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

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	4	The number of test cases is increased.
	7,8	The addition procedure of chemical product is modified to meet settling criteria.
	8	The acceptance criterion of HLSO is added.
	10	Table 2 is modified since the latent debris ratio (particle/fiber) will be finalized during strainer bypass testing.
	11	Table 3 is updated to add test cases of 2 SI flow condition and HLSO operation.

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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 meet water discharged from the break and containment spray to be transported to a sump area for recirculation cooling by the emergency core cooling system (ECCS) and the containment spray system (CSS). The strainer with perforated screen is installed in 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 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 flow for core cooling.

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 a sump strainer is installed to prevent the debris transport to a downstream region. To resolve the in-vessel downstream effect concern, KHNP conducts validation tests of in-vessel downstream effect using a mock-up PLUS7 FA.

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 includes a transparent acryl tank with cylindrical shape and a debris stirring tool. The mixing tank is where debris is added during the test. The mixing tank is manufactured as 1.5 m diameter and 1.5 m height. The debris stirring tool is installed in downward vertically at the top of the mixing tank. The mixing tank has a water suction in downward vertical directions. A chiller piping and heater are installed in mixing tank to control water temperature. This heater is connected with temperature control system, and the water temperature can be controlled from an environmental temperature of approximately 20^{o}C to a high temperature of approximately 60^{o}C. The temperature of the water is measured continuously in the tank by a submerged thermocouple.

2.2 Recirculation System

The recirculation system pumps the water from the tank, through the recirculation piping and test column, and back into the tank. A 1 kW pump draws the water out of the bottom of the mixing tank. The flow rate is controlled by a control system with a computer. A magnetic flow meter measures the flow rate and provides feedback to the control system to maintain constant flow rate. A specific flow rate can be chosen and the flow control automatically regulates the flow rate to maintain that value. The recirculation system is continuous duty to accommodate longer tests.

2.3 Test Column

The FA test column is made with transparent acryl of 30 mm thickness to be visible inside the pool during the test. The test column contains a mock-up PLUS7 FA of 2.5 m height without fuel. The mock-up FA includes a bottom nozzle, debris capturing fuel filter, bottom grid, four spacer grids, top grid, top nozzle and 16 x 16 fuel rods. The water enters from a 40 mm nozzle at the bottom of the test column and flows upward and exits through 40 mm outlet at the top of the pool. The bottom region is made in a cone shape to avoid the settling and loss of debris during the test. The bottom portion and top portion of the pool excluding FA height region play a role of lower plenum and upper plenum of the reactor vessel respectively. The test FA is located on the simulated core support plate of 30 mm thick with 70 mm flow holes.

The water with debris is injected through the bottom nozzle and flow up through the simulated core support plate. As debris catches on the FA, the differential pressure is measured constantly across the combination of bottom nozzle and bottom grid as well as across the entire FA. The temperature of water in the FA pool is measured continuously by a thermocouple inserted through a port in the bottom. The height of the bottom portion and top portion of the FA pool are 500 mm and 300 mm respectively. The outer pitch of the PLUS7 is 206 mm. This dimension is used to size the inside of the FA pool.

2.4 Control and Monitoring System

The computer control system continuously controls the following parameters:

- Water flow rate
- Water temperature

The computer monitoring system continuously records the following data:

- Temperature of the water in the mixing tank and test column
- Flow rate
- Differential pressure from 5 dP gauges

The data can be recorded at a time interval chosen by the operator. The computer is also used to check the slope of the dP or flow versus time graphs in order to determine if the curves have reached a point close enough to equilibrium.

3. Test Conditions

3.1 Test Parameters

This test reflects the recirculation flow, temperature and debris conditions under the recirculation modes after a LOCA. Table 1 and Table 2 represent the test conditions and debris amounts of the APR1400 under a LOCA. After a LOCA, the recirculation flow rate is 18,699 lpm (4,940 gpm), and the debris type and amount in the reactor building are presented in the technical report [Ref. 2]. The number of APR1400 fuel assembly is 241.

For a hot leg (HL) break, the entire ECC water passes through the core to exit the break. The core level is at least equal to the HL nozzle elevation, and the core flow rate is equal to the ECC flow rate. Therefore, the flow rate to be tested is 77.6 lpm (20.5 gpm). It is calculated by dividing 18,699 lpm (4,940 gpm) by 241. The HL break condition at the maximum flow rate is chosen to obtain maximum pressure drop at the test column.

In case of cold leg (CL) break, most of the ECC water spills directly out of the break location. The amount of debris that reaches the reactor vessel lower plenum and core inlet after a CL break is significantly less than that of HL break case. The ECC flow rate per FA is 12.5 lpm (3.29 gpm) for the APR1400 at around 1,200 sec after recirculation start [Ref. 2].

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 to each other, two series of tests are planned. Tests of APR1400-11 through APR1400-54 are for HL break accident, and tests of APR1400-61 through APR1400-104 are for CL break accident.

4. Test Procedure

The recirculating coolant may entrain and transport debris and material that can be categorized as follows;

- Fibrous debris
- Particulate debris
- Chemical products

4.1 Debris Preparation

4.1.1 Particulate

The particulate debris is represented by grinded silica powder (SiO_2) that is 10μm ±5μm in diameter. The silica powder used for testing is a product by 21 Century Silica Co. in Korea. The NRC Safety Evaluation for NEI 04-07 [Ref. 3] identified particle size as a key parameter for the selection of representative debris. All testing are conducted with silica particles approximately 10μm in size, allowing the debris to act as a fine particulate debris that collects within a fiber bed and results in a maximum pressure drop.

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 : 77% ± 10%
- 500 μm ≤ Fiber length < 1000 μm : 18% ± 10%
- Fiber length ≥ 1000 μm : 5% ± 10%

Above fiber distribution is suggested by Argonne National Laboratory test [Ref. 4]. Since the APR1400 uses commercial strainers provided by Transco Products Inc., this fiber length distribution could be applicable to the tests. The fiber is added to the test loop in small batches, typically 10g at a time.

4.1.3 Chemical Precipitate

The chemical precipitation calculations [Ref. 2] present that three chemical products of aluminum oxy-hydroxide, sodium aluminum silicate, and calcium phosphate may be generated. This test uses AlOOH as chemical debris which has been shown by Argonne National Laboratory to produce the highest pressure drop among all of the chemical precipitants [Ref. 4]. ALOOH will bound the combination of all chemical products.

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 ± 1^{o}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 in the loop and at least 20 minutes are allowed to pass 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 Debris Addition Procedure

1. Add 1 liter of liquid to a 10 liter vessel
2. Add particulate debris
3. Shake vigorously until particulate material appears to be evenly dispersed in the liquid
4. Pour particulate slurry into the mixing tank
5. Rinse vessel as needed with mixing tank solution
6. Allow system to equilibrate for 30 minutes

4.2.2 Fiber Debris Addition Procedure

1. Add 1 liter of liquid to a 10 liter vessel
2. Add 10 g/addition fiber
3. Shake vigorously until fiber is well dispersed
4. Slowly pour fiber suspension into mixing tank. Shake if necessary to re-suspend fiber
5. Rinse 10 liter vessel as needed to remove residual fiber
6. Wait 20 minutes
7. Repeat Step 1 through Step 6 until all fiber has been added
8. Allow at least five turnovers of the test loop volume (two turnovers for CL break condition)

4.2.3 Chemical Product Addition Procedure

1. Add 768 g ALOOH to container
2. Add tap water to make a volume of 70 liters (18.4 gallons, 11g/l concentration)
3. Stir until AlOOH dissolves
4. Transfer 5 liters (or 30 liters) of ALOOH from the chemical makeup tank into smaller vessels
5. Slowly pour chemical surrogate into mixing tank. Take every precaution to maintain steady rate of chemical introduction
6. Allow at least three turnovers of the test loop volume

7. Record time and dP
8. Repeat Step 1 through Step 7 until all ALOOH has been added

5. Acceptance Criteria

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

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.

$$dP_{avail} > dP_{debris}$$

The core flow is only possible if the manometric balance between the vertical core inlet and outlet is sufficient to overcome the flow losses in the fuel bundle region at the appropriate flow rate.

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

where:

dP_{avail} = total available driving head

dP_{dz} = pressure head due to liquid level between core inlet and outlet

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

The dP_{avail} for APR1400 is calculated using reactor vessel and steam generator drawing materials. Available driving head at HL break and CL break condition are as follows [Ref. 2].

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

6. Quality Assurance Program

This test is performed under the quality assurance program of the APR1400 [Ref. 5] that satisfies 10 CFR part 50 Appendix-B, 10 CFR Part 21, and ASME NQA-1-2008 and 1a-2009.

7. References

1. Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on Pressurized Water Reactor (PWR) Sump Performance," 1998.
2. KHNP, "APR1400 Design Features to Address GSI-191," APR1400-E-A-T(NR)-13001-P Rev. A, May 2013.
3. NEI 04-07, Rev. 0 "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.
4. JCN 3216, "Technical Letter Report on Evaluation of Chemical Effects; Studies on Precipitates Used in Strainer Head Loss Testing," January 2008.
5. KHNP, "KHNP Quality Assurance Program Description (QAPD) for the APR1400 Design Certification," APR1400-K-Q-TR-11005-NP Rev. 1, May 2012.

Table 1. Test 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	792.5 gpm	3.29 gpm	Boil-off flow rate at 1,200 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 generated in containment	Assumed bypass debris (kg)	Per FA* (g)
Fibrous	NUKON	0	0	0
	Latent fiber**	[7.5] lbs ([3.4] kg)	[3.4]	**14.1**
Particulate	Coating debris	3.1 ft^3 (232.6 kg)	232.6	965.2
	Latent particle**	[192.5] lbs ([87.3] kg)	[87.3]	362.3
Reflective metal insulation		114 ft^3	0	0
Chemical compounds		408.0 lbs (185.1 kg)	185.1	768.0 (70 liters)

* 1/241 of the assumed bypass debris amount

** Will be finalized during strainer bypass testing

Table 3. Schedule of in-vessel downstream effect tests

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Fig. 1. Schematic diagram of the test loop

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Fig. 2. Photo of the test loop