

Test Plan for In-vessel Downstream Effect (IDE) of the APR1400

Revision 4

Non-proprietary

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This test plan for in-vessel downstream effect was prepared to provide the test condition and test method for the pressure drop tests which will be performed at the APR1400 specific conditions.

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Revision History

Revision	Page	Reason for Revision
0	All	First issue
1	6	The number of test cases was increased.
	9	The addition procedure of chemical precipitate was modified to meet settling criteria.
	10	The acceptance criterion of HLSO was added.
	12	Table 2 was modified since the latent debris ratio (particle/fiber) will be finalized during strainer bypass testing.
	13	Table 3 was updated to add test cases of 2 SI flow condition and HLSO operation.
2	4,5,6	Test parameters were described more clearly.
	6,7	The SiC is used for particle surrogate.
	7	The preparation procedure of chemical precipitate was modified to meet settling criteria.
	10	The acceptance criteria were modified by including pressure head due to flow losses in the RCS.
	10,11	Reference 2 and 6 were modified by revised version, and Reference 3 was added.
	12	Table 2 was modified by including the results of strainer bypass testing, and the change of particulate surrogate.
	13	Table 3 was updated to the test schedule.
3	All	Editorial change
	4	Recirculation start time and test flow rate for CL break were modified.
	7	Fiber length distribution was modified based on the APR1400 specific test results.
	7, 9	The procedure of chemical preparation and addition was described more clearly.
	10	The acceptance criteria were modified by changing recirculation start time.
	10, 11	Reference 2 and 6 were modified by revised version, and Reference 5

Revision	Page	Reason for Revision
3	10, 11	was deleted.
	12	Recirculation start time and test flow rate for CL break were modified in Table 1.
	13	Table 3 was modified as follows: <ul style="list-style-type: none"> · Flow rate in Test No. APR1400-61 ~ 91 · Amount of AIOOH addition in Test No. APR1400-51 ~ 101 · Test schedule
4	All	Editorial change
	1	The purpose of revised test plan was added.
	10	<ul style="list-style-type: none"> · The available driving heads under each LOCA scenario were modified reflecting the Ref. 2. · Issue date of Reference 2 was inserted.
	13	The schedule for sensitivity test (Test No. APR1400-28) was added.
	15	Fig. 3 for the comparison of gaps between mock-up fuel assembly and test column was added.

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1. Introduction

The containment building of nuclear power plants is designed to prohibit radioactive materials release and to facilitate core cooling in the event of a postulated loss-of-coolant-accident (LOCA). The cooling process should make water discharged from the break and containment spray be transported to a sump area for recirculation cooling by the emergency core cooling system (ECCS) and the containment spray system (CSS). The strainers with perforated screen are installed in a sump area to prohibit the debris passing to downstream area and to protect the components of the ECCS. However, some fibrous material, particulates and chemical products could be introduced into the ECCS and the reactor coolant system (RCS). This phenomenon could be harmful for long-term core cooling (LTCC) when recirculating coolant is supplied from the containment sump. During operation of ECCS to recirculate coolant from the containment sump, debris in the recirculating coolant may accumulate on the bottom nozzle and fuel rod surface of fuel assembly (FA) causing resistance to core cooling flow.

The scope of Generic Safety Issue 191 (GSI-191) addresses various concerns associated with the operation of the ECCS and the CSS in the recirculation mode [Ref. 1]. These concerns include debris generation associated with a postulated high energy piping break, debris transport to the containment sump when the ECCS is operated in the recirculation mode, and the effects of debris that might pass through the sump strainers on downstream components and fuel regions.

The APR1400 is a new type plant, and sump strainers are installed to prevent the debris transport to a downstream region. To resolve the in-vessel downstream effect concern, KHNP conducts validation tests using a mock-up FA of PLUS7 which is the fuel assembly model of the APR 1400.

The purpose of this test plan is to perform a sensitivity test in the most limiting condition with a re-manufactured test column, which meets the nominal value of the FA pitch and its tolerance (0.58 mm (0.023 inch) \pm 0.15 mm (0.006 inch)), as shown in Figure 3.

2. Test Facility

KHNP designed a test loop to measure the pressure drop across a mock-up PLUS7 FA that simulates the APR1400 FA with a debris laden fluid. A schematic diagram and photo of the test loop are shown in Figure 1 and Figure 2 respectively. The test loop is composed of four main parts:

- Mixing tank system
- Recirculation system
- Test column
- Control and monitoring system

2.1 Mixing Tank System

The mixing tank system is composed of a debris mixing tank and a chemical mixing tank. The debris mixing tank is manufactured as a transparent acryl tank with a cylindrical shape, and it is capable of water suction in the downward vertical direction. A debris stirring tool is installed downward vertically at the top of the tank. A chiller piping and a heater are installed in the tank to control the water temperature. This heater is connected to a temperature control system, and the water temperature can be controlled from an environmental temperature of about 20 °C (68 °F) to a high temperature of 60 °C (140 °F) . A chemical mixing tank is installed on the upper part of the debris mixing tank to control the procedure of chemical surrogates addition to the test loop. It has a cylindrical shape with a 100 liter (26.4 gallon) volume and uses a chemical stirring tool.

2.2 Recirculation System

The circulation system pumps water from the debris mixing tank, through the circulation piping and the test pool, and back into the debris mixing tank. A 1 kW pump draws water out of the bottom of the debris mixing tank. The flow rate is controlled by a control system with a computer. An electromagnetic flow meter measures the flow rate and provides feedback to the control system to maintain a constant flow rate.

2.3 Test Column

The test column is composed of a mock-up fuel assembly in the test pool. The mock-up fuel assembly has a height of 2.5 m (8.2 ft) without fuel pellets, and is located on a simulated core support plate with a thickness of 30 mm (1.18 inch) and 70 mm (2.75 inch) flow holes. It includes top and bottom nozzles, a debris capturing fuel filter, top and bottom grids, four spacer grids, and 16 x 16 fuel rods. Pressure drops are measured at five points: the bottom nozzle (BN) and P-grid, the bottom grid, at four mid grids, at the top grid and top nozzle, and along the full length.

The test pool is made of transparent acryl to be visible inside during the test. Water enters through a 40 mm (1.5 inch) nozzle at the bottom of the test pool and flows upward and exits through a 40 mm (1.5 inch) outlet at the top of the test pool. The bottom unit and top unit of the test pool excluding the fuel assembly region play the respective roles of the lower plenum and upper plenum of the reactor vessel. The water temperature in the test pool is measured by thermocouples (T/Cs) inserted through ports in the bottom and top.

2.4 Control and Monitoring System

The control system regulates continuously the following parameters:

- Water flow rate
- Water temperature

The monitoring system records continuously the following data:

- Water temperature in the test pool and mixing tank
- Flow rate
- Differential pressure(dP) from 5 dP gauges

The data can be recorded at a time interval chosen by the operator. The monitoring system is also used to check the slope of the dP versus time graph in order to evaluate whether the dP meets a steady state condition.

3. Test Conditions

3.1 Test Parameters

This test reflects the recirculation flow, temperatures and debris conditions under the recirculation modes after a LOCA. Table 1 and Table 2 represent the flow conditions and debris amounts of the APR1400 under a LOCA.

3.1.1 Test Flow Rate

After a LOCA, the maximum flow rate to the reactor vessel is expected 4,940 gpm (18,699 lpm) when all four safety injections are available [Ref. 2]. The number of APR1400 fuel assembly is 241.

In the event of a hot leg (HL) break, all the ECC water passes through the core to exit the break location. The HL break condition at the maximum flow rate is chosen to obtain maximum pressure drop at the test column. Therefore, the ECC flow rate per FA is :

$$\frac{4940\text{gpm}}{241} = 20.5\text{gpm} \text{ (77.6 lpm)}$$

In the event of a cold leg (CL) break, most of the ECC water spills directly out of the break location. The maximum ECC flow rate to the core was selected as the core boil-off rate at the time of the start of recirculation. The ECC flow rate per FA is 3.64 gpm (13.8 lpm) at the recirculation start time, which is around 700 seconds after a LOCA [Ref. 2]. For the conservative CL break tests, a multiplier of 1.2 was applied as shown below:

$$\text{Test flow rate} = 3.64 \text{ gpm} \times 1.2 = 4.37 \text{ gpm (16.6 lpm)}$$

3.1.2 Water Temperature and Chemistry

The water temperature at the beginning of test will be set to 22 °C (71.6°F). This temperature will be maintained at 22 °C ± 1 °C during the test. Tap water is used as the testing fluid to adopt the stability of the WCAP-16530-NP precipitates [Ref. 3].

3.1.3 Debris Conditions

The recirculating coolant may entrain debris that can be categorized as particulate, fiber, or chemical precipitates. The weight of latent debris is 200 lbm, composed of 185 lbm of particulate and 15 lbm of fiber. All the debris except for fiber transported to the containment sump is assumed to bypass the strainer [Ref. 2].

Particulate Debris

Epoxy coatings are considered to be destroyed within the Zone of Influence (ZOI). Based on an upstream analysis, the quantity of destroyed coatings is 3.1 ft³. NEI-04-07 estimates the particle size of failed coatings to be 10 μm on average with a density of 94 lbm/ft³ [Ref. 4]. A suitable and common surrogate, as used in the test held in United States, is silicon carbide (SiC) with a mean particle size of 10 μm and material specific gravity of 3.2 which corresponds to a density of 199.5 lbm/ft³. The SiC is selected for resistance to dissolution in the potable water and interaction with other materials. While the requirement for the characteristic size is 10 μm spheres, the SiC surrogate contains a size distribution. This is actually quite conservative since it will create a higher packing density and create more drag and head loss in the debris bed. The size distribution of the SiC used in test will be provided in the test report summary. To determine what amount of SiC is added to the test is important because the volume of particulates is preserved. Therefore, the maximum amount of SiC to be added is calculated as follow:

$$M_p = 3.1 \text{ ft}^3 \times 199.5 \frac{\text{lbm}}{\text{ft}^3} / 241 = 2.57 \text{ lbm} \quad (1164 \text{ g})$$

Similarly, the mass of latent particulate to be added is calculated as follow:

$$M_{lp} = \frac{185 \text{ lbm}}{241} = 0.767 \text{ lbm} \quad (348 \text{ g})$$

Fibrous Debris

Fibrous insulation is not used in the ZOI inside containment of the APR1400. However latent fiber is assumed, and the assumed quantity is 15 lbm. The latent fiber is represented by NUKON® low density fiberglass, which NEI-04-07 recommends, with an as-fabricated density of 2.4 lbm/ft³ (see NEI-04-07 SER Appendix VII). Total strainer bypass fiber for the APR1400, with 15 lbm of latent fiber, is 3.68 lbm [Ref. 2]. The mass of fiber to be added to the test is calculated as follow:

$$M_r = \frac{3.68 \text{ lbm}}{241} = 0.015 \text{ lbm} \quad (6.93 \text{ g})$$

Chemical Precipitates

Based on the design conditions [Ref. 2], the following chemical precipitates may be available in the IRWST sump fluid.

- Calcium Phosphate : 1.5 lbm (0.7 kg)
- Sodium Aluminum Silicate : 9.5 lbm (4.3 kg)
- Aluminum Oxy-hydroxide : 397 lbm (180.1 kg)

Given the relative proportions, since aluminum oxy-hydroxide (AlOOH) can be conservatively used to represent the other precipitates [3], only AlOOH is used in the test. The total chemical precipitate mass of 408 lbm (185.1 kg) will be represented by AlOOH. The chemical precipitate will be prepared in accordance with the WCAP-16530-NP, and batched into the test tank in pre-defined quantities to collect the head loss data [Ref. 3]. This precipitate suspension will have a calculated concentration of 11 grams per liter. The chemical precipitate settling will be measured within 24 hours of the time the precipitate will be used, and the 1-hour settled volume of 10 ml solution will be 6.0 ml or greater, and within 1.5 ml of the freshly prepared precipitate. The volume of prepared AlOOH surrogate for the test is calculated as follow:

$$V_{\text{AlOOH}} = 185.1 \text{ kg} / 241 \times \frac{\text{liter}}{0.01 \text{ kg}} \times \frac{1 \text{ gal}}{3.785 \text{ liter}} = 18.5 \text{ gal} \quad (70 \text{ liters})$$

3.2 Test Matrix

The test matrix and schedule are shown in Table 3. Since the debris condition of HL break and CL break accident are different respectively, two series of tests are planned. Tests of APR1400-11 through APR1400-51 are for HL break accident, and tests of APR1400-61 through APR1400-101 are for CL break accident.

4. Test Procedure

4.1 Debris Preparation

The debris batches will be prepared according to the test matrix.

4.1.1 Particulate

The SiC can be weighed out in dry form and does not require further preparation. Before introduction, water will be carefully added into the buckets and mixed lightly to suspend the particulate and to pour easily.

4.1.2 Fiber

Fibrous debris is represented by fiberglass insulation. The fiber length distribution for this test is listed below:

- Fiber length < 500 μm : []^{TS}
- 500 μm \leq Fiber length < 1000 μm : []^{TS}
- Fiber length \geq 1000 μm : []^{TS}

Above fiber length distribution is based on the results of APR1400 specific strainer bypass test [Ref. 2]. The fiber is added to the test loop in small batches less than 10g at a time.

4.1.3 Chemical Precipitate

AlOOH chemical surrogate of 11 g/L concentration is fabricated as below:

1. Adding 70 liters of water to a chemical makeup tank
2. Adding 4800 g $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ to the chemical makeup tank
3. Stirring until aluminum nitrate dissolves (~ 10 minutes)
4. Adding 1536 grams of sodium hydroxide
5. Stirring for 10 minutes before doing settling test

4.2 Debris Addition

The test procedure is outlined in the following steps.

1. The test loop is filled with water.
2. Debris quantities are measured.
3. The pump is started, and the flow is set to the desired flow rate.
4. The heater/chiller is started, and the temperature is set to the desired temperature.
5. Stabilize at a constant temperature $\pm 1^{\circ}\text{C}$.
6. Start data acquisition system.
7. Record the clean pressure drop.
8. Particulate debris is added to the system, and the pressure drop is recorded.
9. Fiber is added to the loop and at least 1 turnover of the test loop volume is allowed between additions until either a previously defined maximum mass of fiber or the pressure drop exceeds the defined limits of the facility. Pressure drop is recorded.
10. Chemical precipitates are added and pressure drop is recorded.
11. Pressure drop is allowed to reach a predefined steady state for test termination. The final pressure drop readings are recorded, and the test is terminated.

Debris is added in the following sequence: particulate debris, fiber debris, and chemical products.

4.2.1 Particulate Addition Procedure

1. Adding 1 liter of water to a 3 liter vessel
2. Adding particulate debris
3. Shaking vigorously until particulate material appears to be evenly dispersed in the liquid
4. Pouring particulate slurry into the mixing tank
5. Rinsing vessel as needed with mixing tank solution
6. Allowing system to equilibrate for 1 test loop volume turnover time

4.2.2 Fiber Addition Procedure

1. Adding 1 liter of water to a 3 liter vessel
2. Adding 9 (or 6) g fiber
3. Shaking vigorously until fiber is well dispersed
4. Slowly pouring fiber suspension into mixing tank. Shaking if necessary to re-suspend fiber
5. Rinsing 3 liter vessel as needed to remove residual fiber
6. Waiting at least 1 test loop volume turnover time
7. Repeating Step 1 through Step 6 until all fiber has been added
8. Allowing at least 5 turnovers of the test loop volume (2 turnovers for CL break condition)

4.2.3 Chemical Addition Procedure

1. Slowly pouring 5 (30 or 35) liters AIOOH for HL tests, 70 (or 35) liters for CL tests from the chemical makeup tank into the mixing tank
2. Allowing at least 3 turnovers of the test loop volume
3. Recording time and dP
4. Repeating Step 1 through Step 3 until all AIOOH has been added

5. Acceptance Criteria

The objective of in-vessel downstream effect test is to provide reasonable assurance that the sufficient flow will be makeup in the reactor core to remove decay heat. To prove this, it must be demonstrated that the available head to drive ECC flow into the reactor core is greater than the head loss across the reactor core due to possible debris buildup. The following relationship must be true to ensure sufficient flow is available to maintain LTCC:

$$dP_{\text{avail}} > dP_{\text{debris}}$$

The available driving head (dP_{avail}) is a plant-specific value and the pressure drop due to debris (dP_{debris}) is determined by the in-vessel downstream effect test. The core flow is only possible if the manometric balance between the downcomer and the reactor core is

sufficient to overcome the flow losses in the fuel bundle region at the appropriate flow rate.

$$dP_{\text{avail}} = dP_{\text{dz}} - dP_{\text{flow}}$$

where:

dP_{avail} = total available driving head

dP_{dz} = pressure head due to liquid level between downcomer side and core

dP_{flow} = pressure head due to flow losses in the RCS

The dP_{dz} for APR1400 is calculated using reactor vessel and steam generator drawing materials. The dP_{flow} for each LOCA scenario is based on the values provided in LOCA analyses data. Available driving head at HL break and CL break condition are as follows [Ref. 2].

- dP_{avail} at HL break condition : []^{TS}
- dP_{avail} at CL break condition : []^{TS}
- dP_{avail} at CL break after HL switchover (HLSO) : []^{TS}

6. Quality Assurance Program

This test is performed under the quality assurance program of the APR1400 [Ref. 6] that satisfies 10 CFR part 50 Appendix B, 10 CFR Part 21, and ASME NQA-1-2008 and 1a-2009. Whole documents prepared and generated from this test will be archived as QA records

7. References

1. Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on Pressurized Water Reactor (PWR) Sump Performance," 1998.
2. APR1400-E-N-NR-14001-P, Rev. 0, "APR1400 Design Features to Address GSI-191," December 2014.
3. "Final Safety Evaluation by the Office of Nuclear Reactor Regulation, Topical

- Report WCAP-16530-NP-A ‘Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids To Support GSI-191,’” U.S. Nuclear Regulatory Commission, Washington, DC, and Topical Report WCAP-16530-NP-A.
4. NEI 04-07, Rev. 0 “Pressurized Water Reactor Sump Performance Evaluation Methodology,” December 2004.
 5. Not used
 6. APR1400-K-Q-TR-11005-NP, Rev. 4, “KHNP Quality Assurance Program Description (QAPD) for the APR1400 Design Certification,” March 2014.

Table 1. Flow Conditions

LOCA scenario	Core flow direction	APR1400 flow rate	Flow rate/ FA*	Remark
HL Break	Upward	4,940 gpm	20.5 gpm	Max. safeguard flow rate of four SI
CL Break	Upward	880.2 gpm	3.64 gpm	Boil-off flow rate at 700 sec
CL Break after HLSO	Downward	2,470 gpm	10.25 gpm	Max. safeguard flow rate of two SI

*1/241 of the scaling is used for the test

Table 2. Debris types and amounts per FA

Debris type	Specific type	Debris transported to strainer	Assumed bypass debris (kg)	Per FA* (g)
Fibrous	NUKON®	0	0	0
	Latent fiber	15 lbm (6.8 kg)	1.67 ** (3.68 lbm)	6.93
Particulate	Coating debris	3.1 ft ³ (280.5 kg)	280.5	1164
	Latent particle	185 lbm (83.9 kg)	83.9	348
Reflective metal insulation		114 ft ³	0	0
Chemical compounds		408.0 lbm (185.1 kg)	185.1	768 (70 liters)

* 1/241 of the assumed bypass debris amount

** Result of the APR1400 strainer bypass testing [Ref. 2]

Table 3. Schedule of in-vessel downstream effect tests

TS

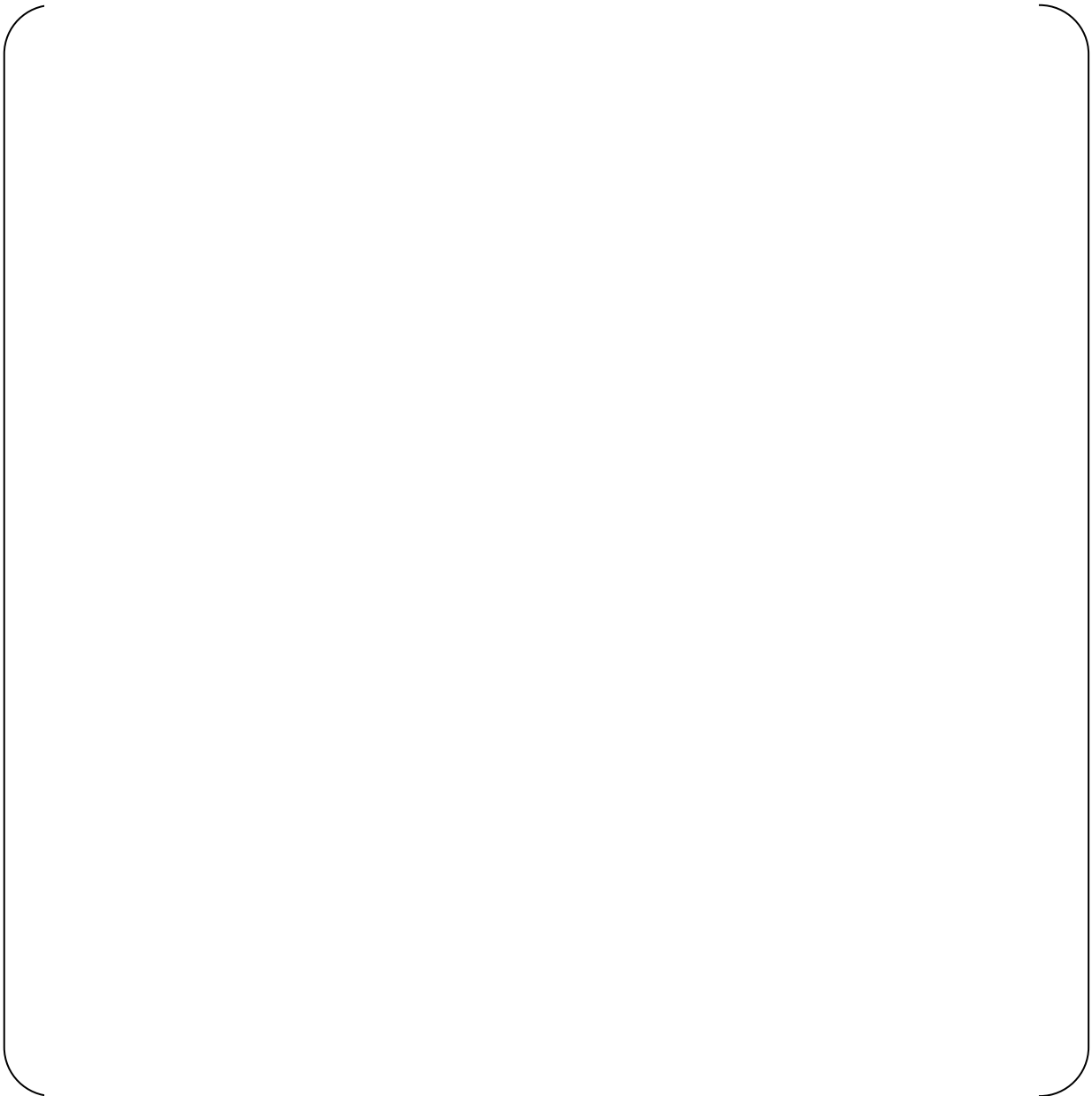




Fig. 1. Schematic diagram of the test loop



Fig. 2. Photo of the test loop

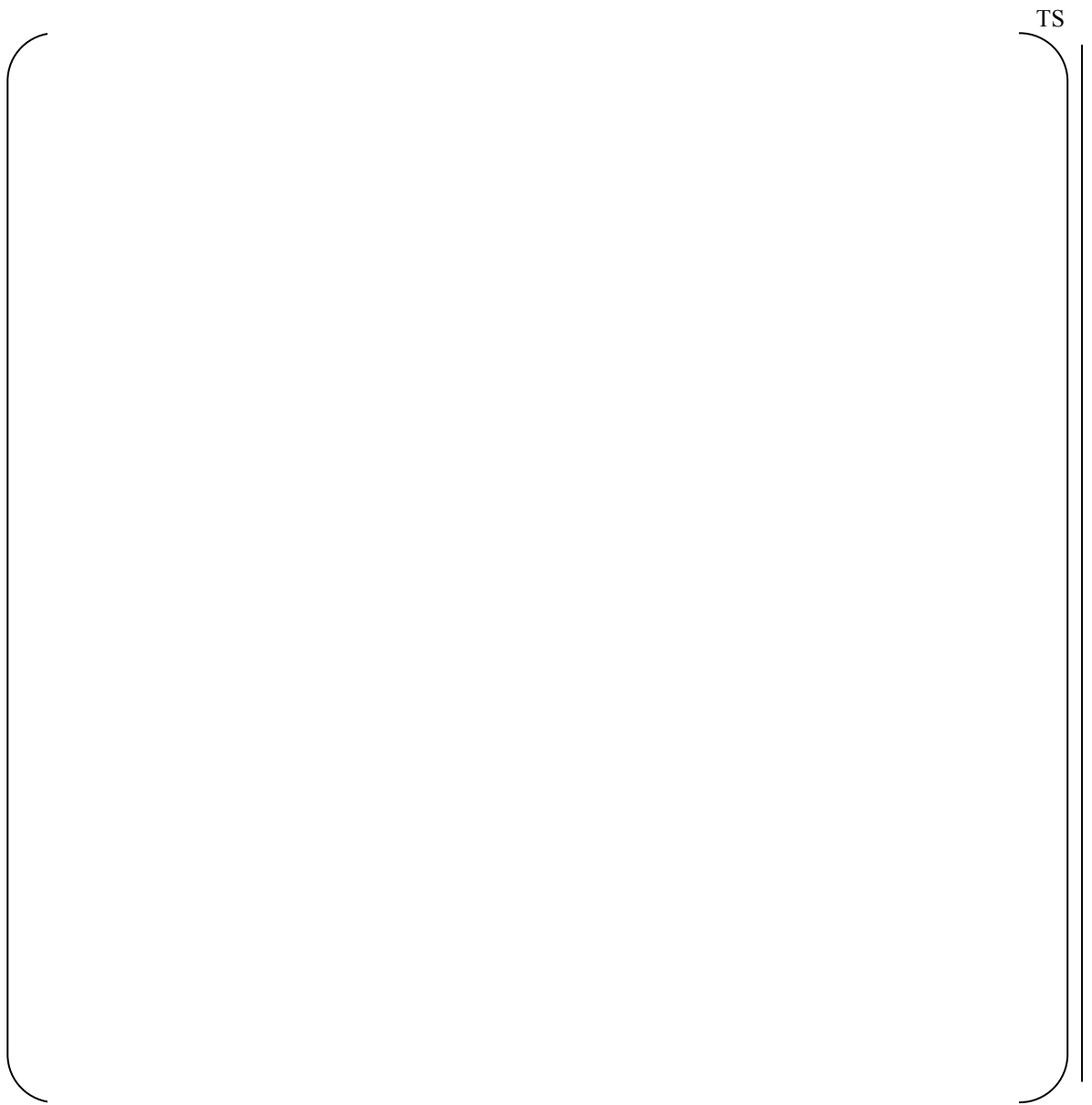


Fig. 3. Comparison of gaps between mock-up fuel assembly and test column (unit: mm)