APR1400 Design Features to Address GSI-191

Technical Report

Non-Proprietary

October 2013

RIVISION HISTORY

Revision	Page (Section)	Description
0	All	Issue for Standard

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 were 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.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS

APR1400	Advanced Power Reactor 1400
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 Pumps
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
FA	Fuel Assembly
GSI	Generic Safety Issue
HELB	High-Energy Line Break
HL	Hot Leg
HLSO	Hoe Leg Switchover
HVT	Holdup Volume Tank
ICI	In-Core Instrumentation
ID	Inside Diameter
IRWST	In-Containment Refueling Water Storage Tank
IWSS	In-Containment Water Storage System
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
NPSH	Net Positive Suction Head
$NPSH_a$	Available NPSH
$NPSH_r$	Required NPSH
$NPSH_{reff}$	Effective Required NPSH

NEI	Nuclear Energy Institute
NRC	US Nuclear Regulatory Commission
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
SG	Steam Generator
SI	Safety Injection
SIAS	Safety Injection Actuation Signal
SIP	Safety Injection Pump
SIS	Safety Injection System
SIT	Safety Injection Tank
SKN 3&4	Shin-Kori Nuclear Power Plant Units 3 and 4
TBE	Thin Bed Effect
TSP	Tri-Sodium Phosphate
UGS	Upper Guide Structure
US	United States of America
ZOI	Zone of Influence

1.0 INTRODUCTION

The purpose of this technical report is to provide the design features and evaluation results of the post-accident performance of the in-containment refueling water storage tank (IRWST) sump strainer of APR1400. It is to confirm that the emergency core cooling system (ECCS) and containment spray system (CSS) recirculation functions under loading conditions are in compliance with the applicable regulatory requirements of US 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 to address Generic Safety Issue (GSI) -191 in accordance with USNRC, SECY-12-0093 (Reference [1-2])

2.0 DESIGN DESCRIPTION

The following section describes the outlines of the current APR1400 design and how it satisfies the recommendations of USNRC Regulatory Guide (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 SI system is composed of four independent mechanical trains (without any cross-tie line among the injection paths) and four electrical divisions. 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 percent 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 percent of the required capacity. The low pressure injection pumps with common header installed in the conventional design are eliminated, and the functions for 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 or 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 (IRWST)

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 30.48 m (100 ft 0 in) 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 USNRC RG 1.82 (Reference [1-1]).

2.3 Design for Prevention of Degraded ECCS 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 the each entrance to HVT. Size of the 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 in), which represents 2.09 m^2 (22.5 ft^2) of screen surface. In addition, the size of the 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 in), which represents 6.68 m^2 (71.85 ft^2). The HVT trash racks prevent debris particles larger than 38.1 mm (1.5 in) 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 entering the HVT. The water then travels into IRWST through the IRWST spillways. The IRWST spillways are located at sufficiently high location to assure that much of the higher-density debris will settle 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 (3/32 in) 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 USNRC 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 in) 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 strainers hole size is smaller than 2.38 mm (3/32 in) in diameter. 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 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.

The criteria for coating are addressed in USNRC 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”. There is no unqualified coating inside the containment.

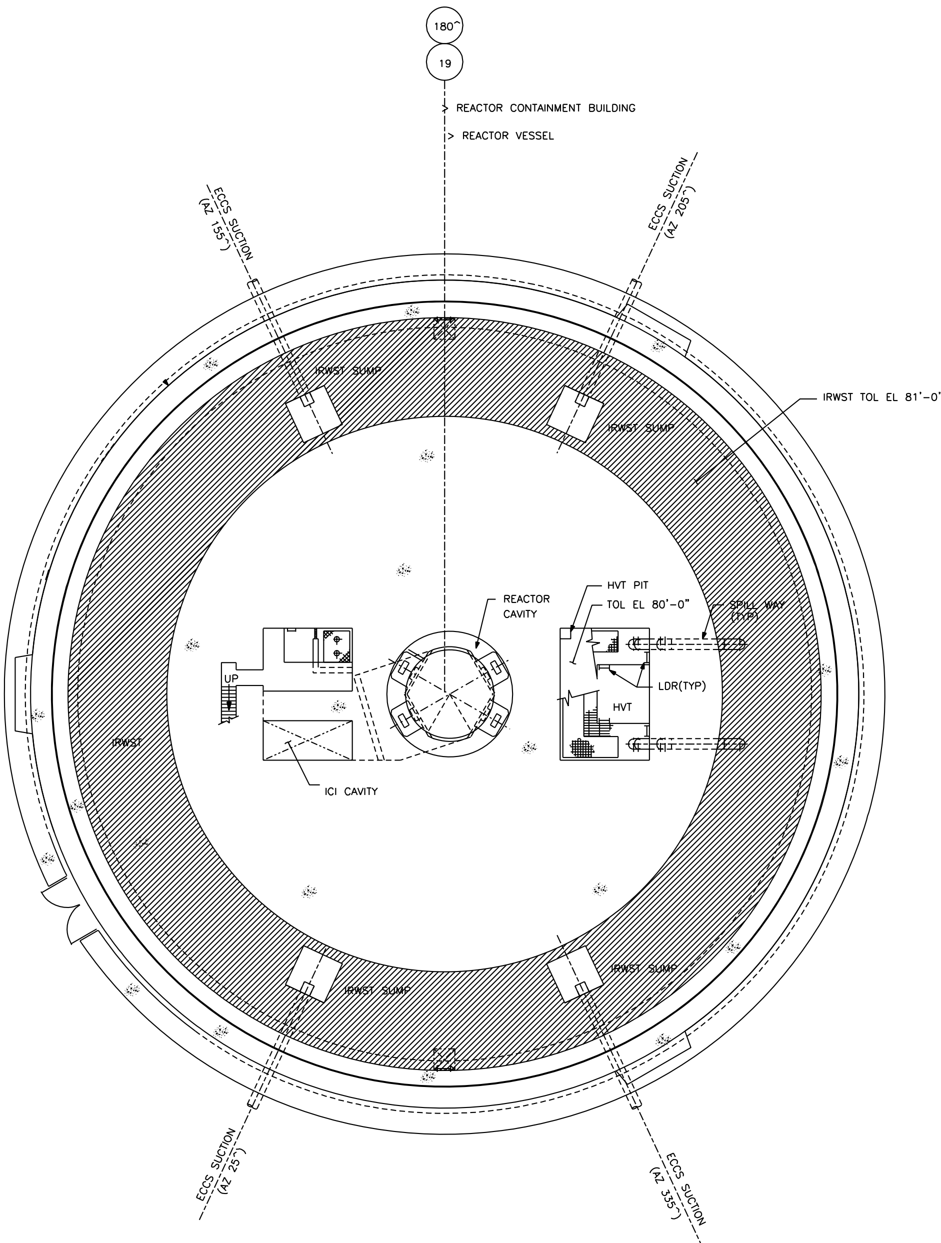

Figure 2.2-1 Plane View of IRWST

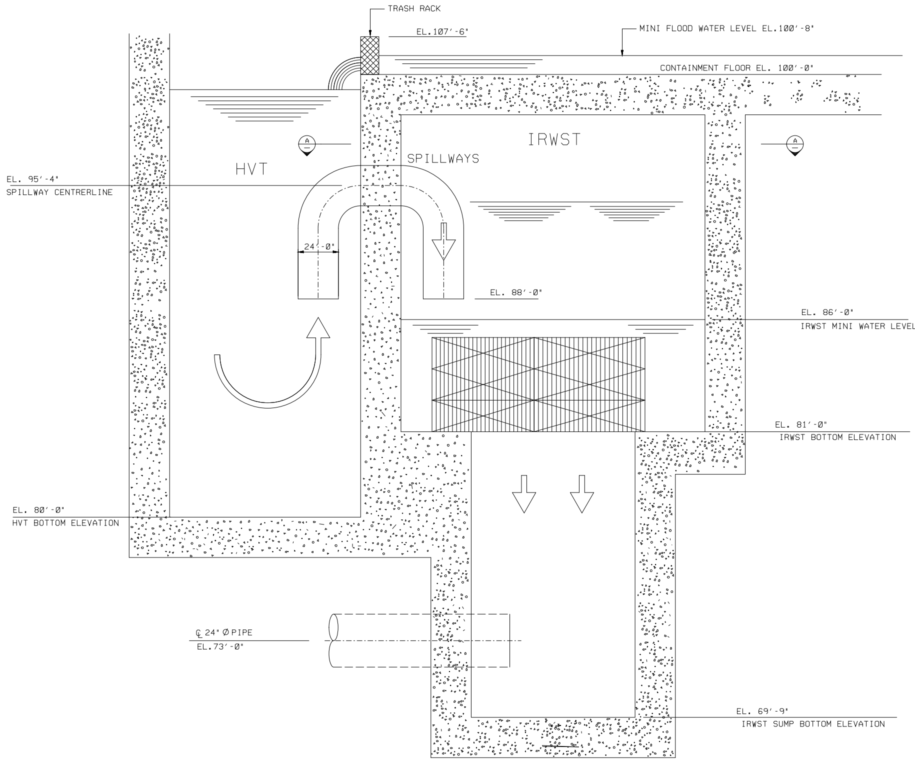

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Figure 2.2-2 IRWST Sump Pit Elevation View

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Figure 2.4-1 IRWST Sump Strainer

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

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

3.0 EVALUATION OF IRWST SUMP STRAINER PERFORMANCE

3.1 Break Selection

The in-containment refueling water storage tank (IRWST) sumps are only vulnerable to debris blockage when the sump is active. The analysis therefore requires an understanding of the accident progression to identify the extent of high-energy line break (HELB) to be evaluated for the potential to generate debris. The accident analysis and operational procedures were 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 identified the high-energy piping systems that were evaluated for a postulated HELB and associated debris generation.

3.1.1 Accident Scenarios

The design basis accidents (DBAs) requiring engineered safety features (ESF) system action are shown in Table 7.3-2 of the Design Control Document (DCD) (Reference [3-1]). These accidents result in full ESF initiation, which initiates four safety injection pumps (SIPs), and two containment spray pumps (CSPs). The shutdown cooling pumps (SCPs) 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)

   The section 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) (inside diameter (ID) 8 in pipe).

   The piping drawings associated with the reactor coolant system (RCS) were reviewed to identify the lines directly attached to the RCS. High-energy lines are shown in the 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 the IRWST sump recirculation.

   The design basis LOCA is based on a postulated double-ended cold leg (CL) (ID 30 in) 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 in), 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 were assessed to identify the break with the potential to generate the largest quantity of debris. The break locations were 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 Shutdown Cooling Pump 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)

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 operated charging system flow is not sufficient to sustain PZR level and pressure. Since SBLOCAs may not be isolated, they must be considered for debris generation, as many could eventually lead to IRWST sump recirculation. According to the Nuclear energy Institute (NEI) 04-07 (Reference [3-2]), only SBLOCA lines 2 in and larger are included in this evaluation up to the first isolation point.

As discussed in the LBLOCA section above, high-energy lines are shown 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 within the licensing basis, are not evaluated for debris generation, and do not lead to IRWST sump recirculation.

The SBLOCA was assessed to identify the break with the potential to generate the largest quantity of debris. The break locations were as follows:

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

3) Other high-energy line break (HELB) Scenarios

While LOCAs were considered the most likely type of debris generating HELBs that could lead to IRWST sump recirculation, other scenarios were evaluated to determine whether or not these breaks 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 operation are initiated upon safety injection actuation signal (SIAS) and containment spray actuation signal (CSAS) after MSLB following Table 7.3-2 of the DCD (Reference [3-1]).

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

3.1.2 Selection of the Postulated Break Location

Break location is selected considering the determination of the size and location of HELBs that produce debris and potentially challenge the performance of the IRWST sump strainers. Since this break location was not known prior to the evaluation, the break selection process required evaluating a number of break locations in order to identify the location that is likely to present the greatest challenge to post-accident sump performance. The debris inventory and the transport path were both considered when making this determination.

Based on the pipe break sizes and locations which are determined as a result of the above reviews of the accident analysis and operational procedures that require the ECCS and CSS to take suction from the IRWST sumps, the postulated break location is selected by considering the guidance recommended in NEI 04-07 (Reference [3-2]) and Safety Evaluation (SE) for NEI 04-07 (Reference [3-3]).

Sections 3.3.4 and 4.2.1 in the 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 the size, quantity, and type of debris are identified. The following general break locations were considered:

Break Criteria

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

2) Largest break with two or more different type of debris

3) Breaks in the most direct path to the sump

4) Large break with the largest potential producing particulate debris to insulation ratio by weight

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

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

The criterion 1) of the above break criteria for postulated break location is bounded by criteria 2) and 4), which are not applied in APR1400 because the type of the insulation used for the piping and the equipment is only the reflective metal insulation (RMI) and particulate insulation is not used. Particulate debris is generated from coating and latent debris. As discussed in Section 3.2 of this report, the coating debris and latent debris of the APR1400 are conservatively considered maximum volume, regardless of the break location. Therefore, the APR1400 does not require identifying the break location that generates maximum volume of particulate debris.

As discussed in Section 2.4, RMI is used for the piping and components in the containment. The diameter of the ZOI is defined as 2 ID of the broken pipe based on the approved methodology, NEI 04-07 Guidance Report amended by NRC Safety Evaluation. Most of RMI debris is generated from itself, which is shielded by primary shield wall as a robust barrier. Therefore, only a small amount of

RMI debris is generated from the RCS pipe which has the largest inner diameter (42 in) and the RCS pipe is selected as the location of the pipe break.

Consequently, the location of break is determined by considering the RMI as the single representative type of debris materials.

For the RMI debris generation, the diameter of the ZOI is defined as 2 ID of the broken pipe. Figure 3.1-1 shows a spherical region within a distance equal to 2 ID of the broken pipe when the junction of the RCS HL line (42 in) and SG is broken. As shown, the boundary of ZOI extends from the center of break to the primary shield wall at right side, a portion of the SG No. 2 at left side, a portion of SG No. 2 at upper side, and a portion of pedestal of SG No. 2 at lower side. Therefore, the worst case of RMI debris generation is inside one SG compartment.

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

For the evaluation of “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 particle debris. As discussed above, the worst case of particulate debris generation is considered in the evaluation.

3.2 Debris Generation

As delineated in Section 3.1.2, the worst case of debris generation is the RCS HL line (42 in) break, RCS CL line (30 in) break, or main steam line (30.907 inch) break. The methodology and results of debris generation used for three limiting break are described in the following subsections.

3.2.1 RCS Hot Leg Line Break

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

In estimating the debris generation, the spherical ZOI is used. The ZOI is defined as the volume about a given HELB in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coatings, and other materials within the zone. NEI 04-07 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, fixed debris) within the ZOI were evaluated. The destruction pressures and associated ZOI radius for material used in the APR1400 are taken from Table 3-2 of the SE for NEI 04-07 (Reference [3-3]) and are provided in Table 3.2-1.

A CAD model was developed for the APR1400 using structural drawings and used to evaluate debris generation. The model includes the structure of the lower and upper containment, components, and pipes. The model was used to assist in the identification of debris sources and robust barriers within a given ZOI.

For the postulated break, a ZOI sphere was placed in the model centered at the break location. The coated surface area within the coating ZOI was then determined using various features of the

Microstation three-dimensional model. Credit was taken in a conservative manner for some areas shielded by robust barriers. The CAD model includes walls, floors, major equipment, structural supports, and pipes. Coated items not included in the CAD model (e.g. grating, minor equipment, valves) were accounted for by incorporating a safety factor in the overall coated steel surface area.
The evaluation of debris generation for each debris type is as follows:

1) Insulation debris

A 42-in break on the SG No. 2 HL pipe (42 in) at the SG nozzle was chosen as discussed in Section 3.1.2.

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

$$\frac{r_{IZOI}}{D_{BREAK}} = 2 \quad \text{---} \ (1)$$

Where,
r_{IZOI} = spherical ZOI radius for RMI
D_{BREAK} = ID of break pipe (42 in)

Using Equation (1), the radius of the spherical ZOI for RMI is calculated as 2.13 m (7 ft). For a given break location, the boundary of the ZOI was shown in the Figure 3.2-1 and 3.2-2.

In accordance with the guidance given in Section 3.4.2.3 of the SE for NEI 04-07 (Reference [3-3]), when a spherical ZOI extends beyond a robust barrier, the barriers may prevent further expansion of the break jet, but they can also cause deflection and reflection. Section 3.4.2.3 of the SER states that when a spherical ZOI extends beyond robust barriers such as walls or encompasses large components such as tanks and SGs, the extended volume may be conservatively truncated. The SER also stipulates that "shadowed" surfaces of components should be included in the analysis.

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

2) Coating debris

The coatings used on structures, system, and components within containment in the APR1400 are qualified coating type, a DBA qualified and acceptable coating system, as discussed in Section 2.6.

As described in Sections 3.4.3.3.3 and 3.4.3.3.4 of NEI 04-07 (Reference [3-2]), qualified and unqualified coatings within the coating ZOI were assumed to fail, and all qualified coatings located outside the coatings ZOI were considered not to fail when subjected to containment spray (CS) or immersed in the post-DBA pool.

As for coating debris, the ZOI for qualified coatings is a sphere with a radius 4 times the break pipe inner diameter in accordance with 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” (Reference [3-4]), which generates the largest amount of coating debris; the volume of coating debris was calculated by multiplying the surface area within the ZOI sphere by the thickness of the coating film.

The most accurate way to quantify the coating debris source term for the ZOI is to base the calculation on the surface within the 4D coating ZOI. This method was accomplished by using the CAD model developed as a part of the IRWST sump analysis and estimating the total concrete and steel surface area within the ZOI. The CAD model was manipulated so that the surface areas of concrete within the 4D ZOI could be calculated. For the postulated break, a ZOI sphere was placed in the model centered at the break location. The painted surface area within the sphere was then determined using various features of Microstation 3D CAD. Credit was taken in a conservative manner for some areas shielded by robust barriers. Table 3.2-2 provides the data of each coating material and/or coating system in coating service level I. The thickness of the coating film was chosen and reflected conservatively from the data in Table 3.2-2.

Using the methodology above, the total qualified coating volume is 0.081 m^3 (2.85 ft^3). However, in order to account for other steel surfaces such as grating and miscellaneous items not included in the CAD model, the coating volume was increased by about 10% to 0.088 m^3 (3.1 ft^3). This gives a total qualified coating volume of 0.088 m^3 (3.1 ft^3).

3) Latent debris

Latent debris is defined as unintended dirt, dust, paint chips, fibers, pieces of paper (shredded or intact), plastic, tape, or adhesive labels, and fines or shards of thermal insulation, fireproof barrier, or other materials that are already present in the containment prior to a postulated break in a high-energy line inside containment. Dust and dirt include miscellaneous particulates already present in containment prior to a postulated pipe break. Potential origins of this material include activities performed during outages and foreign materials brought into containment during outages. The characteristics of latent debris are provided in NUREG/CR-6877 (Reference [3-5]).

In general, the quantity and type of latent debris should be determined based on the walkdown data. However, the walkdown data cannot be used because the APR1400 plant is not construction plant. The 90.72 kg (200 lbs) is assumed to be latent debris. In accordance with the NEI 04-07(Reference [3-2]), the recent sampling of surfaces inside containment at a number of plants in the US indicated that it is likely that the maximum mass of latent debris inside containment is less than 90.72 kg (200 lbs). This value is enough for conservative evaluation of quantity of debris.

In addition, the sacrificial surface area of the IRWST sump strainer is considered for the miscellaneous debris such as tapes, tags, stickers or placards controlled by foreign material control program established by the plant owner. To deal with uncertainty of the

miscellaneous debris, a 2.83 m^3 (100 ft^2) penalty of sacrificial strainer surface area per each strainer is applied as a margin for future detail design and installation of the APR1400.

From the evaluation results of debris generation 1), 2) and 3) above, the amount of insulation, coating, and latent debris assumed for RCS hot leg (42 in) pipe break is summarized in Table 3.2-3.

1) Assessment of material potentially produced corrosion products

The containment materials can contribute to the production of corrosion products due to chemical reactions in the sump pool. The qualified coatings are assumed to fail as a direct result of jet. The failure results in the coated concrete becoming exposed to the sump/spray fluid. Interactions between the sump/spray fluid and structural materials in containment can contribute to corrosion products. The dissolved corrosion products can potentially form new chemical debris sources that can affect ECCS performance at the IRWST sump strainer.

Based on industry research in the US, the PWR Owner’s Group (PWROG) conducted a series of single effects dissolution tests designed to quantify the type and amount of chemical precipitates that would be generated during a post-LOCA environment. The PWROG test program implemented a test matrix that varied individual parameters, such as insulation type or exposed metal surface, neglecting the potential integrated effects that could arise. The PWROG program identified aluminum and calcium as the significant contributors to the production of corrosion products.

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 [3-6]).

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 to conservatively 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 3D model. 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 APR1400 are associated with the following types of equipment:

(a) Four reactor containment fan coolers
(b) Four SG enclosure recirculation fans

(c) Four annulus area recirculation fans
(d) Duct insulation
(e) Ex-core detectors
(f) Refueling equipment
(g) Control element drive mechanism cooling fan
(h) Surveillance capsule handling tools
  (i) Retrieval tool
  (ii) Remote positioning tool

(i) 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 3.2-4.

3.2.2 RCS Cold Leg Line Break

The method used for the debris generation of a RCS HL line break in Section 3.2.1 is applied to the debris generation for RCS CL (30 in) line break.

1) Insulation debris

Using Eq. (1) in Section 3.2.1, the radius of the spherical ZOI for the RCS CL line break is calculated as 1.52 m (5 ft). For a given break location, the boundary of the ZOI was shown in the Figure 3.2-3 and 3.2-4. The volume of insulation debris within the ZOI was calculated using the Microstation 3D program.

2) Coating debris

The boundary of the ZOI for coating debris is calculated as 3.05 m (10.0 ft) by the application of the same method used for RCS HL line break. The amount of coating debris of 0.011 m^3 (0.38 ft^3) is calculated.

3) Latent debris

The amount of latent debris is assumed to be 90.72 kg (200 lbs) based on the same reason used in Section 3.2.1.

4) Assessment of material potentially produced corrosion products

The amount of the potentially produced corrosion products is assumed to be the same quantity specified in Section 3.2.1.

3.2.3 Main Steam Line break

The method used for the debris generation of RCS HL Break in Section 3.2.1 is applied to the debris generation for MSLB (30.907 inch).

1) Insulation debris

Using Eq. (1) in Section 3.2.1, the radius of the spherical ZOI for the MSLB is calculated as 1.58 m (5.2 ft). For a given break location, the boundary of the ZOI was shown in the Figure 3.2-5 and 3.2-6. The volume of insulation debris within the ZOI was calculated using the Microstation 3D program.

2) Coating debris

The boundary of the ZOI for coating debris is calculated as 3.17 m (10.4 ft) by the application of the same method used for RCS HL line break. As shown the Figure 3.2-5 and 3.2-6, the boundary of ZOI is confined in itself, which is not extended to the primary shield wall as robust barrier. Even though there are gratings and support structures within the ZOI, the amount of their coating is expected to be negligible.

3) Latent Debris

The amount of latent debris is assumed to be 90.72 kg (200 lbs) based on the same reason used in Section 3.2.1.

4) Assessment of material potentially produced corrosion products

The amount of the potentially produced corrosion products is assumed to be the same quantity specified in Section 3.2.1.

From the results in Subsection 3.2.1 through 3.2.3 above, the amount of insulation, coating, and latent debris assumed for three break locations is summarized in Table 3.2-3.

From the Table 3.2-3, in the APR1400, the junction of the RCS HL pipe (42 in) and SG was selected as the postulated limiting break location. This selection for break location is reasonable because the SGs have a larger volume of insulation applied to them than does RCS piping and most of the primary system piping is located in this compartment. The more the amount of insulation presents, the larger the volume of debris is 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) Latent debris – Latent debris is dirt, dust, lint, and other miscellaneous materials that may be present inside containment before the initiation of a LOCA.

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

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 indicated that 90.72 kg (200 lbs) of latent debris with a 15 percent / 85 percent (fiber to particulate) spilled to determine latent debris loads. The APR1400 assumes that 90.72 kg (200 lbs) of latent debris with a 7.5 percent / 92.5 percent (fiber to particulate) spilled to determine latent debris loads, all fibrous latent debris within containment is fine, and there is no need for explicitly defining any fibrous debris size characterization.

Fibrous debris is categorized as 4 groups by the SE for NEI 04-07 (Reference [3-3]):

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

2) Small piece that readily sinks in hot water, then transports along the floor when flow velocities and pool turbulence are sufficient

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

4) Large debris that readily sinks in hot water and can transport along the floor when velocities and pool turbulence are sufficient

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

The NEI 04-07 (Reference [3-2]) guideline adopts the value of 75 percent for small fines and 25 percent for large pieces as the size distribution of any type of RMI inside a pipe break ZOI. For the APR1400, 25 percent of the RMI debris generated is large pieces and 75 percent of the RMI debris generated is in the form of small fines.

Section 3.4.3.2 of NEI 04-07 (Reference [3-2]) provides a discussion 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 baseline evaluation. The two size groups are small fines (< 4 in) and large pieces (> 4 in). Small 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. Furthermore, small fines are assumed to be the basic constituent of the material for latent debris and coatings (in the form of individual fibers, particles, and pigments, respectively). The RMI debris is sufficiently dense and the flow rates are also sufficiently small so that the RMI debris is not transported to the APR1400 strainer. RMI is composed of thin layers of stainless steel foil. Stainless steel has a density of 7.85 g/cm^3 (490 lbm/ft^3).

Guidance provided in NEI 04-07 (Reference [3-2]) and the SE for NEI 04-07 (Reference [3-3]) indicates the following effects for coatings:

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 Section 3.4.3.2 of NEI 04-07, all qualified coatings within the ZOI are considered small fine particles with a particulate size of 10 μm (0.394 mil). All coating debris will be suspended and transported in the recirculating water along with the latent debris to the strainers.

The debris characteristics used in the APR 1400 evaluation are presented in Table 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 characteristics of 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 Section 3.6.1 of NEI 04-07 (Reference [3-2]), four major debris transport modes are considered.

1) Blowdown transport - The horizontal and vertical transport of debris by the break jet. All fiber, particulate, and RMI debris are transported to the containment floor. No debris is transported upwards to the containment dome.

2) Washdown (containment spray) transport - The vertical transport of debris by the containment sprays/break flow. Since all fiber, particulate, and RMI debris are modeled as transporting to the containment floor during blowdown, there is no washdown transport.

3) Pool fill-up transport - The horizontal transport of the debris by break and CS flows to active and inactive areas of basement pool. All fiber and particulate debris are transported out of the SG D-rings to the holdup volume tank (HVT) and assumed to be transported to the IRWST. The RMI is sufficiently dense and the flow rates are also sufficiently small so that the RMI debris will not be transported to the APR1400 strainers. No transport to inactive volumes is modeled.

4) Recirculation transport - The horizontal transport of the debris in the active portions of the basement pool by the recirculation flow through the ECCS/CSS. All fiber, particulate, and RMI debris are assumed to be collected in the HVT and transported to the IRWST sump strainers by recirculating water. The RMI is assumed not to be transported to the IRSWT sump strainer because of the containment bottom floor’s (El. 100 ft 0 in) lower postulated flow velocity. Table 4-2 in NEI 04-07 guidance (Reference [3-2]) provides flow characteristics of the RMI debris, and indicates the terminal settling velocity (i.e., 0.113 m/s (0.37 f/s)) and lift over curb velocity (i.e., 0.256 m/s (0.84 f/s)) of the RMI fine debris. These flow velocities demonstrate that the RMI debris settles on the floor and does not rise up to the floor surface even.

All particulate and coating debris are 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 has 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 assumed to be uniformly distributed. All latent fiber is assumed to have the same fiber diameter as Nukon insulation.

The APR1400 has four ECCS/CS trains with an independent strainer for each train. The design requires a minimum three trains in operation assuming another trains have a single failure. Therefore, transported debris in the IRWST is assumed to be distributed to three sumps. However, the APR1400 assumes all of break-generated coating, latent debris, and chemical recipitates will be 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 should maximize the amount of bypass debris, i.e., assume 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 utilizes 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 and the types and quantities of debris are limited to latent fiber and particulate, coatings, and chemical effects.

The strainer is designed based on the following conditions:

1) Flow Condition
   (a) Flow rate (L/m / gpm) ....25,211 / 6,660
   (b) Fluid temperature (°C / °F) ....60 – 110 / 140 - 230

2) Debris Quantities
   (a) Epoxy paint (m^3 / ft^3)...0 - 0.0878 / 0 - 3.1
   (b) Latent fiber (kg / lbs)..6.80 / 15
   (c) Latent particulate (kg / lbs) ....83.91 / 185

3) Chemical debris to have the potential to cause chemical effects

   (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 or qualification 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 provided in the NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing, March 2008 (Reference [3-7]). The test plans and test results are attached in

Appendix B.

Validation of the final strainer sizing of 55.74 m^2 (600 ft^2) was 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 results 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, this pressure drop will be 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 was to develop experimental head loss data associated with the specified debris loadings. Flow sweeps were 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 measured and recorded differential pressure across the strainer, fluid temperature, and pump flow rate for the debris mixtures identified in the test matrix. The testing was designed to either 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 will result in acceptable head loss.

Two tests were performed. The difference between the first and second head loss test is the change in effective surface area of the strainer to account for labels and tags. The first test was run using an effective surface area of 55.74 m^2 (600 ft^2) and the second test was run using an effective surface area of 46.45 m^2 (500 ft^2). This was accomplished by increasing the test flow rate for the second test from 3,157 L/m (834 gpm) to 3,785 L/m (1,000) gpm and increasing the mass of debris per square foot. Additionally as a result of the NRC witnessing the first test, the second test used 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 the test plan. The test plan and test result are attached in Appendix B.

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 15.54 cm-water (0.51 ft-water). Therefore, the debris only head loss for both tests is essentially the same at 9.14 cm-water (0.3 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.”

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.

3.5.3.3 Total Strainer Head Loss

The prototype debris head loss test results and calculated clean strainer head loss were 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 will be conservatively calculated by double counting the clean screen component (using the analytical value and the test value inherent in the measure debris head loss) or 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 the $NPSH_a$ 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 instrumentations. Each SIP is normally aligned with its own suction line from the IRWST and its own discharge line to a direct vessel injection (DVI) nozzle on the reactor vessel (RV) or the DVI nozzle/hotleg. SI lines 1&2 inject the borated water to RCS through the DVI nozzles and SI lines 3 &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 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 high containment pressure signal. For long-term mode, operator actions will be required. Operator actions depend on break size, time into the LOCA, and whether or not the LOCA has been isolated.

The long-term mode is manually initiated at approximately 2~3 hours post-LOCA at which time 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. This configuration with 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 utilizing the SG atmospheric dump valves and auxiliary feedwater system.

The CSS consists of two 100 percent 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 a 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 SCPs, 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 utilized for NPSH evaluation. The maximum flow rate for the SIP and CSP/SCP are 4,675 L/m (1,235 gpm) and 20,536 L/m (5,425 gpm) respectively. The SIP and CSP or SIP and SCP operate simultaneously while drawing from 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 fulfills the requirements of USNRC RG 1.1, "Water Sources for Long-term Recirculation Cooling Following a Loss-of-Coolant Accident" (Reference [3-8]) & 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 USNRC 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, 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 the associated injection valves operate from one emergency power supply, the other SIPs and injection valves from each 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 for one CS pump or for one SC pump). The most limiting single failure for IRWST sump strainer is a single CSP or SCP failure caused by a failure of 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 (212º F). 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 parts of the LOCA transient. Moreover, fluid condensed by passive heat sinks (such as the containment shell liner, supporting structures and concrete) and the containment sprays is added to the IRWST. The condensed water entering the IRWST will be 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 containment spray operation. The condensed water is also saturated at the steam partial pressure.

Therefore, a higher containment pressure provides higher temperature condensed water and higher IRWST liquid temperatures. Similarly, a lower containment pressure provides lower temperature condensed water 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 shows the containment pressure and IRWST water temperature response during 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 KHNP, "Technical Report of LOCA M/E Methodology" (APR1400-Z-A-NR-13007-P, Rev.0 (Proprietary) and APR1400-Z-A-NR-13007-NP, Rev.0 (Non-Proprietary)) (Reference [3-9]). The IRWST maximum water temperature is 103.23 °C (217.82 °F) at 25,510 sec. Containment pressure at the maximum IRWST water temperature is 15.36 psia higher than saturation pressure, which provides reasonable assurance that water temperature will 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 CS System.

(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 the EPRI, Advanced Light Water Reactor Utility Requirements Document Vol. II, ALWR EVOLUTIONARY PLANT, Ch.5 "Engineered Safety System" (Reference [3-10]).

With the CSS actuated, the reactor cavity and in-core instrumentation (ICI) cavity are assumed flooded to a level that can overflow into the floor of El. 100 ft 0 in through the openings of hot and CL pipes (El. 114.29 ft). The HVT is also to a level that is 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 assumption above, IRWST water level for $NPSH_a$ calculation is determined the water level of 5 ft above IRWST bottom (El. 81 ft 0 in). The details of the calculation of minimum water level are given in Section 3.9.2.

(d) Head loss

Head loss calculations for $NPSH_a$ are prepared based on hydraulic models of the system aligned to take suction from the IRWST. The system configurations of SIP suction and CSP/SCP suction are not changed 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 $NPSH_a$ calculation is conservatively based on the maximum pump flow rate. These calculations use Eq. 3-5, 3-14 and 3-15 of Crane Technical Paper No. 410, "Flow of Fluid Through Valves, Fitting, and Pipe" (Reference [3-11]) 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 (Pipe, fitting, and so on) is 10 °C (50 °F) of minimum temperature of IRWST.

(e) Strainer Head Loss

The strainer head loss will use 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 tests plan and results are provided in Appendix B. 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 15.54 cm-water (0.51 ft-water). As a result of the strainer testing, head loss of approximately 41 percent 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 will 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 of 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 [3-12]), uncertainty factors associated with $NPSH_r$ are considered to determine the effective $NPSH_r$ ($NPSH_{reff}$) as follow:

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

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

(a) The $NPSH_r$ varies with changes in pump speed caused by motor slip.
(b) The $NPSH_r$ decreases with increasing water temperature.
(c) Incorrectly designed field suction piping adversely affects the $NPSH_r$.
(d) The air content of the water used in the vendor's test may be lower than that of the pumped water in the field.

The $NPSH_r$ curves have not been adjusted to consider the positive impact of increasing water temperature (factor (b)). This results in a conservative value for $NPSH_r$. A 21 percent margin has been applied to account for the effects of the other three uncertainty factors. This margin is consistent with that used in operating plants. The effective $NPSH_r$ of the procured pump will be confirmed through 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 margin above the nominal $NPSH_r$ (NPSH required 3 percent) identified by the vendor in the preliminary design phase. 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). Also, the design-basis NPSH required for SIP is specified as 6.71 m (22.0 ft), although from 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 are 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 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)

$h_{atm} = h_{vap}$

(b) For T< 100 °C (212 °F)

h_{atm} = maximum of the initial containment pressure before postulated LOCA
h_{vap} = 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 time period prior to the IRWST reaching 100 °C (212 °F), the analysis assumes subcooled liquid at 1 atm (14.7 psia), which was the

containment pressure before the accident. When IRWST temperature is greater than 100 °C (212 °F), the containment pressure I set equal to the IRWST liquid vapor pressure.

The peak IRWST temperature from the Figure 3.6-3 is 103.23 °C (217.82 °F). The limiting evaluation of 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 $NPSH_m$ was calculated for the SIPS and CSPs for coolant temperatures from 48.9 °C (120 °F) to 104.4 °C (220 °F) based on the containment pressure and temperature for the post-accident long-term phase as 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.

Figure 3.6-3 to create the time-dependent NPSH curves shown in Figure 3.6-4 and Figure 3.6-5. 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 Figure 3.6-4 through 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 0.90 m (2.95 ft) for SIP and 0.65 m (2.14 ft) for 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

Section 6.3 of Enclosure 1 to SECY-11-0014 (Reference [3-12]) 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 which correspond to the maximum erosion zone is 8.05 - 10.73 m (26.4 - 35.2 ft). From Table 3.6-2, these pumps will experience maximum erosion when the fluid temperature is between about 90.6 °C (195 °F) and 100 °C (212 °F). Similarly, the maximum erosion $NPSH_a$ range for the CSPs with an $NPSH_r$ of 5.33 m (17.5 ft) is 8.05 - 10.73 m (26.4 - 35.2 ft). From Table 3.6-3, these $NPSH_a$ values occur when the fluid temperature is between about 90.6 °C (195 °F) and 100 °C (212 °F). A review of the temperature data shown in Figure 3.6-3 indicates that the total duration that the IRWST fluid temperature in the range of 90.6 °C (195 °F) and 100 °C (212 °F) is approximately 60,000 seconds (~17 hours), which is within the 100 hour limit recommended in Subsection 6.3.3 of SECY-11-0014 (Reference [3-12]).

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. 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.

3.7.1 Strainer Vortexing

During the prototype testing, visual observations are required to ensure that no significant vortices formed. Vortex and/or swirl up to and including a Type 4 are considered acceptable. The testing was performed at the submergence requirement of 0.61 m (2 ft) submergence and no vortices were observed. Additionally, there is no possibility to occur vortexing and air ingestion geometrically because the IRWST sump strainers in are mounted at the top of the pit with the suction 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 for ECCS pump NPSH of 86 ft 0 in (i.e., 5 ft 0 in above the APR1400 IRWST bottom floor elevation of 81 ft 0 in) and the strainer assembly height of 84 ft 0 in (81 ft 0 in plus 3 ft 0 in), this provides 0.61 m (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 will not be less than the saturation pressure, and flashing will not occur across the strainer surface.

During testing, the maximum observed head loss across the strainer is less than 0.81 feet, which provides additional margin to flashing.

3.7.3 Dearation 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 will 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

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 [3-6]) referenced in USNRC 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 calculated minimum and maximum IRWST pH during operation of the CSS is 7 and 10, respectively. The minimum time to reach a minimum pH of 7.0 is 157 minutes, as shown in Figure 3.8-1. The IRWST pH ranges are included in Table 3.8-1.

3.8.2 Assumptions

1) The maximum IRWST water volume was used for the chemical effects analysis. Using the maximum water volume ensures that the maximum material dissolution and quantity of precipitates are analyzed.

2) Temperature data is only available from zero to 953,000 seconds post-LOCA. Since the mission time is 30 days (2,592,000 seconds), the containment air temperature and IRWST temperatures were extrapolated using a logarithmic fit of the last 9 days of available temperature data to predict the containment air and IRWST temperatures from 953,000 seconds to 2,592,000 seconds. This time period was chosen due to the consistently logarithmic temperature decrease for the entire time period.

3) The maximum IRWST and spray pH profile was used to conservatively maximize dissolution and precipitate generation.

4) The minimum ECCS flow case was used because it results in the highest sump temperatures, and therefore the highest corrosion rate of reactive materials in the sump. Both the minimum and maximum ECCS flow cases result in the comparable containment air temperature profiles.

3.8.3 Evaluation Summary

The APR1400 contains the following types of reactive materials in containment and the IRWST:

1) Reactive Materials

   (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) .... N/A
   (d) Unsubmerged aluminum (m^2 / ft^2) .... 216.09 / 2,326

2) Debris Materials

   (a) Latent fiber (kg / lbs) .... 6.80 / 15

The input data for WCAP-16530-NP chemical product formation, the precipitates produced, and the analysis results are included as Table 3.8-2, Table 3.8-3, and Table 3.8-4 respectively.

3.9 Upstream Effect

3.9.1 Hold-up Volumes

The evaluation of upstream effect is a review of the flow paths leading to the IRWST, identifying those flow paths which could result in blocking the return water that could challenge the IRWST minimum water level evaluation. The evaluation also includes identifying the hold-up volumes, such as recessed areas and enclosed rooms, for which trapped water will not return to the IRWST. All of the hold-up volumes were taken account of in the minimum water level calculation.

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

This 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 secondary shield wall and annulus via the stairway and a ring of deck grating around much of the circumference of the building.

In the refueling cavity, there are two 10 in drain pipes 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 elevation 156 ft 0 in down to the reactor head flange at the elevation 130 ft 0 in. The west part of the cavity encompasses the upper guide structure (UGS) laydown area which extends down to the elevation 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 the 114 ft 6 in.

The cavity would collect approximately 9 percent of the containment main spray flow and fill up except for the two floor drains. Both drains are 10-in-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 the elevation 100 ft 0 in area.

A concern with the refueling cavity is the potential for pieces of debris (e.g., 10 in x 10 in piece of RMI) to migrate to one or both drains and greatly restrict the flow so that the refueling cavity would 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, which hypothetically could hold thousands of cubic feet of water if its drain were blocked. However, this scenario is deemed not credible. No high-energy pipes are in the near vicinity of the 10 in openings that drain the refueling cavity. The 10 in 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 in drain line. Debris would need to be at least 10 in wide to bridge the opening and cause blockage. Smaller debris would pass straight through. Debris would also need

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 containment spray water drain 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 7in) wide pathways are located at the front of the HVT trash racks in the secondary shield wall), the debris will not clog these pathways. As a result, no choke points that may block the flow paths of return water are identified. Therefore, only the hold-up volumes may challenge the minimum water level of the IRWST.

The following assumptions are made in the calculation for hold-up 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 containment spray is delayed in the containment building. The maximum containment spray flow rate for two train operation is assumed to conservatively maximize the containment spray 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 Technical Specification level.

5) The maximum containment atmospheric conditions at CSAS are assumed for each scenario to maximize water that would be held up in the atmosphere. Containment spray 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. Containment spray 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 as no distinction is made for surface area orientation; the water film is assumed 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 hold-up 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 containment spray nozzle and broken pipe. The held-up water on the way to the IRWST will decrease the initial IRWST water level. The following are the source of held-up water on the way to the IRWST.

   (a) Containment spray suspended water in the containment atmosphere
   (b) Containment spray steam water
   (c) Initial filling water for SIS and CSS pipe
   (d) Condensate water on the various surfaces
   (e) Water stream on the El. 100 ft 0 in floor
   (f) Water steam on the refueling cavity floor

2) Inactive pools volume

   An inactive pool volume is defined as a hold-up 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 hold-up volumes are provided in Table 3.9-1.

3.9.2 Minimum Water Level

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 provides the basis for estimating static head in the NPSH evaluation, as discussed in Section 3.6. It was conservatively calculated as follows:

During normal operation, the IRWST is not less than 627,000 gal (74.43 percent water levels) to ensure an adequate supply of borated water to SIS and CSS. The IRWST design to minimize the water evaporation, however, if the water level reaches a level less than 74.43 percent, the makeup operation from the boric acid storage tank via the boric acid makeup pump is activated and continued

until 74.43 percent 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 the postulated accidents. In case of LBLOCA, the water mass in the SIT can contribute to recover the IRWST, and three SITs water of four SITs are considered in the calculation in accordance with the Reference [3-10].

The minimum water level of the IRWST during a LOCA was calculated by subtracting the hold-up volume from the initial water volume in the IRWST and by adding the three SITs volume. The minimum water level used in the NPSH evaluation is calculated as 5 ft above the IRWST bottom (El. 81 ft 0 in), and it is shown in Figure 3.9-3.

Table 3.1-1 Postulated Break Pipe Lines

Pipelines	Size	Location			
	ID (in)	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 Destruction Pressures and Associated ZOI Radius for Material Excerpted from Table 3-2 in SE for NEI 04-07 (Reference [3-3])

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

[1] To be determined by experiment

[2] Not available for evaluation at this time

Table 3.2-2 Coating Materials and Coating Thickness Inside Containment

Coating Application	Coating System	Thickness (mils)	Density (lbm/ft^3)
Containment Liner Plate, Structural Steel	Inorganic Zinc primer	3.0 ~ 5.0	347.7
	Epoxy Finish	3.0 ~ 5.0	104.3
Equipment and Component (less than 200°F)	Epoxy Primer	3.0 ~ 5.0	104.3
	Epoxy Finish	3.0 ~ 5.0	104.3
Equipment and Component (200°F to 750°F)	Inorganic Zinc primer	3.0 ~ 5.0	347.7
Wall and Ceiling Concrete	Epoxy Primer	0.3 ~ 1.0	68.0
	Epoxy Intermediate	10.0 ~ 15.0	129.2
	Epoxy Finish	5.0 ~ 9.0	104.3
Floor Concrete	Epoxy Primer	0.3 ~ 1.0	68.0
	Epoxy Intermediate	20.0 ~ 27.0	129.2
	Epoxy Finish	6.0 ~ 8.0	104.3

Table 3.2-3 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 SER	NEI 04-07 and SER	NEI 04-07 and SER
Break Size (in)		42	30	30.907
Size of ZOI (ft)	Insulation (2D)	7	5	5.2
	Coating (4D)	14	10	10.4
Amount	RMI (ft^3)	114	49	38
	Coating (ft^3)	3.1	0.38	-
	Latent Debris (lbs)	200	200	200

Table 3.2-4 Material Potentially Produced Corrosion Products

Material	Submerged Pool Zone (ft^2)	Un-submerged Spray Zone (ft^2)	Remark
1. Concrete	2.087×10^3	7.257×10^3	
2. Aluminum	N/A	2.326×10^3	
• 4-RCFCs 4-S/G Enclosure - Recirculation Fans - 4-Annulus Area - Recirculation Fans - Duct Insulation	N/A	1.703×10^3	
• Ex-core Detectors	N/A	2.67	
• Refueling Equipment	N/A	1.30×10^2	
• CEDM Cooling Fan	N/A	2.502×10^2	
• Surveillance Capsule - Retrieval Tool - Remote Positioning Tool	N/A	2.40×10^2	

Table 3.3-1 Size and Distribution of Debris

Debris Source Type		Debris Size Distribution	
		Small 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	7.89 g/cm^3 (490 lbm/ft^3)
Coating	Diameter of particle (D_p)	10 μm (3.28x10^{-5} ft)
	Particle Density (μ_p)	1.51 g/cm^3 (94 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)

Table 3.6-1 $NPSH_r$ for SI Pump and CS Pump

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

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-percent drop in pump discharge head. $NPSH_{3\%}$ 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 (Referenc [3-12]), uncertainties associated with $NPSH_r$ are considered to determine the effective $NPSH_r$ ($NPSH_{reff}$).

Table 3.6-2 SI Pump (PP02D) NPSH Results

Sump Temp. (°F)	h_{atm} (ft-water)	h_{static} (ft-water)	h_{loss} (ft-water)	H_{va} (ft-water)	$NPSH_a$ (ft-water)	$NPSH_{reff}$ (ft-water)	Margin (ft-water)
120	34.30	30	55.3	3.95	55.3	22.0	33.3
125	34.34	30	54.71	4.58	54.71	22.0	32.71
130	34.4	30	54.14	5.21	54.14	22.0	32.14
135	34.44	30	53.39	6.00	53.39	22.0	31.39
140	34.49	30	52.65	6.79	52.65	22.0	30.65
145	34.53	30	51.71	7.77	51.71	22.0	29.71
150	34.59	30	50.78	8.76	50.78	22.0	28.78
155	34.65	30	49.62	9.98	49.62	22.0	27.62
160	34.69	30	48.44	11.2	48.44	22.0	26.44
165	34.77	30	47.01	12.71	47.01	22.0	25.01
170	34.82	30	45.56	14.21	45.56	22.0	23.56
175	34.88	30	43.79	16.04	43.79	22.0	21.79
180	34.94	30	42.02	17.87	42.02	22.0	20.02
185	35.02	30	39.88	20.09	39.88	22.0	17.88
190	35.07	30	37.71	22.31	37.71	22.0	15.71
195	35.13	30	35.12	24.96	35.12	22.0	13.12
200	35.21	30	32.53	27.63	32.53	22.0	10.53
205	35.28	30	29.42	30.81	29.42	22.0	7.42
210	35.35	30	26.3	34	26.3	22.0	4.3
212	35.39	30	24.95	35.39	24.95	22.0	2.95
215	37.7	30	24.95	37.7	24.95	22.0	2.95
220	41.54	30	24.95	41.54	24.95	22.0	2.95

Table 3.6-3 CS Pump NPSH Results

Sump Temp. (°F)	h_{atm} (ft-water)	h_{static} (ft-water)	h_{loss} (ft-water)	H_{va} (ft-water)	$NPSH_a$ (ft-water)	$NPSH_{reff}$ (ft-water)	Margin (ft-water)
120	34.30	30.16	10.52	3.95	49.99	17.5	32.49
125	34.34	30.16	10.52	4.58	49.4	17.5	31.9
130	34.4	30.16	10.52	5.21	48.83	17.5	31.33
135	34.44	30.16	10.52	6.00	48.08	17.5	30.58
140	34.49	30.16	10.52	6.79	47.34	17.5	29.84
145	34.53	30.16	10.52	7.77	46.4	17.5	28.9
150	34.59	30.16	10.52	8.76	45.47	17.5	27.97
155	34.65	30.16	10.52	9.98	44.31	17.5	26.81
160	34.69	30.16	10.52	11.2	43.13	17.5	25.63
165	34.77	30.16	10.52	12.71	41.7	17.5	24.2
170	34.82	30.16	10.52	14.21	40.25	17.5	22.75
175	34.88	30.16	10.52	16.04	38.48	17.5	20.98
180	34.94	30.16	10.52	17.87	36.71	17.5	19.21
185	35.02	30.16	10.52	20.09	34.57	17.5	17.07
190	35.07	30.16	10.52	22.31	32.4	17.5	14.9
195	35.13	30.16	10.52	24.96	29.81	17.5	12.31
200	35.21	30.16	10.52	27.63	27.22	17.5	9.72
205	35.28	30.16	10.52	30.81	24.11	17.5	6.61
210	35.35	30.16	10.52	34	20.99	17.5	3.49
212	35.39	30.16	10.52	35.39	19.64	17.5	2.14
215	37.7	30.16	10.52	37.7	19.64	17.5	2.14
220	41.54	30.16	10.52	41.54	19.64	17.5	2.14

Table 3.8-1 Post-LOCA IRWST Chemistry

Short-Term DBA (Accident Initation 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 ≤ Ph ≤ 10	• 4,400 ppm boron as H_3BO_3 • 0 – 50 ppm hydrazine as N_2H_4 • 7.2 ≤ pH ≤ 8.5 • Tri-sodium Phosphate as Buffering agent

Table 3.8-2 Input Data for WCAP-16530-NP Chemical Product Formation

Class	Mater	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	CalSil 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 3.8-3 WCAP-16530 Results Summary

Component	Quantity (kg)
Aluminum oxy-hydroxide	180.6
Sodium aluminum silicate	4.3
Calcium phosphate	0.7

Table 3.8-4 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)
2.0	0.00	0.0	10	135.6	0.001	0.561	0.000
1.6	0.04	0.1	10	139.2	0.0	1.1	0.00
1.2	0.06	0.1	10	141.0	0.0	1.5	0.00
3.0	0.08	0.1	10	143.8	0.0	2.6	0.00
3.2	0.13	0.2	10	147.9	0.0	3.7	0.00
4.9	0.19	0.3	10	153.0	0.0	5.3	0.00
5.5	0.27	0.4	10	158.9	0.0	7.1	0.00
9.4	0.36	0.5	10	165.5	0.0	10.1	0.01
11.6	0.52	0.7	10	173.0	0.0	13.6	0.01
22.9	0.71	1.1	10	183.1	0.1	20.0	0.02
76.1	1.09	2.4	10	202.2	0.3	38.7	0.05
98.4	2.36	4.0	10	222.6	0.8	58.6	0.09
0.0	4.00	4.0	9.25	230.0	0.8	58.6	0.09
241.9	4.00	8.0	8.5	233.6	1.6	69.9	0.20
210.9	8.03	11.5	8.5	235.0	2.3	77.6	0.30
237.8	11.55	15.5	8.5	229.4	3.0	84.4	0.39
291.4	15.51	20.4	8.5	221.6	3.8	90.8	0.40
617.2	20.37	30.7	8.5	209.7	4.2	100.5	0.40
746.4	30.66	43.1	8.5	196.18	4.2	108.2	0.41
1578.7	43.10	69.4	8.5	183.5	4.2	119.0	0.43
2392.0	69.41	109.3	8.5	172.0	4.2	129.6	0.45
3306.3	109.27	164.4	8.5	162.8	4.2	139.5	0.47
3382.5	164.38	220.8	8.5	156.2	4.2	147.2	0.49
2635.0	220.75	264.7	8.5	152.1	4.2	152.2	0.51
3035.5	264.67	315.3	8.5	148.4	4.2	157.1	0.53
3035.5	315.26	365.9	8.5	144.9	4.3	161.3	0.55
3035.5	365.86	416.4	8.5	142.2	4.3	164.9	0.56
3035.5	416.45	467.0	8.5	139.8	4.3	168.2	0.58
3035.5	467.04	517.6	8.5	137.6	4.3	171.1	0.60
3035.5	517.63	568.2	8.5	135.7	4.3	173.8	0.61
3035.5	568.22	618.8	8.5	133.9	4.3	176.2	0.63
3035.5	618.82	669.4	8.5	132.3	4.3	178.5	0.64
3035.5	669.41	720.0	8.5	130.8	4.3	180.6	0.66

Table 3.9-1 Upstream Effects Hold-up Volume

Volume Source	Volume (gal)
[1] Holdup Volume on the way to the IRWST	
- Containment spray suspended water in the containment atmosphere	826
- Containment spray steam water	45,092
- Initial filling water for SI system and CS system pipe	8,078
- Water stream on the El. 100 ft 0 in floor	60,656
- Water stream on the floor of refueling cavity	11,190
- Miscellaneous Hold-up volume	36,987(1)
Subtotal [1]	**162,829**
[2] Inactive Pool Volume	
- HVT Volume	56,080
- Reactor cavity and ICI cavity volume	164,192
- Containment drain sump volume	3,112
- ICI cavity sump volume	898
Subtotal [2]	**224,282**

Note :

(1) The miscellaneous hold-up volume is water volume held-up elsewhere in the reactor building; 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, etc.

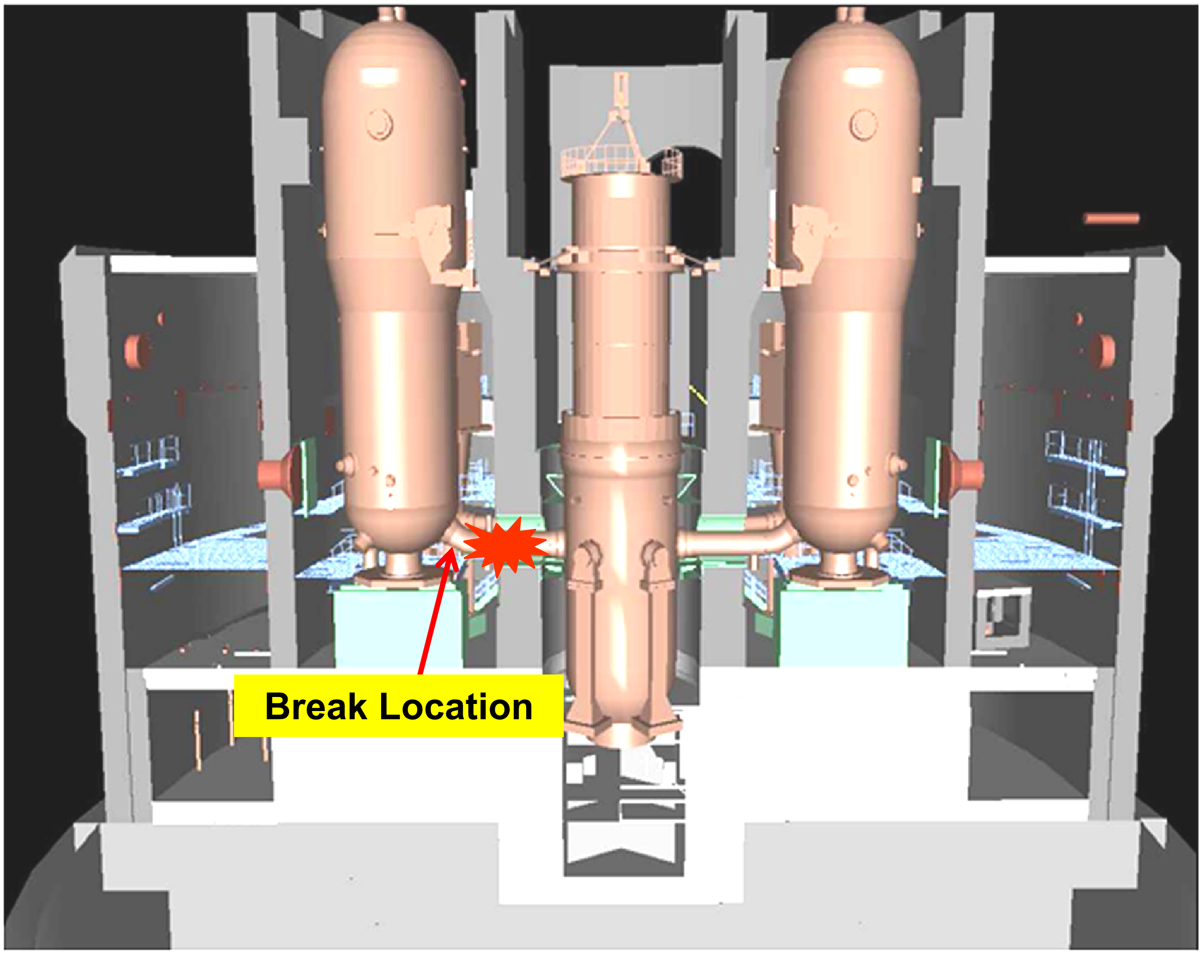


Figure 3.1-1 3D Section View for the Break Location of the RCS Hot Leg Line

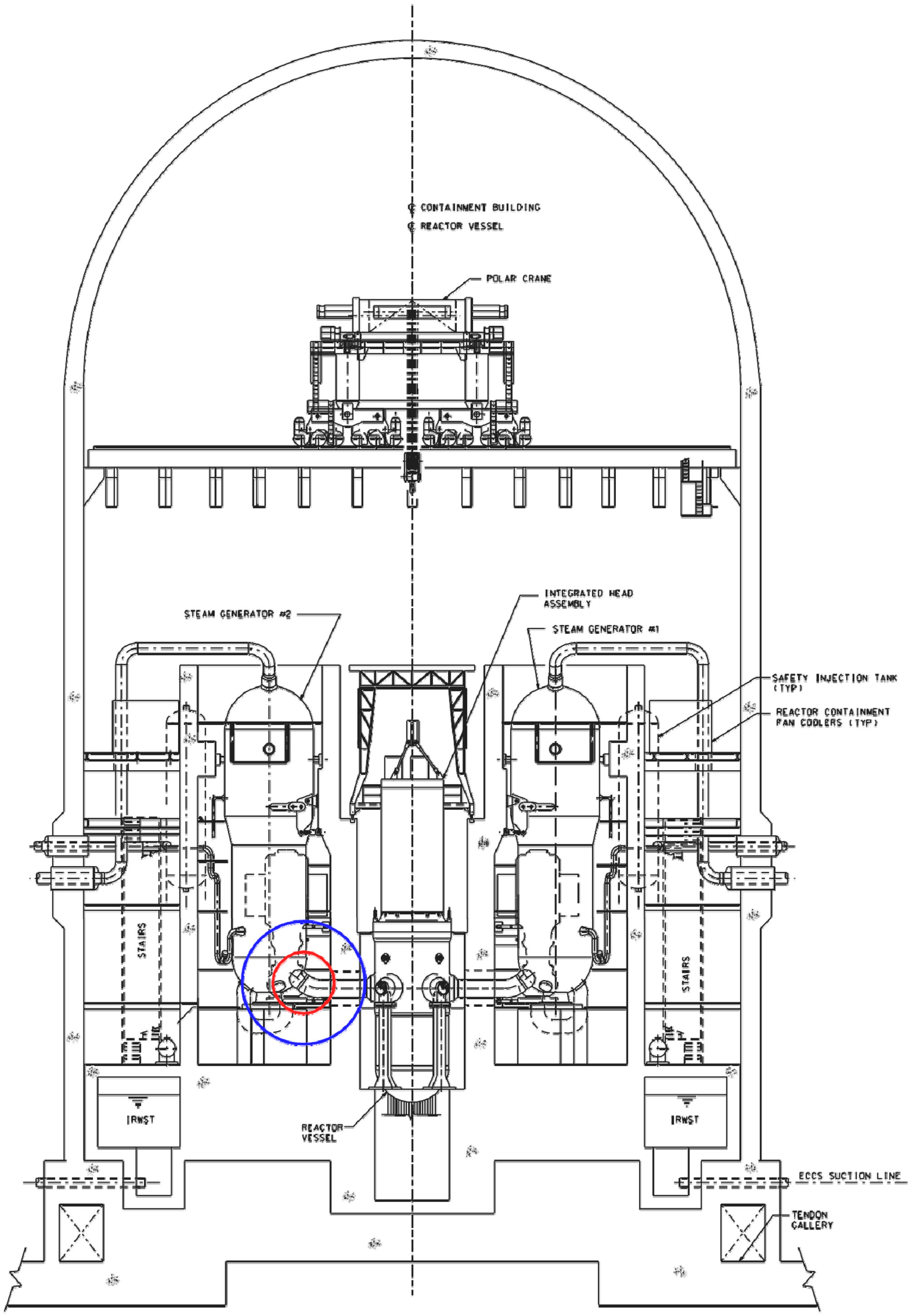


Figure 3.2-1 Sectional View of ZOI for RCS Hot Leg Line Break (Red Color Circle: ZOI for RMI, Blue Color Circle: ZOI for Coating)

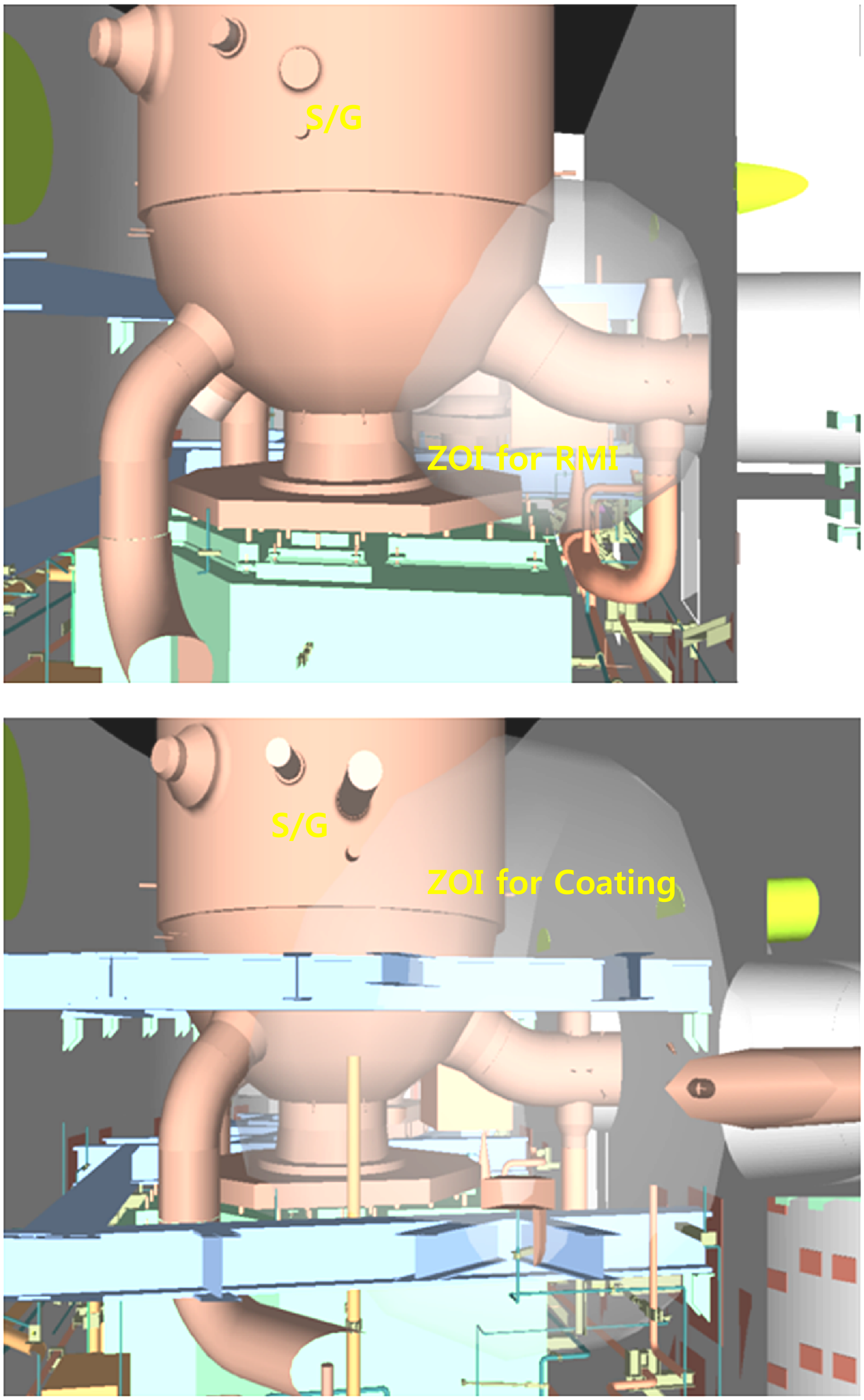


Figure 3.2-2 3D View of ZOI for RCS Hot Leg Line Break

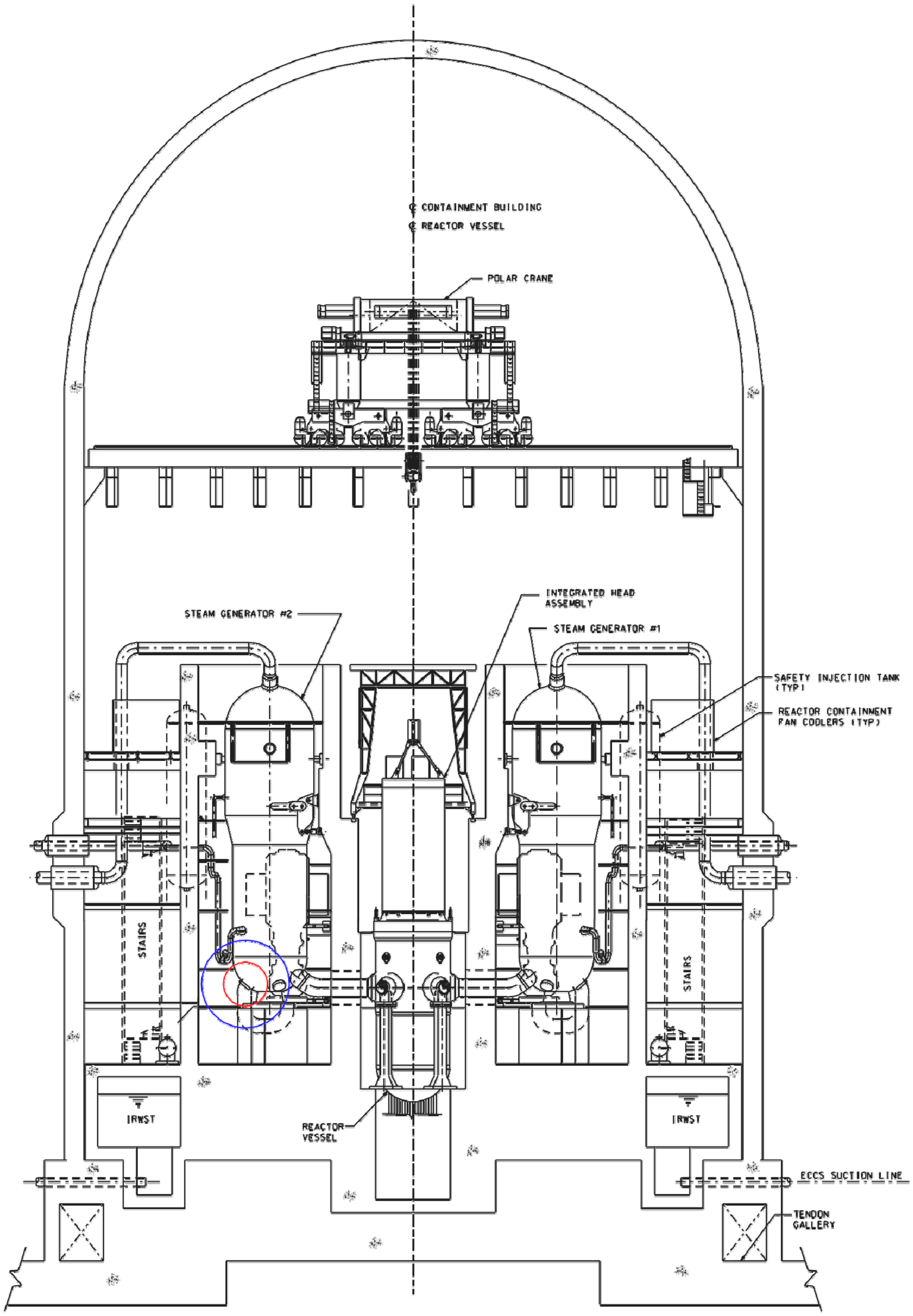
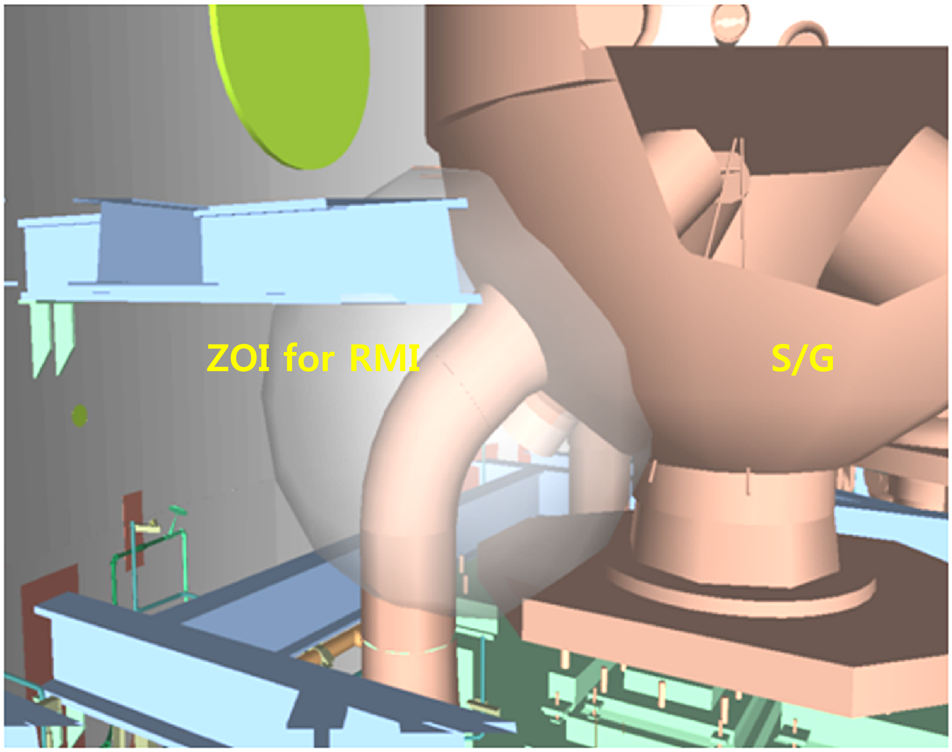


Figure 3.2-3 Sectional View of ZOI for RCS Cold Leg Line Break (Red Color Circle: ZOI for RMI, Blue Color Circle: ZOI for Coating)



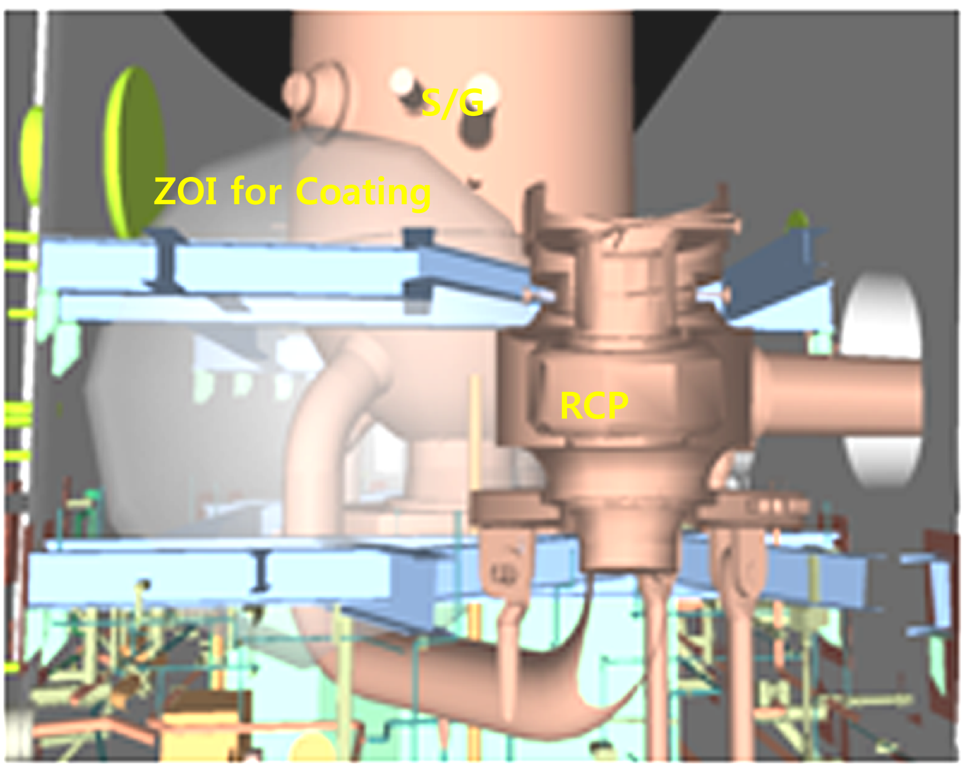


Figure 3.2-4 3D View of ZOI for RCS Cold Leg Line Break

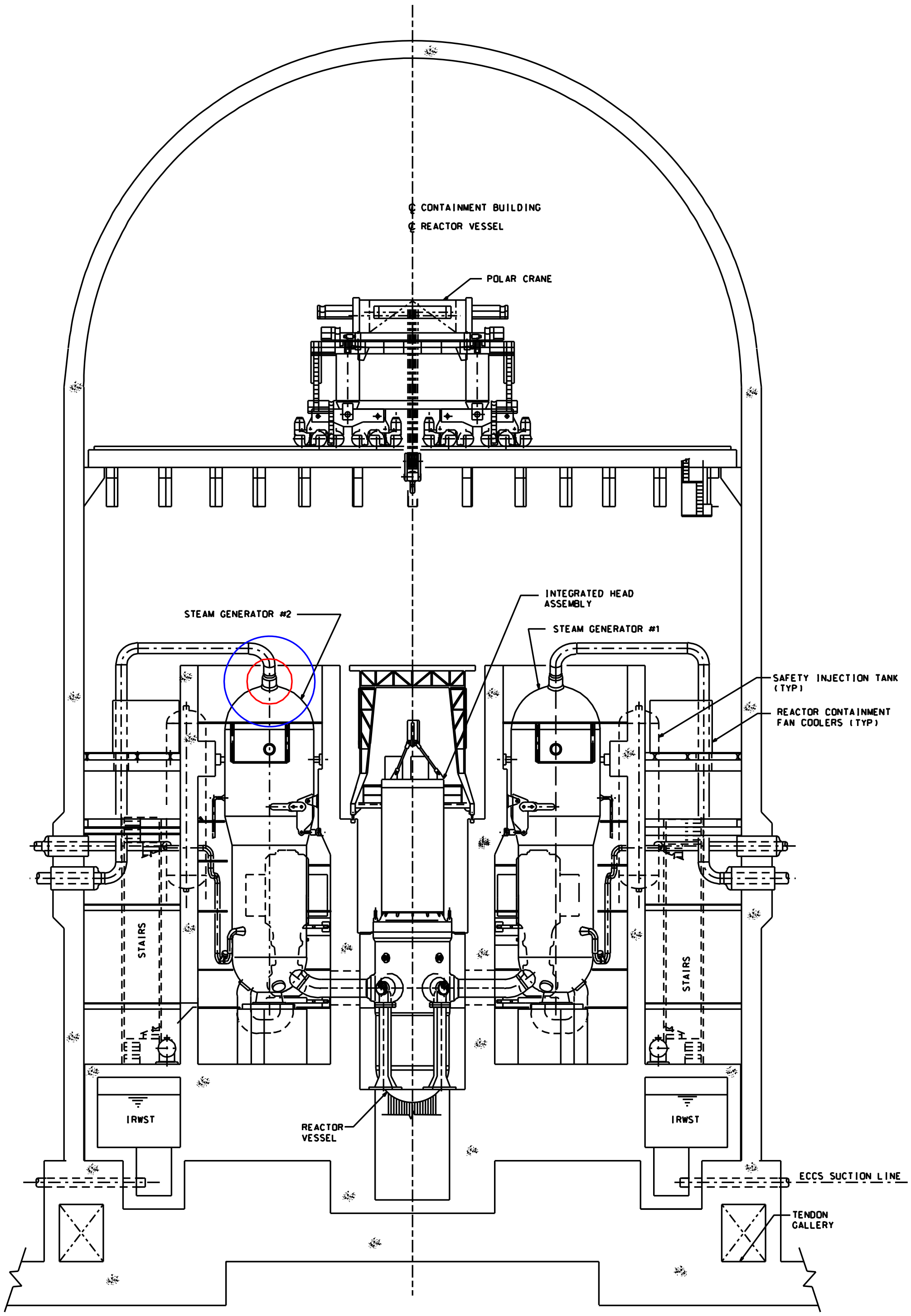


Figure 3.2-5 Sectional View of ZOI for Main Steam Line Break (Red Color Circle: ZOI for RMI, Blue Color Circle: ZOI for Coating)

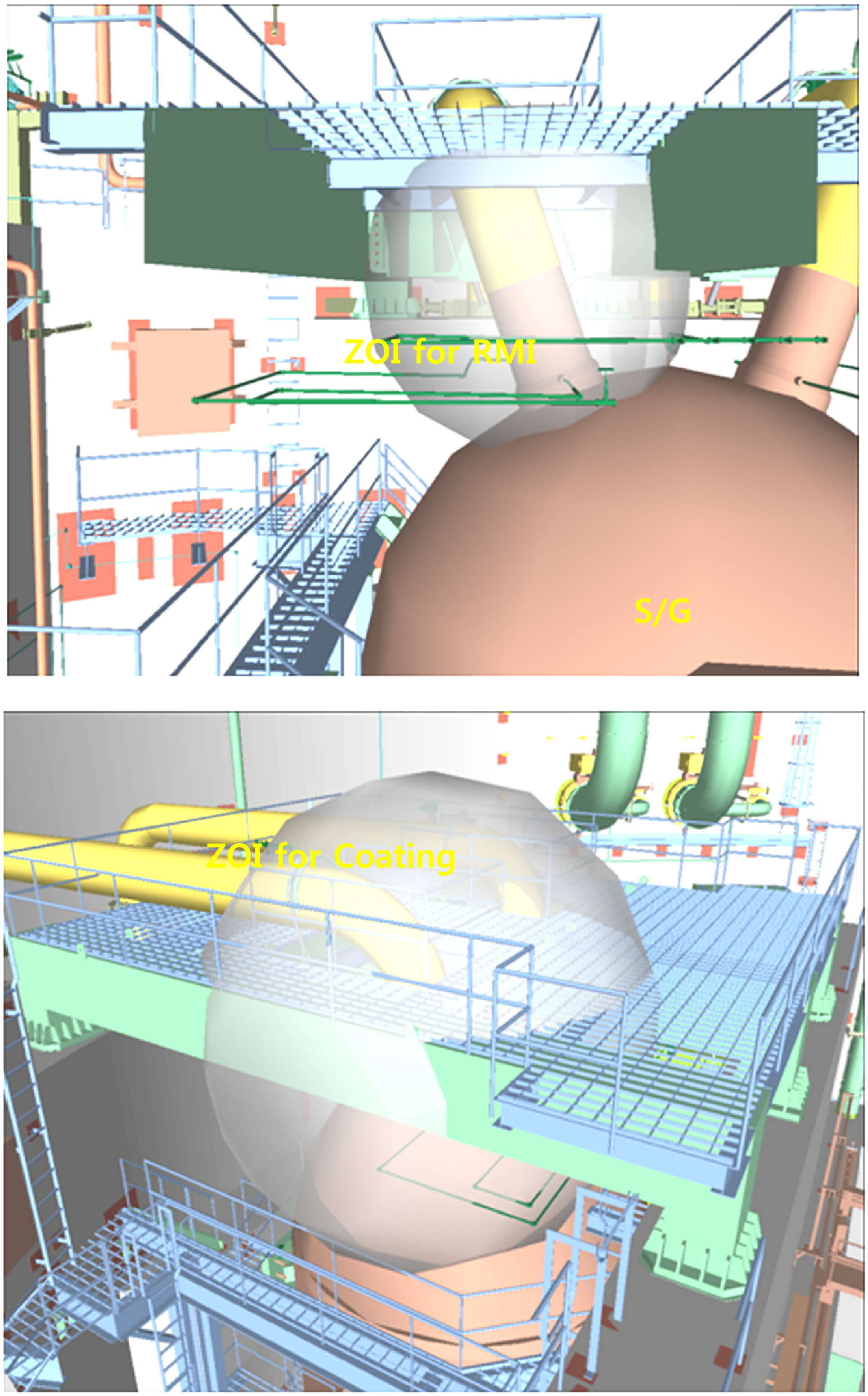


Figure 3.2-6 3D View of ZOI for Main Steam Line Break

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Figure 3.5-1 IRWST Sump Strainer Plan and Elevation View

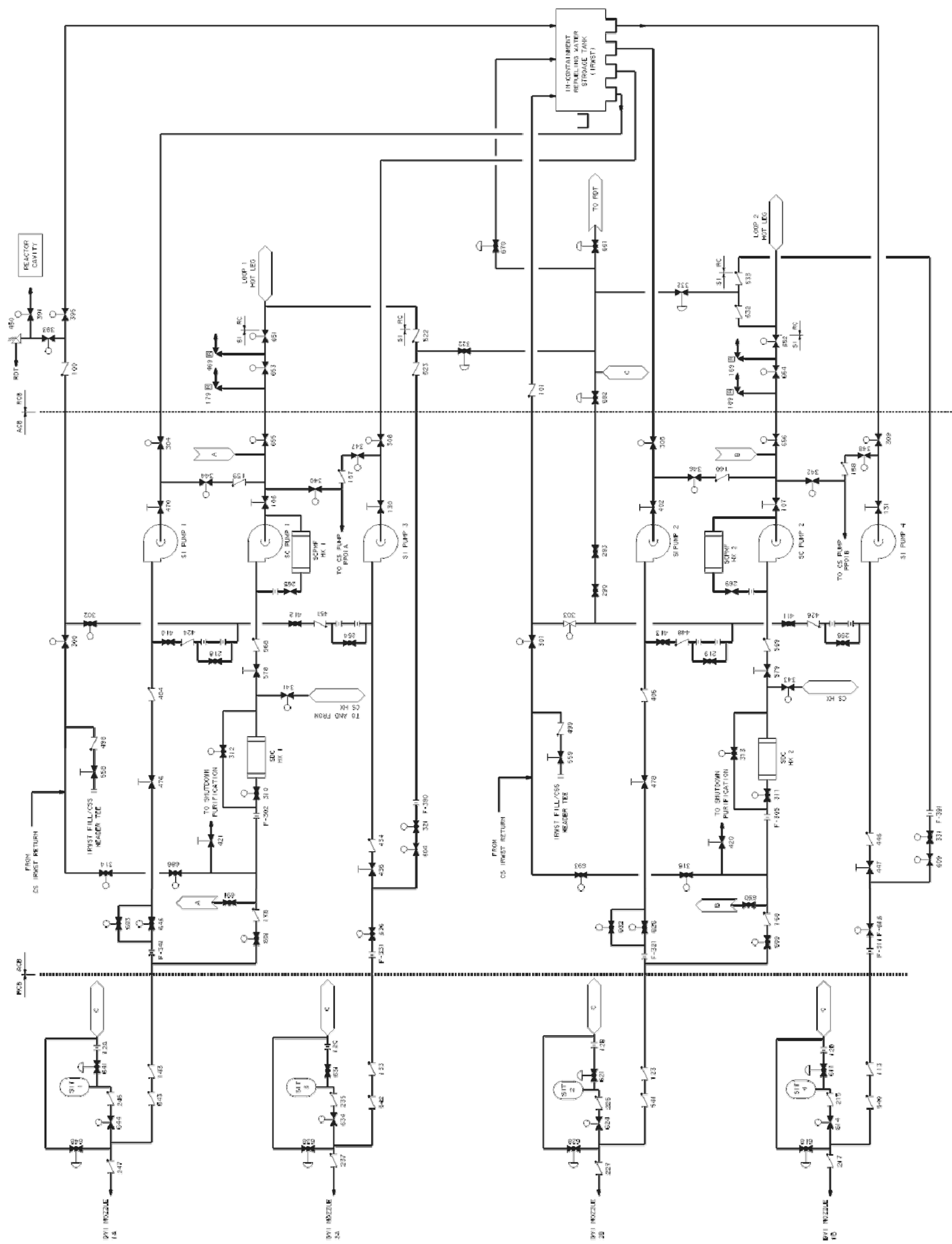

Figure 3.6-1 Schematic Flow Diagram of SI System

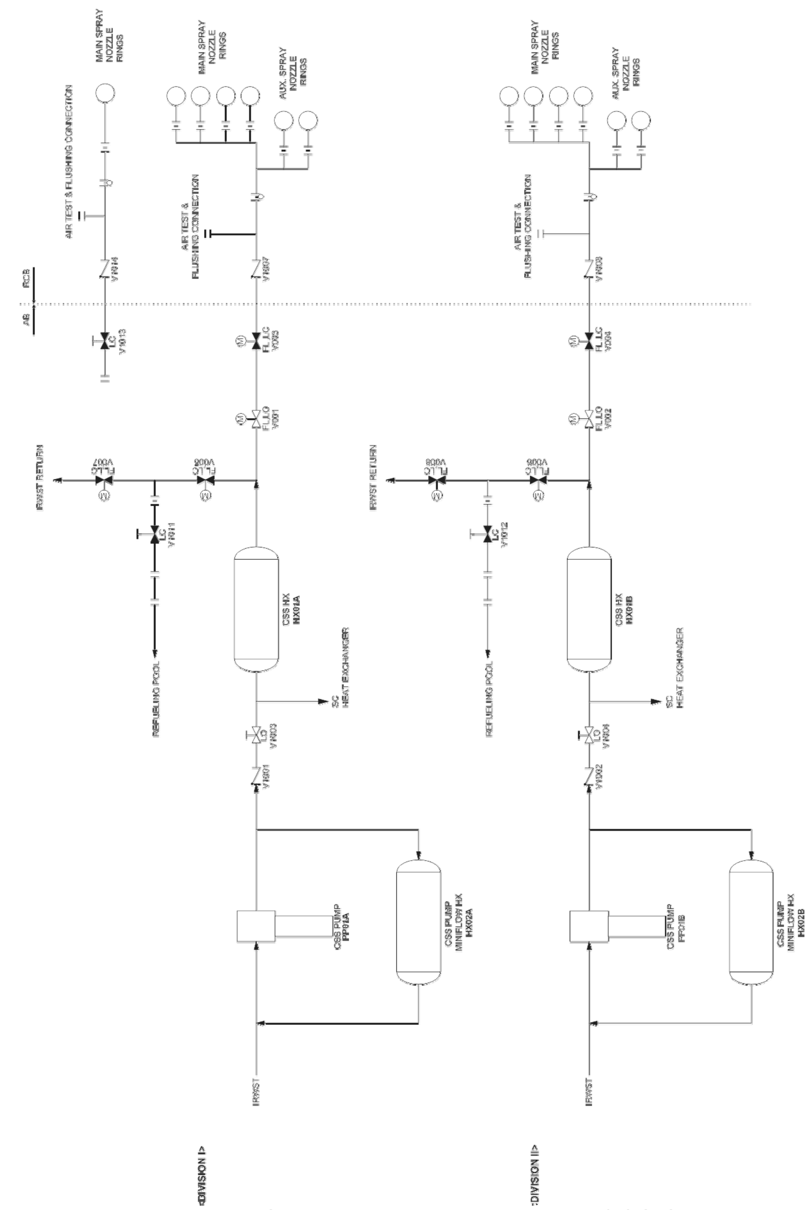

Figure 3.6-2 Schematic Flow Diagram of CS System

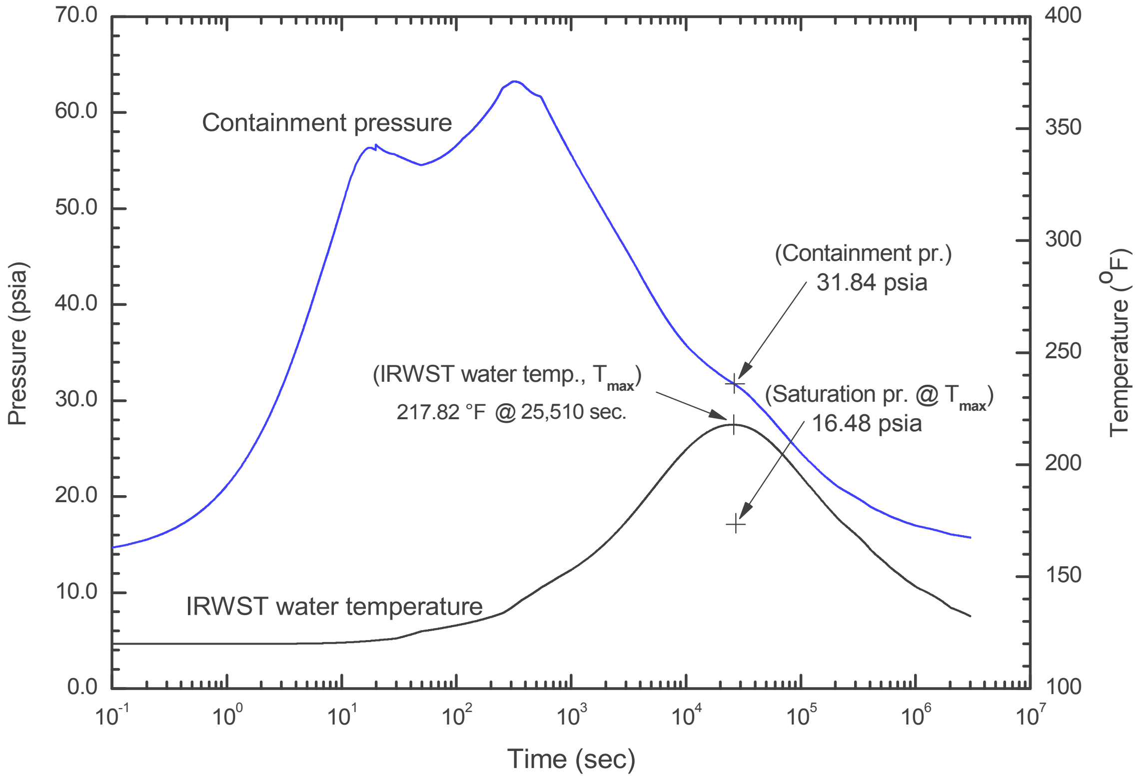

Figure 3.6-3 Containment Pressure and Temperature vs. Time for Long-Term Phase (Double-ended Discharge Leg Slot Break with Minimum ECCS Flow)

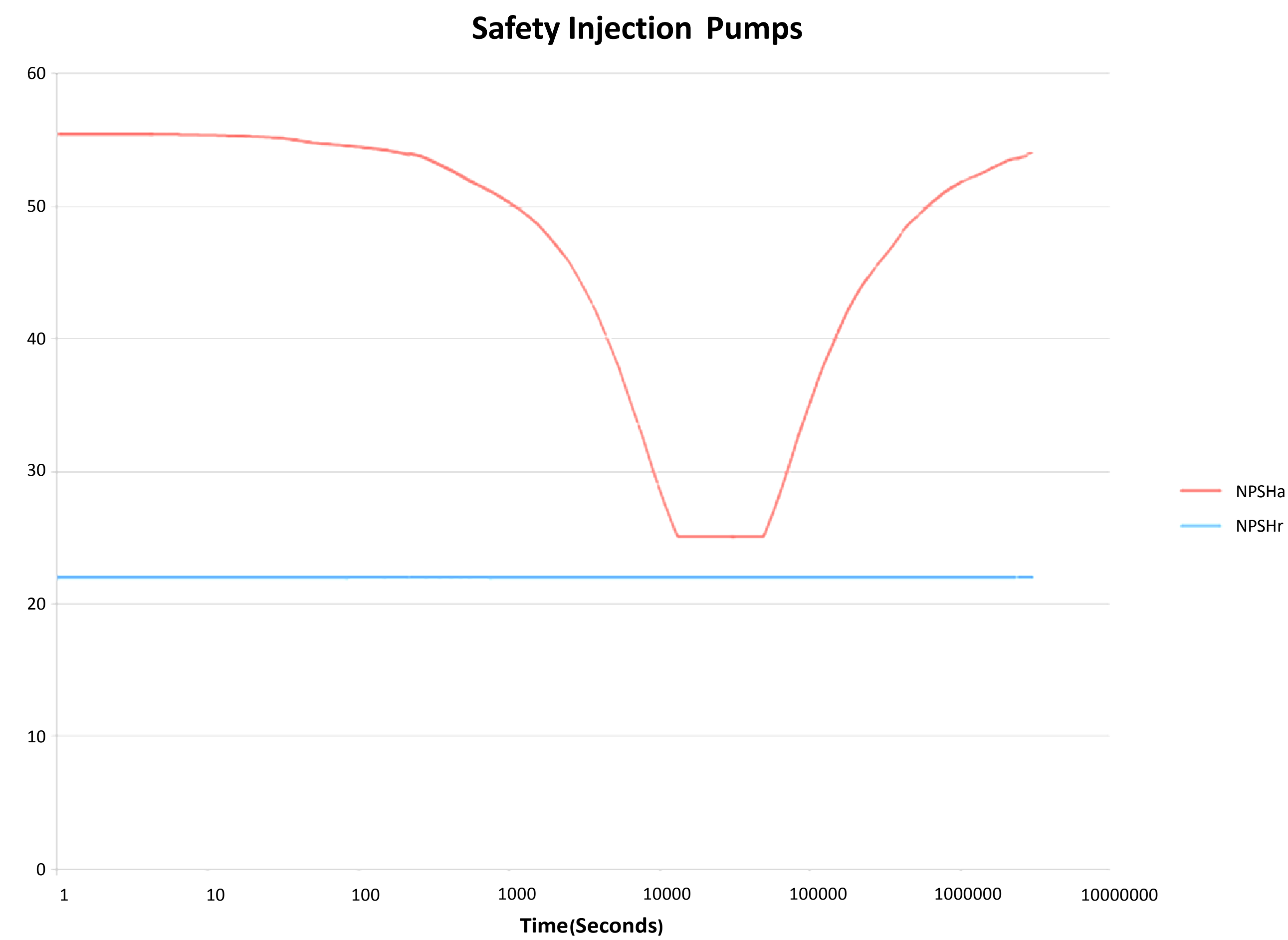

Figure 3.6-4 Limiting SI Pump NPSH vs Time

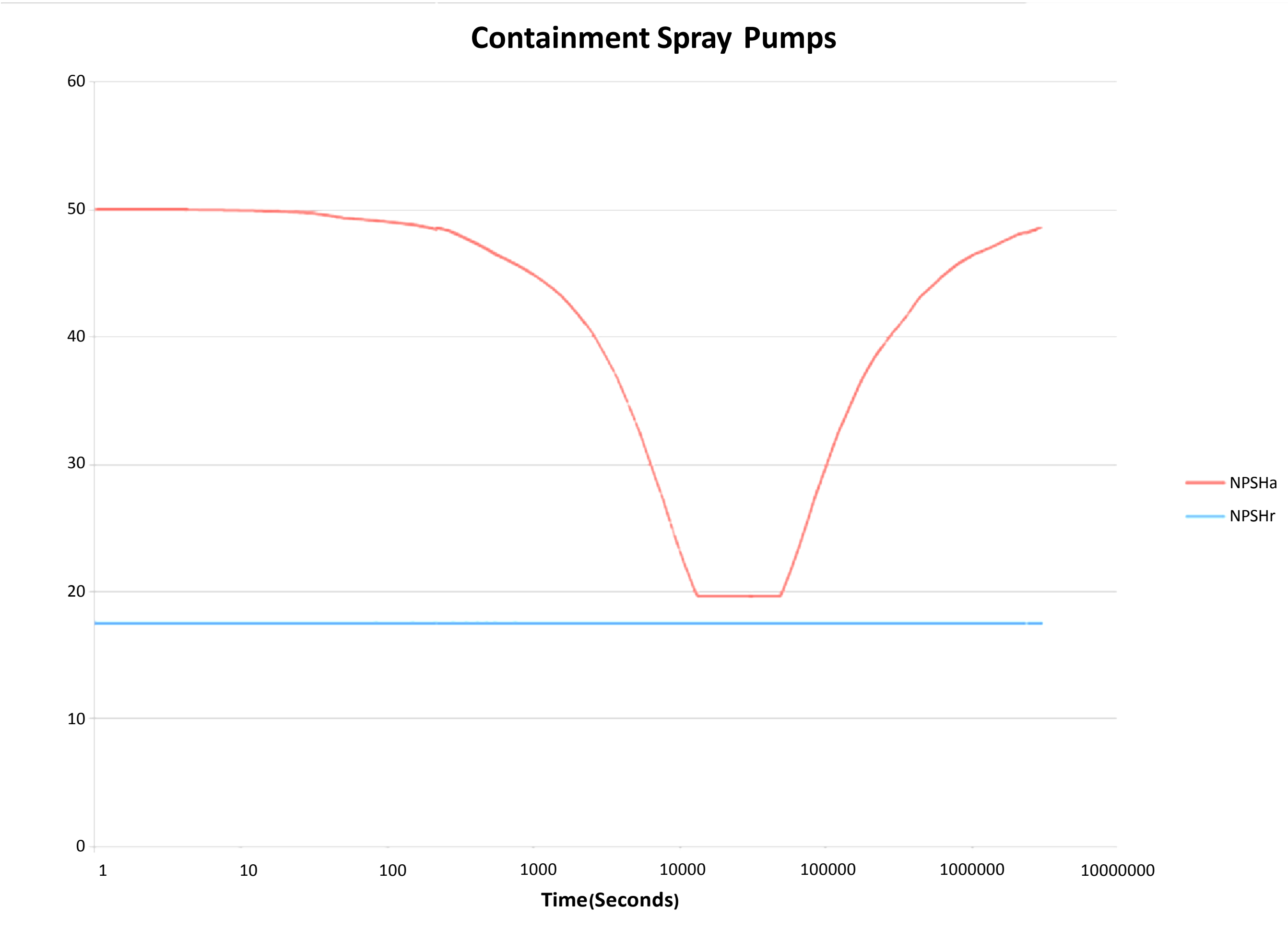

Figure 3.6-5 Limiting CS Pump NPSH vs Time

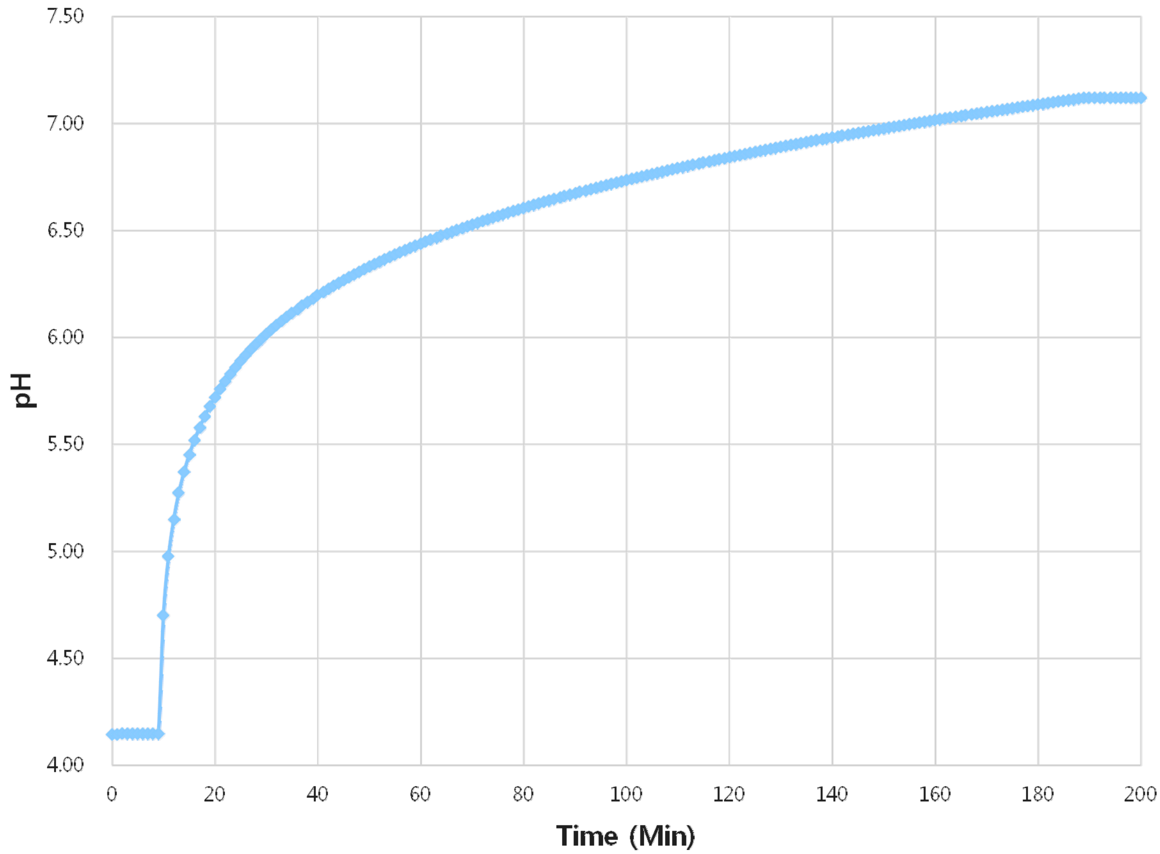

Figure 3.8-1 Minimum IRWST pH vs. Time Curve

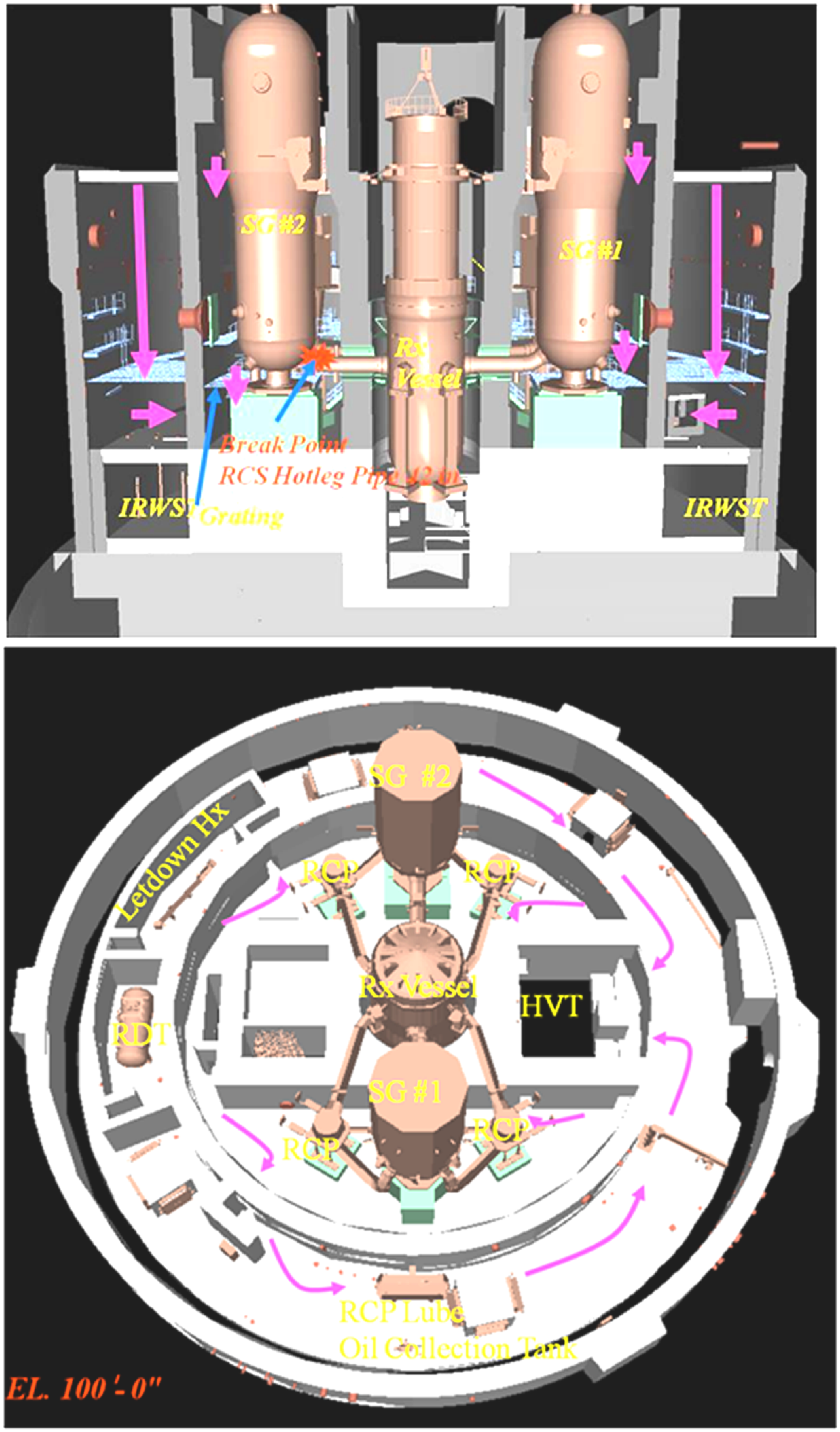

Figure 3.9-1 Schematic of Containment Spray/Blowdown Return Pathways

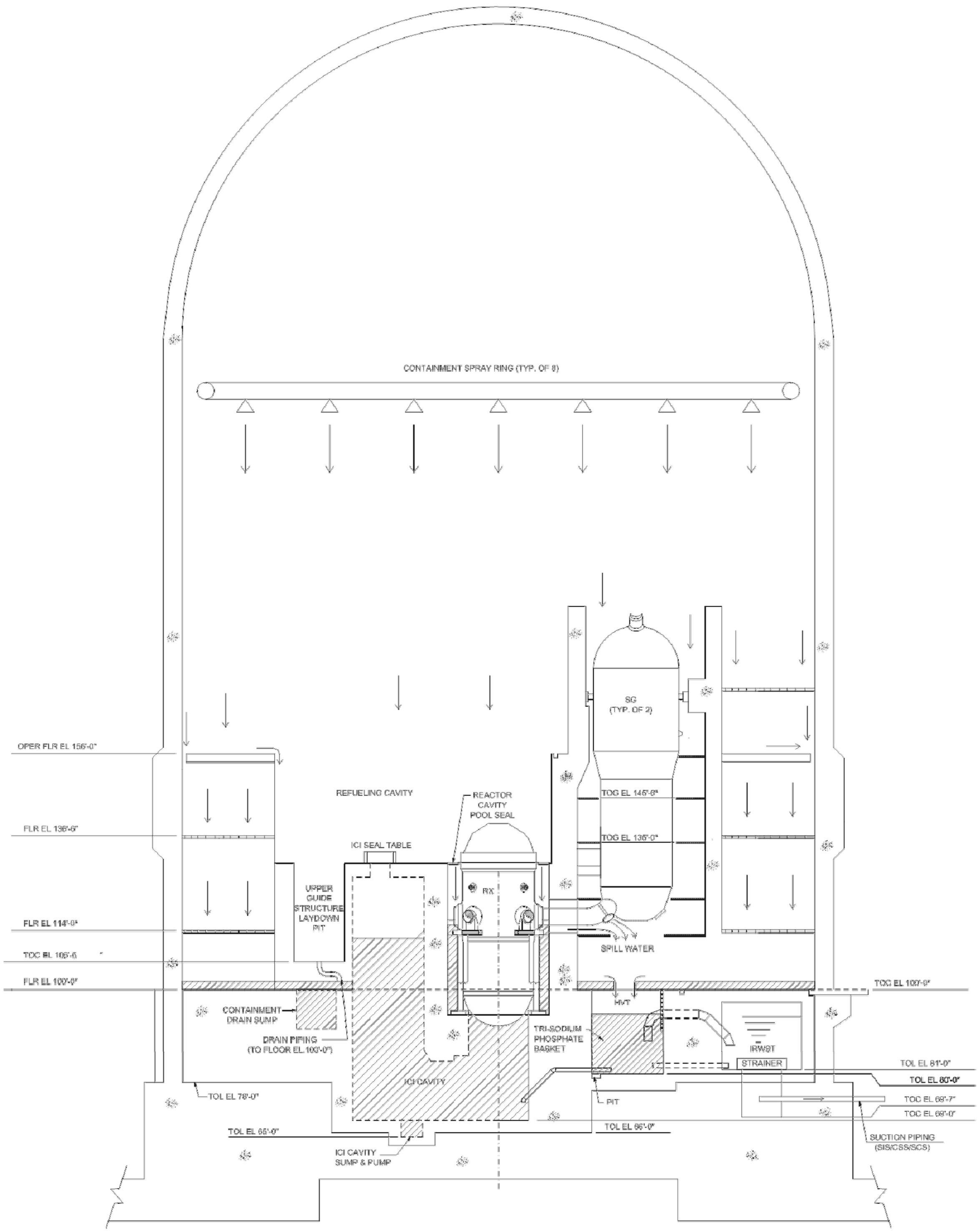

Figure 3.9-2 Schematic of Potential Water Traps in Containment

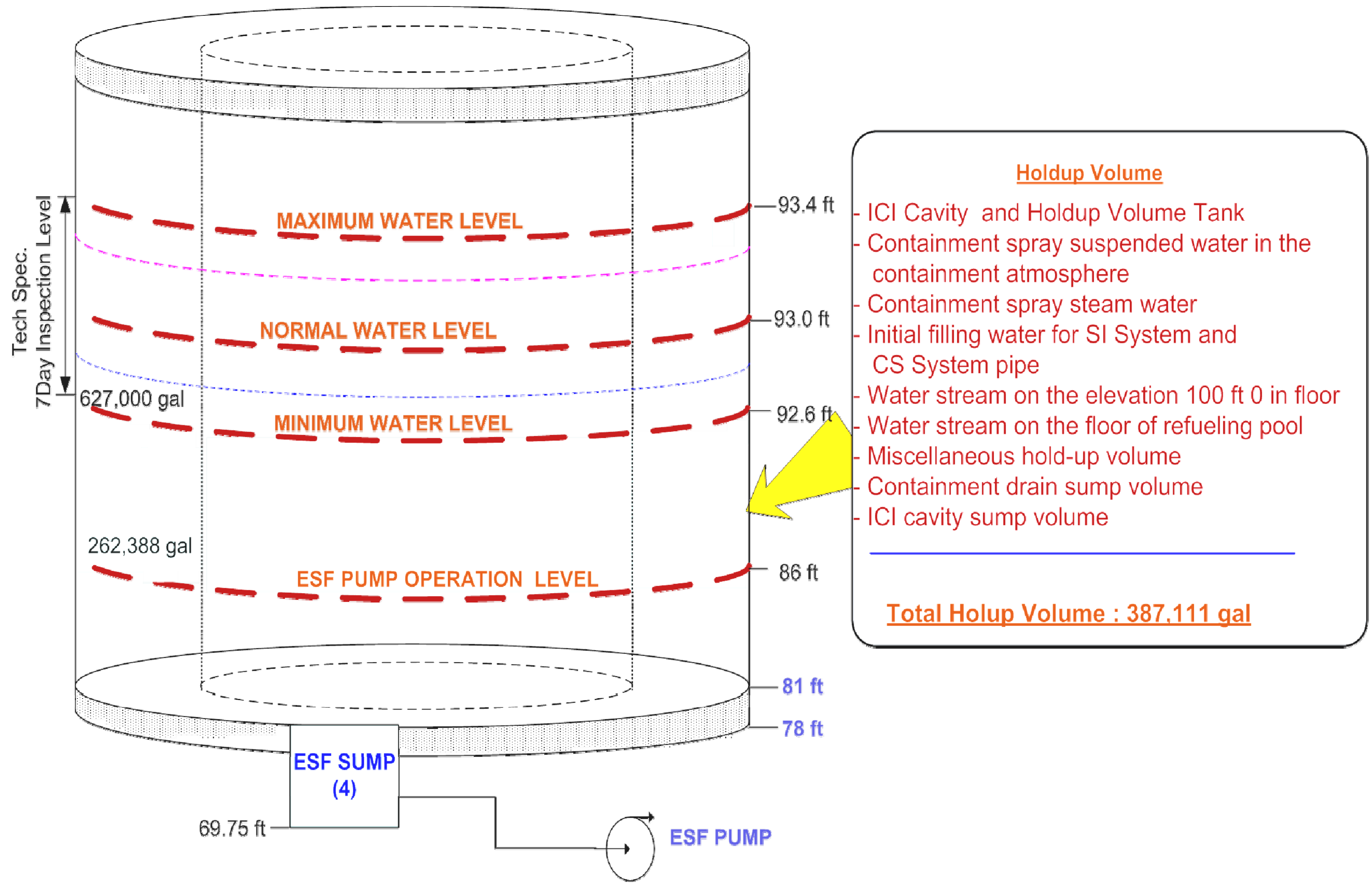

Figure 3.9-3 Schematic Diagram for IRWST Water Volume

4.0 DOWNSTREAM EFFECTS

The requirements of USNRC 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 component in the blockage of downstream components is the fibrous debris materials. 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 lbs) 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 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 was performed. The testing was 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 test plan and result are attached in Appendix B.

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

Since only the higher flow rate strainers will be tested, the following four batches of 0.18 kg (0.40 lbm) (0.0265 in. equivalent thickness) will be 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 was run with four batches of fines representing latent debris added. Filters were 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 7 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 would be 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 lbs) of latent fiber is 1.67 kg (3.68 lbs).

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 guarantee 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 (ECCS)

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 form 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 supplies 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 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 (CSS)

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 percent 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 SBLOCA are considered much smaller than during 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/RHRS/IRWST components in the downstream effects evaluation. These components are in the ECCS 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, small fines, and large pieces. The size range for each size category given in Table 4.2-2 is established based on the following:

1) This evaluation conservatively assumes that 100 percent 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 (3/32 in (0.094 in)).

2) Small fines are defined as debris materials that are less than 101.6 mm (4 in) by 101.6 mm (4 in) size (based on guidance from NEI 04-07 Volume 1, Section 3.6.3).

3) 3. Large pieces are defined as debris materials that are greater than 101.6 mm (4 in) size (based on guidance from NEI 04-07 Volume 1, Section 3.6.3).

The total amount of debris generated during a LBLOCA is estimated in Section 3.2 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 percent of small fines and 25 percent 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 (3/32 in) of the IRWST sump strainers will bypass the sump strainer. As a result, the ECCS will ingest 100 percent 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 percent (see Appendix B). This evaluation uses bounding bypass percentages of 100 percent for latent particulates (i.e., dust and dirt). The bypass percentage for latent fiber uses a conservative of 100 percent. The actual bypass percent for latent fiber is evaluated by qualified test results conducted specific to the APR1400 plant conditions. The tests plan and results are provided in Appendix B. Based on the results of bypass testing, the actual bypass percentage for latent fiber is approximately

25 percent.

Results of the NRC debris generation test documented in NUREG/CR-6808 show that RMI debris size distribution ranges from 6.35 mm (0.25 in) to 152.4 mm (6 in). 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.

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 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.

The debris settlement evaluation (Section G.3.3.1) compares the ECCS fluid velocities with the terminal settling velocities of the debris source materials 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 minimum flow rate of the SI and CS pumps at shutoff head conditions will be verified during component procurement.

CS Pump flow is assumed to be 410 gpm for for evaluating debris settlement in the CSS. Flow is assumed to be 7,123 gpm for component wear rate evaluations. Engineering design range of flow is 480 gpm at shutoff and 6,500 gpm at runout. The component wear rate evaluation is detailed in Section 4.1.3.1.

4.2.2.6 Summary of Assumptions and Conservatisms

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

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

2) Safety Injection Pump flow is assumed to be 303 L/min (80 gpm) for the purposes 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) CS Pump flow is assumed to be 1,552 L/min (410 gpm) for the purposes of calculating settling velocities. Flow is assumed to be 26,963 L/min (7,123 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 2.57 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 2.57 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 percent 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 percent 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 m^3 (250,000 gallons) of water during post-LOCA operation, which is less than the minimum IRWST water volume of 993 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 percent 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, using the qualification guidance of ASME QME-1-2007 endorsed by RG1.100 Revision 3. As part of the qualification process, the pump vendor, at a minimum, will fulfill

the following pump criteria:

1) Provide tests and/or analyses to confirm that the opening sizes and internal running clearances of the LHSI and MHSI pumps yield acceptable operation in post-LOCA fluids for at least 30 days. Also, provide a list of the opening sizes and internal running clearances in the qualification documentation.

2) Provide hydraulic performance test results and/or analyses to confirm that the SI and CS pumps can provide the required safety injection flow for at least 30 days of ECCS post-LOCA operation.

3) Provide tests and/or analyses to confirm that the wear rates of the LHSI and MHSI pump wetted surface materials (e.g., wear rings, pump internals, bearing, casing) provide acceptable operation in the post-LOCA fluids for at least 30 days. Also, provide a list of the wetted pump surfaces materials, hardness of each material, and verification of acceptable wear rates in the qualification documentation.

4) Provide mechanical performance (i.e., pump vibration, rotor dynamics, bearing load) test results and/or analyses to confirm that there will be no adverse changes in system vibration response or rotor dynamics performance during ECCS operation for at least 30 days. Also, provide relevant test results and/or analyses to confirm that any increases in internal bypass flow caused by impeller or casing wear will not decrease the performance of the pumps or cause accelerated internal wear for at least 30 days of post-LOCA operation.

5) Provide mechanical seal assembly performance test results and/or analyses to confirm that ECCS operation with post-LOCA fluids will not impair seal performance, or cause seal failure, or significantly degrade seal leakage during the 30 day post-LOCA mission time.

6) Provide test and/or analysis to confirm:

   - that the cyclone separator or any filtering device designed to protect the mechanical seal, if applicable, is not susceptible to clogging or impairment by fiber or other particulates;

   - that there is no adverse impact on pump performance or reliability, for at least 30 days of operation with post-LOCA fluids.

7) The vendor will also identify any additional potential pump malfunctions, per ASME QME-1-2007.

8) The vendor will verify that the SI and CS pumps provide minimum flow rates of 397 L/min (105 gpm) and 1,817 L/min (480 gpm), respectively, at shutoff head conditions.

9) The vendor will verify that SI and CS pumps provide flow rates at run-out conditions of less than 4,675 L/min (1,235 gpm) and 24,605 L/min (6,500 gpm), respectively.

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/RHR heat exchangers are specified as shell and U-tube units. The heat exchangers are comprised of 31.75 mm (1.25″) OD, BWG 18 (1.25 mm (0.049 in.)), 304 SS tubes. A single unit is provided in each of the two CSS divisions.

The heat exchanger plugging, fouling and wear evaluation are done in the context of the equipment specification. For velocity, a maximum tube velocity of 2.57 m/s (15 ft/s) is assumed. A nominal design and operating heat exchanger velocity range is is 0.91 to 3.05 m/s (3 to 10 ft/s). Therefore the use of 2.57 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 heat exchanger tubes are 31.75 mm (1.25″) OD, 29.26 mm (1.152″) ID, BWG 18 (1.25 mm (0.049 in.)). The perforated plate hole size of the IRWST sump strainers is 2.38 mm (0.094″). 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). Therefore, the debris will not settle in the het exchanger tubes.

These conclusions are consistent with the referenced NRC Safety Evaluation on WCAP-16406-P (Reference 4-1).

4.2.3.2.2 Heat Exchanger Performance and Wear

The CS heat exchanged are sized and designed with a fouling factor of 0.000088 m^2-K/W (0.0005 hr-ft2-°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 decrease 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 will be gradual and is well within the nominal heat exchanger design.

The CS heat exchangers are sized considering maximum heat load including fouling. Therefore, the CS heat exchanges are fully capable of performing their intended function using post-LOCA fluid as the process fluid.

The CS heat exchanger 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.

The vendor will also provide test and/or analysis to confirm that the heat exchanger tube material will not degrade significantly (i.e., “eroded” tube thickness > minimum tube thickness required to retain pressure) in post-LOCA fluid over the 30 day mission time.

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

Piping

Fluid velocity decreases with increase in pipe diameter. Therefore, the lowest velocity in the ECCS will occur in the region with the largest pipe diameter/flow area. Flow velocities in all piping except several cases (24 in, 20 in, and 10 in SI Pump suction line and 12 in SI pump discharge line) are above the settling velocities of the post-LOCA fluid. Refer to Table 4.2-6.

The SI pump suction line is a 24-inch Schedule 80 stainless steel pipe (inside diameter = 547.7 mm (21.562 in)). The velocity in this line at the minimum flow rate is 0.13 m/s (0.43 ft/s). This velocity is less than the terminal settling velocities of the post-LOCA debris materials (Table 4.2-4). Therefore, settling will occur in the SI flow path to the RCS.

The CS pump suction line is a 16-inch Schedule 80 stainless steel pipe (inside diameter = 363.5 mm (14.312 in)). The velocity in this line at the minimum flow rate is 0.25 m/s (0.82 ft/s). This velocity is greater than the terminal settling velocities of the post-LOCA debris materials (Table 4.2-4). Therefore, settling will not occur in the CS flow path to the containment.

Debris settling is a longer term phenomena and has no short term impact on flow. Therefore, the potential of piping plugging or blockage and it’s impact on system operation is very low. Reliability of the SIS is considered in the design, procurement, and installation/layout of components.

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 100 mm (4 in) (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). NUREG/CR-6902 (Reference [4-3]) states that valve openings significantly larger than the debris size will not clog. The strainer hole size is 2.38 mm (0.094 in). The 100 mm (4 in) valve opening is considerably larger than any expected particle passing through the sump strainer. Therefore, the valves will 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 100 mm (4 in) (see Table 4.2-6). Flow velocities in all cases are above the settling velocities of the post-LOCA fluid (refer to Table 4.2-6). Reference 4-3 states that valve openings significantly larger than the debris size will not clog. The strainer hole size is 2.38 mm (0.094 in). The 100 mm (4 in) valve opening is considerably larger than any expected particle passing through the sump strainer. Therefore, the valves will 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 4 in (see Table 4.2-1). Reference 4-3 states that valve openings significantly larger than the debris size will not clog. The strainer hole size is 0.0625 in. Throttle valves are expected to be throttled to a minimum of 50 mm (2 in) open between the valve disc and seat. The 50 mm (2 in) valve opening is considerably larger than any expected particle passing through the sump strainer. Therefore the valves will not clog due to post-LOCA insulation debris.

4) 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 on the main control room (MCR). The orifice sizes are above 20.32 mm (0.8 in). 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.

5) Spray Nozzles

The containment main spray nozzles and auxiliary spray nozzles has an orifice of 13.1 mm (0.516 in) and 5.6 mm (0.22 in) diameter, respectively. This orifice is the smallest portion of spray nozzle. The strainer hole size is 2.38 mm (0.094 in). Reference 4-3 states that valve openings significantly larger than the debris size will not clog. 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 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 26,963 L/min (7,123 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 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 and orifice wear calculation. Based upon the results of wear evaluation for piping and orifice, it is concluded that the system piping and component flow resistances will change minimally during the course of the LOCA. Therefore, flow balances and system performance is not affected in an appreciable manner. The resulting flows and pressures are consistent or conservative with respect to the accident analysis. The minor resistance changes do not affect the system flow calculations and Design Bases analysis.

The wear rate of ECCS valves will be provided by vendor. The vendor will qualify the ECCS valves to operate with the post-LOCA fluids for at least 30 days, using the qualification guidance of ASME QME-1-2007 endorsed by RG1.100 Revision 3. As part of the qualification process, the vendor will provide data and/or analyses to support acceptable wear rates during operation in post-LOCA fluids (Table 4.2-5) at the associated flow velocities listed in Table 4.2-6.

Vendor(s) will also provide tests and/or analyses to support acceptable wear rates of pipes and orifices. In addition, an analysis will be provided to confirm that the overall system resistance/pressure drop across the ECCS is consistent with the safety analysis results for the 30 day mission time.

For conservatism, vendors will perform component wear evaluations at the assumed flow rates/velocities.

4.2.3.4 Instrument Tubing Clogging Evaluation

According to WCAP-16406-P (Reference [4-1]), 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 used in the APR1400 are located either at the horizontal or above.

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.

In-vessel fuel blockage tests performed using particulate, fiber and aluminum oxy-hydroxide precipitate demonstrated that the flow resistance created by the chemical precipitate is significantly less than the pump head that is available in the ECCS 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. The diameter of the ECCS piping, orifices, 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 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 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 (Reference [4-4] and Reference [4-5]) and when the required heat transfer capacity of the ECCS 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 associated with the ECCS. 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 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.

Table 4.1-1 Strainer Flow Rate and Debris Loads

Strainer	Pumps	Flow Rate (gpm)	Plant Strainer Debris Loads (lbm)	Prototype Strainer Debris Load (lbm)
1	SIP + CSP	6,660	6.33	0.79
2	SIP + CSP	6,660	6.33	0.79
3	SIP	1,235	1.17	0.15
4	SIP	1,235	1.17	0.15
Total		15,790	15.0	1.88

Table 4.1-2 Bypass Fiber Weight

Debris Load Addition	Fiber Added (g / lbm)	Bypass Fiber Weight (g)	Cumulative Bypass Fiber Weight (g)
After first fiber addition	181.2 / 0.4	37.16	37.16
After second fiber addition	181.2 / 0.4	29.66	66.82
After third fiber addition	181.2 / 0.4	28.04	94.86
After four fiber addition	181.2 / 0.4	29.08	123.94

Table 4.1-3 Bypass Debris Quantities of IRWST Sump Strainer

Strainer	Pumps	Flow Rate (gpm)	Plant Strainer Debris Loads (lbm)	Prototype Strainer Debris Load (lbm)	Prototype Bypass Debris (lbm)*	Ratio of Surface Areas	Bypassed Fiber Mass (lbm)
1	SIP + CSP	6,660	6.33	0.79	0.1475	8.0	1.18
2	SIP + CSP	6,660	6.33	0.79	0.1475	8.0	1.18
3	SIP	1,235	1.17	0.15	0.082	8.0	0.66
4	SIP	1,235	1.17	0.15	0.082	8.0	0.66
Total		15,790	15.0	1.88	0.459	-	3.68

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

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-PP01A/01B)	Type: Shell and Tue, 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)
Valves	
CS-V1001/1002	Swing check, 18 in
CS-V1003/1004	Gate (Manual), 18 in
CS-V1007/1008	Swing check, 14 in
CS-V1015/1016/1017/1018	Globe (Manual), 4 in
CS-V001/002/003/004	Gate (MOV), 14 in
SI-V304/305	Gate (MOV), 20 in
SI-V470/402/130/131	Gate (Manual), 10 in
SI-V404/405/434/446	Swing check, 4 in
SI-V435/447/476/478	Gate (Manual), 4 in
SI-V308/309	Gate (MOV), 20 in
SI-V347/348	Gate (MOV), 18 in
SI-V157/158	Swing check, 18 in
SI-V340/342	Gate (MOV), 18 in
SI-V424/426/448/451	Swing check, 4 in
SI-V410/411/412/413	Globe (Manual), 4 in
SI-V302/303	Globe (MOV), 4 in
SI-V100/101	Swing check, 10 in
SI-V395	Gate (MOV), 10 in
SI-V959	Gate (Manual), 10 in
SI-V106/107	Gate (Manual), 18 in
SI-V568/569	Swing check, 14 in
SI-V578/579	Gate (Manual), 14 in
SI-V341/343	Gate (MOV), 14 in
SI-V265/269	Globe (Manual), 4 in
SI-V604/609	Gate (MOV), 4 in
SI-V344/346	Gate (MOV), 18 in

(1) Including minimum bypass flow

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

Component	Description
Valves (Cont.)	
SI-V159/160	Swing check, 18 in
SI-V616/626/636/646	Globe (MOV), 4 in
SI-V113/123/133/143	Swing check, 4 in
SI-V540/541/542/543	Swing check, 4 in
SI-V614/624/634/644	Gate (MOV), 12 in
SI-V217/227/237/247	Swing check, 12 in
SI-V217/227/237/247	Swing check, 12 in
SI-V321/331	Globe (MOV, throttling), 4 in
SI-V523/533	Swing check, 4 in
SI-V957/V958	Gate (Manual), 4 in
SI-V522/532	Swing check, 4 in
Orifice	
CS-OR01A/B	CS pump miniflow orifice, 4 in
CS-FE338/348	CS pump outlet flow instrument orifice, 14 in
CS-02A/B, 03A/B	CS main spring ring header orifice, 8 in
CS-OR04A/B	CS main spring ring header orifice, 4 in
CS-OR05A/B, 06A/B	CS auxiliary spring ring header orifice, 4 in
SI-OR01A/B/C/D, 08A/B/C/D, 20A/B/C/D	SI pump miniflow orifice, 4 in
SI-OR02A/B	SC pump miniflow orifice, 4 in
SI-OR06A/B/C/D	SI pump outlet flow orifice, 12 in
SI-OR07A/B	Hotleg injection flow orifice, 4 in
SI-FE311D/321B/331C/341A	SI pump outlet flow instrument orifice, 4 in
SI-FE390C/390D	Hotleg injection flow instrument orifice, 4 in
Containment Spray Nozzle	
Main spray nozzle	Orifice size 0.516 in
Auxiliary spray nozzle	Orifice size 0.22in
Piping	
16" CS Pump Suction Line (SS Sch. 80)	
14" CS Pump Discharge Line (SS Sch. 80)	
12" CS Pump Discharge Line (SS Sch. 80S)	
14" CS Spray Header Line (SS Sch. STD)	
12" CS Spray Header Line (SS Sch. 40S)	
8" CS Spray Header Line (SS Sch 40S)	
6" CS Spray Ring Line (SS Sch 40S)	
4" CS Spray Ring Line (SS Sch 40S)	
24" SI Pump Suction Line (SS Sch. 80)	
20" SI pump Suction Line (SS Sch. 80)	
10" SI Pump Suction Line (SS Sch. 80S)	
4" SI Pump Discharge Line (SS Sch. 120)	
4" SI Pump Miniflow Line (SS Sch. 120)	
4" SI Pump Hotleg Injection (SS Sch. 120)	
4" SI Pump Discharge Line (SS Sch. 160)	
12" SI Pump Discharge Line (SS Sch. 160)	

Table 4.2-2 Size Range of Debris Materials

Debris Size Category	Size Range
Particulates	0 – 0.094 in
Small Fines	< 4 in
Large Pieces	> 4 in

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

Debris Source		Particulate	Small Fines	Large Pieces	Total
Reflective Metal Insulation (RMI) (ft^2/m^2)		0	28.5/2.65	85.5/7.94	114/10.59
Qualified Epoxy Coating (lbm/kg)		291.4/132.2	0	0	291.4/132.2
Latent Debris (lbm)	Particulate	185/83.9	0	0	185/83.9
	Fibers	0	15/6.8	0	15/6.8
Miscellaneous (ft^2/m^2)		0	0	Note	0

Note) To deal with the quantity of miscellaneous debris, a 9.29 m^3 (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 (ft/sec/m/sec)	Reference/Comments
Qualified Epoxy Coatings	0.15/0.046	NEI 04-07 (page 4-34, epoxy)
Latent Debris	0.57*/0.174	The terminal settling velocity of latent debris is estimated relative to the settling velocity of the constituent latent particulate estimated in Section 4.1.2.5.

*The terminal settling velocity of the latent particulate is estimated as:

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

Where:

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

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

d = Diameter of the particle (0.0625 in, 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 (168.6 lbm/ft^3) (Table 5)

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

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

Debris Type	Debris Quantity (lbm)	Density (lb/ft^3)	Mass (lbs)	Concentration (ppm)
Qualified Epoxy Coating	291.4	94	291.4	139.7
Latent Particulates	185	168.6	168.6	88.7
Latent Fiber	15	2.4	15	7.2
Total			475	235.6

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

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	410	13.58	0.57
CS-FE338/348	9.045	480	410	2.04	0.57
CS-OR02A/B	4.441	172	147	3.04	0.57
CS-OR03A/B	5.129	169	145	2.25	0.57
CS-OR04A/B	2.657	27	23	1.33	0.57
CS-OR05A/B	1.323	24	21	4.9	0.57
CS-OR06A/B	1.218	23	20	5.50	0.57
SI-OR01A/B/C/D	0.8	105	80	51.0	0.57
SI-OR02A/B	3.51	105	80	2.65	0.57
SI-OR06A/B	1.594	105	80	12.85	0.57
SI-OR06C/D	1.662	105	80	11.82	0.57
SI-OR07A/B	1.65	105	80	11.99	0.57
SI-OR08A/B/C/D	0.491	105	80	135.39	0.57
SI-20A/B/C/D	1.153	105	80	24.55	0.57
SI-FE311D/321B/331C/341A	2.126	105	80	7.22	0.57
SI-FE390C/390D	2.126	105	80	7.22	0.57
Containment Spray Nozzle					
Main spray nozzle	0.516	15.2	1.3	1.99	0.57
Auxiliary spray nozzle	0.22	3	0.3	2.53	0.57

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

Component	Inner Diameter (inch)	Designed Flow Rate (gpm)	Assumed Flow Rate (gpm)	Assumed Velocity (ft/sec)	Maximum Settling Velocity (ft/sec)
Piping					
16" CS Pump Suction Line (SS Sch. 80)	14.312	480	410	0.82	0.57
14" CS Pump Discharge Line (SS Sch. 80)	12.5	480	410	1.07	0.57
12" CS Pump Discharge Line (SS Sch. 80S)	11.75	480	410	1.21	0.57
14" CS Spray Header Line (SS Sch. STD)	13.25	480	410	0.95	0.57
12" CS Spray Header Line (SS Sch. 40S)	12	432	369	1.05	0.57
8" CS Spray Header Line (SS Sch 40S)	7.981	172	147	0.94	0.57
6" CS Spray Ring Line (SS Sch 40S)	6.065	169	145	1.61	0.57
4" CS Spray Ring Line (SS Sch 40S)	4.026	27	23	0.58	0.57
24" SI Pump Suction Line (SS Sch. 80)	21.562	105	490	0.43	0.57
20" SI pump Suction Line (SS Sch. 80)	17.938	105	490	0.62	0.57
10" SI Pump Suction Line (SS Sch. 80S)	9.75	105	80	0.34	0.57
4" SI Pump Discharge Line (SS Sch. 120)	3.624	105	80	2.49	0.57
4" SI Pump Miniflow Line (SS Sch. 120)	3.624	105	80	2.49	0.57
4" SI Pump Hotleg Injection (SS Sch. 120)	3.624	105	80	2.49	0.57
4" SI Pump Discharge Line (SS Sch. 160)	3.438	105	80	2.76	0.57
12" SI Pump Discharge Line (SS Sch. 160)	10.126	105	80	0.32	0.57

Table 4.2-7 ECCS and CSS Components Wear vs Time

Component	Diametric Wear ($x10^{-4}$, in)	Flow Rate Increase (%)
Orifice		
CS-OR01A/B	0.73	0.004
CS-FE338/348	1.41	0.003
CS-OR02A/B	2.09	0.009
CS-OR03A/B	1.54	0.006
CS-OR04A/B	0.92	0.007
CS-OR05A/B	3.34	0.050
CS-OR06A/B	3.81	0.063
SI-OR01A/B/C/D	3.43	0.086
SI-OR02A/B	0.59	0.003
SI-OR06A/B	10.17	0.128
SI-OR06C/D	9.35	0.113
SI-OR07A/B	9.49	0.115
SI-OR08A/B/C/D	9.11	0.371
SI-OR20A/B/C/D	1.65	0.029
SI-FE311D/321B/331C/341A	5.72	0.054
SI-FE390C/390D	5.72	0.054
Containment Spray Nozzle		
Main spray nozzle	1.36	0.05
Auxiliary spray nozzle	1.97	0.18
Piping		
16" CS Pump Suction Line (SS Sch. 80)	0.59	0.0008
14" CS Pump Discharge Line (SS Sch. 80)	0.74	0.0012
12" CS Pump Discharge Line (SS Sch. 80S)	0.83	0.0014
14" CS Spray Header Line (SS Sch. STD)	0.66	0.0010
12" CS Spray Header Line (SS Sch. 40S)	0.72	0.0012
8" CS Spray Header Line (SS Sch 40S)	0.65	0.0016
6" CS Spray Ring Line (SS Sch 40S)	0.59	0.0020
4" CS Spray Ring Line (SS Sch 40S)	0.59	0.0029
24" SI Pump Suction Line (SS Sch. 80)	0.59	0.0005
20" SI pump Suction Line (SS Sch. 80)	0.59	0.0007
10" SI Pump Suction Line (SS Sch. 80S)	0.59	0.0012
4" SI Pump Discharge Line (SS Sch. 120)	1.59	0.0079
4" SI Pump Miniflow Line (SS Sch. 120)	0.59	0.0029
4" SI Pump Hotleg Injection (SS Sch. 120)	1.59	0.0079
4" SI Pump Discharge Line (SS Sch. 160)	2.19	0.0127
12" SI Pump Discharge Line (SS Sch. 160)	0.59	0.0012

5.0 CONCLUSION

This technical report presents that the design and evaluation result of APR1400 IRWST sump strainer fully supports its safety function under post-accident conditions following USNRC 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 USNRC RG 1.82 Rev.4 requirements and has appropriate design margin to perform safety functions under post-LOCA conditions.

6.0 REFERENCES

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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 [4-6]) and the USNRC safety evaluation (SE) for WCAP-16793-NP Revision 2 (Reference [4-7]).

4.3.1 ECCS Flow Rates

Following a LOCA, the ECCS will deliver fluid and debris to the RCS. Of the debris that reaches the RCS, the amount that is transported to the 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 are as bellows to the LOCA scenarios identified in terms of break locations.

4.3.1.1 Hot Leg Break Condition

In the event of a hot-leg (HL) 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 HL break event, the maximum recirculation flow rate is 4,940 gpm in the APR1400, and the number of fuel assembly (FA) is 241. Since the core bypass flow is not credited, the entire ECC water passes through the core to exit the break. Therefore, the flow rate per FA is calculated to divide 4,940 gpm by 241, and its value is 20.5 gpm. The HL break condition at the maximum flow rate represents the most conservative condition of in-vessel downstream effect tests.

4.3.1.2 Cold Leg Break Condition

In the event of a cold-leg (CL) break, ECC water injected into the failed loop/pipe will exit the break and water injected into the intact loop/pipe will enter the downcomer annulus, ensuring that the downcomer is filled, at minimum, to the bottom of the CL 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 CL nozzles, and any excess water flows out of the CL break location and back into the containment sump.

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 CL break should be significantly less than that of HL break case. The ECC flow rate per FA is 3.29 gpm for the APR1400 at around 1,200 sec after recirculation start as bellows.

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, conservative value of recirculation start time is calculated as follows.

Assumptions

1) The time for debris to reach the reactor vessel is assumed as the time it takes to turn over the IRWST water one time.

2) It is assumed that no mixing occurs in the IRWST, and all the initial IRWST water passes through the system before debris arrives.

3) All of ECCS pumps are operated to estimate earliest time.

Calculations

- IRWST water volume : 627,000 gal
- Total ECC flow rate : 15,790 gpm
- Time for turn over : 627,000 gal / 15,790 gpm $\times$ 60 sec = 2382 sec

The time required for debris to reach reactor vessel is approximately 2,400 sec. Then, half of this time is applied by considering the earliest time that debris can reach the core, and the recirculation start time is set to be **1,200 sec** for downstream effect evaluation. This time is used to determine the core boil-off rate following a CL break with CL injection as follows.

4.3.1.2.2 Core Boil-off Rate

The maximum ECC flow rate to the reactor vessel after a CL break is selected to the core boil-off rate at the time of recirculation start (1,200 sec). The details on calculation method are described in the WCAP-16793-NP Revision 2 (App. K, RAI #18).

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

Core Decay Heat (Q_{DH})

The core heat is calculated as a function of time:

$Q_{DH} = (P/P_o)(P_o)$
where P/P_o = decay heat ratio = $(0.1741)(t^{-0.2805}) = (0.1741)(1200^{-0.2805}) = 0.02387$
P_o = power with uncertainty (MWt) = 4,062.66 MWt

From the above calculations, the core decay heat at the time of 1,200 sec : 97.0 MWt
The equation of decay heat ratio is based on the Appendix K decay heat of 1.2*ANSI '71.

Core Enthalpy Rise (ΔH)

The enthalpy rise in the core is a function of the core inlet subcooling and the saturation pressure at the

core exit. The enthalpy rise in this calculation is the latent heat of vaporization.
Therefore, $\Delta H = h_{fg}$

$h_{fg} = (-0.000131*P^3_{core\_exit}) + (0.02838*P^2_{core\_exit}) - (2.726*P_{core\_exit}) + 1005$

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} = plant-specific containment pressure in the LOCA condition
$dP_{loop} = (k/A^2 * w^2) / (288 * p_{loop} * g_c)$

In this calculation, the maximum containment pressure (68.3 psia) in the LOCA condition is selected for conservatism, and the flow losses are ignored as the values are quite small (<<0.01).

$h_{fg} = (-0.000131*68.3^3) + (0.02838*68.3^2) - (2.726*68.3) + 1005$ = 909.5 Btu/lbm = 2115 kJ/kg

From the above calculations, the core boil-off rate at the time of 1,200 sec ;

$w = Q_{DH}/\Delta H$ = (97.0 MWt × 1000 kWt/MWt)/(2155kJ/kg) = 45.85 kg/s (792.5 gpm)

Therefore, the flow rate per FA is calculated to divide 792.5 gpm by 241, and its value is **3.29 gpm**.

4.3.1.3 Cold Leg Break after HLSO Condition

At the time of 3 hours after a CL break, the operator starts simultaneous HL/DVI line injection (hot leg switchover : HLSO). Two SI pumps are for HL, and two SI pumps are for DVI lines. Since the water injected to DVI lines spills directly out of the break location, the water injected to HL goes down through the reactor core toward the break. Table 4.2.1-1 summarizes the ECCS flow rates per FA following a LOCA.

Table 4.3.1-1 ECCS Flow Rates per FA Following a LOCA

LOCA scenario	Core flow direction	APR1400 flow rate	Flow rate/ FA*	Remark
HL Break	Upward	4,940 gpm	20.5 gpm	Max. safeguard flow rate of four SI
CL Break	Upward	792.5 gpm	3.29 gpm	Boil-off flow rate at 1,200 sec
CL Break after HLSO	Downward	2,470 gpm	10.25 gpm	Max. safeguard flow rate of two SI

* 1/241 of the maximum flow rate for the APR1400

4.3.2 Amount of Bypass Debris per Fuel Assembly

To evaluate the downstream components, a determination of the amount 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. Bypass debris quantities are a function of hole size and strainer surface area (grams/ft^2). While 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 fibrous debris materials. While particulates and chemical effects can become entrained in the recirculation flow path, without any 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 **200 lbs** with 185 lbs of particulate and 15 lbs of fiber. All the debris except fiber transported to the sump 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 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 94 lbs/ft^3. A suitable and common surrogate used in US testing is silicon carbide (SiC) with a mean particle size of 10 μm and material specific gravity of 3.2 which corresponds to a density of 199.5 lbs/ft^3. Silicon carbide is selected for resistance to dissolution in the potable water and interaction with other materials. While the requirement for the characteristic size is 10 μm spheres, the SiC surrogate contains a size distribution. This is actually quite conservative since it will create a higher packing density and create more drag and head loss in the debris bed. The source and measured size distribution of the SiC used in testing will be provided in the test report summary (Reference [4-8]). In determining the amount of SiC to add to the test, it is important that the volume of particulates is preserved. Therefore the maximum amount of SiC to be added to the test is:

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

Similarly, the mass of latent particulate to be added to the test is:

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

Fibrous Debris

The latent fiber is represented by NUKON low density fiberglass which per NEI-04-07 has an as-fabricated density of 2.4 lbs/ft^3 (see NEI-04-07 SER Appendix VII). The source of the NUKON used in testing is provided in the test report summary (Reference [4-8]). Total strainer bypass fiber for the APR1400 with 15 lbs of latent fiber is 3.68 lbs (Section 4.1). The mass of fiber to be added to the test is:

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

Chemical Precipitates

Based on the design conditions (Section 3.8), the following chemical precipitates may be available in the IRWST sump fluid.

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

Given the relative proportions and since aluminum oxy-hydroxide can be conservatively used to represent the other precipitates (Reference [3-6]), only AlOOH is used in the test program. The total chemical precipitate mass of 185.1 kg is represented by AlOOH. This precipitate suspension must have a calculated concentration of 11 g precipitate/L of water. The volume of prepared AlOOH surrogate for the test is :

$$V_{AlOOH} = 185.1kg/241 \times \frac{L}{0.011kg} \times \frac{1gal}{3.758L} = 18.4gal \text{ (70 L)}$$

The bypass debris types and amounts per FA are summarized in Table 4.2.2-1.

4.3.2.1 Fiber Loads at Hot-leg Break Condition

In the event of a hot-leg (HL) 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** at HL break condition.

4.3.2.2 Fiber Loads at Cold-leg Break Condition

In the event of a cold-leg (CL) break, only a part of ECC water is injected into the core. The core flow rate is limited by the core boil-off rate as described in Section 4.2.1.2.2. This section describes the total amount of fiber loads during 30 day period following a CL break LOCA event.

Assumptions

1) All debris is generated during the first 1200 sec (20 min) after the CL break.

2) All debris is completely mixed into the IRWST at 1200 sec.

3) Debris is not trapped at any part of 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 : 3.68 lbs)
M_{Water} : total amount of IRSWT water (262.388 gal)
M_{BO} : total amount of boil-off water

$$M_{BO} = \int_{20}^{t\max} W_{BO}(t) \cdot dt$$

Where W_{BO} : boil-off rate
tmax: mission time without operator actions (30 days = 43,200 min)

The time dependent boil-off rate at 43,200 min is calculated by the methods described in Section 4.2.1.2.2, and the value is 0.38 gpm as shown in Figure 4.2.2-1.

Calculation

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Table 4.3.2-1 Bypass Debris Types and Amounts per FA

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

* 1/241 of the assumed bypass debris amount

** Result of the APR1400 strainer bypass testing

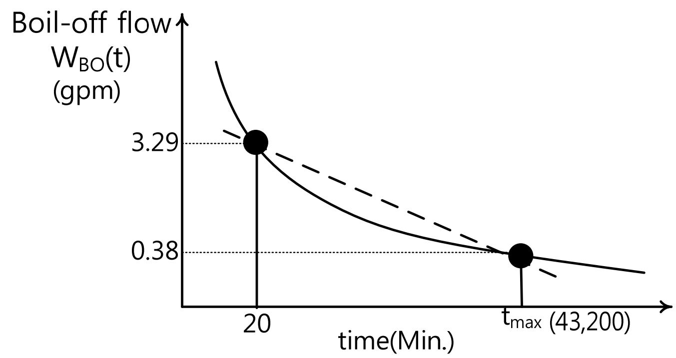

Figure 4.3.2-1 Boil-off rate during 30 days

4.3.3 Available Driving Head

It must be demonstrated that the available head to drive 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 sufficient flow is available to maintain 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) DC, 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 is based on the values provided in LOCA analyses.

4.3.3.1 Available Driving Head at HL Break Condition

In the event of a HL break, the driving force is the manometric balance between the liquid in the DC and core as shown in Figure 4.2.3-1. Should a debris bed begin to build up in the core, the liquid level will begin to build in the cold legs and SG. As the level begins to rise in the SG tubes, the elevation head to drive the flow through the core increases as well. The driving head reaches its peak when the shortest SG tube has been filled or the SG and HL have been filled.

Assumptions

1) Core voiding is neglected and the core liquid level is assumed to be at the bottom of the hot leg. This is conservative because it maximizes the static head of the liquid in the core region.

2) The DC liquid density is based on the sump liquid conditions. Since density is inversely proportional to liquid temperature, and a lower density will reduce the driving head from the DC, a conservatively high sump liquid temperature is selected. The liquid density is also a function of the containment pressure. The containment pressure is as high as 68.3 psia early in the event and then continually decreases throughout the event. A density corresponding to this saturation pressure is approximately 57.2 lbm/ft3.

3) The conditions in the core result in a liquid density that is less than the liquid density of the DC. Therefore, it is conservative to set the core liquid density equal to the density of the DC liquid.

4) The reactor vessel DC and lower plenum k/A2 is small (typically << 0.1). Further, the liquid density is large (> 57.2 lbm/ft3) and bulk velocity is low. Therefore, the losses in these regions can be neglected.

Calculations

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All the inputs are found from APR1400 drawings and evaluations. The values in Table 4.2.3-1 are used to calculate the HL break available head loss. As stated in the assumptions, the flow losses in the DC, lower plenum and core are negligible. Therefore, the HL $dP_{available}$ is as follow:

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4.3.3.2 Available Driving Head at CL Break Condition

In the event of a CL break, the driving force is the manometric balance between the liquid in the DC and core as shown in Figure 4.2.3-2. The ECC water from each DVI lines runs to the break, ensuring that the DC is full to at least the bottom of the CL nozzles. The $dP_{available}$ is established by the manometric balance between the DC liquid level, the core liquid level, and pressure drop through the RCS loops due to the steam flow:

Assumptions

1) The core void fraction (α) changes with time so a time dependent relationship is used. The details on void fraction calculation are described in the WCAP-16793-NP Revision 2 (App. K, RAI #18).

2) The assumptions used in HL break case (# 2, 3, 4) are also applied to CL break case.

3) Following a break in the CL pump suction pipe, the steam exiting the core will pass through the HLs, steam generators (SGs), and CLPS pipe to the break. Shortly after the LOCA, the steaming rate will be sufficient to keep all the loop seals open. As the core boil-off rate decreases, the steam velocities through the loops will decrease such that the loops seals may begin to re-form. It is assumed that steam venting through all loops following a CL pump suction break occurs with the initiation of HL injection at 3 hours. Following a break in the CL pump discharge pipe, steam exiting the core will pass through the HLs, SGs, and CLs to the break. The pump spillover elevation precludes liquid from falling back over the pump into the CL pump suction pipe in the intact loops. Therefore, the loop seals do not re-form, and all loops continue to vent steam. Therefore, loop seal re-formation is not considered in the calculation of the available driving head for breaks with cold leg injection.

Calculations

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The values in Table 4.2.3-2 are used to calculate the CL break available head loss. The dP_{avail} for a CL 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 boiloff rate decreases with time, the minimum dP_{avail} for a CL break is calculated at the recirculation start time (1,200 sec)

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4.3.3.3 Available Driving Head at CL Break after HLSO Condition

In the event of a CL break after HLSO operation, the driving force is the manometric balance between the liquid in the DC and core as shown in Figure 4.2.3-3. Should a debris bed begin to build up in the core, the liquid level will begin to build in the HLs and SG. As the level begins to rise in the SG tubes, the elevation head to drive the flow through the core increases as well. The driving head reaches its peak when the shortest SG tube has been filled or the SG and HL have been filled.

Assumptions

1) The assumptions used in HL break case (# 1, 2, 3) are also applied to CL break after HLSO case.
2) The flow losses in reactor core, lower plenum, reactor vessel DC and HL are based on the values in LOCA analyses.

Calculations

TS

All the inputs are found from APR1400 drawings and evaluations. The values in Table 4.2.3-3 are used to calculate the CL break after HLSO operation available head loss. The $dP_{available}$ is as follow:

TS

Table 4.3.3-1 Inputs for Calculation of HL dP_{avail}

Variable	Description	Unit	Value	Comments
Z_{so}	Hot leg or SG spillover elevation	m		DC and core liquid density is selected at the max. saturation pressure (68.3psia,301.2°F)
$Z_{core\text{-}in}$	Bottom of active fuel	m		
ρ_{DC}	Downcomer(DC) liquid density	kg/m³		
Z_{brk}	Z_{RVCl}-Z_{IDHL}/2	m		
Z_{RVCL}	RV nozzle centerline	m		
Z_{IDHL}	Inner diameter of HL pipe	m		
ρ_{core}	Core liquid density	kg/m³		

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Table 4.3.3-2 Inputs for Calculation of CL dP_{avail}

Variable	Description	Unit	Value	Source
$Z_{core\text{-}out}$	Top of active fuel	m		DC and core liquid density is selected at the max. saturation pressure (68.3psia, 301.2 °F)
$Z_{core\text{-}in}$	Bottom of active fuel	m		
ρ_{DC}	Downcomer(DC) liquid density	kg/m³		
Z_{brk}	Z_{RVCl}-Z_{IDCL}/2	m		
Z_{RVCL}	RV nozzle centerline	m		
Z_{IDCL}	Inner diameter of CL pipe	m		
ρ_{core}	Core liquid density	kg/m³		
α_{core}	Core void fraction (=1.1128*t^-01183)			

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Table 4.3.3-3 Inputs for Calculation of CL after HLSO dP_{avail}

Variable	Description	Unit	Value	Comments
Z_{so}	Hot leg or SG spillover elevation	m		DC and core liquid density is selected at the max. saturation pressure (68.3psia,301.2 °F)
$Z_{core\text{-}in}$	Bottom of active fuel	m		
ρ_{DC}	Downcomer(DC) liquid density	kg/m³		
Z_{brk}	Z_{RVCl}-Z_{IDCL}/2	m		
Z_{RVCL}	RV nozzle centerline	m		
Z_{IDCL}	Inner diameter of CL pipe	m		
ρ_{core}	Core liquid density	kg/m³		

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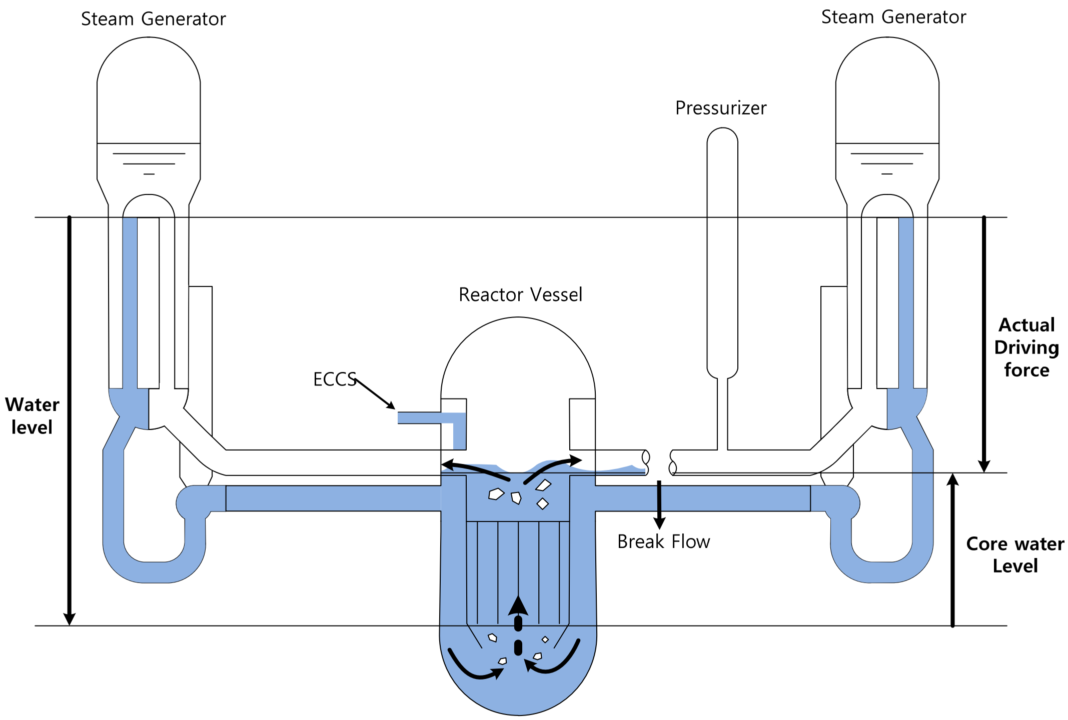

Figure 4.3.3-1 Available Driving Head at HL Break Condition

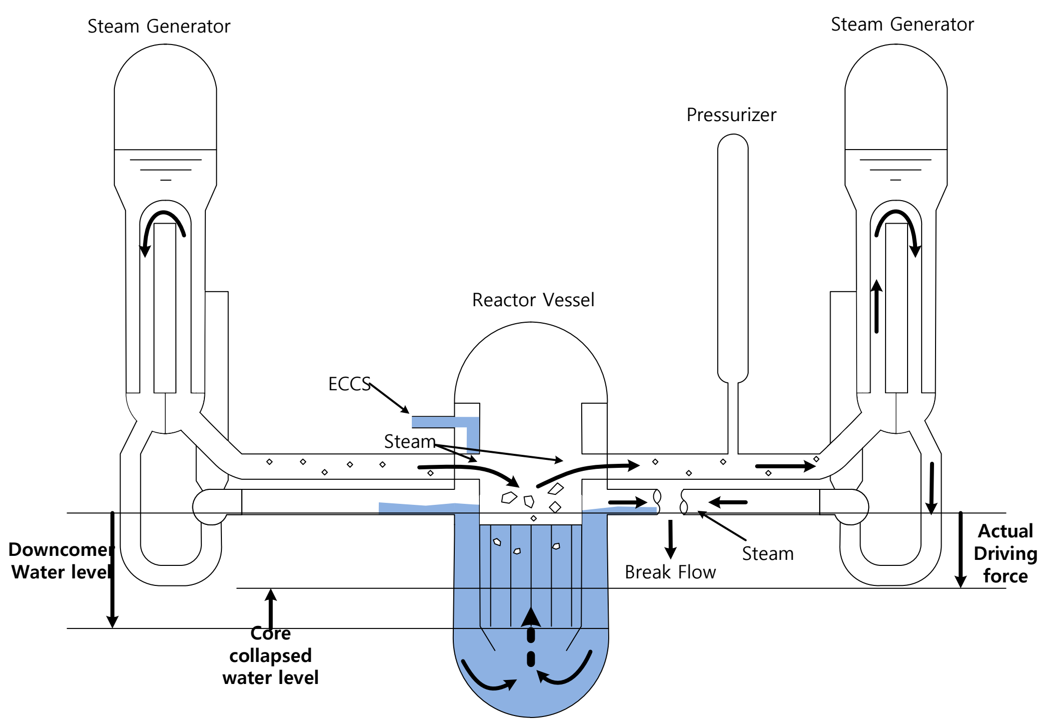

Figure 4.3.3-2 Available Driving Head at CL Break Condition

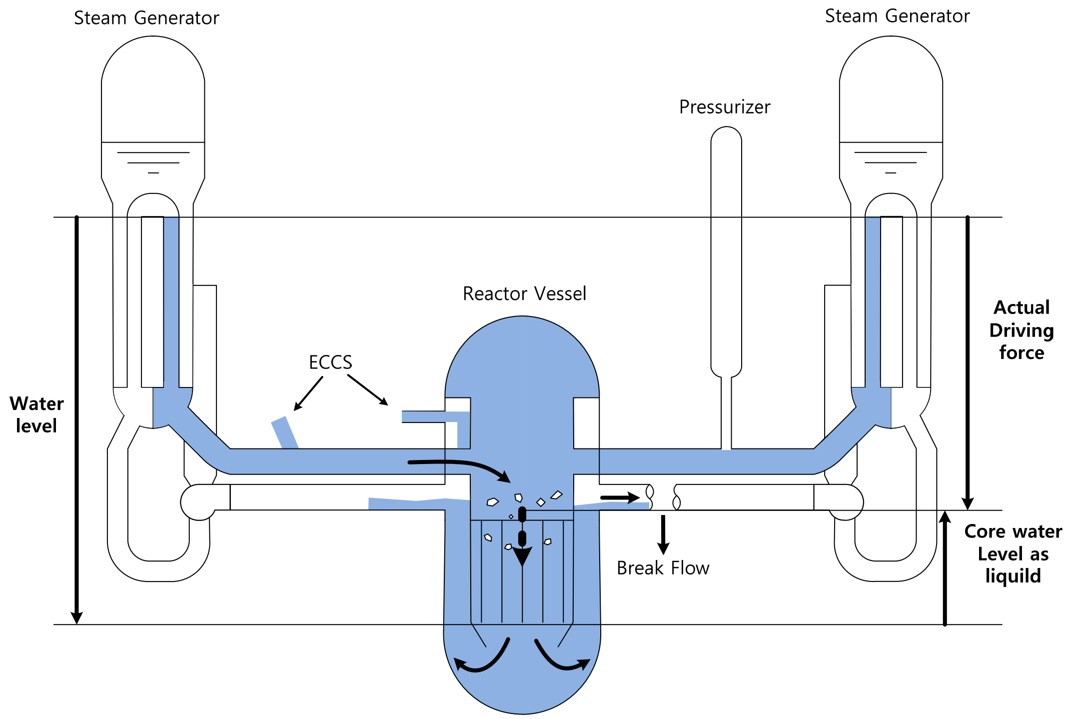

Figure 4.3.3-3 Available Driving Head at CL Break after HLSO Condition

4.3.4 LOCADM Calculations

This section provides evaluation results of two parameters of cladding temperature and cladding deposit thickness for the APR1400 during 30 day period following a LOCA event.

WCAP-16793-NP Revision 2, developed by the PWR Owners Group (PWROG), defines an U.S.NRC approved methodology for evaluating the impact of debris on long-term fuel cladding performance subsequent to a LOCA event. The methodology and the implementing software, an Excel spreadsheet based tool identified as the LOCA Deposition Model (LOCADM), evaluates the 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 WCAP-16530-NP-A (Reference [3-6]) are used in the LOCADM methods to determine the types and concentrations of the chemical species present in the ECCS 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 LOCA event duration.

LOCADM is used with the methodology provided in WCAP-16793-NP Revision 2 and the guidance provided in the USNRC SE (Reference [4-7]) to evaluate cladding deposit thickness and temperature for the APR1400.

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 fuel deposits of material on the fuel shall not exceed 0.050 inches 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 sump environment from particulate, fibrous and chemical debris generated during the LOCA event and transported into the core by ECCS safety injection coolant, on long-term cooling of the fuel. Specific to this evaluation methodology, the PWROG developed the LOCADM which implements the WCAP chemical dissolution and deposition models for conservatively evaluating two parameters critical to long-term cooling - cladding deposit thickness and cladding temperature. These particular parameters are compared against U.S.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 LOCADM:

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

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

3) OG-07-419 (Reference [4-9]) transmitting LOCADM.xls with some discussion of selected input parameters

4) OG-07-534 (Reference [4-10]) providing discussion of Options 1 and 2 for modeling Modes 1 and 2

5) OG-08-64 (Reference [4-11]) providing guidance to address an U.S.NRC concern that short term aluminum release is under predicted by LOCADM.

LOCADM evaluates conditions during the event through the four plant operating modes during a LOCA event (Reference [4-10]):

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 accumulators and IRWST

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

3) Mode 3: recirculation from the sump

4) Mode 4: hot leg injection

Figure 4.2.4-1 shows the schematic diagram of the LOCADM physical model of the APR1400. 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 balance of 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 containment sump

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 is comprised of recirculation water that is injected into the intact loop (i.e., ‘RecircLqFlow’) and the broken loop (i.e., ‘RecircBypass’)

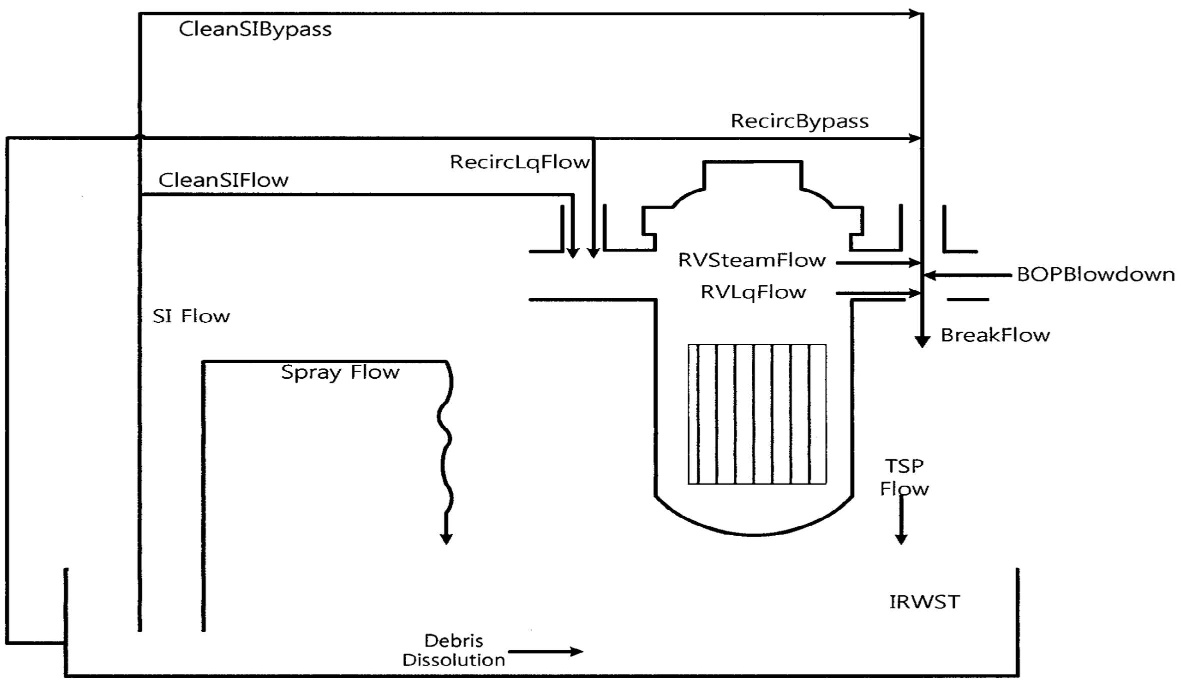

Figure 4.3.4-1 Flow Paths and Definitions for LOCADM

Figure 4.3.4-1 Flow Paths and Definitions for LOCADM

4.3.4.3 Assumptions

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

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

2) It is assumed that 12.5 ft3 of fiber debris (a density of 2.4 lbm/ft^3) bypasses the ECCS sump strainers and is entrained in safety injection and recirculation flows.

   Basis : There is no fiber insulation inside the Zone of Influence. Only latent fiber amount is assumed to be 15 lbm inside the entire containment. However, 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 900 seconds (15 minutes).

4) It is assumed that Mode 4 for hot let 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 'TimeInput'

Guidance for input to populate the 'TimeInput' worksheet comes primarily from the 'Instructions' worksheet in the LOCADM spreadsheet itself. The input consists primarily of times during and subsequent to the LOCA event and the corresponding fluid temperatures and flows, and plant operating mode.

Time, sec

In order to model the start of recirculation at 15 minutes post-LOCA and 1.5 hours post-LOCA, time steps were added to the base worksheet at a) 900 and 901 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 10 pH for the first 15 minutes post-LOCA and 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 thicknesses and slightly higher cladding temperatures.

IRWST Temperature, °F

The IRWST temperature profile used for this calculation is shown in Table 4.2.4-1.

Spray Flow, lbm/sec

The containment spray flow, in accordance with the guidance provided in Reference [4-10] for LOCADM Option 2 operation, is set to zero for all input times.

Spray pH

The containment spray pH profile is set to a pH of 10.0 for the first 15 minutes post-LOCA and 8.5 thereafter. As discussed above, the use of the higher values is conservative as a higher pH enhances dissolution of debris in the sump and components wetted by the sump fluid thereby generating larger scale thicknesses and slightly higher cladding temperatures.

Reactor Vessel Coolant Temperature, °F

The RV coolant temperature is assumed to be 10 °F higher than the containment temperature. The containment temperature profile is shown in Table 4.2.4-1.

Clean Safety Injection Flow into Reactor Vessel, 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 maximum steaming rate.

Recirculation Flow into Reactor Vessel, lbm/sec

The recirculation flow into the reactor vessel, in accordance with the guidance provided in Reference [4-10] 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, lbm/sec

While APR1400 implement TSP for sump coolant pH control, its impact on sump pH is accounted for in the sump coolant pH profile. As such, the TSP dissolution rate is unused and values are set to 0.

Reactor Vessel Pressure in Upper Plenum, psia

Reference [4-10] 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 14.7 psia.

Maximum Steaming Rate, lbm/sec

The 'Maximum Steaming Rate' is evaluated internally in LOCADM. The calculated values have not been 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 has been entered for 'Metallic Aluminum Alloy 1100 or Unknown Alloy Type'.

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1) aluminum submerged (ft^2) :

2) aluminum submerged (lbm) :

3) aluminum not submerged (ft^2) :

4) aluminum not submerged (lbm) :

Calcium Silicate

Included in this materials type are low density calcium silicate mat insulation, asbestos and asbestos containing insulation, and high density refractory materials (e.g., transite). No calcium silicate material types have been used in the APR1400.

E-Glass

Included in this material type is fiberglass insulation.

- Fiberglass insulation : 12.5 ft^3

Using a density of 2.4 lbm/ft^3, a value of 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. 9,344 ft^2 of concrete is exposed in containment.

Coolant

Coolant material inputs are provided to specify coolant specific characteristics for input to LOCADM. Table 4.2.4-2 and Table 4.2.4-3 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 itself. The input consists primarily of material densities with material amounts drawn from 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 57.9 lbm/ft^3.

4.3.4.4.4 Spreadsheet ‘CoreDataInput’

Guidance for input to populate the ‘CoreDataInput’ worksheet comes primarily from the ‘Instructions’ worksheet in the LOCADM spreadsheet itself. The input is grouped into three different matrices – input used for these cases are 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)

Reference [4-6] (Page E-16) indicates that the limiting value for the thermal conductivity of PWR crud is 0.52 W/m-K. This value will be input for 'Crud Thermal Conductivity' for the LOCADM evaluations for the APR1400.

LOCA Deposit Thermal Conductivity (W/m K)

Reference [4-6] (Page E-16) indicates that the limiting value for the thermal conductivity of post-LOCA deposits is 0.2 W/m K. This value will be input for 'LOCA Deposit Thermal Conductivity' for the LOCADM evaluations for the APR1400.

Fuel Rod OD (inches)

A value of 0.374 inches is used.

Pellet Stack Length (inches)

A value of 150 inches is used.

Average Cladding Oxide Thickness (microns)

As discussed in References [4-7] and [4-9], 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:

$$\text{Oxide initial} = 0.02252 \times 0.17 \times 1.56 \times 1000 = 5.972 \text{ mil} = 152\ \mu m$$

For the conservative evaluation, the average cladding oxide thickness is considered to be the same as peak initial oxide thickness of 152 μm.

Average Starting Crud Thickness (microns)

Reference [4-10] indicates that the value input for 'Average Starting Crud Thickness' is the maximum bounding value of 140 μm by the maximum values of the 'Relative Crud Thickness' multipliers in the axial and fuel region matrices. For the conservative evaluation, the average initial crud thickness is considered to be the same as maximum bounding value of 140 μm.

Number of Regions

Reference [4-6] 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 [4-10] 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 (inches)

The distance from the top of the active region to the bottom of the hot leg inlet is 39.748 inches.

4.3.4.4.4.2 Core (Axial) Elevation Characteristics

Reference [4-10], 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 4.2.4-5.

4.3.4.4.4.3 Fuel Region (Radial) Characteristics

Reference [4-6], 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 4.2.4-6 along with the bases for those particular numbers.

Region

Consistent with CE NSSSs implementing 16x16 fuel 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 [4-6], 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 through 3 sums to 56,876 which 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 itself. The switches permit factoring in reductions in the projected chemical effects by crediting inhibition of corrosion and/or solubility limits.

Table 4.3.4-1 Time Dependent Temperature Data

Time (sec)	IRWST Temp (ºF)	CTMT Temp (ºF)	RV Coolant Temp (ºF)
3	120.0	220.0	230.0
17	120.6	264.2	274.2
40	122.4	261.7	271.7
114	125.1	265.4	275.4
121	125.3	265.8	275.8
301	130.0	273.1	283.1
600	140.2	269.1	279.1
900	140.2	269.1	279.1
901	148.3	264.5	274.5
1202	153.6	261.2	271.2
2409	166.3	250.7	260.7
3002	171.4	246.6	256.6
3606	175.9	243.0	253.0
5224	175.9	243.0	253.0
5225	185.6	235.4	245.4
9429	200.2	223.8	233.8
12002	204.8	219.8	229.8
28002	210.1	208.1	218.1
80002	190.9	187.7	197.7
100002	185.1	182.6	192.6
1000182	146.5	146.5	156.5
2600000	134.3	134.3	144.3

Table 4.3.4-2 Containment Material Input

Class	Material	Value
Metallic Aluminum	Aluminum Submerged (ft^2)	
	Aluminum Submerged (lbm)	
	Aluminum Not-Submerged (ft^2)	
	Aluminum Not-Submerged (lbm)	
Calcium Silicate	CalSil Insulation(ft^3)	
	Asbestos Insulation (ft^3)	
	Kaylo Insulation (ft^3)	
	Unibestos Insulation (ft^3)	
E-glass	Fiberglass Insulation (ft^3)	
	NUKON (ft^3)	
	Temp-Mat (ft^3)	
	Thermal Wrap (ft^3)	
Silica Powder	Microtherm (ft^3)	
	Min-K (ft^3)	
Mineral Wool	Min-Wool (ft^3)	
	Rock Wool (ft^3)	
Aluminum Silicate	Cerablanket (ft^3)	
	FiberFrax Durablanket (ft^3)	
	Kaowool (ft^3)	
	Mat-Ceramic (ft^3)	
	Mineral Fiber (ft^3)	
	PAROC Mineral Wool (ft^3)	
Concrete	Concrete (ft^2)	

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Table 4.3.4-3 Coolant Material Inputs

Parameter	Unit	Value	Note
IRWST Water Density	lbm/ft^3		Min. Liq. Density
Initial IRWST Water Volume	ft^3		Minimum IRWST Level for SIS NPSH during LOCA Recirculation
Initial IRWST Water Mass	lbm		Minimum IRWST Level for SIS NPSH during LOCA Recirculation
Core Region Water Density	lbm/ft^3		Minimum Liquid Density
Initial Core Region Water Volume	ft^3		OG-07-419
Initial Core Region Water Mass	lbm		from Min. Liquid Density and Initial Core Region Water Volume

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Table 4.3.4-4 Core Modeling Parameters

Variable	Units	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 4.3.4-5 Axial Nodalization and Input Values

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

Table 4.3.4-6 Radial Nodalization and Input Values

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

4.3.4.5 Results

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In conclusion, the maximum total deposit thickness and the peak cladding temperature are maintained within the WCAP-16793-NP LTCC criteria with enough margin, and the LTCC can be maintained.

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Figure 4.3.4-2 Maximum LOCA Scale Thickness

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Figure 4.3.4-3 Fuel Cladding Temperature

4.3.5 Evaluation Summary

The intent of this section is to assess the in-vessel downstream effects of the APR1400 applying the evaluation methods and acceptance bases provided in the WCAP-16793-NP Revision 2 and the U.S.NRC safety evaluation (SE) for WCAP-16793-NP Revision 2.

To maintain the 15 gram/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 20.5 gpm in the HL break condition, and 3.29 gpm at around 1,200 sec after recirculation start in the CL break condition.

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

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The test results of in-vessel downstream effect of the APR1400 are provided in the technical report (Reference [4-8]).

In conclusion, sufficient long-term core cooling following a LOCA in the APR1400 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.