Design Features to Address GSI-191

Revision 3

Non-Proprietary

February 2018

REVISION HISTORY

Revision	Date	Section(s) or Page(s)	Description
0	December 2014	All	First Issue
1	March 2017	Sections 2.6, 3.8, 6	Added the description of how the NRC guidance on chemical effects is applied to the APR1400 chemical effects evaluation and added the references (per RAI 391-8462 Q34)
		Section 3.3	Added the justification of assumption that all coating debris are in a small particulate form (per RAI 391-8462 Q32)
		Section 3.4	Corrected the debris transport location (per RAI 25-7844 Q10).
		Section 3.6.2	Supplemented the description of the uncertainty in NPSHr for the SI pumps and CS pumps (per RAI 25-7844 Q6)
		Sections 3.8.1, 3.8.2, and Table 3.8-1	Discussed LOCA water pH values for the short-term and long term DBA condition (per action item 6-19 Q8 and Q8 R1)
		Section 3.8.2	Revised the assumption for the IRWST water volume (per action item 6-19 Q6)
		Section 3.8.2	Deleted the assumption for the temperature profiles (per RAI 404-8488 Q11)
		Section 3.8.2 and Figure 3.8-1	Revised the pH curve in the chemical effects analysis (per RAI 391-8462 Q38)
		Section 3.8.2	Clarified the operating time of the CSS used in the chemical effects analysis (per action item 6-19 Q9 R1)
		Sections 3.6.2, 3.9.1, 3.9.2, and Figure 3.9-3	Corrected the minimum NPSH margins for the SI pumps and CS pumps and clarified the minimum water level of IRWST for ESF operation (per 6.3 NPSH Audit)
		Table 3.3-2	Added the reference for density values for epoxy and inorganic zinc coatings (per RAI 391-8462 Q33)
		Table 3.8-2	Added the basis of 10% margin in the duct insulation area (per action item 6-19 Q10)
		Tables 3.8-4, 3.8-5	Updated the chemical effects analysis inputs and results based on the updated temperature profiles (per RAI 391-8462 Q35)
		Section 4.2	Clarified the statement (per RAI 63-7983 Q12)
		Section 4.2.2.3, and Table 4.2-1	Revised Section 4.2.2.3 to be consistent with Table 4.2-1 and updated the list of the SIS and CSS components that need to be included in the downstream effects evaluation (per RAI 63-7983 Q13)

Revision	Date	Section(s) or Page(s)	Description
1	March 2017	Sections 4.2.2.4, 6, and Table 4.2-8	Added the wear rate information with respect to the various system materials including references (per RAI 63-7983 Q26)
		Sections 4.2.2.5, 4.2.2.6, 4.2.3.3.2, and Tables 4.2-5, 4.2-7	Simplified the flowrates of SIS and CSS assumed for the component wear rate evaluation, incorporated the revised the debris concentration to the wear rate evaluation, and clarified the minimum IRWST water volume for ESF operation (per RAI 63-7983 Q16)
		Section 4.2.2.5	Added the missing test condition for SIS and CSS pumps to be consistent with Section 4.2.3.1 (per RAI 63-7983 Q15)
		Sections 4.2.3.1, 4.2.3.2.2, 4.2.3.3.2	Specified that the pump and valve qualification will be accomplished by test or a combination of test and analysis in accordance with ASME QME-1-2007 (per RAI 63-7983 Q17 and Q18)
		Sections 4.2.3.2, 4.2.3.2.1, 4.2.3.2.2	Added the evaluation for the effects of post-LOCA debris for the CS pump miniflow heat exchangers (per RAI 266-8338 Q31)
		Section 4.2.3.2	Specified that heat exchanger plugging, fouling, wear and heat transfer performance in the presence of post-LOCA debris will be evaluated by the vendor during the procurement process (per RAI 63-7983 Q20)
		Section 4.2.3.2	Added the design information for the minimum flow velocity through the heat exchanger tubes (per RAI 63-7983 Q19)
		Section 4.2.3.3.1, and Tables 4.2-6, 4.2-9	Added conservative assumptions to evaluate debris settling in piping, valves, orifices, and spray nozzles and revised Table 4.2-6 to simplify the assumed component flow rates and velocities (per RAI 63-7983 Q22)
		Section 4.2.3.3.1	Added the description of debris settling in globe valves (per RAI 63-7983 Q23)
		Section 4.2.3.3.2	Added the evaluation of wear rate for the containment spray nozzles (per RAI 63-7983 Q21)
		Section 4.2.3.3.2	Added the CSS valve qualification (per RAI 63-7983 Q25)
		Section 4.2.3.3.2	Added the evaluation and verification of the potential increase in flowrates in the ECCS and CSS due to component wear (per RAI 63-7983 Q24 R1)
		Section 4.2.3.4	Clarified the instrument connection locations in instrument tubing clogging evaluation (per RAI 63-7983 Q27)
		Section 4.2.3.5	Added the chemical effects evaluation for the CS pumps and containment spray nozzles (per RAI 63-7983 Q29)
		Sections 3.6.1, 4.3.2.2, and 4.3.5	Revised the start time of hot leg switchover operation

Revision	Date	Section(s) or Page(s)	Description
1	March 2017	Sections 4.3.3.1, 4.3.3.2, 4.3.3.3, 4.3.4.5, 4.3.6, 4.3.7, and Tables 4.3-3, 4.3-4, 4.3-5, 4.3-8, 4.3-12	Revised the basis of downcomer liquid density and the related available driving heads for each LOCA scenario (per RAI 404-8488 Q11)
		Sections 4.3.4.3, 4.3.4.4.1, 4.3.4.4.2, Tables 4.3-6, 4.3-7, and Figures 4.3-6, 4.3-7	Revised the assumption of the RV coolant temperature and the evaluation of deposition on the fuel (LOCADM) (per RAI 404-8488 Q11 and Q11 R1)
		Section 6	Updated the references
2	October 2017	Section 3.8.2	Revised the assumption of the maximum IRWST water volume with justification (per RAI 520-8693 Q42)
		Sections 4.2.3.1 and 4.2.3.3.2	Revised the ECCS and CSS pumps and valves wear evaluation (per RAI 63-7983 Q18 R2)
		Sections 4.2.3.2.2, 4.2.3.3.2, and 4.2.4	Revised the wear evaluation of the piping, spray nozzles, and orifices and added the overall system evaluation (per RAI 63-7983 Q24 R2)
		Section 4.2.3.3.1, and Table 4.2-9	Revised the fluid flow velocities based on expected pump operation (Per RAI 543-8734 Q46)
		Section 4.2.3.3.1, and Tables 4.2-6 and 4.2-9	Revised the debris settling evaluation (per RAI 63-7983 Q22 R1)
		Table 4.2-1	Added, changed, or deleted the SI and CS components required to be included in the downstream effects evaluation (per RAI 63-7983 Q13 R1)
		Table 4.2-7	Revised the component wear rate evaluation (per RAI 63-7983 Q16 R1)
3	February 2018	Sections 3.8.2, 4.3.2, and 6, and Tables 3.8-4, 3.8-5, and 4.3-2	Revised the assumption and calculation results of chemical effects analysis (per RAI 520-8693 Q43)

ABSTRACT

This technical report describes the design features of the APR1400 that address Generic Safety Issue (GSI)-191 (NUREG/CR-6874, "Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation"). This report also provides an assessment of the APR1400 design based on the guidance and requirements in Nuclear Energy Institute 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology," and the associated NRC Safety Evaluation ("Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC-Generic Letter 2004-02"), as well as industry guidance and industry testing to address and resolve GSI-191 issues.

Evaluations are conducted of the effects of design basis accident conditions on the ability of structures, systems, and components to mitigate the consequences of the accidents and to maintain long-term core cooling in a manner consistent with the governing regulatory requirements of NRC Regulatory Guide 1.82 (Rev.4).

The APR1400 is designed as a "low fiber plant" to resolve GSI-191 issues by applying the lessons learned from operating plants and by using industry trends related to the resolution of the GSI-191 issue, including the exclusion of fibrous material within the zone of influence of a high-energy line break.

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ACRONYMS AND ABBREVIATIONS

ALWR	advanced light water reactor
APR1400	Advanced Power Reactor 1400
ASME	American Society of Mechanical Engineers
BOP	balance of plant
BWG	Birmingham Wire Gauge
CAD	computer-aided design
CEDM	control element drive mechanism
CFS	cavity flooding system
CL	cold leg
CS	containment spray
CSAS	containment spray actuation signal
CSB	core support barrel
CSHX	containment spray heat exchanger
CSP	containment spray pump
CSS	containment spray system
DBA	design basis accident
DC	downcomer
DCD	Design Control Document
DVI	direct vessel injection
ECCS	Emergency Core Cooling System
ESF	engineered safety features
EPRI	Electric Power Research Institute
FA	fuel assembly
GSI	Generic Safety Issue
HELB	high-energy line break
HL	hot leg
HLSO	hot leg switchover
HVAC	heating, ventilation, and air conditioning
HVT	holdup volume tank
ICI	in-core instrumentation
ID	inside diameter
IOZ	inorganic zinc
IRWST	in-containment refueling water storage tank
IWSS	in-containment water storage system
KEPCO	Korea Electric Power Corporation
KHNP	Korea Hydro & Nuclear Power Co., Ltd.
LBLOCA	large break LOCA
LOCA	loss-of-coolant accident
LOCADM	LOCA deposition model
LOOP	loss of offsite power
LTCC	long-term core cooling
MSLB	main steam line break
NEI	Nuclear Energy Institute
NPSH	net positive suction head
$NPSH_a$	available NPSH
$NPSH_r$	required NPSH

$NPSH_{reff}$	effective required NPSH
NRC	Nuclear Regulatory Commission
NUREG	U.S. Nuclear Regulatory Commission Regulation
POSRV	pilot operated safety relief valve
PWR	pressurized water reactor
PWROG	PWR Owners Group
PZR	pressurizer
RCP	reactor coolant pump
RCS	reactor coolant system
RG	regulatory guide
RMI	reflective metal insulation
RV	reactor vessel
SBLOCA	small break LOCA
SC	shutdown cooling
SCP	shutdown cooling pump
SCS	shutdown cooling system
SE	safety evaluation
SECY	Office of the Secretary of the Commission
SG	steam generator
SI	safety injection
SIAS	safety injection actuation signal
SIP	safety injection pump
SIS	safety injection system
SIT	safety injection tank
TBE	thin bed effect
TSP	tri-sodium phosphate
UGS	upper guide structure
WCAP	Westinghouse Commercial Atomic Power
ZOI	zone of influence

1 INTRODUCTION

The purpose of this technical report is to describe the design features and evaluation results of the post-accident performance of the in-containment refueling water storage tank (IRWST) sump strainer of the Advanced Power Reactor 1400 (APR1400). The purpose is also to confirm that the emergency core cooling system (ECCS) and containment spray system (CSS) recirculation functions under loading conditions are in conformance with the applicable regulatory requirements of Nuclear Regulatory Commission (NRC) Regulatory Guide (RG) 1.82, Rev.4 (Reference [1-1]).

This report includes:

1) Description of the design of the IRWST, ECCS performance, IRWST sump strainer, insulation, and coating

2) Evaluation of IRWST sump strainer performance including break selection, debris generation, characteristics, transport, head loss, net positive suction head (NPSH) for ECCS pumps and CSS pumps, chemical effects, and upstream effect

3) Evaluation of downstream effects

4) Conclusion regarding the APR1400 design features in addressing Generic Safety Issue (GSI) -191 in accordance with SECY-12-0093 (Reference [1-2])

2 DESIGN DESCRIPTION

The following section describes the outlines of the current APR1400 design and how it satisfies the recommendations of NRC RG 1.82 (Reference [1-1]).

2.1 Emergency Core Cooling/Containment Spray System

The ECCS removes heat from the reactor core following postulated design basis accidents (DBAs). The function of the APR1400 ECCS is performed with the safety injection system (SIS).

The SIS is composed of four independent mechanical trains (without any cross-tie line among the injection paths) and four independent electrical trains. Each train has one active safety injection pump (SIP) and one passive safety injection tank (SIT) equipped with a fluidic device.

To mitigate loss-of-coolant accident (LOCA) conditions, each train provides 50% of the minimum injection flow rate for breaks larger than the size of a direct vessel injection (DVI) line. For breaks equal to or smaller than the size of a DVI line, each train has 100% of the required capacity. The low pressure injection pumps with common header installed in the conventional design are eliminated, and the functions for safety injection (SI) and shutdown cooling (SC) are separated.

The core cooling water is designed to be injected directly into the reactor vessel (RV), which eliminates the possibility of a spill of the injected flow through the broken cold leg (CL). For this purpose, four SI lines are connected directly to the nozzles located above the hot legs (HLs) and CLs on the upper portion of the RV.

The CSS is a safety grade system designed to reduce containment pressure and temperature from a main steam line break (MSLB) or a LOCA and remove fission products from the containment atmosphere following a LOCA.

The CSS uses the IRWST and has two independent trains that consist of two containment spray pumps (CSPs), two containment spray heat exchangers (CSHXs), two containment spray (CS) mini-flow heat exchangers, two independent spray headers, and associated piping, valves, and instrumentation. Post-accident pH control of the sprayed fluid is provided by using tri-sodium phosphate (TSP) that is stored in the holdup volume tank (HVT).

The CSS provides sprays of borated water to the containment atmosphere from the upper regions of the containment. The spray flow is provided by the CSPs which take suction from the IRWST. The CSPs start upon the receipt of a safety injection actuation signal (SIAS) or a containment spray actuation signal (CSAS). The pumps discharge through the CSHXs and the spray header isolation valves to their respective spray nozzle headers, then into the containment atmosphere.

Spray flow to the CS headers is not provided until a CSAS automatically opens the CS header isolation valves. The spray headers are located in the upper part of the containment building to allow the falling spray droplets time to approach thermal equilibrium with the steam-air atmosphere. Condensation of the steam by the falling spray results in a reduction of containment pressure and temperature.

The CSPs are designed to be functionally interchangeable with the shutdown cooling pumps (SCPs). The CSPs and CSHXs can be used as a backup to the SCPs and SC heat exchangers to provide residual heat removal or to provide cooling of the IRWST. This design gives the CSS higher reliability compared with a conventional plant.

2.2 In-Containment Refueling Water Storage Tank

The in-containment water storage system (IWSS) performs water collection, delivery, storage, and heat sink functions inside the containment during normal operation and accident conditions. The IWSS comprises the IRWST, HVT, and cavity flooding system (CFS).

The IRWST and HVT are integral parts of the internal structure of containment building and reinforced concrete structures with a stainless steel liner on surfaces expected to be in direct contact with borated water. The IRWST is located below El. 100 ft in the floor slab between the secondary shield wall outside and the inner containment wall inside. The tank has a continuous ring around the lower containment. The IRWST is a protected, reliable, and safety-related source of borated water for the SIS and CSS. A plan view of the IRWST is shown in Figure 2.2-1. Elevation views of the IRWST sump pit and HVT are shown in Figure 2.2-2.

To minimize the corrosion of the stainless steel in the containment during a LOCA, long-term post-LOCA pH control of the IRWST water is provided by granular TSP, which is stored in baskets in the HVT. The stainless steel baskets have a solid top and bottom with mesh sides to provide reasonable assurance of dissolution when submerged in water.

As shown in Figure 2.2-1, each quadrant of the IRWST contains suction piping and the IRWST sump arrangements for the CS, SC, and SI pumps. The suction pipe is located within the IRWST sump pits. An IRWST sump strainer covers each IRWST sump pit in accordance with the guidance in NRC RG 1.82 (Reference [1-1]).

2.3 Design for Prevention of Degraded Emergency Core Cooling System Performance

1) Location of HVT trash rack

   There are four entrances to the HVT. Two entrances are located in the side wall of the HVT within secondary shield wall. Two entrances are located facing the opening in the shield wall. A vertical trash rack is located at each entrance to HVT. Size of each HVT trash rack located in the side wall of the HVT is 0.91 m x 2.29 m (3 ft x 7 ft 6 inch), which represents 2.09 m^2 (22.5 ft^2) of screen surface. In addition, the size of each HVT trash racks facing the opening in the shield wall is 2.92 m x 2.29 m (9 ft 7 in x 7 ft 6 inch), which represents 6.68 m^2 (71.85 ft^2). The HVT trash racks prevent debris particles larger than 38.1 mm (1.5 inch) from entering the HVT. However, smaller debris particles may enter the HVT, but particles with high density and insufficient hydrodynamic force acting on them sink to the bottom of the HVT. The remaining particles are entrained in the flow to the spillways that interconnect to the HVT and the IRWST.

2) Location of IRWST sump strainer

   Following an accident, water introduced into containment drains to the HVT. The HVT trash rack prevents larger debris from entering the HVT. The water then travels into the IRWST through the IRWST spillways. The IRWST spillways are located at sufficiently high location to assure that much of the higher-density debris settles to the bottom of the HVT. IRWST sump strainers are not installed in these spillways to assure that the flow from HVT to IRWST is not interrupted. This water goes into the SIS suction line through IRWST sump strainers. The fine debris that is introduced into the IRWST is prevented from entering the SIS suction pipe by four IRWST sump strainers. These strainers have the capability of removing particles greater than 2.38 mm (0.094 inch) in diameter. The IRWST sump strainers are the final barrier to debris before the ECCS and CSS suction lines. It is expected that the strainers have capability adequately to block any amount of debris (insulation, coating, and latent debris) without degrading ECCS and CSS performance.

3) Location of engineered safety features (ESF) pump suction

To meet the multi-sump requirement of NRC RG 1.82 (Reference [1-1]), the general plant arrangement separates redundant trains of the CSS, SCS, and SIS. This results in an arrangement of two SI pumps, one CS pump and one SC pump in each division. Within each division, the two SI trains (and each CS/SC train) are separated by a quadrant wall to isolate the trains from each other to the practically maximum extent. Each of the four SI pumps has its own suction connection to the IRWST and each of the two CS pumps and two SC pumps shares one of these four connections.

2.4 IRWST Sump Strainer

Following an accident, water introduced into containment drains to the HVT. Any debris in the containment could be transported to the HVT with this fluid. Debris bigger than 38.1 mm (1.5 inch) in diameter is prevented from entering the HVT by a vertical HVT trash rack at the entrance to the HVT (see Figure 2.2-2). A trench at the base of the HVT trash rack prevents any high-density debris swept along the floor by fluid flow toward the HVT from reaching the HVT trash rack. The vertical orientation of the HVT trash rack helps impede the deposition of debris buildup on the IRWST sump strainer surface. Particles that are smaller than the HVT trash rack mesh enter the HVT.

High-density debris that enters through the HVT trash rack accumulates in the bottom of the HVT. The IRWST spillways are located at a high elevation to provide reasonable assurance that much of the higher density debris (and debris that tends to sink slowly) settles to the bottom of the HVT before spilling over into the IRWST. Debris that remains in suspension makes its way to the IRWST spillways. The spillways are shown in Figure 2.2-2.

The fine debris introduced into the IRWST is prevented from entering the pump suction by the IRWST sump strainers as shown in Figure 2.4-1. The IRWST strainer hole diameter is less than 2.38 mm (0.094 inch). The strainer design includes redundancy, a large surface area to account for potential debris blockage and maintain safety performance, corrosion resistance, and a strainer hole size to minimize downstream effects. The strainer is composed of tubular cartridges that allow flexibility in the final strainer size. The IRWST sump strainers are mounted on four sump pits with access that allows inspection of the sump pit and inlet suction pipe. The final strainer size (surface area) is presented in Subsection 3.5.2. Detailed drawings of the tubular strainer cartridge are presented in Figure 2.4-2 and 2.4-3.

2.5 Insulation

The insulation applied to equipment and pipes in the containment of the APR1400 is as follows:

1) Equipment

Reflective metal insulation (RMI) is applied to the reactor coolant pumps (RCP), the steam generators (SG), pressurizer (PZR), letdown heat exchanger, regenerative heat exchanger, reactor drain tank, and the RV in the areas that have large amount of insulation potentially subjected to jet impingement from a high-energy line break (HELB).

No other equipment inside containment is insulated. In addition, heating, ventilation, and air conditioning system within the zone of influence (ZOI) is not required to have insulation.

2) Pipe lines

RMI is applied to all pipes inside the containment for heat conservation, personal protection, and anti-sweet. Particulate insulations for equipment and pipe are not used in the APR1400.

2.6 Coatings

The coating on structures, system, and components within containment shall use only qualified coating type which is qualified and acceptable coating system in a DBA. No unqualified coatings are to be used inside containment.

The criteria for coating are addressed in NRC RG 1.54, Rev.2, “Service Level I, II, and III Protective Coatings Applied to Nuclear Power Plants” (Reference [2-1]) and ASTM D 3911-08 (Reference [2-2]), “Standard Test Method for Evaluating Coatings Used in Light-Water Nuclear Power Plants at Simulated Design Basis Accident (DBA) Conditions”. Coatings are evaluated with consideration of the coating type, condition assessment program, generation assumption, assumed characteristics, transport assumption, and head loss testing in accordance with "NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation," Enclosure 2 to Revised Guidance for Review of Final Licensee Responses to Generic Letter 2004-02 (Reference [2-3]). These evaluations are described in the pertinent sections of this report and DCD (Reference [3-1]). No exception is taken with regard to the guidance.

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Figure 2.2-1 Plan View of IRWST

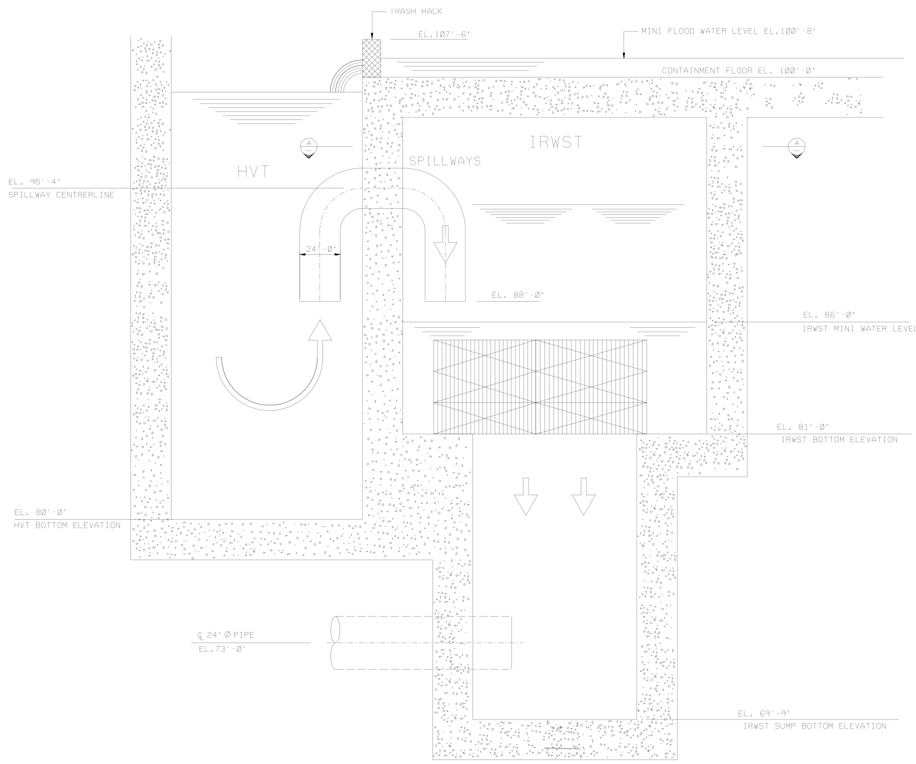

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Figure 2.2-2 IRWST Sump Pit Elevation View

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Figure 2.4-1 IRWST Sump Strainer

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Figure 2.4-2 IRWST Sump Strainer Drawing (Isometric View)

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Figure 2.4-3 IRWST Sump Strainer Drawing (Top and Section Views)

3 EVALUATION OF IRWST SUMP STRAINER PERFORMANCE

3.1 Break Selection

The in-containment refueling water storage tank (IRWST) sumps are vulnerable to debris blockage only when the sumps are active. The analysis therefore requires an understanding of the accident progression to identify the extent of a high-energy line break (HELB) to be evaluated for the potential to generate debris. The accident analysis and operational procedures are reviewed to determine the scenarios that require the emergency core cooling system (ECCS) and containment spray system (CSS) to take suction from the IRWST sumps. The review identifies the high-energy piping systems that are evaluated for a postulated HELB and associated debris generation.

3.1.1 Accident Scenarios

The design basis accidents (DBAs) that require engineered safety features (ESF) system action are shown in Table 7.3-2 of the Design Control Document (DCD) (Reference [3-1]). These DBAs result in full ESF initiation, which includes the initiation of four safety injection pumps (SIPs) and two containment spray pumps (CSPs). Shutdown cooling pump (SCP) may be initiated when the CSP is not available.

The design basis accidents that result in debris generation are:

1) Large break loss-of-coolant accident (LBLOCA)

   Subsection 6.3.1 of the DCD (Reference [3-1]) classifies LBLOCAs as a rupture of the reactor coolant pressure boundary with a total cross-sectional area larger than 0.046 m^2 (0.5 ft^2) (ID 8 inch pipe).

   The piping drawings associated with the reactor coolant system (RCS) are reviewed to identify the lines directly attached to the RCS. High-energy lines are listed in Table 3.6-1 of the DCD (Reference [3-1]). The applicable LOCA boundary is located within the secondary shield wall. It is concluded, therefore, that LOCAs outside the secondary shield wall are not included in the licensing basis, are not evaluated for debris generation, and do not lead to IRWST sump recirculation.

   The design basis LOCA is based on a postulated double-ended cold leg (CL) (ID 30 inches) guillotine break on the reactor coolant pump (RCP) discharge line. From a debris generation perspective, however, the hot leg (HL) and crossover legs are larger in diameter (ID 42 inches), which increases the zone of influence (ZOI) and also increases the potential for debris generation since break ZOIs may extend to adjacent loops.

   Six separate LBLOCAs are assessed to identify the break with the potential to generate the largest quantity of debris. The break locations are as follows:

   (a) 30 inch RCS CL
   (b) 42 inch RCS HL steam generator (SG) nozzles
   (c) 12 inch pressurizer (PZR) surge line
   (d) 16 inch SCP Inlet lines
   (e) 12 inch direct vessel injection (DVI) lines
   (f) 12 inch safety injection tank (SIT) injection lines

2) Small break loss-of-coolant accident (SBLOCA)

An SBLOCA is classified as a rupture of the reactor coolant pressure boundary with a total cross-sectional area less than 0.046 m^2 (0.5 ft^2) in which the normally operating charging system flow is not sufficient to sustain the PZR level and pressure. Since SBLOCAs may not be isolated, they must be considered for debris generation because many could lead to IRWST sump recirculation. According to NEI 04-07 (Reference [3-2]), only SBLOCA lines with 2 inches and larger are included in the evaluation up to the first isolation point.

High-energy lines are listed in Table 3.6-1 of the DCD (Reference [3-1]). The applicable LOCA boundary is located within the secondary shield wall. It is concluded, therefore, that LOCAs outside the secondary shield wall are not included in the licensing basis, are not evaluated for debris generation, and do not lead to IRWST sump recirculation.

SBLOCAs are assessed to identify the break with the potential to generate the largest quantity of debris. The break locations are as follows:

(a) 7.75 inch pilot operated safety relief valve (POSRV) lines
(b) 3 inch charging lines
(c) 4 inch PZR spray lines

3) Other HELB scenarios

While a LOCA is considered the most likely type of a debris generating HELB leading to IRWST sump recirculation, other HELB scenarios are evaluated to determine whether these breaks could result in debris generation followed by the need for ECCS recirculation as a means of long-term core cooling (LTCC). As long as the RCS remains intact, the intent in pressurized water reactor (PWR) design is to provide decay heat removal via the SG until the plant can be cooled down, depressurized, and placed on the shutdown cooling system (SCS). Based on the establishment of decay heat removal via the SGs, it can be stated that the ECCS flow through the core is not necessary for long-term decay heat removal. Therefore, the analysis of the effects of debris generation from these scenarios on ECCS recirculation performance is not necessary.

However, the main steam line break (MSLB) is included in the debris generation since SIP and CSP operations are initiated upon safety injection actuation signal (SIAS) and containment spray actuation signal (CSAS) after an MSLB, as shown in Table 7.3-2 of the DCD (Reference [3-1]).

Based on the accident scenarios 1), 2), and 3) as described above, the pipes considered to be postulated break points for an evaluation of sump strainer performance are listed in Table 3.1-1.

3.1.2 Selection of the Postulated Break Location

The postulated break location is selected considering the size and location of HELBs that produce debris and potentially challenge the performance of the IRWST sump strainers. Since the break location is not known prior to the evaluation, the break selection process requires evaluating a number of break locations to identify the location that is likely to present the greatest challenge to post-accident sump performance. The debris inventory and transport path are both considered.

The selection of the postulated break location is based on the pipe break sizes and locations that are provided in accident analyses and operational procedures that require the ECCS and CSS to take suction from the IRWST sumps and according to the guidance in NEI 04-07 (Reference [3-2]) and the Safety Evaluation (SE) of NEI 04-07 (Reference [3-3]).

Subsections 3.3.4 and 4.2.1 of NEI 04-07 recommend that a sufficient number of breaks in each high-

pressure system that rely on recirculation be considered to ensure that the breaks that bound variations in debris generation by size, quantity, and type of debris are identified.

The following break location criteria are considered.

1) Pipe break in the RCS or main steam system/feedwater system (MS/FW) with the largest potential for producing debris

2) Largest break with two or more types of debris

3) Breaks in the most direct path to the sump

4) Large break with the potential for producing the highest of particulate debris to insulation by weight

5) Breaks that generate thin bed - high particulate with 1/8 inch fiber

According to Subsection 3.3.4.1, item 7 in the SE of NEI 04-07 (Reference [3-3]), piping with a diameter of less than 2 inches can be excluded when determining limiting break conditions.

For break criteria 1) and 2), a break of the RCS or MS/FW piping connected to major equipment generates maximum debris loads (insulation, coating, and other debris sources) because the RCS or MS/FW piping (RCS hot leg line (42 inch), RCS cold leg line (30 inch), and Main Steam line (30.907 inch)) have the largest pipe diameters resulting in the largest ZOIs for debris generation. In addition, RCS piping generates the maximum number of types of debris including insulation, coating, and other debris sources.

An evaluation of break criterion 3) is not necessary because there are no breaks with a high-energy line within the IRWST, and four strainers and sumps are located inside the IRWST compartment, which is protected from the high-energy piping system in the containment.

Break criterion 4) does not apply to the APR1400 because only RMI is used on piping and particulate insulation is not used.

For an evaluation of the thin-bed effect (TBE) associated with the break criterion 5), it is well known that head loss due to TBE depends on the amount of particulate debris. As described above, the worst case of particulate debris generation is considered.

Based on the above evaluation, the worst case break location for debris generation is a break of RCS or MS/FW system piping located in one SG compartment (RCS hot leg line (42 inch), RCS cold leg line (30 inch), and main steam line (30.907 inch)).

Based on the guidance in Reference [3-3], the postulated break location in the APR1400 is selected to result in maximum debris loads and variety of debris types.

3.2 Debris Generation

The sources of debris in the APR1400 are insulation, coating, and latent debris. RMI and coating debris are considered as the potential debris sources following a HELB.

As described in Subsection 3.1.2, the worst cases of debris generation are the RCS hot leg line (42 inch) break, RCS cold leg line (30 inch) break, and main steam line (30.907 inch) break. A spherical ZOI is used to estimate the volume of generated debris. Figures 3.2-1 through 3.2-3 show a sectional view of the ZOI for each break location.

For latent debris, the 90.72 kg (200 lbm) is assumed as latent debris in accordance with NEI 04-07 (Reference [3-2]).

The detailed evaluation methodology and results of debris generation used for the three limiting break are described in Appendix B. From the evaluation results in Appendix B, the amount of insulation, coating, and latent debris assumed for the three break locations is summarized in Table 3.2-1.

As shown in Table 3.2-1, the junction of the RCS HL pipe (42 inch) and SG is selected as the postulated break location. This break location is reasonable because the SGs have a larger volume of insulation than RCS piping and most of the primary system piping is located in this SG compartment. The larger amount of insulation presents and the greater volume of debris are transported to the IRWST sump strainer. This results in the maximum head loss across the IRWST sump strainer.

3.3 Debris Characteristics

Three potential sources of debris are evaluated for their impacts on the APR1400 recirculation flow path and LTCC. These debris sources are as follows:

1) ZOI coatings – Coatings in the ZOI of a LOCA are assumed to fail as fines (small particles) and to be transported to the strainer.

2) Latent debris – Latent debris is dirt, dust, lint, and other miscellaneous materials that may be present inside containment before the initiation of a LOCA.

3) Post-accident chemical effects – Post-accident chemical effects are the result of containment sump fluid reacting chemically with materials inside containment and producing chemical precipitates.

NEI 04-07 indicates that 90.72 kg (200 lbm) of latent debris with a 15% / 85% (fiber to particulate) spilled to determine latent debris loads. However, the APR1400 design assumes that 90.72 kg (200 lbm) of latent debris with a 7.5% / 92.5% (fiber to particulate) spilled to determine latent debris loads, that all latent fibrous debris within containment is fine, and that there is no need to define fibrous debris size.

Fibrous debris is categorized in Reference [3-3] as follows:

1) Fines that easily remain suspended in water, even relatively quiescent water

2) Small piece that readily sinks in hot water and can transport along the floor when flow velocity and pool turbulence are sufficient

3) Large piece that readily sinks in hot water and can transport along the floor when velocity and pool turbulence are sufficient

4) Intact debris that readily sinks in hot water and can transport along the floor when velocity and

pool turbulence are sufficient

Therefore, all latent fibrous debris assumed as fines easily remains suspended in water (even relatively quiescent water) and collects in the sumps.

NEI 04-07 (Reference [3-2]) guidance is 75% fines and 25% large pieces as the size distribution of any type of RMI inside a pipe break ZOI. The evaluation of the APR1400 design follows the guidance in NEI 04-07 (Reference [3-2]) of 75 percent small fines and 25 percent large pieces as the size distribution of any type of RMI inside a pipe break ZOI.

Subsection 3.4.3.2 of NEI 04-07 (Reference [3-2]) describes of the debris size distributions that have been used in various studies and specifies a two-size distribution for material inside the ZOI of a postulated break for the evaluation. The two sizes are fines (< 4 inch) and large pieces (> 4 inch). Fines are defined as any material that could transport through gratings, trash racks, and/or radiological protection fences by blowdown, containment sprays, or post-accident pool flows. Fines are assumed to be the basic constituent of the material for latent debris (for fibers and particles), and coatings (in the form of individual fibers, particles, and pigments, respectively). RMI debris is sufficiently dense and the flow rates are also sufficiently small to prevent the RMI debris from being transported to the APR1400 strainer. RMI is composed of thin layers of stainless steel foil. Stainless steel has a density of 7.85 g/cm3 (490 lbm/ft3).

NEI 04-07 (Reference [3-2]) and the SE for NEI 04-07 (Reference [3-3]) indicate the following coating effects:

1) All coatings in the ZOI will fail.

2) All qualified coatings outside the ZOI remain intact unless damaged or degraded.

3) All unqualified coatings in containment will fail.

Per Subsection 3.4.3.2 of NEI 04-07 (Reference [3-2]), all qualified coatings within the ZOI are considered fine particles with a size of 10 μm (0.394 mil). All coating debris is suspended and transported in the recirculating water along with the latent debris to the strainers. The APR1400 strainer is not susceptible to coating debris in the form of chips since chips will settle and not accumulate in such a way to block the strainer (such as in a pit configuration), and the failure characteristic of inorganic zinc and epoxy coatings from industry experience is erosion resulting in very small particulates from the substrate due to the jet impingement.

The debris characteristics used in the APR 1400 evaluation are presented in Tables 3.3-1 and 3.3-2.

3.4 Debris Transport

Debris transport quantifies debris that transports to the sump strainer. The amount of debris generation and the characteristics of the debris transport are used to determine debris accumulation.

The blockage of the strainers and its effect on the net positive suction head (NPSH) of the pumps are considered conservatively when the accumulation has reached its maximum.

In accordance with the guidance provided in Subsection 3.6.1 of NEI 04-07 (Reference [3-2]), the following four major debris transport modes are considered.

1) Blowdown transport - Horizontal and vertical transport of debris by the break jet. All debris by the break jet is transported to the containment floor. No debris is transported upwards to the containment dome.

2) Washdown (containment spray) transport - Vertical transport of debris by the containment sprays/break flow. Since all debris is modeled as transporting to the containment floor during blowdown, there is no washdown transport.

3) Pool fill-up transport - Horizontal transport of the debris by break and CS flows to active and inactive areas of the basement pool. All debris are transported out of the SG D-rings to the holdup volume tank (HVT) and assumed to be transported to the IRWST. The large piece of RMI insulation is not transported to IRWST sump strainers located in the IRWST because of sufficient density (Table 3.3-2) and slow flow rates. No transport to inactive volumes is modeled.

4) Recirculation transport - Horizontal transport of the debris in the active portions of the basement pool by the recirculation flow through the ECCS/CSS. All latent debris and failed coating are conservatively assumed to be collected in the HVT and transported to the IRWST sump strainers by recirculating water. The only small amount of RMI debris is assumed to be transported to the HVT and the IRWST in the APR1400. The sump approach flow velocity (i.e., 0.088 m/s (0.29 ft/s)) at the IRWST is lower than the terminal settling velocity (i.e., 0.113 m/s (0.37 ft/s)) and lift over curb velocity (i.e., 0.256 m/s (0.84 ft/s)) of the RMI fine debris addressed in Table 4-2 of NEI 04-07 (Reference [3-2]). Therefore, RMI debris transported in the IRWST settles on the IWRST floor around the sump and does not rise to the strainer surface.

All particulate and coating debris is assumed to be fine enough to remain in suspension due to turbulence and to be transported to the IRWST sump strainers. This assumption provides the most conservative upper limit for the debris transport evaluation and includes the debris breaking down to its minimum size initially so no further particle size reduction occurs during transport.

Latent debris is categorized as fiber and particulates and is assumed to be uniformly distributed. All latent fiber is assumed to have the same fiber diameter as NUKON insulation.

The APR1400 design has four ECCS/CS trains with an independent strainer for each train. The design requires a minimum of three trains in operation assuming that the fourth train has a single failure. Therefore, transported debris in the IRWST is assumed to be distributed to three sumps. However, the APR1400 design assumes that all of break-generated coating, latent debris, and chemical precipitates are transported directly to a single sump for conservatism for the strainer head loss evaluation and the NPSH evaluation. For the bypass debris fraction, the number of available sumps maximizes the amount of bypass debris (i.e., assumes four operating sumps). No credit is taken for debris settlement on the floor or entrapment in ineffective pool.

3.5 Debris Head Loss

3.5.1 IRWST Sump Strainer Design Conditions

The APR1400 uses RMI as the primary insulation system and does not use fibrous or other problematic materials inside containment. The only source of fibrous insulation is therefore latent debris. The types and quantities of debris are limited to latent fiber and particulate, coatings, and chemical effects.

The design of the strainer is based on the following:

1) Flow condition
   (a) Flow rate (L/min / gpm) .... 25,211 / 6,660
   (b) Fluid temperature (°C / °F)........ 60 - 121.1 / 140 - 250

2) Debris quantity
   (a) Epoxy coating (m^3 / ft^3) .... 0 - 0.0878 / 0 - 3.10
   (b) Latent fiber (kg / lbm)........ 6.80 / 15
   (c) Latent particulate (kg / lbm) .... 83.91 / 185

3) Chemical debris with potential to cause chemical effects (Table 3.8-2)

   (a) Submerged concrete (m^2 / ft^2) .... 193.89 / 2,087
   (b) Unsubmerged concrete (m^2 / ft^2) .... 674.20 / 7,257
   (c) Submerged aluminum (m^2 / ft^2) 0
   (d) Unsubmerged aluminum (m^2 / ft^2) .... 216.09 / 2,326

3.5.2 IRWST Sump Strainer Sizing

The strainer evaluation methodology is based on the integration of an analytical determination of the clean strainer head loss and the results of a prototypical debris head loss test. Given the difficulties with analytical predictions of debris head loss with chemical precipitates, scaled testing provides the best measurement of strainer performance under these debris conditions. The strainer testing is performed in accordance with the head loss testing guidance in the NRC Staff Review Guidance Regarding Generic Letter 2004-02, “Closure in the Area of Strainer Head Loss and Vortexing” (Reference [3-4]). The detailed test plan is provided in “APR1400 IRWST ECCS Sump Strainer Prototype Hydraulic Qualification Test Plan” (Reference [3-5]) and the test result is provided in Appendix C of this report.

Validation of the final strainer sizing of 55.74 m^2 (600 ft^2) is accomplished by testing the prototype strainers with flows and scaled debris loads for the design conditions and extrapolating the results to the design basis temperature range. A detailed view of the sump strainer is provided in Figure 3.5-1.

3.5.3 IRWST Sump Strainer Head Loss

3.5.3.1 Clean Strainer Head Loss

The strainer is designed to fit over the top of the IRWST sump pits with flow directly into the pit to minimize clean strainer head losses. As a calculation result of the clean strainer head losses, 7.62 cm-water (0.25 ft-water) for a temperature of 60 °C (140 °F) is determined. Given the low head loss of the clean strainer in the testing, this calculated head loss is conservatively applied to the higher temperatures. It is conservative since the clean head loss is a direct function of fluid density and the density of the fluid decreases with an increase in temperature.

3.5.3.2 Debris Head Loss

The objective of the prototype debris head loss tests is to develop experimental head loss data associated with the specified debris loadings. Flow sweeps are conducted to obtain additional head loss data as a function of flow rate (i.e., velocity) for potential use in the temperature correction analysis. The testing includes measurements of differential pressure across the strainer, fluid temperature, and pump flow rate for the debris mixtures identified in the test matrix. The testing is designed to demonstrate that the head loss associated with the strainer is acceptable for the design debris loading or to identify the maximum allowable debris loading that results in acceptable head loss.

Two head loss tests are performed. The difference between tests is the change in effective surface area of the strainer to account for labels and tags. The first test uses an effective surface area of 55.74 m^2 (600 ft^2), and the second test uses an effective surface area of 46.45 m^2 (500 ft^2). These two tests are accomplished by increasing the test flow rate for the second test from 3,157 L/min (834 gpm) to 3,785 L/min (1,000) gpm and increasing the mass of debris per square foot. Additionally as a result of the NRC's witnessing the first test, the second test uses fiber prepared to heavily favor Class 1 and 2 fiber classes.

The details of the testing program and selection of the prototype are discussed in Reference [3-5] and the test result is provided in Appendix C of this report.

The maximum head loss for the 46.45 m^2 (500 ft^2) effective strainer area with the maximum debris load is 24.69 cm-water (0.81 ft-water) at the design flow rate and includes a clean screen component of 15.85 cm-water (0.52 ft-water). Therefore, the debris only head loss for both tests is essentially the same at 8.84 cm-water (0.29 ft-water). While the flow rates/debris mass per unit area are slightly different, the results are nearly identical and repeatable and considerably less than the 60.96 cm-water (2 ft-water) allowable head loss. The results are due to the very low debris load that is insufficient to cover the screen completely, similar to that of the "clean plant criteria."

These test results are experimentally measured in a test fluid at approximately 31.1 °C (88 °F). Therefore, it is conservative to use these values at higher temperatures since fluid density and viscosity decrease with increasing temperature.

3.5.3.3 Total Strainer Head Loss

The prototype debris head loss test results and calculated clean strainer head loss are combined to provide a total strainer head loss that is compared to the allowable head loss.

The total strainer head loss value is the sum of the clean strainer head loss and debris head loss. This is conservatively calculated by double counting the clean screen component using the analytical value and the test value inherent in the measure debris head loss. Therefore, 7.62 cm-water (0.25 ft-water) plus 24.69 cm-water (0.81 ft-water) equals 32.31 cm-water (1.06 ft-water) at 60 °C (140 °F). Consequently, the result of a total strainer head loss less than the allowable head loss validates the design.

3.6 Net Positive Suction Head

NPSH is a measure of the fluid energy at a pump inlet. Required NPSH ($NPSH_r$) is the minimum fluid energy, in excess of the vapor pressure energy, required at the pump inlet to prevent cavitation from occurring inside the pump and to obtain satisfactory operation. NPSH is typically specified by the pump manufacturer and is a function of the pump flow rate. Available NPSH ($NPSH_a$) is the fluid energy available at the pump inlet based on the system configuration and operating conditions. The NPSH margin ($NPSH_m$) is the difference between $NPSH_a$ and $NPSH_r$ and must be greater than zero to preclude pump cavitation.

3.6.1 System Operation

Figure 3.6-1 shows the schematic flow diagram of the ECCS. Emergency core cooling is provided by the safety injection system (SIS). The SIS consists of four mechanically separated trains, four SITs, and associated valves, piping and instrumentation. Each SIP is normally aligned with its own suction line from the IRWST and its own discharge line to a DVI nozzle on the reactor vessel (RV) or the DVI nozzle/hot leg. SI lines 1 and 2 inject the borated water to the RCS through the DVI nozzles and SI lines 3 and 4 inject the borated water to the DVI nozzles or HL injection lines during the long-term mode.

The SIS automatically goes into operation upon indication that a significant breach in the RCS boundary has occurred. The SIPs are automatically initiated by the SIAS, and the short-term mode of operation is also initiated upon an SIAS. An SIAS is produced upon two-out-of-four coincident low PZR pressure or a high containment pressure signal. Operator actions are required to initiate the long-term mode. Operator actions depend on break size, time into the LOCA, and whether the LOCA has been isolated.

The long-term mode is manually initiated at approximately 1 to 2 hours post-LOCA when HL injection valves in the discharge piping of SIPs 3 and 4 are opened, and the DVI flow path cold side valves of SIPs 3 and 4 are closed. The DVI nozzle flow paths of SIPs 1 and 2 remain open. The configuration of SIPs 3 and 4 injecting into the HLs and SIPs 1 and 2 injecting into their respective DVI nozzle provides circulation flow through the core. For SBLOCAs, the SIPs provide makeup for spillage, while the RCS is cooled down and depressurized to shutdown cooling (SC) initiation conditions using the SG atmospheric dump valves and auxiliary feedwater system.

The CSS consists of two 100% capacity trains, each of which has two independent CSPs, two containment spray heat exchangers (CSHXs), two CS mini-flow heat exchangers, CS headers, and associated valves. Figure 3.6-2 shows the schematic flow diagram of CSS.

The CSPs are automatically actuated by an SIAS or a CSAS from the ESF actuation system. The CSAS is initiated by a coincidence of two-out-of-four high-high containment pressure signals or two remote manual signals from the control room or by loss of power to two-out of-four actuation logic channels. The CSAS opens the CS header isolation valves to the containment.

Once the CSPs are started and the valves are opened, the spray water flows into the CS headers. These headers contain spray nozzles that break the flow into small droplets enhancing the water's cooling effect on the containment atmosphere. As these droplets fall to the containment floor, they absorb heat until they reach thermal equilibrium with the containment. The units are designed to reduce the containment atmosphere pressure 24 hours after an accident to half of the calculated peak pressure. The CSPs are functionally interchangeable with the SCPs when not required to perform their requisite design basis function, assuming a loss of offsite power (LOOP) and single failure. The CSPs can be used as a backup to the SCPs to provide residual heat removal, and the CSPs and the CSHXs can be used as a backup to the SCPs and the SC heat exchangers to provide cooling of the IRWST.

The CSPs, SCPs, and SIPs are normally aligned to the IRWST inside the containment. These pumps take suction directly from the IRWST. Four IRWST sump strainers are installed in the IRWST and each

strainer is for one of the four trains.

The flow rates of the SIP and CSP are shown in Table 3.6-1 and these values are used for NPSH evaluation. The maximum flow rate for the SIP and CSP/SCP are 4,675 L/min (1,235 gpm) and 20,536 L/min (5,425 gpm) respectively. The SIP and CSP or SIP and SCP operate simultaneously while drawing from the sump.

3.6.2 Available NPSH Calculation

The containment pressure is assumed to be equal to the initial containment pressure prior to the start of the accident (for sump fluid temperatures below the saturation temperature corresponding to this containment pressure). This methodology conforms with the requirements of NRC RG 1.1, "Water Sources for Long-term Recirculation Cooling Following a Loss-of-Coolant Accident" (Reference [3-6]) and RG 1.82 (Reference [1-1]) that the $NPSH_a$ be evaluated without crediting any increase in pressure resulting from accident conditions at low temperatures. This approach ensures that sufficient containment pressure is available under all accident conditions and that defense-in-depth is maintained by preserving the independence of systems designed to prevent accidents and those designed to mitigate the effects of accidents. It is assumed that the containment pressure remains constant at the pre-accident value consistent with NRC RG 1.82 and RG 1.1, for sump fluid temperatures lower than the corresponding initial saturation vapor pressure. For temperatures higher than this initial saturation pressure condition, the containment pressure is assumed to be equal to the sump fluid vapor pressure.

1) Assumptions

(a) Single failure

Each of the four SIPs is provided with a separate suction line from the IRWST and a separate discharge line to one of four DVI nozzles. One SIP and associated injection valves in each train are powered from the independent emergency power supply. This provides the automatic operation of three trains of SIPs in the unlikely event of a concurrent LOOP and the failure of an active component, including a standby generator. Therefore, a single failure in any single train does not affect flow rate through any other strainer or SI train.

The CSP and SCP consist of two trains and an IRWST sump strainer is installed for each train (i.e., one IRWST sump strainer is installed for one CS pump or for one SC pump). The most limiting single failure for the IRWST sump strainer is a single CSP or SCP failure caused by the failure of an emergency bus. Therefore, a single failure in other trains does not affect flow rate through the IRWST sump strainer.

(b) Containment pressure

For the minimum $NPSH_a$ calculation, no additional containment pressure is credited above the initial containment pressure for low sump fluid temperatures (i.e., below approximately 100 °C (212 ºF). For higher sump fluid temperatures, the containment pressure is assumed to equal the saturation pressure corresponding to the sump water temperature.

During LOCA and post-LOCA conditions for the APR1400, containment pressure always exceeds the saturated vapor pressure at the IRWST water temperature.

During a LOCA, mass and energy are released from the primary system to both the vapor phase (containment atmosphere) and to the IRWST (liquid phase) inside the containment volume. Steam released from the primary system postulated break maintains the containment atmosphere at saturated conditions during almost all of the LOCA transients. Moreover, fluid condensed by passive heat sinks (such as the containment shell liner,

supporting structures and concrete) and the CS is added to the IRWST. The condensed water entering the IRWST is at the steam partial pressure in the containment atmosphere. After the long-term operation, the IRWST liquid temperature is strongly affected by the liquid water condensed from the atmosphere during the CS operation. The condensed water is also saturated at the steam partial pressure.

Therefore, a higher containment pressure provides condensed water at a higher temperature and higher IRWST liquid temperatures. Similarly, a lower containment pressure provides condensed water at lower temperature and a lower IRWST liquid temperature. For the purposes of the $NPSH_a$ determinations for ECCS pumps, the APR1400 does not consider the IRWST vapor saturation pressure (based on IRWST liquid temperature) to exceed the containment pressure for any postulated DBA.

Figure 3.6-3 (Figure 6.2.1-4 of Reference [3-1]) shows the containment pressure and IRWST water temperature response during a LOCA and MSLB accident. The IRWST temperatures are calculated conservatively by mixing the condensed liquid in the containment with the IRWST water. The limiting case is the double-ended discharge leg slot break with minimum SI flow from Reference [3-7]. The IRWST maximum water temperature is 119.15 °C (246.47 °F) at 16,007 seconds. Containment pressure at the maximum IRWST water temperature is 1.07 kg/cm^2 (15.21 psia) higher than saturation pressure, which provides reasonable assurance that water temperature does not exceed the saturation temperature in the range of containment pressures analyzed. Therefore, the assumption that containment pressure and IRWST vapor pressure are equal when evaluating $NPSH_a$ is appropriate and conservative for the ECCS and CSS.

(c) Water level

The contribution of the volume of water spillage from the RCS is conservatively neglected, and the volume of water spillage from SITs is available in three of four SITs in accordance with EPRI, Chapter 5, “Engineered Safety System,” in Vol. II, “ALWR Evolutionary Plant,” of Advanced Light Water Reactor Utility Requirements Document (Reference [3-8]).

With the CSS actuated, the reactor cavity and in-core instrumentation (ICI) cavity are assumed to be flooded to a level that can overflow onto the floor at El. 100 ft through the openings of HL and CL pipes at El. 114.29 ft. The HVT is also just below the level at which water begins to return to the IRWST through the spillways.

Spray water is held up on surfaces throughout the containment. The accumulation of water inside the containment includes water held up on horizontal surfaces, clogged floor drains, water held up in containment spray pipes, water in the containment atmosphere, water film on vertical surfaces, puddles trapped on equipment, water soaked into insulation, and the containment free volume filled with steam.

Based on the above assumption, the IRWST water level for the $NPSH_a$ calculation is determined to be 1.52 m (5 ft) above the IRWST bottom (El. 81 ft). The details of the minimum water level for ESF operation are described in Subsection 3.9.2.

(d) Head loss

Head loss calculations for the $NPSH_a$ are based on hydraulic models of the system aligned to take suction from the IRWST. The system configurations of SIP suction and CSP/SCP suction do not change during an accident. Therefore, these system configurations result in the highest sump flow rate, which is used for sizing the IRWST sump strainers. The flow rate for the $NPSH_a$ calculation is conservatively based on the maximum pump flow rate. These calculations use Equations 2-1, 2-3, and 2-4 of Crane Technical Paper No. 410, “Flow

of Fluid through Valves, Fitting, and Pipe" (Reference [3-9]) to determine the head loss due to frictional resistance in the piping and line losses due to other component. The water temperature used for head loss calculation (e.g., pipe, fitting) is 10 °C (50 °F) of the IRWST minimum temperature.

(e) Strainer head loss

The strainer head loss uses a conservative of 60.96 cm-water (2 ft-water) over the temperature of interest. The actual debris head loss is evaluated by qualified test results conducted specific to the APR1400 plant conditions. The detailed test plan is provided in Reference [3-5] and the test result is provided in Appendix C of this report. Based on the results of strainer testing, the maximum head loss for the 46.45 m^2 (500 ft^2) effective strainer area with the maximum debris load is 24.69 cm-water (0.81 ft-water) at the design flow rate and includes a clean screen component of 15.85 cm-water (0.52 ft-water). As a result of the strainer testing, a head loss of approximately 41% of the strainer design head loss ensures adequate NPSH margin for the ECCS pumps.

The strainer head loss of 60.96 cm-water (2 ft-water) represents a conservative bounding value and does not require temperature adjustment. It is conservative to use these values at higher temperatures since fluid density and viscosity decrease with increasing temperature.

(f) Required NPSH

Generally, the $NPSH_r$ (3%) is identified by the pump vendor through testing as the $NPSH_r$ to prevent a 3% loss in pump head ($NPSH_{r3\%}$) at rated flow. $NPSH_r$ is a property of the pump itself. Following the guidance in SECY-11-0014, "Use of Containment Accident Pressure in Analyzing Emergency Core Cooling System and Containment Heat Removal System Pump Performance in Postulated Accidents" (Reference [3-10]), the following uncertainty factors associated with $NPSH_r$ are considered to determine the effective $NPSH_r$ ($NPSH_{reff}$) as follows:

$NPSH_{reff}$ = (1 + uncertainty) $NPSH_{r3\%}$

The following uncertainty factors that affect $NPSH_r$ developed during pump testing are considered:

(1) The $NPSH_r$ varies with changes in pump speed caused by motor slip.
(2) The $NPSH_r$ decreases with increasing water temperature.
(3) Incorrectly designed field suction piping adversely affects the $NPSH_r$.
(4) The air content of the water used in the vendor's test may be lower than that of the pumped water in the field.
(5) Wear ring leakage impacts $NPSH_r$.

The $NPSH_r$ curves have not been adjusted to consider the positive impact of increasing water temperature (factor (2)). This results in a conservative value for $NPSH_r$. A 21% total uncertainty has been applied to account for the effects of the other four uncertainty factors. This uncertainty is consistent with that used in operating plants. The effective $NPSH_r$ of the procured pump will be confirmed through American Society of Mechanical Engineers (ASME) QME-1 qualification.

Therefore:

$NPSH_{reff}$ = (1 + 0.21) $NPSH_{r3\%}$

$NPSH_m$ = $NPSH_a$ - $NPSH_{reff}$

In the APR1400 design, the design basis NPSH required (effective NPSH required) for the CSPs and SIPs is specified to include the margin above the nominal $NPSH_r$ (NPSH required 3%) identified by the vendor. The design basis $NPSH_r$ for the CSP is specified as 5.33 m (17.5 ft), although the nominal value provided by the pump vendor is 4.39 m (14.4 ft). In addition, the design basis NPSH required for the SIP is specified as 6.71 m (22.0 ft), although the nominal value provided by the pump vendor is 5.56 m (18.23 ft).

The $NPSH_r$ for the CSPs and SIPs at the design flow rates is shown in Table 3.6-1.

2) Calculation results

An evaluation of the SIP and CSP demonstrates that $NPSH_a$ is sufficient during postulated DBAs.

The $NPSH_a$ is a function of the suction piping system and is calculated using the following general equation:

$NPSH_a = h_{atm} + h_{static} - h_{loss} - h_{vp}$

Where:

h_{atm} = Head on the liquid surface resulting from the pressure in the atmosphere above the IRWST, (ft-water)
h_{static} = Head resulting from the difference in elevation between the liquid surface and centerline of pump suction, (ft-water)
h_{loss} = Head loss resulting from fluid friction and fittings in the flowpath to the pump suction flange, (ft-water)
h_{vp} = Head equivalent to the vapor pressure of the water at the water temperature, (ft-water)

For this analysis, h_{atm} and h_{vap} are considered as the following based on the maximum of the initial containment pressure and the saturation pressure at the temperature (T) of the pumped fluid.

(a) For T > 100 °C (212 °F)

h_{atm} = h_{vp}

(b) For T< 100 °C (212 °F)

h_{atm} = Head equivalent to maximum of the initial containment pressure before postulated LOCA
h_{vp} = Head equivalent to vapor pressure at T

The head equivalent to the vapor pressure of the water at the water temperature varies with temperature. For IRWST water properties during the period before the IRWST reaches 100 °C (212 °F), the analysis assumes subcooled liquid at 1 atm (14.7 psia), which is the containment pressure before the accident. When the IRWST temperature is greater than 100 °C (212 °F), the containment pressure is equal to the IRWST liquid vapor pressure.

The peak IRWST temperature from Figure 3.6-3 is 119.15 °C (246.47 °F). The limiting evaluation of the NPSH credits containment accident pressure since it conservatively assumes the IRWST liquid is at the saturation pressure corresponding to the peak calculated IRWST temperature.

The $NPSH_m$ is calculated for the SIPs and CSPs for coolant temperatures from 48.9 °C (120 °F) to 121.1 °C (250 °F) based on the containment pressure and temperature for the post-accident long-term phase, as shown in Figure 3.6-3. The $NPSH_m$ for the SIPs for the range of post-LOCA coolant temperatures is included as Table 3.6-2, and the $NPSH_m$ for the CSPs is included as Table

3.6-3.

The time-dependent NPSH curves shown in Figures 3.6-4 and 3.6-5 are based on Figure 3.6-3. These figures represent the most limiting pumps (CSP PP01B and SIP PP02D) and demonstrate positive NPSH margin for all ESF pumps over a full range of IRWST temperatures.

As illustrated in Figures 3.6-4 and 3.6-5, the $NPSH_a$ exceeds the $NPSH_r$ for all expected sump temperatures (and therefore, at all times throughout the LOCA transient). The minimum $NPSH_m$ calculated with this methodology is approximately 0.53 m (1.73 ft) for the SIP and 0.91 m (3.0 ft) for the CSP. Therefore, the IRWST sump strainer of the APR1400 provides sufficient $NPSH_a$ to ensure reliable operation of the ECCS pumps and CSPs.

3.6.3 Cavitation Erosion

Subsection 6.3 of Enclosure 1 of SECY-11-0014 (Reference [3-10]) describes the erosion effects of pump operation due to insufficient NPSH margin. Pump tests indicate that the zone of maximum erosion rate lies between $NPSH_m$ ratios ($NPSH_a/NPSH_r$) of 1.2 to 1.6, and guidance is provided to limit the time of operation in this zone to 100 hours. For the SIPs with an $NPSH_r$ of 6.71 m (22.0 ft), the range of $NPSH_a$ values that correspond to the maximum erosion zone is 8.05 to 10.73 m (26.4 to 35.2 ft). From Table 3.6-2, these pumps experience maximum erosion when the fluid temperature is between about 87.8 °C (190 °F) and 98.9 °C (210 °F). Similarly, the maximum erosion $NPSH_a$ range for the CSPs with an $NPSH_r$ of 5.33 m (17.5 ft) is 6.40 to 8.53 m (21.0 to 28.0 ft). From Table 3.6-3, these $NPSH_a$ values occur when the fluid temperature is between approximately 93.3 °C (200 °F) and 100 °C (212 °F). A review of the temperature data in Figure 3.6-3 indicates that the total duration, when the IRWST fluid temperature is between 90.6 °C (190 °F) and 100 °C (212 °F), is approximately 90,000 seconds (approximately 25 hours), which is within the 100 hour limit recommended in Subsection 6.3.3 of SECY-11-0014 (Reference [3-10]).

3.7 Strainer Vortexing, Air Injection, Flashing, and Deaeration Assessment

IRWST sump strainer submergence is adequate to preclude vortexing, sump fluid flashing, and deaeration induced by excessive differential pressure drop. Vortexing could cause the ingestion of unacceptable quantities of air into the ECCS pumps and CSPs, potentially resulting in unacceptable pump performance. When flashing to steam, water can result in recirculating coolant that transforms a portion of the fluid into the vapor phase if the strainer pressure drop is sufficiently large.

3.7.1 Strainer Vortexing

During the prototype testing, visual observations are required to ensure that no significant vortices have formed. Vortex and/or swirl up to and including a Type 4 are considered acceptable. The testing is performed at the submergence requirement of 60.96 cm (2 ft) submergence, and no vortices are observed. Additionally, there is no possibility of the occurrence of vortexing or air ingestion geometrically because the IRWST sump strainers are mounted at the top of the pit and suction is taken at the bottom of the pit.

3.7.2 Flashing in the Debris Bed

The strainer flashing requirement is conservatively met if the pressure drop across the debris bed is less than the submergence. Based on the IRWST minimum water level of El. 86 ft (i.e., 1.52 m (5 ft) above the APR1400 IRWST bottom floor of El. 81 ft) for ECCS pump NPSH and the strainer assembly height of 84 ft (81 ft plus 3 ft), this provides 60.96 cm (2 ft) submergence under LOCA conditions. The maximum strainer head loss is 32.31 cm-water (1.06 ft-water) at 60 °C (140 °F). The strainer submergence level exceeds the associated head loss. If the surface pressure is conservatively assumed at the saturation pressure of the IRWST water temperature, the local static pressure after the strainer is not less than the saturation pressure, and flashing does not occur across the strainer surface.

During testing, the maximum observed head loss across the strainer is less than 24.69 cm (0.81 ft), which provides additional margin to flashing.

3.7.3 Deaeration of Sump Fluid at Strainer

The IRWST sump strainer submergence during post-LOCA is greater than the observed head loss under loss of coolant conditions. Since solubility of gas in water is directly proportional to the fluid pressure, the increase in solubility of air due to the static pressure increase of the water above the strainer is more than enough to compensate for the decrease in solubility of air due to the head loss across the strainer. Therefore, deaeration of fluid does not occur. The design head loss value is a conservative value aimed primarily at minimizing the calculated NPSH for the ECCS pumps, and does not imply deaeration even though it may be greater than the strainer submergence.

3.8 Chemical Effects

A chemical effects evaluation is performed following the chemical effects evaluation process shown in Figure 1 of Enclosure 3 of Reference [2-3]. No exception is taken with regards to the guidance provided.

In order to assess potential chemical effects in the APR1400 sump, the materials that are in the containment building that may react with coolant in the post-accident containment environment have been identified. Reactive plant materials in the containment building are categorized as metallic and non-metallic items and generally include insulation and concrete, as well as other potential sources of aluminum. The materials inventory includes the overall mass, location in containment and potential for being sprayed with or immersed in coolant following a LOCA.

The WCAP-16530-NP methodology (Reference [3-11]) referenced in NRC RG 1.82 (Reference [1-1]) provides a conservative model to predict the corrosion and dissolution of containment materials in a post-LOCA environment and the formation of chemical precipitates for participating PWRs. The primary corrosion products contributing to these chemical precipitates are calcium, silicon, aluminum, and the precipitates that can form aluminum oxy-hydroxide, calcium phosphate, and sodium aluminum silicate. Surrogate suspensions of chemical precipitates representing this chemical debris can be included as an additional debris source to the strainer testing program to qualify the strainer for “chemical effects.” The quantities of chemical precipitates are based on reactive material surface areas and quantities, temperature, water level, pH, and other parameters related to the plant specific environment and post-accident evolution.

3.8.1 Containment Spray pH Control

The pH of IRWST water is evaluated to provide reasonable assurance that the calculated minimum and maximum pH values under any possible water chemistry conditions caused by a LOCA are between 7.0 and 8.5. The IRWST and containment spray pH ranges are 4 to 10 for short term DBA condition, based on APR1400 operating conditions and past operating experience, and 7 to 8.5, using the tri-sodium phosphate as buffering agent, for long term DBA condition. These values are based on the maximum and minimum pH calculations. The IRWST pH ranges are included in Table 3.8-1.

3.8.2 Assumptions

1) The maximum IRWST water volume is used for the chemical effects analysis in terms of the concentration or solubility of the elements even though the sensitivities for the minimum and maximum IRWST water volumes have no impact on the final precipitates results due to the limited amount of fiberglass debris.

2) The maximum IRWST and spray pH values of 10 for short-term DBA and 8.5 for long-term DBA from Table 3.8-1 are conservatively used because total dissolution and precipitate generation increase as pH increases, as shown in Figure 6.5-5 of Reference [3-11]. Figure 3.8-1 shows the IRWST and containment spray pH versus time curve used in the chemical effects analysis.

3) The limiting LOCA scenario that yields the highest sump temperature is used to maximize the amount of chemical precipitates. The containment and sump temperature profiles extended to 30 days are calculated using the GOTHIC computer code. The detailed model description to calculate the highest sump temperature is provided in Appendix B of Reference [3-7].

4) The CSS is operated from the accident initiation and continued for 30 days to maximize the exposure of containment spray to unsubmerged materials.

3.8.3 Evaluation Summary

Aluminum and concrete, the identified containment materials to be considered for chemical effect in the APR1400, are significant contributors to production of the corrosion products based on WCAP-16530-NP (Reference [3-11]).

The concrete in the reactor containment is the only concrete with qualified coating. Qualified coatings are assumed to fail as a direct result of the HELB ZOI. The failure results in the coated concrete becoming exposed to the sump/spray fluid. An applied ZOI for qualified coatings is 10 times the ID of the ruptured pipe for a conservative estimate. Under most circumstances, a 10D ZOI expands beyond the walls and floor of the break compartment. In this case, it is conservative to estimate the surface area of the concrete as the sum of the areas of the walls and floor of the compartment (including any other concrete surfaces inside the compartment). This value is larger than the quantity of qualified coatings (4D ZOI) destroyed by the HELB.

The surface area of concrete structures with qualified coating is estimated from the civil structural drawings and three-dimensional computer-aided design (CAD) program. The surface area consists of walls, floors, and equipment pedestals. Only the surface area that is contact with the sump pool and containment spray is provided. The estimated surface areas are divided into two categories: submerged (pool) and unsubmerged (spray) surface areas.

The sources of aluminum in containment of the APR1400 are associated with the following types of equipment:

1) Heating, ventilation, and air conditioning (HVAC) equipment (four reactor containment fan coolers, four SG enclosure recirculation fans, four annulus area recirculation fans, and duct insulation)
2) Ex-core detectors
3) Refueling equipment
4) Control element drive mechanism (CEDM) cooling fan
5) Surveillance capsule handling tools (retrieval tool and remote positioning tool)
6) POSRV SIEKA-Actuators

The aluminum surface area is broken down into submerged and unsubmerged (spray) zones.

The amount of concrete and aluminum in the containment is provided in Table 3.8-2.

The input data for WCAP-16530-NP chemical product formation, the precipitates produced, and the analysis results are included in Tables 3.8-3, 3.8-4, and 3.8-5, respectively.

3.9 Upstream Effect

3.9.1 Holdup Volumes

The evaluation of the upstream effect is a review of the flow paths leading to the IRWST, identifying the flow paths that could result in blocking the return water that challenges the IRWST minimum water level evaluation for ESF operation. The evaluation also includes identifying the holdup volumes, such as recessed areas and enclosed rooms, for which trapped water does not return to the IRWST. All of the holdup volumes are taken account of in the minimum water level calculation.

Figures 3.9-1 and 3.9-2 show a schematic of CS and blowdown return pathways, and the schematic of potential water traps in containment. During long-term cooling subsequent to an RCS pipe break, borated water is drawn from the IRWST by the SIPs and injected into the RV for core cooling.

The water is ejected to the bottom floor of the containment within the secondary shield wall through the horizontal platforms which are constructed of open grating within the SG compartments.

The CSPs also draw water from the IRWST sumps to cool the containment building. This water rains down on all containment surfaces, and then drains to the bottom floor of containment within the secondary shield wall and annulus via the stairway and a ring of deck grating around much of the circumference of the building.

There are two 10 inch drain pipes in the refueling cavity that are connected to the bottom portion of the containment. The refueling cavity surrounds the upper part of the reactor and extends from the operating floor at El. 156 ft down to the reactor head flange at El. 130 ft. The west part of the cavity encompasses the upper guide structure (UGS) laydown area which extends down to El. 106 ft 6-3/8 in. The east part of the refueling cavity encompasses the fuel transfer system upender and core support barrel (CSB) laydown area. The fuel transfer system upender and the CSB laydown area extends down to El. 114 ft 6 in.

The cavity can collect approximately 9% of the containment main spray flow and fill up except for the two floor drains. Both drains are 10 inch diameter drain pipes in the floor of the refueling cavity liner. One combined drain is the CSB laydown area and the fuel transfer system upender area, and the other is the UGS laydown area. Both drain to El. 100 ft area.

A concern with the refueling cavity is the potential for pieces of debris (e.g., a 25. 4 cm x 25.4 cm (10 inch x 10 inch) piece of RMI) to migrate to one or both drains and greatly restrict the flow so that the refueling cavity may fill. The water sprayed on the refueling cavity area is finally gathered to the lowest parts of the refueling cavity, UGS laydown area, and CSB laydown area, which hypothetically could hold thousands of cubic feet of water if their drains are blocked. However, this scenario is deemed not credible. No high-energy pipes are near the 10 inch openings that drain the refueling cavity. The 10 inch drains are open with no covers, grates, or screens, so the minimum flow restriction in the cavity drain line flow path is the inner diameter of the 10 inch drain line. Debris needs to be at least 10 inches wide to bridge the opening and cause blockage. Smaller debris passes straight through. Debris also needs to be planar in order to adequately seal the opening. A crumpled piece of RMI would not seal the opening.

Water spilled from RCS break and the uniformly distributed CS water drains back to the HVT, and then drains to the IRWST via spillways. Since there are four pathways on the bottom floor of the containment (two 0.91 m (3 ft) wide pathways are personnel entrances leading into secondary shield wall from annulus and two 2.92 m (9 ft 7 inch) wide pathways are located at the front of the HVT trash racks in the secondary shield wall), the debris would not clog these pathways. As a result, no choke points that could block the

flow paths of return water are identified. Therefore, only the holdup volumes may challenge the minimum water level of the IRWST for ESF operation.

The following assumptions are made in the calculation for holdup volume conservatism:

1) The LBLOCA is assumed so that the coolant completely fills the reactor cavity and ICI cavity.

2) The water transfer from the HVT into the IRWST is assumed to spill over into the IRWST through one spillway to maximize water volume to be held up in the HVT.

3) A portion of the CS is delayed in the containment building. The maximum CS flow rate for a two-train operation is assumed to conservatively maximize the CS hold up.

4) The amount of water needed to fill the SIS and CSS is the volume of SIS and CSS piping above the minimum water level during normal operation.

5) The maximum containment atmospheric conditions at CSAS are assumed for each scenario to maximize water that would be held up in the atmosphere. CS water may be held up in the containment atmosphere, in the containment spray droplets, and in the condensation on containment building and equipment surfaces. A fraction of the total water delivered to containment evaporates in the containment atmosphere. The evaporation quantity is calculated based on the steam mass and pressure conditions at CSAS as determined in the associated analyses. CS volume holdup is determined by calculating the fall time at terminal velocity for water droplets from the main spray median header height and the average drop diameter, and the fall time at terminal velocity for droplets from the auxiliary spray median header height and average drop diameter. The delayed volume is thus the product of the fall time and the maximum spray flow rate for each system.

6) Condensation holdup on horizontal and vertical surfaces for containment walls, structures, and equipment is determined by calculating a total surface area and then applying a uniform water film thickness. This value is considered conservative because no distinction is made for surface area orientation; the water film is assumed to be uniform over all horizontal and vertical surfaces.

7) The minimum IRWST and SIT volumes are assumed to minimize water transferred to the containment floor during injection.

The holdup volumes are categorized into two groups: Holdup volume on the ways to the IRWST and inactive pool volume. Two groups are defined as follows:

1) Holdup volume on the ways to the IRWST

In a LOCA, the IRWST water returns from the CS nozzle and broken pipe. The held-up water on the way to the IRWST decreases the initial IRWST water level. The following are the source of held-up water on the way to the IRWST.

(a) CS suspended water in the containment atmosphere
(b) CS steam water
(c) Initial filling water for the SIS and CSS pipe
(d) Condensate water on various surfaces
(e) Water stream on the floor at El. 100 ft

(f) Water steam on the refueling pool floor

2) Inactive pools volume

An inactive pool volume is defined as a holdup volume that entraps return that will not contribute to recovering the IRWST water level. The following are considered as the ineffective pools:

(a) HVT water volume to fill up to level that can flow back into the IRWST through the spillways
(b) Reactor cavity and ICI cavity volume
(c) Containment drain sump volume
(d) ICI cavity sump volume

The calculated holdup volumes are provided in Table 3.9-1.

3.9.2 Minimum Water Level for ESF operation

The following assumptions are made for water sources to minimum water level determination:

1) Water sources available to provide flood water volume are the IRWST volume.

2) RCS spillage from a break point is not credited.

3) Three SITs volumes are added to the IRWST inventory to establish the total volume of water available for flooding.

4) The minimum IRWST and SIT volumes are assumed to minimize water transferred to the containment floor during injection.

The minimum water level of IRWST for ESF operation provides the basis for estimating static head in the NPSH evaluation, as described in Section 3.6. It is conservatively calculated as follows:

During normal operation, the IRWST is not less than 2,373.5 m^3 (627,000 gallons, 74.43% water levels of the IRWST) to ensure an adequate supply of borated water to the SIS and CSS. The IRWST is designed to minimize water evaporation, however, if the water reaches a level of less than 74.43%. The makeup operation from the boric acid storage tank via the boric acid makeup pump is activated and continued until 74.43% water level is recovered. This level is defined as “below normal water level” of the IRWST and is used as the initial water level for postulated accidents. In case of an LBLOCA, the water mass in the SIT can contribute to recovering the IRWST, and water in three of the four SITs is considered in the calculation in accordance with Reference [3-8].

The minimum water level of the IRWST for ESF operation during a LOCA is calculated by subtracting the holdup volume from the initial water volume in the IRWST and by adding the volume in three SITs. The minimum water level for ESF operation used in the NPSH evaluation is calculated as 1.52 m (5 ft) above the IRWST bottom (El. 81 ft) and is shown in Figure 3.9-3.

Table 3.1-1 Postulated Break Pipe Lines

Pipe Lines	Size	Location			
	ID (inch)	Inside Secondary Shield Wall			Outside Secondary Shield Wall
		SG Compartment		PZR Compartment	
		No. 1	No. 2		
Hot leg lines	42	X	X		
Cold leg lines	30	X	X		
PZR surge line	12		X		
SCP inlet lines	12.812	X	X		
DVI lines	10.126	X	X		
Charging line	2.624		X		
PZR aux. spray line	2.624		X		
POSRV lines	7.75			X	
SIT injection lines	10.126	X	X		X
Main steam lines	30.907	X	X		X

Table 3.2-1 Debris Generation for Break Locations

Item \ Break Location		RCS Hot Leg Line	RCS Cold Leg Line	Main Steam Line
Applicable Methodology		NEI 04-07 and SE	NEI 04-07 and SE	NEI 04-07 and SE
Break Size (cm / inch)		106.7 / 42	76.2 / 30	78.5 / 30.907
Size of ZOI (m / ft)	Insulation (2D)	2.13 / 7	1.52 / 5	1.58 / 5.2
	Coating - 4D (epoxy) - 10D (IOZ)	 4.27 / 14 10.67 / 35	 3.05 / 10 7.62 / 25	3.17 / 10.4 7.92 / 26
Amount	RMI (m^3 / ft^3)			
	Coating (m^3 / ft^3) - 4D (epoxy) - 10D (IOZ)	0.086 / 3.03 0.052 / 1.82 0.034 / 1.21	0.039 / 1.39 0.005 / 0.18 0.034 / 1.21	0.012 / 0.42 0.006 / 0.21 0.006 / 0.21
	Latent Debris (kg / lbm)	90.72 / 200	90.72 / 200	90.72 / 200

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Note :

(1) For strainer design, epoxy coating of 3.10 ft^3 is conservatively used.

Table 3.3-1 Size and Distribution of Debris

Debris Source Type		Debris Size Distribution	
		Fines (%)	Large Pieces (%)
RMI		75	25
Coating		100	0
Latent	Fiber	7.5	0
	Particle	92.5	0

Table 3.3-2 Debris Properties

Debris Source Type	Property	Value
RMI	Density	7.85 g/cm^3 (490 lbm/ft^3)
Coating	Diameter of particle (D_p)	10 μm (3.94x10^{-4} inch)
	Particle density (μ_p) [(1)] - epoxy - IOZ	1.51 g/cm^3 (94 lbm/ft^3) 7.32 g/cm^3 (457 lbm/ft^3)
Latent Particulate	Particle density (μ_p)	2.70 g/cm^3 (168.6 lbm/ft^3)
Latent Fiber (NUKON)	As-fabricated (theoretical Packing) density (c_o)	0.038 g/cm^3 (2.4 lbm/ft^3)
	Fiber density (μ_f)	1.50 g/cm^3 (93.6 lbm/ft^3)

Note:
(1) Referenced from Table 3-3 of NEI-04-07

Table 3.6-1 NPSHr for SI Pump and CS Pump

Pump	Flow Rate (L/min / gpm)	$NPSH_{r3\%}$ (1) (m-water/ft-water)	$NPSH_{reff}$ (2) (m-water/ft-water)
SI pump	4,675 / 1,235	5.56 / 18.23	6.71 / 22
CS pump	20,536 / 5,425	4.39 / 14.4	5.33 / 17.5

Note :

(1) $NPSH_{r3\%}$ is provided by the pump vendor as a result of factory testing as the value of NPSH which results in a 3% drop in pump discharge head. $NPSH_{r3\%}$ is a property of the pump itself.

(2) $NPSH_{reff}$ (effective required NPSH) is the $NPSH_{r3\%}$ value with uncertainties in $NPSH_r$ included. Following the guidance of SECY-11-0014 (Reference [3-10]), uncertainties associated with $NPSH_r$ are considered to determine the effective $NPSH_r$ ($NPSH_{reff}$).

Table 3.6-2 SI Pump NPSH Evaluation Results

Sump Temp. (°F)	h_{atm} (ft-water)	h_{static} (ft-water)	h_{loss} (ft-water)	H_{vp} (ft-water)	$NPSH_a$ (ft-water)	$NPSH_{reff}$ (ft-water)	Margin (ft-water)
120	34.30	30	6.28	3.95	54.08	22.0	32.08
125	34.34	30	6.28	4.58	53.49	22.0	31.49
130	34.4	30	6.28	5.21	52.92	22.0	30.92
135	34.44	30	6.28	6.00	52.17	22.0	30.17
140	34.49	30	6.28	6.79	51.43	22.0	29.43
145	34.53	30	6.28	7.77	50.49	22.0	28.49
150	34.59	30	6.28	8.76	49.56	22.0	27.56
155	34.65	30	6.28	9.98	48.40	22.0	26.40
160	34.69	30	6.28	11.2	47.22	22.0	25.22
165	34.77	30	6.28	12.71	45.79	22.0	23.79
170	34.82	30	6.28	14.21	44.34	22.0	22.34
175	34.88	30	6.28	16.04	42.57	22.0	20.57
180	34.94	30	6.28	17.87	40.80	22.0	18.80
185	35.02	30	6.28	20.09	38.66	22.0	16.66
190	35.07	30	6.28	22.31	36.49	22.0	14.49
195	35.13	30	6.28	24.96	33.90	22.0	11.90
200	35.21	30	6.28	27.63	31.31	22.0	9.31
205	35.28	30	6.28	30.81	28.20	22.0	6.20
210	35.35	30	6.28	34	25.08	22.0	3.08
212	35.39	30	6.28	35.39	23.73	22.0	1.73
215	37.7	30	6.28	37.7	23.73	22.0	1.73
220	41.54	30	6.28	41.54	23.73	22.0	1.73
225	45.98	30	6.28	45.98	23.73	22.0	1.73
230	50.43	30	6.28	50.43	23.73	22.0	1.73
235	55.65	30	6.28	55.65	23.73	22.0	1.73
240	60.89	30	6.28	60.89	23.73	22.0	1.73
245	66.95	30	6.28	66.95	23.73	22.0	1.73
250	73.06	30	6.28	73.06	23.73	22.0	1.73

Table 3.6-3 CS Pump NPSH Evaluation Results

Sump Temp. (°F)	h_{atm} (ft-water)	h_{static} (ft-water)	h_{loss} (ft-water)	H_{vp} (ft-water)	$NPSH_a$ (ft-water)	$NPSH_{reff}$ (ft-water)	Margin (ft-water)
120	34.30	30.16	9.67	3.95	50.85	17.5	33.35
125	34.34	30.16	9.67	4.58	50.26	17.5	32.76
130	34.4	30.16	9.67	5.21	49.69	17.5	32.19
135	34.44	30.16	9.67	6.00	48.94	17.5	31.44
140	34.49	30.16	9.67	6.79	48.20	17.5	30.70
145	34.53	30.16	9.67	7.77	47.26	17.5	29.76
150	34.59	30.16	9.67	8.76	46.33	17.5	28.83
155	34.65	30.16	9.67	9.98	45.17	17.5	27.67
160	34.69	30.16	9.67	11.2	43.99	17.5	26.49
165	34.77	30.16	9.67	12.71	42.56	17.5	25.06
170	34.82	30.16	9.67	14.21	41.11	17.5	23.61
175	34.88	30.16	9.67	16.04	39.34	17.5	21.84
180	34.94	30.16	9.67	17.87	37.57	17.5	20.07
185	35.02	30.16	9.67	20.09	35.43	17.5	17.93
190	35.07	30.16	9.67	22.31	33.26	17.5	15.76
195	35.13	30.16	9.67	24.96	30.67	17.5	13.17
200	35.21	30.16	9.67	27.63	28.08	17.5	10.58
205	35.28	30.16	9.67	30.81	24.97	17.5	7.47
210	35.35	30.16	9.67	34	21.85	17.5	4.35
212	35.39	30.16	9.67	35.39	20.50	17.5	3.00
215	37.7	30.16	9.67	37.7	20.50	17.5	3.00
220	41.54	30.16	9.67	41.54	20.50	17.5	3.00
225	45.98	30.16	9.67	45.98	20.50	17.5	3.00
230	50.43	30.16	9.67	50.43	20.50	17.5	3.00
235	55.65	30.16	9.67	55.65	20.50	17.5	3.00
240	60.89	30.16	9.67	60.89	20.50	17.5	3.00
245	66.95	30.16	9.67	66.95	20.50	17.5	3.00
250	73.06	30.16	9.67	73.06	20.50	17.5	3.00

Table 3.8-1 Post-LOCA IRWST Chemistry

Short-Term DBA (Accident Initiation up to 4 hours)	Long-Term DBA (4 hours up to 30 days)
• 4,400 ppm boron as H_3BO_3 • 0 - 50 ppm hydrazine as N_2H_4 • $4 \leq pH \leq 10$	• 4,400 ppm boron as H_3BO_3 • 0 - 50 ppm hydrazine as N_2H_4 • $7.0 \leq pH \leq 8.5$ • Tri-sodium phosphate as buffering agent

Table 3.8-2 Material Potentially Produced Corrosion Products

Material	Submerged Pool Zone (m^2 / ft^2)	Un-submerged Spray Zone (m^2 / ft^2)	Remark
1. Concrete	193.89 / 2,087	674.20 / 7,257	
2. Aluminum	N/A	216.09 / 2,326	
• HVAC Equipment - 4 Reactor Containment Fan Coolers - 4 SG Enclosure Recirculation Fans - 4 Annulus Area Recirculation Fans - Duct Insulation	N/A	154.87 / 1,667 (1)	
• Ex-core Detectors	N/A	0.25 / 2.67	
• Refueling Equipment	N/A	12.08 / 130	
• CEDM Cooling Fan	N/A	23.24 / 250.2	
• Surveillance Capsule - Retrieval Tool - Remote Positioning Tool	N/A	22.30 / 240	
• POSRV SIEKA-Actuators	N/A	3.36 / 36.2	

Note :

(1) Considering uncertainty of duct insulation area, 10% margin is added based on the engineering judgment.

Table 3.8-3 Input Data for WCAP-16530-NP Chemical Product Formation

Class	Material	Amount	Notes
Coolant	Sump Pool Volume (ft^3)	89,728	
Metallic Aluminum	Aluminum Submerged (ft^2)	0	
	Aluminum Submerged (lbm)	10,000,000	
	Aluminum Not-Submerged (ft^2)	2,326	
	Aluminum Not-Submerged (lbm)	10,000,000	
Calcium Silicate	Calcium Silicate Insulation(ft^3)	0	
	Asbestos Insulation (ft^3)	0	
	Kaylo Insulation (ft^3)	0	
	Unibestos Insulation (ft^3)	0	
E-glass	Fiberglass Insulation (ft^3)	6.25	
	NUKON (ft^3)	0	
	Temp-Mat (ft^3)	0	
	Thermal Wrap (ft^3)	0	
Silica Powder	Microtherm (ft^3)	0	
	Min-K (ft^3)	0	
Mineral Wool	Min-Wool (ft^3)	0	
	Rock Wool (ft^3)	0	
Aluminum Silicate	Cerablanket (ft^3)	0	
	FiberFrax Durablanket (ft^3)	0	
	Kaowool (ft^3)	0	
	Mat-Ceramic (ft^3)	0	
	Mineral Fiber (ft^3)	0	
	PAROC Mineral Wool (ft^3)	0	
Concrete	Concrete (ft^2)	9,344	
Trisodium Phosphate (TSP)	Trisodium Phosphate Hydrate (lbm)	1	Flag=0 if no TSP, ≠0 if use TSP as buffering agent
Interam	Interam (ft^3)	0	

Table 3.8-4 WCAP-16530 Results Summary

Component	Quantity (kg / lbm)
Aluminum oxy-hydroxide	153.6 / 338.7
Sodium aluminum silicate	4.36 / 9.60
Calcium phosphate	0.71 / 1.56

Table 3.8-5 Results for the APR1400, Maximum Water Volume, Minimum ECCS Flow

Interval Duration (min)	Start of Interval (hrs)	End of Interval (hrs)	Average Interval pH	Average Temp (°F)	NaAlSi3O8 Precipitate (kg)	AlOOH Precipitate (kg)	Ca3(PO4)2 Precipitate (kg)
2.3	0.00	0.0	10	126.1	0.00	0.7	0.00
1.7	0.04	0.1	10	132.8	0.00	1.2	0.00
1.7	0.07	0.1	10	137.1	0.00	1.8	0.00
3.3	0.10	0.2	10	143.8	0.00	2.9	0.00
4.2	0.15	0.2	10	152.5	0.01	4.2	0.00
6.7	0.22	0.3	10	163.6	0.01	6.0	0.00
10.1	0.33	0.5	10	178.3	0.03	8.2	0.01
14.9	0.50	0.8	10	196.6	0.07	11.0	0.01
21.8	0.75	1.1	10	215.0	0.15	14.7	0.02
30.0	1.11	1.6	10	229.7	0.32	19.3	0.04
36.5	1.61	2.2	10	239.5	0.56	24.7	0.06
66.7	2.22	3.3	10	245.6	1.08	34.7	0.09
40.0	3.33	4.0	9.25	248.7	1.33	37.8	0.11
45.0	4.00	4.8	8.5	249.3	1.54	39.7	0.14
165.1	4.75	7.5	8.5	248.4	2.31	46.3	0.22
200.2	7.50	10.8	8.5	244.7	3.17	53.3	0.32
266.9	10.84	15.3	8.5	237.9	4.16	60.6	0.39
417.1	15.29	22.2	8.5	228.1	4.16	68.8	0.40
665.7	22.24	33.3	8.5	216.6	4.16	77.4	0.41
1000.2	33.33	50.0	8.5	205.3	4.17	85.2	0.42
1166.9	50.00	69.5	8.5	195.9	4.18	91.1	0.43
2167.2	69.45	105.6	8.5	186.7	4.19	98.0	0.45
2833.6	105.57	152.8	8.5	177.0	4.21	104.5	0.48
4167.3	152.80	222.3	8.5	168.5	4.23	112.4	0.51
6664.8	222.25	333.3	8.5	161.4	4.26	123.3	0.56
3166.8	333.33	386.1	8.5	157.3	4.27	128.0	0.58
2833.4	386.11	433.3	8.5	155.4	4.28	132.0	0.60
2833.4	433.34	480.6	8.5	153.7	4.30	135.9	0.62
2833.4	480.56	527.8	8.5	152.0	4.31	139.6	0.64
2833.4	527.78	575.0	8.5	150.4	4.32	143.2	0.65
2833.4	575.00	622.2	8.5	149.3	4.33	146.8	0.67
2833.4	622.23	669.5	8.5	148.6	4.34	150.2	0.69
2833.4	669.45	716.7	8.5	147.8	4.36	153.6	0.71

Table 3.9-1 Upstream Effects on Holdup Volume

Volume Source	Volume (m^3 / gal)
[1] Holdup Volume on the way to the IRWST	
- Containment spray suspended water in the containment atmosphere	3.13 / 826
- Containment spray steam water	170.69 / 45,092
- Initial filling water for SI system and CS system pipe	30.58 / 8,078
- Water stream on the El. 100 ft floor	229.61 / 60,656
- Water stream on the floor of refueling cavity	42.36 / 11,190
- Miscellaneous holdup volume	140.01 / 36,987(1)
Subtotal [1]	**616.37 / 162,829**
[2] Inactive Pool Volume	
- HVT volume	212.29 / 56,080
- Reactor cavity and ICI cavity volume	621.53 / 164,192
- Containment drain sump volume	11.78 / 3,112
- ICI cavity sump volume	3.40 / 898
Subtotal [2]	**849.00 / 224,282**

Note :

(1) The miscellaneous holdup volume is water volume holdup elsewhere in the reactor building (eg., water on horizontal surface area before cascading through openings on its way back to the IRWST (assume floor drains are clogged), film of water in vertical surfaces of concrete structures, film of water on side surface of equipment, and puddles trapped on top of the concrete structure and equipment).

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Figure 3.2-1 Sectional View of the ZOI for RCS Hot Leg Line Break

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Figure 3.2-2 Sectional View of the ZOI for RCS Cold Leg Line Break

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Figure 3.2-3 Sectional View of the ZOI for Main Steam Line Break

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Figure 3.5-1 IRWST Sump Strainer Plan and Elevation View

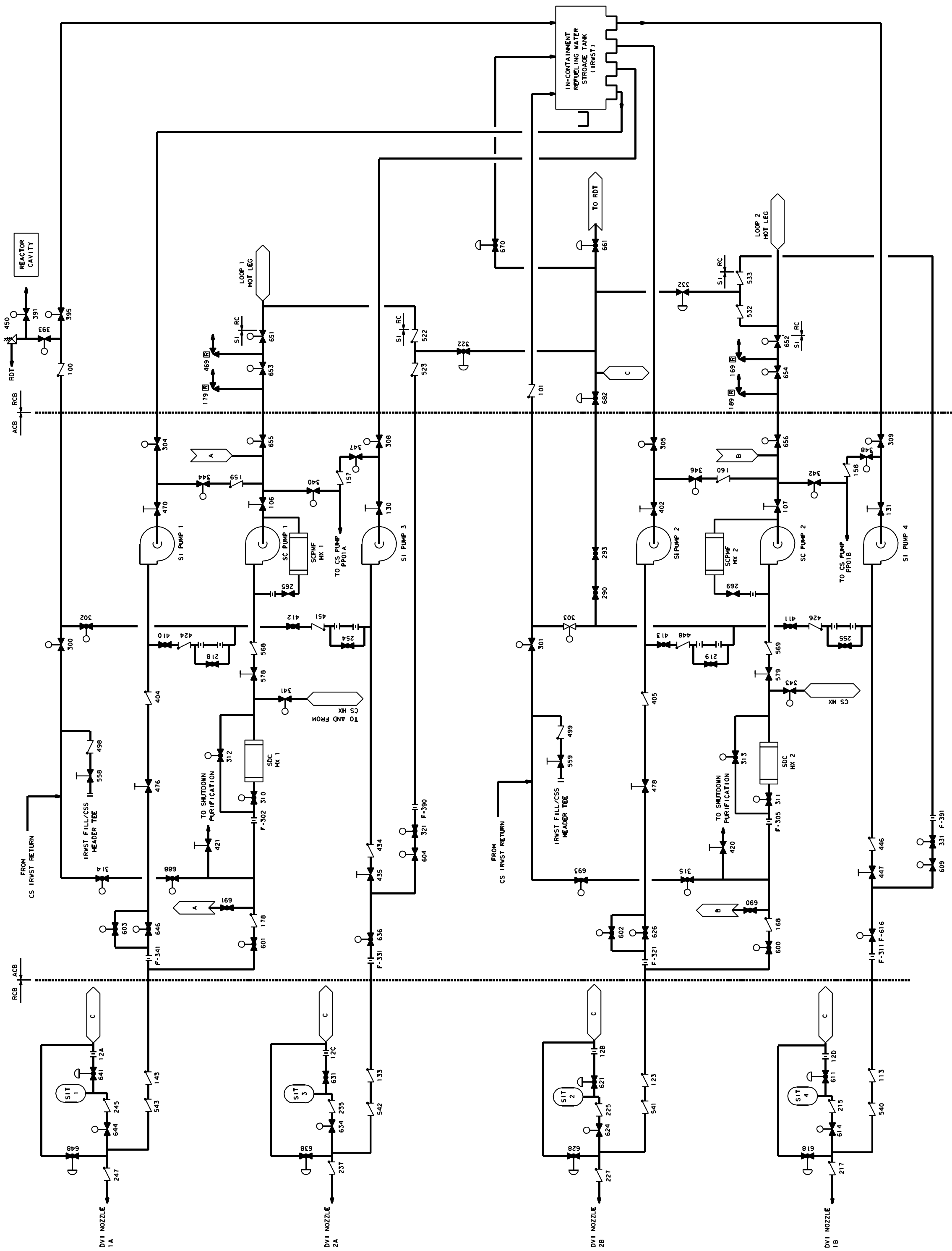

Figure 3.6-1 Schematic Flow Diagram of SI System

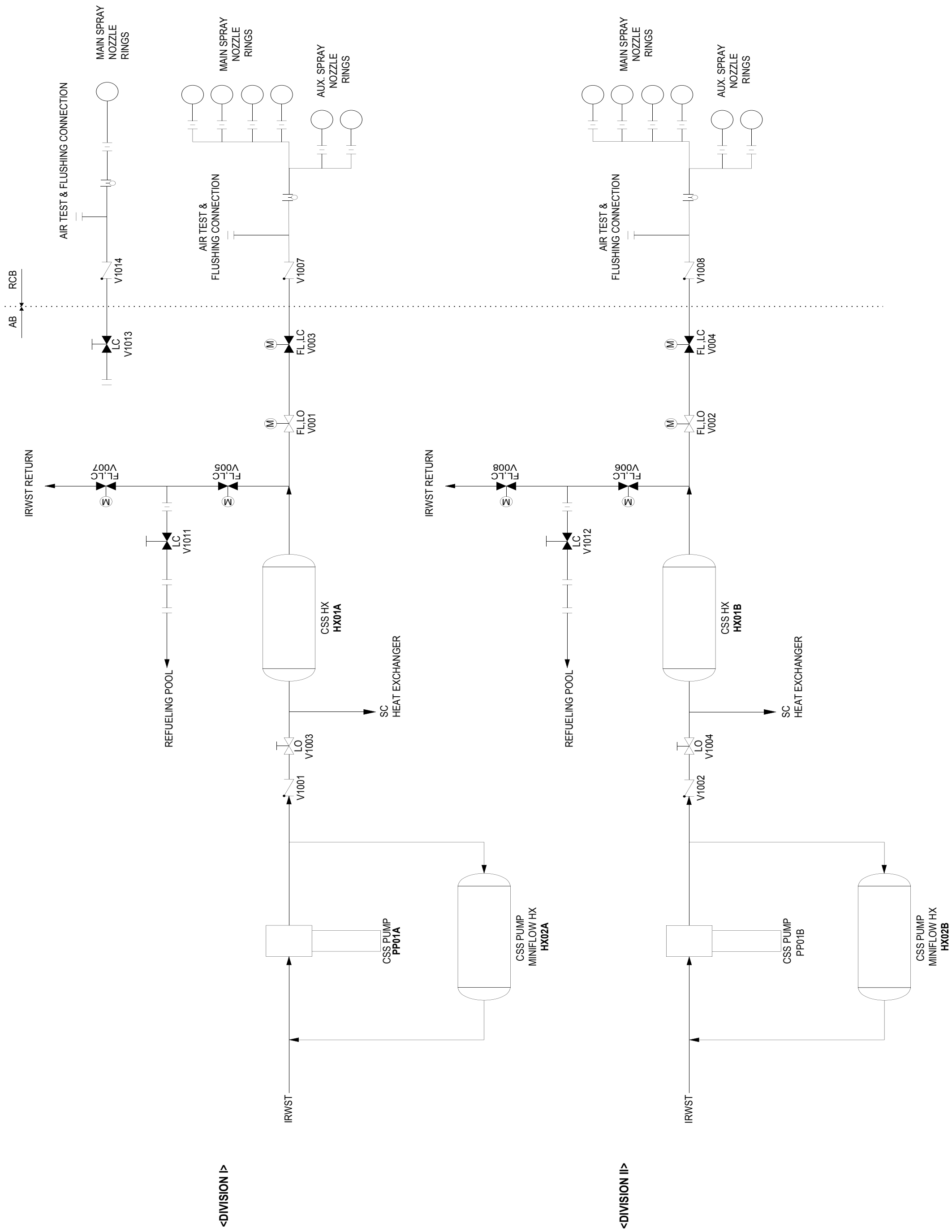

Figure 3.6-2 Schematic Flow Diagram of CS System

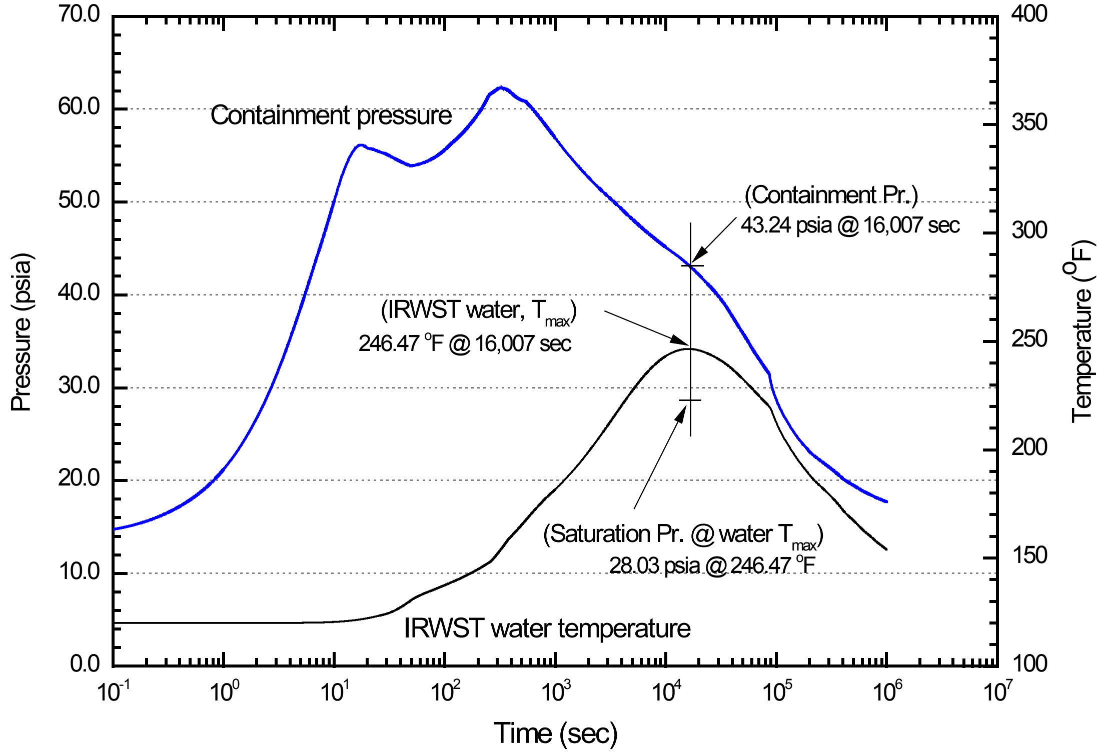

Figure 3.6-3 Containment Pressure and Temperature vs. Time for Long-Term Phase (Double-ended Discharge Leg Slot Break with Minimum ECCS Flow)

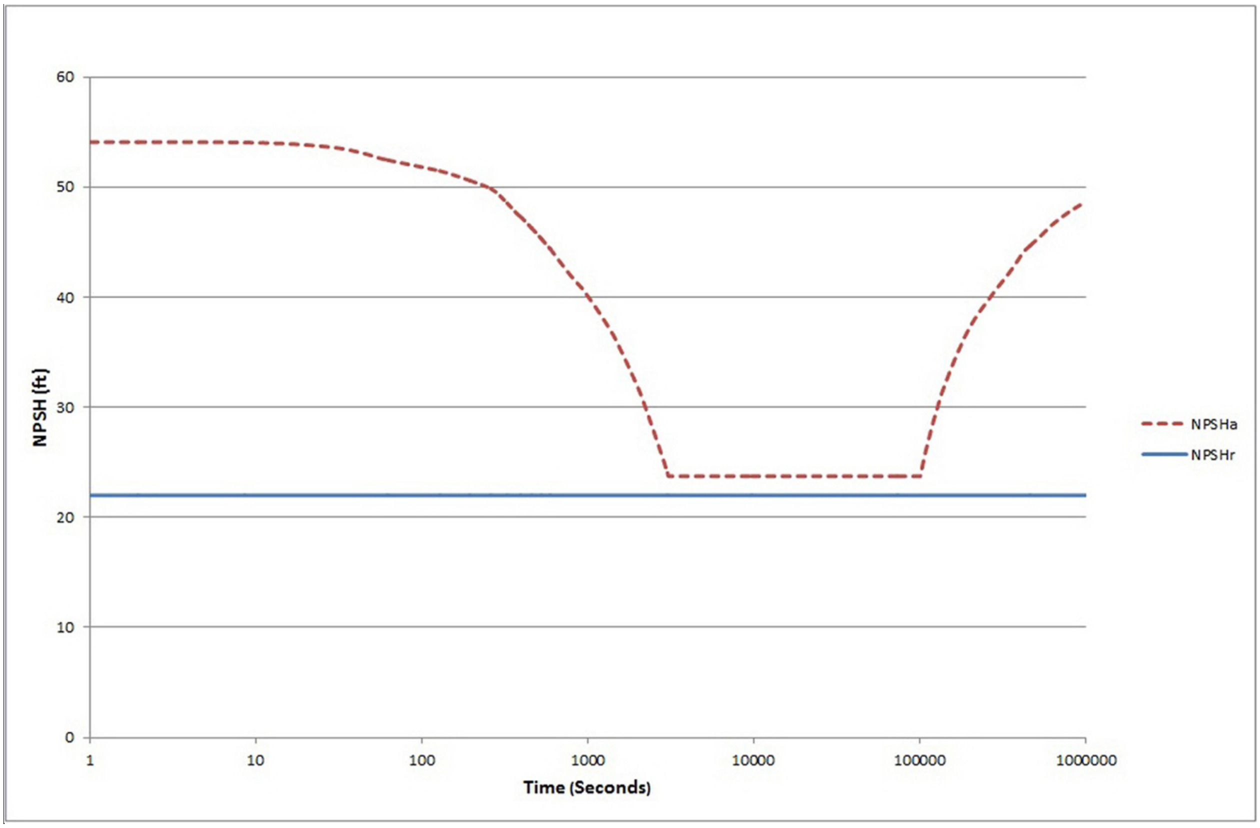

Figure 3.6-4 Limiting SI pump NPSH vs. Time

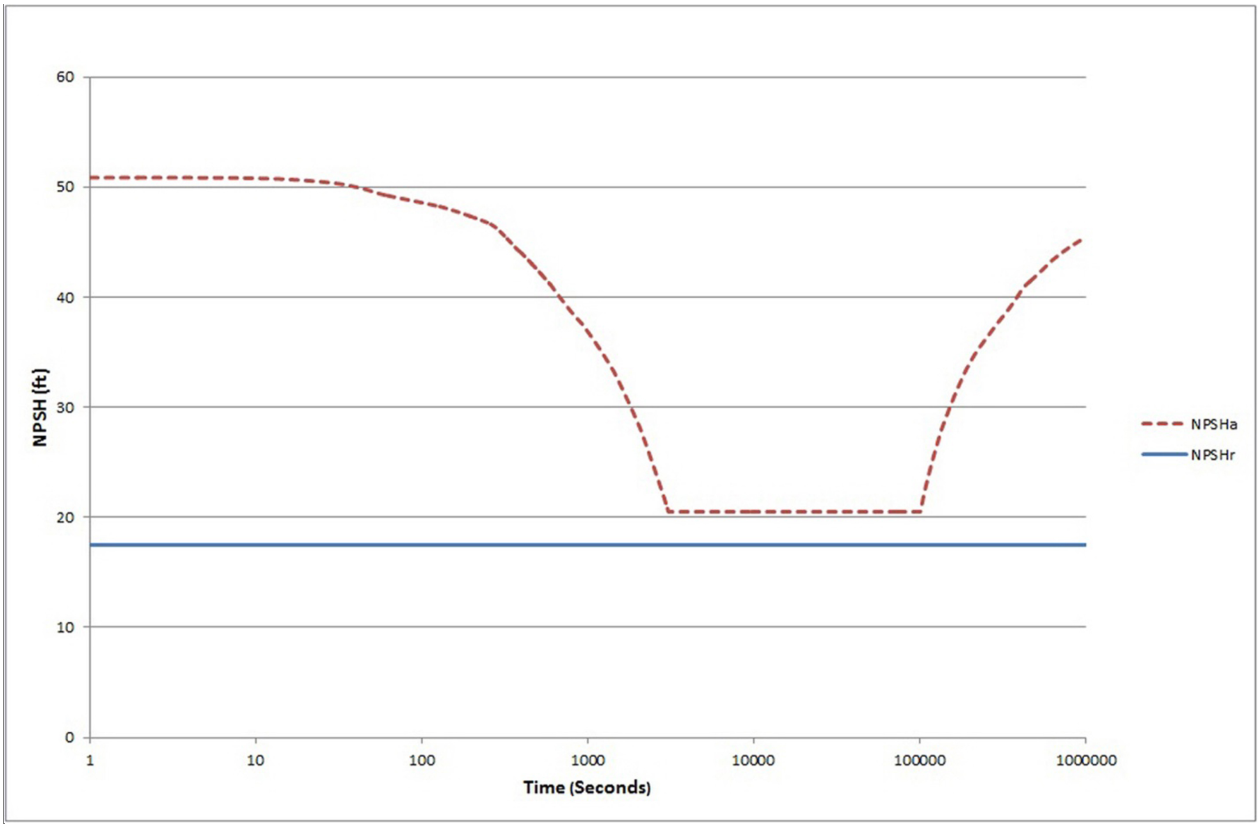

Figure 3.6-5 Limiting CS pump NPSH vs. Time

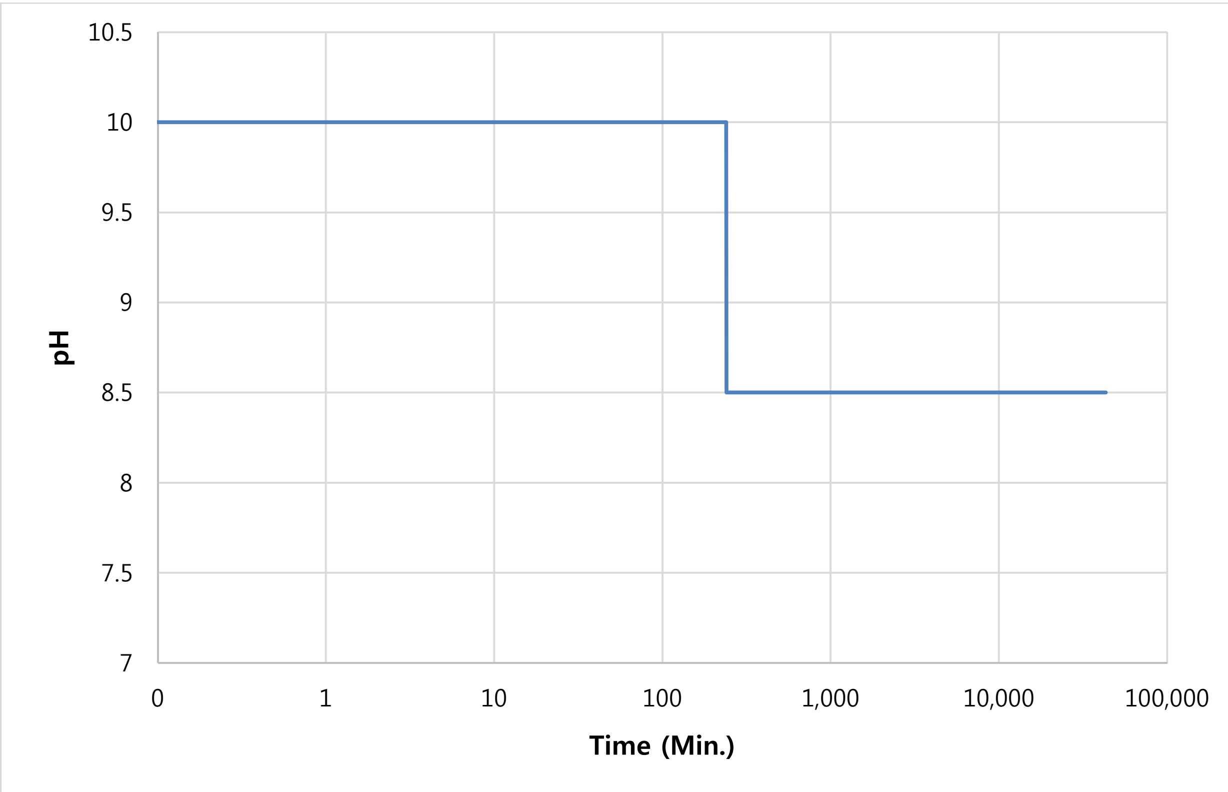

Figure 3.8-1 IRWST and Containment Spray pH vs. Time Curve used in Chemical Effects Analysis

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Figure 3.9-1 Schematic of Containment Spray/Blowdown Return Pathways

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Figure 3.9-2 Schematic of Potential Water Traps in Containment

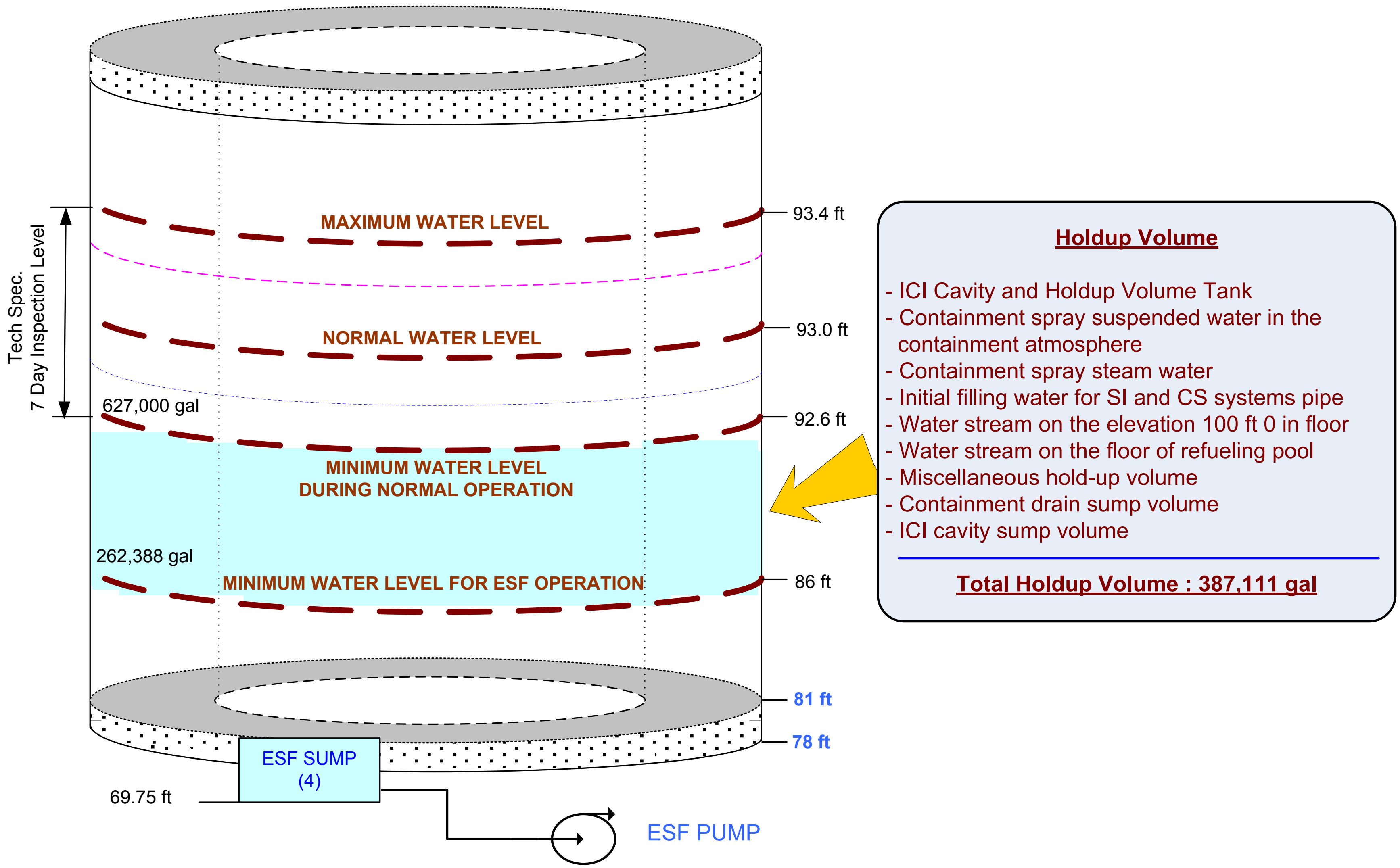

Figure 3.9-3 Schematic Diagram for IRWST Water Volume

4 DOWNSTREAM EFFECTS

The requirements of NRC RG 1.82, Rev. 4 (Reference [1-1]), state that potential IRWST sump strainer downstream flow restrictions due to debris blockage shall be evaluated to ensure appropriate long-term recirculation cooling, containment cooling, and containment pressure control capabilities.

To evaluate the downstream components, a determination of the quantity of the bypass debris is necessary. Given that the strainer is fabricated from perforated plate, the strainer should be sized large enough to produce an acceptable pressure drop for the debris load, but not excessively large that it passes too much bypass debris.

The key material in the blockage of downstream components is the fibrous debris. While particulates and chemical precipitates effects can become entrained in the recirculation flow path, without any fibrous materials, a debris bed and blockage point is difficult to form. The total fibrous debris load at the strainer has been established at 6.80 kg (15 lbm) of latent fiber.

There are four independent 55.74 m^2 (600 ft^2) ECCS strainer trains in the APR1400, and the conservative scenario for bypass is assumed that all pumps are operating as designed and no single failure. Shutdown cooling pumps (SCPs) are not operational at this time.

4.1 Strainer Bypass Testing

To establish the quantity of fibrous debris that could potentially penetrate (bypass) the strainer, prototype testing is performed. The testing is performed with only fibrous debris as adding particulates may reduce the amount of bypass debris due to clogging at the strainer. During the fuel blockage testing, varying amounts of particulate to fiber ratios can be explored to determine the limiting amount of particulate (up to the maximum amount). Additionally, unlike head loss testing, the most conservative approach with bypass testing is to assume all sump strainers are active running at the maximum flow rates since it stands to reason that more mass flow rate and more perforated plates causes more bypass. The detail test plan is provided in “APR1400 IRWST ECCS Sump Strainer Bypass Test Plan” (Reference [4-1]) and the test result is provided in Appendix C of this report.

The test measured the bypass of the maximum fiber load of 6.80 kg (15 lbm) scaled to the prototype strainer area of 6.98 m^2 (75.1 ft^2). Batches are tested at a size distribution of 100% fines to maximize bypass. Since all four strainers could be active, the debris load is distributed to each of the strainers based on flow rate. Therefore, two of the strainers get 25,211 L/min / 59,772 L/min (6,660 gpm / 15,790 gpm) x 6.80 kg (15 lbm), or 2.87 kg (6.33 lbm) of debris and two of the strainers get 4,675 L/min / 59,772 L/min (1,235 gpm / 15,790 gpm) x 6.80 kg (15 lbm), or 0.53 kg (1.17 lbm) of debris. Strainer flow rates and debris loads are included in Table 4.1-1.

Since only the higher flow rate strainer is tested, the following four batches of 181.2 g (0.40 lbm) (0.0265 in. equivalent thickness) are added to the test to provide bypass performance data of the test strainer over a range fiber thickness. It should be noted that the four batches produces twice the required debris load of 0.36 kg (0.79 lbm).

A single bypass test is run with four batches of fines representing latent debris added. Filters are installed downstream of the prototype strainer to collect bypassed fiber. Filters are installed downstream of the prototype strainer to collect bypassed fiber. No fiber is allowed to recirculate back into the tank and flowstream. A new filter is valved in and the old valved out for each batch or fiber addition. The time between each fiber addition is approximately seven pool turnovers. The resulting bypass fiber weights

are presented in Table 4.1-2.

To determine the plant strainer bypass debris, the cumulative quantity of bypass debris from the prototype test is scaled by a ratio of the plant strainer to the prototype strainer (600/75.1 = 8.0). The cumulative bypass quantities for debris loads are presented in Table 4.1-2. The total bypass debris is the sum of the bypass debris for all active strainers and presented in Table 4.1-3.

Total bypass debris for the APR1400 with 6.80 kg (15 lbm) of latent fiber is 1.67 kg (3.68 lbm).

4.2 Ex-Vessel Downstream Effects

The objective of ex-vessel downstream effects evaluation is to assess the systems and components of the APR 1400 emergency core cooling system (ECCS) and the containment spray system (CSS) to ensure that these systems are designed to be operable under post loss-of-coolant accident conditions (LOCA).

4.2.1 System Descriptions

4.2.1.1 Emergency Core Cooling System

The ECCS is designed to perform the following major functions:

1) Inject borated water into the reactor coolant system (RCS) through direct vessel injection (DVI) nozzles to flood and cool the core following a LOCA, thus preventing a significant amount of cladding failure along with subsequent release of fission products into the containment and maintaining the core subcritical

2) Provide removal of heat form the core for extended periods of time following a LOCA

3) Inject borated water into the RCS to increase shutdown margin following a rapid cooldown of the system due to a steam line break

4) Prevent boron precipitation in the RCS during long-term mode of operation

5) Provide inventory makeup and boration for reactivity control during a safe shutdown if necessary

6) Provide feed flow for feed-and-bleed operation in conjunction with pressurizer (PZR) pilot operated safety relief valves (POSRVs) to remove core decay heat during beyond design basis event of a total loss of feed water to steam generators

The ECCS consists of four mechanically separate trains, four safety injection tanks (SITs), and associated valves, piping, instrumentation. Each train contains one SI pump, one SIT, and associated suction and discharge paths. The pumps take suction from the in-containment refueling water storage tank (IRWST). Motor-operated valves and pump in each train receive power from either the normal power source or the emergency diesel generators. Power connections are through four independent electrical trains with each train providing power to one bus. In the event of a LOCA, in conjunction with a single failure in the electrical supply, the flow from at least two safety injection pumps (SIPs) is available for core protection. One independent electrical train, as described above, supplies power to three SIPs and associated valves. Other independent electrical trains supply power to the remaining three SIPs and associated valves.

Each SIP discharge line is connected to the DVI nozzle or the DVI nozzle/hot leg (HL). The ECCS lines 1&2 inject the borated water to RCS through the DVI nozzles and the ECCS lines 3&4 inject the borated water to the DVI nozzles or HL injection lines for the long-term mode. This is illustrated in Figure 3.6-1.

The ECCS lines contain the ECCS line isolation valves and ECCS HL isolation valves.

Flow restricting devices in the discharge line of the SIPs prevent the associated pump form exceeding runout flow following a large break LOCA. The safety injection (SI) isolation valves are normally closed during power operation. The remainder of the ECCS is aligned for injection, but does not operate.

Whenever pressurizer pressure is above 42.18 kg/cm^2 (600 psia), the SITs are isolated from the RCS by only two check valves in series. If RCS pressure should fall below SIT pressure, the tanks will begin to discharge borated water into the RCS. Thus the tanks comprise an extremely reliable passive core flooding system. SIPs are used to inject borated water (feed function) into the RCS and restore the RCS liquid inventory when the RCS pressure decreases rapidly by opening POSRVs during beyond design basis accident (DBA) of a total loss of feedwater to steam generators (SGs).

4.2.1.2 Containment Spray System

The CSS is designed to perform the following major functions:

1) Reduce the containment atmosphere pressure and temperature below containment design limits with margin in the event of a postulated LOCA or main steam line break (MSLB) inside containment, by removing heat from containment atmosphere.

2) Limit airborne iodine and particulate fission product inventory in the containment atmosphere in the event of a postulated LOCA.

3) Provide a backup to the shutdown cooling system (SCS) for residual heat removal and for cooling of the IRWST during post-accident feed and bleed operations utilizing the safety injection system (SIS) and POSRVs.

4) Provide post-accident containment atmosphere mixing to prevent high local hydrogen concentration within the containment.

5) Ensure a post-LOCA spray water chemistry condition within a proper pH range which is required for hydrogen control, material compatibility and long-term iodine control against re-evolution.

6) Provide post-accident long-term cooling of the IRWST to remove the decay heat only when the containment spray operation via spray header is not available to protect the equipment located inside the containment after 30 days following the accident.

The CSS is an engineered safety feature (ESF) designed to remove heat and fission products from the containment atmosphere in the event of a LOCA and a main steam or feedwater line break inside containment and thereby to limit the leakage of airborne activity from the containment.

The CSS is also designed to maintain post-LOCA IRWST water pH level between 7.0 and 8.5 following a LOCA. Post-accident pH control of the IRWST water is provided using tri-sodium phosphate (TSP) that is stored in the holdup volume tank (HVT) of the in-containment water storage system (IWSS).

The CSS consists of two redundant 100% capacity trains. Each train includes a containment spray pump (CSP), a containment spray heat exchanger (CSHX), a containment spray (CS) mini-flow heat exchanger, a main spray header with nozzles, an auxiliary spray header with nozzles, and associated valves, piping and instrumentation.

The CSS provides sprays of water to the containment atmosphere from the upper regions of the containment and below the operating floor. The spray flow is provided by the CSPs which take suction from the IRWST. The CSPs start upon the receipt of a SIAS or a CSAS. The CSPs discharge water through the CSHXs and the spray header isolation valves to their respective spray nozzle headers, then into the containment atmosphere. Spray flow to the containment spray headers is not provided until a containment spray actuation signal (CSAS) automatically opens the containment spray header isolation valves. The main spray headers are located in the upper part of the reactor containment building to allow the falling spray droplets to reach thermal equilibrium state with the steam-air atmosphere. Condensation of the steam by the falling spray results in a reduction of containment pressure and temperature. The main spray also acts to mix the containment atmosphere by direct and indirect convective flows, and also acts to absorb and retain certain radioisotopes which may be present in a post-accident environment.

The auxiliary spray headers from each train are located below the operating floor and header nozzles are arranged to promote mixing of the containment atmosphere within the auxiliary sprayed region and between the annulus area below the operating floor and the main sprayed region above the operating floor.

The CSPs are designed to be functionally interchangeable with the shutdown cooling pumps (SCPs). Though not required for normal operation or accident mitigation, interchangeability of the pumps allows the CSPs to back up the SCPs when the CSPs are not needed for their requisite function (i.e., during refueling or long term cooling operation). In addition, the CSPs and CSHXs can be used as a backup to the SCPs and heat exchangers to provide cooling of the IRWST during post-accident feed and bleed operations when the steam generators are not available to cool the RCS. The suction and discharge lines of the CSP and the SCP are interconnected with a valve.

A minimum flow line is provided on each CSP discharge line, and is connected to the CSP suction line. These minimum flow paths ensure that the CSPs are not deadheaded if the CSPs are inadvertently run against a closed system.

4.2.2 Design Inputs/Evaluation Assumptions

4.2.2.1 LOCA Scenarios

Downstream effect evaluation of the ECCS and CSS operation includes small break LOCA (SBLOCA) and large break LOCA (LBLOCA) conditions.

1) LBLOCA scenario

   The limiting LBLOCA is assumed to a double ended guillotine cold leg (CL) line break at the discharge of the reactor coolant pump (RCP).

   During this event the SITs discharge to the RCS as soon as RCS pressure decreases below SIT pressure. As a conservative estimate in the calculation of the reflood portion of the accident, no credit is taken for SIP flow until the SITs empty.

2) SBLOCA scenario

   The most limiting SBLOCA is assumed to occur in a DVI line break LOCA.

   The worst case SBLOCA assumes some time delay before pumped flow reaches the core. For

the larger range of small breaks, the rate of blowdown is such that the increase in fuel clad temperature is terminated mainly by the SITs, with pumped flow then providing continued cooling. As break size continues to decrease, the SITs and an SIP both play a part in terminating the rise in clad temperature.

Above process (blowdown, passive injection, and recovery) takes longer time period compared with LBLOCA and the duration depends on the break size and the performance of the ECCS.

For this evaluation, the SBLOCA is bounded by the LBLOCA and post-LOCA long-term cooling. The debris quantity and the ECCS flows during the SBLOCA are considered much smaller than during the LBLOCA.

Therefore, the SBLOCA scenario in the evaluation of the downstream effect is bounded by the conditions of the LBLOCA scenario.

4.2.2.2 Mission Time

Mission time represents the maximum period of time for which a System, Structure or Component remains to perform their safety function. It is the accident analysis credit time.

For this evaluation, the mission time of the downstream effect evaluation is defined as 30 days following the Chapter 15 of the DCD (Reference [3-1]).

4.2.2.3 Components of Interest

Table 4.2-1 lists the ECCS and CSS components in the downstream effects evaluation. These components are in the ECCS and CSS flow path during SBLOCA and LBLOCA operations.

4.2.2.4 Post-LOCA Fluid Constituents

Debris in the post-LOCA fluid consists of latent debris (particulate and fiber), coating particles (i.e., epoxy), insulation materials, and miscellaneous debris. Miscellaneous debris includes materials placed inside containment for an operational, maintenance, or engineering purpose. Materials include tape, tags, stickers, adhesive labels used for component identification, fire barrier materials, and other materials (e.g., rope, fire hoses, ventilation filters, plastic sheeting).

Debris sizes are classified as particulates, fines, and large pieces. The sizes in Table 4.2-2 are based on the following:

1) This evaluation conservatively assumes that 100% of the particulates will bypass the IRWST sump strainers. Therefore, it is reasonable to assert that the size of the particulate debris is less than (or equal to) the perforated plate hole size of the IRWST sump strainers, 2.38 mm (0.094 inch).

2) Fines are defined as debris materials that are less than 101.6 mm (4 inch) by 101.6 mm (4 inch), based on NEI 04-07 Volume 1, Subsection 3.6.3 (Reference [3-2]).

3) Large pieces are defined as debris materials that are greater than 101.6 mm (4 inch), based on

NEI 04-07 Volume 1, Subsection 3.6.3 (Reference [3-2])..

The total amount of debris generated during an LBLOCA is estimated in Appendix B of this report and summarized in Table 4.2-3. The amount of reflective metallic insulation (RMI) listed in Table 4.2-3 is based on a size distribution of 75% of small fines and 25% for large pieces.

The amount of debris that passes through the IRWST sump strainer depends on the size of the strainer hole, ratio of open to closed area of the strainer, the fluid approach velocity to the strainer, and the strainer geometry. This evaluation assumes that LBLOCA debris materials that are less than or equal to the perforated plate hole size 2.38 mm (0.094 inch) of the IRWST sump strainers will bypass the sump strainer. As a result, the ECCS will ingest 100% of the coating particulates.

Miscellaneous debris materials are large pieces with a debris size range that is significantly greater than the perforated plate hole size sump strainer. As a result, the ECCS will not ingest miscellaneous debris materials.

Bypass testing of the latent debris yielded a fiber bypass percentage of less than 25% (see Appendix D). This evaluation uses bounding bypass percentages of 100% for latent particulates (i.e., dust and dirt). The bypass percentage for latent fiber uses a conservative of 100%. The actual bypass percent for latent fiber is evaluated by qualified test results conducted specific to the APR1400 plant conditions. The detail test plan is provided in Reference [4-1] and the test result is provided in Appendix D of this report. Based on the results of bypass testing, the actual bypass percentage for latent fiber is approximately 25%.

Results of the NRC debris generation test documented in NUREG/CR-6808 (Reference [4-2]) show that RMI debris size distribution ranges from 6.35 mm (0.25 inch) to 152.4 mm (6 inch). RMI debris will not bypass the sump screens and enter the ECCS because the size of the RMI debris is greater than the perforated plate hole size sump strainer. As a result, this evaluation assumes no RMI bypasses through the sump strainer.

Reference information (Reference [3-12]) on material properties to evaluate the wear rate of the components is provided in Table 4.2-8.

4.2.2.5 ECCS Flow Rate and Flow Velocity

The APR1400 is a fixed resistance system under valve wide-open conditions. Emergency Operating Procedures do allow for operator action to throttle flow based on main control room (MCR) indication. The range of operation is therefore assumed to be from shutoff head conditions to runout conditions.

To evaluate debris settlement and component wear during an LBLOCA, this evaluation conservatively assumes ECCS and CSS flow rates ranging from shutoff head conditions to runout conditions.

Safety Injection Pump flow is assumed to be 303 L/min (80 gpm) for evaluating debris settlement in the SIS. Flow is assumed to be 6,057 L/min (1,600 gpm) for component wear rate evaluations. Engineering design range of flow is 397 L/min (105 gpm) at shutoff and 4,675 L/min (1,235 gpm) at runout.

CS pump flow is assumed to be 1,514 L/min (400 gpm) for evaluating debris settlement in the CSS. Flow is assumed to be 27,255 L/min (7,200 gpm) for component wear rate evaluations. Engineering design range of flow is 1,817 L/min (480 gpm) at shutoff and 24,605 L/min (6,500 gpm) at runout. The component wear rate evaluation is detailed in Subsection 4.2.3.1.

The terminal settling velocities of the debris source materials are listed in Table 4.2-4. The velocity of the debris in the post-LOCA fluid is equal to the velocity of the fluid. If the ECCS fluid velocity is greater than the terminal settling velocity of the debris, the debris will not settle.

The flow rate of the SI and CS pumps at shutoff head and run-out conditions will be verified during component procurement.

4.2.2.6 Summary of Assumptions and Conservatisms

Assumptions and conservatisms used in this evaluation are summarized as follows:

1) Only 100% of all particulates (i.e., coating debris, latent particulates) and 100% of latent fiber are assumed to pass through the strainers and enter into the ECCS and CSS. RMI doesn't bypass through the sump strainer because the size of the RMI debris is greater than the perforated plate hole size sump strainer.

2) SIP flow is assumed to be 303 L/min (80 gpm) for the purpose of calculating settling velocities. Flow is assumed to be 6,057 L/min (1,600 gpm) for the purpose of component wear rate evaluations. Engineering design range of flow is 397 L/min (105 gpm) at shutoff and 4,675 L/min (1,235 gpm) at runout.

3) CSP flow is assumed to be 1,514 L/min (400 gpm) for the purposes of calculating settling velocities. Flow is assumed to be 27,255 L/min (7,200 gpm) for the purpose of component wear rate evaluations. Engineering design range of flow is 1,817 L/min (480 gpm) at shutoff and 24,605 L/min (6,500 gpm) at runout.

4) Wear is calculated from "time zero", i.e. start of the event. Worst case fluid properties are assumed to be present. This assumption is conservative since it does not credit debris transport or the slow increase of fluid properties due to long term mixing.

5) Fluid velocity through a single CS heat exchanger tube is assumed to be 4.57 m/s (15 ft/s). A nominal design and operating heat exchanger velocity range is 0.91 to 3.05 m/s (3 to 10 ft/s). Therefore, the use of 4.57 m/s (15 ft/s) is conservative from a heat exchanger design perspective and bounds the heat exchanger design and procurement specifications.

Table 4.2-5 lists the amount of debris in the post-LOCA fluid (downstream of the IRWST sump strainer) that will be used for confirmatory tests. The amount of debris in the ECCS during post-LOCA operation is based on above assumption 1). The amount of latent debris in Table 4.2-5 is conservatively based on the maximum amount of latent particulates and 100% of the maximum amount of fiber listed in Table 4.2-3.

The size range of the debris materials is based on (i) the assumption that 100% of particulates will bypass the ECCS strainers, and (ii) guidance from NEI 04-07 Volume 2 Appendix V. The concentration of the post-LOCA fluid constituents is conservatively estimated based on the assumption that the IRWST contains 946.4 m^3 (250,000 gallons) of water during post-LOCA operation, which is less than the minimum IRWST water volume for ESF operation of 993.2 m^3 (262,388 gallons). Estimating the debris concentration at less than the expected IRWST volume yields a more concentrated debris-laden fluid for confirmatory tests, and produces conservative test results.

4.2.3 ECCS Component Evaluations

This section evaluates the ECCS pumps, heat exchangers, valves, instrument tubes, and piping regarding wear, blockage, and fouling (heat exchanger).

4.2.3.1 SI and CS Pump Evaluation

The SI pumps are motor-driven horizontal, multistage, centrifugal pumps with mechanical seals. The pumps are sized to deliver 3,085 L/min (815 gpm) at a discharge head of 869 m (2,850 ft). The CS pumps are motor-driven centrifugal pumps with mechanical seals. The pumps are sized to deliver 20,536 L/min (5,425 gpm) (including bypass flow 1,609 L/min (425 gpm)) at a discharge head of 125 m (410 ft). The 100% capacity design flow rate is based upon a 57.5 L/min (15.2 gpm) flow per nozzle.

The SI and CS pumps and associated mechanical seals will be qualified to operate with the post-LOCA fluids for at least 30 days in accordance with ASME QME-1-2007 as endorsed by RG 1.100 Revision 3. As a part of qualification, three aspects of pump operability, i.e. hydraulic performance, mechanical shaft seal assembly performance, and pump mechanical performance (vibration), are considered in evaluating the SI and CS pumps for operation with debris-laden water in accordance with the guidance of RG 1.82 Revision 4.

4.2.3.2 Heat Exchanger Evaluation

The CSHXs are used to remove heat from the containment atmosphere during and after an accident. The units are designed to reduce the containment atmosphere pressure in 24 hours after an accident to half of the calculated peak pressure. The CS miniflow heat exchangers are used to remove heat generated by running the CS pump when operating at miniflow (i.e., against a closed main discharge path or against a back pressure that is higher than the sum of the pump suction pressure and total developed pump head).

The CS heat exchangers and CS miniflow heat exchangers are specified as shell and U-tube units. The CS heat exchangers are composed of 31.75 mm (1.25 inch) OD, Birmingham Wire Gauge (BWG) 18 (1.24 mm (0.049 inch)), 304 SS tubes. The CS miniflow heat exchangers are composed of 22.23 mm (0.875 inch) OD, Birmingham Wire Gauge (BWG) 18 (1.24 mm (0.049 inch)), 304 SS tubes.

The heat exchanger plugging, fouling, wear, and heat transfer performance in the presence of post-LOCA debris will be evaluated by the vendor during the procurement process with a certificate of compliance to provide verification that the heat exchanger meets procurement specifications. For velocity, a maximum tube velocity of 4.57 m/s (15 ft/s) is assumed. A nominal design and operating heat exchanger velocity range is 0.91 to 3.05 m/s (3 to 10 ft/s). Therefore the use of 4.57 m/s (15 ft/s) is conservative from a heat exchanger design perspective and bounds the heat exchanger design and procurement specification(s).

4.2.3.2.1 Heat Exchanger Plugging

The CS heat exchanger tubes are 31.75 mm (1.25 inch) OD, 29.26 mm (1.152 inch) ID, BWG 18 (1.24 mm (0.049 inch)). The CS miniflow heat exchanger tubes are 22.23 mm (0.875 inch) OD, 19.74 mm (0.777 inch) ID, BWG 18 (1.24 mm (0.049 inch)). The perforated plate hole size of the IRWST sump strainers is 2.38 mm (0.094 inch). The heat exchanger tubes are significantly larger than the largest expected particle size. Therefore, a heat exchanger tube will not be plugged or blocked by post-LOCA debris. The flow velocity within a heat exchanger tube is significantly greater than the terminal settling velocity of the debris (Table 4.2-4) because the heat exchanger is designed with a tube flow velocity not to

be less than 3 ft/s to prevent deposition of suspended materials in transition areas of heat exchangers, piping, etc. Therefore, the debris will not settle in the heat exchanger tubes.

These conclusions are consistent with the referenced NRC Safety Evaluation on WCAP-16406-P (Reference [4-3]).

4.2.3.2.2 Heat Exchanger Performance and Wear

The CS heat exchangers and CS miniflow heat exchangers are sized and designed with a fouling factor of 0.000088 m^2-K/W (0.0005 hr-ft^2-°F/Btu) to maximize heat transfer efficiency and performance. The post-LOCA fluid could potentially cause particulate fouling of the heat exchanger tubes if the fluid velocity is less than the terminal settling velocity of the debris. However, fouling is considered a long-term phenomenon. In addition, the heat load of the CS heat exchangers is greatest at the start of the event and decreases rapidly over the first 24 hours. Heat removal capacity is not degraded over this short period. Any potential reduction in capability over the 30 day mission time is gradual and well within the nominal heat exchanger design.

The CS heat exchangers' and CS miniflow heat exchangers' tubes are specified to be constructed of 304 stainless steel. Stainless steel is appropriate for use as heat exchanger tubing and is standard for use in mildly abrasive applications. The tube material will not significantly degrade considering operation with post-LOCA fluid over an intended mission time of 30 days.

Therefore, the CS heat exchangers and CS miniflow heat exchangers are fully capable of performing their intended function using post-LOCA fluid as the process fluid.

The tube wear for the CS heat exchangers and CS pump miniflow heat exchangers is evaluated assuming a free-flowing wear model, the mission time of 30 days, and conservative mass concentration of debris of 1,000 ppm, which is larger than that in Table 4.2-5. The tube wear for the CS heat exchangers and CS pump miniflow heat exchangers is commonly calculated to 0.064 mm (0.00252 inch). The available thicknesses for erosion, i.e. the actual wall thickness minus the required wall thickness to retain pressure, are calculated to 0.381 mm (0.015 inch) for CS heat exchanger and 0.635 mm (0.025 inch) for CS pump miniflow exchanger. The total tube wear during the mission time (30 days) is very small comparing the available thickness for erosion. Therefore, the heat exchanger tubes have sufficient thickness to withstand the erosion effects of the debris particles.

4.2.3.3 Evaluation of Valves, Orifices and Pipes

4.2.3.3.1 Blockage and Debris Settling Evaluation for Valves, Orifices and Pipes

The strainer hole size is 2.38 mm (0.094 inch). Therefore, when the gap of the components is 2.38 mm (0.094 inch) + 0.238 mm (0.0094 inch) (10%) or 2.62 mm (0.103 inch) or less than this value, the flow-path or component may be blocked. This is consistent with Reference [4-3]. Components that are in the flow-paths during accidents are listed in Table 4.2-1.

<u>Piping</u>

Fluid velocity decreases with an increase in pipe diameter. Therefore, the lowest velocity in the ECCS occurs in the region with the largest pipe diameter/flow area. Flow velocities in all piping except several cases (24 inch, 20 inch, and 10 inch SI Pump suction lines and 12 inch SI pump discharge line) are above

the settling velocities of the post-LOCA fluid. Refer to Table 4.2-6.

Some conservative assumptions are considered to facilitate the comparison and are discussed below.

First, the pump shutoff flow rates at which pump cavitation is likely to occur, rather than the design flow rates, are used to calculate the flow velocities. This lowers the flow velocities for additional conservatism for the debris settling evaluation. These calculated velocities are compared to the settling velocities of 0.046 m/s (0.15 ft/s) and 0.002 m/s (0.008 ft/s) for coating and latent fiber, respectively, as reported in Table 4-2 of NEI 04-07. Since the assumed flow velocities are considerably higher than the settling velocities, the debris is not likely to settle in the SI and CS systems. For latent particle debris, there is no information in NEI 04-07, so terminal settling velocity is conservatively calculated using Stokes' Law.

All particle sizes used for terminal settling velocity of the latent particle debris are assumed to be the strainer hole size of 0.094 inch, which is considerably large compared to Table V-2 of SE for NEI 04-07. This maximizes the terminal settling velocity. The maximum terminal settling velocity is considerably higher than the terminal settling velocities for other debris listed in Table 4-2 of NEI 04-07. Sufficient conservatism is thus provided for the debris settling evaluation.

Because debris settling is a longer term phenomenon, there is no short term impact on the flow velocities over the time period of interest. This fact, combined with the conservatism in the flow velocities and the latent particle debris terminal settling velocity make the probability of blockages in piping extremely low.

Based on the above considerations, debris settling will not occur or affect system operation in piping and any associated valves where the flow velocity for latent debris is less than the terminal settling velocity.

The piping and associated valves with lower assumed flow velocity than the debris settling velocity are listed in Table 4.2-9. In the listed piping and associated valves, the fluid flow velocities are calculated based on the expected pump operation. The results show that the debris will not settle because the calculated fluid flow velocities are much higher than the terminal settling velocity of 0.7 ft/sec under the expected pump operating conditions. Therefore, there will be no impact of the latent debris on the system operation under expected pump operating conditions.

Valves

The valve types that are used in the flow-path during an accident are gate, check, globe and butterfly valves, see Table 4.2-1.

1) Gate valves

   Gate valves are used full-open or full-close. The gate valve sizes are above 101.6 mm (4 inch) (see Table 4.2-1). Flow velocities in all cases except for gate valves on 20 inch and 10 inch SI pump suction lines and 18 inch CS pump suction lines are above the settling velocities of the post-LOCA fluid (refer to Table 4.2-6). NUREG/CR-6902 (Reference [4-4]) states that valve openings significantly larger than the debris size will not clog. The strainer hole size is 2.38 mm (0.094 inch). The 101.6 mm (4 inch) valve opening is considerably larger than any expected particle passing through the sump strainer. Therefore, the valves do not clog due to post-LOCA insulation debris.

2) Check valves

   Check valves are used with sufficient flow rate, and check valve sizes are above 101.6 mm (4 inch) (see Table 4.2-6). Flow velocities in all cases except for check valves on 12 inch SI pump suction lines and 18 inch CS pump suction lines are above the settling velocities of the post-LOCA fluid (refer to Table 4.2-6). Reference [4-4] states that valve openings significantly larger than the

debris size will not be clogged. The strainer hole size is 2.38 mm (0.094 inch). The 101.6 mm (4 inch) valve opening is considerably larger than any expected particle passing through the sump strainer. Therefore, the valves do not clog due to post-LOCA insulation debris.

3) Globe valves

ECCS and CSS flow is controlled though a combination of orifices and throttled valves. Globe valves normally are full open but may be used for throttling system flow. ECCS and CSS pressure and flow are monitored in the MCR. In general, if a globe valve is in a throttled position and it begins to clog, system flow will decrease. Operator action may be taken to open the valve, thus clearing the potential clog. In the APR1400, globe valve sizes are above 101.6 mm (4 inch) (see Table 4.2-1). Flow velocities in all cases are above the settling velocities of the post-LOCA fluid (refer to Table 4.2-6). Reference [4-4] states that valve openings significantly larger than the debris size will not be clogged. The strainer hole size is 2.38 mm (0.094 inch). Throttle valves are expected to be throttled to a minimum of 50.8 mm (2 inch) open between the valve disc and seat. The 50.8 mm (2 inch) valve opening is considerably larger than any expected particle passing through the sump strainer. Therefore the valves do not clog due to post-LOCA insulation debris.

Orifice

ECCS and CSS flow is controlled though a combination of orifices and throttled valves. Orifices are used for throttling system flow. ECCS and CSS pressure and flow are monitored in the MCR. The orifice sizes are above 20.3 mm (0.8 inch). Flow velocities in all cases are above the settling velocities of the post-LOCA fluid (Table 4.2-6). Therefore, the potential of orifice plugging is very low.

Spray Nozzles

The containment main spray nozzles and auxiliary spray nozzles has an orifice of 13.1 mm (0.516 inch) and 5.6 mm (0.22 inch) diameter, respectively. This orifice is the smallest portion of spray nozzle. The strainer hole size is 2.38 mm (0.094 inch). Containment spray nozzles are significantly larger than the strainer hole size. Their one-piece design provides a large, unobstructed flow passage that resists clogging by particles. Therefore, the potential of spray nozzle plugging is very low.

4.2.3.3.2 Wear Rate Evaluation for Valves, Orifices, Spray Nozzle, and Pipes

Erosive wear is caused by particles that impinge on a component surface and remove material from the surface because of momentum effects. The wear rate of a material depends on the debris type, debris concentration, material hardness, flow velocity, and valve position.

Flow rates of 6,057 L/min (1,600 gpm) and 27,255 L/min (7,200 gpm)) for SIS and CSS, respectively, are conservatively assumed for the wear rate evaluation of the components listed in Table 4.2-1. The ECCS and CSS design flow rates listed in Table 4.2-1 include the maximum flow rate of the SI pump, CS pump, and the sum of the SIS and CSS flows based on system configuration.

Table 4.2-7 contains a summary of the piping, spray nozzles, and orifice wear calculation. The results show that the system piping and component flow resistances will be changed minimally during the course of the LOCA. The expanded nozzle orifice size due to wear reduces the nozzle orifice pressure drop slightly, which allows entrained gas to be retained in the sprayed water. This effect creates a more even flow of sprayed water through the nozzle orifice..

The ECCS and CSS valves will be qualified to operate with the post-LOCA fluids for at least 30 days in accordance with ASME QME-1-2007 as endorsed by RG 1.100 Revision 3. As a part of the qualification, the wear evaluation for the ECCS and CSS valves in the flow path during an accident, such as gate, check, globe and butterfly valves, is performed. The valves are not required to be throttled in the system operation because the systems are flow balanced by the flow orifices. An increase in flow area due to erosive wear applies to manually throttled valves only, in accordance with the guidance provided in NRC Information Notice 97-76. In addition, because the valve wall is always generally thicker than the pipe wall thickness, and if the thickness of associated pipes are acceptable, the valves are also acceptable. Therefore, there is no expected impact due to erosive wear on the ECCS and CSS valves. These valves therefore comply with the guidance of RG 1.82 Revision 4.

4.2.3.4 Instrument Tubing Clogging Evaluation

According to WCAP-16406-P (Reference [4-3]), when the instrument tubing lines maintain a solid state prior to emergency core cooling operation, it is determined tubing integrity is not affected because there is almost no possibility of debris ingestion, and the evaluation shows there are no effects from flow blockage and wear because flow velocities in all cases are above the settling velocities of the post-LOCA fluid. Also, all instrument connections are at the side or at the top of the pipe and the SIS and CSS do not contain any bottom-mounted instrument connections.

4.2.3.5 Chemical Effects Evaluation

Chemical precipitates (aluminum oxy-hydroxide, sodium aluminum silicate and calcium phosphate) are formed when concrete and LOCA-generated debris materials are exposed to the buffering materials in the IRWST. This reaction forms additional solid species that could potentially pass through the sump screen and degrade the performance of the ECCS and CSS.

In-vessel fuel blockage tests performed using particulate, fiber and aluminum oxy-hydroxide precipitate demonstrate that the flow resistance created by the chemical precipitate is significantly less than the pump head that is available in the ECCS and CSS piping system. Secondly, similar to the particulate and fiber debris materials, only chemical precipitates smaller than (or equal to) the perforated plate hole size of IRWST sump strainer will be ingested by the ECCS and CSS. The diameter of the ECCS and CSS piping, orifices, spray nozzles, valves and heat exchanger tubes are significantly larger than the size of the ingested chemical precipitates, and the velocity of the post-LOCA fluid is expected to be sufficient to avoid settling. Therefore, components downstream of the sump strainers are not expected to become clogged with chemical precipitates such that blockage of flow occurs.

In addition, the qualification of the ECCS and CSS pumps, performed with conservative amounts of post-LOCA debris (Table 4.2-5), in accordance with ASME QME-1-2007, will include confirmation that the internal running clearance of the ECCS and CSS pumps is sufficiently large enough to avoid clogging, and supports acceptable pump and seal operation during the 30-day post-LOCA mission time.

The chemical precipitates are also unlikely to reduce the efficiency of the heat exchanger because most precipitates will form later in the post-LOCA event when temperatures have decreased ((NUREG/CR-6913 (Reference [4-5]) and NUREG/CR-6914 (Reference [4-6])) and when the required heat transfer capacity of the CSS heat exchangers has ample margin. Precipitates that form soon after the pipe break are only expected to form, at most, thin deposit films on the heat exchanger tubes. Deposit thicknesses are limited by scrubbing from particulate in the coolant as well as the relatively high flow rate and pressure differential. In addition, the CS heat exchangers are designed and specified with conservative fouling

factors to maximize heat transfer efficiency and performance. Operating experience has also demonstrated that fouling is a long-term phenomenon and heat exchangers can still perform adequately with significant fouling. Therefore, the chemical precipitates are not expected to significantly impair the heat transfer capability of the CS heat exchangers.

4.2.4 Overall System Evaluation

The flow increase less than 3% for an individual component due to erosive wear is considered as insignificant because the 3% value is well within nominal components manufacturing tolerances and well within the standard fluid flow calculation tolerances. Furthermore, if the flow increase for individual component is less than 3 %, the total system flow increase will become less than 3% and will be also considered as insignificant to the system flow calculations and design basis analysis.

The tube wear for the CS heat exchangers and CS pump miniflow heat exchangers is commonly calculated to 0.064 mm (0.00252 inch). The increase of tube flow area due to tube wear will result in the flow increase of 0.9% for the CS heat exchangers and 1.3% for the CS pump miniflow heat exchangers.

The flow increase in the piping, orifices, and spray nozzles are listed in the Table 4.2-7. The maximum flow increase of the components in the flow path of ECCS and CSS does not exceed 3% except for SI-OR08A/B/C/D orifices. These orifices are installed with the other orifices (SIOR01A/B/C/D) in series on the SI pump miniflow path for the flow balance. A sufficient pressure drop will be still developed in the miniflow path through the other orifice with much less erosive wear; i.e., the flow balance to the miniflow path is still assured. In reality, the actual flow increase due to erosive wear through the orifices will be much less since the design flow to the miniflow path is 50% less than the assumed flow rate. Therefore, flow increase in the piping, orifices, and spray nozzles does not affect the overall injection flow path to the RCS and the overall spray flow path to the containment. In addition, the system flow rate and discharge pressure for the ECCS and CSS are continuously monitored in the MCR. Although valves in the flow path do not need to be adjusted during an accident, if necessary, safety injection and hot leg injection isolation valves may be throttled to satisfy the desired flow rate.

Based upon the results of wear evaluation for each component of ECCS and CSS, the flow increase due to wear does not exceed 3% in all flow paths of ECCS and CSS. Therefore, flow balances and system performance are not affected in an appreciable manner. The anticipated downstream effects on resulting flows and pressures are consistent or conservative with respect to the inputs used accident analysis. The minor resistance changes do not affect the system flow calculations and design basis analysis.

4.2.5 Evaluation Summary

The intent of this section is to assess the downstream effects of ECCS and CSS of the APR1400 under post-LOCA conditions following new requirement.

The result of assessment is that ECCS and CSS of the APR1400 are fully designed to perform their safety function under post-LOCA conditions. This result also verifies that inadequate core or containment cooling does not occur because of debris blockage at flow restrictions, plugging or excessive wear of close-tolerance component (e.g., pumps, heat exchangers, piping, valves, spray nozzles) in the flow path.

4.3 In-Vessel Downstream Effects

The objective of in-vessel downstream-effects evaluation is to demonstrate that there is reasonable assurance that sufficient long-term core-cooling (LTCC) is achieved to satisfy the requirements of 10 CFR 50.46, with debris and chemical products that are postulated to be transported to the reactor vessel.

This evaluation for the APR1400 is performed applying the evaluation methods and acceptance bases provided in the WCAP-16793-NP Revision 2 (Reference [4-7]) and the NRC safety evaluation (SE) for the WCAP-16793-NP Revision 2 (Reference [4-8]).

4.3.1 ECCS Flow Rates

Following a LOCA, the ECCS will deliver fluid and debris to the RCS. The amount of debris that reaches the reactor core is dependent on the ECCS injection configuration and break location. For the APR1400, ECC flow is delivered to the direct vessel injection (DVI) lines or hot-legs. The ECC flow rates to the break locations identified in LOCA scenarios are as follows.

4.3.1.1 Hot-leg Break Condition

In the event of a hot-leg break, the coolant pumped into the DVI lines is forced into the reactor vessel, down the downcomer and up through the reactor core toward the break. During the LTCC period, core flow, plus a small amount of core-bypass flow, is equal to the total ECC flow delivered to the downcomer.

After a hot-leg break event, the maximum recirculation flow rate is 18,699 L/min (4,940 gpm), and the number of fuel assemblies (FA) is 241. Since the core bypass flow is not credited, all the ECC water passes through the reactor core to exit the break. Therefore, the flow rate per FA is calculated to divide 18,699 L/min (4,940 gpm) by 241, and its value is 78 L/min (20.5 gpm). The hot-leg break condition at the maximum flow rate is chosen to obtain maximum pressure drop at the test column.

4.3.1.2 Cold-leg Break Condition

In the event of a cold-leg break, ECC water injected into the failed loop will exit the break and water injected into the intact loop will enter the downcomer annulus, ensuring that the downcomer is filled, at minimum, to the bottom of the cold-leg nozzle. The core flow is only what is required to make up for core boiling to remove the decay heat. The ECC water keeps the downcomer full to at least the bottom of the cold-leg nozzles, and any excess water flows out of the cold-leg break location and back into the IRWST.

In this case, 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 cold-leg break should be significantly less than that from a hot-leg break. The ECC flow rate per FA is 14 L/min (3.65 gpm) at recirculation start time (around 700 seconds after LOCA) as follows.

4.3.1.2.1 Recirculation Start Time

The APR1400 has no sump switch-over operation as the ECCS pump suction is aligned to the IRWST during the LTCC period. To provide the required time for debris to reach the reactor vessel after a LOCA, a conservative value of recirculation start time is calculated as follows.

TS

The time required for debris to reach the reactor vessel is approximately 1,400 seconds. Half of this time is used for considering unknowns (like mixing) and the recirculation start time is set at **700 seconds** for downstream effect evaluation. This time is used to determine the core boil-off rate following a cold-leg break with DVI, as follows.

4.3.1.2.2 Core Boil-off Rate

The core boil-off rate at the time of recirculation start (700 seconds) is selected as the maximum ECC flow rate to the reactor vessel after a cold-leg break. Details of the calculation method are described in Section 3.5.3 of the Reference [4-9].

Core boil-off rate (w) = (core decay heat)/(core enthalpy rise) = $Q_{DH}/\Delta H$

Core Decay Heat (Q_{DH})

The core decay heat is calculated as a function of time:

$Q_{DH} = (P/P_o)(P_o)$

TS

Core Enthalpy Rise (ΔH)

The enthalpy rise in the core is a function of core inlet subcooling and the saturation pressure at the core exit. The enthalpy rise in this calculation is the latent heat of vaporization.

Therefore, $\Delta H = h_{fg}$

Where h_{fg} is determined using the core exit pressure, which is based on the containment pressure plus an increase for flow losses through the loops.

$P_{core\_exit} = P_{cont} + dP_{loops}$

Where,

P_{cont} = containment pressure at the LOCA condition

dP_{loop} = pressure drops through the loops

TS

Therefore, the flow rate per FA is calculated by dividing 3,322 L/min (877.6 gpm) by 241, and its value is 14 L/mim (3.64 gpm).

4.3.1.3 Cold-leg Break after HLSO Condition

Three hours after a cold-leg break, the operator starts simultaneous hot-leg/DVI line injection (hot-leg switchover: HLSO). Two SI pumps are for hot-legs, and two SI pumps are for DVI lines. Since the water injected into DVI lines spills directly out of the break location, the water injected into hot-legs goes down through the reactor core toward the break. Table 4.3-1 summarizes the ECCS flow rates per FA, following a LOCA.

4.3.2 Amount of Bypass Debris per Fuel Assembly

To evaluate the downstream components, a determination of the quantity and characteristics of the bypass debris is necessary. Given that the strainer is fabricated from perforated plate, the strainer should be sized large enough to produce an acceptable pressure drop for the debris load, but not excessively large that it passes too much bypass debris. The quantity of bypass debris is a function of hole size and strainer surface area. While the amount of bypass debris is also a function of the velocity of the fluid passing and carrying the debris through the strainer holes, this is implicit in the surface area of the strainer and the design flow rate.

The key component in the blockage of downstream components is the presence of fibrous debris materials. Particulates and chemical effects can become entrained in the recirculation flow path, but without fibrous materials, a debris bed and blockage point cannot form.

The APR1400 is a “low fiber” plant, and there is no fibrous insulation inside the zone of influence (ZOI). Only latent debris is assumed, and its design value is limited to 90.72 kg (200 lbm) with 83.91 kg (185 lbm) of particulate and 6.8 kg (15 lbm) of fiber. All the debris (except fiber) that is transported to the IRWST is assumed to bypass the strainer.

Particulate Debris

Epoxy coatings are considered to be destroyed within the ZOI. Based on the upstream analysis, the quantity of destroyed coatings is 0.0878 m^3 (3.1 ft^3). NEI-04-07 (Reference [3-2]) estimates the particle size of failed coatings to be 10 μm on average with a density of 1.51 g/cm^3 (94 lbm/ft^3). A suitable and common surrogate used in the tests in the United States, is silicon carbide (SiC). It has a mean particle size of 10 μm (3.94×10^{-4} inch) and material specific gravity of 3.2, which corresponds to a density of 3.20 g/cm^3 (199.5 lbm/ft^3). The SiC is selected for resistance to dissolution in the tab water and interaction with other materials. While the requirement for the characteristic size is 10 μm (3.94×10^{-4} inch) spheres, the SiC surrogate contains a range of particles sizes. Use of this material 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 is available in the test report (Reference [4-10]). Determining the amount of SiC 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 follows:

$$M_p = 3.1 ft^3 \times 199.5 \frac{lbm}{ft^3} / 241 = 2.57 lbm \text{ (1,164 g)}$$

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

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

Fibrous Debris

The latent fiber is represented by NUKON low density fiberglass (recommended by NEI-04-07) with an as-fabricated density of 0.038 g/cm^3 (2.4 lbm/ft^3) (see NEI-04-07 SER Appendix VII). The source of the NUKON used in tests is available in (Reference [4-10]). Total strainer bypass fiber for the APR1400 with 6.80 kg (15 lbm) of latent fiber is 1.67 kg (3.68 lbm) (Section 4.1). The mass of fiber to be added to the test is:

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

Chemical Precipitates

Based on the design conditions (Table 3.8-4), the following chemical precipitates are available in the IRWST fluid.

- Calcium Phosphate : 0.71 kg (1.56 lbm)
- Sodium Aluminum Silicate : 4.36 kg (9.6 lbm)
- Aluminum Oxy-hydroxide : 153.6 kg (338.7 lbm)

Given the relative proportions, since aluminum oxy-hydroxide can be conservatively used to represent the other precipitates (Reference [3-11]); only AlOOH is used in the test. The total chemical precipitate mass of 158.67 kg (349.8 lbm) is represented by AlOOH. This precipitate suspension has a calculated concentration of 11g/L. The volume of prepared AlOOH surrogate for the test is calculated as follows:

$$V_{AlOOH} = 158.67 kg / 241 \times \frac{liter}{0.011 kg} \times \frac{1 gal}{3.785 liter} = 15.8 gal \text{ (59.8 liters)}$$

The bypass debris types and amounts per FA are summarized in Table 4.3-2.

4.3.2.1 Fiber Loads at Hot-leg Break Condition

In the event of a hot-leg break, all the coolant pumped into the DVI lines is forced into the reactor vessel, down the downcomer and up through the reactor core toward the break. Since the alternate flow paths in the reactor vessel are not credited for demonstrating adequate LTCC in the APR1400 design evaluation, the fiber loads per FA is equal to the calculated value **6.93 g** (0.015 lbm) under the hot-leg break condition.

4.3.2.2 Fiber Loads at Cold-leg Break Condition

In the event of a cold-leg break, only a part of ECC water is injected into the core. The core flow rate is limited by the core boil-off rate (already described in Section 4.3.1.2.2). The current section describes the total amount of fiber loads following a cold-leg break.

Assumptions

1) All debris is generated during the first 700 seconds (11.7 minutes) after the cold-leg break.

2) All debris is completely mixed into the IRWST at 700 seconds.

3) Debris is not trapped at any location along the flow paths.

Equations

The total amount of debris transported to the core (M_{CORE}) is calculated as follows:

$$M_{CORE} = M_{tot} \frac{M_{BO}}{M_{Water}}$$

where,

M_{tot} : total amount of bypass debris (fiber : 1.67 kg (3.68 lbm))
M_{Water} : minimum amount of IRSWT water (993.2 m^3 (262,388 gal))
M_{BO} : total amount of boil-off water

$$M_{BO} = \int_{11.7}^{t\max} W_{BO}(t) \cdot dt$$

Where,

W_{BO} : boil-off rate
t_{max} : start time of HLSO operation (2 hours) + 2 hour for conservatism = 4 hours (240 minutes)

The time dependent boil-off rate at 240 minutes is calculated by the methods described in Section 4.3.1.2.2, and the value is 1,491 L/min (393.9 gpm) as shown in Figure 4.3-1.

Calculation

TS

4.3.3 Available Driving Head

It must be demonstrated that the available head to drive the ECC 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 that a sufficient flow is available to maintain the LTCC:

$dP_{avail} > dP_{debris}$

The core flow is only possible if the manometric balance between the downcomer (DC) and the core is sufficient to overcome the flow losses in the reactor vessel (RV) downcomer, RV lower plenum, core, and loops, 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 flow losses (dP_{flow}) for each LOCA scenario are based on the values provided in LOCA analyses (Reference [4-11]).

4.3.3.1 Available Driving Head under the Hot-leg Break Condition

In the event of a hot-leg break, the driving force is the manometric balance between the liquid in the downcomer and the core, as shown in Figure 4.3-2. If a debris bed begins to build up in the core, the liquid level will begin to build in the cold legs and steam generators (SGs). As the level begins to rise in the SG tubes, the elevation head driving the flow through the core increases as well. The driving head reaches its peak when the shortest SG tube has been filled.

Assumptions

1) The core liquid level is assumed to be at the bottom of the hot leg.

2) The downcomer liquid density is based on the RCS pressure. Since density is inversely proportional to liquid temperature, and a lower density will reduce the driving head from the downcomer, a conservatively high RCS temperature is selected. So, the saturated water density the highest RCS pressure of 3.312 kg/cm^2A (47.113 psia) is assumed (929.15 kg/m^3 (58.0 lbm/ft^3)).

3) The reactor vessel downcomer and lower plenum k/A^2 is small (typically << 0.1). Further, the liquid density is large (> 929.15 kg/m^3 (58.0 lbm/ft^3)) and bulk velocity is low. Therefore, the losses in these regions can be neglected.

4) To account for the potential for voiding in the SG tubes, it is assumed that the siphon break occurs at the bottom of the SG tubesheet.

5) The flow losses in reactor core and loops are based on the values in the data from LOCA analyses.

Calculations

TS

The inputs are found in APR1400 drawings and evaluations. The values in Table 4.3-3 are used to calculate the hot-leg break available head loss. As stated in the assumptions, the flow losses in the downcomer and lower are negligible. Therefore, the hot-leg $dP_{available}$ is as follows:

TS

4.3.3.2 Available Driving Head under the Cold-leg Break Condition

In the event of a cold-leg break, the driving force is the manometric balance between the liquid in the downcomer and core, as shown in Figure 4.3-3. The ECC water from each DVI line runs to the break, ensuring that the downcomer is full to at least the bottom of the cold-leg nozzles. The $dP_{available}$ is established by the manometric balance between the downcomer liquid level and the core liquid level considering the pressure drop through the RCS loops due to the steam flow.

Assumptions

1) The assumptions used in the case of a hot-leg break (assumptions # 2, 3, 5) are also applied to the cold-leg break case excluding the water density.
2) The saturated water density at the highest RCS pressure of 4.469 kg/cm^2A (63.57 psia) is assumed (919.59 kg/m^3 (57.41 lbm/ft^3)).

Calculations

TS

The values in Table 4.3-4 are used to calculate the cold-leg break available head loss. The dP_{avail} for a cold-leg break is dependent upon the time at which the value is calculated. Therefore, the inputs described here can be used to calculate the expected dP_{avail} as a function of time. Since, the boil-off rate decreases with time, the minimum dP_{avail} for a cold-leg break is calculated at the recirculation start time

(700 seconds.)

TS

4.3.3.3 Available Driving Head under the Condition of Cold-leg Break after HLSO

In the event of a cold-leg break after HLSO operation, the driving force is the manometric balance between the liquid in the downcomer and the core, as shown in Figure 4.3-4. If a debris bed begins to build up in the core, the liquid level will begin to build in the HLs and SGs. As the level begins to rise in the SG tubes, the elevation head driving the flow through the core increases as well. The driving head reaches its peak when the shortest SG tube has been filled.

<u>Assumptions</u>

1) The assumptions used in the case of a hot-leg break (# 2, 5) are also applied to the case of a cold-leg break after HLSO excluding the water density.
2) The HLSO operation is assumed to start at 1.5 hours after a cold-leg break for the earliest time.
3) The saturated water density at the highest RCS pressure of 3.71 kg/cm^2A (52.7 psia) is assumed (925.65 kg/cm^3 (57.78 lbm/ft^3)).

<u>Calculations</u>

TS

The inputs are found in APR1400 drawings and evaluations. The values in Table 4.3-4 are used to calculate the available head loss for a cold-leg break after HLSO. The $dP_{available}$ is as follows:

TS

4.3.4 LOCADM Calculations

This section provides evaluation results of two parameters (cladding temperature and cladding deposit thickness) during the 30 day period following a LOCA.

WCAP-16793-NP Revision 2, developed by the PWR Owners Group (PWROG), defines an NRC approved methodology for evaluating the impact of debris on long-term fuel cladding performance subsequent to a LOCA. The methodology and the implementing software, an Excel spreadsheet based tool identified as the LOCA Deposition Model (LOCADM), is used to evaluate the effect from deposition of chemical species carried into the core by safety injection coolant, on the fuel and the resultant cladding temperatures. The chemical-effects-modeling methods developed in (Reference [3-11]) are used in the LOCADM methods to determine the types and concentrations of the chemical species present in the safety injection coolant.

LOCADM uses a conservative model for decay heat generation and heat removal to evaluate local core boiling and the subsequent deposition of dissolved solids on the surfaces of fuel rods. The combination of deposit thickness and conductivity, coolant temperature and localized decay heat generation are then used to determine cladding temperature throughout the duration of a LOCA event.

LOCADM is used with the methodology provided in Reference [4-7] and the guidance provided in (Reference [4-8]) to evaluate cladding-deposit thickness and temperature.

4.3.4.1 Acceptance Bases

The following acceptance bases are selected for the evaluation according to the WCAP-16793-NP:

1) The maximum clad temperature shall not exceed 800 °F.

2) The thickness of the cladding oxide and the deposits of material on the fuel shall not exceed 0.050 inch in any fuel region.

4.3.4.2 Methodology

WCAP-16793-NP Revision 2 was developed by the PWROG to evaluate the long-term effect of chemical species generated in the containment IRWST environment from particulate, fibrous and chemical debris generated during the LOCA and transported into the core by safety injection coolant. Specific to this evaluation methodology, the PWROG developed a LOCADM that implements chemical dissolution and deposition models for conservatively evaluating two parameters critical to long-term cooling: cladding deposit thickness and cladding temperature. These parameters are compared with NRC accepted criteria to determine if long-term cooling requirements are met, based on plant-specific inputs and debris loads.

The following documents provide the primary guidance in the application of a LOCADM:

1) WCAP-16793-NP Revision 2, Section 7, Appendix E

2) NRC SE for WCAP-16793-NP Revision 2

3) OG-07-419 (Reference [4-12]) transmitting LOCADM.xls with some discussion of selected input parameters

4) OG-07-534 (Reference [4-13]) providing discussion of Options 1 and 2 for modeling Modes 1 and 2

5) OG-08-64 (Reference [4-14]) providing guidance to address an NRC concern that short term aluminum release is under predicted by the LOCADM

LOCADM evaluates conditions during the event through the four plant operating modes during a LOCA event (Reference [4-13]):

1) Mode 1: Blowdown/Refill—blowdown of water from the RCS as a consequence of the break, refill of the vessel by injection from the safety injection tanks and IRWST

2) Mode 2: After vessel refill but before recirculation begins

3) Mode 3: Recirculation from the IRWST

4) Mode 4: Hot leg injection

Figure 4.3-5 shows the schematic diagram of the LOCADM physical model. The schematic shows the reactor vessel with the RCS break, the core, the containment and IRWST. The following definitions are provided:

1) BreakFlow – reflects coolant that drains directly from the RCS break

2) BOPBlowdown – coolant that flows from the other parts of the plant back into the reactor vessel and containment

3) RVLqFlow – coolant that drains from the reactor vessel through the RCS break

4) RVSteamFlow – steam that vents from the RCS to containment through the RCS break

5) TSPFlow – tri-sodium phosphate flow into the IRWST

6) SprayFlow – containment spray drawn from the IRWST

7) SIFlow - safety injection flow that is drawn from the IRWST and injected into the intact loop (i.e., 'CleanSIFlow') and into the broken loop (i.e., 'CleanBypass')

8) The recirculation flow drawn from the IRWST includes recirculation water injected into the intact loop (i.e., 'RecircLqFlow') and the broken loop (i.e., 'RecircBypass')

4.3.4.3 Assumptions

The following assumptions have been made regarding inputs to provide a conservative evaluation.

1) It is assumed that all aluminum exposed to containment spray, and submerged in the IRWST sumps, is pure unalloyed aluminum (i.e., Alloy 1100).

2) It is assumed that 0.36 m^3 (12.5 ft^3) of fiber debris (a density of 0.038 g/cm^3 (2.4 lbm/ft^3)) bypasses the ECCS sump strainers, and is entrained in the safety injection and recirculation flows.

   Basis: There is no fiber insulation inside the ZOI. Only latent fiber amount is assumed to be 6.80 kg (15 lbm) inside the entire containment. However, 13.6 kg (30 lbm) of latent fiber is assumed to bypass the ECCS sump strainers for conservatism.

3) It is assumed that Mode 3 for recirculation injection from the IRWST begins at 700 seconds.

4) It is assumed that Mode 4 for hot-leg switch over injection from the IRWST begins at 5,225 seconds (1.45 hours).

4.3.4.4 Inputs

APR1400 specific inputs used in the LOCADM evaluations are discussed below.

4.3.4.4.1 ‘Time-Input’

Guidance for input to populate the ‘Time-Input’ worksheet comes primarily from the ‘Instructions’ worksheet in the LOCADM spreadsheet. The input consists primarily of times during, and subsequent to, the LOCA, the corresponding fluid temperatures and flows, and the plant-operating mode.

Time, seconds

In order to model the start of recirculation at 700 seconds post-LOCA and 1.45 hours post-LOCA, time steps are added to the base worksheet at a) 700 and 701 seconds, and b) 5,224 and 5,225 seconds. The calculations have been executed with a mission time of 30 days consistent with WCAP-16793-NP methodology.

IRWST pH

The IRWST pH profile is assumed to be pH 10 for the first 4 hours post-LOCA, and pH 8.5 thereafter. The use of the higher values is conservative as a higher pH enhances dissolution of debris in the IRWST, thereby generating larger scale thickness and slightly higher cladding temperatures.

IRWST Temperature, °C (°F)

The IRWST temperature profile used for this calculation is shown in Table 4.3-6.

Spray Flow, kg/sec (lbm/sec)

The containment spray flow, in accordance with the guidance provided (Reference [4-13]) for LOCADM Option 2 operation, is set to zero for all input times.

Spray pH

The containment-spray pH profile is set to pH 10.0 for the first 4 hours post-LOCA, and pH 8.5 thereafter. As discussed above, the use of the higher values is conservative as a higher pH enhances dissolution of debris in the IRWST and components wetted by the IRWST fluid, thereby generating larger scale thickness and slightly higher cladding temperatures.

Reactor Vessel Coolant Temperature, °C (°F)

The RV coolant temperature is assumed to calculate the RV pressure which is shown in DCD Tier 2, Table 6.2.1-7 Part B. The temperature profile is shown in Table 4.3-6.

Clean Safety Injection Flow into Reactor Vessel, kg/sec (lbm/sec)

The clean safety injection flow is set to zero for Modes 1, 3, and 4. The clean safety injection flow for Mode 2 is obtained from the maximum steaming rate.

Recirculation Flow into Reactor Vessel, kg/sec (lbm/sec)

The recirculation flow into the reactor vessel, in accordance with the guidance provided (Reference [4-13]) for LOCADM Option 2 operation is set to:

1) ‘0’ for Modes 1 and 2

2) the ‘Reactor Vessel Steam Flow’ (i.e., Column V) for Mode 3

3) the calculated recirculation flow for Mode 4

TSP Dissolution Rate, kg/sec (lbm/sec)

While the APR1400 implements TSP for IRWST coolant pH control, its impact on IRWST pH is accounted for in the IRWST coolant pH profile. Therefore, the TSP dissolution rate is unused and the value is set to '0'.

Reactor Vessel Pressure in Upper Plenum, kg/cm^3 (psia)

Reference [4-13], indicates that the saturation pressure at the reactor coolant temperature should be entered until the saturation pressure falls below the containment pressure, at which point the containment pressure should be entered. Values provided for 'Reactor Vessel Pressure in Upper Plenum' are evaluated internally by LOCADM. For conservatism, calculated sub-atmospheric pressures are reset to 1 atm (14.7 psia).

Maximum Steaming Rate, lbm/sec

The 'Maximum Steaming Rate' is evaluated internally in LOCADM. The calculated values are not overwritten and remain as calculated.

4.3.4.4.2 'Materials Input'

Guidance for input to populate the 'Materials Input' worksheet comes primarily from the 'Instructions' worksheet in the LOCADM spreadsheet itself. The input consists primarily of material types, their surface areas or volumes, and/or masses.

Metallic Aluminum Alloy 1100 or Unknown Alloy Type

As the specific aluminum alloy has not been specified, information regarding submerged and unsubmerged aluminum is entered as 'Metallic Aluminum Alloy 1100 or Unknown Alloy Type'.

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1) aluminum submerged (m^2 / ft^2) :

2) aluminum submerged (kg / lbm) :

3) aluminum not submerged (m^2 / ft^2) :

4) aluminum not submerged (kg / lbm) :

Calcium Silicate

This material type includes low density calcium silicate mat insulation, asbestos and asbestos-containing insulation, and high density refractory materials (e.g., transite). However, no calcium silicate materials are used in the APR1400.

E-Glass

This material type includes fiberglass insulation.

- Fiberglass insulation : 0.36 m^3 (12.5 ft^3)

Using a density of 0.038 g/cm^3 (2.4 lbm/ft^3), a value of 0.36 m^3 (12.5 ft^3) is entered for 'Fiberglass

Insulation'.

Concrete

Exposed concrete surfaces in containment are input to allow consideration of chemical leaching and dissolution. 868.1 m^2 (9,344 ft^2) of concrete is exposed in containment. In the LOCADM input, 1,736 m^2 (18,688 ft^2) was used by applying the "bump-up" factor of 2.

Coolant

Coolant material inputs are provided to specify coolant specific characteristics for input to LOCADM. Table 4.3-7 and Table 4.3-8 summarize the containment material inputs and coolant material inputs, respectively.

4.3.4.4.3 'Materials Conversions'

Guidance for input to populate the 'Materials Conversions' worksheet comes primarily from the 'Instructions' worksheet in the LOCADM spreadsheet. The input consists primarily of material densities with material amounts drawn from the worksheet 'Materials Input' and multiplied by the density values to generate the material masses (in kg) and total material class masses (in kg). The IRWST water density is assumed to be 0.93 g/cm^3 (57.9 lbm/ft^3).

4.3.4.4.4 Spreadsheet 'Core-Data-Input'

Guidance for input to populate the 'Core-Data-Input' worksheet comes primarily from the 'Instructions' worksheet in the LOCADM spreadsheet. The input is entered into three different matrices—the input used for this is discussed below.

4.3.4.4.4.1 Summary of Core and Fuel Characteristics

Global characteristics for the reactor core and fuel are provided in this matrix.

100% Reactor Power (MW Thermal)

The core thermal power is 3,983 MWth.

Crud Thermal Conductivity (W/m K)

Page E-16 of Reference [4-7] indicates that the limiting value for the thermal conductivity of PWR crud is 0.52 W/m·K. This value is input for 'Crud Thermal Conductivity' for the LOCADM evaluations.

LOCA Deposit Thermal Conductivity (W/m K)

Page E-16 of Reference [4-7] indicates that the limiting value for the thermal conductivity of post-LOCA deposits is 0.2 W/m·K. This value is input for 'LOCA Deposit Thermal Conductivity' for the LOCADM evaluations.

Fuel Rod OD (inch)

A value of 9.50 mm (0.374 inch) is used.

Pellet Stack Length (inch)

A value of 3.81 m (150 inch) is used.

Average Cladding Oxide Thickness (microns)

As discussed in References [4-8] and [4-12], the average initial fuel oxide thickness is evaluated by assuming the maximum extent of cladding oxidation as per 10CFR50.46 (i.e., 17%) and multiplying by 1.56. For these analyses, the peak initial oxide thickness is determined to be:

$$\text{Oxide initial} = 0.02252\times0.17\times1.56 \times 1000 = 5.972 \text{ mil} = 152\ \mu m\ (5.97\text{x}10^{-3} \text{ inch})$$

For conservative evaluation, the average cladding-oxide thickness is considered to be the same as peak initial oxide thickness of 152 μm (5.97x10^{-3} inch).

Average Starting Crud Thickness (microns)

Reference [4-13] indicates that the value input for 'Average Starting Crud Thickness' is the maximum bound value of 140 μm (5.51x10^{-3} inch), multiplied by the maximum values of the 'Relative Crud Thickness' multipliers in the axial and fuel region matrices. For conservative evaluation, the average initial crud thickness is considered to be the same as the maximum bound value of 140 μm (5.51x10^{-3} inch).

Number of Regions

Reference [4-7] provides guidance on the number of core regions to be used in the LOCADM analyses. Table E-1 indicates that this input parameter is to be set to 3 for CE type NSSSs. This nodalization is maintained for the LOCADM analyses documented in this calculation.

Number of Axial Nodes

Reference [4-13] indicates in Table 9, that this input parameter should be set to '3'. This is maintained for the LOCADM analyses documented in this calculation.

Distance from Hot Leg Inlet to Top of Pellet Stack (inch)

The distance from the top of the active region to the bottom of the hot leg inlet is 1.01 m (39.748 inch).

4.3.4.4.4.2 Core (Axial) Elevation Characteristics

Reference [4-13], Table 9, provides recommended values for all plant types. These values have been input for the LOCADM cases executed for the APR1400. Parameter variations as a function of axial position are provided in Table 4.3-10.

4.3.4.4.4.3 Fuel Region (Radial) Characteristics

Reference [4-7], Table E-1, provides recommended values for the number of rods per region and the relative power fraction for all US PWR plant types. Values specific to a CE reactor design using a 16x16 fuel-array are provided. The specific values input to LOCADM are summarized in Table 4.3-11 along with the bases for those particular numbers.

Region

Consistent with CE NSSSs implementing 16x16 fuel-array designs, three radial core regions are modeled. This nodalization is maintained for the APR1400 LOCADM analyses documented in this Technical Report.

Relative Power, Number of Rods

Reference [4-7], Table E-1, provides recommended values of the number of rods per region and the relative power fraction for all plant types. Values specific to a CE reactor design using a 16x16 fuel-array have been used in LOCADM evaluation. The total number of fuel rods specified for Regions 1-3, sums to 56,876. This corresponds to 241 assemblies comprised of a 16x16 lattice that has 20 rods replaced by control rods and instrumentation thimbles (i.e., a net of 236 fuel rods per assembly).

4.3.4.4.5 Spreadsheet ‘Switches’

Guidance for input to populate the ‘Switches’ worksheet comes primarily from the ‘Instructions’ worksheet in the LOCADM spreadsheet. The switches permit factoring in reductions in the projected chemical effects by crediting inhibition of corrosion and/or solubility limits.

4.3.4.5 Results

[ ]TS

In conclusion, the maximum total deposit thickness and the peak cladding temperature are maintained within acceptance bases provided in Reference [4-7] with sufficient margin.

4.3.5 Boric Acid Precipitation

The APR1400 design uses boron to control core reactivity, and is subject to concerns regarding potential post-LOCA boric acid precipitation (BAP) in the core. To prevent the core region boric acid concentration from reaching the precipitation point, there is a procedure that instructs the operators to initiate a hot-leg switchover operation within 2 hours after a cold-leg break (Reference [4-9]).

There are additional concerns about the potential for debris in the core to change flow patterns or otherwise inhibit the mixing of boric acid that could result in earlier BAP. Debris beds within the core could block the coolant channels and inhibit core cooling when higher amounts of fiber are involved.

To address these concerns on higher fibrous-debris loads, the APR1400 is designed as a “low fiber plant” by exclusion of fibrous material within the zone of influence of a high-energy line break. The maximum anticipated fibrous-debris load for a cold-leg break is about [ ]TS grams per fuel assembly (Section 4.3.2.2). This is less than the 7.5 grams (0.017 lbm) limit accepted by the NRC (Reference [4-8]).

Therefore, it is concluded that the debris ingested by the reactor vessel would not significantly affect the mixing capability of boric acid in the APR1400.

4.3.6 Fuel Assembly Testing

APR1400 fuel-assembly tests have been performed to confirm that the head losses caused by debris

deposited on a fuel assembly, meet the available driving head following a LOCA.

In this test, various ranges of debris amounts (15 g (0.033 lbm) of fiber, 900 g (1.984 lbm) of particulates, and 768 g (1.693 lbm) of chemical debris) are applied. The testing represents that the particle-to-fiber ratio of ‘1’ produces the highest pressure drop for constant fiber loading under the hot-leg break condition, and ‘50’ under cold-leg break condition. The presence of chemical debris causes an additional increase in the overall pressure drop. However, after some amount of chemical debris is added, subsequent chemical debris does not increase the pressure drop. A summary of test results is presented in Table 4.3-12.

The pressure drop criterion of the hot leg-break condition is [ ]TS kPa. All the test results show lower pressure drop than the acceptance criterion, and the highest pressure-drop is [ ]TS kPa. The pressure drop acceptance criterion for the cold-leg break condition is [ ]TS kPa, and the highest pressure drop is [ ]TS kPa. Figures 4.3-8 and 4.3-9 present the pressure-drops for hot-leg break and cold-leg break tests, which give the limiting results. Detailed descriptions of the test results are found in (Reference [4-10]).

Therefore, a sufficient driving force is available to maintain an adequate flow rate, and the long-term core cooling capability is adequately maintained in the APR1400.

4.3.7 Evaluation Summary

The intent of this section is to assess the in-vessel downstream effects of the APR1400, by applying the evaluation methods and acceptance bases provided in Reference [4-7] and [4-8].

To remain within the 15 gram (0.033 lbm)/FA fiber limit, there is no fibrous insulation within the ZOI. The evaluation results of the APR1400 in-vessel downstream effects are:

1) Following a LOCA, the ECC flow rate per FA is 78 L/min (20.5 gpm) for the hot-leg break condition, and 14 L/min (3.64 gpm) for the cold-leg break condition.

2) The amount of bypass fiber per FA is less than the 15 gram (0.033 lbm) limit.

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5) The debris ingested by the reactor vessel would not significantly affect the mixing capability of boric acid in the APR1400.

6) A sufficient driving force is available to maintain an adequate flow rate, and the long-term core cooling capability is adequately maintained in the APR1400

In conclusion, sufficient long-term core cooling following a LOCA in the APR1400 is achieved, given the presence of the range of debris and chemical products postulated to be transported to the reactor vessel.

Table 4.1-1 Strainer Flow Rate and Debris Loads

Strainer	Pumps	Flow Rate (L/min / gpm)	Plant Strainer Debris Loads (kg / lbm)	Prototype Strainer Debris Load (kg / lbm)
1	SIP + CSP	25,211 / 6,660	2.87 / 6.33	0.36 / 0.79
2	SIP + CSP	25,211 / 6,660	2.87 / 6.33	0.36 / 0.79
3	SIP	4,675 / 1,235	0.53 / 1.17	0.07 / 0.15
4	SIP	4,675 / 1,235	0.53 / 1.17	0.07 / 0.15
Total		59,772 / 15,790	6.80 / 15.0	0.85 / 1.88

Table 4.1-2 Bypass Fiber Weight

Debris Load Addition	Fiber Added (g / lbm)	Bypass Fiber Weight (g / lbm)	Cumulative Bypass Fiber Weight (g / lbm)
After first fiber addition	181.2 / 0.40	37.16 / 0.08	37.16 / 0.08
After second fiber addition	181.2 / 0.40	29.66 / 0.07	66.82 / 0.15
After third fiber addition	181.2 / 0.40	28.04 / 0.06	94.86 / 0.21
After fourth fiber addition	181.2 / 0.40	29.08 / 0.06	123.94 / 0.27

Table 4.1-3 Bypass Debris Quantities of IRWST Sump Strainer

Strainer	Pumps	Flow Rate (L/min / gpm)	Plant Strainer Debris Loads (kg / lbm)	Prototype Strainer Debris Load (kg / lbm)	Prototype Bypass Debris (kg / lbm)	Ratio of Surface Areas	Bypassed Fiber Mass (kg / lbm)
1	SIP + CSP	25,211 / 6,660	2.87 / 6.33	0.36 / 0.79	0.067 / 0.1475	8.0	0.54 / 1.18
2	SIP + CSP	25,211 / 6,660	2.87 / 6.33	0.36 / 0.79	0.067 / 0.1475	8.0	0.54 / 1.18
3	SIP	4,675 / 1,235	0.53 / 1.17	0.07 / 0.15	0.037 / 0.082	8.0	0.30 / 0.66
4	SIP	4,675 / 1,235	0.53 / 1.17	0.07 / 0.15	0.037 / 0.082	8.0	0.30 / 0.66
Total		59,772 / 15,790	6.80 / 15.0	0.85 / 1.88	0.208 / 0.459	-	1.67 / 3.68

Table 4.2-1 Components in the Flow Path during an LBLOCA (1 of 3)

Component	Description	
Pumps		
SI pump (SI-PP02A/02B/02C/02D)	Type: multi-stage centrifugal pump Arrangement: horizontal Flow rate: ~4,675 L/min (1,235 gpm) (maximum)(1)	
CS Pump (CS-PP01A/01B)	Type: centrifugal Arrangement: vertical Flow rate: ~24,605 L/min (6,500 gpm) (maximum)(1)	
Heat Exchangers		
CS Heat Exchanger (CS-HE01A/01B)	Type: shell and tube, U-tube, horizontally mounted Number of shell in series:1 Number of tube passes: 2 Tube material; austenitic steel Flow rate: ~18,927 L/min (5,000 gpm) (during LBLOCA Containment Spray)	
CS Pump Miniflow Heat Exchanger (CS-HE02A/02B)	Type: shell and tube, U-tube, horizontally mounted Number of shell in series:1 Number of tube passes: 2 Tube material; austenitic steel Flow rate: ~1,817 L/min (480 gpm)	
Valves		
CS-V1001/1002	Swing check,	14 inch
CS-V1003/1004	Gate (manual),	14 inch
CS-V1007/1008	Swing check,	14 inch
CS-V1015/1016/1017/1018	Globe (manual),	4 inch
CS-V001/002/003/004	Gate (MOV),	14 inch
SI-V304/305	Gate (MOV),	20 inch
SI-V470/402/130/131	Gate (manual),	10 inch
SI-V404/405/434/446	Swing check,	4 inch
SI-V435/447/476/478	Gate (manual),	4 inch
SI-V308/309	Gate (MOV),	20 inch
SI-V347/348	Gate (MOV),	18 inch
SI-V157/158	Swing check,	18 inch
SI-V424/426/448/451	Swing check,	4 inch
SI-V410/411/412/413	Globe (manual),	4 inch
SI-V302	Gate (manual)	4 inch
SI-V303	Globe (MOV),	4 inch
SI-V100/101	Swing check,	10 inch
SI-V395	Gate (MOV),	10 inch
SI-V959	Gate (manual),	10 inch
SI-V604/609	Gate (MOV),	4 inch

Note :

(1) Including minimum bypass flow

Table 4.2-1 Components in the Flow Path during an LBLOCA (2 of 3)

Component	Description	
Valves (Cont.)		
SI-V616/626/636/646	Globe (MOV),	4 inch
SI-V113/133	Swing check,	4 inch
SI-V123/143	Swing check,	12 inch
SI-V540/542	Swing check,	4 inch
SI-V541/543	Swing check,	12 inch
SI-V614/624/634/644	Gate (MOV),	12 inch
SI-V217/227/237/247	Swing check,	12 inch
SI-V321/331	Globe (MOV),	4 inch
SI-V523/533	Swing check,	4 inch
SI-V957/V958	Gate (manual),	4 inch
SI-V522/532	Swing check,	4 inch
Orifice		
CS-OR01A/B	CS pump miniflow orifice,	4 inch
CS-FE338/348	CS pump outlet flow instrument orifice,	14 inch
CS-02A/B, 03A/B	CS main spring ring header orifice,	8 inch
CS-OR04A/B	CS main spring ring header orifice,	4 inch
CS-OR05A/B, 06A/B	CS auxiliary spring ring header orifice,	4 inch
SI-OR01A/B/C/D, 08A/B/C/D, 20A/B/C/D	SI pump miniflow orifice,	4 inch
SI-OR06A/B/C/D	SI pump outlet flow orifice,	4 inch
SI-OR07A/B	Hotleg injection flow orifice,	4 inch
SI-FE311D/321B/331C/341A	SI pump outlet flow instrument orifice,	4 inch
SI-FE390C/391D	Hotleg injection flow instrument orifice,	4 inch
Containment Spray Nozzle		
Main spray nozzle	Orifice size 13.1 mm (0.516 inch)	
Auxiliary spray nozzle	Orifice size 5.6 mm (0.22 inch)	
Piping		
18 inch CS pump suction line (SS Sch. 80)		
16 inch CS pump suction line (SS Sch. 80)		
14 inch CS pump discharge line (SS Sch. 80)		
12 inch CS pump discharge line (SS Sch. 80S)		
14 inch CS spray header line (SS Sch. STD)		
12 inch CS spray header line (SS Sch. 40S)		
8 inch CS spray header line (SS Sch 40S)		
6 inch CS spray ring line (SS Sch 40S)		
4 inch CS spray ring line (SS Sch 40S)		
4 inch CS pump miniflow line (SS Sch 40)		
10 inch SI IRWST return line (SS Sch 120)		
24 inch SI pump suction line (SS Sch. 80)		
20 inch SI pump suction line (SS Sch. 80)		
10 inch SI pump suction line (SS Sch. 80S)		
4 inch SI pump discharge line (SS Sch. 120)		
4 inch SI pump miniflow line (SS Sch. 120)		
4 inch SI pump hot leg Injection line (SS Sch. 120)		

Table 4.2-1 Components in the Flow Path during an LBLOCA (3 of 3)

Component	Description
Piping (Cont.)	
4 inch SI pump discharge line (SS Sch. 160)	
12 inch SI pump discharge line (SS Sch. 160)	

Table 4.2-2 Size Range of Debris Materials

Debris Size Category	Size
Particulates	0 - 2.38 mm (0 - 0.094 inch)
Fines	< 101.6 mm (4 inch)
Large pieces	> 101.6 mm (4 inch)

Table 4.2-3 Total Quantity of Debris Generated during an LBLOCA

Debris Source		Particulate	Fines	Large Pieces	Total
RMI (m^3 / ft^3)					
Qualified epoxy coating (kg / lbm)		132.2(1) / 291.4	0	0	132.2 / 291.4
Latent debris (kg / lbm)	Particulate	83.9 / 185	0	0	83.9 / 185
	Fibers	0	6.8 / 15	0	6.8 / 15
Miscellaneous (m^2 / ft^2)		0	0	- (2)	0

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Note :
(1) For strainer design, epoxy coating of 3.10 ft^3 is conservatively used.
(2) To deal with the quantity of miscellaneous debris, a 9.29 m^2 (100 ft^2) penalty of sacrificial strainer surface area per sump is applied.

Table 4.2-4 Terminal Settling Velocity of Debris Source Materials

Debris Source Material	Terminal Settling Velocity (m/s / ft/s)	Reference/Comments
Qualified epoxy coatings	0.046 / 0.15	NEI 04-07 (page 4-34, epoxy)
Latent debris	0.213 / 0.70 (1)	The terminal settling velocity of latent debris is estimated relative to the settling velocity of the constituent latent particulate estimated in Subsection 4.2.2.5.

Note :

(1) The terminal settling velocity of the latent particulate is estimated as:

$$w = 1.068\sqrt{\frac{(\rho_s - \rho)\cdot g \cdot d}{\rho}}$$

Where:

w = terminal settling velocity of the particle (m/s (ft/s))

g = gravitational acceleration (9.81 m/s^2 (32.2 ft/s^2))

d = Diameter of the particle (2.38 mm (0.094 inch), the particle size is assumed to be the same as the perforated plate hole size of the IRWST sump strainers)

ρ_s = mass density of the particle (2.70 g/cm^3 (168.6 lbm/ft^3)) (Table 3.3-2)

ρ = mass density of the fluid (1.00 g/cm^3 (62.4 lbm/ft^3), density at 0°C (32°F))

Table 4.2-5 Post-LOCA Fluid Constituents Downstream of IRWST Sump Strainer

Debris Type	Debris Quantity	Density	Debris Mass (kg / lb)	Concentration (ppm)
Qualified epoxy coating	0.0878 m^3 / 3.1 ft^3	1.51 g/cm^3 / 94 lb/ft^3	132.2 / 291.4	148
Latent particulates	83.9 kg / 185 lb	-	83.9 / 185	94
Latent fiber	6.8 kg / 15 lb	-	6.8 / 15	8
Total	-	-	222.9 / 491.4	250

Table 4.2-6 Affected Equipment/Flow Rates (1 of 2)

Component	Inner Diameter (inch)	Designed Flow Rate (gpm)	Assumed Flow Rate (gpm)	Assumed Velocity (ft/sec)	Maximum Settling Velocity (ft/sec)
Orifice					
CS-OR01A/B	3.51	480	400	13.25	0.70
CS-FE338/348	9.045	480	400	1.99	0.70
CS-OR02A/B	4.441	172	150	3.10	0.70
CS-OR03A/B	5.129	169	150	2.33	0.70
CS-OR04A/B	2.657	27	20	1.16	0.70
CS-OR05A/B	1.323	24	20	4.66	0.70
CS-OR06A/B	1.218	24	20	5.50	0.70
SI-OR01A/B/C/D	0.8	105	80	51.00	0.70
SI-OR06A/B	1.594	105	80	12.85	0.70
SI-OR06C/D	1.662	105	80	11.82	0.70
SI-OR07A/B	1.65	105	80	11.99	0.70
SI-OR08A/B/C/D	0.491	105	80	135.39	0.70
SI-OR20A/B/C/D	1.153	105	80	24.55	0.70
SI-FE311D/321B/331C/341A	2.126	105	80	7.22	0.70
SI-FE390C/391D	2.126	105	80	7.22	0.70
Containment Spray Nozzle					
Main spray nozzle	0.516	15.2	1.5	2.30	0.70
Auxiliary spray nozzle	0.22	3	0.3	2.53	0.70

Table 4.2-6 Affected Equipment/Flow Rates (2 of 2)

Component	Inner Diameter (inch)	Designed Flow Rate (gpm)	Assumed Flow Rate (gpm)	Assumed Velocity (ft/sec)	Maximum Settling Velocity (ft/sec)
Piping					
18" CS pump suction line (SS Sch. 80)	16.124	480	400	0.63	0.70
16" CS pump suction line (SS Sch. 80)	14.312	480	400	0.80	0.70
14" CS pump discharge line (SS Sch. 80)	12.5	480	400	1.04	0.70
12" CS pump discharge line (SS Sch. 80S)	11.75	480	400	1.18	0.70
14" CS spray header line (SS Sch. STD)	13.25	480	400	0.93	0.70
12" CS spray header line (SS Sch. 40S)	12	432	400	1.13	0.70
8" CS spray header line (SS Sch 40S)	7.981	172	150	0.96	0.70
6" CS spray ring line (SS Sch 40S)	6.065	106	80	0.89	0.70
4" CS spray ring line (SS Sch 40S)	4.026	27	20	0.50	0.70
4" CS pump miniflow line (SS Sch 40)	4.026	480	400	10.07	0.70
10" SI IRWST return line (SS Sch 120)	9.062	480	400	1.99	0.70
24" SI pump suction line (SS Sch. 80)	21.562	585	480	0.42	0.70
20" SI pump suction line (SS Sch. 80)	17.938	585	480	0.61	0.70
10" SI pump suction line (SS Sch. 80S)	9.75	105	80	0.34	0.70
4" SI pump discharge line (SS Sch. 120)	3.624	105	80	2.49	0.70
4" SI pump miniflow line (SS Sch. 120)	3.624	105	80	2.49	0.70
4" SI pump hot leg Injection line (SS Sch. 120)	3.624	105	80	2.49	0.70
4" SI pump discharge line (SS Sch. 160)	3.438	105	80	2.76	0.70
12" SI pump discharge line (SS Sch. 160)	10.126	105	80	0.32	0.70

Table 4.2-7 ECCS and CSS Components Wear during 30 days

Component	Design Flow Rate (gpm)	Assumed Flow Rate (gpm)	Assumed Velocity (ft/sec)	Diametric Wear ($x10^{-4}$, in)	Flow Rate Increase (%)
Orifice					
CS-OR01A/B	509	900	29.80		
CS-FE338/348	5,991	7,200	35.91		
CS-OR02A/B	2,149	3,600	74.47		
CS-OR03A/B	2,111	3,600	55.83		
CS-OR04A/B	339	450	26.01		
CS-OR05A/B	304	450	104.89		
CS-OR06A/B	295	450	123.76		
SI-OR01A/B/C/D	105	200	127.50		
SI-OR06A/B	1,130	1,600	256.92		
SI-OR06C/D	1,130	1,600	236.33		
SI-OR07A/B	1,130	1,600	239.78		
SI-OR08A/B/C/D	105	200	338.48		
SI-OR20A/B/C/D	105	200	61.38		
SI-FE311D/321B/331C/341A	1,130	1,600	144.43		
SI-FE390C/391D	1,130	1,600	144.43		
Containment Spray Nozzle					
Main spray nozzle	18	30	45.97		
Auxiliary spray nozzle	4	6	50.58		
Piping					
18" CS pump suction line (SS Sch. 80)	6,500	7,200	14.34		
16" CS pump suction line (SS Sch. 80)	6,500	7,200	14.34		
14" CS pump discharge line (SS Sch. 80)	6,500	7,200	18.80		
12" CS pump discharge line (SS Sch. 80S)	6,500	7,200	21.28		
14" CS spray header line (SS Sch. STD)	5,991	7,200	16.73		
12" CS spray header line (SS Sch. 40S)	5,392	7,200	20.40		
8" CS spray header line (SS Sch 40S)	2,149	3,600	23.06		
6" CS spray ring line (SS Sch 40S)	1,319	1,800	19.97		
4" CS spray ring line (SS Sch 40S)	339	450	11.33		
4" CS pump miniflow line (SS Sch 40)	509	900	22.65		
10" SI IRWST return line (SS Sch 120)	6,500	7,200	35.77		
24" SI pump suction line (SS Sch. 80)	6,660	7,200	6.32		
20" SI pump suction line (SS Sch. 80)	6,660	7,200	9.13		
10" SI pump suction line (SS Sch. 80S)	1,235	1,600	6.87		
4" SI pump discharge line (SS Sch. 120)	1,235	1,600	49.71		
4" SI pump miniflow line (SS Sch. 120)	105	200	6.21		
4" SI pump hot leg Injection line (SS Sch. 120)	1,130	1,600	49.71		
4" SI pump discharge line (SS Sch. 160)	1,130	1,600	55.23		
12" SI pump discharge line (SS Sch. 160)	1,130	1,600	6.37		

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Table 4.2-8 Wear Rates of Material under Abrasive Slurries

Material	Wear Rates [mm/year (inches/year)]	
	Coarse Sand	
	2.13 m/sec (7 ft/sec)	4.58 m/sec (15 ft/sec)
Steel	0.65 (0.0256)	1.81 (0.0713)
Aluminum	1.81 (0.0713)	7.48 (0.2945)
Polyethylene	0.06 (0.0024)	0.46 (0.0181)
ABS	0.36 (0.0142)	2.07 (0.0815)
Acrylic	0.99 (0.0390)	4.10 (0.1614)
Geometric Average	4.6183	

Table 4.2-9 Piping and Associated Valves with Lower Assumed Flow Velocity than Settling Velocity

Piping	Associated valves	Description	Flow velocity (ft/sec) (1)
4" CS spray ring line	None		7.12
24" SI pump suction line	None		5.84
20" SI pump suction line	SI-V-304/305/308/309	Gate (MOV), 20 inch	8.44
10" SI pump suction line	SI-V-130/131/402/470	Gate (Manual), 10 inch	5.30
12" SI pump discharge line	SI-V-123/143/217/227/237/ 247/541/543	Swing Check, 12 inch	4.50
18" CS pump suction line	SI-V-347/348 SI-V-157/158	Gate(MOV), 18 inch Swing Check, 18 inch	8.51

Note:

(1) The fluid flow velocity is based on the expected pump operation and much higher than the terminal settling velocity of 0.7 ft/sec.

Table 4.3-1 ECCS Flow Rates per FA Following a LOCA

LOCA Scenario	Core Flow Direction	APR1400 Flow Rate	Flow Rate/ FA (1)	Remark
Hot-leg line break	Upward	18,700 L/min (4,940 gpm)	78 L/min (20.5 gpm)	Maximum flow rate of four SI
Cold-leg line break	Upward	3,322 L/min (877.6 gpm)	14 L/min (3.64 gpm)	Boil-off flow rate at 700 seconds
Cold-leg line break after HLSO	Downward	9,350 L/min (2,470 gpm)	39 L/min (10.25 gpm)	Maximum flow rate of two SI

Note :
(1) 1/241 of maximum flow rate

Table 4.3-2 Bypass Debris Types and Amounts per FA

Debris Type	Specific Type	Debris Generated in Containment	Assumed Bypass Debris (kg)	Per FA [(1)] (g)
Fibrous	NUKON	0	0	0
	Latent fiber	6.8 kg (15 lbm)	1.67 [(2)] (3.68 lbm)	6.93
Particulate	Coating debris	280.5 kg (3.1 ft^3)	280.5	1,164
	Latent particle	83.9 kg (185 lbm)	83.9	348
Reflective metal insulation				
Chemical compounds		158.67 kg (349.8 lbm)	158.67	658.3 (59.8 liters)

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Note :

(1) 1/241 of the assumed bypass debris amount

(2) Result of the APR1400 strainer bypass testing

Table 4.3-3 Inputs for Calculation of Hot-leg dP_{avail}

Variable	Description	Unit	Value	Comments
Z_{SG}	Bottom of the SG tubesheet	m		DC liquid density is selected at the saturation pressure (3.312 kg/cm^3 (47.113 psia), DCD Table 6.2.1-8 Part B, 599.9 sec).
$Z_{core-in}$	Bottom of active fuel	m		
ρ_{DC}	Downcomer (DC) liquid density	kg/m^3		
Z_{RVCL}	RV nozzle centerline	m		

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Table 4.3-4 Inputs for Calculation of Cold-leg dP_{avail}

Variable	Description	Unit	Value	Source
$Z_{core\text{-}in}$	Bottom of active fuel	m		DC liquid density is selected at the saturation pressure (4.469 kg/cm^3 (63.57 psia), DCD Table 6.2.1-7 Part B, 600.0 sec)
ρ_{DC}	DC liquid density	kg/m^3		
Z_{brk}	Z_{RVCl}-Z_{IDCL}/2	m		
Z_{RVCL}	RV nozzle centerline	m		
Z_{IDCL}	Inner diameter of cold-leg pipe	m		

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Table 4.3-5 Inputs for Calculation of Cold-leg after HLSO dP_{avail}

Variable	Description	Unit	Value	Comments
Z_{so}	SG spillover elevation	m		DC liquid density is selected at the saturation pressure (3.71 kg/cm^3 (52.769 psia), DCD Table 6.2.1-8 Part B, 3,996.9 sec)
$Z_{core\text{-}out}$	Top of active fuel	m		
ρ_{DC}	DC liquid density	kg/m^3		
Z_{RVCL}	RV nozzle centerline	m		

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Table 4.3-6 Time Dependent Temperature Data

Time (sec)	IRWST Temp (ºF)	CTMT Temp (ºF)	RV Coolant Temp (ºF)
3	120	213.5	586.1
17	121.4	265.8	374.4
40	126.7	262.8	307.4
114	137.8	266	302.4
121	138.3	266.3	302.1
301	151.1	274	296
600	169.1	271.2	296.9
700	173	269.9	295.9
701	173	269.9	295.9
900	178.7	267.5	294.1
1202	184.9	264.7	292.2
2409	203.4	258.5	287.8
3002	210.2	256.9	286.7
3606	215.9	255.5	285.5
5224	227.3	252.6	283.4
5225	227.3	252.6	283.1
9429	241	248.2	280
12002	244	246.5	278.9
14400	245.1	245.2	278
14401	245.1	245.2	278
28002	241.9	238.6	273.6
80002	221.4	218.6	261.3
100002	212.4	208.4	255.6
1000182	153.8	152.2	231.8
2600000	140.9	139.3	231.8

Table 4.3-7 Containment Material Input

Class	Material	Value
Metallic aluminum	Aluminum submerged (ft^2)	0.0
	Aluminum submerged (lbm)	0.0
	Aluminum not-submerged (ft^2)	4,652
	Aluminum not-submerged (lbm)	7,598
Calcium silicate	Calcium silicate insulation(ft^3)	0
	Asbestos insulation (ft^3)	0
	Kaylo insulation (ft^3)	0
	Unibestos insulation (ft^3)	0
E-glass	Fiberglass insulation (ft^3)	12.5
	NUKON (ft^3)	0
	Temp-Mat (ft^3)	0
	Thermal wrap (ft^3)	0
Silica powder	Microtherm (ft^3)	0
	Min-K (ft^3)	0
Mineral wool	Min-wool (ft^3)	0
	Rock wool (ft^3)	0
Aluminum silicate	Cerablanket (ft^3)	0
	FiberFrax durablanket (ft^3)	0
	Kaowool (ft^3)	0
	Mat-ceramic (ft^3)	0
	Mineral fiber (ft^3)	0
	PAROC mineral wool (ft^3)	0
Concrete	Concrete (ft^2)	18,688

Table 4.3-8 Coolant Material Inputs

Parameter	Unit	Value	Note
IRWST water density	g/cm^3 (lbm/ft^3)		Minimum liquid density
Initial IRWST water volume	m^3 (ft^3)		Minimum IRWST level for SIS NPSH during LOCA recirculation
Initial IRWST water mass	kg (lbm)		Minimum IRWST level for SIS NPSH during LOCA recirculation
Core region water Density	g/cm^3 (lbm/ft^3)		Minimum liquid density
Initial core region water volume	m^3 (ft^3)		OG-07-419
Initial core region water mass	kg (lbm)		From minimum liquid density and initial core region water volume

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Table 4.3-9 Core Modeling Parameters

Variable	Unit	Value	
		WCAP-16793-NP	APR1400
100% reactor power	MWt	3,188	3,983
Crud thermal conductivity	W/m-K	0.52	0.52
LOCA deposit thermal conductivity	W/m-K	0.2	0.2
Fuel rod OD	Inches	0.36	0.374
Pellet stack length	Inches	120	150
Average cladding oxide thickness	Microns	20	152 (OG-07-419)
Average starting crud thickness	Microns	30	140 (OG-07-419)
Number of regions	(200 max)	4	3
Number of axial nodes (up and down each region)	(10 max)	3	3
Distance from hot-leg inlet to top of pellet stack	Inches	47	39.748

Table 4.3-10 Axial Nodalization and Input Values

Elevation	Relative Power
1 (Top)	0.95
2	1.10
3(Bottom)	0.95

Table 4.3-11 Radial Nodalization and Input Values

Region	Relative Power	Number of Rods	Percentage of Rods
1	1.65	1	0.0018%
2	1.56	235	0.4132%
3	1.00	56,640	99.5851%

Table 4.3-12 Summary of Fuel Assembly Test Results

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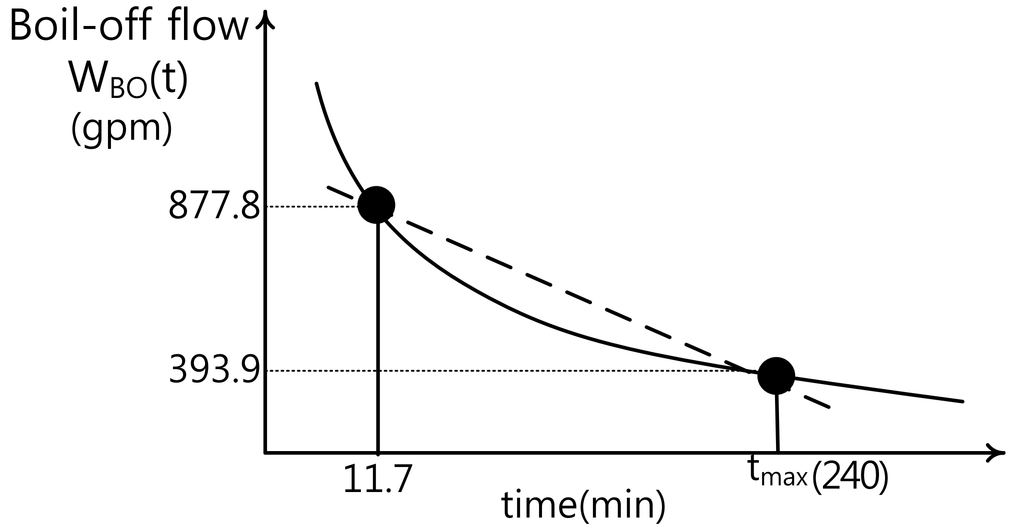

Figure 4.3-1 Boil-off Rate during 4 Hours

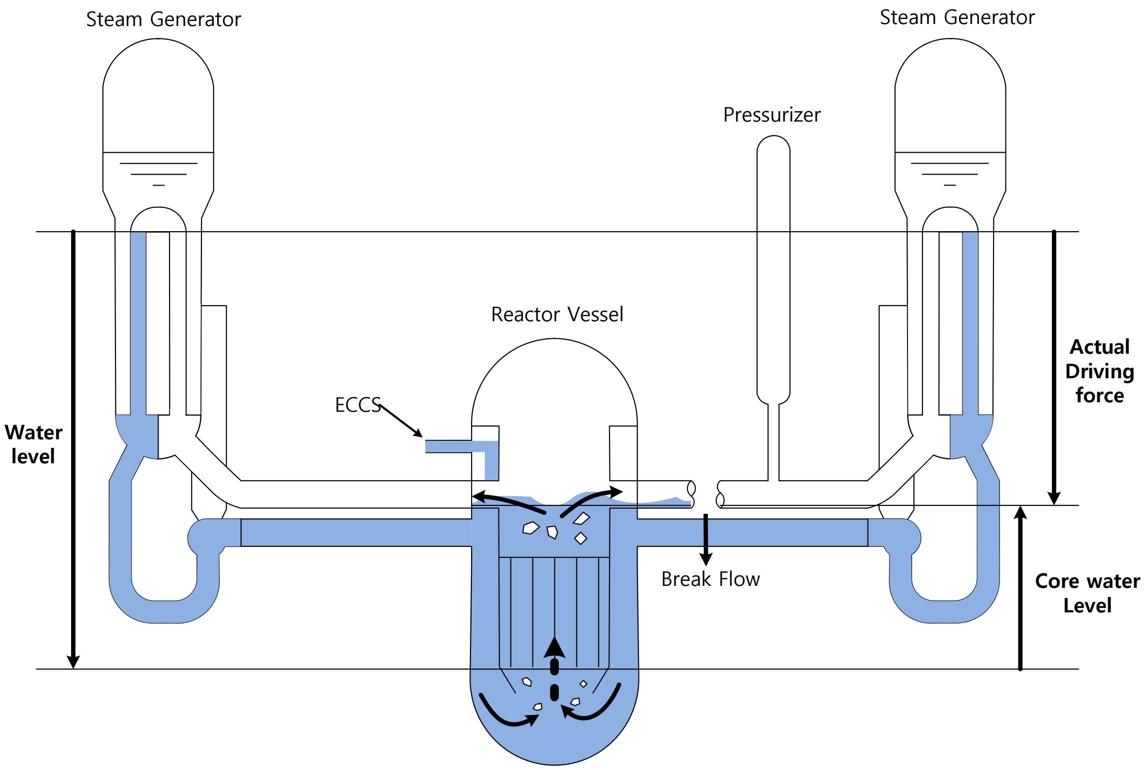

Figure 4.3-2 Available Driving Head at Hot-Leg Break Condition

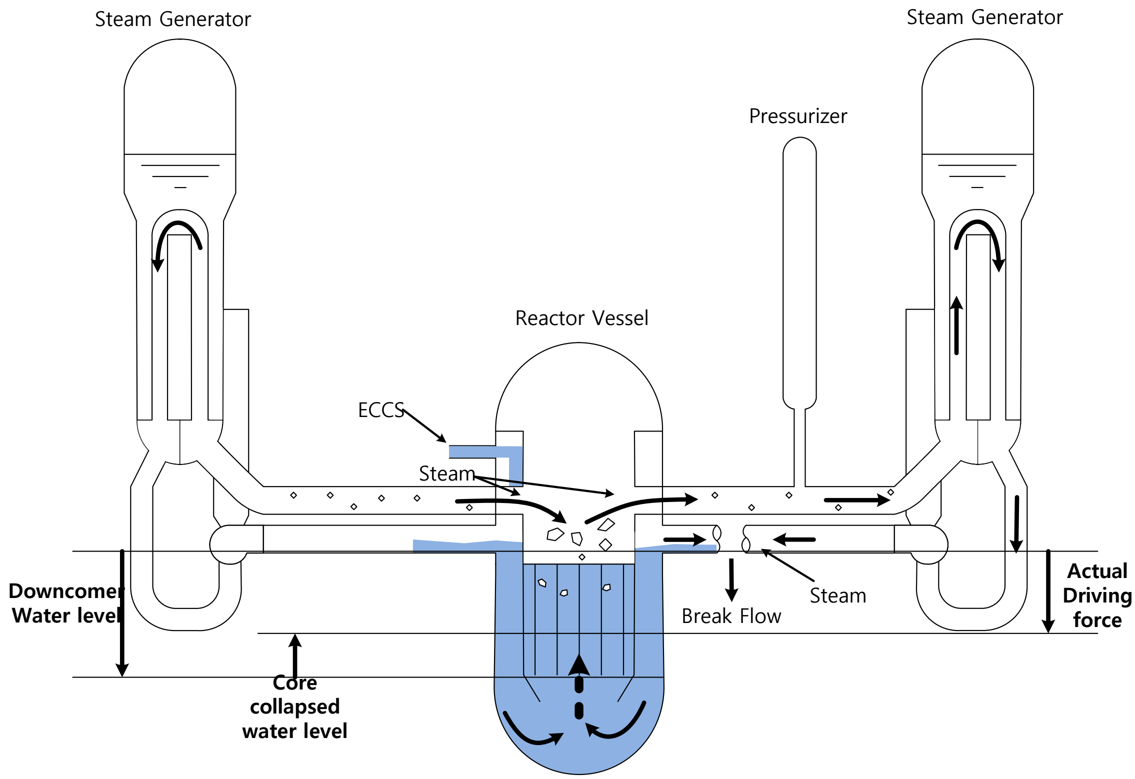

Figure 4.3-3 Available Driving Head at Cold-Leg Break Condition

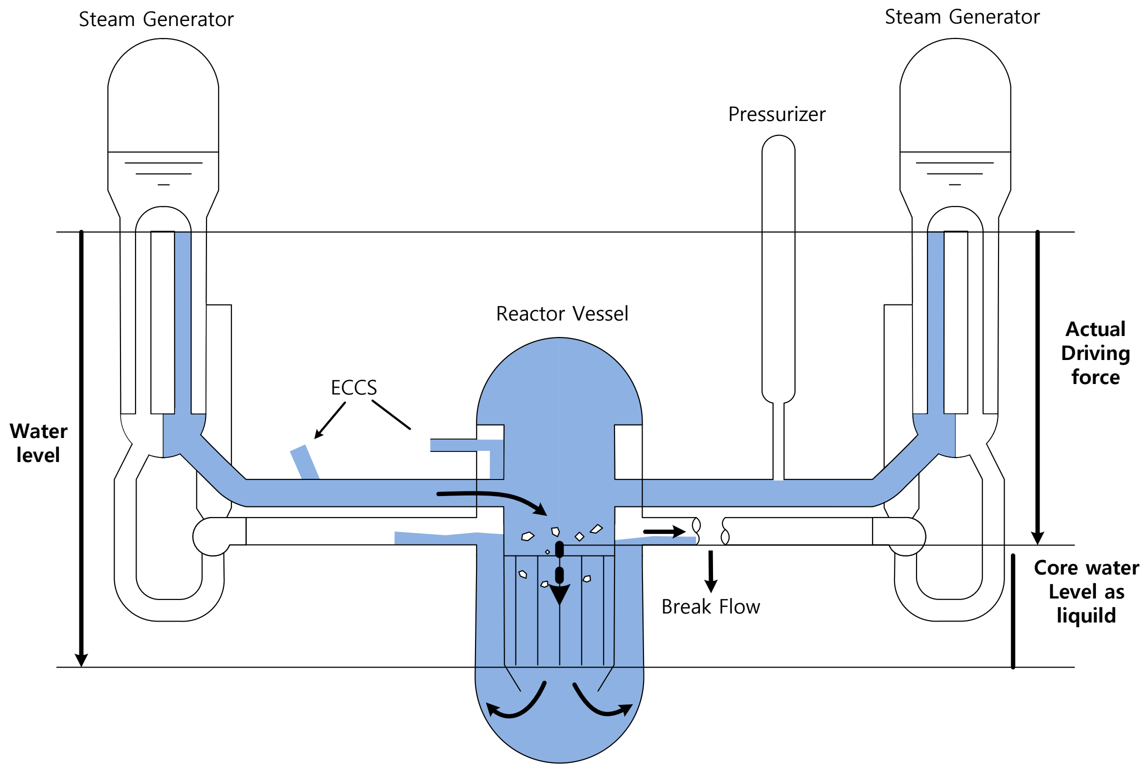

Figure 4.3-4 Available Driving Head at Cold-Leg Break after HLSO Condition

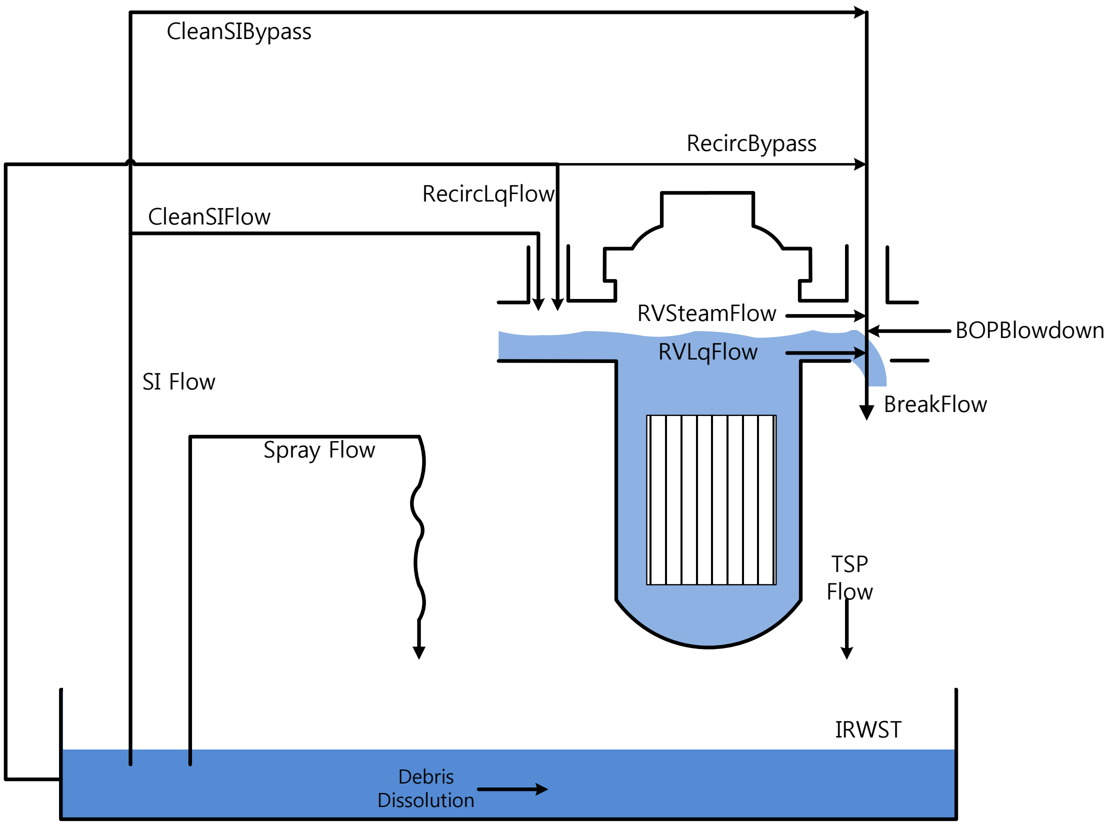

Figure 4.3-5 Flow Paths and Definitions for LOCADM

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Figure 4.3-6 Maximum LOCA Scale Thickness

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Figure 4.3-7 Fuel Cladding Temperature

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Figure 4.3-8 Pressure Drop (APR1400-21; P:F=1:1, 77.6 L/min)

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Figure 4.3-9 Pressure Drop (APR1400-95; P:F=1:50, 16.6 L/min)

5 CONCLUSION

This technical report presents that the design and evaluation result of the APR1400 IRWST sump strainer fully support its safety function under post-accident conditions following NRC RG 1.82, Rev.4, requirements. The break selection, debris generation, characteristics, transport, and head loss are evaluated considering appropriate conservatism. Using these data, chemical effects, upstream effect, and downstream effect as well as NPSH of the ECCS and CSS pumps are evaluated to verify that there is no significant impact on ECCS and CSS pumps, and related systems.

Therefore, this report concludes that the APR1400 design fully satisfies NRC RG 1.82, Rev.4, requirements and has appropriate design margin to perform safety functions under post-LOCA conditions.

6 REFERENCES

1-1 Regulatory Guide 1.82, "Water Sources for Long-term Recirculation Cooling Following a Loss-of-Coolant Accident," Revision 4, U.S. Nuclear Regulatory Commission, March 2012.
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2-1 Regulatory Guide 1.54 Revision 2, "Service Level I, II, and III Protective Coatings Applied to Nuclear Power Plants," U.S. Nuclear Regulatory Commission, October 2010.
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Appendix A

Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1	**General** This section includes regulatory positions on design criteria, performance standards, and analysis methods that relate to all water-cooled reactor types (Section C.1.1) and to specific light-water reactor types (PWRs in Section C.2 and BWRs in Section C.3). As stated in the introduction to this guide, the purpose of the guidance is to identify information and methods that the NRC staff considers acceptable for use in evaluating analytical techniques and implementing regulations related to water sources for long-term cooling of both existing and future reactor systems.	**No response necessary – Introductory Material.**
1.1	**Regulatory Positions Common to All Water-Cooled Reactors** Research, analysis, and lessons learned have shown that similar approaches are appropriate for water-cooled reactors in a number of areas when the long-term recirculation capability evaluation is performed. These areas include net positive suction head (NPSH) evaluation, selection of limiting pipe breaks, debris generation, debris transport, coating debris, latent debris, sump structure, downstream effects, chemical effects, structural analyses, and head loss testing.	**No response necessary – Introductory Material.**

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1	**Emergency Core Cooling System Sumps, Suppression Pools, Suction Strainers, and Debris Interceptors** The emergency core cooling system (ECCS) sumps or suppression pools, which are the source of water for functions such as ECCS and containment heat removal following a loss of coolant accident (LOCA), should contain an appropriate combination of the features and capabilities listed below to ensure the availability of the water sources for long-term cooling.	**No response necessary – Introductory Material.** The design features and capabilities that minimize the potential for loss of water sources for long-term cooling are presented below.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.1	A minimum of two independent ECCS suction strainers should be provided, each with sufficient capacity to accommodate the full plant debris loading while providing sufficient flow to one train of the ECCS and containment heat removal pumps. To the extent practical, the redundant suction strainers should be physically separated from each other by structural barriers to preclude damage resulting from a LOCA, such as whipping pipes or high-velocity jet impingement.	**Conformance.** Four separate, independent, and redundant trains of the safety injection system (SIS) and containment spray system (CSS) with two safety injection (SI) pumps and one containment spray (CS) pump in each division are provided. Within each division, the two SI trains (and each CS train) are separated by a quadrant wall to isolate the trains from each other to the maximum extent practical. Each of the four SI pumps has its own suction connection to the in-containment refueling water storage tank (IRWST), and each of two CS pumps shares one of these four connections. Four sumps are provided in the IRWST. Each IRWST sump contains paired CSS/SCS and SI suction pipes (two sumps: SI and CS pump suction pipes, two sumps: SI and SC pump suction pipes). Each pair of CSS/shutdown cooling system (SCS) and SI suction pipes ends in a suction sump, with each suction sump installed adjacent to an associated strainer (four total). Four strainers and sumps are located inside the IRWST isolated compartment, which protect high-energy piping systems in containment. The IRWST is inside the vertical concrete of the reactor containment buildings. The IRWST is toroidal and arranged continuously around the lower containment. The bottom of the IRWST is formed by the upper concrete of the internal structure. The top is formed by the concrete slab. This provides for an enclosed structure. The strainers are installed away from the spargers to minimize the effect of hydrodynamic loads induced by the discharge of water, air, and single- and two-phase steam due to the opening of the pressurizer pilot-operated safety relief valves (POSRVs) into the IRWST.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.2	The containment floor in the vicinity of floor-mounted ECCS strainers should slope gradually downward away from the strainers to retard floor debris transport and reduce the fraction of debris that might reach the suction strainer. Similar floor sloping should be used in the vicinity of a sump pit if the ECCS strainers are installed in a pit configuration. Debris interceptors or curbs can also be used to retard debris transport.	**Not applicable** The APR1400 design does not require that the floor in the vicinity of the IRWST sumps be sloped away from the sump for the following reasons: The trench is provided upstream of the trash racks facing each opening in the shield wall to prevent high-density debris from being swept along the floor into the holdup volume tank (HVT). The vertical trash racks, located at the entrance to the HVT on El. 100′-0″, will intercept any debris entering the HVT. The IRWST, due to the location of the isolated compartment, is not subject to heavy debris loading. The IRWST sump strainers have a significant surface area and the effect of debris will be minimal. All these features, coupled with the very low flow velocities in the IRWST, will significantly reduce the amount of debris that might reach the strainer.
1.1.1.3	The inlet of pumps required for long-term cooling should be protected by a suction strainer placed upstream of the pumps to prevent the ingestion of debris that may damage components or block restrictions in the systems served by the pumps.	**Conformance.** Each IRWST sump contains paired CSS/SCS and SI suction pipes (two sumps: SI and CS pump suction pipes, two sumps: SI and SC pump suction pipes). Each pair of CSS/SCS and SI suction pipes ends in a suction sump, with each suction sump installed adjacent to an associated strainer (total four strainers). The strainers in the IRWST filter the finer debris (typically down to 2.34 mm (0.094 in) that is passed through the HVT trash rack plus any debris left in the IRWST from maintenance operations. This provides more area to stop debris while allowing more than adequate flow for the safety system.

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.4	All drains from the upper regions of the containment should terminate in such a manner that direct streams of water will not directly impinge on, or discharge in close proximity to, the ECCS strainers. Streams of drainage from upper containment may contain entrained debris and could also result in air ingestion and other issues if they directly impinge on the strainers. The drains, drain piping internal clearances, and other pathways that connect containment compartments with potential break locations to the sump or suppression pool should be designed to ensure that they would not become blocked by the debris; this will ensure that water needed for an adequate NPSH margin could not be held up or diverted from the pool.	**Conformance.** The IRWST sumps are located inside the IRWST compartment where drains do not directly impinge on them. The drain piping empties into the containment drain sump. There are no drains or narrow pathways directly to the IRWST. Floor drain piping that collects in the containment sump, such as the compartment floor and operating floor, is assumed to become blocked. CS water is drained to lower containment levels by stairway openings, equipment hatch, or compartment access openings. These openings are not considered to be narrow pathways vulnerable to blockage. Since the floor drains are assumed to be blocked, an amount of CS water is assumed to collect and remain on various containment levels. The heights of the water remaining on the containment floors are assumed to be 5.08 cm (2 in) on the floors above El. 114′-0″, 30.48 cm (12 in) on the refueling cavity, 11.11 cm (4.375 in) in the annulus area, and 31.32 cm (12.332 in) in the secondary shield wall on the El. 100′-0″ floor. This amount of remaining water is factored into the return water holdup volume in the calculation of IRWST water levels.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.5	Trash racks, suction strainers, and debris interceptors should be capable of withstanding the loads imposed by expanding jets, missiles, the accumulation of debris, and pressure differentials caused by post-LOCA blockage under design-basis or realistic flow conditions, whichever causes the greater loads. When evaluating the impacts from potential expanding jets and missiles, licensees should justify credit for any protection offered by surrounding structures or credit for remoteness of trash racks and strainers from potential high-energy sources.	**Conformance.** A vertical trash rack is located at each entrance to the HVT. Two trash racks are located in the side wall of the HVT within the secondary shield wall. Two trash racks are located facing the opening in the secondary shell wall from the annulus. The trash racks are designed to seismic Category I and provide distance for protection from jet impingement and missiles. The strainers and sumps are located inside the IRWST compartment. The IRWST is protected by concrete walls and structures, so the strainer will not be exposed to missiles. Strainers are designed to seismic Category I. The structural analysis of the strainer includes static loads imposed by maximum flow with the debris in place and hydrodynamic loads from a seismic event.
1.1.1.6	ECCS strainers, trash racks, and debris interceptors should be designed to withstand the inertial and hydrodynamic effects caused by the vibratory motion of a safe-shutdown earthquake following a LOCA without loss of structural integrity.	**Conformance.** The strainer design basis includes seismic and hydrodynamic loads caused by design basis safe shutdown earthquake (SSE).
1.1.1.7	Licensees should select materials for debris interceptors, trash racks, and suction strainers that do not degrade during periods of inactivity or operation and that have a low sensitivity to stress-assisted corrosion or general corrosion that may be induced by chemically reactive spray or by the containment or suppression pool liquid during a LOCA.	**Conformance.** The strainers are made of stainless steel materials that resist degradation during inactive periods and resist degradation in the chemically reactive post-LOCA environment.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.8	Licensees should choose a suction strainer design (i.e., size and shape) that will prevent unacceptable loss of NPSH margin from debris accumulation during the period that the ECCS and CSS are required to operate in order to maintain long-term cooling or to maximize the time before the loss of NPSH caused by debris blockage when used with an active mitigation system (see Section C.1.1.4).	**Conformance.** The IRWST sump strainers are designed so that NPSH is not lost even with maximum debris loading due to their large surface area, which provides ample filtration area. An active strainer blockage mitigation system is not applicable to the APR1400.
1.1.1.9	Licensees should assess the possibility of debris clogging narrow flow passages downstream of the ECCS strainer to ensure adequate long-term recirculation cooling, containment cooling, and containment pressure control capabilities. The size of the openings in the strainer should be determined by considering the flow restrictions of systems served by the containment pool. Licensees should consider the potential for long, thin slivers passing axially through the suction strainer and then reorienting and clogging at any flow restriction downstream.	**Conformance.** The debris strainers are made of stainless steel and could use perforated plate with a 2.38 mm (0.094 in) diameter hole. The APR1400 design has been evaluated for strainer downstream effects. All downstream components are capable of fulfilling their design basis functions for the required duration the post-LOCA.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.10	Licensees should consider the buildup of debris and chemical reaction products at downstream locations, including containment spray nozzle openings, HPSI throttle valves, coolant channel openings in the core fuel assemblies, fuel assembly inlet debris screens, ECCS pump seals, bearings, and impeller running clearances. The design of the ECCS pumps is a large factor in determining the sensitivity of the pump operability to ingestion of debris. Three aspects of pump operability— hydraulic performance, mechanical shaft seal assembly performance, and pump mechanical performance (vibration)—must be considered when evaluating the ECCS pumps for operation with debris-laden water. Westinghouse Commercial Atomic Power (WCAP)-16406-P-A, “Evaluation of Downstream Sump Debris Effects in Support of GSI-191” 5 (Reference 21), and its SE (Reference 22) provide evaluation methods and criteria that the NRC considers acceptable. If wear or internal blockage evaluations indicate that a component may not be able to accomplish its design function throughout its mission time and that it is not practical to install a suction strainer with openings small enough to filter out debris that cause excessive damage to ECCS pump seals or bearings, the NRC expects licensees to modify the ECCS pumps or procure new ECCS pumps that can operate long term under the postulated conditions. WCAP-16793-NP, Revision 2, “Evaluation of Long-Term Cooling Considering Particulate, Fibrous, and Chemical Debris in the Recirculating Fluid,” issued October 2011 (Reference 23), discusses a method for use in evaluating the downstream impact of debris on the fuel assemblies,	**Conformance.** The WCAP-16406-P methodology and its associated acceptance criteria were used to evaluate APR1400 downstream ECCS and CSS components. The effects of debris ingested through the containment sump strainer during the recirculation mode of the ECCS and CSS include erosive wear, abrasion, and potential blockage of flow paths. The smallest clearance found for heat exchangers, orifices, and spray nozzles in the recirculation flow path is 9.271 mm (0.365 in) for orifices on the SI pump discharge flow path; therefore, no blockage of the ECCS flow path is expected with an IRWST sump strainer with a hole size of 2.38 mm (0.094 in). The instrumentation tubing is also evaluated for potential blockage of the sensing lines. The transverse velocity past this tubing is sufficient to prevent debris settlement into these lines, so no blockage will occur. The heat exchangers, orifices, and spray nozzles were evaluated for the effects of erosive wear over the mission time of 30 days. The erosive wear on these components is determined to be insufficient to affect system performance. For pumps, the effect of debris ingestion through the IRWST sump strainer on three aspects of operability, including hydraulic performance, mechanical shaft seal assembly performance, and mechanical performance (vibration) of the pump, were evaluated. The hydraulic and mechanical performance of the pump was determined to be unaffected by the recirculating debris.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.10 (cont.)	as discussed further in Section C.1.3.8.b of this guide. (At the time this guide was revised, the NRC staff had not yet completed its review of WCAP-16793-NP). WCAP-16530-NP-A, “Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids To Support GSI- 191,” issued March 2008 (Reference 24), provides a general approach to conducting chemical effects evaluations, as discussed in Section C.1.3.10 of this guide.	A LOCADM calculation is performed to assess the in-vessel downstream effect on the APR1400, applying the evaluation methods and acceptance bases provided in WCAP-16793-NP, Revision 2. An analysis was performed to determine the type and quantity of chemical precipitates that may form in the post-LOCA recirculation fluid for the APR1400 design. The analysis evaluated these post-LOCA chemical effects using the methodology developed in WCAP-16530-NP-A.
1.1.1.11	ECCS strainers and suction inlets for pumps required for long-term ECCS, CSS, or suppression pool cooling functions should be designed to prevent degradation of pump performance through air ingestion, flashing, and other adverse hydraulic effects (e.g., circulatory flow patterns, high-intake head losses, gas void intrusion).	**Conformance.** During a LOCA, the minimum depth of water in the IRWST is1.52 m (5 ft). At that minimum depth, the top of each strainer is submerged 0.61 m (2 ft) below the surface of the IRWST water. The minimum water level is sufficient to preclude adverse hydraulic effects (e.g., vortex formation and high suction head loss). A low approach velocity at the strainer surface also mitigates the risk of a vortex.
1.1.1.12	Advanced strainer designs have demonstrated capabilities that are not provided by simple flat plate or basket type strainers or screens. The performance characteristics and effectiveness of such designs should be supported by appropriate test data for any particular intended application.	**Conformance.** Advanced strainer designs have demonstrated capabilities that are not provided by simple flat plate or basket type strainers or screens. The performance characteristics and effectiveness of such designs should be supported by appropriate test data for any particular intended application. Under the APR1400 design attributes, the IRWST sump strainers are verified by testing for head loss or chemical effects.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.1.13	Prototypical head loss testing should be done to verify suction strainer designs. Section C.1.3.12 provides guidance on prototypical head loss testing.	**Not applicable.** Prototypical head loss testing is done to verify suction strainer designs. Section C.1.3.12 provides guidance on prototypical head loss testing.
1.1.2	**Minimizing Debris** The debris and chemical reaction products (see Sections C.1.3.3 and C.1.3.10) that could accumulate on the suction strainer should be minimized.	The design features and capabilities employed to minimize debris are presented below.
1.1.2.1	Licensees should maintain debris source terms to less than the amount assumed in the strainer performance analysis. For example, cleanliness programs should ensure that the assumed latent debris and suppression pool sludge loading is not exceeded, and controls should be maintained to ensure that problematic debris (e.g., insulations, signage, coatings, foreign materials, and chemically reactive materials) are not introduced into containment to an extent that would exceed the analytically assumed values. In addition, permanent plant changes inside containment should be programmatically controlled so as to not change the analytical assumptions and numerical inputs of the licensee analyses.	**To be addressed by the combined license (COL) applicant.** Performance of the strainers is enhanced by cleanliness programs that limit debris in the containment. A COL applicant that references the APR1400 design certification is to describe the containment cleanliness program that limits debris in containment.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.2.2	When latent debris is a significant source of debris (i.e., latent debris contributes more than a minimal amount to strainer head loss) that can affect strainer performance or create downstream effects, periodic containment surveys or sampling should be performed to verify that the amount of latent debris is within the assumed limits. Such periodic monitoring may not be necessary if the latent debris evaluation incorporates sufficient conservatism to account for the substantial uncertainties associated with latent debris sampling (See section 1.3.6 for more information regarding latent debris).	**To be addressed by the COL applicant.** As noted in Item 1.1.2.1, this is to be developed by the COL applicant. The program will be established for control a permanent and temporary modifications to ensure that potential quantities of post-accident debris are maintained within the bounds of the analyses and design bases that support ECC and CS recirculation functions and ensure the long term core cooling requirements of 10 CRF 50.46. The program will also be established for control the foreign material exclusion to limit the introduction of foreign material and debris sources into containment.
1.1.2.3	Licensees should adequately assess any new or unanalyzed potential debris sources (e.g., fiber and coatings) resulting from future equipment modifications inside containment against assumptions of debris quantities and types inside containment, as specified in the post-accident sump/pool analysis. Additionally, licensees should assess tags and labels, which can fail and be transported to the strainer, and determine a sacrificial strainer area to account for the strainer area that could become fully blocked by these transportable tags, labels, and other miscellaneous debris.	**To be addressed by the COL applicant.** The APR1400 does not define specific type of materials for miscellaneous debris, such as tapes, tags or stickers, because these are controlled by foreign material control program established by plant owner. To deal with this uncertainty, a 9.29 m^2 (100 ft^2) penalty of sacrificial strainer surface area per sump is applied as a margin for future detail design and installation of the APR1400.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.2.4	Licensees should consider using insulation types (e.g., reflective metallic insulation) that transport less readily and cause less severe head losses once deposited onto the strainer in place of insulation types (e.g., fibrous and microporous) that can become debris which can more readily transport to the strainer and cause higher head losses. If insulation is replaced or otherwise removed during maintenance, abatement procedures should be established to avoid generating latent debris in the containment.	**Not applicable.** (This item applies to potential insulation replacement after the plant is licensed and is operating) The APR1400 design uses reflective metal insulation (RMI) for piping and components inside containment. Use of fibrous or particulate insulation could adversely affect sump strainer performance and is limited to the greatest extent practicable. Programmatic controls will be in place to verify containment cleanliness and provide reasonable assurance that no problematic material is present in the containment.
1.1.2.5	To minimize potential debris caused by the chemical reaction of the pool water with metals in the containment, licensees should reduce as much as practical the exposure of bare metal surfaces (e.g., aluminum and uncoated carbon steel) to containment cooling water through spray impingement or immersion either by removal or by chemical-resistant protection (e.g., qualified coatings or jacketing).	**Conformance.** Trisodium phosphate (TSP) is used as a buffering agent, and the use of the aluminum is minimized to preclude adverse chemical effects. As part of the evaluation of IRWST strainer performance for the APR1400, a chemical effects evaluation was conducted to identify specific compounds and quantities of materials that may precipitate within IRWST sump following a LOCA. An analysis was performed to determine the type and quantity of chemical precipitates that may form in the post-LOCA recirculation fluid for the APR1400 design. The analysis evaluated these post-LOCA chemical effects using the methodology developed in WCAP-16530-NP-A.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.3	**Instrumentation and Operator Actions** If a licensee relies on operator actions to mitigate the consequences of the accumulation of debris on the ECCS suction strainer, it should ensure that safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps is available in the control room. If a licensee relies on operator actions to prevent the accumulation of debris on ECCS suction strainers or to mitigate the consequences of the accumulation of debris on the ECCS strainers, it should evaluate whether the operator has adequate indications, training, time, procedural guidance, and system capabilities to perform the necessary actions.	**Not applicable.** The APR1400 does not rely on operator action as the primary mitigation strategy. CS pump and SI pump operating information is available in the main control room (MCR) to assist in an NPSH evaluation, which includes flow, suction, and discharge pressure.
1.1.4	**Active Systems** An active device or system may be provided to prevent excessive accumulation of debris on the ECCS strainers or to mitigate the consequences of debris accumulation on the strainers. An active system should be able to prevent the accumulation and entry into the system of debris that may block restrictions found in the systems served by the ECCS pumps. The operation of the active component or system should not adversely affect the operation of other ECCS components or systems. In some operational modes, an active system may allow more debris to pass through the strainer. If this is the case, then the downstream effects analysis should be performed accordingly. Performance characteristics of an active system should be supported by appropriate test data that address head loss performance. Active systems should meet the requirements for redundancy for active components.	**Not applicable.** An active strainer blockage mitigation system is not applicable to the APR1400.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.1.5	**Inspection** To ensure the operability and structural integrity of the ECCS strainers and associated structures, access openings may be necessary to permit inspection of the ECCS strainers and associated structures, sump pits, and pump suction piping inlets. On a regular basis, licensees should inspect (including visual examination) strainers, trash racks, vortex suppressors, and pump suction piping inlets for evidence of structural degradation, potential for debris bypass, and presence of corrosion or debris blockage. The licensee should conduct similar inspections for drainage flowpaths (e.g., refueling cavity drains, floor drains), debris interceptors, trash racks, and other design features upstream of the ECCS strainers that are credited in the strainer performance analysis. Inspection of the ECCS strainer, associated structures, and upstream components is best conducted late in a refueling outage to ensure the absence of debris generated by construction or maintenance in the vicinity of the ECCS strainers and upstream design features.	**Conformance.** Personnel hatches are provided on top of the IRWST for access to the IRWST and strainers include openings to allow inspection, so that structural integrity can be confirmed. Access into the sump allows inspection of piping ends and evidence of structural distress or abnormal corrosion of strainers can be detected. The sump and strainer are inspected as part of the containment closeout process to minimize the potential for operation with an unacceptable configuration. In-service inspection of strainers is addressed in the Technical Specification surveillance 3.5.2.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.2	**Evaluation of Alternative Water Sources** Licensees should establish emergency operating procedures to use alternative water sources, either safety-related or non-safety-related, that will be activated if unacceptable head loss renders the ECCS strainers inoperable. For some plant designs, the use of alternative water sources may involve replenishing the inventory of the water storage tank that served as the source of inventory for core cooling during the injection phase of the LOCA. In this case, if the flow rate of the makeup supply to the alternative water source is not larger than the core boiloff rate, procedures should direct replenishment of the water storage tank with alternative water sources following the switchover to recirculation. This flowpath should have a sufficient flow rate to ensure that an adequate water supply will be available in the water storage tank if excessive debris blockage subsequently renders the ECCS strainers inoperable. Licensees should periodically inspect and maintain the valves needed to align the ECCS, CSS, and suppression pool cooling pumps from the recirculation water source to an alternative water source. The impact of adding water volume to containment should be evaluated, if this step is to be used.	**Not applicable.** The APR1400 design does not require an alternate source of water. As described in Item 1.1.3, operator actions are not relied upon to mitigate the consequences of debris accumulation. The strainer is adequately sized to provide reasonable assurance that the available NPSH is sufficient.

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3	**Evaluation of Long-Term Recirculation Capability** a. To demonstrate that a combination of design features and operator actions are adequate to ensure long-term cooling and that the criteria of 10 CFR 50.46(b)(5) will be met following a LOCA, licensees should evaluate the long-term recirculation capability. The techniques, assumptions, and guidance described below should be used in a plant-specific evaluation to ensure that any implementation of a combination of the features and capabilities listed in Section C.1.1 are adequate to ensure the availability of a reliable water source for long-term recirculation following a LOCA. These assumptions and guidance can also be used to develop conditions for the suction strainer testing.	**Conformance.**

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3 (cont.)	b. Licensees should evaluate (1) ECCS strainer hydraulic performance (e.g., geometric effects, air ingestion, flashing, gas void accumulation), (2) debris effects (e.g., break selection, debris generation, debris transport, latent debris, chemical precipitation, upstream, downstream, interceptor blockage, strainer head loss, and structural integrity), and (3) the combined impact on NPSH available at the pump inlet to confirm and ensure that long-term recirculation cooling can be accomplished following a LOCA. Such an evaluation should demonstrate adequate strainer and pumping performance (e.g., adequate pump NPSH margins, adequate strainer structural strength, and no excessive air ingestion). Licensees should also assess the susceptibility to debris blockage of the containment drainage flowpaths to the recirculation sump or suppression pool. A holdup of water to the pool could affect the NPSH available, flashing and/or air ingestion evaluations. In addition, licensees should assess the structural adequacy of any interceptors or trash racks used to prevent debris blockage of these flowpaths to protect against a reduction in available NPSH if substantial amounts of water are held up or diverted away from the sump or suppression pool. A susceptibility assessment should also be made of the flowpaths and components downstream of the strainers to failure from debris blockage, particulate ingestion, and abrasive effects to protect against long-term degradation.	As part of the GSI resolution for the APR1400 design, IRWST sump performance was evaluated in accordance with NRC RG 1.82 requirements. Vortexing, air injection, flashing, and deaeration were assessed to address adverse hydraulic effects. The break selection, debris generation, and debris transport were analyzed to identify the potential debris that may reach the strainers in the IRWST assuming a number of conservative considerations. The characteristics of potential debris are set, identified, and referred appropriately, and used in the NPSH evaluation of SI, CS, and SC pumps, as well as in the design values for purchase specification of IRWST sump strainers. The upstream effect used to identify the flowpaths that could result in blocking the return water, which could challenge the IRWST minimum water level evaluation, was evaluated and the downstream effects of debris flow through the strainers were also evaluated. As a result of the evaluation, it was verified that the APR1400 design does not challenge long-term recirculation capability in the event of a postulated LOCA.

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.1.1	The design of the emergency core cooling and containment heat removal systems should ensure that sufficient available NPSH is provided to the system pumps, assuming the maximum expected temperature of the pumped fluid and no increase in containment pressure from that present before the postulated LOCA. a. It is conservative to assume that the containment pressure equals the vapor pressure of the pool water. This ensures that credit is not taken for containment pressurization during the transient. b. For PWR subatmospheric containments, this guidance should apply after termination of the injection phase. For these subatmospheric containments, before termination of the injection phase, NPSH analyses should include conservative predictions of the containment atmospheric pressure and sump water temperature as a function of time.	**Conformance with exception.** The APR1400 design does not fully conform to Section 1.3.1.1. Credit was taken for containment accident pressure in determining available NPSH of SI pumps and SC/CS pumps of the APR1400. The containment pressure is assumed to be equal to the initial containment pressure prior to the start of the accident. This fulfills the requirements of RG 1.1 and RG 1.82 that the NPSH available is evaluated without crediting any increase in pressure resulting from accident conditions at low temperatures less than 100 °C (212 ºF). This approach verifies that sufficient containment pressure is available under accident conditions. For temperatures higher than the initial saturation pressure, containment pressure was assumed to be equal to the sump fluid vapor pressure. The NPSH margin calculation was conducted to verify that NPSH available margin exists.
1.3.1.2	For certain operating reactors in which it is not practicable to alter the design, conformance with Section C 1.3.1.1 may not be possible. In these cases, the determination of available NPSH should not include containment pressure above that which is necessary to preclude pump cavitation. The calculation of available containment pressure and sump/pool water temperature as a function of time should underestimate the expected containment pressures and overestimate the sump/pool water temperatures when determining available NPSH for this situation.	**Not applicable.** As described in Item 1.3.1.1, credit was taken for containment accident pressure in determining available NPSH.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.1.3	If credit is taken for operation of an ECCS or containment heat removal pump in cavitation, licensees should conduct prototypical pump tests along with a posttest examination of the pump to demonstrate that pump performance will not be degraded and that the pump continues to meet all of the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time period for which the performance tests demonstrate that the pump meets the performance criteria.	**Not applicable.** As described in Item 1.3.1.1, the SI pumps and SC/CS pumps are designed with sufficient NPSH margin to preclude pump cavitation.
1.3.1.4	Because high water temperatures reduce available NPSH and can affect the potential for flashing and impacts fluid properties, such as density and viscosity, the determination of the water temperature should include the decay and residual heat produced following accident initiation. This calculation should include the uncertainty in the determination of the decay heat (uncertainty in decay heat is typically included at the 2-sigma level). The licensee should calculate the residual heat with margin.	**Conformance.** The containment post-LOCA pressure and IRWST temperature profiles were used in NPSH calculation. The calculation for IRWST water temperature includes decay heat with margin and all residual heat sources.
1.3.1.5	The correction factor for pumping high-temperature fluid discussed in ANSI/HI 1.3-2009 (Reference 5) to determine the margin between the available and required NPSH for the ECCS and the containment heat removal systems should not be used.	**Conformance.** The assessment of available NPSH for the SI pumps and CS pumps of the APR1400 conservatively does not use the hot fluid correction factor specified in ANSI/HI 1.3-2009 to allow for reduction in NPSH required.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.1.6	The calculation of available NPSH should take into account the minimum calculated height of water above the pump suction and strainer surfaces. The calculated height of water should not consider quantities of water that do not contribute to the sump or suppression pool (e.g., atmospheric steam, pooled water on floors and in refueling canals, spray droplets and other falling water, holdup in containment coolers, water held up by upstream obstructions, and the volume of empty system piping). Licensees should not credit non-leaktight structures, such as ducting for heating, ventilation, and air conditioning, for the displacement of water for the purposes of determining the minimum water level. The calculated height of water available should not include the amount of water in enclosed areas that cannot readily be returned to the sump or suppression pool. Minimum water level calculations should consider worst-case break locations (e.g., breaks at high elevations) that could lead to a minimum quantity of reactor coolant reaching the sump or suppression pool. Licensees should consider volume shrinkage of the reactor coolant inventory as it cools in terms of crediting the contribution of spilled coolant to the sump or suppression pool and in terms of the volume reduction of the coolant remaining in the primary system that will allow the ECCS to inject additional inventory into the primary system before filling it. Licensees should explicitly consider the limiting small-break LOCA water level because elevated break locations may be possible and certain sources of inventory (e.g., PWR accumulators) may not inject.	**Conformance.** The minimum water level in the IRWST during post-LOCA is 26.2 m (86.0 ft) (1.52 m (5 ft) above the IRWST bottom floor at elevation 81′-0″). The minimum post-LOCA water level in the IRWST was used in evaluation of available NPSH for SI pumps and SC/CS pump. The evaluation of minimum water level includes identifying the holdup volumes, such as water volume lost to the containment atmosphere and on containment wall surfaces, piping fill volume, flooded volume of all compartments in the containment at an elevation lower than the main spillways, spray volume, and other water volumes that could affect the flood height.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.1.7	Licensees should calculate the pipe and fitting resistance and the nominal strainer resistance without blockage by debris in a recognized, defensible method or determine it from applicable experimental data. The clean strainer head loss (i.e., the friction head loss caused by the passage of flow through the strainer and any associated connecting pipes and plenums) calculations should consider the distribution of flow through the strainer that produces the highest head loss. For some curvilinear-type strainer designs, this occurs with a filtering debris bed near the strainer outlet and a clean strainer where the unobstructed flowpath is longer. If the strainer were partially covered with a filtering debris bed, much of the strainer flow could occur through the unblocked strainer surfaces, which could be more limiting for some designs.	**Conformance.** The calculation of hydraulic resistance of piping, fittings, and valves was performed using a conservative value from Crane Technical Paper 410. The clean strainer head loss was performed using widely recognized and approved industry standards.
1.3.1.8	Licensees should use Sections C 1.3.10 and C 1.3.11 to determine strainer head loss caused by blockage from LOCA-generated debris and its chemical reaction products or from foreign material in the containment that is transported to the suction intake screens.	**Conformance.** The strainer head loss use a conservative of 0.61 m-water (2 ft-water) over the temperature of interest. The actual debris head loss is evaluated by qualified test results conducted specific to the APR1400 plant conditions. Based on the results of strainer testing, the maximum head loss for the 46.45 m^2 (500 ft^2) effective strainer area with the maximum debris load is 24.69 cm-water (0.81 ft-water) at the design flow rate and includes a clean screen component of 15.85 cm-water (0.52 ft-water). The strainer testing head loss of approximately 41% of the design strainer head loss of 60.96 cm-water (2.0 ft-water) ensures adequate NPSH margin for the ECCS pumps.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.1.9	Licensees should calculate available NPSH as a function of time until it is clear that the available NPSH will not decrease further.	**Conformance.** The NPSH margin calculation as a function of time was performed to provide reasonable assurance that NPSH available margin exists.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.2	**Pipe Break Characterization** a. A sufficient number of high-energy pipe break locations resulting in ECCS recirculation should be considered to reasonably bound variations in debris generation by the size, quantity, and type of debris. The objective of the break selection process is to identify the break location and size that results in debris generation that produces the maximum head loss across the sump screen. Licensees should consider all aspects of the accident scenario for each postulated break location, including debris generation, debris transport, latent debris, coating debris, chemical effects, upstream and downstream effects of debris accumulation, and sump screen head loss. b. The objective of strainer head loss testing is to simulate the debris from the break location that transports the maximum amount of debris to the sump strainer or the combination of debris types that produces the maximum head loss. At a minimum, licensees should consider the postulated break locations and pipe break characteristics described in the following sections. c. Section 3.3.3 to 3.3.5 of NEI 04-07 (Reference 26) and the associated SE (Reference 27) and Section 3.2.1.1 of Reference 15 provide additional guidance in break selection	**Conformance.** The methodology described in NEI 04-07 and the NRC Safety Evaluation Report (SER) for NEI 04-07 was used to assess pipe break characterization. The following general break locations are considered: • Break Type No. 1: Break in the reactor coolant system (RCS) with the largest potential for debris • Break Type No. 2: Largest break with two or more different types of debris • Break Type No. 3: Break in the most direct path to the sump • Break Type No. 4 : Large break with the largest potential particulate debris to insulation ratio by weight • Break Type No. 5 : Break that generates “thin bed”-high particulate with low fiber The debris generated by the most limiting cases in Break No. 1 bounds Break Nos. 2 and 4 because the only type of insulation used for the piping and equipment in containment is RMI. There are no breaks of a high-energy line within the IRWST, and Break No. 3 is not evaluated. Therefore, Break Nos. 1 and 5 are applicable. The junction of the RCS hot leg pipe (106.7 cm (42 in)) and the steam generator was selected as the postulated limiting break

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.2 (cont.)		location. Destruction of insulation and coatings conservatively used a zone of influence (ZOI) from a 106.7 cm (42 in) hot leg break. As noted in Item 1.3.2.2, the D-ring with the largest debris generation source is used. Further evaluation is addressed in the sump design technical report.
1.3.2.1	Licensees should consider breaks where debris is most easily transported to the suction strainer (e.g., breaks in areas with the most direct path to the sump strainer or suppression pool).	**Conformance.** See response to Item 1.3.2.
1.3.2.2	Licensees should consider a spectrum of breaks, including the breaks with the largest quantity and greatest variety of debris within the expected zone of influence (ZOI).	**Conformance.** See response to Item 1.3.2
1.3.2.3	Licensees should consider medium and large breaks that have the greatest potential ratio of particulate to fibrous insulation debris by weight and breaks that generate an amount of fibrous debris that, after its transport to the strainer, could form a thin layer that could subsequently filter sufficient particulate debris to create a relatively high head loss (called the “thin-bed effect”). A “thin bed” is a relatively thin layer of debris on a screen or strainer that causes a large flow resistance and, consequently, a large pressure drop for flowing liquid.	**Conformance.** The performance of the IRWST sump strainers is based upon strainer validation testing. Four types of debris were used in the test. Aged Nukon fiberglass prepared as fines to simulate latent fiber, silicon carbide to simulate epoxy paint, sand mixture to simulate latent particulate, and aluminum oxy-hydroxide to simulate chemical debris The IRWST sump strainer testing has shown a thin bed developed on the strainer.
1.3.2.4	Licensees should disregard break exclusion zones in their evaluations (i.e., pipe breaks must be postulated in break exclusion zones).	**Conformance.** The break exclusion zone was not considered in the APR1400 design in accordance with the general guidance of NEI 04-07.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.2.5	Licensees should exclude NRC Branch Technical Position (BTP) 3-4, “Postulated Rupture Locations in Fluid System Piping inside and outside Containment” (Reference 25), as a basis for selecting break locations because limiting conditions for ECCS strainer performance are not related to the pipe vulnerability issues addressed in BTP 3-4.	**Conformance.** The APR1400 design did not use BTP 3-4 as a basis for determining potential break location.
1.3.2.6	Licensees should consider locations that result in a unique debris source term (i.e., not multiple, identical locations). Particular consideration should be given to breaks that result in the destruction of materials known to cause high head loss, such as microporous insulation (e.g., calcium silicate, Min-K, and Microtherm).	**Not applicable.** The APR1400 design does not use microporous insulation in the containment.
1.3.2.7	If the LOCA blowdown does not generate a significant amount of fibrous debris, the contribution of latent debris sources may become the limiting factor in ECCS strainer and downstream evaluations.	**Not applicable.** No fibrous debris is generated by LOCA blowdown in the APR1400 design because RMI, which contains no fibrous material, is used on components that may be subjected to jet impingement loads from a LOCA jet. **Conformance.** The APR 1400 design is used 90.72 kg (200 pounds) of latent debris in the evaluation of debris generation and 92.5% of the latent debris is considered particulate, and 7.5% is considered fibrous. These values are used for the evaluation of sump strainer performance.
1.3.2.8	If long-term cooling requires recirculation flow through the ECCS strainer for non-LOCA HELBs (e.g., main steam break, feedwater line break), then licensees should use the same selection criteria for break locations as those specified for a LOCA.	**Conformance.** Main steam line break was used as the non-LOCA event in the APR1400 evaluation of debris generation.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.3	**Debris Generation/Zone of Influence** The initial pressure wave and erosion associated with the jet impingement can generate debris from the blowdown of a ruptured pipe. Insulation, coatings, fire barriers, shielding blankets, and other materials that are located within a material-dependent range of distances from the pipe rupture location can become debris as the result of the LOCA blowdown. The volume of space affected by this impact, or ZOI, is modeled to define and characterize the debris generated.	**Informational Material.**
1.3.3.1	**Zone of Influence Model** a. The size and shape of the ZOI should be consistent with experiments performed for specific debris sources (e.g., insulation, coatings, fire barrier materials). The ZOI should extend until the pressure wave impulse and jet pressures decrease below the experimentally determined damage pressures appropriate for the debris source.	**Conformance.** The method described in NEI 04-07 and the NRC SER for NEI 04-07 is used for determining the ZOI in assessing debris generation for the APR1400.
	b. Licensees should use the volume of material contained within the ZOI to estimate the amount of debris generated by a postulated break. The size distribution of debris created in the ZOI should be determined from applicable experiments. It is noted that if robust barriers intersect the postulated jet zone, the extended volume may be truncated within the limitations of NEI 04-07, "PWR Sump Performance Evaluation Methodology," Section 3.4.2.3, and its associated SE (References 26 and 27).	**Conformance.** The debris size distribution for RMI debris used in the APR1400 debris generation evaluation is broken into two categories, 75% small fines and 25% large pieces, based on NEI 04-07 and the NRC SER for NEI 04-07. Small fines are defined as debris capable of passing through openings in gratings, trash racks, and radiological fences that are smaller than a nominal 101.6 mm (4 in). Thus, within small fines, there are fines and small pieces.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.3.1 (cont.)	c. Licensees should use the pressure wave impulse and jet impingement generated during the postulated pipe break as the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the ZOI.	**Conformance.** The APR1400 design uses the guidance provided in NEI 04-07 and the NRC SER for NEI 04-07 to determine the size or size distribution of debris generated within the ZOI.
	d. Licensees should perform debris generation testing to determine the ZOI in a manner that is prototypical of the plant condition. Test scaling is complicated because material destruction may result from both pressure waves and jet impingement. Scaling considerations for debris generation testing include the test fluid used (e.g., air or saturated water), the initial thermodynamic conditions of the test fluid, the rupture disk opening time, the blowdown period, the size and orientation of the test nozzle relative to the target, and the specific configuration of the target material to the various plant materials to which it is being applied (e.g., insulation jacketing seam, jacketing thickness, and banding and latching strength The staff has not developed specific guidance for the performance of ZOI testing. Methods and results are reviewed on a case-by-case basis. One example is the Air Jet Impact Tests documented in Section 3.2.1 of the NRC RG (Reference 15).	**Not Applicable.** The method described in the NEI 04-07 and NRC's SER for NEI 04-07 is utilized for determining the ZOI in assess debris generation of the APR1400.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.3.1 (cont.)	e. If the evaluation uses simplified ZOI models, such as the spherical ZOI models that are discussed in Section 3.2.1 of NEDO-32686-A (Reference 15) and Section 3.4.2 of NEI 04-07 (References 26 and 27), licensees should apply sufficient conservatism to account for simplifications and uncertainties in the model. For example, a spherical ZOI model assumes that the blowdown from a LOCA is evenly distributed in all directions radiating from the break location. Although, with sufficiently conservative inputs, a spherical model may be appropriate for estimating the loadings of debris within a ZOI, such a model does not account for non-uniform blowdown that could create damage in a particular direction at much greater distances from the break. Therefore, such a spherical model would likely be non-conservative when specifying an exclusion zone for particularly problematic materials (e.g., calcium silicate insulation for a PWR with a trisodium phosphate buffer, fibrous debris for a plant with a limited strainer area that intends to demonstrate that a fibrous debris bed cannot be formed).	**Not applicable.** As noted in Item 1.3.3.1, the APR1400 design use the spherical ZOI model described in the NEI 04-07 and NRC's SER for NEI 04-07. The APR1400 design has no problematic debris generated by LOCA blowdown.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.3.2	Certain types of material used in small quantities inside the containment can, with adequate justification, be demonstrated to make a marginal contribution to the debris loading for the ECCS sump. If debris generation and debris transport data have not been determined experimentally for such material, the material may be grouped with another material with similar physical and chemical characteristics existing in large quantities. For example, a small quantity of fibrous filtering material may be grouped with a substantially large quantity of fibrous insulation debris, and the debris generation and transport data for the filter material need not be determined experimentally. However, such analyses are valid only if the small quantity of material treated in this manner does not have a significant effect when combined with other materials (e.g., combining a small quantity of calcium silicate with fibrous debris may not be valid).	**Conformance.** The APR1400 uses the methodology outlined in the NEI 04-07 guidance report and it is associated with NRC SER to determine the debris loading that will result in the maximum head loss across the sump strainer. The APR1400 evaluation conservatively assumed that all latent debris will be transported to the sump strainer and RMI debris will not be transported to sump strainer. All particulate and coating debris is assumed to be fine debris and 100% transported to the sump strainer. The chemical debris that is generated during long-term recirculation is considered in the strainer head loss evaluation.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.3.3	All insulation (e.g., fibrous, calcium silicate, and reflective metallic); painted surfaces; fire barrier materials; and fibrous, cloth, plastic, or particulate materials within the ZOI should be considered as potential debris sources. Licensees should use applicable test data as the basis for predicting the size of the postulated debris. For breaks postulated in the vicinity of the containment penetrations, licensees should also consider the potential for debris generation from the packing materials used in the penetrations. In addition, licensees should consider breaks that could destroy the insulation installed on the pressure vessel. The potential for particulate debris to be generated by the action of pipe rupture jets stripping off paint or coatings and erosion of concrete at the point of impact should also be considered.	**Conformance.** All potential debris material within the ZOI that could adversely affect the operation of the ECCS and CSS following a LOCA is considered in the APR1400 debris generation evaluation.
1.3.3.4	In addition to debris generated by jet forces from the pipe rupture, the analyses should consider (1) debris existing before the pipe rupture that is transported to the suppression pool, (2) debris created by the reactor pressure vessel environment (i.e., thermal and chemical), (3) debris created by the atmospheric environment (i.e., thermal and chemical), and (4) debris created by the environment of the submerged containment or suppression pool, as appropriate. Examples of debris created by the environment include disbanded coatings in the form of chips and particulates or the formation of chemical products caused by chemical reactions in the containment pool or the suppression pool or the reactor vessel (see Sections C.1.3.5 and C.1.3.10).	**Conformance.** Debris created by the resulting reactor pressure vessel environment (thermal and chemical) is considered in the APR1400 debris generation evaluation. This type of debris includes disbandment of coating and formation of chemical debris (precipitants) caused by adverse chemical effects.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.3.5	The analyses should consider debris erosion that results from continued degradation of insulation and other debris when subjected to turbulence caused by cascading water flows from upper regions of the containment or that result from the flows in the sump or suppression pool or chemical decomposition. The determination of eroded quantities for various types of debris should be based on testing that is prototypical of plant conditions. In the absence of applicable testing, demonstrably conservative assumptions should be used. (For example, the SE for NEI 04- 07 Appendix III (Reference 27) recommends using a bounding value of 90% erosion for fibrous debris).	**Not applicable.** The APR1400 evaluation assumed that the post-LOCA 30-day erosion of fiber insulation debris in containment is no longer required to be considered because all the fiber debris is assumed to be fines. The effect of erosion during post-LOCA 30-day operation is not required to be considered for RMI debris characterization.
1.3.4	**Debris Transport** The debris transport evaluation determines the fraction of containment debris that is transported to the ECCS strainer.	**Informational Material.**

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.4.1	The calculation of debris quantities transported to the ECCS strainers should consider all modes of debris transport, including blowdown transport, spray transport, washdown transport, and transport within the containment pool. Consideration of containment pool debris transport should address (1) debris transport during the pool fill phase, as applicable, and during the recirculation phase, (2) the velocity and turbulence in the sump, suppression pool, or storage tank (i.e., turbulence caused by the flow of water to the ECCS strainers, water splashing down from the break, containment spray drainage, and the discharge of pressure-relief flowpaths such as from downcomers, vents, and safety/relief valve spargers), and (3) the density, characteristic size, and other properties of the debris. Section 3.2.3 of the SE for NEDO-32686-A, (Reference 15), and Section 3.6 of the SE for NEI-04-07 (Reference 27) discuss staff accepted methods to evaluate debris transport. NUREG/CR-6369 (Reference 28) is also a useful reference document for debris transport evaluations. Section 3.6.4 of NEI 04-07 (Reference 26) contains a sample calculation for debris transport that the staff finds acceptable.	**Conformance.** The evaluation of debris quantities transported from debris sources to the sump strainer is conservatively bounded by the assumption that all latent debris will be transported to the sump strainer and RMI debris will not be transported to sump strainer. All particulate and coating debris is assumed to be small fine debris and 100% transported to the sump strainer. The chemical debris that is generated during long-term recirculation is considered in the strainer head loss evaluation.
1.3.4.2	Transport analyses within the containment pool should include debris that may transport through the following modes: (1) floating along a water surface, including debris that may float temporarily because of air entrapment, (2) traveling with the containment flow (i.e., debris suspended within the flow) because of neutral buoyancy or turbulence (e.g., individual fibers and fine particulates), and (3) settling to the floor and tumbling along the floor to reach the strainer.	**Conformance.** See response to Item 1.3.4.1.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.4.3	The debris transport analyses should consider each type of insulation (e.g., fibrous, calcium silicate, and reflective metallic), other debris such as chemical precipitates, coatings, latent debris, and debris size (e.g., fine, readily suspendable, small, large, and intact). The analyses should also consider the potential for further decomposition of the debris as it is transported to the ECCS strainers.	**Conformance.** See response to Items 1.3.4.1 and 1.3.3.5.
1.3.4.4	An acceptable analytical approach to predict debris transport resulting from fluid flows caused by long-term recirculation or pool fill is to use appropriately verified computational fluid dynamics (CFD) simulations in combination with experimental debris transport data. The CDF simulations can be used to predict fluid flows, while debris transport thresholds can be determined experimentally. Section 4.2.4 of NEI 04-07 (Reference 26) and Section 4.2.4 and Appendix III in the associated SE (Reference 27) provide guidance and an example of this approach. Alternative methods for debris transport analyses are also acceptable, provided that they are supported by adequate validation of analytical techniques using experimental data to ensure that the debris transport estimates are conservative with respect to the quantities and types of debris transported to the strainer.	**Not applicable** Conservative assumptions regarding debris transport as provided in response to Item 1.3.4.1 are used in the APR1400; hence, use of CFD is unnecessary.

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1.3.4.5	The analysis may credit curbs for removing heavier debris that has been shown analytically or experimentally to travel by sliding along the containment floor and that cannot be lifted off the floor within the calculated water velocity range. Curbs around the ECCS strainers may reduce or prevent some types of debris from transporting to floor- or pit-mounted strainers during the pool fill phase (see NUREG/CR-6772 (Reference 13) for limitations).	**Not applicable.** Curbs are not considered in the APR1400 to maximize debris transport to the sump strainer.
1.3.4.6	If transported to the containment pool, all debris that would remain suspended because of turbulence (e.g., fine fibrous and particulates) should be considered to reach the ECCS strainers. However, if settlement of fine fibrous and particulate debris is credited during recirculation or pool fill, licensees should provide adequate theoretical and experimental basis to demonstrate that such settling is prototypical of plant conditions. This settlement analysis should include the potential for natural convection through the water column providing a motive force to keep the material in suspension.	**Not applicable.** Conservative assumptions regarding debris transport as provided in response to Item 1.3.4.1 are used for the APR1400.
1.3.4.7	In lieu of performing detailed blowdown and washdown debris transport analyses, licensees can conservatively assume that all debris entering or originating in the sump or suppression pool is transported to the ECCS strainers when estimating strainer debris bed head loss.	**Conformance.** See response to Item 1.3.4.

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1.3.4.8	The effects of floating or buoyant debris on the integrity of the ECCS strainers and on the strainer head loss should be considered during the initial filling of the sump (if applicable) and during recirculation. For strainers that are not fully submerged or are only shallowly submerged, floating debris could contribute to the debris bed head loss. Entrapped air may cause some types of debris to temporarily float; the debris may then be transported to the vicinity of the ECCS strainers by surface currents and then sink on top of the strainers. A design feature (e.g., use of trash racks and solid cover plate) that keeps floating debris from reaching the sump or suppression pool strainer could reduce head loss caused by floating or buoyant debris.	**Not applicable.** As noted in Item 1.1.1.11, the top of each strainer is submerged below the surface of the IRWST water. The strainers are always fully submerged for the post-LOCA, which minimizes the effects of floating or buoyant debris on the integrity of the sump strainer and on subsequent head loss.
1.3.4.9	**Use of Debris Interceptors** Credit for the performance of debris interceptors upstream of the ECCS strainers should be based on results of tests that are demonstrated to be either conservative or representative with respect to the plant condition. If the interceptors are credited with capturing fine debris to reduce the ECCS strainer debris load, licensees should perform time-dependent analyses and tests that consider the conditions that would lead to minimum debris capture fractions. This analysis also should include the potential of trapped debris further eroding into fines that could then pass through the interceptors. Iterative analyses of the flow in the sump or suppression pool (e.g., multiple computational fluid dynamics simulations that have been acceptably verified) may be necessary if the blockage of the interceptors has a significant impact on the containment pool flow pattern.	**Not applicable.** No debris interceptors are installed or credited in the APR1400.

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1.3.5	**Coating Debris** Coating debris is generated from the postulated failure (destruction) of both DBA-qualified and unqualified coatings within the ZOI and from the postulated failure of unqualified coatings outside the ZOI. NRC reports entitled, "NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Coatings Evaluation," issued March 2008 (Reference 29), and "Revised Guidance Regarding Coatings Zone of Influence For Review of Final Licensee Responses To Generic Letter 2004-02, 'Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents At Pressurized-Water Reactors,'" dated April 6, 2010 (Reference 30), provide a general approach to conducting plant-specific coatings evaluation.	**Informational Material.**
1.3.5.1	Licensees should use a ZOI for coatings that is determined by applicable testing and plant specific analysis. The fluid used for the test, i.e., steam, air, two-phase water, should be representative of the plant exposure conditions.	**Non Conformance.** A ZOI of 4D in the evaluation of the quantity of coating debris was used based on the NRC letter in 2010 (Reference [4] of Appendix B).
1.3.5.2	All (100 percent) unqualified coatings should be assumed to fail. However, licensees may also be able to demonstrate the performance of their unqualified coatings through plant-specific and coating-specific testing.	**Not applicable.** Unqualified coatings are not used in reactor containment in the APR1400. Hence, a coating-specific test is unnecessary.
1.3.5.3	Licensees should determine the debris characteristics (e.g., size, shape, density) of failed coatings separately for each coating within containment.	**Conformance.** Per Section 3.4.3.2 of NEI 04-07, all qualified coatings within the coating ZOI are assumed to fail and all qualified coatings located outside the coatings ZOI are considered not to fail. The size of coating debris is considered to be small fines.

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1.3.5.4	Licensees may determine coating chip debris transportability in flowing water by using the results in NUREG/CR-6916 (Reference 14) to the extent they apply to a licensee's plant-specific coating types.	**Not applicable.** As noted in Item 1.3.4.1, all particulate and coating debris is assumed to be small fine debris and 100% transported to the sump strainer.
1.3.6	**Latent Debris** a. Latent debris present in containment during operation may contribute significantly to head loss across the ECCS strainers. Licensees must determine the types, size, quantities, and locations of latent debris. NEI 04-07, and its associated SE (Reference 26 and 27), provide general considerations for latent debris in terms of its potential impact on strainer blockage and some plant-specific variables. In collecting latent debris samples for analysis, licensees should use a sampling technique with demonstrated collection efficiency for fine particulate and fibrous debris. NEI 02-01, "Condition Assessment Guidelines: Debris Sources inside PWR Containments," dated September 30, 2002 (Reference 31), provides an accepted approach for determining latent debris quantities.	**Conformance.** As noted in Item 1.3.2.7, 90.72 kg (200 lbm) of latent debris was used in the APR1400 debris generation evaluation. The 92.5% of the latent debris is considered particulate and 7.5% is considered fibrous.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.6 (cont.)	b. Applicants or licensees should not assume that their (existing) foreign material exclusion programs have entirely eliminated miscellaneous debris. Results from plant-specific walkdowns should be used to determine a realistic amount of latent debris in containment and to monitor cleanliness programs for consistency with committed estimates. Evaluation of the results of latent debris walkdowns should include sufficient conservatism to account for substantial uncertainties inherent in the debris sampling and collection process. In lieu of plant-specific walkdowns, 10 CFR Part 52 applicants may perform conservative analyses that are based on latent debris measurements made for operating plants.	**Conformance.** See responses to Items 1.1.2.1 and 1.1.2.2.
1.3.7	**Upstream Effects** a. Section 7.2 of the staff's SE on NEI 04-07 (Reference 27) provides guidance on evaluating the flowpaths upstream of the PWR containment sump for the holdup of inventory, which could limit flow to, and possibly starve, the suction strainer. A similar approach may be used for BWRs.	**Conformance.** The APR 1400 design is evaluated for upstream effects to assess the flowpaths upstream of the IRWST sump for holdup of inventory that could reduce flow to and possibly starve the sump.

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NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
1.3.7 (cont.)	b. Licensees should use the results of their debris assessments to estimate the potential for water inventory holdup. Based on these assessments and the mapping of probable flowpaths, licensees should determine whether trash racks or debris interceptors are necessary to protect flowpaths in upper containment to prevent the holdup of water upstream of the sump, storage tank, or suppression pool. Licensees should also evaluate the effect that the placement of curbs and debris interceptors may have on the holdup of water en route to the sump, storage tank, or suppression pool.	**Conformance.** See responses to Items 1.1.1.2, 1.3.4.5, and 1.3.4.9.
1.3.8	**Downstream Effects** a. Debris may be carried downstream of the ECCS strainer, thus causing downstream blockage or wear and abrasion. The three areas of concern identified are (1) blockage of system flowpaths at narrow flow passages (e.g., containment spray nozzles, some pump internal flow passages, and tight-clearance valves), (2) wear and abrasion of surfaces (e.g., pump running surfaces) and heat exchanger tubes and orifices, and (3) blockage of flowpaths through fuel assemblies.	**Conformance.** The APR1400 downstream effects evaluation of debris ingestion on the auxiliary equipment, including the pumps, heat exchangers, orifices, spray nozzles, and instrumentation tubing, follow the methodology in WCAP-16406-P-A.

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1.3.8 (cont.)	b. The quantity and size characteristics of this strainer bypass debris will be unique to each strainer vendor and plant-specific debris mixtures and should be determined during strainer head loss tests, as discussed in Section 1.3.12.g. WCAP-16406-P-A (Reference 21) provides a method that the NRC considers acceptable for PWR licensees to use in evaluating the downstream impact of sump debris on the performance of their ECCSs, CSSs, and components following a LOCA. The NRC has received WCAP-16793-NP (Reference 23) for review.7 This report provides a method and reference for PWR licensees whose plants are bounded by its input assumptions to use in evaluating the downstream impact of sump debris on the performance of fuel following a LOCA, subject to the conditions and limitations specified in the NRC SE to be prepared for WCAP-16793-NP, Revision 2. Neither of these reports applies to BWRs at this time.	**Informational Material.**
1.3.9	**Strainer Structural Analysis** This Regulatory Position also applies to trash racks and debris Interceptors, if used.	

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1.3.9.1	General items identified for consideration in the structural analyses should include (1) the verification of maximum differential pressure caused by the combined clean strainer and worst case debris scenario at rated flow rates or maximum realistic flow rates, whichever is greater, (2) geometry concerns (i.e., mesh and frame versus perforated plate), (3) ECCS strainer material selection for the post-accident environment (i.e., corrosion-resistant materials that can withstand the post-LOCA environment), and (4) the addition of hydrodynamic loads.	**Conformance.** The strainers are installed away from the spargers to minimize the effect of hydrodynamic loads induced by the discharge of water, air, and single- and two-phase steam due to the opening of the pressurizer POSRVs into the IRWST. Strainers are designed to seismic Category I and quality Class Q. The structural analysis of the strainer is performed to verify the structural adequacy of the sump strainer, including seismic, differential pressure, and hydrodynamic loads. The strainers are made of stainless steel materials that resist degradation during inactive periods and resist degradation in the chemically reactive post-LOCA environment.
1.3.9.2	Licensees should compute structural loads on a strainer using the maximum pressure drop across the strainer. Licensees should also evaluate the limiting conditions corresponding to the break location and debris source term that induce the maximum total head loss at the ECCS strainer.	**Conformance.** See response to Item 1.3.9.1.
1.3.9.3	For some licensees, the minimum structural design criterion for the ECCS strainer can depend on the plant's NPSH margin. Plant-specific licensing bases may dictate the structural capacity of the ECCS strainer for supporting water flow through a debris bed under recirculation velocities, depending on strainer geometry (i.e., fully submerged versus partially submerged or vented designs).	**Conformance.** See response to Item1.3.9.1.

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1.3.9.4	Load combinations (e.g., safe-shutdown earthquake, deadweight, crush pressure, thermal, and live loads) used for structural analysis should be performed in accordance with the specific plant licensing basis requirements and the applicable design code of record. Licensees should also reference Regulatory Guide 1.92, “Combining Modal Responses and Spatial Components in Seismic Response Analysis” (Reference 32), when analyzing the seismic loading conditions during the structural analyses of the strainers.	**Conformance.** The sump strainers are safety-related components and are designed to meet the APR1400 seismic Category I requirements based on NRC RG 1.92.
1.3.9.5	Licensees should include the effects of the fluid temperature and containment ambient temperature (e.g., restrained thermal growth, temperature dependent material properties) in determining the structural integrity of the strainer.	**Conformance.** See response to Item 1.3.9.1.
1.3.9.6	Licensees should perform an evaluation to determine the possibility for dynamic loading on the strainers caused by HELBs and other structures, systems, and components that could produce missiles, pipe whipping, or jet impingement loads. Chugging and condensation oscillation loads can be a significant contributor in some BWR designs. This evaluation should be done in accordance with GDC 4 and should be based on the plant’s design basis for postulated dynamic effects within the region of the strainers. Based on the SE for NEI 04-07 (Reference 27), in general, if a postulated pipe break is located more than 10 pipe diameters away from the strainer, the dynamic effects of such a break may be neglected with respect to the structural integrity effects on the strainer.	**Conformance.** See response to Item 1.3.9.1.

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1.3.10	**Chemical Reaction Effects**	
	a. Chemical reaction products in the post-LOCA environment of containments can contribute to blockage of the ECCS strainers and increase the associated head loss. The final SE by the Office of Nuclear Reactor Regulation on WCAP-16530-NP-A (Reference 24), and the NRC report entitled, "NRC Staff Review Guidance Regarding Generic Letter 2004-02, Closure in the area of, Plant-Specific Chemical Effect Evaluations" (Reference 33), provide a general approach to conduct plant-specific chemical effects evaluation.	**Conformance.** A chemical effects analysis was performed for the APR1400. The quantity of chemicals dissolved in the post-LOCA sump pool is determined using WCAP-16530-NP and associated letters and SE. The dissolved chemical quantities along with the boron and phosphate concentrations due to the borated sump water and TSP, respectively, were considered in the evaluation of chemical effects.
	b. During a LOCA, materials in the ZOI of the break can become debris that may transport to the containment pool where spray solution, spilled reactor coolant, and water from other safety injection sources accumulate. Subsequently, the combination of spray chemicals, insulation, corroding metals, and submerged and unsubmerged materials can create a potential condition for the formation of chemical substances that may impede the flow of water through the ECCS suction strainers or downstream components in the ECCS, CSS, or reactor coolant system.	**Conformance.** As part of the APR1400 IRWST strainer performance evaluation, a chemical effects evaluation was conducted to identify specific compounds and quantities of materials that may precipitate within the reactor containment sump pool following a LOCA. An analysis was performed to determine the types and quantities of chemical precipitates that may form in the post-LOCA recirculation fluid for the APR1400 design.
	c. New reactors with configurations different than those of operating PWRs (e.g., different containment materials, lack of buffering agents) may require additional evaluation.	**Conformance.** See responses to Items 1.1.2.5, 1.3.10.a, and 1.3.10.b.

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1.3.11	**Debris Accumulation, Head Loss, and Vortexing** a. In a letter to NEI dated March 28, 2008 (References 4 and 8), the NRC provided guidance for evaluating the potential for debris accumulation and its impact on strainer head loss during a LOCA that could impede or prevent the ECCS or CSS from performing its intended safety functions. b. Testing and analyses performed to address GL 2004-02 indicate that the maximum head losses for the ECCS strainers in some plants can occur when a layer of fiber just thick enough to fully cover the strainer accumulates on the strainer along with a bounding quantity of fine particulate matter. This case may result in a thin, dense debris bed with low porosity that could maximize head loss. The thickness of the fiber layer necessary to filter fine particulate cannot be specified in general, but it is dependent on a number of factors, including the strainer design, the strainer geometry and orientation, the approach velocity, the type and size of the fibrous debris, the type of particulate debris, and the presence of chemical effects. Appendix A, Section 6, of Reference 8 provides testing methods acceptable to the NRC staff to evaluate thin bed effects.	**Informational Material.**
1.3.11 (cont.)	c. Other testing and analyses have shown that the maximum debris loading case can also be a limiting head loss condition for strainers. Therefore, licensees should test for both the thin-bed and maximum loading cases. If the maximum debris loading case can result in a circumscribed debris accumulation, licensees should ensure that the strainer design and head loss test scaling accounts for this effective reduction in the strainer surface area.	

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1.3.11.1	Debris accumulation on the ECCS strainers for the head loss evaluation should be based on the amount of debris generated and the formation of different combinations of fibers and particulate mixtures (e.g., a fiber bed with a minimum thickness necessary to effectively filter particulate debris, as well as maximum debris loading) using the guidelines described in Section C.1.3.3 and on the debris transported to the strainers in accordance with Section C.1.3.4. The evaluation should be based on plant-specific debris loads determined in accordance with these regulatory positions.	**Conformance.** The performance of the sump strainers is based on conservative assumptions relative to the quantity of debris, ECC and CS flow, and temperature conditions.
1.3.11.2	The degree of ECCS strainer submergence (full or partial) at the time of switchover to recirculation should be considered in calculating the available (wetted) screen area. For plants in which certain pumps take suction from the ECCS strainers before the switchover of other pumps, the available NPSH for these pumps should consider the submergence of the strainers at the time these pumps initiate suction through the strainers. Unless otherwise shown experimentally, licensees should assume that debris is uniformly distributed over the available strainer surface.	**Not applicable.** Following an accident, water spilled from an RCS break and the uniformly distributed CS water drains back to the HVT. The water drains into the HVT and is ultimately returned to the IRWST through the IRWST spillways, by gravity, once the HVT water level reaches the IRWST spillways. The APR1400 eliminates the need to switch over from the injection mode to the recirculation mode.

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1.3.11.3	Strainer submergence should be adequate to preclude vortexing, sump fluid flashing, and deaeration induced by excessive differential pressure drop. Vortexing can cause the ingestion of unacceptable quantities of air into the ECCS and CSS pumps, potentially resulting in unacceptable pump performance. Water, when flashing to steam, can result in recirculating coolant that transforms a portion of the fluid into the vapor phase if the strainer pressure drop is sufficiently large. For partially submerged strainers, licensees should evaluate the potential for vortex formation internal to the strainer. Deaeration can similarly result in ingested air and unacceptable pump performance, whereas both deaeration and sump fluid flashing can result in an unacceptable increase in strainer head loss caused by the increased resistance associated with two-phase flow.	**Conformance.** The top of each strainer is submerged below the surface of the IRWST water. The minimum water level is sufficient to preclude adverse hydraulic effects (e.g., vortex formation, sump fluid flashing, and deaeration).
1.3.11.4	Licensees should validate the adequacy of ECCS strainer designs through testing applicable to plant-specific conditions. Analytical or empirical head loss correlations should not be used to validate plant-specific debris bed head losses. However, correlations may be useful in conducting scoping evaluations for conditions and debris loads with the range of applicable test data.	**Conformance.** See response to Item 1.3.2.3.

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1.3.12	**Prototypical Head Loss Testing** a. The methodology to predict the key inputs to the head loss testing has been conservatively developed and documented in NEI 04-07, referred to as the guidance report and its associated SE (References 26 and 27). Additionally, the NRC staff review guidance (Reference 8) provides a general approach to conducting plant-specific prototype head loss testing. This guidance report document discusses the staff positions on various aspects of head loss testing including scaling of the plant strainer design to the test strainer module, similitude considerations for debris transport and debris accumulation on the strainer, surrogate debris similitude requirements, and posttest data processing extrapolation.	**Conformance.** The performance of the IRWST sump strainers is based on conservative assumptions relative to the quantity of debris, ECCS flow, and temperature conditions. The strainer design provides sufficient strainer area for acceptable strainer head loss under debris laden conditions. The strainer head loss is validated by testing. The APR1400 design is such that the IRWST sumps remain continuously submerged.

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1.3.12 (cont.)	b. The objective of prototypical head loss testing is to determine the potential peak or bounding head loss that could occur across a suction strainer debris bed during a postulated LOCA scenario. If the test facility is scaled properly and the testing procedures are conservative, the measured head loss is also expected to be conservative. To ensure adequate strainer function, licensees should design the test facility properly and conduct testing following conservative testing procedures. The conditions within the test tank should be prototypical or conservative with respect to the plant, including the postulated debris loading, the recirculation system hydraulics, and key aspects of various accident scenarios. The primary scaling parameters include the screen area, the dimension of the strainer elements (e.g., disks), and the submergence level, the number of strainer elements, the debris amounts, and the local fluid flow conditions, as applicable. These parameters affect the flow velocities approaching the test strainer and the velocities through accumulated debris.	**Conformance.** The prototypical head loss test is designed in accordance with the head loss testing guidance provided in NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing dated March 2008. This staff guidance provides acceptable methods to perform prototype strainer head loss testing. Further details regarding the strainer head loss test are discussed in Reference [3-5] and Appendix C.
	c. The test specifications should be designed to determine a reasonably bounding head loss from all of the possible types of debris beds that could accumulate on the strainer considering the plant specific debris quantities that would transport.	**Conformance.** See response to Item 1.3.2.3.

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1.3.12 (cont.)	d. Post-test evaluations are required to validate the head loss results, apply the results to the proposed strainer, and ensure that the debris penetrating the strainer cannot cause adverse effects to downstream equipment. Licensees that want to scale the results of head loss tests conducted using colder water to the plant water temperatures should ensure that boreholes, bed degradation, open strainer area, or other phenomena that could affect the head loss response of the debris bed do not have a non-conservative effect when the temperature is scaled. The NRC does not recommend scaling of head loss results to alternate approach velocities or debris loadings because the theoretical debris bed head loss behavior is not well understood and the results of experiments examining these parameters have varied.	**Conformance.** See response to Item 1.3.12.b.
	e. Licensees may need to extrapolate the results of head loss testing for a time period matching the mission time of the ECCS. The method of extrapolation used should be one that conservatively fits the data (e.g., linear, log, quadratic) over the time period of interest.	**Conformance.** See response to Item 1.3.12.b.

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1.3.12 (cont.)	f. Because of the complexity of modeling and scaling multiple, complex physical phenomena in a single test, licensees should conduct head loss tests in a manner that ensures complete transport of debris (as determined by transport analysis) to the test strainer. Agitation of the test fluid with stirrers may be necessary to achieve conservative debris transport. If desired, licensees may conduct separately testing to credit reductions in debris transport (i.e., settling) to the strainer under conditions that are conservatively or prototypically scaled to the plant condition. However, strainer head loss testing that credits debris settlement within the test tank should carefully evaluate the flow characteristics (e.g., velocity and turbulence) in the test to ensure that the simulated flows are prototypical or conservative with respect to the plant condition. Licensees should consider scaling of debris per unit area of floor in the flume versus debris per unit floor area of the plant with respect to effects on debris transport caused by potential piling up of debris in areas of flow restrictions. The quantity of debris per unit width of the flume relative to the flow passages in the plant is also an important scaling parameter. Licensees should also give special consideration to the adequacy of other aspects of the test protocol, such as debris preparation, addition sequencing, debris concentration in the flume, and test flume geometry, to conclude that similar or larger amounts of debris settling would occur in the plant containment. Consideration should also be given to how debris settlement during a head loss test impacts other aspects	**Conformance.** See response to Item 1.3.12.b.

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1.3.12 (cont.)	of the analysis. For example, allowing debris to settle in the test tank can lead to a failure to account for erosion of this settled debris in the analysis. Because of the practical inability to simultaneously scale multiple, complex phenomena associated with debris transport and head loss in a rigorous way, licensees should apply conservatism to tests that model both transport and head loss. Section 4.0 of Appendix A of Reference 8 provides more details on this topic.	**Conformance.** See response to Item 1.3.12.b.

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1.3.12 (cont.)	g. Licensees may sample the flows downstream of the test strainer to determine the amount of debris passing through the strainer. The sampling should be performed on a frequency that ensures adequate characterization of the total bypass content. This debris could potentially damage or clog components, such as pumps, throttling valves, or components within the reactor core. Licensees may use the downstream debris characteristics to determine the likelihood that downstream blockage or wear and abrasion could threaten long-term core cooling or impact heat transfer of the fuel cladding. The conditions for the limiting downstream sampling tests will typically differ from the conditions for the limiting debris bed head loss tests because a filtering debris bed will tend to reduce the quantity of debris that passes through the strainer. A large strainer surface area, higher ECCS flow rates, low rate of debris introduction into the water, or thinner debris beds can result in higher quantities of bypass debris. Licensees may need to conduct separate strainer pass-through tests for fibrous and particulate debris to avoid crediting filtration caused by one debris type that might affect the other debris type. Collecting bypass debris in a filter with very small pore size, downstream of the strainer has also been successfully used to characterize the bypass content8.	**Conformance.** See response to Item 1.3.12.b.

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1.3.12 (cont.)	h. The analyses and testing should consider worst-case single failures. For example, licensees with plant designs that include low-pressure safety injection (LPSI) pumps that shut down during the switchover from the refueling water storage tank to the sump should consider one LPSI train failure to stop. This assumption leads to a conservatively calculated maximum flow rate to and through the screen.	**Conformance.** See response to Item 1.3.12.b.
	i. The time dependence of debris arrival at the strainer is difficult to model in a practical number of head loss tests. A conservative assumption is that all of the LOCA debris is present on the strainer at the beginning of recirculation. This debris should include the debris generated from the LOCA blowdown, failed unqualified coatings, eroded fine debris, chemical precipitates, and all other debris predicted to transport to the strainer.	**Conformance.** See response to Item 1.3.12.b.
	j. Head loss testing for complex combinations of debris that typically result from limiting plant debris loads has, in some cases, shown significant variation for the same debris loading. As a result, licensees should ensure that head loss test results have been demonstrated to be sufficiently repeatable, in light of known margins, uncertainties in debris quantities, the collective body of knowledge from tests on similar strainers, and other relevant information.	**Conformance.** See response to Item 1.3.12.b.

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1.3.12 (cont.)	k. Proper debris introduction procedures should take into account the fact that variations in the sequence and rate of debris introduction can potentially affect the head loss measurement. The approach that is considered most conservative is to introduce the debris slowly into the test tank with the pump running and prototypical hydraulic conditions established. The most transportable debris should be added first and the least transportable last. Licensees may also use other approaches, if justified. Testing that takes credit for near-field settlement should either realistically or conservatively simulate the strainer upstream flow and turbulent conditions. Licensees should conduct proper analytical evaluation of the similitude between the test tank and the actual plant condition. The NRC staff considers computational fluid dynamic codes to be useful tools to assist the evaluation. Surrogate debris materials used in head loss testing should be either the actual plant materials or suitable substitutions. Licensees should justify substitutions by comparing the important characteristics of the plant debris sources and the surrogate to ensure that the debris preparation creates prototypical or conservative debris characteristics.	**Conformance.** See response to Item 1.3.12.b.
2	**Regulatory Positions Specific to Pressurized Water Reactors** Any evaluation of the susceptibility of a PWR to debris blockage should address the considerations and events shown in Figure 3 (see page 33).	**Informational Material.**

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
2.1	**Emergency Core Cooling System Sumps, Strainers, and Debris Interceptors** Distribution of water sources and containment spray between the sumps should be considered in the calculation of boron concentration in the sumps for evaluating post-LOCA subcriticality and shutdown margins. Typically, these calculations are performed assuming minimum boron concentration and maximum dilution sources. Similar considerations should also be given in the calculation of time for hot-leg switchover, which is calculated assuming maximum boron concentration and a minimum of dilution sources. Additionally, the evaluation of debris transport to the sump screen should consider the time to switch over to sump recirculation and the operation of containment spray.	**Conformance.** Four separate, independent, and redundant trains of the SIS and CSS with two SI pumps and one CS pump in each division are provided. Within each division, the two SI trains (and each CS train) are separated by a quadrant wall to isolate the trains from each other to the maximum extent practical. Each of the four SI pumps has its own suction connection to the IRWST and each of two CS pumps shares one of these four connections. The four sumps are provided in the IRWST. Each IRWST sump contains paired CSS/SCS and SI suction pipes (two sumps: SI and CS pump suction pipes, two sumps: SI and SC pump suction pipes). Each pair of CSS/SCS and SI suction pipes ends in a suction sump, with each suction sump installed adjacent to an associated strainer (total four strainers). The IRWST contains approximately 2,456.7 m^3 (649,000 gal) of 4,000 ~ 4,400 ppm boric acid at pH 3.8 ~ 10.5. To minimize the corrosion of stainless steel in containment during a LOCA, long-term post-LOCA pH control (between 7.0 and 10.0 within the first 4 hours, between 7.0 and 8.5 up to 30 days after 4 hours) of the IRWST water is provided by granular trisodium phosphate (TSP), which is stored in the HVT. The stainless steel TSP storage baskets have a solid top and bottom with mesh sides to provide reasonable assurance of dissolution when submerged in water. The risk of dilution is considered negligible because the amount of diluent required to achieve a significant reduction in boron concentration is unrealistic (i.e., without being undetected).

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
2.1.1	The ECCS strainers should be located on the lowest general area floor elevation in the containment, exclusive of the reactor vessel cavity and the normal drainage sump, to maximize the pool depth relative to the strainers. Design considerations for recirculation strainers should ensure that they protect the pump inlets for which they supply water. A curb could be provided upstream of the strainers to prevent high-density debris from being swept along the floor into the sump strainer. To be effective, the height of the curb should be appropriate for the pool flow velocities and plant debris types because debris can be carried over a curb if the velocities are sufficiently high. Estimation of pool flow velocities should include both the pool fill (as applicable) and recirculation phases of the event. Licensees should also consider that turbulence in the pool may keep some debris in suspension that would otherwise settle. Experiments documented in NUREG/CR-6772 (Reference 13) and NUREG/CR-6916 (Reference 14) demonstrated that some types of settled debris could transport across the containment pool floor to the suction strainer by sliding or tumbling at typical containment pool velocities.	**Conformance.** The methodology described in NEI 04-07 and the associated NRC SER was used to perform the analysis of susceptibility of the ECCS and CSS recirculation functions to the adverse effects of post-accident debris blockage and operation with debris-laden fluids.

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
2.1.1 (cont.)	The ECCS strainer structures should include access openings and other design features, as required, to facilitate inspection of the strainer structures, any vortex suppressors, and the pump suction piping inlets. Where consistent with overall design and functionality, the top of the ECCS strainer structures should be a solid cover plate that is designed to be fully submerged after a LOCA and completion of the ECCS injection from the water storage tank. The cover plate is intended to provide additional protection to debris interceptor structures from LOCA-generated loads and from water drainage from upper containment. However, the design should also provide a means for venting any air trapped underneath the cover.	
2.2	**Chemical Reaction Effects**	
	a. The Westinghouse report, WCAP-16530-NP-A, and the limitations discussed in the associated SE (Reference 24) provide an acceptable approach for PWRs to evaluate chemical effects that may occur in a post-accident containment sump pool.	**Conformance.** See response to Item 1.3.2.
	b. Plant-specific information should be used to determine chemical precipitate inventory in containment. However, plant specific chemical effect evaluations should use a conservative analytical approach. Additionally, “NRC Staff Review Guidance Regarding Generic Letter 04-02 Closure in the Area of Plant-Specific Chemical Effect Evaluations” (Reference 33) provides a general approach for PWR licensees to conduct plant-specific chemical effect evaluations.	**Conformance.** See response to Item 1.3.10.

Appendix A – Comparison of IRWST Sump Strainer Design to NRC RG 1.82 Requirements

NRC RG Item No.	Regulatory Position	APR1400 Design Features and Capabilities
2.2. (Cont.)	c. WCAP-16793-NP "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," (Reference 23) is still under review by the NRC staff. When approved by the staff, it, along with the SE, will provide guidance for evaluation of chemical debris within the reactor.	**Conformance.** The testing and analysis were performed for in-vessel downstream effects using the methodology developed in WCAP-16793-NP to demonstrate reasonable assurance that sufficient LTCC is achieved for PWRs to satisfy the requirements of 10 CFR 50.46 for debris and chemical products that might be transported to the reactor vessel and core by the coolant recirculating from the containment sump.

Appendix B

Debris Generation Evaluation for the APR1400

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B.1 INTRODUCTION

The potential sources of debris in the Advanced Power Reactor 1400 (APR1400) are insulation, coating, and latent debris. The Reflective metal insulation (RMI) and coating debris are considered the potential source of debris following a high-energy line break (HELB).

The spherical zone of influence (ZOI) is used in estimating debris generation. The ZOI is defined as the volume about a given HELB area in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coatings, and other materials within the zone. Nuclear Energy Institute (NEI) 04-07 (Reference [1-1]) defines the ZOI as spherical and centered at the break site or location. The radius of the sphere is determined by the pipe diameter and the destruction pressures of the potential target insulation or debris material. All significant debris sources (e.g., insulation, debris) within the ZOI are evaluated. The destruction pressures and associated ZOI radius for material used in the APR1400 are taken from Table 3-2 of the Safety Evaluation (SE) of NEI 04-07 (Reference [1-2]), and are provided in Table B.1-1 of this appendix.

In accordance with the guidance in Section 3.4.2.3 of the SE of NEI 04-07 (Reference [1-2]), when a spherical ZOI extends beyond a robust barrier, the barriers may prevent expansion of the break jet, but it can also cause deflection and reflection. Section 3.4.2.3 of the SE of NEI 04-07 (Reference [1-2]) states that when a spherical ZOI extends beyond robust barriers such as walls or encompasses large components such as tanks and steam generators, the extended volume may be conservatively truncated. The SE of NEI 04-07 also stipulates that "shadowed" surfaces of components are included in the analysis.

These approaches are used for the evaluation of debris generation. The boundary of the spherical ZOI is conservatively truncated. The calculation assumes that all RMI within the ZOI becomes debris.

A three-dimensional (3D) computer-aided design (CAD) model based on structural drawings is developed for the APR1400 and is used to evaluate debris generation. The model includes the structure of the lower and upper containment, components, and pipes and is used to assist in the identification of debris sources and robust barriers within a given ZOI. The figures used in this appendix were developed from the 3D CAD model.

For the postulated break, a ZOI sphere is placed in the model centered at the break location. The coated surface area within the coating ZOI is then determined using various features of the 3D CAD model. Credit is taken in a conservative manner for some areas shielded by robust barriers. The 3D CAD model includes walls, floors, major equipment, structural supports, and pipes. Coated items not included in the 3D CAD model (e.g., miscellaneous steels such as grating, minor equipment, and valves) are considered in calculating value with safety factor in the coated surface area.

Figures B.1-1 through B.1-3 show sectional views of the ZOI for each break location.

Table B.1-1 Destruction Pressures and Associated ZOI Radii for Materials from Table 3-2 of the SE of NEI 04-07 (Reference [1-2])

Insulation Types	Destruction Pressure (psig)	ZOI Radius/ Break Diameter
Protective coating (epoxy and epoxy-phenolic paints)	TBD(1)	NA(2)
Protective coatings (untopcoated inorganic zinc)	TBD(1)	NA(2)
Transco RMI Darchem DARMET	114	2.0
Jacked NUKON with Sure-Hold® bands Minor® with Sure-Hold® bands	90	2.4
K-wool	24	5.4
Cal-Sil (Al. cladding, SS bands)	24	5.45
Temp-Mat with stainless steel write retainer	10.2	11.7
Unjacketed NUKON, Jacketed NUKON with standard bands Knaupf ET panel	6	17.0
Koolphen-K	3.6	22.9
Min-K Mirror® with standard bands	2.4	28.6

Note :

(1) To be determined experimentally
(2) Not available for evaluation at this time

B.2 EVALUATION OF INSULATION DEBRIS GENERATION

As described in Section 2.5 of the main body of this technical report, RMI is the only insulation used for equipment and piping in containment. For RMI debris generation, the diameter of the ZOI is defined as 2 inside diameters (IDs) of the broken pipe based on the approved methodology, the SE for NEI 04-07 (Reference [1-2]).

The ZOI for RMI is applied using the criteria in Table 3-2 of the SE of NEI 04-07 (Reference [1-2]).

$$\frac{r_{IZOI}}{D_{BREAK}} = 2 \qquad (1)$$

Where,

r_{IZOI} = spherical ZOI radius for RMI

D_{BREAK} = ID of break pipe

RMI thickness that is used is [ ]TS based on Reference [2-1].

Figures B.2-1, B.2-2, and B.2-3 show a spherical region within a distance equal to 2 IDs of the broken pipe when the junctions of the reactor coolant system (RCS) hot leg line (42 inch), RCS cold leg line (30 inch), and main steam line of the steam generator (SG) are broken.

B.2.1 Insulation Debris Generation from an RCS Hot Leg Line Break (42 inches)

Using Equation (1), the radius of the spherical ZOI for RMI is calculated as 7 ft.

The boundary of the ZOI is shown in Figures B.1-1 and B.2-1, and extends from the center of the break to the primary shield wall on the right side, a portion of the SG No. 2 on the left side, a portion of SG No. 2 on the upper side, and a portion of the pedestal of SG No. 2 on the lower side.

Surface areas for separate parts are shown in Figure B.2-4 and calculated in Table B.2-1.

Table B.2-1 RMI Generated from an RCS Hot Leg Line Break

Area		Part No.	Surface Area (ft^2)	Volume (ft^3)
Hot Leg Line	Nozzle (A_N)	1		
	Pipe (A_P)	2		
Surge/SC Line (A_S)		3		
Steam Generator Lower Shell (A_D)		4		
Steam Generator Skirt (A_K)		5		
Total				

TS

B.2.2 Insulation Debris Generation from an RCS Cold Leg Line Break (30 inches)

Using Equation (1), the radius of the spherical ZOI for RMI is calculated as 5 ft.

The boundary of the ZOI is shown in Figures B.1-2 and B.2-2. Surface areas for separate parts are shown on Figure B.2-5 and calculated in Table 2-2.

Table B.2-2 RMI Generated from an RCS Cold Leg Line Break

Area		Part No.	Surface Area (ft^2)	Volume (ft^3)
Cold Leg Line	Nozzle (A_N)	1		
	Pipe (A_P)	2		
Steam Generator Lower Shell (A_D)		3		
Steam Generator Skirt (A_K)		4		
Total				

TS

B.2.3 Insulation Debris Generation from a Main Steam Line Break (30.907 inches)

Using Equation (1), the radius of the spherical ZOI for RMI is calculated as 5.2 ft.

The boundary of the ZOI is shown in Figures B.1-3 and B.2-3. Surface areas for separate parts are shown on Figure B.2-6 and calculated in Table 2-3.

Table B2-3 RMI Generated from a Main Steam Line Break

Area		Part No.	Surface Area (ft^2)	Volume (ft^3)
Main Steam Line	Nozzle (A_N)	1		
	Pipe (A_P)	2		
Steam Generator Lower Shell (A_D)		3		
Total				

TS

B.3 EVALUATION OF COATING DEBRIS GENERATION

As described in Sections 3.4.3.3.3 and 3.4.3.3.4 of NEI 04-07 (Reference [1-1]), qualified and unqualified coatings within the coating ZOI are assumed to fail and all qualified coatings located outside the coating ZOI are considered not to fail when subjected to containment spray or immersed in the post-DBA pool.

All coatings used on structures, system, and components within containment in the APR1400 are qualified coatings, which are a DBA-qualified and acceptable coating system as described in Section 2.6 of main body of this technical report.

Based on Reference [3-1], the ZOI for qualified epoxy coatings is a sphere with a radius 4 times the break pipe inner diameter (4D), and the ZOI for untopcoated inorganic zinc (IOZ) coatings inside containment use a sphere with radius 10 times the break pipe inner diameter (10D). The volume of coating debris is calculated by multiplying the surface area of the ZOI sphere by the thickness of the coating film.

Untopcoated IOZ coatings are used only for equipment (reactor coolant pump (RCP) and RCP motor) and supports (SG, RCP, and surge line) in the 10D ZOI of the RCS hot leg line break and cold leg line break. In addition, there is no untopcoated IOZ coating in the 10D ZOI of the main steam line break.

The coating thickness based on the data shown in Table B.3-1 and evaluated for the APR1400 is used in the evaluation of coating debris generation with conservatism.

Table B.3-1 Coating Materials and Coating Thickness inside Containment

Coating Application	Coating System	Thickness (mils)
Containment Liner Plate, Structural Steel	Inorganic Zinc primer	3.0 ~ 5.0
	Epoxy Finish	3.0 ~ 5.0
Equipment and Component (less than 200°F)	Epoxy Primer	3.0 ~ 5.0
	Epoxy Finish	3.0 ~ 5.0
Equipment and Component (200°F to 750°F) (1)	Inorganic Zinc primer	3.0 ~ 5.0
Wall and Ceiling Concrete	Epoxy Primer	0.3 ~ 1.0
	Epoxy Intermediate	10.0 ~ 15.0
	Epoxy Finish	5.0 ~ 9.0
Floor Concrete	Epoxy Primer	0.3 ~ 1.0
	Epoxy Intermediate	20.0 ~ 27.0
	Epoxy Finish	6.0 ~ 8.0

Note :

(1) Evaluation equipment and components in the 10D ZOI of the RCS hot/cold leg line and main steam line break are, for example, RCP, RCP motor, and supports (RCP, SG, and surge line).

Coating debris generation is also evaluated using the CAD model developed as a part of the in-containment refueling water storage tank (IRWST) sump analysis and an estimate of the total concrete and steel surface area within the ZOI. This methodology is the same as methodology that is used to evaluate insulation debris generation. The 4D of the ZOI for epoxy and the 10D for the IOZ are used to determine a surface area. Credit is taken in a conservative manner for some areas shielded by robust barriers. The 3D view for the D-ring of the Steam Generator No.2 compartment is shown in Figure B.3-1.

B.3.1 Coating Debris Generation from an RCS Hot Leg Line Break (42 inches)

Using Equation (1), the 4D and 10D radii of the spherical ZOI are calculated as 14 ft and 35 ft, respectively.

The boundary of the ZOI is shown in Figures B.1-1, B.3-2, and B.3-3. Surface areas for separate parts of epoxy coating and untopcoated IOZ parts are shown in Figures B.3-4 and B.3-5, and calculated in Tables B.3-2 and B.3-3, respectively.

Table B.3-2 Epoxy Coating (4D) Generated from an RCS Hot Leg Line Break

Area	Part No.	Surface Area (ft^2)	Thickness (mils)	Volume (ft^3)
Wall Surface for D-Ring of SG Compartment	1	470.09	25	0.98
	2	14.07	25	0.03
	3	14.07	25	0.03
	4	145.07	25	0.30
SG Pedestal Wall Surface	5	38.52	25	0.08
	6	38.52	25	0.08
	7	92.81	25	0.19
Miscellaneous Steels	-	300	5	0.12
Total				1.82

Table B.3-3 IOZ Coating (10D) Generated from an RCS Hot Leg Line Break

Area	Surface Area (ft^2)	Thickness (mils)	Volume (ft^3)
RCP Motor Pedestal	1140.97	5	0.48
RCP Casing Cover	139.93	5	0.06
RCP Supports	631.63	5	0.26
SG Support	492.77	5	0.21
Surge Line Supports	200.00	5	0.08
Miscellaneous Steels	300	5	0.12
Total			1.21

B.3.2 Coating Debris Generation from an RCS Cold Leg Line Break (30 inch)

Using Equation (1), the 4D and 10D radii of the spherical ZOI are calculated as 10 ft and 25 ft, respectively.

The boundary of the ZOI is shown in Figures B.1-2, B.3-6, and B.3-7. Surface areas for separate parts of epoxy coating and untopcoated IOZ parts are shown in Figures B.3-8 and B.3-9, and calculated in Tables B.3-4 and B.3-5, respectively.

Table B.3-4 Epoxy Coating (4D) Generated from an RCS Cold Leg Line Break

Area	Part No.	Surface Area (ft^2)	Thickness (mils)	Volume (ft^3)
SG Pedestal Wall Surface	1	1.33	25	0.00
	2	7.32	25	0.02
	3	13.15	25	0.03
	4	4.81	25	0.01
Miscellaneous Steels	-	300	5	0.12
Total				0.18

Table B.3-5 IOZ Coating (10D) Generated from an RCS Cold Leg Line Break

Area	Surface Area (ft^2)	Thickness (mils)	Volume (ft^3)
RCP Motor Pedestal	1140.97	5	0.48
RCP Casing Cover	139.93	5	0.06
RCP Supports	631.63	5	0.26
SG Support	492.77	5	0.21
Surge Line Supports	200.00	5	0.08
Miscellaneous Steels	300	5	0.12
Total			1.21

B.3.3 Coating Debris Generation from a Main Steam Line Break (30.907 inches)

Using Equation (1), the 4D and 10D radii of the spherical ZOI are calculated as 10.4 ft and 26 ft, respectively.

The boundary of the ZOI is shown in Figures B.1-3, B.3-10, and B.3-11. Surface areas for separate parts of epoxy coating and untopcoated IOZ parts are shown in Figures B.3-12 and B.3-13, and calculated in Tables B.3-6 and B.3-7, respectively.

Table B.3-6 Epoxy Coating (4D) Generated from a Main Steam Line Break

Area	Surface Area (ft^2)	Thickness (mils)	Volume (ft^3)
Miscellaneous Steels	500	5	0.21
Total			0.21

Table B.3-7 IOZ (10D) Generated from a Main Steam Line Break

Area	Surface Area (ft^2)	Thickness (mils)	Volume (ft^3)
Miscellaneous Steels	500	5	0.21
Total			0.21

B.4 EVALUATION OF LATENT DEBRIS GENERATION

Latent debris is defined as unintended dirt, paint chips, and fiber, which consist principally of fiber and particle debris.

The quantity and type of latent debris is usually determined based on walkdown data, but walkdown data cannot be used because the APR1400 plant is a construction plant. A recent sampling of surfaces inside containment at a number of plants in the United States indicate that it is likely that the maximum mass of latent debris inside containment is less than 200 lbm (Reference [1-1]). This value (200 lbm) is therefore sufficient for a conservative evaluation of the quantity of debris.

B.5 CONCLUSION

The total amount of insulation, coating and latent debris for each break location, based on the results of the evaluation, is summarized in Table B.5-1.

Table B.5-1 Debris Generation for Each Break Location

Item \ Break Location		RCS Hot Leg Line	RCS Cold leg Line	Main Steam Line
Applicable Methodology		NEI 04-07 and SE	NEI 04-07 and SE	NEI 04-07 and SE
Break Size (cm / inch)		106.7 / 42	76.2 / 30	78.5 / 30.907
Size of ZOI (m / ft)	Insulation (2D)	2.13 / 7	1.52 / 5	1.58 / 5.2
	Coating - 4D (Epoxy) - 10D (IOZ)	4.27 / 14 10.67 / 35	3.05 / 10 7.62 / 25	3.17 / 10.4 7.92 / 26
Amount	RMI Insulation (m^3 / ft^3)			
	Coating (m^3 / ft^3) - 4D (Epoxy) - 10D (IOZ)	0.086 / 3.03 (1) 0.052 / 1.82 0.034 / 1.21	0.039 / 1.39 0.005 / 0.18 0.034 / 1.21	0.012 / 0.42 0.006 / 0.21 0.006 / 0.21
	Latent Debris (kg / lbm)	90.72 / 200	90.72 / 200	90.72 / 200

TS

Note :

(1) For strainer design, epoxy coating of 3.10 ft^3 is conservatively used.

From the Table B.5-1, the break location of the junction of between the RCS hot leg pipe (42 inches) and the SG is selected as the worst case for generating maximum debris loads. This break location is reasonable because the SGs have a larger volume of debris applied to them than the RCS piping and because most of the primary system piping is located in the SG compartment. The more the debris presents, the greater the volume of debris is transported to the sump strainer. Therefore, this break location results in the maximum head loss across the sump strainer.

B.6 REFERENCES

1-1 NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology," Nuclear Energy Institute, May 2004.

1-2 Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Nuclear Energy Institute Guidance Report (Proposed Document Number NEI 04-07), "Pressurized Water Reactor Sump Performance Evaluation Methodology," Nuclear Energy Institute, December 2004.

2-1 "Detailed Heat Loss Calculation for the Reactor Vessel Insulation at Shin-Kori Nuclear Power Plant 3&4" (SKN 3&4 PNS No.: 9-113-Z-301-001C), Doosan Heavy Industries & Construction Co., Ltd., January 2011.

3-1 NRC Letter to NEI, "Revised guidance regarding coatings zone of influence for review of final licensee responses to Generic Letter 2004-02, Potential Impact of Design Basis Accidents at Pressurized Water Reactors," U.S. Nuclear Regulatory Commission, April 2010.

TS

Figure B.1-1 Sectional View of ZOI for an RCS Hot Leg Line Break (2D for RMI; 4D and 10D for Coating)

TS

Figure B.1-2 Sectional View of ZOI for an RCS Cold Leg Line Break (2D for RMI; 4D and 10D for Coating)

TS

Figure B.1-3 Sectional View of ZOI for a Main Steam Line Break (2D for RMI; 4D and 10D for Coating)

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Figure B.2-1 3D Model View of 2D ZOI for an RCS Hot Leg Line Break

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Figure B.2-2 3D Model View of 2D ZOI for an RCS Cold Leg Line Break

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Figure B.2-3 3D Model View of 2D ZOI for a Main Steam Line Break

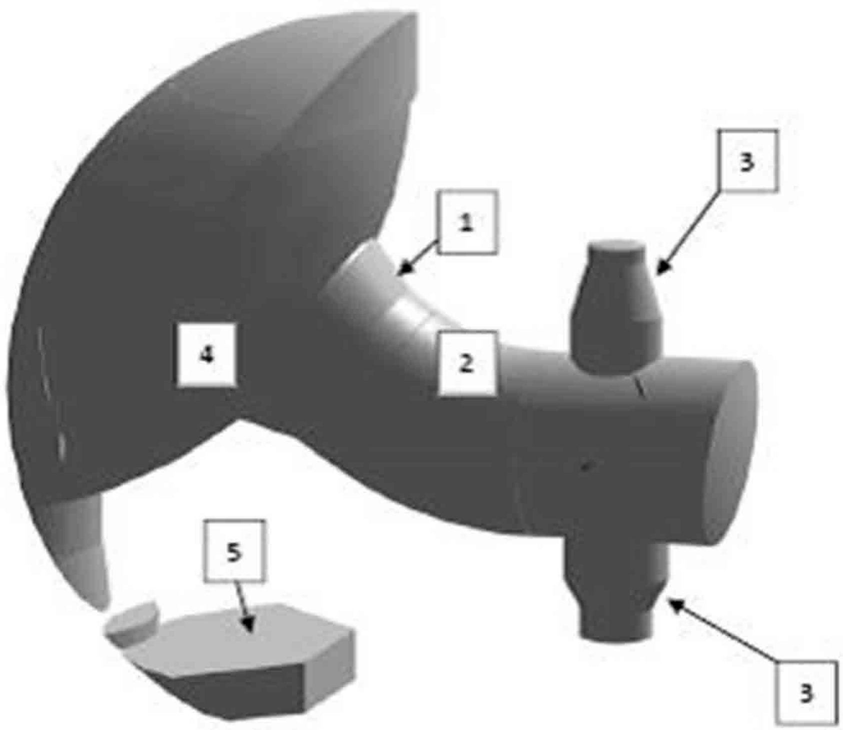

Figure B.2-4 Separate Parts of Surface Areas for an RCS Hot Leg Line Break (2D ZOI)

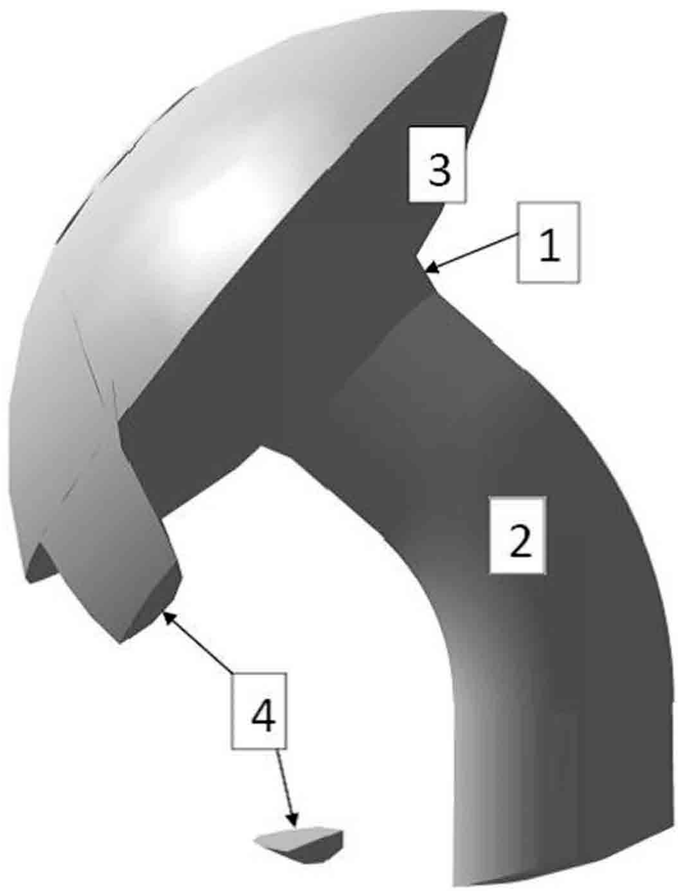

Figure B.2-5 Separate Parts of Surface Areas for an RCS Cold Leg Line Break (2D ZOI)

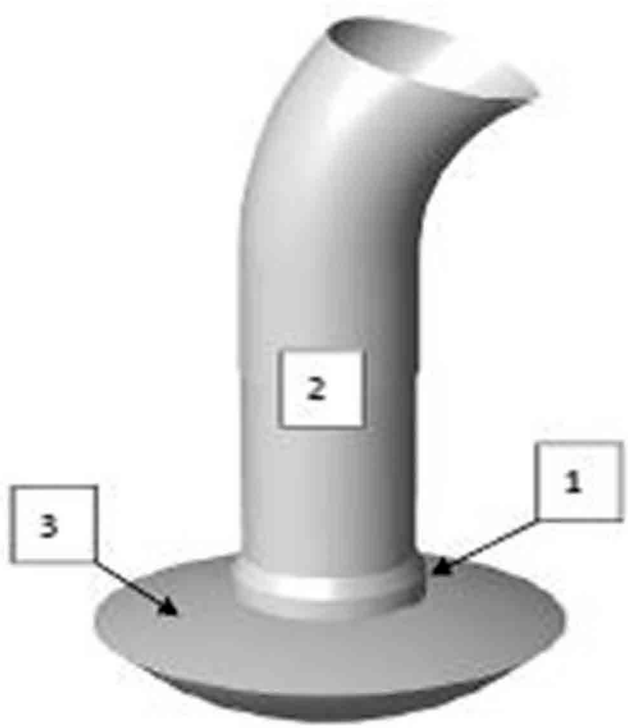

Figure B.2-6 Separate Parts of Surface Areas for a Main Steam Line Break (2D ZOI)

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Figure B.3-1 3D Model View of the D-Ring of Steam Generator No.2 Compartment

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Figure B.3-2 3D Model View of 4D ZOI for an RCS Hot Leg Line Break

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Figure B.3-3 3D Model View of 10D ZOI for an RCS Hot Leg Line Break

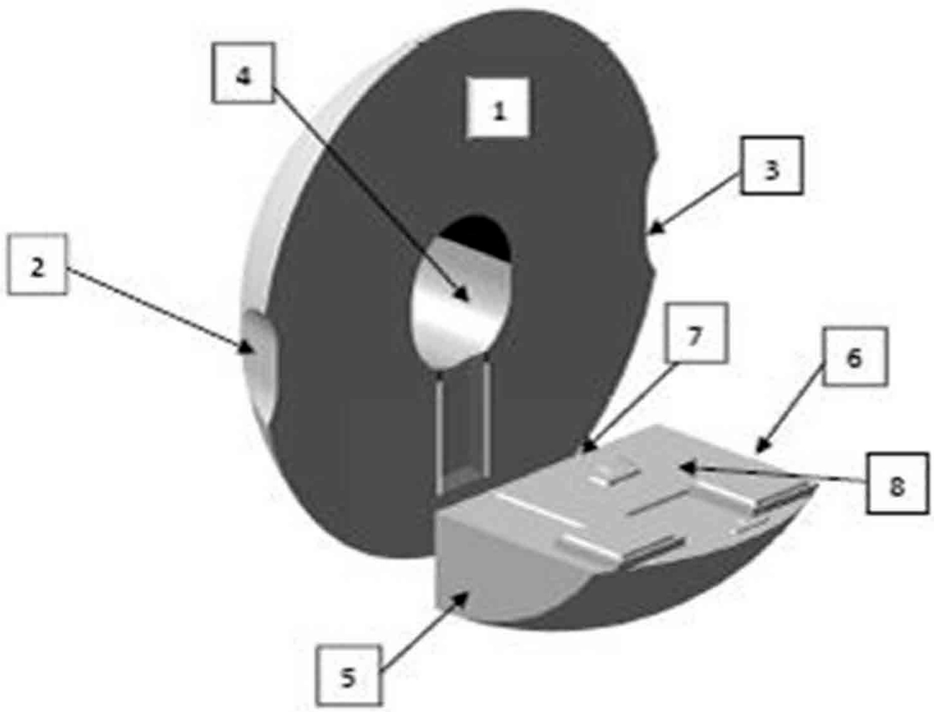

Figure B.3-4 Separate Parts of Surface Areas for an RCS Hot Leg Line Break (4D ZOI)

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Figure B.3-5 3D Model View of Surface Areas for an RCS Hot Leg Line Break (10D ZOI)

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Figure B.3-6 3D Model View of 4D ZOI for an RCS Cold Leg Line Break

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Figure B.3-7 3D Model View of 10D ZOI for an RCS Cold Leg Line Break

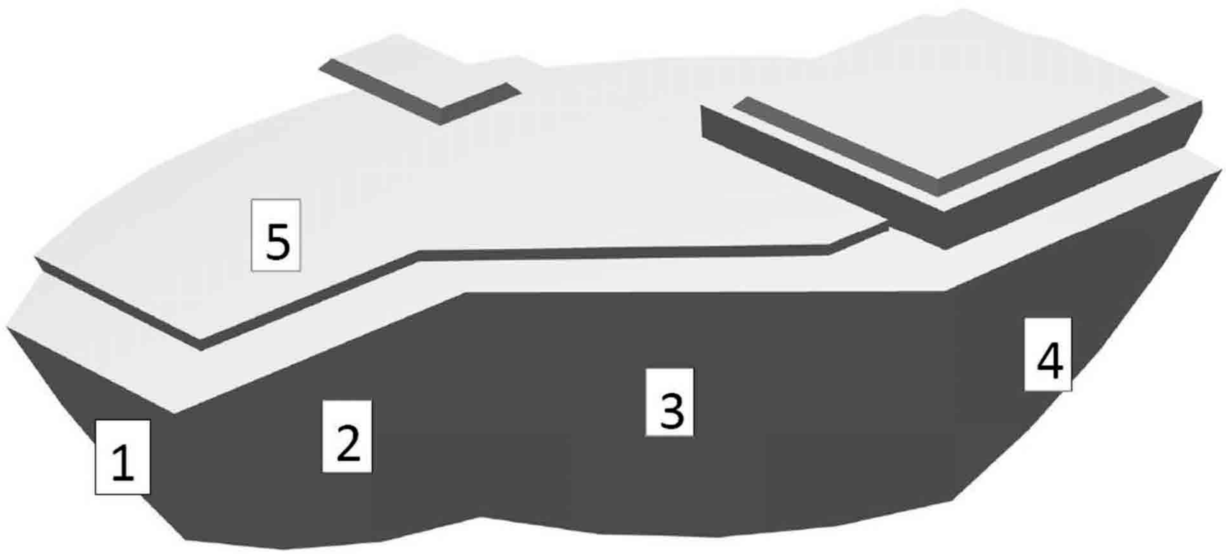

Figure B.3-8 Separate Parts of Surface Areas for an RCS Cold Leg Line Break (4D ZOI)

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Figure B.3-9 3D Model View of Surface Areas for an RCS Cold Leg Line Break (10D ZOI)

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Figure B.3-10 3D Model View of 4D ZOI for a Main Steam Line Break

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Figure B.3-11 3D Model View of 10D ZOI for a Main Steam Line Break

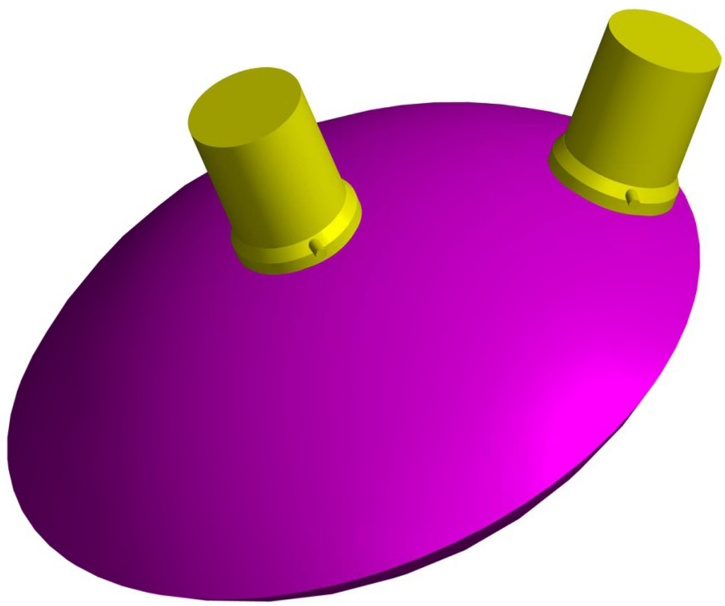

Figure B.3-12 Separate Parts of Surface Areas for a Main Steam Line Break (4D ZOI)

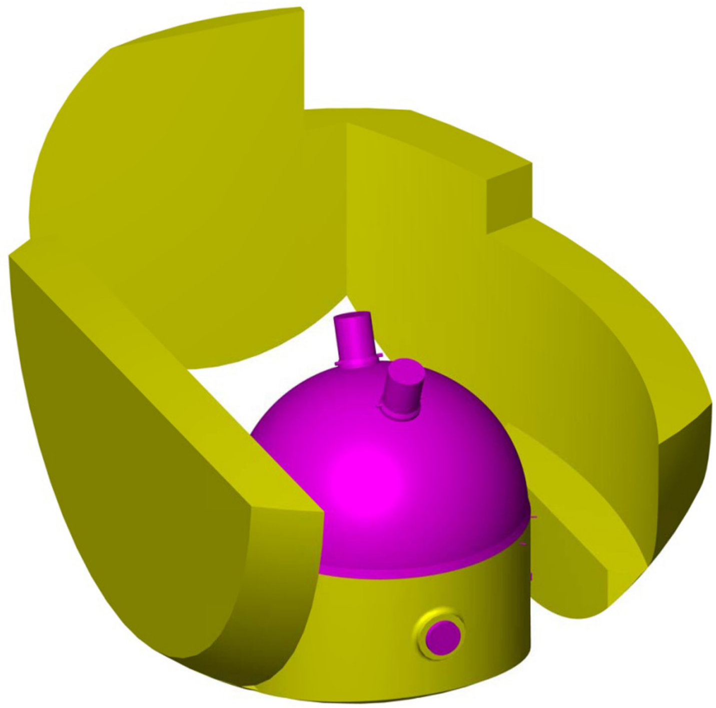

Figure B.3-13 3D Model View of Surface Areas for a Main Steam Line Break (10D ZOI)

Appendix C

Head Loss Test Report for the IRWST Sump Strainer

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C.1 INTRODUCTION

If a loss of coolant accident (LOCA) were to occur, it is postulated that this LOCA could generate and transport debris to the IRWST sump strainer. The debris that could accumulate on the strainer may form a debris bed and increase the head los across the strainer. The purpose of these tests is to develop data to validate the IRWST sump strainer performance using conservative assumptions. Flow sweeps were also conducted to adjust the head loss over the range of fluid temperatures required for the strainer operation. Acceptance evaluation will be performed separately from this report.

The tests were conducted following test plans (Reference [1-1] and [1-2]) developed by Structural Integrity Associates. The principal difference between the tests was that the first test was based on a plant strainer area of 55.74 m^2 (600 ft^2) and the second test was based on a strainer area of 46.45 m^2 (500 ft^2), 9.29 m^2 (100 ft^2) was assumed blocked by tags (Reference [1-1] and [1-2]).

C.2 TEST FACILITY DESCRIPTION

C.2.1 Flow Loop

The test facility consists of an approximately 4.57 m (15 ft) diameter tank that is 2.13 m (7 ft) deep. The flow returns into the tank from a 6 inch pipe with a tee that is pointed at the floor in the center of the tank. The exit of the tee is approximately 0.05 m (2 inch) above the floor so that the return flow sweeps along the floor then up the tank walls to help suspend debris. The tank can hold approximately 35.96 m^3 (9500 gallons) of water.

The test strainer is located next to the return pipe with the strainer plenum mounted 0.15 m (6 inch) above the tank floor. The top of the strainer elements are 1.19 m (46.75 inch) above the tank floor. Six agitators (trolling motors) are located at approximately every 60 degrees at an approximately 3.66 m (12 ft) diameter (see Figure C.2-1).

The suction pipe is attached to the strainer and runs to the Godwin CD150M pump. The discharge of the pump goes to a flow meter, flow control valve, and then back into the tank (see Figure C.2-2, and Figure C.2-3 for a schematic).

Flow rate can be controlled by a combination of a variable frequency drive (VFD) that drives the pump, the gate valve, or a bypass line which provides a short circuit path between the suction and discharge of the pump. Typically, the VFD is used to control the flow rate during a test, unless very low flow rates need to be achieved.

C.2.2 Instrumentation

Head loss across the strainer was measured by two independent Rosemount model 1151 differential pressure transducers. One transducer was scaled to 0-100 in of water and the second was scaled to 0 - 7.62 m (0 - 300 inch) of water. These transducers were calibrated to +/-0.125% of their range. The low side of the differential pressure transducer was connected to the pressure tap on the strainer plenum and the high side of the pressure transducers was connected to a tap on the tank wall.

Flow rate was measured by a six-inch Omega model MG1000 electromagnetic flow meter. The flow meter was installed on the discharge side of the pump more than 50 diameters upstream of the pump with a straight section of pipe upstream and downstream of the flow meter. A flow control valve was installed downstream of the straight section of piping.

Water temperature was measured with a type T thermocouple installed in the tank near the water surface. The thermocouple was connected to an Omega DP-41 TC-A process meter.

All of these instruments were connected to a Dataq DI-220 data acquisition system running LSP60 software. This software records data every two seconds to disk in tab delimited format in engineering units. The software also provides plotting and digital displays of all of the instrumentation being recorded.

C.3 TEST PROTOTYPE

A prototype Transco strainer was tested (see Figures C.2-1 and C.3-1). The strainer consists of three strainer cartridges each with four tubes bolted to a plenum that allows a flow path from each tube to the pump suction pipe. The three cartridges were labelled as C4570-004, C4570-005, and C4570-006. The surface area of this configuration is 6.97 m^2 (75.1 ft^2) with perforated plate hole size of 2.38 mm (0.094 inch) in Reference [1-1]. The plenum was mounted 0.15 m (6 inch) above the tank floor.

C.4 DEBRIS DESCRIPTION

Four types of debris were used in the test. Aged Nukon fiberglass was prepared as fines to simulate latent fiber, silicon carbide to simulate epoxy paint, sand mixture to simulate latent particulate, and aluminum oxy-hydroxide to simulate chemical debris (Reference [1-1] and [1-2]).

C.4.1 Latent Fiber

For this test fiber, fines were tested to simulate latent debris. Fiber was prepared from aged Nukon fiberglass. The fiberglass was obtained heat treated from Performance Contracting Inc. lot number J-006-12HT*LN-1840. The heat treating process followed PCI procedure DPP-01 which heated one side of the insulation on a hot plate at 300 °C (572 °F) for 6 to 8 hours. The received insulation was inspected visually to confirm that the heat treatment produced a color gradient appropriate for aged fiber (see Figure C.4-1).

The use of fiberglass insulation, such as Nukon is recommended as a surrogate for dry latent debris (Reference [4-1]). The fiber was processed into fines. For test APR1400-HL-0813-1, the fiber was shredded once, then separated by a pressure washer, and stirred with a mixer. Typical fiber is shown below in Figure C.4-2. These fibers have a significant amount of class 1 and 2 fibers, but also significant amount of class 3 fibers as defined in (Reference [4-2]). For test APR1400-HL-0913-2, the fibers were triple shredded, separated by a pressure washer, and stirred by a mixer in a more dilute fiber water mixture. The suspended fibers are shown in Figure C.4-3 which are nearly all class 1 and 2 (Reference [4-2]).

C.4.2 Silicon Carbide

ElectroCarb black silicon carbide (size 800) was obtained from Electro Abrasives in Buffalo NY. These particles have an average diameter of approximately 10 μm (3.94×10^{-4} inch) as measured by the manufacturer. A sample of the silicon carbide was microscopically measured and had an average diameter of 8.64 μm (3.40×10^{-4} inch) (Shoemaker, Kevin, M&P Lab Report 0929, January 13, 2009).

C.4.3 PWR Sand Mix

PWR sand mix is defined to have a target size distribution as shown in Table C.4-1. The PWR mix was made by combining three types of sand. Paver leveling sand from Home Depot was used for the coarse sand. It was passed through a 2,000 μm (7.87×10^{-2} inch) sieve and no material passed through a 500 μm (1.97×10^{-2} inch) sieve. Glass bead blasting media was obtained in two different size ranges from Potters Industries in Pottsdam, New York (through McMaster Carr). The size labelled 40-60 mesh, lot number 1052713PO-2236 was all medium classification, all the sand passed through a 500 μm (1.97×10^{-2} inch) sieve and did not pass through a 75 μm (2.95×10^{-3} inch) sieve. The second size was labelled 170 - 325 mesh, lot number 1072313PO-3118 and was a combination of fine and medium sizes. 75.94% of the sand passed through a 75 μm (2.95×10^{-3} inch) sieve (fine) and 24.06% passed through a 500 μm (1.97×10^{-2} inch) sieve but was captured on the 75 μm (2.95×10^{-3} inch) (medium). To create the sand mixture 28% of the total amount was weighed out from the paver sand. To create the fine sand 48.7% of the total amount was weighed out of the 170 - 325 mesh, which produced 37% fines and 11.7% medium.

The rest of the medium sand, 23.3% of the total, was weighed from the 40-60 mesh sand.

Table C.4-1 Target Size Distribution (Reference [1-1] and [1-2])

Sand Recipe	Target (%)	Classification
< 75 μm (2.95×10^{-3} inch)	37	Fine
> 75 μm (2.95×10^{-3} inch) and < 500 μm (1.97×10^{-2} inch)	35	Medium
> 500 μm (1.97×10^{-2} inch) and < 2,000 μm (7.87×10^{-2} inch)	28	Coarse

C.4.4 Aluminum Oxy-hydroxide

Aluminum Oxy-hydroxide was fabricated following WCAP-16530-NP-A and the associated safety evaluation (Reference [4-3] and [4-4]). The chemicals to make the aluminum oxy-hydroxide, aluminum nitrate and sodium hydroxide were obtained from Fisher Scientific.

The aluminum oxy-hydroxide was made at a concentration of 0.011 g/cm^3 (0.69 lbm/ft^3) immediately prior to the test and a settling test was performed to ensure the chemical surrogate met the requirements in Reference [4-4].

C.5 TEST PROCEDURE SUMMARY

C.5.1 Debris Preparation

C.5.1.1 Particulate Preparation

The particulate, sand mixture and silicon carbide, was split into buckets with approximately 4.54 kg (10 lbm) in each bucket. About 0.011 m^3 (3 gallons) of water was carefully added to each bucket and the mixture was agitated with a propeller agitator attached to a drill motor. The particulate and water was mixed to suspend the debris to facilitate pouring the mixture into the tank.

C.5.1.2 Fiber Preparation

Fiber fines were prepared based on NEI guidance (Reference [5-1]). For both tests the debris preparation was similar, but the second test ARPR1400-HL-0913-2 did additional shredding and fiber dilution to ensure the fiber added to the tank was nearly all class 1 and 2 (Reference [4-2]) and had no agglomeration as it was added.

For both tests, aged Nukon fiberglass insulation was cut into approximately 7.62 cm by 7.62 cm (3 inch by 3 inch) pieces. The cut pieces were then shredded in a leaf shredder/chipper, separated by a pressure washer, put into buckets, agitated by a mixer, and then poured into the tank.

For test APR1400-HL-0813-1, the fiber was shred a single time. The fiber was weighed into batches of 0.43 kg (0.95 lbm). A batch of fiber of 0.43 kg (0.95 lbm) was placed in 0.015 m^3 (4 gallons) of water in a 0.121 m^3 (32 gallon) plastic container. The fiber was thoroughly wet and then separated using a pressure washer with a fan nozzle for approximately 4 minutes. The fiber was then separated into buckets. The fiber water mixture was then agitated with a propeller mixer at high speed for one minute, and the fiber water mixture was added to the tank around the perimeter where the flow turbulence and upwelling diluted the fiber mixture (See Figure C.4-2). Photographs and video were taken of the fiber addition (for example see Figure C.5-2).

For test APR1400-HL-0913-2, the fiber was shredded three times. The shred fiber was then weighed into 2 batches of 0.52 kg (1.15 lbm). A batch was split into three approximately equal portions and each third was placed into plastic container (approximately 0.121 m^3 (32 gallons)) with approximately 0.008 m^3 (2 gallons) of water. The fiber was thoroughly wet. The fiber was then separated using a pressure washer with a fan nozzle for 4 minutes. The water fiber mixture was then further diluted into eight 0.019 m^3 (5 gallon) buckets with a total of 0.011 m^3 (3 gallons) of water in each bucket. Immediately prior to adding the fiber, the fiber was agitated with a propeller mixer on high for one minute. A sample of this fiber water mixture was taken to ensure the process produced fines that were nearly all class 1 and 2 fines (Reference [4-2]) (see Figure C.4-3). The fiber mixture was added to the tank and there were no fiber clumps as the fiber was poured into the tank. Photographs and video were taken of the fiber addition (for example see Figure C.5-3).

C.5.1.3 Aluminum Oxy-hydroxide Preparation

Aluminum Oxy-hydroxide (ALOOH) is made following the WCAP-16350 recipe (Reference [4-3]). Given the volume of ALOOH required the amount of water is determined from the concentration (0.011 g/cm^3 (0.69 lbm/ft^3)).

Water is added to a clean plastic tank. Aluminum nitrate nonahydrate is added slowly to the water at 6.25 lb/lb of ALOOH. The water is mixed by a stirrer. After the aluminum nitrate has all dissolved, sodium hydroxide is added at 2.0 lb/lb of ALOOH. The suspension must be mixed for at least one hour. A sample is taken and placed undisturbed in a graduated cylinder for an hour to perform a settling test.

After one hour, greater than 60% of the volume must remain cloudy.

The ALOOH is mixed in a plastic tank. The required amount of volume is weighed out into plastic containers and poured into the tank around the perimeter.

C.5.2 Test Setup

The test setup consisted of cleaning the facility and cleaning and assembling the strainer as shown in Figure C.2-1. The configuration is sketched in Figure C.5-5. The strainer was checked to ensure there were no gaps greater than 2.38 mm (0.094 inch). The tank and piping were filled with water at 26.7 °C (80 °F), the minimum temperature required in the test plan. The water level was set at 24 in above the top of the strainer tubes.

C.5.3 Test Initiation

Both tests were initiated by conducting a clean flow sweep. Because they had different target flow rates the sweeps occurred at slightly different target flow rates. All 6 agitators were on for both tests.

C.5.4 Debris Addition

After the clean flow sweeps were completed, particulate was added to the tank. Particulate was distributed into 0.019 m^3 (5 gallon) buckets and mixed with water. The particulate was added as slurry to make it easier to add the particulate in the tank. The buckets were poured around the perimeter of the tank. For each test there was a single addition of particulate, see Figure C.5-1 for typical addition. Several buckets were added at consecutively to complete the addition.

After the particulate was allowed to circulate for a minimum of 2 pool turnover times (PTOs), the first of two batches of fiber were added. Fiber was added as slurry around the perimeter of the tank (see Figures C.5-2 and C.5-3). Several buckets were added at consecutively to complete the addition. The second batch of fiber was added after 10 PTOs and the head loss reached its stability criterion (< 1% head loss change in one hour). The head loss was so low that a 1% change in one hour was difficult to determine, but the head loss essentially remained constant to meet this criterion.

Chemical debris was then added from plastic 0.114 m^3 (30 gallon) containers and poured around the perimeter of the tank. For test APR-HL-0813-1, three chemical additions of 0.189 m^3 (50 gallons) each were added. The head loss did not increase for the last two additions so no more additions were required. For test APR-HL- 0913-2, the measured head loss increased slightly for the first three chemical additions so the total load of chemicals was added in five batches.

C.5.5 Test Termination

Each subtest was terminated by completing the required minimum time and reaching the head loss stability requirement, if applicable. Clean flow sweeps were conducted for the time required and then that test was terminated. Particulate additions were conducted for the time required and then that sub-test was terminated. Fiber and chemical addition sub-tests were terminated upon completing at least 10 PTOs and reaching head loss stability of < 1%/hour. Final flow sweeps were terminated after completing the required 2 PTOs at each flow rate.

C.5.6 Post Test Observations

C.5.6.1 Test APR1400-HL-0813-1

After the test, the suction and discharge vents were opened very slowly to minimize disturbance of the debris bed. Typically draining with heavy debris beds does disturb the debris bed because debris can

easily fall off vertical surfaces, especially when there is little head loss across the debris bed.

Figures C.5-6 and C.5-7 show that the strainer in the water was being drained from the tank. Some open area appears to have remained during the test. There are areas where debris has fallen off the strainer perforated plate also. The debris bed is thinner at the top of the strainer elements. Both photos show each strainer element covered by differing amounts of debris.

Figure C.5-8 shows two opposite sides of the strainer. The photo on the left shows the left side of the strainer looking from the suction pipe (suction pipe is near the right side of the photo). The photo on the right is the right side of the strainer (suction pipe is on the left side of the photo). The cylinder nearest the suction pipe on the left side appears cleaner than the other cylinders because debris has fallen off the strainer. Figure C.5-9 shows details of those cylinder bottoms. Figure C.5-10 illustrates typical view inside of strainer tubes after drain down.

C.5.6.2 Test APR1400-HL-0913-2

After the test, the suction and discharge vents were opened very slowly to minimize disturbance of the debris bed, just as in the previous test. Typically draining with heavy debris beds does disturb the debris bed because debris can easily fall off vertical surfaces, especially when there is little head loss across the debris bed.

In this test, the debris did not fall off the left cylinder closest to the suction pipe. Based on this comparison between Figure C.5-11 and the left photo in Figure C.5-8, there is no effect of agitation on the debris build up to the strainer. Figure C.5-12 compares the left side and right side of the strainer after drain down and it is clear that debris falls off of different cylinders in an unpredictable manner. Figure C.5-13 shows the ends of the strainer and Figure C.5-14 shows the typical view inside of the strainer tubes after drain down, note that debris falls off in an unpredictable manner.

Similar to the previous test, no debris was found on the tank floor.

C.5.6.3 Test Discrepancies and Nonconformances

For test APR1400-HL-0913-2, the flow meter was used outside of its calibrated range, but well within its operating range. The meter was calibrated to 3,407 L/min (900 gpm), but can operate to 9085 L/min (2,400 gpm). The flow meter has two outputs an electrical output that is recorded on the data acquisition system and a display on the meter itself. For the test, the electrical output was rescaled from 3,407 L/min (900 gpm) to 4,542 L/min (1,200 gpm) maximum. The electrical output was compared to the display at several flow rates and compared to within 3.8 L/min (1 gpm). No further action was required.

For test APR1400-HL-0913-2, five (5) chemical additions were used, instead of four (4), at the request of the test director. The third chemical addition was increased from 0.189 m^3 (50 gallons) to 0.379 m^3 (100 gallons). The additional chemical addition was used to provide additional resolution in case head loss increased significantly.

C.6 RESULTS OF TESTING

Test APR1400-HL-0813-1 was started on 28 August 2013 and finished on 29 August 2013. Test APR1400-0913-2 was started on 12 September 2013 and finished on 13 September 2013.

C.6.1 Clean Flow Sweeps

The clean flow sweep data are shown in Table C.6-1 and plotted in Figure C.6-1. The data for the two tests are very consistent and the higher flow point for test APR1400-HL-0913-2 fits the same second order polynomial curve as test APR1400-HL-0813-1.

Table C.6-1 Clean Flow Sweep Results

Test APR1400-HL-0813-1		Test APR1400-HL-0913-2	
Flow Rate (gpm)	Head Loss (in-water)	Flow Rate (gpm)	Head Loss (in-water)
833	4.3	1003	6.2
739	3.4	738	3.4
660	2.7	665	2.8
582	2.1	573	2.1
493	1.5	495	1.6
658	2.7	662	2.7
833	4.3	1002	6.2

C.6.2 Test Conditions

Test APR1400-HL-0813-1 was run assuming a 55.74 m^2 (600 ft^2) strainer and test APR1400-HL-0913-2 was run assuming a 46.45 m^2 (500 ft^2) strainer (assumed blockage by tags and other debris) (Reference [1-1] and [1-2]). The flow rate and debris amounts were scaled by the ratio of the test strainer area to the plant strainer area and therefore saw an increase for the second test of 20%.

Table C.6-2 Comparison of Head Loss Test Conditions

Quantity	APR1400-HL-0813-1	APR1400-HL-0913-2
Flow rate (gpm)	834	1000
Silicon carbide(lbm)	77.4	92.9
Sand mix (lbm)	23.1	27.8
Fiber (lbm) (total)	1.90	2.30
Chemical (gallons) (max)	556.5	667.8

The as-tested test matrices are shown in Tables C.6-3 and C.6-4. The quantities in the tables indicate

the amount of debris added during a particular subtest. Note that for test APR1400-HL-0813-1 only three chemical additions were required because head loss did not increase for the last two chemical additions. For test APR1400-HL-0913-2, the full chemical load was added in five additions.

Table C.6-3 Test Matrix for APR1400-HL-0813-1

Subtest (1)	Flow rate	Latent Fiber (lbm)	Dirt/Dust (lbm)	Coatings (lbm)	ALOOH (gal)
P.1	834	0	23.1	77.4	0
F.1	834	0.95	0	0	0
F.2	834	0.95	0	0	0
C.1	834	0	0	0	50
C.2	834	0	0	0	50
C.3	834	0	0	0	50
C.4	834	0	0	0	0
V.1	834	Water level was reduced to 2.0 ft above the strainer to check for vortexing			
FS	Various	Flow was reduced in 100 gpm increments to 234 gpm			

Note :

(1) P : Parriculate addition
F : Fiver addition
C : Chemical addition
V : Vortexing
FS : Flow sweet

Table C.6-4 Test Matrix for APR1400-HL-0913-2

Subtest	Flow rate	Latent Fiber (lbm)	Dirt/Dust (lbm)	Coatings (lbm)	ALOOH (gal)
P.1	1000	0	27.8	92.9	0
F.1	1000	1.15	0	0	0
F.2	1000	1.15	0	0	0
C.1	1000	0	0	0	50
C.2	1000	0	0	0	50
C.3	1000	0	0	0	100
C.4	1000	0	0	0	200
C.5	1000	0	0	0	267.8
V.1	834	Water level was reduced to 2.0 feet above the strainer to check for vortexing			
FS	Various	Flow was reduced in 100 gpm increments to 500 gpm			

C.6.3 APR1400-HL-0813-1 Debris Head Loss Results

Debris head loss test results for each of the subtests in Table C.6-3 are shown in Table C.6-5 and plotted in Figure C.6-2.

Table C.6-5 Head Loss Test Results for APR1400-HL-0813-1

Subtest	Flow rate (gpm)	Temperature (°F)	Head Loss (in-water)
P.1	835	82	4.5
F.1	833	82	5.8
F.2	831	83	6.5
C.1	834	84	7.5
C.2	834	85	7.7
C.3	834	85	7.8
FS	729	85	6.0
FS	630	85	4.5
FS	536	85	3.4
FS	430	85	2.2
FS	333	85	1.4
FS	236	86	0.9

C.6.4 APR1400-HL-0913-2 Debris Head Loss Results

Debris head loss test results for each of the subtests in Table C.6-4 are shown in Table C.6-6 and plotted in Figure C.6-3.

Table C.6-6 Head Loss Test Results for APR1400-HL-0913-2

Subtest	Flow rate (gpm)	Temperature (°F)	Head Loss (in-water)
P.1	1009	81	6.4
F.1	999	82	8.1
F.2	998	82	8.4
C.1	996	84	9.0
C.2	998	85	9.4
C.3	999	86	9.6
C.4	1000	88	9.7
C.5	999	88	9.7
FS	899	88	7.9
FS	798	88	6.2
FS	700	88	4.9
FS	601	88	3.6
FS	496	88	2.5

C.6.5 Vortex Tests

For both APR1400-HL-0813-1 and APR1400-HL-0913-2, no air entrainment or vortexing was seen. Photographs and video were taken of the strainer submerged at two feet of water at test flow rate. For test APR1400-HL-0813-1 after the flow sweep was complete, the flow rate was increased to the target flow rate to demonstrate the lack of vortex formation for test witnesses. No vortices are identified during the tests (Figure C.6-4).

C.7 QUALITY ASSURANCE

All quality-related activities were performed in accordance with the Continuum Dynamics, Inc. Quality Assurance Manual (Reference [7-1]). Quality-related activities are those which are directly related to the planning, execution and objectives of the test. Supporting activities such as test apparatus design, fabrication and assembly are not controlled by the C.D.I. Quality Assurance Manual. C.D.I.'s Quality Assurance Program provides for compliance with the reporting requirements of 10 CFR Part 21. All instrument certifications, instrument calibrations, testing procedures, data reduction procedures, and test results are contained in a Design Record File which (upon completion) will be kept on file at C.D.I. offices.

C.8 CONCLUSION

To develop experimental head loss data associated with the specified debris loadings, two tests (APR1400-HL-0813-1 and APR1400-HL-0913-2) were performed. The first test was performed using an effective surface area of 55.74 m^2 (600 ft^2) and the second test was performed using an effective surface area of 46.45 m^2 (500 ft^2). The difference between the first and second head loss test is the change in effective surface area of the strainer to consider a 9.29 m^2 (100 ft^2) penalty of sacrificial strainer surface. This was accomplished by increasing the test flow rate for the second test from 3,157 L/min (834 gpm) to 3,785 L/min (1,000) gpm and increasing the mass of debris per square foot.

The maximum head loss for the 46.45 m^2 (500 ft^2) effective strainer area with the maximum debris load is 24.69 cm-water (0.81 ft-water) at the design flow rate and includes a clean screen component of 15.85 cm-water (0.52 ft-water). Therefore, the debris only head loss for both tests is essentially the same at 8.84 cm-water (0.29 ft-water). While the flow rates/debris mass per unit area is slightly different, the results are nearly identical and repeatable and considerably less than the 60.96 cm-water (2 ft-water) allowable head loss. This is due to the very low debris load that is insufficient to cover the screen completely, similar to that of the “clean plant criteria.”

Table C.8-1 Final Head Loss Test Results

	Strainer with 46.45 m^2 (500 ft^2)	Strainer with 55.74 m^2 (600 ft^2)
Clean strainer head loss	15.85 cm-water (0.52 ft-water)	10.97 cm-water (0.36 ft-water)
Debris head loss	8.84 cm-water (0.29 ft-water)	8.84 cm-water (0.29 ft-water)
Total strainer head loss	24.69 cm-water (0.81 ft-water)	19.81 cm-water (0.65 ft-water)

These test results were experimentally measured in a test fluid at approximately 31.1 °C (88 °F). Therefore, it is conservative to use these values at higher temperatures since fluid density and viscosity will decrease with increasing temperature.

For strainer vortexing, visual observations were performed and no vortices were observed.

C.9 REFERENCES

1-1 APR1400-E-A-T(NR)-13002-NP, "APR1400 IRWST ECCS Sump Strainer Prototype Hydraulic Qualification Test Plan," Rev. 1, KHNP, August 2013.

1-2 Test Plan No. 1300462.402, "APR1400 IRWST ECCS Sump Strainer Prototype Hydraulic Qualification Test Plan," Structural Integrity Associates, Rev. 2, September 2013.

4-1 Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Nuclear Energy Institute Guidance Report (Proposed Document Number NEI 04-07), "Pressurized Water Reactor Sump Performance Evaluation Methodology," Nuclear Energy Institute, December 2004.

4-2 NUREG/CR-6808, "Knowledge Base for the Effects of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance," U.S. Nuclear Regulatory Commission, February 2003.

4-3 WCAP-16530-NP-A, "Evaluation of post-Accident Chemical Effect in Containment Sump Fluid to Support GSI-191," Rev.0, Westinghouse Electric Corporation, April 2008.

4-4 "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, December 2007.

5-1 "ZOI Fibrous Debris Preparation: Processing, Storage, and Handling," Nuclear Energy Institute, Revision 1 January 2012.

7-1 "Quality Assurance Manual," Continuum Dynamics, Inc., Revision 14, February 2006.

TS

Figure C.2-1 Prototype Strainer in the Test Tank

Figure C.2-2 Pump (on left), and Data Acquisition Flow Meter/DP Cells (on right)

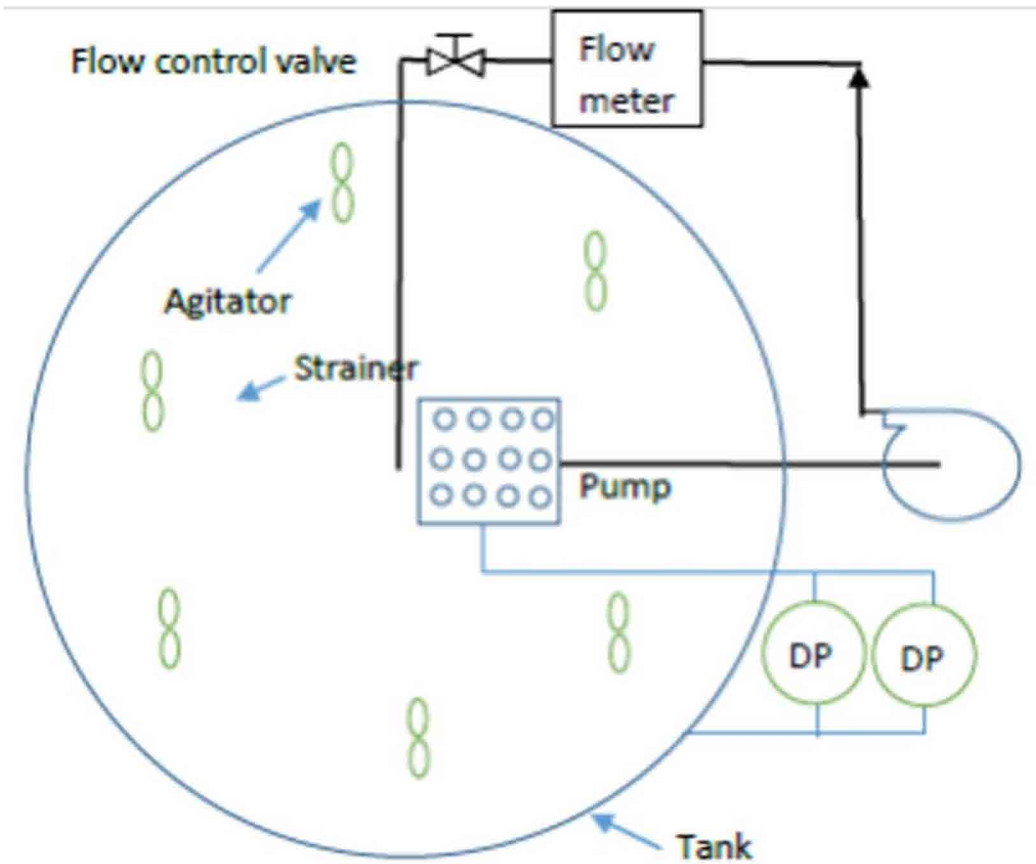

Figure C.2-3 Flow Schematic of Test Setup

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Figure C.3-1 Test Strainer Drawing

Figure C.4-1 Aged Fiber Sample

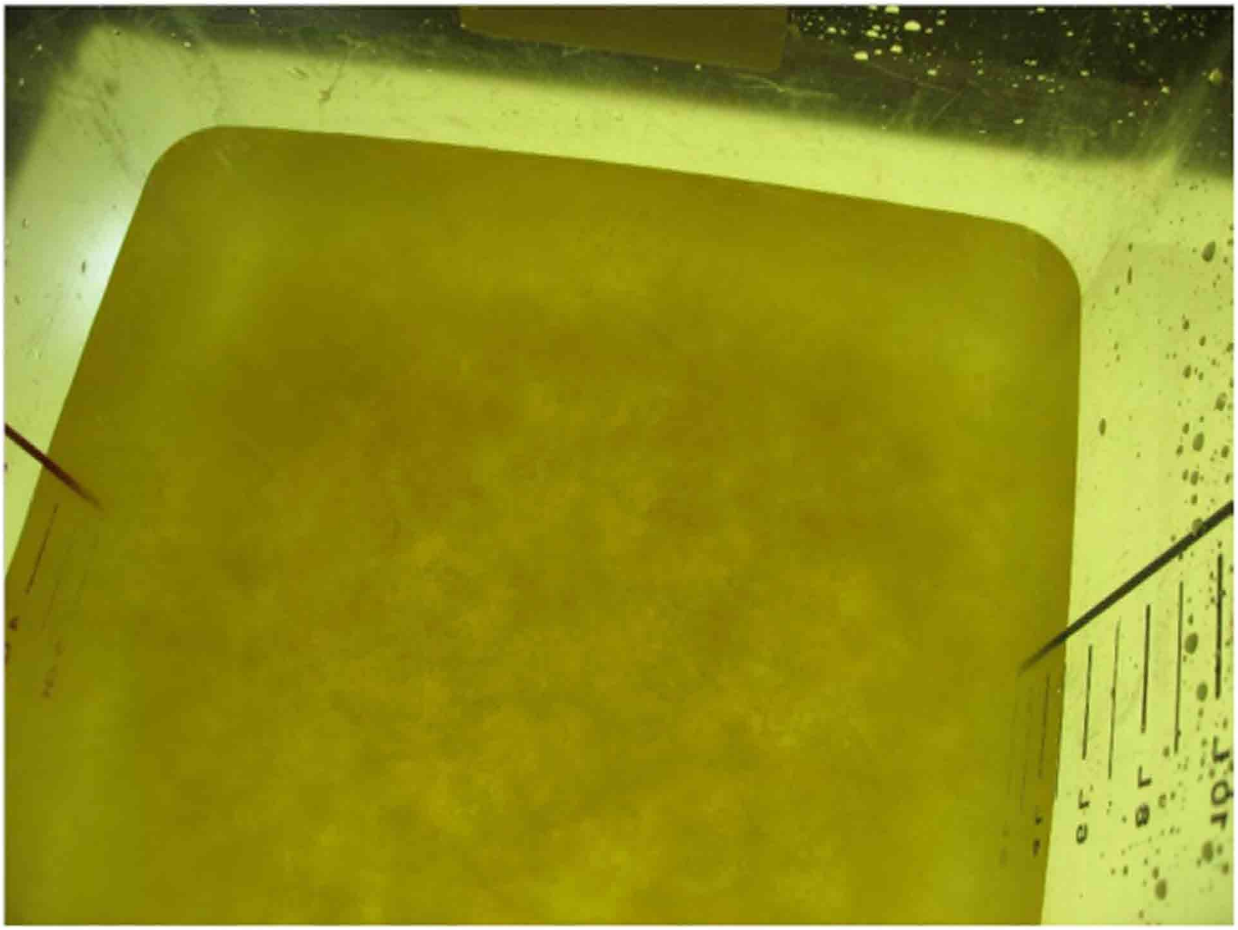
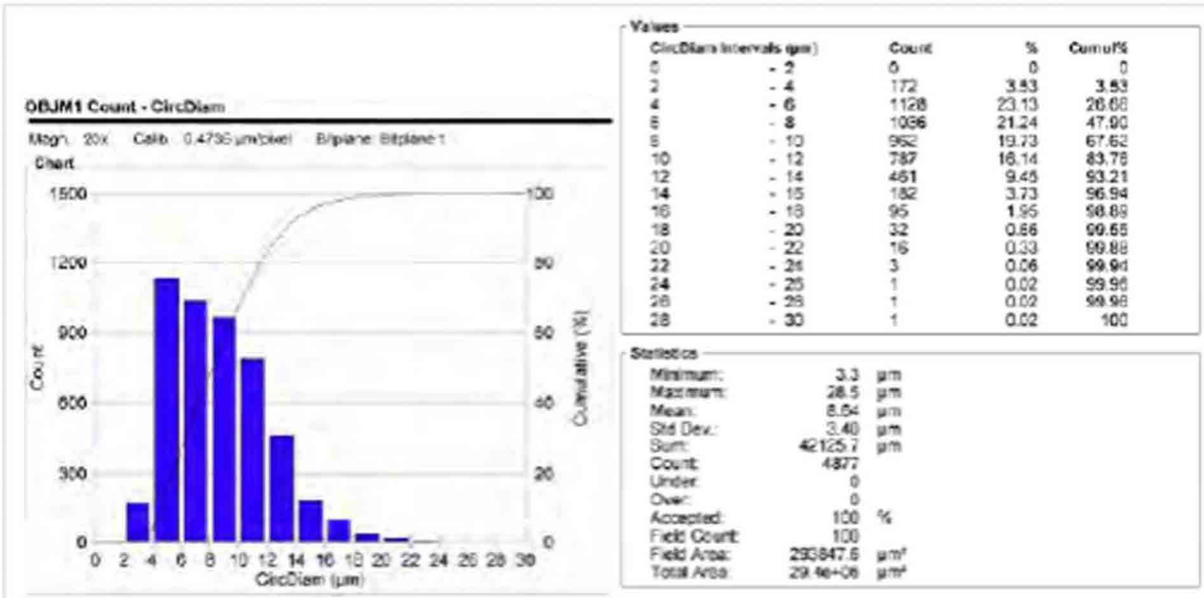


Figure C.4-2 Fiber Used in APR1400-HL-0813-1

Figure C.4-3 Fiber Used in APR1400-HL-0913-2



Values

CircDiam Intervals (µm)		Count	%	Cumul%
0	- 2	0	0	0
2	- 4	172	3.53	3.53
4	- 6	1128	23.13	26.66
6	- 8	1036	21.24	47.90
8	- 10	962	19.73	67.62
10	- 12	787	16.14	83.76
12	- 14	461	9.45	93.21
14	- 16	182	3.73	96.94
16	- 18	95	1.95	98.89
18	- 20	32	0.66	99.55
20	- 22	16	0.33	99.88
22	- 24	3	0.06	99.94
24	- 26	1	0.02	99.96
26	- 28	1	0.02	99.98
28	- 30	1	0.02	100

Statistics

Minimum:	3.3	µm
Maximum:	28.5	µm
Mean:	8.64	µm
Std Dev.:	3.40	µm
Sum:	42125.7	µm
Count:	4877	
Under:	0	
Over:	0	
Accepted:	100	%
Field Count:	100	
Field Area:	293847.6	µm²
Total Area:	29.4e+06	µm²

Figure C.4-4 Measured Size Distribution of Black Silicon Carbide

Figure C.5-1 Typical Particulate Addition (Silicon Carbide on Left, Sand Mixture on Right)

Figure C.5-2 Typical Fiber Fines Addition for APR1400-HL-0813-1

Figure C.5-3 Typical Fiber Fines Addition for APR1400-HL-0913-2

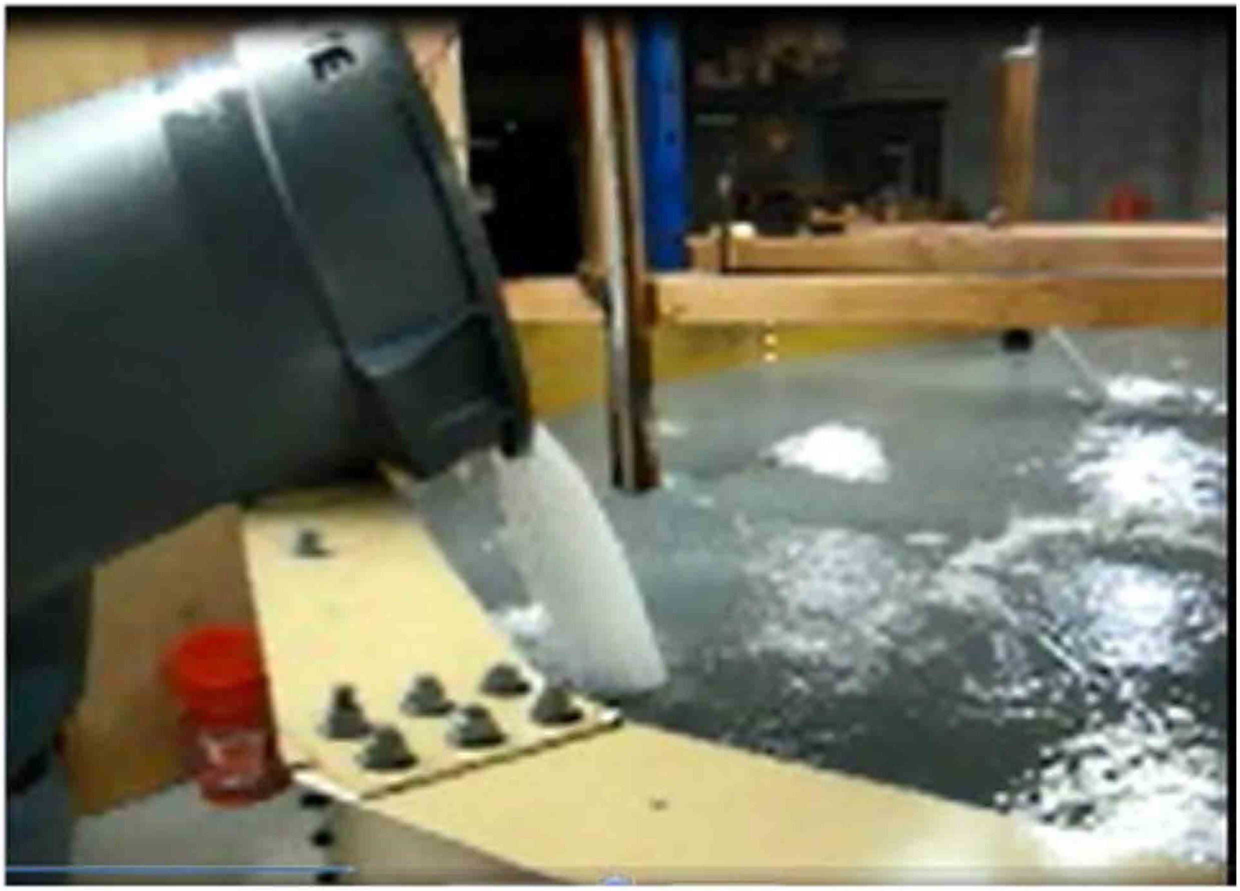


Figure C.5-4 Typical Chemical Debris Addition

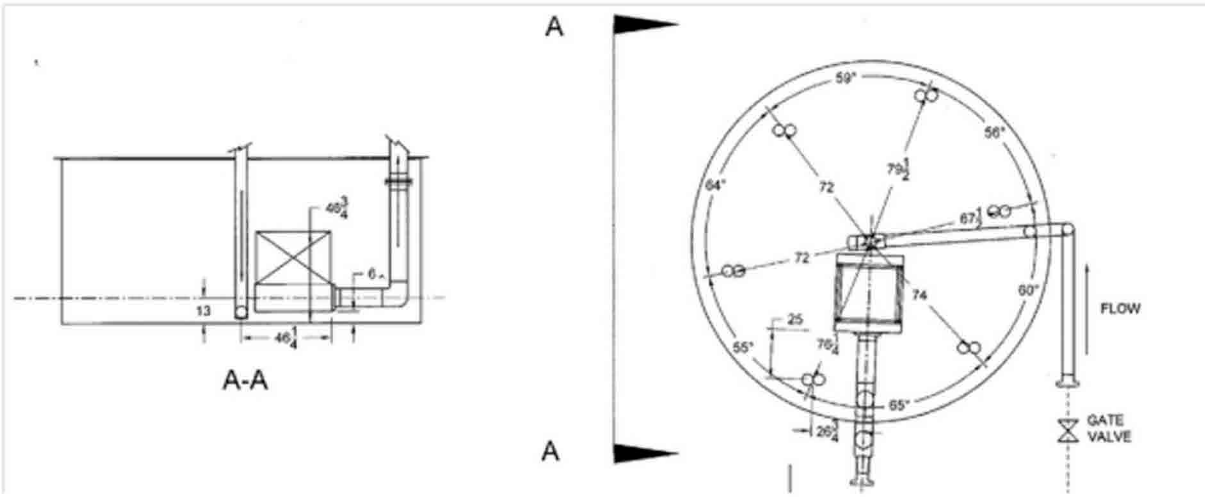


Figure C.5-5 Test Facility Layout

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Figure C.5-6 Post-test During Draining (Suction Pipe is at Top of Photo)

TS

Figure C.5-7 Post-test During Draining (Suction Pipe is at Right)

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Figure C.5-8 Post-test During Draining (Left and Right Sides of the Strainer)

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Figure C.5-9 Cylinders Bottom Left Side of Strainer Showing Debris Having Fallen Off Strainer (Away From (on top) and Near (on bottom) Suction Pipe)

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Figure C.5-10 Typical View Inside Strainer Tubes After Drain Down

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Figure C.5-11 Left Side of Strainer During Drain Down (Suction Pipe is on Right of Photo)

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Figure C.5-12 Comparison of Left and Right Side of the Strainer After Drain Down

TS

Figure C.5-13 Comparison of Ends of the Strainer After Drain Down

TS

Figure C.5-14 Typical View Inside of Strainer Tubes After Drain Down

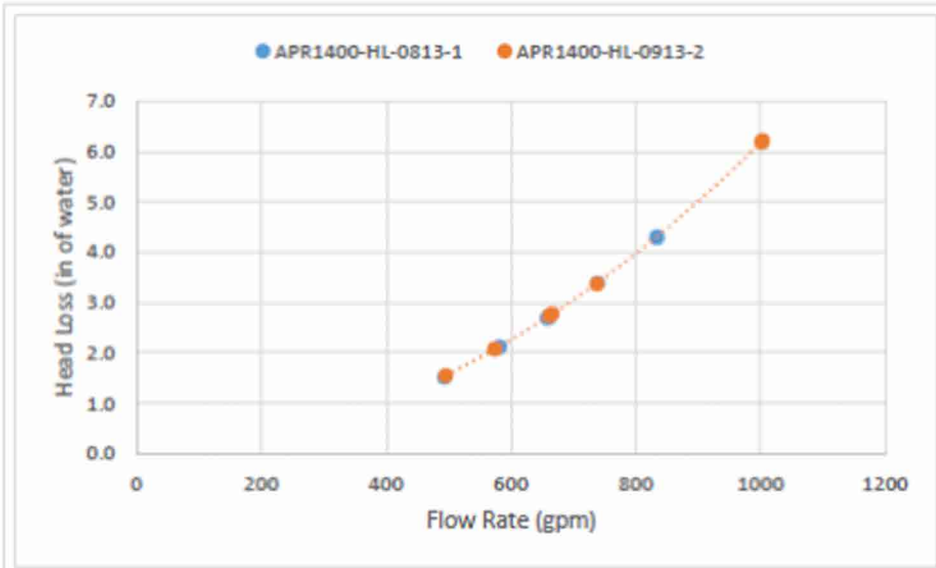

Figure C.6-1 Clean Flow Sweep Data

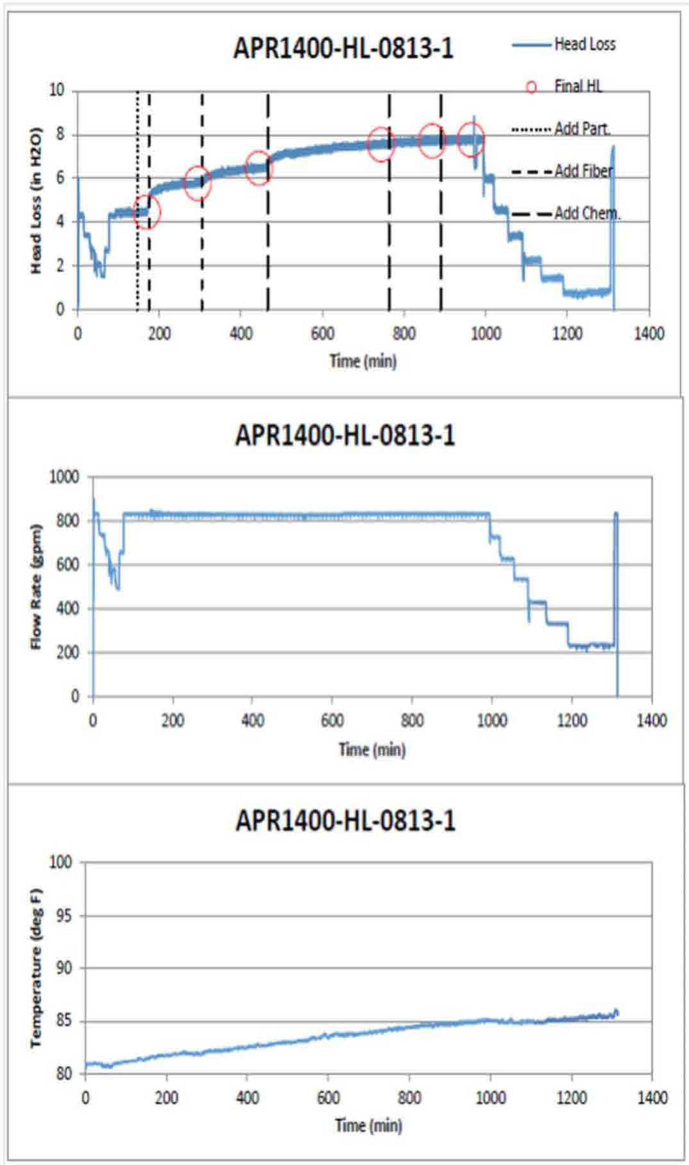

Figure C.6-2 Time Histories of Head Loss, Flow Rate, and Temperature (APR1400-HL-0813-1)

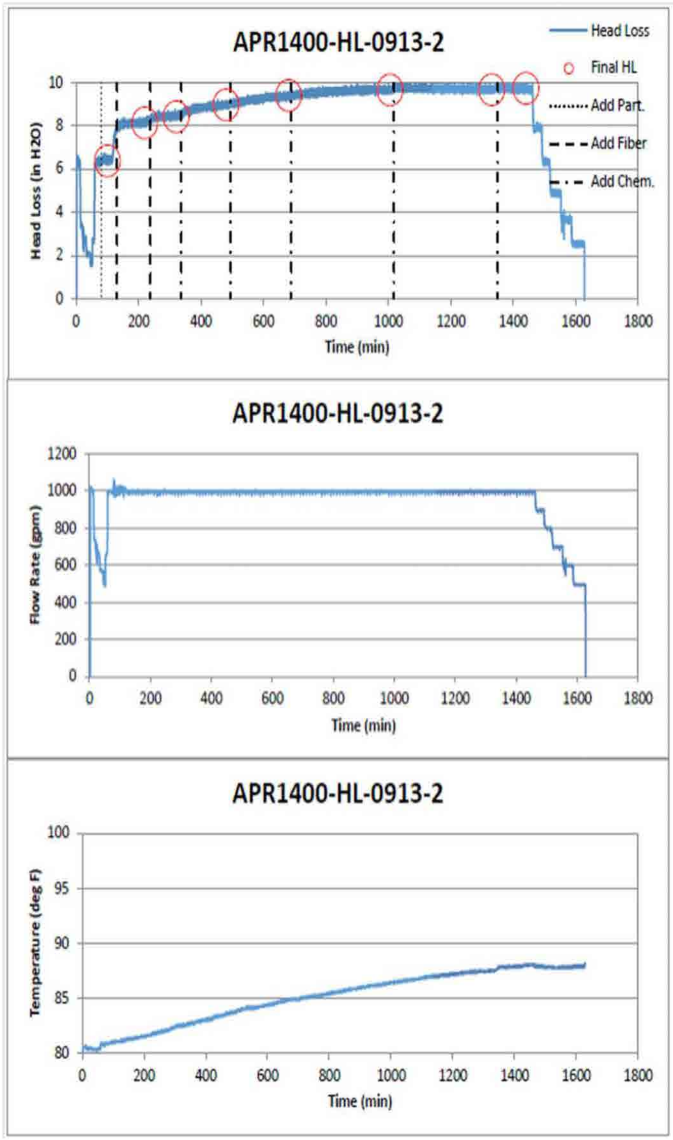

Figure C.6-3 Time Histories of Head Loss, Flow Rate, and Temperature (APR1400-HL-0913-2)

Figure C.6-4 Vortex Identification During APR1400-HL-0813-1 (on left) and APR1400-HL-0913-2 (on right)

Appendix D

Bypass Test Report for the IRWST Sump Strainer

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LIST OF FIGURES

D.1 INTRODUCTION

If a loss of coolant accident (LOCA) were to occur, it is postulated that this LOCA could generate and transport debris to the Emergency Core Cooling Suction (ECCS) strainer. Some of the debris deposited on the ECCS strainer may pass through the strainer and could challenge the long term core cooling capability of the plant. The primary debris type of concern is fibrous material which potentially could form a debris bed downstream of the strainer, for example on the fuel grids. Particulate and chemical debris are assumed to pass through the strainer, and are therefore excluded from the bypass test.

The purpose of this test is to measure the quantity of fiber that can pass through the ECCS strainer. The test was conducted following a test plan (Reference [1-1]) developed by Structural Integrity Associates.

D.2 TEST FACILITY DESCRIPTION

D.2.1 Flow Loop

The test facility consists of an approximately 4.57 m (15 ft) diameter tank that is 2.13 m (7 ft) deep. The flow returns into the tank from a 6 inch pipe with a tee that is pointed at the floor in the center of the tank. The exit of the tee is approximately 0.05 m (2 inch) above the floor so that the return flow sweeps along the floor then up the tank walls to help suspend debris. The tank can hold approximately 35.96 m^3 (9500 gallons) of water. The tank was covered by a tarp to prevent dust and debris from falling into the tank.

The test strainer is located next to the return pipe with the strainer plenum mounted 0.15 m (6 inch) above the tank floor. The top of the strainer elements are 1.19 m (46.75 inch) above the tank floor. Six agitators (trolling motors) are located at approximately every 60 degrees at an approximately 3.66 m (12 ft) diameter (see Figures D.2-1 and D.2-2).

The suction pipe is attached to the strainer and runs to the Godwin CD150M pump. The discharge of the pump goes to a flow meter, flow control valve, and then back into the tank (see Figures D.2-2 and D.2-3, and Figure D.2-4 for a schematic).

Flow rate can be controlled by a combination of a variable frequency drive (VFD) that drives the pump, the gate valve, or a bypass line which provides a short circuit path between the suction and discharge of the pump. Typically, the VFD is used to control the flow rate during a test, unless very low flow rates need to be achieved.

D.2.2 Instrumentation

Head loss across the strainer was measured by two independent Rosemount model 1151 differential pressure transducers. One transducer was scaled to 0-100 in of water and the second was scaled to 0 - 7.62 m (0 - 300 inch) of water. These transducers were calibrated to +/-0.125% of their range. The low side of the differential pressure transducer was connected to the pressure tap on the strainer plenum and the high side of the pressure transducers was connected to a tap on the tank wall.

Flow rate was measured by a six-inch Omega model MG1000 electromagnetic flow meter. The flow meter was installed on the discharge side of the pump more than 50 diameters upstream of the pump with a straight section of pipe upstream and downstream of the flow meter. A flow control valve was installed downstream of the straight section of piping.

Water temperature was measured with a type T thermocouple installed in the tank near the water surface. The thermocouple was connected to an Omega DP-41 TC-A process meter.

All of these instruments were connected to a Dataq DI-220 data acquisition system running LSP60 software. This software records data every two seconds to disk in tab delimited format in engineering units. The software also provides plotting and digital displays of all of the instrumentation being recorded.

D.3 TEST PROTOTYPE

A prototype Transco strainer was tested (see Figures D.2-1 and D.3-1). The strainer consists of three strainer cartridges each with four tubes bolted to a plenum that allows a flow path from each tube to the pump suction pipe. The three cartridges were labelled as C4570-004, C4570-005, and C4570-006. The surface area of this configuration is 6.97 m^2 (75.1 ft^2) with perforated plate hole size of 2.38 mm (0.094 inch) in Reference [1-1]. The plenum was mounted 0.15 m (6 inch) above the tank floor.

D.4 DEBRIS DESCRIPTION

For this test fiber, fines were tested to simulate latent debris. Fiber was prepared from aged Nukon fiberglass. The fiberglass was obtained heat treated from Performance Contracting Inc. lot number J-006-12HT*LN-1840. The heat treating process followed PCI procedure DPP-01 which heated one side of the insulation on a hot plate at 300 °C (572 °F) for 6 to 8 hours. The received insulation was inspected visually to confirm that the heat treatment produced a color gradient appropriate for aged fiber (see Figure D.4-1).

The use of fiberglass insulation, such as Nukon is recommended as a surrogate for dry latent debris (Reference [4-1]). The fiber was processed into fines, mostly class 1 and 2, as defined in Reference [4-2]) for use in the test. The processing steps are described in Section 5 and photographs of the end result of the suspended fibers are shown in Figure D.4-2.

D.5 TEST PROCEDURE SUMMARY

D.5.1 Debris Preparation

Fiber fines were prepared based on NEI guidance (Reference [5-1]). Aged Nukon fiberglass insulation was cut into approximately 7.62 cm by 7.62 cm (3 inch by 3 inch) pieces. The cut pieces were then shredded in a leaf shredder/chipper, and the shredded fiber was then passed through the leaf shredder and additional two times. The fiber was shredded three times. The shred fiber was then weighed into 4 batches of 0.18 kg (0.4 lbm). A batch was placed into plastic container (approximately 0.121 m3 (32 gallons)) with approximately 0.008 m3 (2 gallons) of water. The fiber was thoroughly wet. The fiber was then separated using a pressure washer with a fan nozzle for 4 minutes.

The water fiber mixture was then further diluted into eight 0.019 m^3 (5 gallon) buckets with a total of 0.011 m^3 (3 gallons) of water in each bucket. Immediately prior to adding the fiber, the fiber was agitated with a propeller mixer on high for one minute. A sample of this fiber water mixture was taken to ensure the process produced fines that were nearly all class 1 and 2 fines (Reference [4-2]) (see Figure D.4-2). The fiber mixture was added to the tank and there were no fiber clumps as the fiber was poured into the tank. Photographs and video were taken of the fiber addition (for example see Figure D.5-1).

D.5.2 Test Setup

The test setup consisted of cleaning the facility and cleaning and assembling the strainer as shown in Figure D.2-1. The configuration is sketched in Figure D.5-2. The strainer was checked to ensure there were no gaps greater than 2.38 mm (0.094 inch). The tank and piping were filled with water at 22.2 °C (72 °F), which is above the 15.6 °C (60 °F) minimum required in the test plan. The water level was set 24 inches above the top of the strainer tubes.

All 9 filter housings were fitted with 1 μm (3.94×10^{-5} inch) felt filters to clean the water prior to the test starting. The data acquisition system was started and then the pump was turned on. The flow rate was set to 3,407 L/min (900 gpm), slightly greater than the target flow rate of 3,157 L/min (834 gpm), to improve pre-filtering. The water was filtered for greater than 10 pool turn over times (PTOs).

D.5.3 Filter Weighing

Each filter was numbered to identify the filter. Filters were stored in a room at 35% relative humidity and 25.6 °C (78 °F) for several days prior to the test. The filters were weighed individually and in groups of eight, since they would be used in groups of eight. The filters were weighed in the same room in which they were stored.

After the test the filters were allowed to dry in lab conditions. After most of the water was removed from the filters, the filters were hung in racks in the filter weighing room at the same conditions they were initially stored and weighed.

The filters were allowed to dry for several days and then weighed three times over a period of several hours to ensure the weight was stable. The post-test filters were weighed in the same groups of eight that they were used (and originally weighed).

D.5.4 Test Initiation

The test was initiated by setting the flow rate to 3,157 L/min (834 gpm) and swapping out the pre-filters for pre- weighed control filters. Data was already being acquired for head loss across the strainer, flow rate, and water temperature. Control filters were placed in eight of the filter housings with flow going through each of these eight filters. The ninth filter housing remained shut off and a pre-weighed, numbered filter that would be used to collect fiber was placed in that housing. No flow was going through that filter during the control filter portion of the test.

D.5.5 Filter Swapping

Filter swapping was performed to minimize flow disturbance and to avoid disturbing the debris bed on the strainer. Filters were swapped one at a time (only a portion of the flow could be disturbed). There were always eight filters active and one filter with no flow. To swap filters the valve on the downstream side of the unused filter was opened. Then the upstream valve of the unused filter was opened while the upstream valve of the neighboring active filter was closed. The new filter was now active.

The downstream valve on the used filter was closed completely isolating the filter. The vent valve on the filter was opened and then the drain valve was opened. The filter top was opened and when the water level in the filter housing was below the top of the filter, the drain valve was closed, the filter bag was removed and its number was recorded. Note that water draining from the filter housing drained through the filter bag and any fiber would be captured by the filter.

A new pre-weighed numbered filter (belonging to the same set of filters) was placed in the open filter housing. The filter number was recorded. The filter was sealed into the filter housing. Air was removed from the filter housing by cracking the upstream valve and allowing air to exit from the vent valve. Any water that exited through the vent passed through the removed filter to capture any fiber in the water. The filter was then hung up on a rack to dry.

This process was repeated for all filters and the last filter remained closed until the next filter change.

D.5.6 Debris Addition

After filter switching was complete fiber was added to the tank. Fiber fines were added from eight buckets and poured into the tank around the perimeter where the upwelling caused high level of turbulence. The fibers were suspended in the water and added to the tank without any visible fiber clumps.

There were four fiber additions of 0.18 kg (0.4 lbm) of fines.

D.5.7 Test Termination

The pre-filtering continued for a minimum of 10 PTOs prior to terminating this sequence and swapping filters for control filters. Filter swapping occurred after a minimum of 3 PTOs for the control filters. A minimum of 7 PTOs was used prior to terminating a fiber addition by swapping filters. After each fiber addition the pool was checked visually that all of the fiber was on the strainer. If no fiber was seen in the

pool, then after 2 additional PTOs fiber swapping was started.

After the fourth batch of fiber was added and 7 PTOs were completed the test was terminated by stopping the pump. The tank was then drained while photographing and videotaping the debris on the strainer and the clean tank. The last set of filters were removed from the filter housings and allowed to dry.

D.5.8 Post Test Observations

The fiber debris was collected on the bottom of the strainer tubes on both the inside and outside. The fiber was built up to a height of 12.70 cm - 20.32 cm (5 - 8 inch) (see Figures D.5-3 and D.5-4). The debris bed was less than 2.54 cm (1 inch) thick at the bottom and tapered to a thin coating at the top of the fiber (see Figure D.5-5). The debris remained on the strainer after the drain down and no fiber was found in the tank.

D.5.9 Test Discrepancies and Nonconformances

None.

D.6 RESULTS OF TESTING

A single bypass test was run. The bypass test was identified as APR1400-Bypass-0913-1. Four batches of fines representing latent debris were added at the times shown in Table D.6-1 and graphically in Figure D.6-1. Note that time zero on the plot represents 9:36 AM when the data acquisition unit was started. A PTO during pre-filtering was 9 minutes and during the test was 10 minutes. Note that during filter switching and venting all water that might contain water still passed through the filters.

Table D.6-1 Sequence of Events for Test APR1400-Bypass-0913-1

Event	Time	Number of PTOs
Pre-filtering	9:46AM to 12:31 PM	18
Switch filters	12:31 PM to 1:05PM	3.4
Control filter	1:10PM to 1:40PM	3
Switch filters	1:41PM to 2:05PM	2.4
First fiber addition	2:39PM to 2:45PM	0.6
Collect first fiber addition	2:45PM to 4:00PM	7.5
Switch Filters	4:13PM to 4:43 PM	3
Second fiber addition	5:00PM to 5:05PM	0.5
Collect second fiber addition	5:05PM to 6:18PM	7.3
Switch Filters	6:18PM to 6:45 PM	2.7
Third fiber addition	6:59PM to 7:04PM	0.5
Collect third fiber addition	7:04PM to 8:15PM	7.1
Switch Filters	8:16PM to 8:43 PM	2.7
Fourth fiber addition	8:51PM to 8:56PM	0.5
Collect fourth fiber addition	8:56PM to 10:10PM	7.4

D.6.1 Fiber Captured

Table D.6-2 lists the amount of fiber fines added and the change in weight for the control filters and the filters that captured fiber after each fiber addition. Note that most of the strainer area remained open for all additions (see Figure D.5-3). Each fiber addition was terminated after the tank appeared visually clear of fiber, which was confirmed near 5 PTO, then waiting two additional PTO for a minimum time of 7 PTO (see Table D.6-1). PTO was counted from the end of each fiber addition.

Table D.6-2 Summary of fiber bypass

Condition	Fiber added (g / lbm)	Filter weight change (g / lbm)
Control filters	0 / 0	0 / 0
After first fiber addition	181.2 g / 0.40 lbm	37.16 / 0.08
After second fiber addition	181.2 g / 0.40 lbm	29.66 / 0.07
After third fiber addition	181.2 g / 0.40 lbm	28.04 / 0.06
After fourth fiber addition	181.2 g / 0.40 lbm	29.08 / 0.06

D.6.2 Time Histories of Head Loss, Flow Rate, and Temperature

A plot of the head loss, flow rate and temperature are shown as a function of time in Figure D.6-1.

D.6.3 Bypass Fiber Length

Fiber that bypassed the strainer was captured in filter bags downstream of the test strainer. A random ample of fiber was removed from two of the filter bags, number 29 and number 21, from test APR1400-Bypass-0913-1. These fiber samples were from the second and third addition of the four fiber additions. The samples were obtained by manually removing a fiber from the filter bags. These fiber samples were analyzed with Lorentzen and Wettre Fiber Tester to determine fiber length distribution for bypassed fiber.

A total of 164,328 fibers (104,228 fibers for bag number 29, and 60,100 fibers for bag number 21) were identified with 59.4% less than or equal to 0.5 mm (0.020 inch) in length, 26.3% between 0.5 mm (0.020 inch) and 1.0 mm (0.039 inch) in length, and 14.3% that were greater than 1.0 mm (0.039 inch) in length (Table D.6-3). The bypassed fiber length distribution is shown in Figure D.6-2.

These fiber lengths are longer than the size distribution of bypassed fiber generally used by the pressurized water reactor owners group, which has 77% of the fibers less than 0.5 mm (0.020 inch), 18% between 0.5 mm (0.020 inch) and 1.0 mm (0.039 inch), and 5% greater than 1.0 mm 1 mm (0.039 inch) (Reference [6-1]), but this makes the fiber length distribution conservative for downstream effects (Reference [6-1]).

Table D.6-3 Bypassed Fiber Length Distribution in Value

Length	Percentage (%)		Total (%)	Ref. (%)
	Filter #29	Filter #21		
Fiber length ≤ 0.5 mm	60.0	58.4	59.4	77
0.5 mm < Fiber length ≤1.0 mm	26.0	26.7	26.3	18
1.0 mm < Fiber length	14.0	14.9	14.3	5

D.7 QUALITY ASSURANCE

All quality-related activities were performed in accordance with the Continuum Dynamics, Inc. Quality Assurance Manual (Reference [7-1]). Quality-related activities are those which are directly related to the planning, execution and objectives of the test. Supporting activities such as test apparatus design, fabrication and assembly are not controlled by the C.D.I. Quality Assurance Manual. C.D.I.'s Quality Assurance Program provides for compliance with the reporting requirements of 10 CFR Part 21. All instrument certifications, instrument calibrations, testing procedures, data reduction procedures, and test results are contained in a Design Record File which (upon completion) will be kept on file at C.D.I. offices.

D.8 CONCLUSION

To establish the quantity of fibrous debris that could potentially penetrate the strainer, prototype test was performed. The test was performed with only fibrous debris as adding particulates may reduce the amount of bypass debris due to clogging at the strainer. Additionally, the most conservative approach with bypass test is to assume all sump strainers are active running at the maximum flow rates since it stands to reason that more mass flow rate and more perforated plates causes more bypass.

To determine the plant strainer bypass debris, the cumulative quantity of bypass debris from the prototype test was scaled by a ratio of the plant strainer to the prototype strainer (600/75.1 = 8.0). The cumulative bypass quantities for debris loads are presented in Table D.8-1. The total bypass debris is the sum of the bypass debris for all active strainers as presented in Table D.8-2.

Total bypass debris for the APR1400 with 6.80 kg (15 lbm) of latent fiber is 1.67 kg (3.68 lbm) (~ 25%). The fibrous debris size distribution is measured to be 59.4% shorter than 0.5 mm (0.020 inch), 26.3% between 0.5 mm (0.020 inch) and 1.0 mm (0.039 inch), and 14.3% longer than 1.0 mm (0.039 inch). These test results about bypass rate and fibrous debris size distribution are used for inputs of the APR1400 in-vessel downstream effect tests.

Table D.8-1 Cumulative Prototype Bypass Debris

Fiber added (g/lbm)	Bypassed fiber weight (g/lbm)
181.4 / 0.40	37.16 / 0.08
362.8 / 0.40	66.82 / 0.15
544.2 / 0.40	94.86 / 0.21
725.6 / 0.40	123.94 / 0.27

Table D.8-2 APR1400 Bypass Debris Quantities

Strainer	Pumps	Flow rate (L/min / gpm)	Plant strainer debris load (kg / lbm)	Prototype strainer debris load (kg / lbm)	Prototype bypass debris (kg / lbm)*	Ratio of surface areas	Bypassed fiber mass (kg / lbm)
1	SIP+CSP	25,211 / 6,660	2.87 / 6.33	0.36 / 0.79	0.067 / 0.1475	8.0	0.54 / 1.18
2	SIP+CSP	25,211 / 6,660	2.87 / 6.33	0.36 / 0.79	0.067 / 0.1475	8.0	0.54 / 1.18
3	SIP	4,675 / 1,235	0.53 / 1.17	0.07 / 0.15	0.037 / 0.082	8.0	0.30 / 0.66
4	SIP	4,675 / 1,235	0.53 / 1.17	0.07 / 0.15	0.037 / 0.082	8.0	0.30 / 0.66
Total		59,772 / 15,790	6.80 / 15.0	0.85 / 1.88			1.67 / 3.68

*Conversion from gram to lbm is 453 g/lbm

D.9 REFERENCES

1-1 APR1400-E-A-T(NR)-13003-P, "APR1400 IRWST ECCS Sump Strainer Bypass Test Plan," Rev. 1, KHNP, August 2013.
4-1 Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Nuclear Energy Institute Guidance Report (Proposed Document Number NEI 04-07), "Pressurized Water Reactor Sump Performance Evaluation Methodology," Nuclear Energy Institute, December 2004.
4-2 NUREG/CR-6808, "Knowledge Base for the Effects of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance," U.S. Nuclear Regulatory Commission, February 2003.
5-1 "ZOI Fibrous Debris Preparation: Processing, Storage, and Handling," Nuclear Energy Institute, Revision 1 January 2012.
6-1 Duke Energy, "Path Forward for Resolution of GSI-191," May 2013.
7-1 "Quality Assurance Manual," Continuum Dynamics, Inc., Revision 14, February 2006.

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Figure D.2-1 Prototype Strainer in the Test Tank

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Figure D.2-2 Filter Housings

Figure D.2-3 Pump (on left), and Data Acquisition Flow Meter/DP Cells (on right)

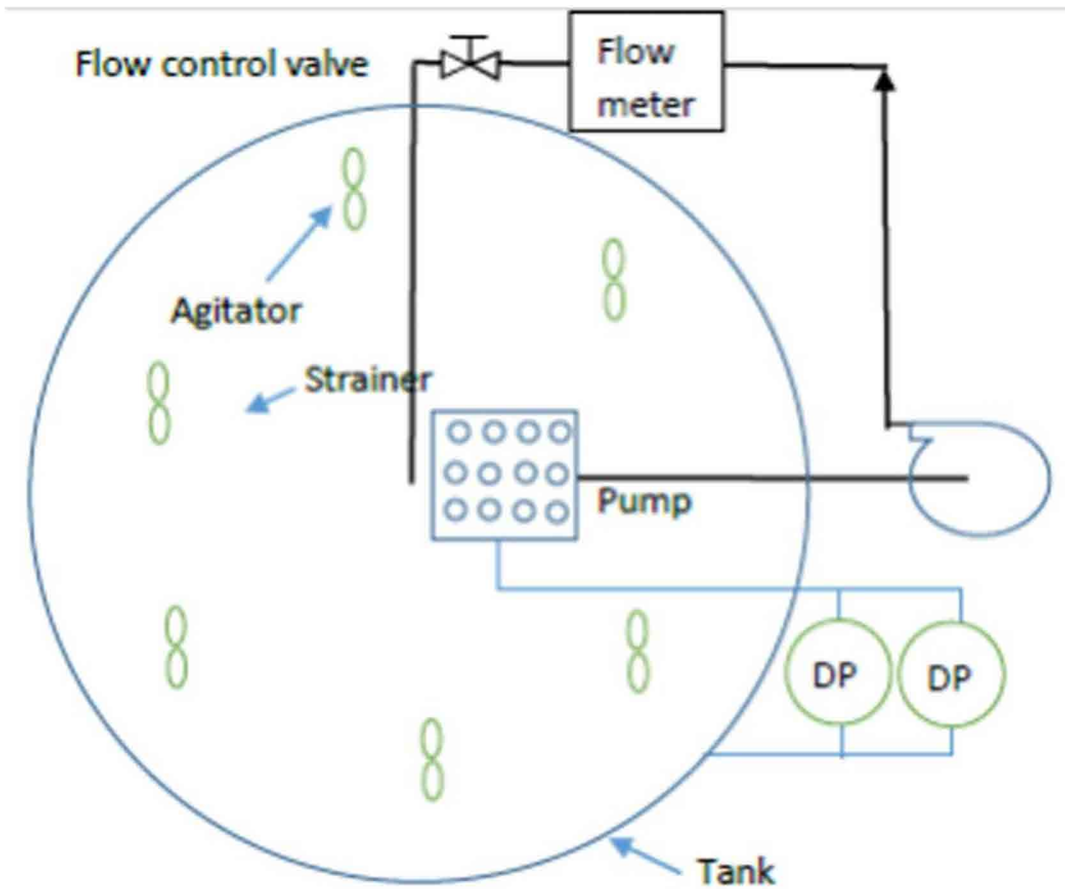

Figure D.2-4 Flow Schematic of Test Setup

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Figure D.3-1 Test Strainer Drawing

Figure D.4-1 Aged Fiber Sample

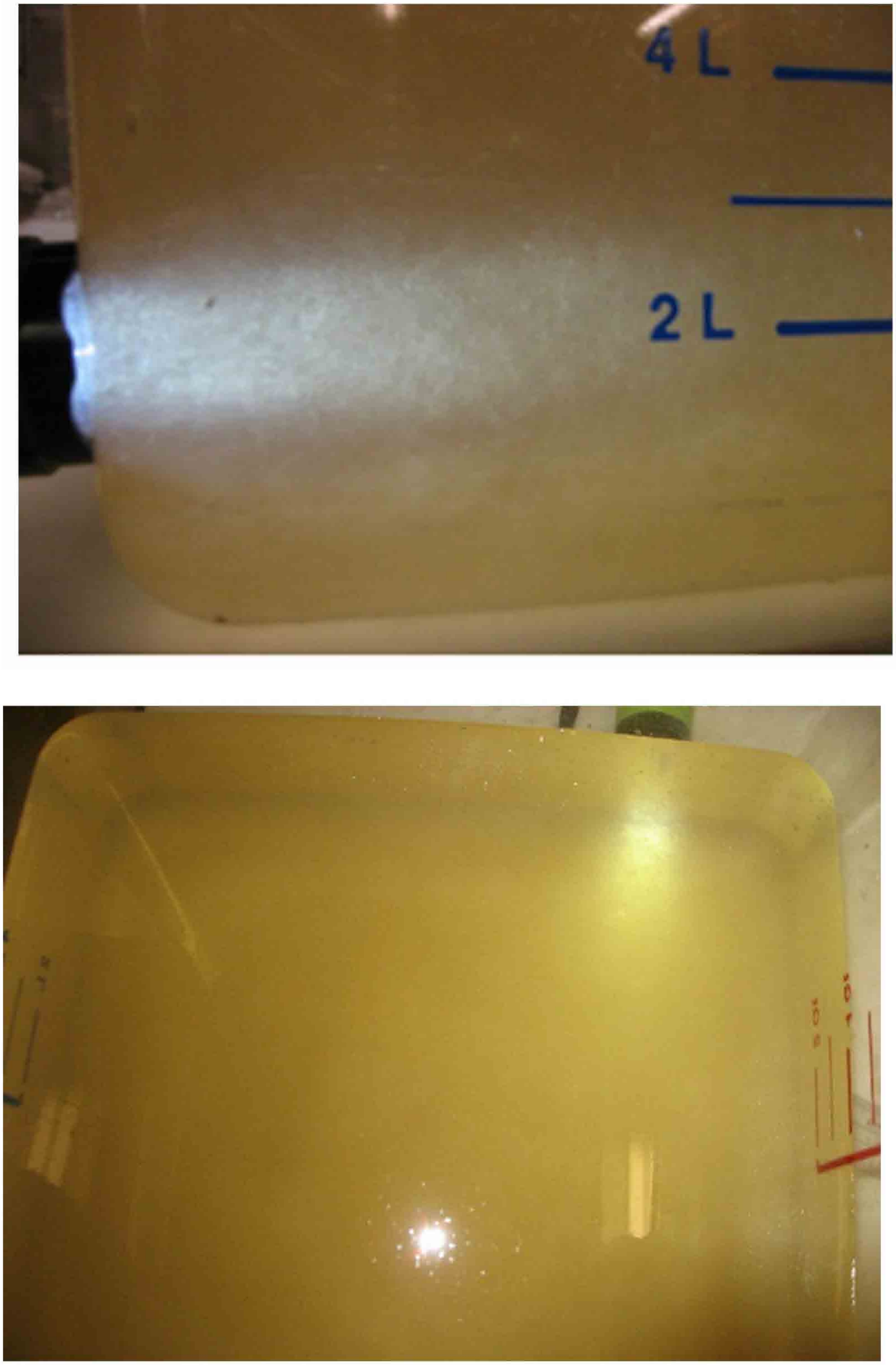

Figure D.4-2 Simulated Latent Debris Suspended in Water

Figure D.5-1 Typical Fiber Fine Addition

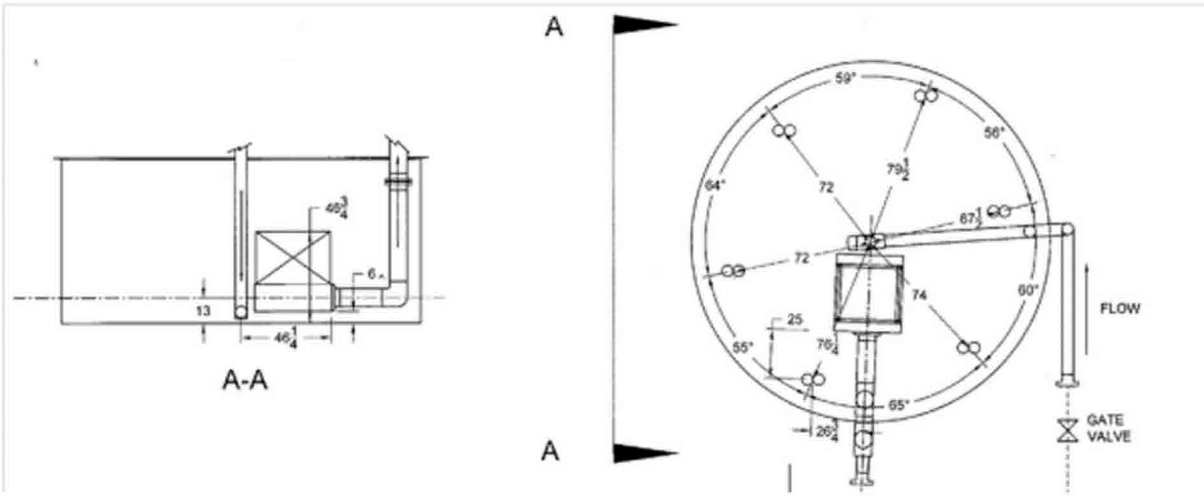

Figure D.5-2 Test Facility Layout

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Figure D.5-3 Strainer After Test and Drain Down

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Figure D.5-4 Strainer Tube Inside After Test and Drain Down

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Figure D.5-5 Detail of the Fiber Buildup Outside of the Fiber Tube

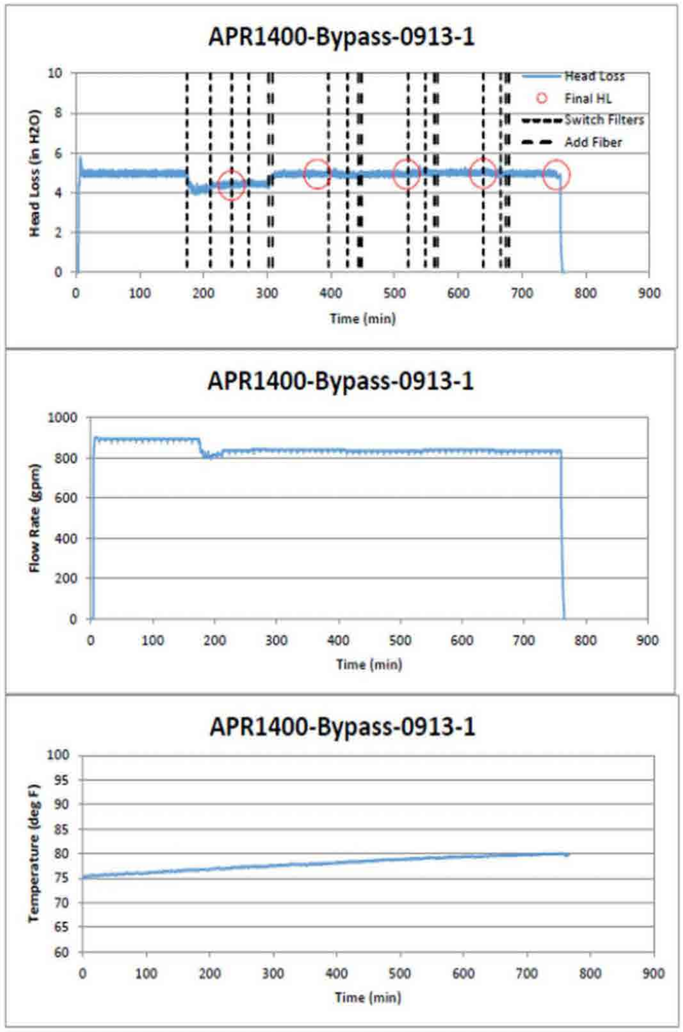

Figure D.6-1 Time Histories of Head Loss, Flow Rate, and Temperature

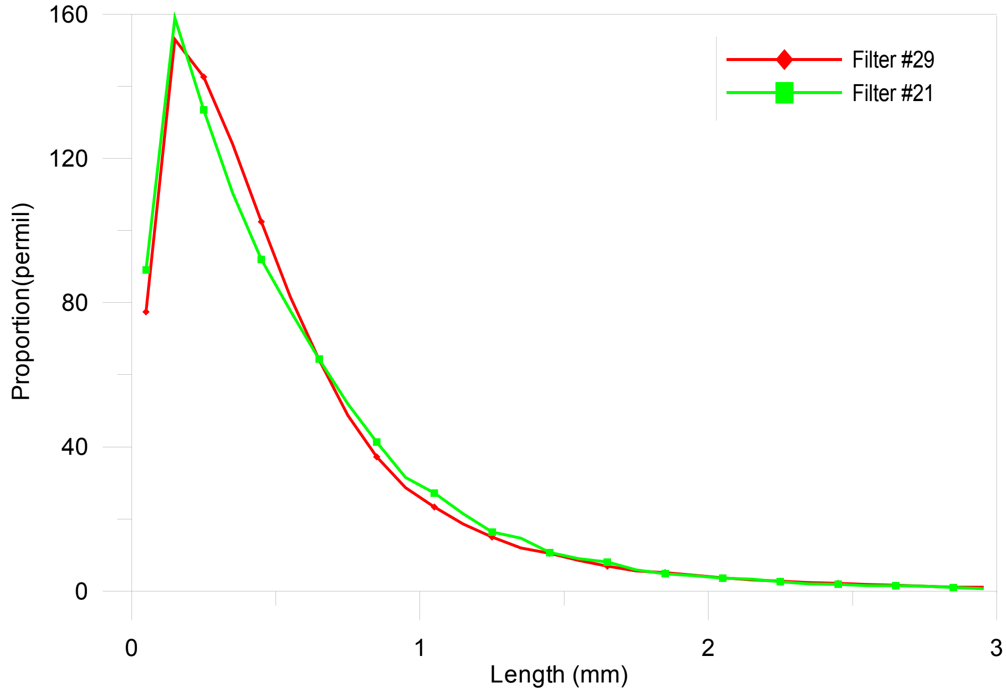

Figure D.6-2 Bypassed Fiber Length Distribution

Appendix E

Structural Drawings

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Figure E.1 Reactor Containment Building Section “A-A”

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Figure E.2 Reactor Containment Building Section “B-B”

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Figure E.3 Reactor Containment Building-Concrete Outline Dimensional EL. 81'-0"

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Figure E.4 Reactor Containment Building-Concrete Outline Dimensional EL. 100’-0”

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Figure E.5 Reactor Containment Building-Concrete Outline Dimensional EL. 114'-0"

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Figure E.6 Reactor Containment Building-Concrete Outline Dimensional EL. 136'-6"

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Figure E.7 Reactor Containment Building-Concrete Outline Dimensional EL. 156’-0”

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Figure E.8 Primary Shield Wall (Plan EL.69'-0")

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Figure E.9 Primary Shield Wall (Plan EL.100'-0")

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Figure E.10 Reactor & ICI Cavity Detail (Plan EL.69'-0")

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Figure E.11 Primary Shield Wall (Plan EL.117'-4")

TS

Figure E.12 Primary Shield Wall (Plan EL.130'-0")

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Figure E.13 Primary Shield Wall (Plan EL.130'-0")

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Figure E.14 Internal Structure (Plan EL.100'-0")

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Figure E.15 Internal Structure (Plan EL.114'-0")

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Figure E.16 Internal Structure (Plan EL.136'-6")

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Figure E.17 Internal Structure (Plan EL.156'-0")