Experimental Study on RCCV of ABWR Plant
Part 1: Outline of Research Study

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1. INTRODUCTION

Steel containment vessels have generally been used for BWR (Boiling Water Reactor)-type nuclear power plants in Japan. However, in accordance with the development of the advanced-type BWR (ABWR), the introduction of a reinforced concrete containment vessel (hereinafter called "RCCV") has been proposed because it enables greater freedom in flexibility of configuration. A considerable number of research reports on experimental studies concerning RCCV's have been published recently, reflecting the developments in the field. The study presented here aimed to accumulate basic data on RCCV's and verify the integrity and ultimate strength of a trial-designed RCCV and the validity of its design method.

2. OUTLINE OF RCCV

For the trial-designed RCCV, two boundaries, the pressure boundary for maintaining pressure and the leakage boundary for preventing any form of leakage, which in conventional steel containment vessels are formed by structural members and leak-resisting members, are formed by reinforced concrete and steel lining, respectively. The principal features of the RCCV are as follows.

(1) The reactor containment vessel is made of reinforced concrete, composed of cylindrical wall, top slab, and base mat, and a removable steel drywell head forms the primary containment pressure boundary together with them.

(2) A liner of 6.4mm is provided at the inner surface of the RCCV to maintain leak-tight integrity of the containment.

(3) The RCCV cylindrical wall is integrated with the floor slab of reactor building, and further, the top slab is integrated with fuel-pool girders which are connected with the reactor building walls and floors.

(4) The diaphragm floor is a slab of reinforced concrete, integrated with the RCCV and supported by Reactor Pressure Vessel (RPV) pedestal.

Figure 1 shows the plan and vertical-section of the reactor building and the RCCV. The dimensions of the RCCV are about 29m for the inner diameter, about 29.5m for the height from the upper edge of the base mat to the lower edge of the top slab, and about 40m for the total height up to the top of the fuel-pool girder.

3. TRIAL DESIGN FOR RCCV

The trial design of the RCCV is based on the "Technical Standard of Concrete Containments for Nuclear Power Plants (Draft)" by the Agency of Natural Resource and Energy in Ministry of International Trade and Industry in Japan

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(hereinafter called "MITI-CCV Technical Standard (Draft)") and the several Standards for Structural Calculations of the Architectural Institute of Japan. As shown in Figure 2, the types of load taken into account for the design are dead load, live load, piping load, internal pressure load, thermal load, and seismic load (Design horizontal shear stress; $\tau_d=23.4\text{kgf/cm}^2$ (2.29Mpa)). The design internal pressure load, $P_d$, is $3.16\text{kgf/cm}^2$ (0.31Mpa) and the ambient design temperature during an accident in the reactor containment vessel is $171^\circ\text{C}(340^\circ\text{F}).$

As for seismic force, the RCCV was designed by allowable stress design method so that the seismic force, which was determined by comparing the maximum design earthquake $S_1$ (for $S_1$ the maximum horizontal acceleration obtained from the analysis of earthquake motion, taking into account the condition of the ground concerned, was 300gal.) and the static seismic force, which are based on the seismic design guideline in Japan. In addition, it was confirmed that the ultimate strength of the structure was sufficiently safe for the extreme design force $S_2$ (in such a case the maximum horizontal acceleration would be 450gal.).

The materials used in the trial design are concrete of design compressive strength $300\text{kgf/cm}^2$ (29.4Mpa), main reinforcing bar of 51mm-diameter, whose yield strength is $3500\text{kgf/cm}^2$ (SD3S; 343Mpa), and liner of SGV49(equivalent to ASME SA416Gr.70).

Stress analyses were made by three-dimensional FEM technique considering that RCCV is integrated with the reactor building through the floors and fuel-pool girders. The outline of three-dimensional FEM model is shown in Figure 3. Programs such as NASTRAN were used for the analyses.

Figure 4 shows the designed reinforcing bar arrangement and details of the RCCV. The stress calculation for the cross-section was carried out using an elastic FEM technique, and the reinforcement ratio for the cylindrical part was determined to be 1.3 to 1.8% in the vertical direction and 1.4 to 2.0% in the horizontal direction.

4. TEST PROGRAMS

The experimental study was planned to cover a series of a variety of tests to verify the design formula which was used for the RCCV trial design and to confirm the vessel's integrity, etc. Figure 5 explains the parts of RCCV which were tested. A flow chart of the series of tests is given in Figure 6.

5. OUTLINE OF TEST RESULTS

The ultimate strength of the reinforced concrete structure of the trial-designed RCCV was evaluated, along with its integrity on the design load level, applicability of the design standard and the validity of the design method.

The results obtained from the tests can be summarized as follows.

(1) Integrity of RCCV on the design load level
(a) Excessive cracks did not occur.
(b) An elastic behaviour was observed in its deformation and stiffness, accompanied by an appropriate recovery rate.
(c) The strain in the reinforcing bars was lower than the level that corresponds to the allowable stress.
(d) It was confirmed that the liner and its anchors performed good deformability to the structure without failure or pull-out, which proved the tightness of the liner against leakage.
(e) The temperature of the concrete around the penetrations was within the allowable limit.

Accordingly, it was concluded that the behaviour of the main reinforcement was within an elastic range and liner including its anchor possessed sufficient strength against design load, and the integrity of the structure of the RCCV was finally confirmed.

(2) Ultimate strength of RCCV on the ultimate load level
(a) The top slab and the cylindrical part of the RCCV possessed enough strength against the internal pressure load, the maximum capacity was four times the design internal pressure.

(b) The ultimate shear capacity of the RCCV was confirmed to be 3.6 times the design horizontal load.

Concerning the strengths of various parts of the RCCV, their calculated values obtained from the various strength evaluation equations are reported in the succeeding paper (Saito et al., 1989). They showed that the RCCV had a sufficient safety margin in strength in comparison with the design load.

(3) Validity of the design method

The structural design of the RCCV was performed by the three-dimensional FEM analysis. The rebar stress evaluated from the measured rebar strain under the internal pressure corresponding to the Structural Integrity Test, was between 0.70 and 0.86 times the value obtained from the elastic FEM analysis. This result suggests that the analytical method is appropriate.

6. CONCLUSIONS

It was confirmed that the RCCV, which was designed as the integrated structure with the reactor building, had high integrity as a containment vessel under the design load level, and that its ultimate capacity was four times the design internal pressure load and about 3.6 times the design horizontal load.

7. ACKNOWLEDGMENT

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REFERENCES


Figure 1  Plan and Section of Trial-Designed Reactor Building

Figure 2  Types of Load for the Design

Figure 3  3D FEM Model for Trial-Designed Reactor Building
Figure 4 Re-Bar Arrangement for Trial-Designed RCCV
Figure 5  Experimental Studies and Their Position

- **1.** Experiment of Total Model in Large Scale
  - Total Model Demonstration Experiment (Part 6.7)
- **2.** Experiment of Thermal Load of High Temperature Pipe Penetration
  - Partial Model Demonstration Experiment (Part 8)
- **3.** Transverse Shear Experiments on Disk Model
  - Basic Experiments (Part 2)
- **4.** Shear Experiment of Liner Anchor (Part 8)
  - Partial Model Demonstration Experiment (Part 4)
- **5.** Structural Experiments on Re-bar Joint
  - Partial Model
- **6.** Transverse Shear Experiments on Disk Model
  - Transverse Shear Experiments on Beam Element
  - Basic Experiments (Part 3)

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Figure 6  Flow Chart of Experimental Study of RCCV Structure

- **1.** Experiment of Total Model in Large Scale
  - 1 specimen
  - Internal pressure
  - Thermal load
  - Horizontal force
  - 1/6, 1/12
- **2.** Experiment of Top Slab
  - 1 specimen
  - Internal pressure
  - Thermal load
  - 1/10
- **3.** Experiment on Joint of Diaphragm Floor
  - 4 specimens
  - Tension
  - Shear
  - 1/3
- **4.** Shear Experiment of Liner Anchor
  - 10 specimens
  - Shear
  - 1/1
- **5.** Torsional Loading Experiments on Cylinder with Openings
  - 2 specimens
  - In-plane shear
  - 1/12
- **6.** Experiment of Thermal Load on High Temperature Pipe Penetration
  - 1 specimen
  - Thermal load
  - 1/1
- **7.** Transverse Shear Experiments on Disk Model
  - 4 specimens
  - Membrane
  - Bending
  - Shear
  - 1/5, 1/6

A. Verification of the RCCV's Integrity
B. Confirmation of the Ultimate Strength
C. Applicability of the Design Standard
D. Validity of the Design Method
E. Establishment of the Design Standard