damper were organized by dimensionless numbers and were independent with scaling.

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.

The ACC design is expected to improve the 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 an inherently 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, provides additional time for actuation of backup emergency power for loss of power coincident with a large break LOCA, and reduces the net maintenance and testing burden by the elimination of low head safety injection pumps from the LOCA mitigation strategy.

Attachment 1

Test Data

Full Height 1/2 Scale Tests

Case 1 ;	A1-1
Case 2 ;	A2-1
Case 3 ;	A3-1
Case 4 ;	A4-1
Case 5 ;	A5-1
Case 6 ;	A6-1
Case 7 ;	A7-1

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec).	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (°C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	test tank pres. (kg/cm2)	flow damper outlet pres. (kg/cm2)	test tank level (m)	tank warer temperature (^{0}C)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

time (sec)	stand pipe water level (m)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case1)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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Full Height 1/2 Scale Test Data (Case2)

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Full Height 1/2 Scale Test Data (Case2)

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Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case2)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case2)

time (sec)	stand pipe water level (m)

time (sec)	stand pipe water level (m)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case2)

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time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case2)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case2)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case2)

time (sec)	stand pipe water level (m)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

1/2 Test Data (Case3)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

time (sec)	stand pipe water level (m)

1/2 Test Data (Case3)

time (sec)	stand pipe water level (m)

1/2 Test Data (Case3)

time (sec)	stand pipe water level (m)

1/2 Test Data (Case3)

time (sec)	stand pipe water level (m)

1/2 Test Data (Case3)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case4)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case4)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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Full Height 1/2 Scale Test Data (Case4)

time (sec)	stand pipe water level (m)

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time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case5)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

time (sec)	stand pipe water level (m)

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Full Height 1/2 Scale Test Data (Case6)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case6)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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Full Height 1/2 Scale Test Data (Case6)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case6)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank water temperature (^0C)

Full Height 1/2 Scale Test Data (Case6)

time(sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank water temperature (^0C)

Full Height 1/2 Scale Test Data (Case6)

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Full Height 1/2 Scale Test Data (Case6)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case6)

time (sec)	stand pipe water level (m)

Full Height 1/2 Scale Test Data (Case7)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case7)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case7)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank water temperature (^0C)

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time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case7)

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time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case7)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	*test tank level (m)*	tank warer *temperature* (^0C)

Full Height 1/2 Scale Test Data (Case7)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

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Full Height 1/2 Scale Test Data (Case7)

time (sec)	test tank pres. (kg/cm^2g)	flow damper outlet pres.(kg/cm^2g)	test tank level (m)	tank warer temperature (^0C)

Full Height 1/2 Scale Test Data (Case7)

time (sec)	stand pipe water level (m)

Attachment 2

Flow Characteristics of Flow Damper

Full Height 1/2 Scale Tests

Case 1 ;	B1-1
Case 2 ;	B1-2
Case 3 ;	B1-3
Case 4 ;	B1-4
Case 5 ;	B1-5
Case 6 ;	B1-6
Case 7 ;	B1-7

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case1))

Large Flow		Small Flow	
σv	Cv	σv	Cv

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case2))

Large Flow		Small Flow	
σv	Cv	σv	Cv

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case3))

Large Flow		Small Flow	
σv	Cv	σv	Cv

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case4))

Large Flow		Small Flow	
σv	Cv	σv	Cv

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case5))

Large Flow		Small Flow	
σv	Cv	σv	Cv

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case6))

Large Flow		Small Flow	
σv	Cv	σv	Cv

Flow Characteristics of Flow Damper (Full Height 1/2 Scale Test (Case7))

Large Flow		Small Flow	
σv	Cv	σv	Cv