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

Revision 3

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: · Flow rate in Test No. APR1400-61 ~ 91 ·Amount of AlOOH addition in Test No. APR1400-51 ~ 101 ·Test schedule

Table of Contents

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 strainer with perforated screen is 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 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 using a mock-up FA of PLUS7 which is the fuel assembly model of the APR1400.

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 a computerized 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 computerized control system. 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 target value.

2.3 Test Column

The FA test column is made with transparent acryl of 25 mm thickness for the pool inside to be visible. The test column contains a mock-up PLUS7 FA of 2.5 m height without fuel pellets. 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, flows upward, and exits through 40 mm outlet at the top of the pool. The bottom region is shaped as a cone to avoid settling and loss of debris during the test. The bottom and top portion of the pool excluding FA height region play roles 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 deposits on the FA, the differential pressure is measured constantly between bottom nozzle and bottom grid, and measured across the entire FA with the same concept up to 5 dP gauges. The temperature of water in the FA pool is measured continuously by a thermocouple inserted at 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 206.6 mm. This dimension is used to size the inside of the FA pool.

2.4 Control and Monitoring System

The computerized control system controls continuously the following parameters:

- Water flow rate
- Water temperature

The computerized monitoring system records continuously 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 set 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 status of data.

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 core is expected 4,940 gpm (18,699 lpm) when the four safety injections are available [Ref. 2]. The number of APR1400 fuel assembly is 241.

In case of hot leg (HL) break, the entire 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 :

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

In case of cold leg (CL) break, most of the ECC water spills directly out of the break location. The maximum ECC flow rate to the core after a CL break is selected to the core boil-off rate at the time of recirculation start. The ECC flow rate per FA is 3.65 gpm (13.8 lpm) for the APR1400 at recirculation start time (around 700 seconds after ECC start) [Ref. 2]. For the conservative CL break tests, a multiplier of 1.2 was applied as shown below:

$$\text{Test flow rate} = 3.65 \text{ gpm} \times 1.2 = 4.38 \text{ gpm (16.6 lpm)}$$

3.1.2 Water Temperature and Chemistry

The water temperature at the beginning of test will be set to 22 ^{o}C (71.6°F). This temperature will be maintained at 22 ^{o}C ± 1 ^{o}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 and transport debris and material that can be categorized as particulate, fiber, and chemical precipitates. The weight of latent debris is 200 lbs, composed of 185 lbs of particulate and 15 lbs of fiber. All the debris except 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 the upstream analysis, the quantity of destroyed coatings is 3.1 ft^3. NEI-04-07 estimates the particle size of failed coatings to be 10 μm on average with a density of 94 lbs/ft^3 [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 lbs/ft^3. 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:

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

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

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

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 lbs. The latent fiber is represented by NUKON low density fiberglass, which NEI-04-07 recommends, with an as-fabricated density of 2.4 lbs/ft^3 (see NEI-04-07 SER Appendix VII). The source of the NUKON used in test will be provided in the test report summary. Total strainer bypass fiber for the APR1400, with 15 lbs of latent fiber, is 3.68 lbs [Ref. 2]. The mass of fiber to be added to the test is calculated as follow:

$$M_f = \frac{3.68 lbs}{241} = 0.015 lbs \quad (6.93\text{ g})$$

<u>Chemical Precipitates</u>

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

- Calcium Phosphate : 0.7 kg
- Sodium Aluminum Silicate : 4.3 kg
- Aluminum Oxy-hydroxide : 180.1 kg

Given the relative proportions, since aluminum oxy-hydroxide can be conservatively used to represent the other precipitates [3], only AlOOH is used in the test. The total chemical precipitate mass of 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:

$$V_{AlOOH} = 185.1 kg / 241 \times \frac{liter}{0.011 kg} \times \frac{1 gal}{3.785 liter} = 18.5 gal \quad (70\text{ liters})$$

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 ≤ Fiber length < 1000 μm : [ ]TS
- Fiber length ≥ 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 $Al(NO_3)_3.9H_2O$ to the chemical makeup tank
3. Stirring until aluminum nitrate dissolves (~ 10 minutes)
4. Adding 1536 grams of sodium hydroxide
5. Stirring for 1 hour 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 ± 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 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 AlOOH 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 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 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:

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

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.

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

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,” (To be published).
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	3.65 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 lbs (6.8 kg)	1.67 ** (3.68 lbs)	6.93
Particulate	Coating debris	3.1 ft^3 (280.5 kg)	280.5	1164
	Latent particle	185 lbs (83.9 kg)	83.9	348
Reflective metal insulation		114 ft^3	0	0
Chemical compounds		408.0 lbs (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

TS

Fig. 1. Schematic diagram of the test loop

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Fig. 2. Photo of the test loop