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US-APWR

3rd Pre-Application Review Meeting
Advanced Accumulator

November 29, 2006

Mitsubishi Heavy Industries, Ltd.

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3. Detailed Design of As-installed Acc
4. Confirmation Testing Program of Acc
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1. Introduction

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1. Introduction

- The Advanced Accumulator design that will be included in MHI's revolutionary Advanced Pressurized Water Reactors (APWR)

- The APWR's Advanced Accumulator is incorporated into the safety system design in order to provide the low pressure injection function of conventional Emergency Core Cooling Systems (ECCS) using accumulator and the safety injection pump

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1. Introduction

- This arrangement simplifies the configuration of the ECCS
- Details of the Advanced Accumulator will be presented in the topical report for review and approval by the United States Nuclear Regulatory Commission (USNRC)
- MHI will provide the out line of the topical report (function, principles, structures, verification, etc.) of the Advanced Accumulator design

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2. Characteristics of Advanced Accumulator (Acc)

➢ Contents

2.1 Function of Acc

2.2 Principle of Acc

2.3 Requirements for Performance of Acc

2.4 Expected Characteristics of Acc

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2.1 Function of Acc

- **ECCS injection during large break LOCA**

Step1: Core Refilling

Rapidly inject the water with large flow to fill the lower plenum and downcomer of the reactor vessel in a short time

Step2: Core Reflooding

Recover the core water level using the water head in the downcomer. Core injection keeps the high water level in the downcomer and re-floods the core immediately

Step3: Long Term Cooling

After core reflooding is completed, inject water to accommodate the water reduction due to the evaporation by decay heat and maintain the core reflooding condition

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2.1 Function of Acc

➢Comparison between Current 4 Loop Plant and US-APWR

Residual Heat Removal System performs as Low Head Injection System in conventional plants

⇩

Advanced accumulator is integrated function of Low Head Injection System

Item	US Current 4 Loop Plant	US-APWR
Step1 Core Refilling	Accumulator System	Accumulator System
Step2 Core Reflooding	Low Head Injection System High Head Injection System	Accumulator System High Head Injection System
Step3 Long term cooling	Low Head Injection System High Head Injection System	High Head Injection System

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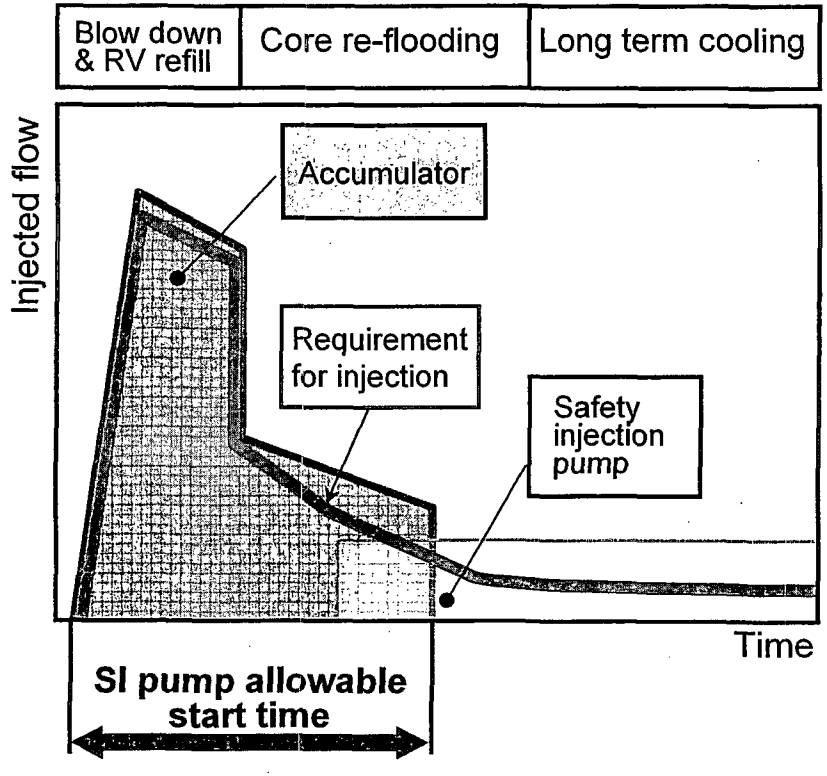
2.1 Function of Acc

- Automatic switching of injection flow rate by flow damper
- Integrated function of low head injection system
- Long accumulator injection time allows more time for safety injection pump to start



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2.1 Function of Acc

- **System configuration of ECCS and Containment Spray System / Residual Heat Removal System**
  - ✓ Four Accs are installed and each Acc connects to one Reactor Coolant System (RCS) cold leg
  - ✓ Four High Head Injection subsystems are installed and inject following accumulator injection
  - ✓ Low Head Injection subsystems are not installed; instead, Four CS/RHRS subsystems including pumps are provided for Containment Spray and Residual Heat Removal subsystem

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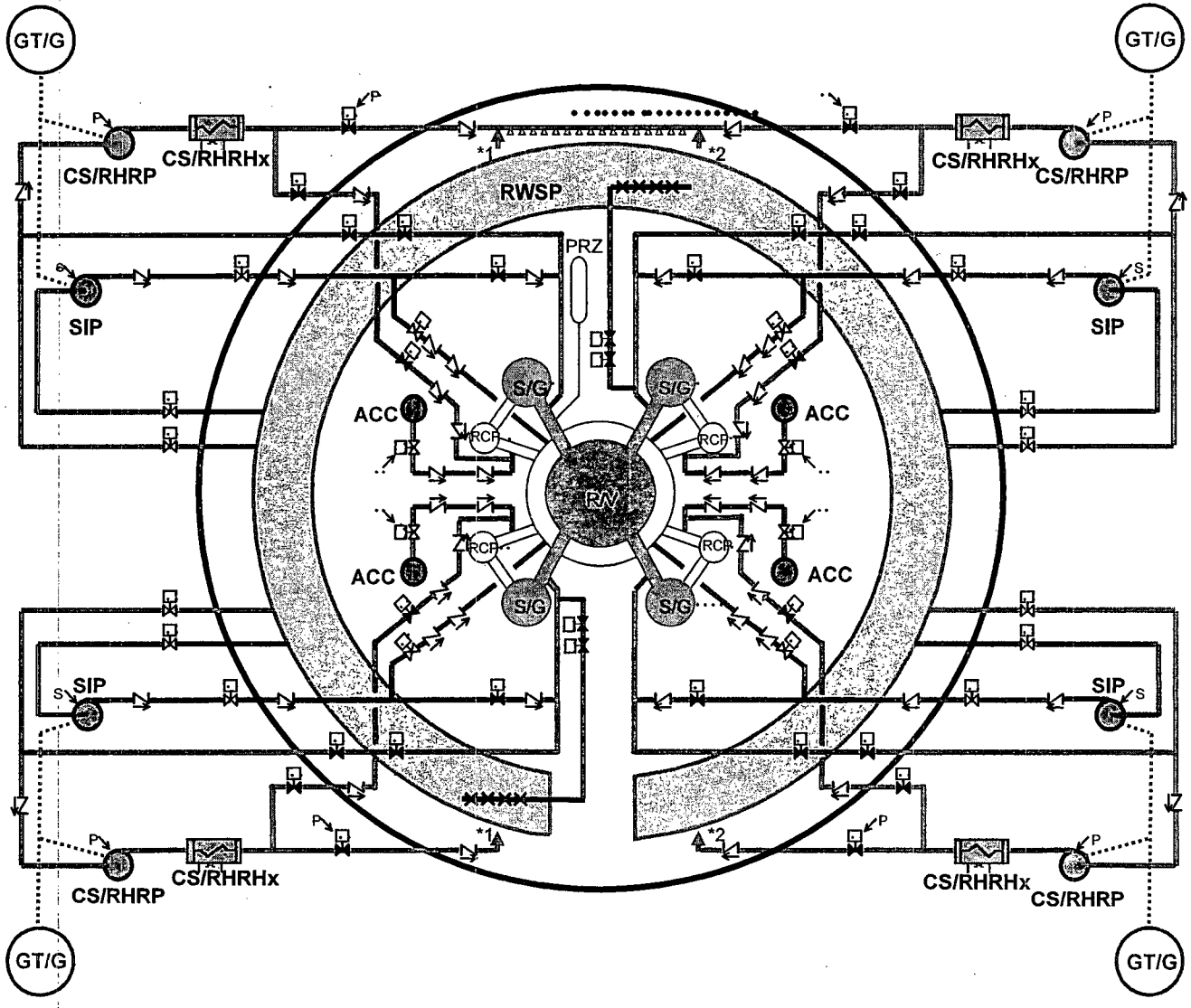
2.1 Function of Acc



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2.2 Principle of Acc

➢ Conventional Fluidic Device

✓ Vortex Amplifier

- Similar to but slightly different from a flow damper in shape and function
- Composed of a vortex chamber and three ports for supply, control and output of flows
- Vortex is used for control flow

Fluidic Device: Device controlling flow without moving parts

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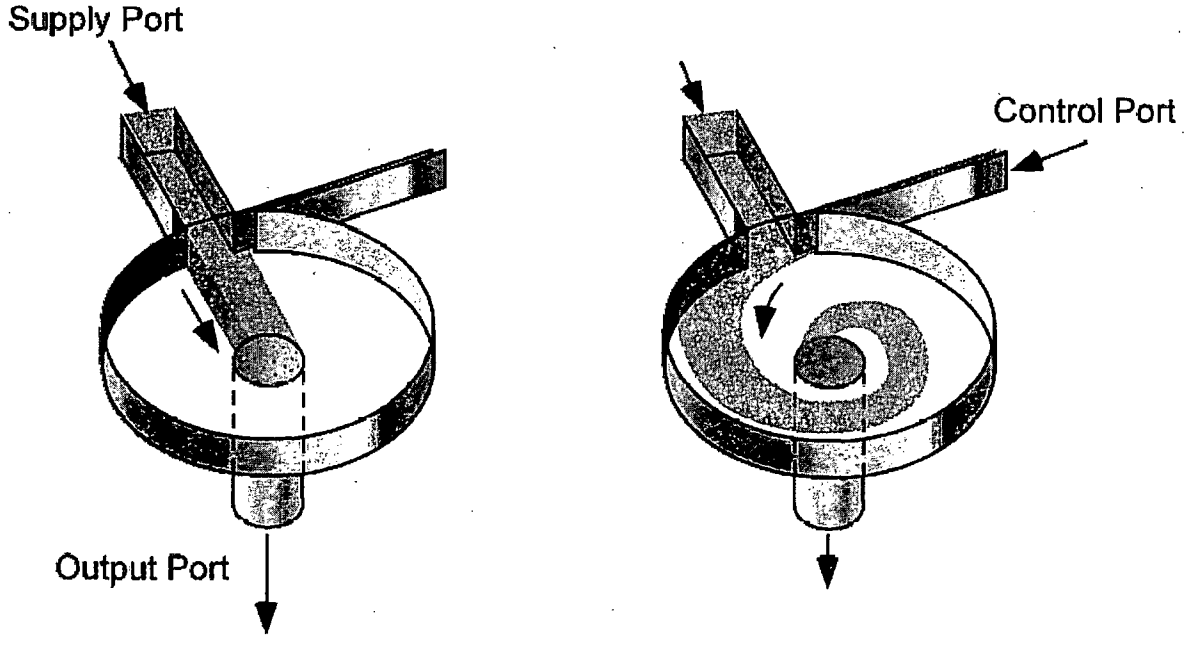
2.2 Principle of Acc

Vortex Amplifier



(a) Without Control Flow

Absence of a vortex yields low resistance

(b) With Control Flow

Strong vortex yields high resistance

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2.2 Principle of Acc

➢ Advanced Accumulator

✓ Structure

- Vortex Chamber at bottom of Accumulator Tank
- Standpipe connected to vortex chamber
- Inlet port of standpipe at the middle of Accumulator Tank
- Outlet pipe of vortex chamber connected to injection pipe

✓ Differences from Vortex Amplifier

- Collision of two flows makes no vortex
- Single flow makes a strong vortex
- Standpipe is used for switching flow rates
- Outlet pipe is composed of a throat and a diffuser to improve its function

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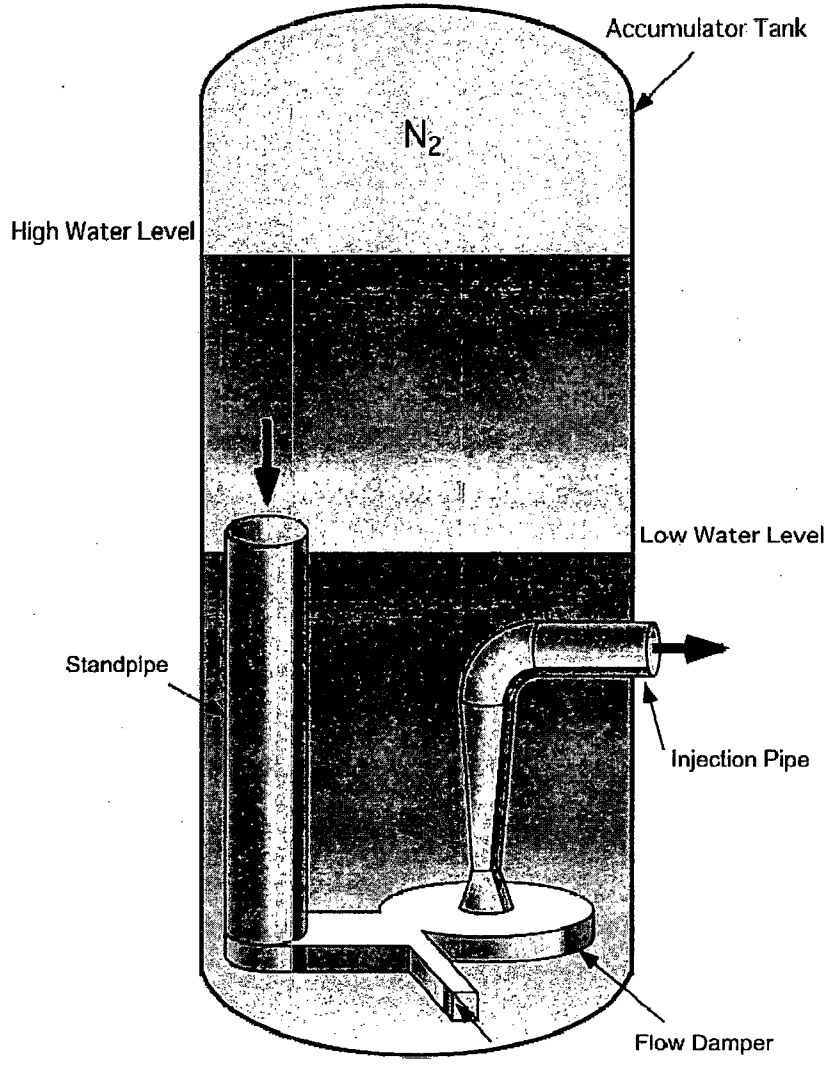
2.2 Principle of Acc

Advanced Accumulator



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2.2 Principle of Acc

- **At high water level**
  - ✓Water comes into both large and small flow pipes
  - ✓The flows collide with each other not to form a vortex in the vortex chamber
  - ✓Large flow rate comes off
- **At low water level**
  - ✓Water stops flowing to the standpipe
  - ✓The flow from the small flow pipe forms a strong vortex in the vortex chamber
  - ✓Small flow rate comes off

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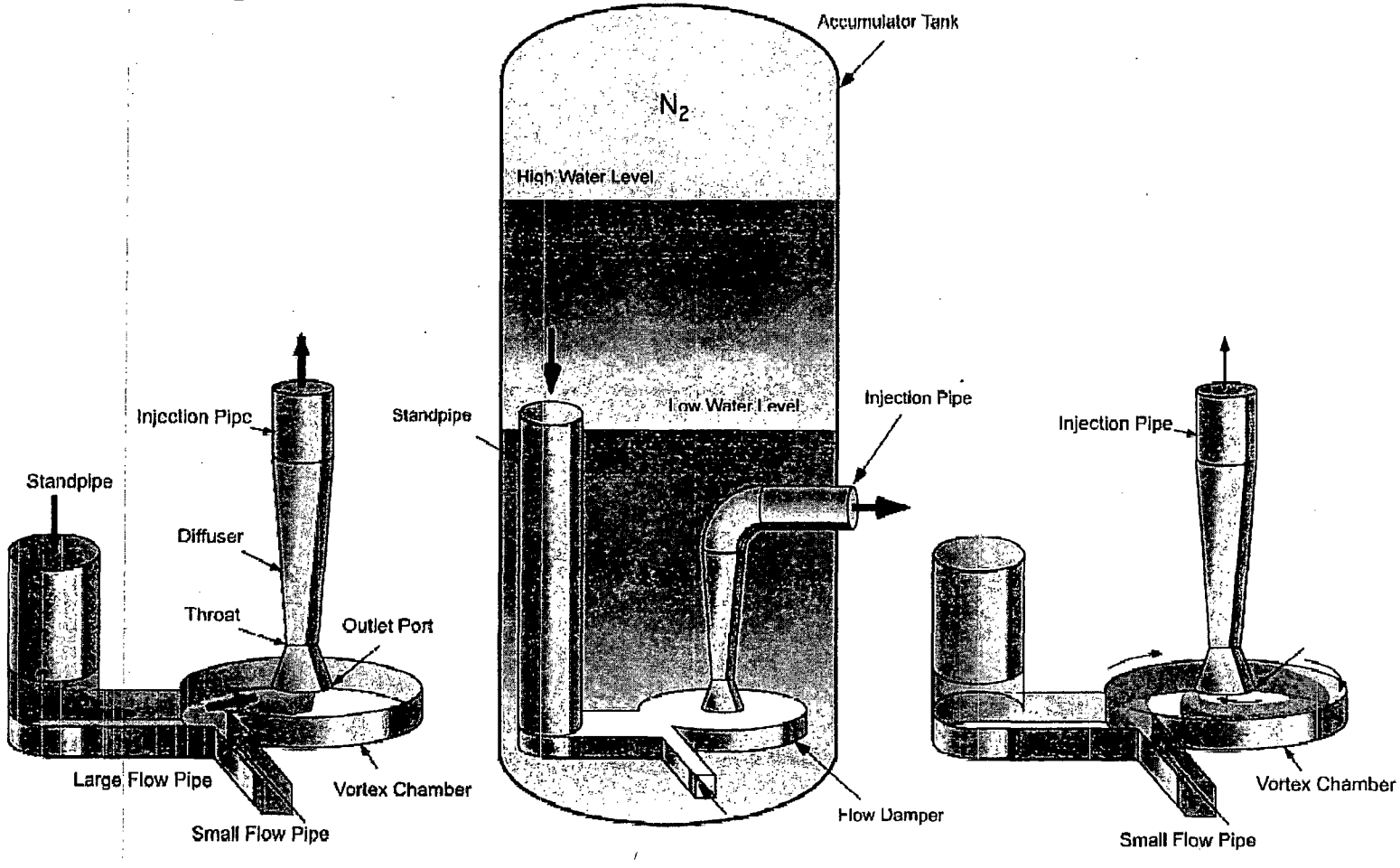
2.2 Principle of Acc

➢Principle



(b) Large Flow Rate (RV Refilling)

(a) Water Levels in Accumulator Tank

(c) Small Flow Rate (Core Reflooding)

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2.2 Principle of Acc

- **Flow damper**
  - ✓ Composed of a vortex chamber and three pipes for large flow-rate, small flow-rate and outlet of flows
  - ✓ Small flow pipe tangentially attached to the vortex chamber
  - ✓ Large flow pipe radially attached to the vortex chamber
  - ✓ Angle of collision determined to cancel out the angular momentums of the incoming flows
  - ✓ The throat portion is provided at the outlet of the vortex chamber to form the strong vortex during small flow
  - ✓ Outlet pipe composed of a throat and a diffuser connected to the injection pipe

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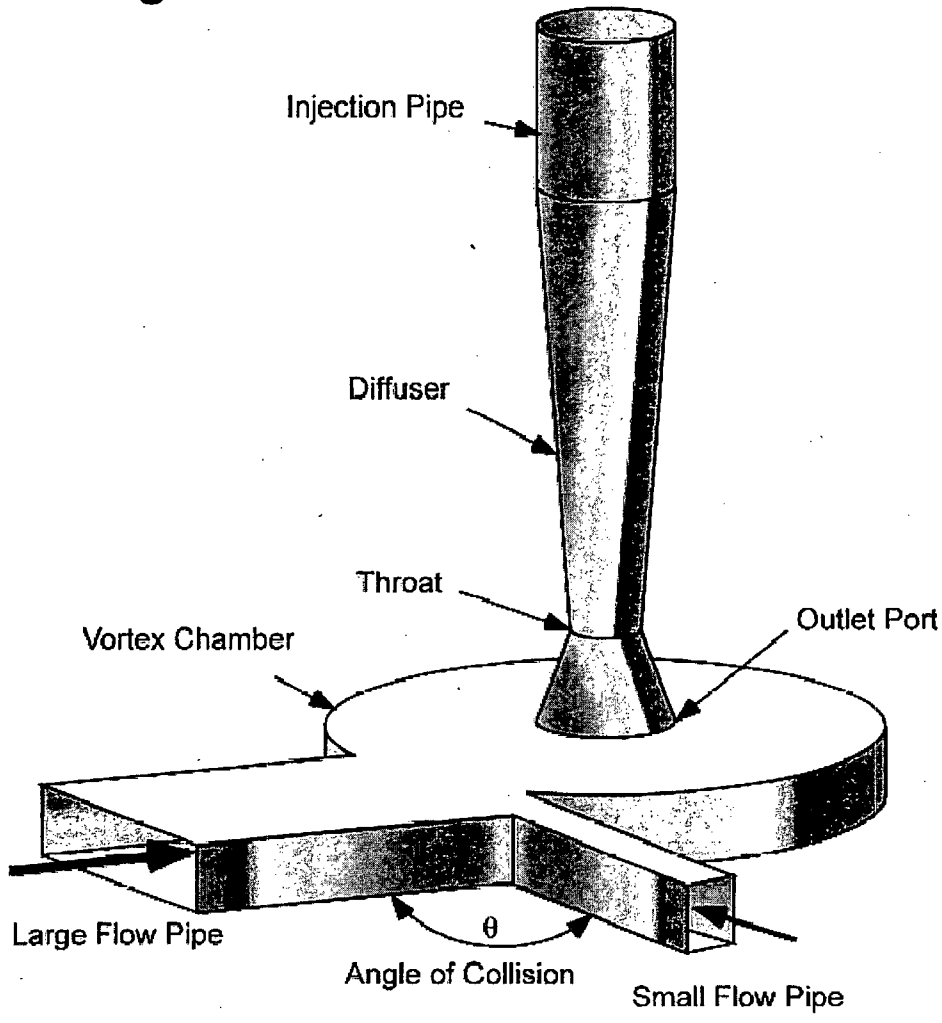
2.2 Principle of Acc

- **Flow Damper**
  - ✓ **Mechanical Configuration**



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2.2 Principle of Acc

➢ Expected Phenomena 1

✓ At large flow rate

- Flow resistance similar to that of conventional pipes
- Form resistance is dominant over friction
- Friction can be evaluated with a Reynolds number, while form resistance is independent of it
- Diffuser reduces pressure losses
- Cavitation at the throat affects flow rates
- <u>Cavitation factor and Reynolds numbers are the parameters of flow rates</u>

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2.2 Principle of Acc

➢ Expected Phenomena 2

✓When switching flow rate

- Water stops flowing into the standpipe and forms water surface in it
- Inertia of water column makes water surface undershoot below the balanced level with pressure difference between in and out of the standpipe
- Water surface recovers to the level thereafter
- Standpipe is designed to maintain water level in it and prevent gas leakage

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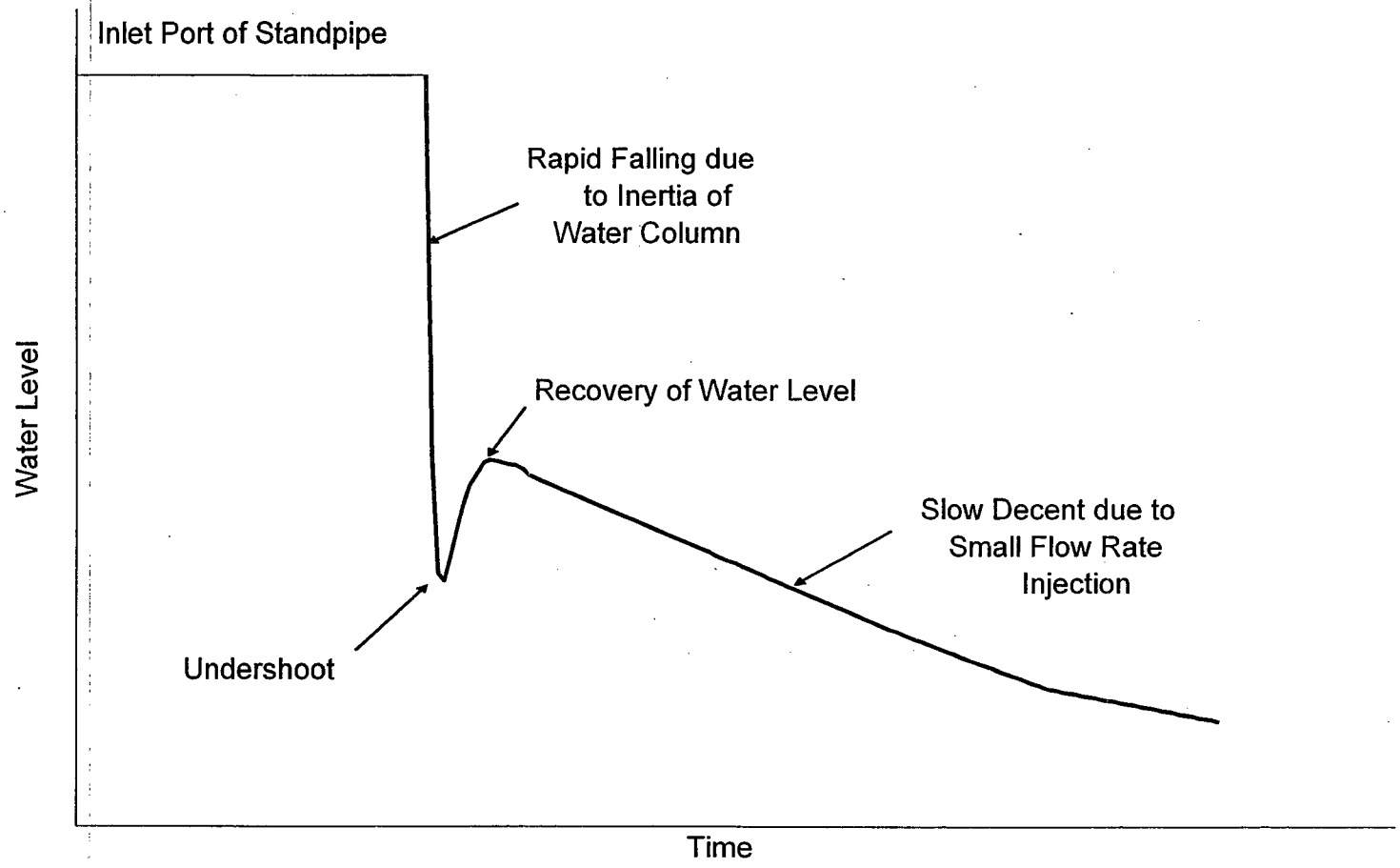
2.2 Principle of Acc

➢Expected Phenomena 3

Water Level in Standpipe (image chart)



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2.2 Principle of Acc

➢ Expected Phenomena 4

✓At small flow rate 1

- Strong and steady vortex flow is formed in the vortex chamber
- Large pressure drop exists along the radius of the vortex chamber
- Difference of water levels in and out of the standpipe is equal to the dynamic pressure in the small flow-rate pipe, which is much smaller than pressure drop in the chamber
- It is the main feature to prevent gas leakage without moving parts

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2.2 Principle of Acc

➢ Expected Phenomena 5

✓ At small flow rate 2

- Pressure recovery in the diffuser is small
- Minimum pressure in the vortex chamber is almost as same as that in the injection pipe
- Cavitation may not affect flow rate
- Vortex flow undergoes rapid acceleration to hold boundary layers down so that friction may be negligible
- Consequently, flow rate coefficients will be common for any size of flow dampers

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2.3 Requirements for Performance of Acc

Fundamental safety requirements

↓

Function of Acc during large LOCA

↓

Performance requirements for Acc

↓

Assume related parameters

↓

Design requirements for Acc

(Design targets for Acc)

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2.3 Requirements for Performance of Acc

- **Fundamental safety requirements**
  - ✓ Limit the Peak Clad Temperature (PCT) under 2200°F (1200°C) during large LOCA

- **Function of Acc during large LOCA**
  - ✓ **Step1:**
    Refilling the lower plenum and downcomer immediately during refilling period following reactor coolant blow down
  - ✓ **Step2:**
    Establish the core reflooding condition by maintaining the downcomer water level after refilling the core

- **Performance requirements**
  - ✓ Requirements for large flow injection from step1 function
  - ✓ Requirements for small flow injection from step2 function

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2.3 Requirements for Performance of Acc

- **Performance requirements for large flow injection**

  - ✓The water volume for large flow injection in Acc should cover the lower plenum and downcomer regions of reactor vessel
    - The lower plenum and downcomer is filled as rapidly as possible during refilling period

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2.3 Requirements for Performance of Acc

- **Performance requirements for small flow rate**
  - ✓ Downcomer water-head is driving force for ECCS flow into core
  - ✓ Requirement :
    <u>Downcomer should be filled with ECCS water</u>
  - ✓ Setting up by "BASH-M" re-flooding analysis
  - ✓ Required flow rate is obtained from the core flow rate calculated by the hypothetical LOCA analysis, which assumes downcomer is filled with sufficient ECCS flow

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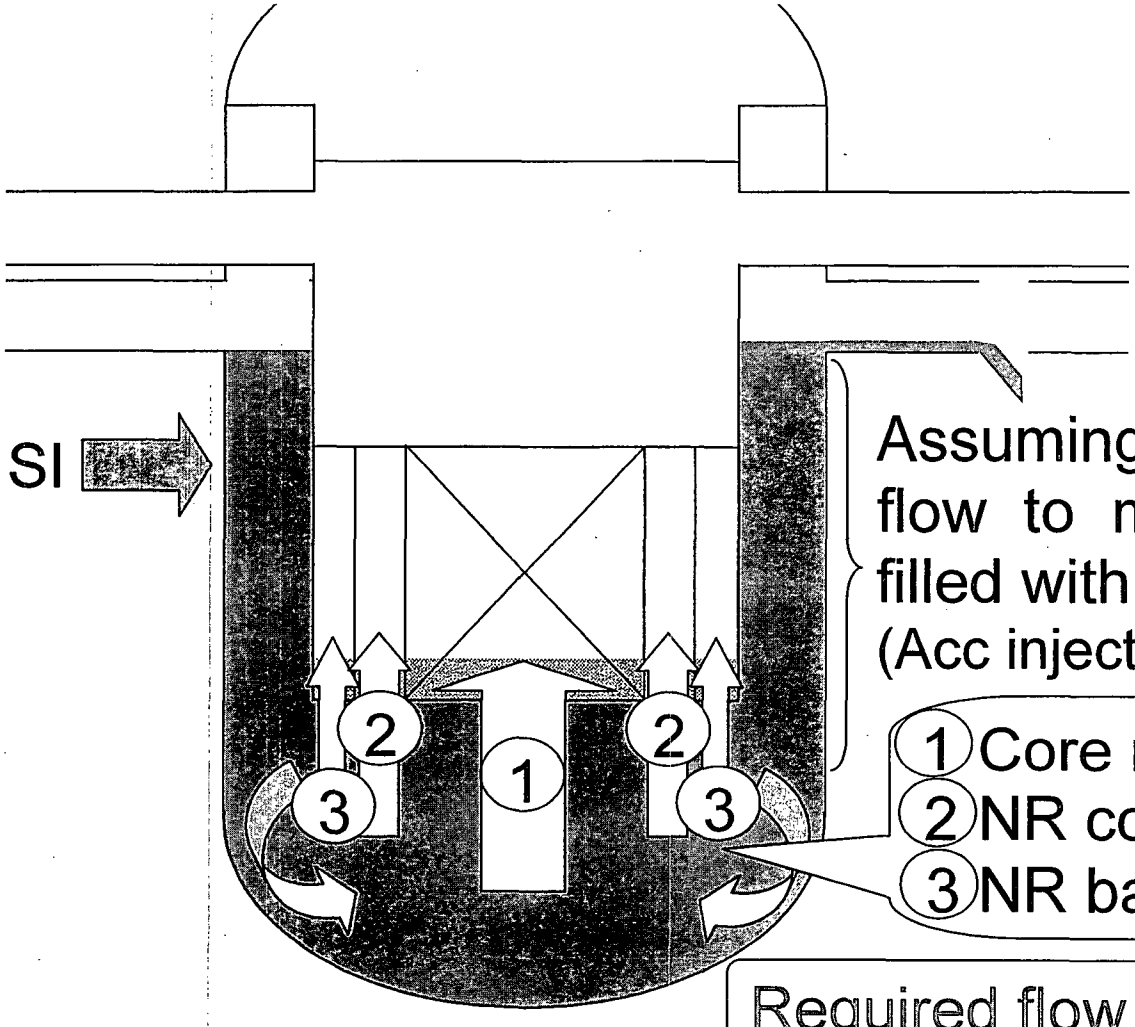
2.3 Requirements for Performance of Acc

➢Calculation of the required flow rate



Assuming the sufficient SI flow to maintain downcomer filled with water.
(Acc injection is not simulated.)

1 Core region
2 NR cooling-holes region
3 NR back side region

Required flow rate = 1 + 2 + 3

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2.3 Requirements for Performance of Acc

Required ECCS injection flow rate

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2.3 Requirements for Performance of Acc

➢ Design requirements for large flow injection

✓ Resistance coefficient of large flow injection should be approx.[ ]

- After refilling stage, the core reflooding starts. The starting time of core reflooding is dominant factor for the PCT.
- Resistance coefficient :[ ]of large flow injection limits the PCT under [ ]°F ([ ]°C) based on previous experience.

Note;
PCT is strictly limited under 2200°F (1200°C).
For the 2200°F (1200°C), more larger resistance coefficient may be acceptable.
"Resistance coefficient[ ]" is not a strict requirement but a target.

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2.3 Requirements for Performance of Acc

- Expected large flow characteristics
  - ✓ Assume major parameters
    - Large flow injection water volume: [ ]ft^3 ([ ]m^3)
    - Initial gas volume: [ ]ft^3 ([ ]m^3)
    - Initial gas pressure: [ ]psi ([ ]MPa[gage])

      Note;

      1. Water volume satisfies performance requirements. Details are discussed in section 3.1.
      2. Other parameters are set based on previous experience.
  - ✓ Calculate large flow injection
    - Typical depressurization of RCS is assumed
    - Survey flow rate of large flow injection

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2.3 Requirements for Performance of Acc

➢ Expected large flow characteristics (cont.)

✓ Calculation method

$$P_{gas} - P_{inj} = K \cdot \gamma \frac{U^2}{2g} - \gamma\left(H_t - H_p\right)$$

$$P_{gas} = \left(\frac{V_{gas0}}{V_{gas}}\right)^{\kappa} \cdot P_{gas0}$$

$$\frac{dV_{gas}}{dt} = A \cdot U$$

P_{gas}	: Accumulator gas pressure
P_{gas0}	: Initial accumulator gas pressure
V_{gas}	: Accumulator gas volume
V_{gas0}	: Initial accumulator gas volume
P_{inj}	: Pressure at the injection point (RCS pressure)
K	: Resistance coefficient of Acc system
H_t	: Water level elevation of Acc
H_p	: Elevation of the injection point
U	: Velocity in injection pipe
A	: Cross section inside of the injection pipe
g	: Gravity acceleration
t	: Time
γ	: Specific weight
κ	: Politropical index

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2.3 Requirements for Performance of Acc

- Expected large flow characteristics (cont.)
  - ✓ Calculation results

[ ]

- Expected flow rate at the end of large flow injection from the simulation results: [ ]
  (Resistance coefficient of AC injection line: [ ])

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2.3 Requirements for Performance of Acc

- Design requirements for small flow injection
  - ✓ Required small injection flow rate
    - Performance requirement: [ ]gpm ([ ]m3/h) [total]
    - Assuming 3 out of 4 Accs available
    - Required small injection flow rate: [ ]gpm/Acc ([ ]m3/h/Acc) ([ ]gpm/3Accs =[ ]gpm/Acc)
  - ✓ Large injection flow rate
    - Expected flow rate at the end of large flow injection from the calculation results: [ ]gpm ([ ]m3/h)

✓ Design requirement (Design target)

- Flow-switching ratio from large flow to small flow: approx[ ]
  - Less than[ ]of ratio achieves required small injection flow rate [ ]
  - Design target is set to[ ]with margin

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2.4 Expected Characteristics of Acc

- Condition of calculate the injection characteristics
  - ✓ Large flow injection water volume: [ ] ft^3 ([ ] m^3)
  - ✓ Initial gas volume: [ ] ft^3 ([ ] m^3)
  - ✓ Initial gas pressure: [ ] psi ([ ] MPa[gage])
  - ✓ Resistance coefficient of flow damper in large flow injection: approx.[ ]
  - ✓ Resistance coefficient of accumulator injection piping and valve expect for flow damper: [ ]
  - ✓ Flow-switching ratio: approx.[ ]
- Confirm the performance expected

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2.4 Expected Characteristics of Acc

- Calculation result of expected performance

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3. Detailed Design of As-installed Acc

Contents

3.1 Design Basis and Specification of Acc

3.2 Structure of Acc

3.3 Structure of the Flow Damper

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3.1 Design Basis and Specification of Acc

- **Function of Acc during large LOCA**
  - ✓Each Acc connects to corresponding RCS cold leg (4 Accs in all) and functions to inject water in large flow rate into the core during reactor vessel (RV) refilling process and also injects water at small flow rate during core reflooding process

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3.1 Design Basis and Specification of Acc

➢ Goals to perform the function

✓ Refilling process (large flow injection)

- Inject water of [ ] ft^3 ([ ] m^3) immediately that is equivalent to the volume of the downcomer and lower plenum of RV to complete reflooding

✓ Reflooding process (small flow injection)

- Continues injecting water for approx. [ ] seconds* following the refilling process to maintain downcomer water level

* The duration of small flow injection is associated with Safety Injection (SI) pump capacity. It is assumed that the duration of small flow injection from accumulator is [ ] seconds and then the injection from SI Pumps take over.

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3.1 Design Basis and Specification of Acc

➢ Basis of volume of Acc

✓ Basis of large flow injection volume

approx.[ ]

= approx.[ ] ft^3/Acc ([ ] m^3/Acc)

- The volume of an Acc is specified [ ] ft^3 ([ ] m^3), which is [ ] ft^3 ([ ] m^3) plus margin

Note;

(a) Total volume of the downcomer and the lower plenum

(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 required to the core injection

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3.1 Design Basis and Specification of Acc

➢ Basis of volume of Acc (cont.)

✓ Basis of small flow injection volume

- The expected duration of small flow injection of Acc is [ ] seconds and [ ] ft^3 ([ ] m^3) of injection water is required
- Thus, [ ] ft^3 ([ ] m^3) of injection water volume is specified assuming the margin with [ ] ft^3 ([ ] m^3)

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3.1 Design Basis and Specification of Acc

➢ Basis of volume of Acc (cont.)

✓ Volume of a single Acc ; 3,180 ft^3 ($90m^3$)

- Large flow injection volume ; [ ] ft^3 ([ ] m^3)
- Small flow injection volume ; [ ] ft^3 ([ ] m^3)
- Air space and dead water volume

⇩

- The validity of the volume will be confirmed in ECCS analysis

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3.1 Design Basis and Specification of Acc

➢ Specification of Acc

Type:	Vertical cylindrical
Number:	4
Volume:	3,180 ft^3 (90 m^3)
Maximum design pressure:	[ ]psig ([ ]MPa)
Maximum design temperature:	[ ]°F([ ]°C)
Large flow injection volume:	[ ]ft^3 ([ ]m^3)
Small flow injection volume:	[ ]ft^3 ([ ]m^3)

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3.2 Structure of Acc

- **Measure dimensions of Acc**
  - ✓ **Total height [ ]ft ([ ]m)**
  - ✓ **Inner diameter [ ]ft ([ ]m)**

Outlet pipe : drawn from the upper side of the flow damper

⇩

Un-available water is less than the case of drawn from lower side

Flow Damper

Outline drawing of Acc

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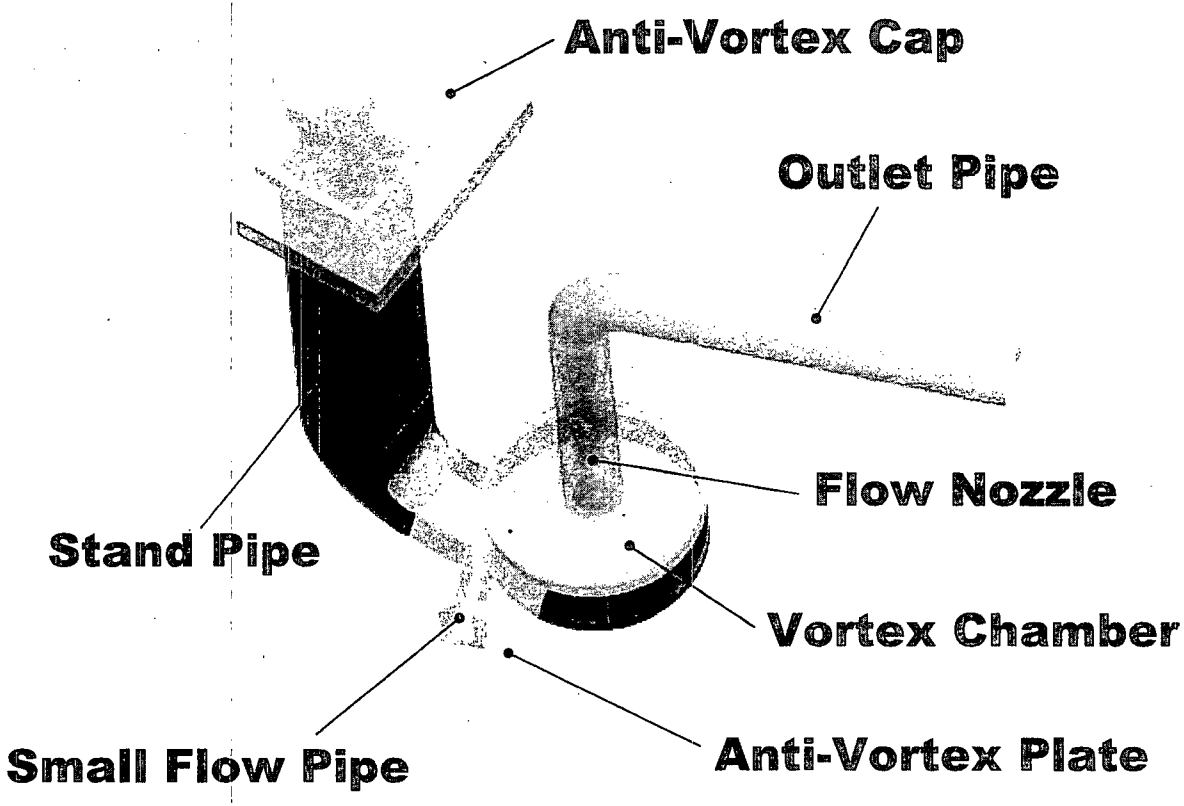
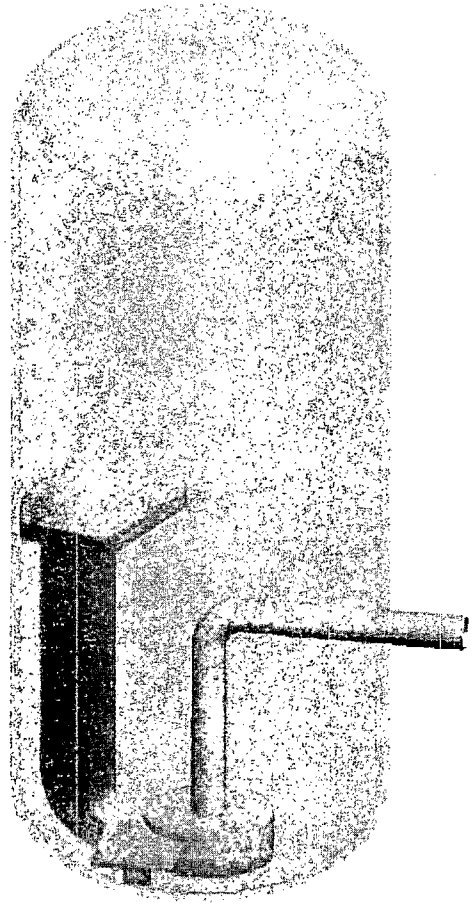
3.3 Structure of the flow Damper

➢ Structure of the flow damper





Flow Damper

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3.3 Structure of the flow Damper

➢ Detailed structure of the flow damper

a)	The anti-vortex cap installed on the standpipe inlet prevents the forming of vortex and allowing the air into the flow damper just before the flow switching and improves the flow-switching characteristics
b)	The inlet of the standpipe is set at the water level for switching flow rate from large flow to small flow
f)	The small flow piping is connected to the vortex chamber tangentially and reduces the flow resistance
d)	The throat portion and diffuser are provided on the outlet piping to increase the flow resistance during small flow and to recover the pressure during large flow and connect the downward piping smoothly

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4. Confirmation Testing Program of Acc

Contents

4.1 Purpose of the Confirmation Tests
4.2 Detailed Description of Tests and Results
4.3 Scalability and Validity of Flow Rate Characteristics

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4.1 Purpose of the Confirmation Tests

US-APWR

Confirmation tests were conducted to determine whether expected performance was met based on the operation principle of Acc and discussion of performance requirements.

The test program was conducted as a joint study between five utilities* and MHI.

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

- Confirmation items
  - Item1:Principle of flow damper
  - Item2:Anti-vortex function of at the end of large flow
  - Item3: Water level transient in the standpipe at flow switching

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4.1 Purpose of the Confirmation Tests

- Confirmation items (Cont.)

  Item4: Performance of the flow damper during large and small flow

  Item5: Water level when switching flow rate

  Item6: Effect of dissolved nitrogen gas

  Item7: Flow characteristics are characterized by normalized numbers

  Item8: Flow characteristics (cavitation factor and flow coefficient) are independent of scaling

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4.1 Purpose of the Confirmation Tests

Item1:Confirmation of the principle of flow damper

- ✓ Observe the characteristics of the flow in the vortex chamber of the flow damper during large flow injection, large to small flow switching, and small flow injection
- ✓ Confirm its function was as expected

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4.1 Purpose of the Confirmation Tests

Item2:Confirmation of anti-vortex function at the end of large flow injection

- ✓ Anti-vortex cap is provided at the top of the standpipe
- ✓ Potential appearance of a vortex when the water level comes down to it
- ✓ The tests were conducted to confirm the anti-vortex cap prevented vortex from occurring

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4.1 Purpose of the Confirmation Tests

Item3:Confirmation of water level transient in the standpipe at flow switching

- ✓ When switching flow, water level temporarily undershoots in the standpipe due to inertia
- ✓ Water level in the standpipe recovers thereafter due to the difference of water levels in the tank and the standpipe
- ✓ Confirm that gas not go into the flow damper during switching flow by measuring the water level transient

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4.1 Purpose of the Confirmation Tests

Item4:Confirmation of performance during large and small flows

✓ Confirm that the performance of the flow damper during large and small flows meets the design target

- Resistance coefficient of large flow
- Switching-flow-rate

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4.1 Purpose of the Confirmation Tests

Item5:Confirmation of water level when switching flow

- ✓ Injection flow rate changes from large to small when water level in the tank comes down to the lower end of the cap of the standpipe
- ✓ However, in the actual tank, water level when switching flow may have some variations
- ✓ Therefore, the actual switching level was confirmed through the tests

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4.1 Purpose of the Confirmation Tests

Item6:Confirmation of effect of dissolved nitrogen gas

- ✓ Pressure in the accumulator is established using compressed nitrogen gas (nitrogen gas may dissolve in water)
- ✓ Gas comes out of the water and may affect the flow characteristics of the flow damper
- ✓ A test was conducted with nitrogen-saturated water to determine the effect of dissolved gas

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4.1 Purpose of the Confirmation Tests

Item7:Confirmation that flow characteristics are represented by normalized numbers (cavitation factor and flow coefficient)

- ✓The throat portion is provided at the outlet of the vortex chamber to form the strong vortex during small flow
- ✓Cavitation occurs and affects the flow characteristics
- ✓The tests were conducted to confirm that the flow characteristics obtained through the tests

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4.1 Purpose of the Confirmation Tests

Item8:Confirmation that flow characteristics are independent of scaling

- ✓ The similarity law is applicable to design of the flow damper and performance evaluation
- ✓ Additional tests will be conducted to confirm the following item:
  - To confirm validity of applying the similarity law that evaluates the performance of the actual flow damper using test results of the scale model and to acquire the data required

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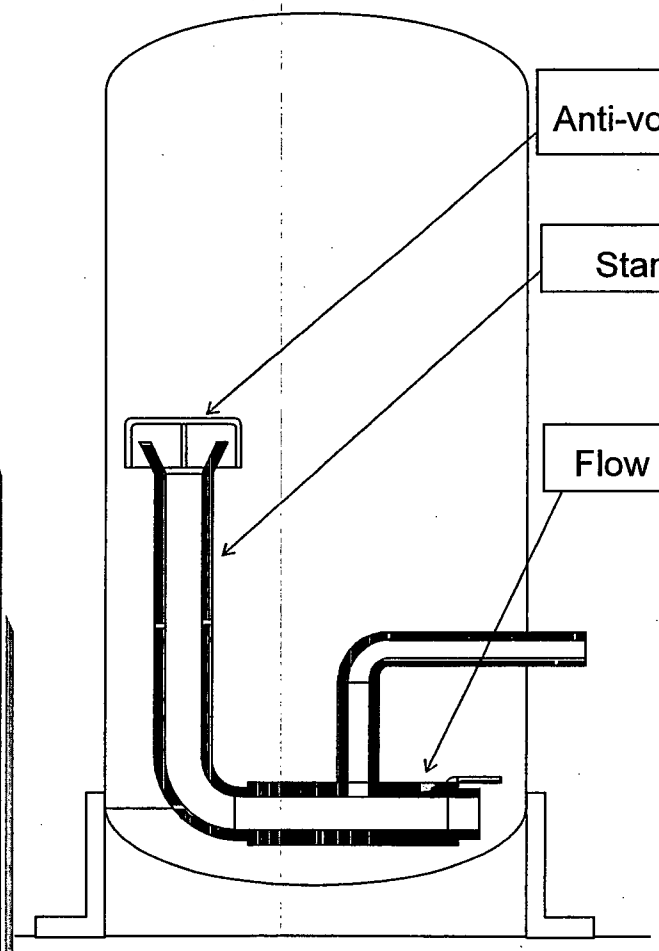
4.1 Purpose of the Confirmation Tests



Anti-vortex cap

Standpipe

Flow damper

Items to be confirmed	Testing
Anti-vortex function of at the end of large flow (Item2)	Visualization Tests
Standpipe water level transient at flow switching (Item3)	Visualization Tests
Flow switching water level (Item5)	Visualization Tests
Principle of flow damper (Item1)	Actual Pressure Injection Tests
Performance of the flow damper during large/small flow (Item4)	Actual Pressure Injection Tests
Effect of dissolved nitrogen gas (Item6)	Low Pressure Injection Tests
Flow characteristics are characterized by normalized numbers (Item7)	Low Pressure Injection Tests
Flow characteristics (cavitation factor and flow coefficient) are independent of scaling (Item8)	Low Pressure Injection Tests

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4.2 Detailed Description of Tests and Results

- **Four kinds of scale models were made**
  - ✓ Demonstration of switching flow (1/8.4 scale visualization tests)
  - ✓ Confirmation of sharp shutoff of flow into the standpipe (1/3.5 scale visualization tests)
  - ✓ Confirmation of the flow rate characteristics under low pressure (1/5 scale visualization and low pressure injection tests)
  - ✓ Confirmation tests under actual pressure (1/2 scale actual pressure injection tests)

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4.2 Detailed Description of Tests and Results

US APWR

(1) 1/8.4 scale tests

1/8.4 scale tests

- Objectives

Demonstration of switching flow

✓ Confirmation of operation principle of the flow damper

- Visualizing the characteristics of flows in the flow damper and the standpipe during large flow injection, large to small flow switching, and small flow injection
- Observing the characteristics of the flow in the vortex chamber and switching flow

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

- Visualizing the behavior of the water level in the standpipe at flow-switching

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4.2 Detailed Description of Tests and Results

1/8.4 scale tests

- Test apparatus
  - ✓Visualization tests of operation principle of the flow damper were conducted
  - ✓Test apparatus consisted of Acc model, exhaust tank and injection piping
  - ✓Scale of the flow damper was 1/8.4

    (The scale selected to be movable to anywhere for demonstration)
  - ✓Vortex chamber was upright style
  - ✓Front panel was made of transparent acrylic resin (standpipe and the flow damper were visualized)

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4.2 Detailed Description of Tests and Results

1/8.4 scale tests

Visualization Test Apparatus of Operation Principle of Flow Damper

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4.2 Detailed Description of Tests and Results

1/8.4 scale tests

- Test apparatus detail parameters

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4.2 Detailed Description of Tests and Results

US-APWR

1/8.4 scale tests

- Test conditions
  - ✓There was no special requirement for the test conditions
  - ✓The following conditions were employed for simplicity
    - Pressure of air space was [ ] MPa ([ ] psi)
    - Pressure in backpressure tank was atmospheric pressure
- Parameters to be measured
  - ✓Flows in the accumulator tank, the standpipe, the small flow rate pipe and the vortex chamber were visualized
  - ✓Flow rate was measured and displayed on CRT but not recorded
  - ✓Pressure in Accumulator Tank was monitored but not recorded
- Measuring equipment
  - ✓Pressure gauges
  - ✓Flow meter
  - ✓Flow switching is observed on display of flow rate

Draft Slide

4.2 Detailed Description of Tests and Results

1/8.4 scale tests

- Test results and discussions
  - ✓ **Characteristics of flow in the vortex chamber during large flow**

- Vortex was not formed in the vortex chamber
- Air bubbles traced the flow after the collision of the incoming flows from the large and small flow pipes

12.48 seconds after initiation of the test

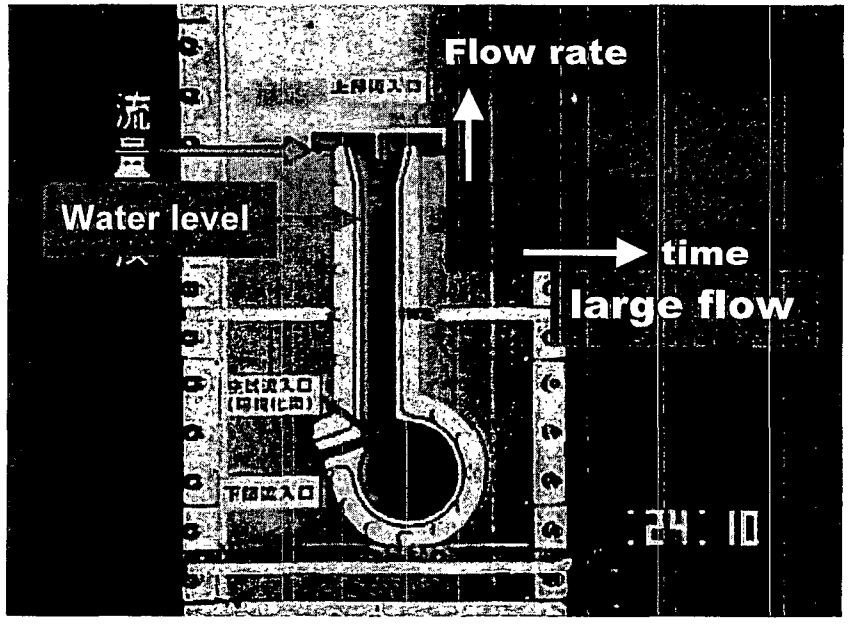
Draft Slide

4.2 Detailed Description of Tests and Results

US-APWR

✓ **Characteristics of flow just before large/small flow switching**

1/8.4 scale tests



•Water level in the standpipe temporarily undershooted, and, recovered thereafter

23.37 and 24.10 seconds after initiation of test

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4.2 Detailed Description of Tests and Results

US-APWR

✓ Characteristics of flow just after flow switching

1/8.4 scale tests

- Flow switched sharply from large to small flows in a short time

27.81 seconds after initiation of test

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4.2 Detailed Description of Tests and Results

US APWR

✓ **Characteristics of flow in the vortex chamber during small flow**

1/8.4 scale tests

- Strong and steady vortex was formed at the center of the chamber
- Air bubbles injected as tracers were swirling into the outlet

34.13 seconds after initiation of test

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4.2 Detailed Description of Tests and Results

US-APWR

1/8.4 scale tests

✓ **Basic performance of the flow damper is confirmed as follows:**

(1) Water level is higher than the top of the standpipe (large flow)

- Flows from standpipe and the small flow pipe collide to each other in the vortex chamber and go to the outlet directly
- Vortex is not formed in the vortex chamber
- Resistance is small and large flow rate comes off

(2) Water level is lower than the top of the standpipe (small flow)

- Flow from the standpipe stops and only the flow from the small pipe flows into the vortex chamber
- Strong and steady vortex is formed
- Resistance is large and the injection flow rate becomes small

Draft Slide

4.2 Detailed Description of Tests and Results

US-APWR

1/8.4 scale tests

(3) During the flow switching

- Water level in the standpipe temporarily undershooted due to inertial force
- Water level recovered soon and the flow in the standpipe stopped so that the water level was maintained
- Gas did not enter from the standpipe to the vortex chamber

4.2 Detailed Description of Tests and Results

1/3.5 scale tests

(2) 1/3.5 scale tests

- Objectives
  - ✓ Confirmation of the flow and vortex appearance in the tank using a standpipe inlet model and anti-vortex cap
    - The Acc design utilizes the anti-vortex cap at the top of the standpipe to prevent the forming of a vortex and the gas leakage during the flow switching
    - Without the anti-vortex cap, it was foreseen that gas leakage affecting the flow, and flow rate could not be smoothly switched

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4.2 Detailed Description of Tests and Results

US APWR

1/3.5 scale tests

- Test apparatus
  - ✓The test apparatus consisted of a standpipe, a test tank, a pump and a piping
  - ✓The anti-vortex cap was made of transparent acrylic resin so as to observe the characteristics of the vortex at the inlet of the standpipe
  - ✓The scale of the inlet of the standpipe is approx. 1/3.5 for easy observation

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4.2 Detailed Description of Tests and Results

US-APWR

1/3.5 scale tests

Flow diagram of the visualization test apparatus of anti-vortex cap

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4.2 Detailed Description of Tests and Results

1/3.5 scale tests

Outline drawing of the visualization test apparatus of anti-vortex cap

Draft Slide

4.2 Detailed Description of Tests and Results

US APWR

1/3.5 scale tests

Full view of the 1/3.5 scale test apparatus

Draft Slide

4.2 Detailed Description of Tests and Results

1/3.5 scale tests

- Test conditions

Froude numbers were used to simulate the flow conditions at the time of switching flow rates

✓Pressure in Accumulator Tank :atmospheric pressure

✓Flow rates :[ ]to[ ]m^3/s ([ ]to[ ]gpm)

✓Anti-vortex Cap with Skirt :(1) attached and (2) not attached

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4.2 Detailed Description of Tests and Results

US-APWR

1/3.5 scale tests

- Parameters to be measured
  - ✓Transients of flow rate
  - ✓Water level in the tank

- Measuring equipment
  - ✓Ultrasonic flow meter
  - ✓Ruler attached on the sidewall of the tank

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4.2 Detailed Description of Tests and Results

- Test results and discussions (Flow characteristics)

1/3.5 scale tests

T No.1 : Without cap

T No.2 : With cap

Gas entrainment

No Gas entrainment

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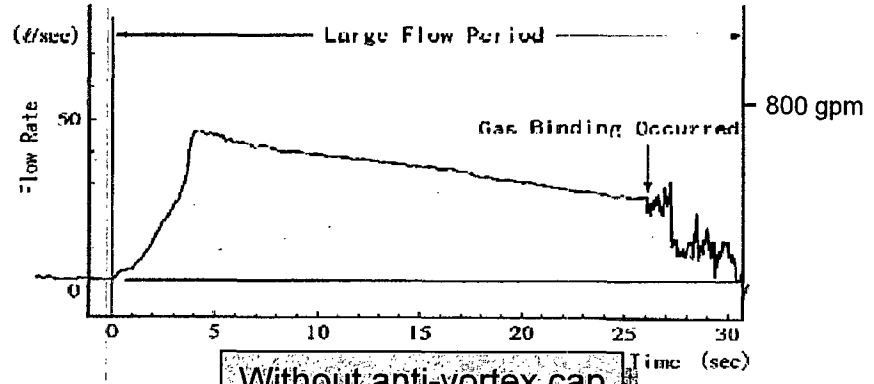
4.2 Detailed Description of Tests and Results

- Test results and discussions (Flow Characteristics)

1/3.5 scale tests

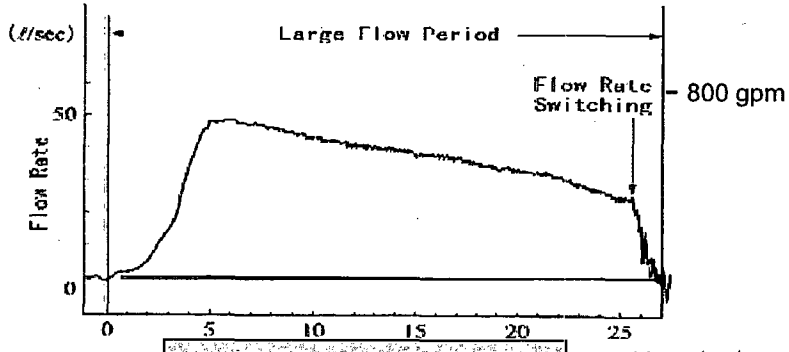


Without anti-vortex cap

✓Gas leakage started at 26 seconds

✓Variation of the flow rate became bigger for several seconds

✓Flow rate became smaller, and it took as long as five seconds until the flow rate became zero



With anti-vortex cap

✓Flow rate became zero in approx. one second from 25.5 seconds

✓Flow rate switched more quickly than the case without the anti-vortex cap

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(3) 1/5 scale tests

1/5 scale tests

➢ Objectives

✓ Confirmation of operation principle of the flow damper
Visualizing flow in the flow damper during large to small flow switching and small flow to confirm the flow characteristics

✓ Flow behavior during flow switching
Visualizing flow in the vortex chamber during large flow and flow switching, and a vortex during small flow

✓ Confirmation of performance during large and small flows
Evaluating the cavitation factor and flow coefficient during large and small flows to get the flow characteristics.

The flow characteristics obtained by the tests were compared with the results of 1/2 scale tests to confirm the validity of applying the similarity design method.

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4.2 Detailed Description of Tests and Results

US APWR

1/5 scale tests

➢ Test apparatus

- ✓ Test apparatus consisted of a tank, a flow damper, a standpipe, an injection piping and an exhaust tank
- ✓ The flow damper made of transparent acrylic resin was installed outside of the test tank so as to the characteristics of flow in the flow damper could be observed
- ✓ A ball gate valve was provided in the injection line for isolation pipe and a gate valve to adjust the resistance
- ✓ The test tank for multipurpose use was modified to simulate transient water level in an accumulator tank
- ✓ The scale of the flow damper was 1/5 so that several models could be installed and tested at the pressure of 1MPa

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4.2 Detailed Description of Tests and Results

1/5 scale tests

- Test apparatus

Draft Slide

4.2 Detailed Description of Tests and Results

1/5 scale tests

- Test apparatus

Draft Slide

4.2 Detailed Description of Tests and Results

US-APWR

1/5 scale tests

Outline drawing of the test apparatus

Draft Slide

4.2 Detailed Description of Tests and Results

1/5 scale tests

- Test apparatus
  - ✓ Test apparatus detailed parameters

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4.2 Detailed Description of Tests and Results

1/5 scale tests

➢ Test method

Visualization test method

✓ The flow in the flow damper was recorded using a video camera and observed

Low pressure test method

✓ Pressures in the test tank, the injection pipe and the exhaust tank, and water levels in the test tank and the standpipe were measured and recorded by PC, flow rate coefficient and the cavitation factor were calculated

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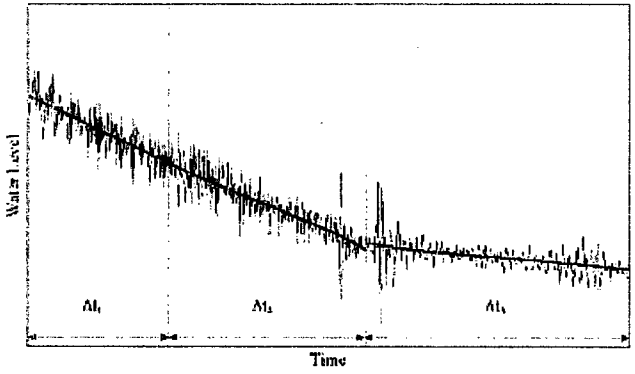
4.2 Detailed Description of Tests and Results

➢ Data Processing

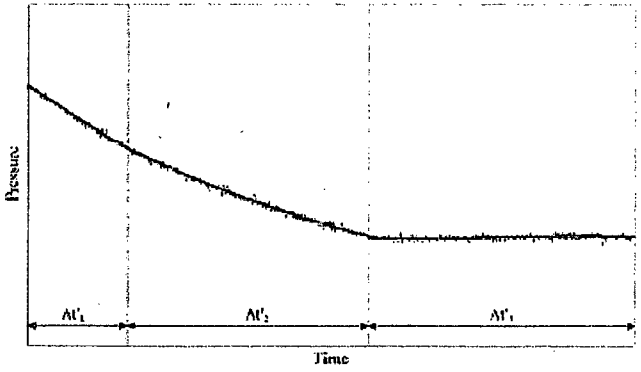
1/5 scale tests

In order to eliminate noises from the measured pressures and the water levels in the accumulator tank, the measured data were divided into several time sections as Δt_1, Δt_2, Δt_3, ... and $\Delta t'_1$, $\Delta t'_2$, $\Delta t'_3$, ...as shown in Figures (a) and (b).



(a) Measured Water Level in Accumulator Tank

A smoothened expression of water levels with polynomials was made to every section by the least-squares method.



(b) Measured Pressure in Accumulator Tank

A smoothened expression of pressures with polynomials was made to every section by the least-squares method.

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4.2 Detailed Description of Tests and Results

1/5 scale tests

➢ Data Processing (Cont.)

The flow rate coefficient and the cavitation factor σ_v are defined as follows;

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

$$\zeta_v = \frac{(P_A + \rho g H) - \left(P_D + \frac{\rho V_D^2}{2} + \rho g H'\right)}{\frac{\rho V_D^2}{2}}$$

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

ζ_v	:	Resistance coefficient of flow damper
P_A	:	Test tank pressure (Pa)
ρ	:	Density of water (kg/m^3)
g	:	Acceleration of gravity (m/sec^2)
H	:	Distance between water surface and center of flow damper (m)
H'	:	Distance between center of flow damper and the point P_D (m)
P_{at}	:	Atmospheric pressure (Pa)
P_v	:	Vapor pressure of water (Pa)
P_D	:	Static pressure of flow damper outlet piping (Pa)*
V_D	:	Velocity in the flow damper outlet piping (m/sec)*
σ_v	:	Cavitation factor

*These parameters were the value converted from the scale of prototype

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4.2 Detailed Description of Tests and Results

1/5 scale tests

- **Test conditions**
  - ✓ Visualization tests

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4.2 Detailed Description of Tests and Results

US APWR

1/5 scale tests

➢ Test conditions (cont.)

- ✓ Characteristic confirmation tests

- ✓ Initial Water Level in Test Tank :(1) level simulating the total water volume and (2) level of the inlet port of the standpipe
- ✓ Opening time of Valve :quickly as possible

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4.2 Detailed Description of Tests and Results

1/5 scale tests

➢ Parameters to be measured

- ✓ Water level, pressure and temperature in Test Tank
- ✓ Water level in Stand Pipe
- ✓ Pressure in Injection Pipe
- ✓ Flow in Vortex Chamber was visualized

➢ Measuring equipment

- ✓ Level gauges
- ✓ Pressure gauges
- ✓ Temperature gauges

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4.2 Detailed Description of Tests and Results

1/5 scale tests

- Test results

Flow of large flow

Vortex was not formed in the vortex chamber during large flow

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4.2 Detailed Description of Tests and Results

1/5 scale tests

Flow of large-to-small flow switching

Flow rate smoothly switched in a short time
Gas entrainment from the standpipe did not occur

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4.2 Detailed Description of Tests and Results

1/5 scale tests

Flow of small flow

Strong and steady vortex was formed in the vortex chamber

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4.2 Detailed Description of Tests and Results

US-APWR

1/5 scale tests

Summary of visualization tests

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4.2 Detailed Description of Tests and Results

US-APWR

1/5 scale tests

✓ Data can be profiled with normalized numbers

✓ Flow-switching ratio is approx.[ ]

- Flow rate sharply switched at the top of stand pipe

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4.2 Detailed Description of Tests and Results

1/5 scale tests

➢ Discussions and summary

✓ Confirmation of principle of the flow damper

- During large flow injection
  - It was confirmed that the vortex was not formed in the vortex chamber during large flow injection
- During large to small flow switching
  - It was confirmed that the flow to the outlet pipe, formed a swirl approx. in one second after the start of the flow switching
  - It was also confirmed that the flow rate smoothly switched in a short time
- During small flow injection
  - It was confirmed that the flow swirl quickly traveled to the outlet, and a strong and steady vortex was formed

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4.2 Detailed Description of Tests and Results

1/5 scale tests

➢ Discussions and summary (cont.)

✓ Confirmation of performance

- Data can be characterized by normalized numbers (cavitation factor and flow rate coefficient)
- The characteristics of large flow injection shows that the flow rate coefficient increased as the cavitation factor increased
- Flow-switching ratio is approx.[ ]
- The characteristics of small flow injection shows that the flow rate coefficient was independent of the cavitation factor

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(4) 1/2 scale tests

1/2 scale tests

➢ **Objectives**

✓ Confirmation of expected performance

- Resistance coefficient of flow damper: approx.[ ]
- Flow-switching ratio of large to small flows: approx.[ ]

✓ Flow characteristics

- Confirm that the flow coefficient obtained by the tests was characterized by normalized numbers (cavitation factor and flow coefficient)

✓ Confirmation of the water level where switching flow

✓ Evaluation of the effect of dissolved nitrogen gas

- Conduct the tests to evaluate the effect of dissolved gas under water

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4.2 Detailed Description of Tests and Results

1/2 scale tests

➢ Test facility

- ✓ The test facility consisted of a test tank, a flow damper, an injection pipe and an exhaust tank
- ✓ Heights of the test tank and the standpipe were the full scales and the diameters of the test tank and the flow damper were 1/2 scales
  - The water volume and the flow rate became 1/4, and the tests could be conducted simulating the actual time
  - Transient of the water level during flow switching in the standpipe could be as same as the actual one
- ✓ An air–operated ball valve was provided in the injection line for isolation and a gate valve to adjust the pipe resistance

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4.2 Detailed Description of Tests and Results

1/2 scale tests

- Test facility (cont.)

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4.2 Detailed Description of Tests and Results

1/2 scale tests

- Test facility (cont.)

Overview of the Test Facility

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4.2 Detailed Description of Tests and Results

US-APWR

➢ Test facility (cont.)

1/2 scale tests

Outline Drawing of the Test facility

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4.2 Detailed Description of Tests and Results

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➢ Test facility (cont.)

1/2 scale tests

Actual size

1 / 2 model size

Configurations of Actual and Test Tanks

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4.2 Detailed Description of Tests and Results

US-APWR

➢ Test conditions

1/2 scale tests

Test case	Test Tank pressure MPa (psi)	Exhaust Tank pressure MPa (psi)	Objective
Case1	4.04 (586)	0.098 (14)	Obtain data for ECCS performance evaluation during large LOCA
Case2	4.53 (657)	0.098 (14)	Obtain data for high pressure design
Case3	5.22 (758)	0.098 (14)	Obtain data of large differential pressure
Case4	4.04 (586)	0.49 (71)	Obtain data of small differential pressure

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4.2 Detailed Description of Tests and Results

US APWR

➢ Test conditions (cont.)

1/2 scale tests

- ✓ Resistance Coefficient of Injection Pipe : [ ]
- ✓ Initial Water Level in Accumulator Tank : actual operating condition
- ✓ Opening Time of Valve : [ ] sec*

* Set as short as possible to get data at small cavitation factors

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4.2 Detailed Description of Tests and Results

1/2 scale tests

➢ Parameters to be measured

- ✓ Water level, pressure and temperature in test tank
- ✓ Water level in standpipe
- ✓ Pressures in injection pipe and exhaust tank

➢ Measuring equipment

- ✓ Level gauges
- ✓ Pressure gauges
- ✓ Temperature gauges

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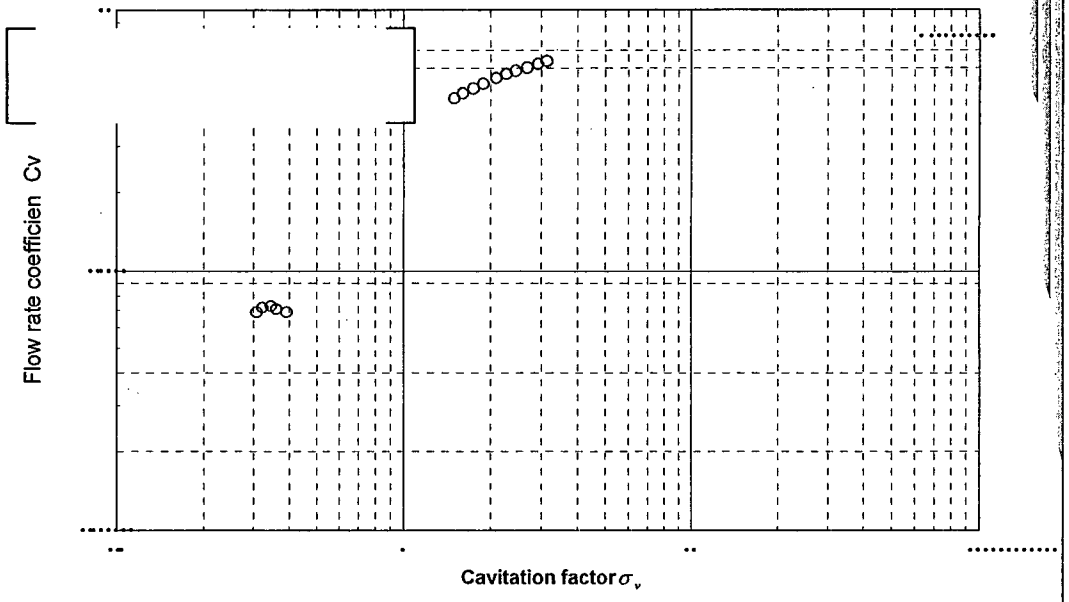
4.2 Detailed Description of Tests and Results

US-APWR

1/2 scale tests

➢Case1

- Initial Tank Pressure: 586psig
- Initial Back-Pressure: 14psig



✓ Data can be profiled with normalized numbers
✓ Resistance coefficient of large flow injection is mostly less than[ ]
✓ Flow-switching ratio is approx.[ ]

- Water level is maintained in a stand pipe
- Flow rate sharply switches at the top of stand pipe

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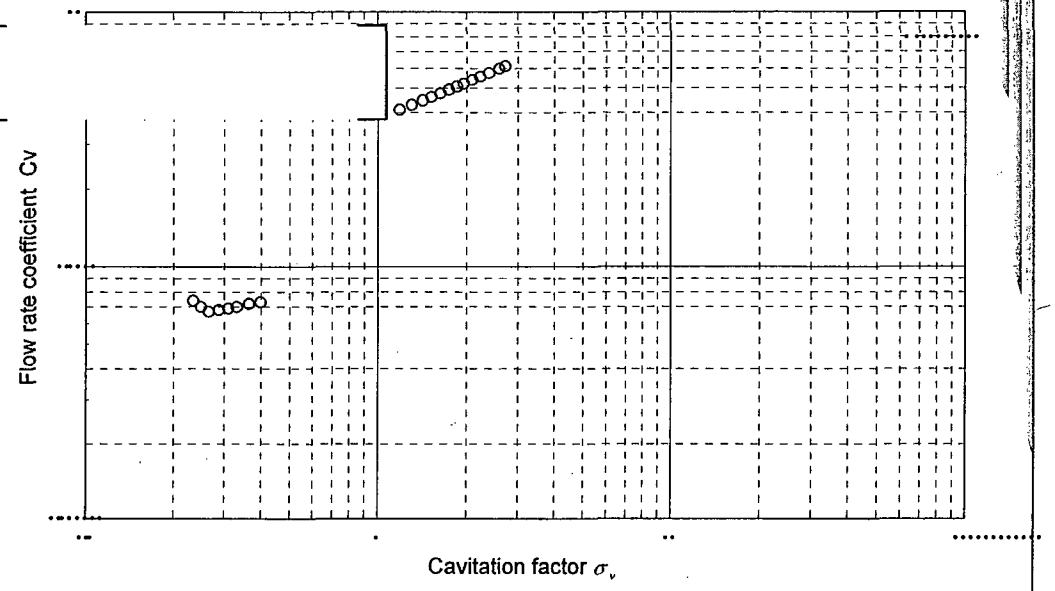
4.2 Detailed Description of Tests and Results

1/2 scale tests

➢Case2

- Initial Tank Pressure: 657psig
- Initial Back-Pressure: 14psig



✓Data can be profiled with normalized numbers

✓ Resistance coefficient of large flow injection is mostly less than[ ]

✓ Flow-switching ratio is approx.[ ]

- Water level is maintained in a stand pipe
- Flow rate sharply switches at the top of stand pipe

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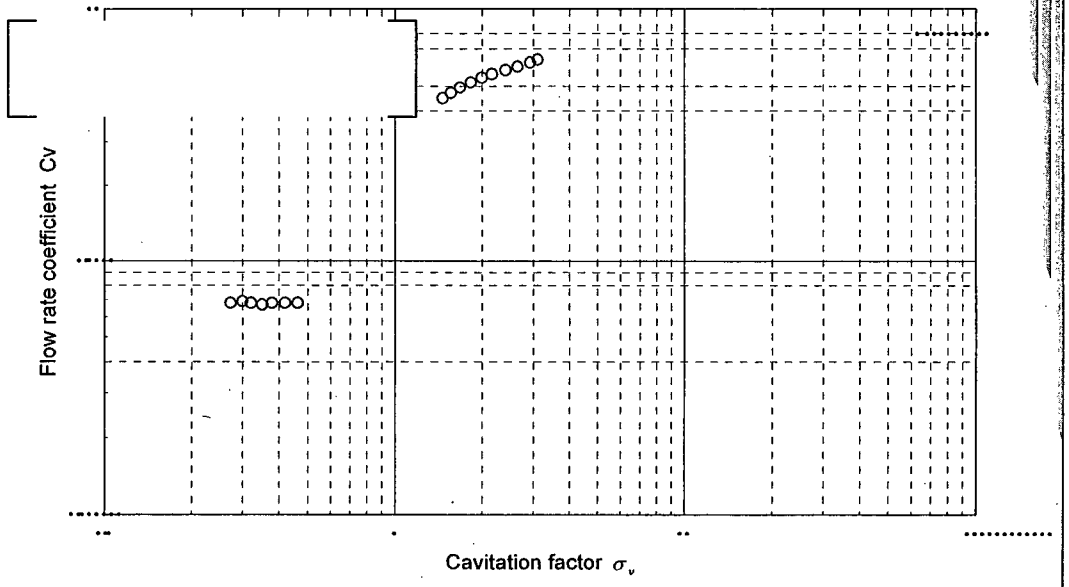
4.2 Detailed Description of Tests and Results

US-APWR

1/2 scale tests

➢Case3

- Initial Tank Pressure: 758psig
- Initial Back-Pressure: 14psig



✓ Data can be profiled with normalized numbers
✓ Resistance coefficient of large flow injection is mostly less than[ ]
✓ Flow-switching ratio is approx.[ ]

- Water level is maintained in a stand pipe
- Flow rate sharply switches at the top of stand pipe

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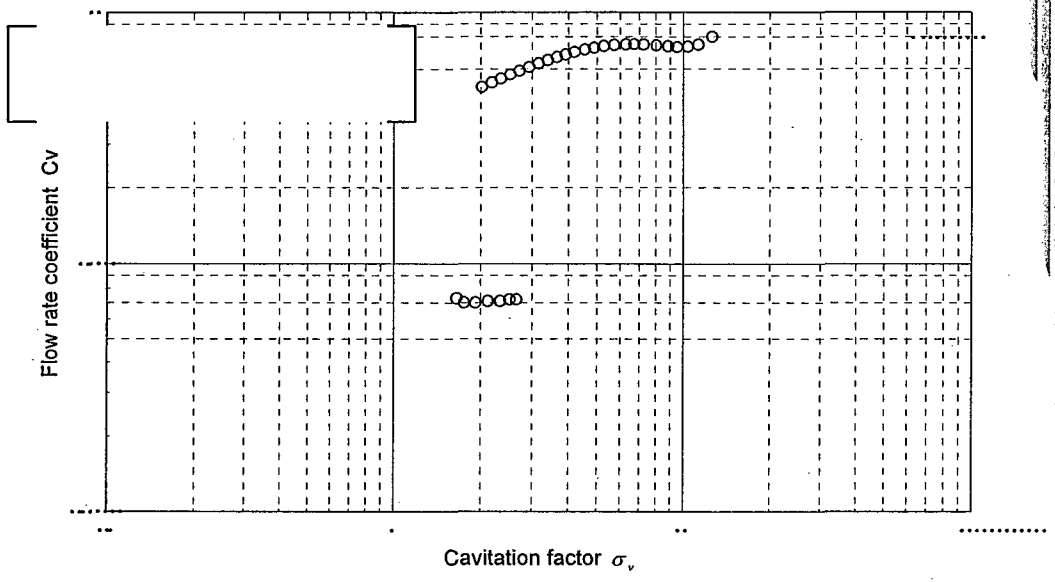
4.2 Detailed Description of Tests and Results

1/2 scale tests

➢Case4

- Initial Tank Pressure: 586psig
- Initial Back-Pressure: 71psig



✓Data can be profiled with normalized numbers

✓Resistance coefficient of large flow injection is mostly less than[ ]

✓Flow-switching ratio is approx.[ ]

- Water level is maintained in a stand pipe
- Flow rate sharply switches at the top of stand pipe

Draft Slide

4.2 Detailed Description of Tests and Results

1/2 scale tests

➢Case5

✓Data can be profiled with normalized numbers
✓Resistance coefficient of large flow injection is mostly less than[ ]
✓Duration of large flow injection is just a little longer (approx.[ ]sec.) than in Case 1
✓Flow-switching ratio is approx.[ ]
- •Water level is maintained in a stand pipe
- •Flow rate sharply switches at the top of stand pipe

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4.2 Detailed Description of Tests and Results

1/2 scale tests

➢Case6

✓Data can be profiled with normalized numbers
✓Resistance coefficient of large flow injection is mostly less than[ ]
✓Flow-switching ratio is approx.[ ]

•Water level is maintained in a stand pipe
•Flow rate sharply switches at the top of stand pipe

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4.2 Detailed Description of Tests and Results

1/2 scale tests

➢Case7

✓Data can be profiled with normalized numbers
✓Resistance coefficient of large flow injection is mostly less than[ ]
✓Flow-switching ratio is approx.[ ]

•Water level is maintained in a stand pipe
•Flow rate sharply switches at the top of stand pipe

Draft Slide

4.2 Detailed Description of Tests and Results

1/2 scale tests

Discussions and summary

- Performance confirmation during large flow
  - ✓In case of LOCA condition, resistance coefficient was approx.[ ]
  - ✓The results were consistent with the performance goal

- Performance confirmation during small flow (flow switching ratio)
  - ✓The flow rates before and after the flow switching were approx.[ ]m^3/s (approx.[ ]m^3/h) and approx.[ ] m^3/s (approx.[ ]m^3/h)
  - ✓The flow-switching ratio was approx.[ ]
  - ✓The results were consistent with the performance goal

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4.2 Detailed Description of Tests and Results

US-APWR

1/2 scale tests

Discussions and summary (cont.)

- Water level when switching flow
  - ✓It was confirmed that flow rate was switched at the expected water level
  - ✓Water levels for flow-switching were within the range from [ ]mm to[ ]mm of the expected water level
  - ✓Water level for flow-switching was limited to a sufficiently small range

- Water level undershoot when switching flow rate
  - ✓The undershoot of water level in each test during the flow switching was shorter than the height of the standpipe and sufficient margins were provided to prevent gas entrainment

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4.2 Detailed Description of Tests and Results

1/2 scale tests

Discussions and summary (cont.)

- The effect of dissolved nitrogen gas
  - ✓In the test with nitrogen-saturated water, the duration of large flow injection was only slightly longer (approx.[ ] seconds)
  - ✓Water in the actual accumulator tank is not saturated with nitrogen, so it can be assumed that dissolved nitrogen is less effective
- The result of the simulation of the function test
  - ✓It was confirmed that the cavitation factors over a wide range can be obtained

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4.3 Scalability and Validity of Flow Rate Characteristics

➢ Normalized Parameters

✓ Navier-Stokes equation gives :

- Reynolds number :fluid viscosity for internal flow
- Froude number :gravity for free surface

✓ Cavitation gives :

- Cavitation factor :generation of bubbles for internal flow

- A Reynolds number and a cavitation factor affect flow rate characteristics of flow dampers
- A Froude number determines the time scale of transients of water levels in accumulator tank and standpipe

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4.3 Scalability and Validity of Flow Rate Characteristics

- **Reynolds numbers**
  - ✓ Actual plant : Re=[ ]
  - ✓ 1/2-scaled Model : Re=[ ]
  - ✓ 1/5-scaled Model : Re=[ ]

  Reynolds numbers are calculated with respect to the throat

- **Cavitation factor**
  - ✓ Cavitation factors are common for the actual plant and the models

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4.3 Scalability and Validity of Flow Rate Characteristics

Draft Slide

4.3 Scalability and Validity of Flow Rate Characteristics

- **Scalability**
  - ✓ Flow rate coefficients with respect to cavitation factors collapsed into same lines for large and small flow rates respectively
  - ✓ The effect of friction is negligible
  - ✓ The measured characteristics can be applicable to the actual plant with respect to a cavitation number

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4.3 Scalability and Validity of Flow Rate Characteristics

- **Validity of data for large flow rate injection**
  - ✓ Flow rate coefficient lessens as a cavitation factor gets smaller
    - It is reasonable because cavitation is stronger for a small cavitation factor
  - ✓ Flow rate coefficient approaches a constant value as a cavitation factor gets larger
    - It is reasonable because cavitation vanishes for a large cavitation factor
- **Validity of data for small flow rate injection**
  - ✓ Flow rate coefficient is independent of cavitation factor
    - It is reasonable because there is no effect of cavitation

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5. Concept and Justification of Safety Analysis Model

Contents

5.1 Characteristic Equations of Flow Rate for Safety Analysis

5.2 Uncertainty of Characteristic Equations

5.3 Errors of Water Level for Switching Flow Rate

5.4 Acc Simulation Method for Safety Analysis

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5.1 Characteristic Equations of Flow Rate for Safety Analysis

Experimental formulae were derived separately for large and small flow rate injections by curve fitting using the data of ½-scaled tests

- **For large flow rate injection**

$$C_v = 0.7787 - 0.6889\exp(-0.5238\sigma_v)$$

- **For small flow rate injection**

$$C_v = 0.07197 - 0.01904\exp(-6.818\sigma_v)$$

- **Flow resistance coefficient**

$$\zeta_v = \frac{1}{C_v^{\,2}}$$

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5.1 Characteristic Equations of Flow Rate for Safety Analysis

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5.2 Uncertainty of Characteristics Equations

- **Estimation of uncertainty**
  - ✓ Data of ½-scaled model were used to make the characteristic equations
  - ✓ Estimation of uncertainty was carried out in accordance with the Japanese version of "Measurement Uncertainty," Supplement on Instruments and Apparatus, Part 1, ASME Performance Test Codes, (ANSI/ASME PTR 19.1-1985) translated and printed by JSME, 1987
- **Causes of uncertainty**
  - ✓ Experimental errors
  - ✓ Instrumental errors
  - ✓ Manufacturing errors

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5.3 Errors of Water Level for Switching Flow Rate

- **Errors of switching level**
  - ✓ Displacement of water level at switching of flow rates from the elevation of the inlet port of the standpipe
  - ✓ Water level at switching of flow rates was defined as an intersecting point of two curves of water levels for large and small flow rate injections

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5.4 Acc Simulation Method for Safety Analysis

➢ Simulation Model

- ✓ Resistance coefficient ζ_v is calculated using the correlation between σ_v and C_v
- ✓ Correlation is incorporated into the LOCA analysis code and ζ_v is calculated at each time-step

➢ Computational procedure for ζ_v

1) σ_v is calculated from the flow condition at flow damper

$$\sigma_v = \frac{P_D + P_{at} - P_v}{\left(P_g - P_D\right) - \frac{\rho V_D^2}{2} + \rho g H}$$

σ_v	:	Cavitation factor
P_{at}	:	Atmospheric pressure
P_D	:	Flow damper outlet pressure
P_g	:	Holding Gas pressure in accumulator
P_v	:	Vapor pressure
ρ	:	Density of water
g	:	Acceleration of gravity
H	:	Height from accumulator water level to outlet pipe
V_D	:	Velocity in injection pipe

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5.4 Acc Simulation Method for Safety Analysis

➢Computational procedure for ζ_v (Cont.)

2) C_v is calculated using the following correlations :

For Large Flow-Rate: $C_v = 0.7787 - 0.6889\exp(-0.5238\sigma_v)$

For Small Flow-Rate: $C_v = 0.07197 - 0.01904\exp(-6.818\sigma_v)$

3) C_v is converted to ζ_v

- $_v = 1/C_v^2$

4) Total resistance coefficient calculation

$$K_{acc} = \zeta_v + K_{pipe}$$

K_{acc} : Total resistance coefficient of accumulator and injection pipe

K_{pipe} : Total resistance coefficient of injection pipe

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

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5.4 Acc Simulation Method for Safety Analysis

- Preliminary Plant Analysis

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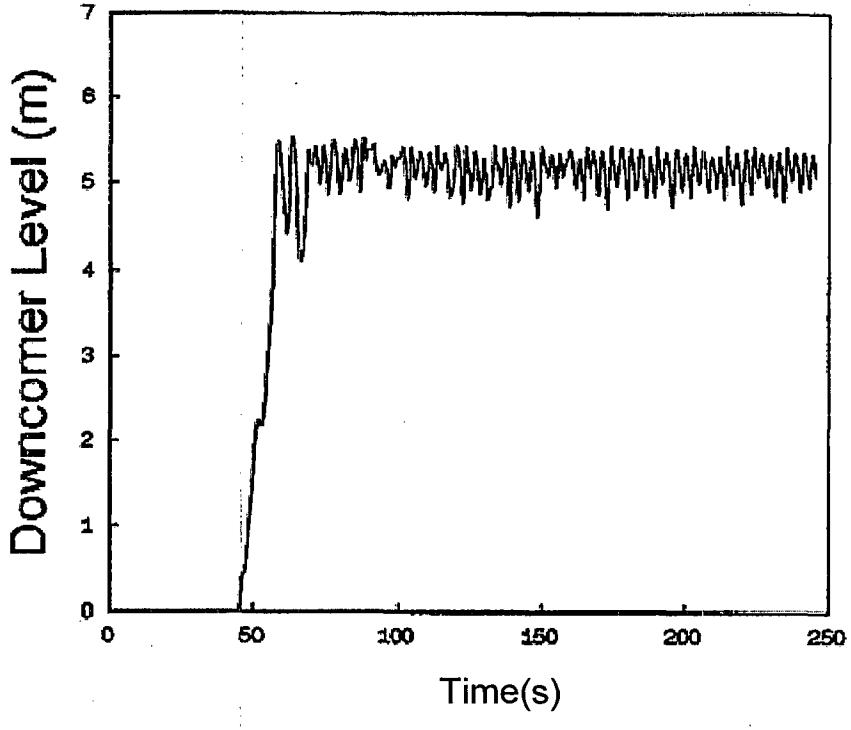
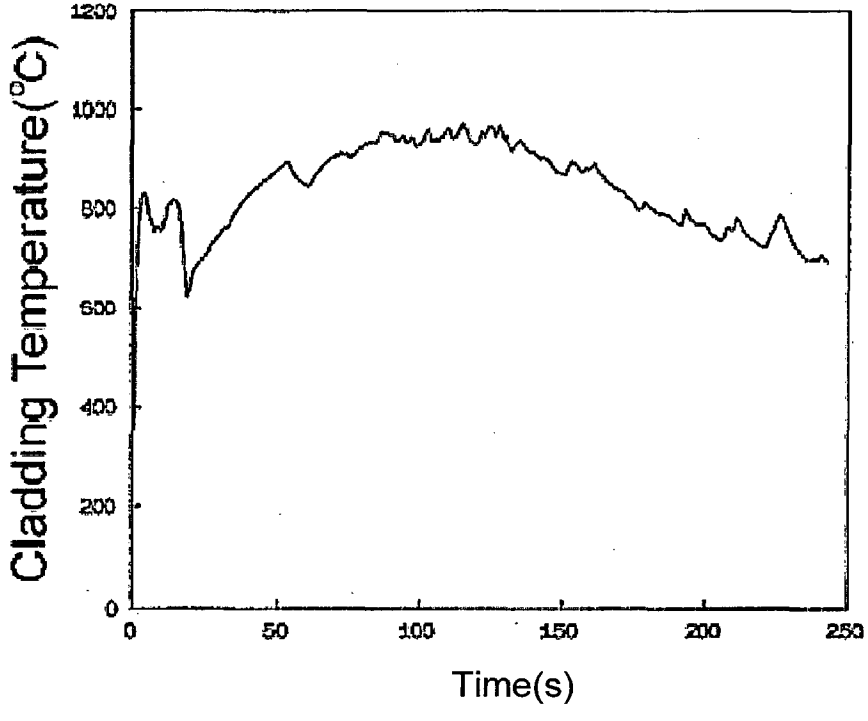
5.4 Acc Simulation Method for Safety Analysis

➢ Preliminary Plant Analysis (Cont.)

(Japanese APWR results by SATAN-M and BASH-M)



Downcomer Level



Fuel Cladding Temperature

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6. Summary

- The Advanced Accumulator design has been validated by the four kinds of tests
- These tests and evaluations have demonstrated that the behavior of the design is scalable
- The testing performed covered the full range of the expected applicability of the system installed in an APWR under design basis LOCA conditions

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6. Summary

- Testing fully investigated the features of this passive system thus ensuring a well understood performance of this component
- Empirical flow coefficients have been developed using these test results for use in an integrated thermal hydraulic model of the APWR Reactor Coolant and ECCS systems