19.39 In-Vessel Retention of Molten Core Debris

19.39.1 Introduction

In-vessel retention of molten core debris through water cooling of the external surface of the reactor vessel is a severe accident management feature of the AP1000. During postulated severe accidents, the accident management strategy to flood the reactor cavity with in-containment refueling water storage tank water and submerge the reactor vessel is credited with preventing vessel failure in the AP1000 probabilistic risk assessment. The water cools the external surface of the vessel and prevents molten debris in the lower head from failing the vessel wall and relocating into containment. Retaining the debris in the reactor vessel protects containment integrity by eliminating the occurrence of ex-vessel severe accident phenomena, such as ex-vessel steam explosion and core-concrete interaction, which have large uncertainties with respect to containment integrity.

The AP1000 provides for in-vessel retention with features that promote external cooling of the reactor vessel:

- The reliable multi-stage reactor coolant system depressurization system results in low stresses on the vessel wall after the pressure is reduced.

- The vessel lower head has no vessel penetrations to provide a failure mode for the vessel other than creep failure of the wall itself.

- The floodable reactor cavity can submerge the vessel above the coolant loop elevation with water intentionally drained from the in-containment refueling water storage tank.

- The reactor vessel insulation provides an engineered pathway for water-cooling the vessel and for venting steam from the reactor cavity.

19.39.2 Background on the Application of In-Vessel Retention to the Passive Plant

The Risk-Oriented Accident Analysis Methodology (ROAAM) analysis of the in-vessel retention phenomena (References 19.39-1 and 19.39-2) provided the basis for the application of the in-vessel retention accident management strategy to the AP600 passive plant and quantification of vessel failure in the AP600 PRA (Reference 19.39-3). The ROAAM included an analysis of the in-vessel melt progression and evaluation of the structural and thermal challenges to the vessel during the relocation to the lower head, including in-vessel steam explosion. Testing and evaluation of the uncertainties associated with the thermal loads produced by the in-vessel circulating molten debris pool, and heat removal limitations due to boiling crisis on the exterior vessel surface were performed in the ACOPO (19.39-4) and ULPU programs (References 19.39-1 and 19.39-5). The ROAAM concluded that the limiting challenge to the vessel integrity is the thermal loading produced during the steady-state heat transfer to the lower head wall after complete debris relocation to the lower plenum. The in-vessel retention ROAAM analyses and testing showed that the water in the AP600 cavity will remove the heat produced by the molten debris bed in the lower head with significant margin while the structural integrity of the lower head was maintained.

Based on the ROAAM results, vessel failure in the AP600 was considered to be physically unreasonable, and a probability of zero was applied to vessel failure in the AP600 PRA (Reference 19.39-3) if the following conditions of the ROAAM analysis were met:

- The reactor coolant system was depressurized.
- The reactor vessel was submerged sufficiently to wet the heated surface.
- Reactor vessel reflective insulation and containment water recirculation flow paths allowed sufficient ingress of water and venting of steam from the cavity.
- The treatment of the lower head outside surface (painting, coatings, etc.) did not interfere with water cooling of the vessel.

19.39.3 Application of In-Vessel Retention to the AP1000 Passive Plant

To establish a strong basis for crediting in-vessel retention in the AP1000, the following steps are taken:

- Establish design measures to increase the capability of the water to remove heat from the external surface of the reactor vessel (increase critical heat flux).
- Demonstrate that the thermal failure remains the limiting failure over the structural failure for the AP1000.
- Demonstrate that the AP1000 in-vessel melt progression does not change from the AP600 melt progression in such as way as to challenge the vessel integrity during relocation.
- Demonstrate that the heat load correlation, as applied from the ACOPO program (Reference 19.39-4), scales appropriately to the AP1000.
- Quantify the thermal loads using probability distributions developed specifically for the AP1000.

These items are discussed in the following sections.

19.39.4 Reactor Vessel Failure Criteria

The conclusions of the structural analyses performed for the AP600 in Reference 19.39-1 can be extrapolated to the AP1000. Thus, for the AP1000, success of in-vessel retention can be based solely on the thermal success criterion.

19.39.5 In-Vessel Melt Progression and Relocation

The AP1000 core and lower internals geometry has been changed from the AP600 geometry as a result of the higher power output. The core is made up of 157 fuel assemblies with a 14-foot active fuel length. To accommodate the larger reactor core, the thick stainless steel reflector has been replaced by a 7/8″ thick core stainless steel shroud. The thick bottom plate of the shroud is mounted flush on the support plate. There are no former plates in the annulus between the shroud and the core barrel. The core barrel is 2″ thick and hangs from the upper head flange. Cooling holes through the core shroud provide cooling flow to the shroud from the core flow.

The phenomena associated with melting the core and the relocation of the molten debris to the lower plenum play an important role in the composition and configuration of the debris pool (Reference 19.39-2). In turn, the characteristics of the debris pool significantly impact the heat loading to the lower head wall and the challenge to lower head integrity (Reference 19.39-1). Therefore, understanding the melting and relocation scenarios plays an important role in the assessment of in-vessel retention of molten core debris in the lower plenum.

The important conclusions from the analysis of the lower plenum debris pool formation are:

- The lower plenum debris bed is cooled with water during the entire relocation process prior to contact with the support plate. Transient debris configurations are not predicted to threaten vessel integrity.

- The lower plenum oxide debris subsumes the lower core support plate before dry out in the lower plenum occurs. If the relocated debris is assumed to be instantaneously quenched in the lower plenum water, the oxide debris contacts the lower support plate before the debris can return to a superheated condition. Therefore, the lower core support plate, core shroud and a sizeable fraction of the core barrel are subsumed in the debris bed. The focusing effect is mitigated.

- The lower plenum debris bed is predicted to form a metal layer over oxide pool configuration.

- The potential for debris interaction creating a bottom metal pool of uranium dissolved in zirconium is expected to be small.

- The earliest time to achieve the fully molten, circulating debris bed in the lower plenum is 2.7 hours after event initiation.

19.39.6 Application of Heat Transfer Correlations to the AP1000

19.39.6.1 Debris Pool to Vessel Wall Heat Transfer

The heat transfer from the oxide pool containing the decay heat producing fission products to the lower head of the reactor vessel is described using correlations that were developed in the Department of Energy (DOE) program for the AP600 in-vessel retention assessment.

The correlations developed in the ACOPO experiments and used in the AP600 in-vessel retention ROAAM for heat transfer from the debris pool to the lower head wall are applicable for use in the AP1000 in-vessel retention analysis.

19.39.6.2 Vessel Wall to External Cooling Water Heat Transfer

The heat transfer from the vessel wall to the cooling water is limited by the transition to film boiling at the external surface of the vessel wall. The maximum heat flux that can be removed prior to the transition to film boiling is the critical heat flux. If the heat flux from the debris pool to the wall is less than the critical heat flux, the vessel maintains sufficient strength to carry the load on the vessel. At heat fluxes above the critical heat flux, the external wall temperature increases significantly, the strength of the wall is lost, and the vessel fails.

Testing has been performed with ULPU-2000 Configuration IV (reference 19.39-4) which demonstrates the feasibility of increasing the critical heat flux for AP1000. The heat removal capability is enhanced by constructing a hemispherical baffle outside the lower head to channel the cooling water flow and by assuring the flooding level in the containment outside the reactor vessel is sufficient for two phase natural circulation (Reference 19.39-4).

The AP1000 employs a reactor vessel insulation design that provides water inlet, steam venting and a baffle around the lower head to enhance the heat removal and increase the critical heat flux on the reactor vessel external surface. The insulation is vented from the annulus between the insulation and vessel to the vessel nozzle gallery at the 98 ft elevation.

19.39.7 Quantification of Heat Load on the Reactor Vessel Wall

With the baffle installed in the AP1000 and the cavity adequately flooded, significant margin-to-failure for in-vessel retention via external reactor vessel cooling is achieved.

Based on the results of the ROAAM testing and analysis and the UPLU-2000 Configuration IV testing, vessel failure is concluded to be physically unreasonable in the AP1000 PRA provided the following conditions are met:

- The reactor coolant system is depressurized.
- The vessel is submerged adequately to promote natural circulation of water through the baffle surrounding the lower head.
- Reactor vessel reflective insulation remains structurally sound under the pressure loads produced by the boiling external to the reactor vessel, allows water inlet at the bottom and venting of steam at the top, and provides the proper baffling to increase the critical heat flux on the external surface of the vessel lower head.
- The reactor vessel external surface conditions do not preclude the wetting phenomena identified as the cooling mechanism in the ULPU testing.

19.39.8 Reactor Coolant System Depressurization

Reactor coolant system depressurization is discussed in Section 19.36.

19.39.9 Reactor Cavity Flooding

Reactor cavity flooding is accomplished through either operator action or through the progression of the accident. The operator floods the cavity by opening a motor-operated valve and a squib valve in the recirculation lines between the in-containment refueling water storage tank and the containment recirculation sump, as shown in Figure 19.39-15. The operator action is prescribed by entering the AFR-C.1 Function Restoration Guideline (Reference 19.39-6) when the core-exit thermocouples reach 1200°F. The water floods the containment by flowing out of the recirculation screens, filling the containment floodable region of the containment, shown in Figure 19.39-15, to at least the 107′ 2″ elevation, shown in Figure 19.39-16.

To achieve the high critical heat flux for the AP1000 lower head, water level in containment must be sufficient for two phase natural circulation flow. The vents from the AP1000 reactor vessel insulation exit to the vessel nozzle gallery at the 98 ft elevation. It is conservatively assumed that the water level in the containment has to reach the 98 ft elevation within seventy minutes after the core exit temperature exceeds 1200°F, for successful vessel cooling.

The AP600 procedures instructed the operator to flood the reactor cavity at the end of AFR-C.1 Function Restoration Guideline before entering the severe accident management guidelines. The AP1000 requires the cavity to be flooded to a higher level and more quickly than the AP600. For the AP1000, the operator action to initiate cavity flooding has been moved to the entry of the AFR-C.1 Function Restoration Guideline to meet the time requirement for cavity flooding success.

19.39.10 Reactor Vessel Insulation Design Concept

With respect to in-vessel retention severe accident management, the goal of the reactor vessel insulation is to ensure that there will always be an adequate water layer next to the reactor vessel to promote heat transfer from the reactor vessel. The insulation will define an optimized flow path next to the lower head to enhance the critical heat flux. The cooling of the vessel in a severe accident is accomplished by providing:

- A means of allowing water free access to the region between the reactor vessel and insulation.

- A frame that maintains the structural integrity of the insulation surrounding the lower head which provides the baffle for the water flow next to the vessel.

- A means to vent steam generated by the water cooling the vessel wall from the insulation surrounding the reactor vessel.

- A support frame to prevent the insulation panels above the vessel lower head from breaking free and blocking water from cooling the reactor vessel exterior surface.

19.39.10.1 Description of Reactor Vessel Insulation and Venting

Subsection 5.3.5 provides a description of the reactor vessel insulation and the functional requirements for the insulation.

19.39.10.2 Design Analysis of the Insulation and Support Frame

The insulation forms an engineered pathway to enhance the cooling of the external surface of the reactor vessel during in-vessel retention. Structural support to maintain this pathway must be provided.

19.39.10.3 Reactor Vessel External Surface Treatment

Based on the reactor vessel system design specification, the only treatment of the external surface of the reactor vessel is a protective paint applied by the manufacturer prior to shipping. The paint protects the vessel carbon steel surface. Testing of the paint in ULPU-2000 configuration III concluded that the aged painted surface did not inhibit the wetability of the lower head (Reference 19.39-1).

19.39.11 Reactor Vessel Failure

Based on the analysis of in-vessel retention, an intact reactor vessel remains intact if the reactor coolant system is depressurized and the reactor vessel is adequately submerged.

19.39.12 Summary

In-vessel retention of molten core debris via external reactor vessel cooling can be accomplished in the AP1000.

- The reactor vessel insulation must provide a structurally sound baffle around the lower head and lower cylinder of the vessel to channel the flow between the vessel and insulation. An insulation design that provides the proper water inlet, steam venting and flow baffling is specified for the AP1000.

- The reactor cavity must be flooded to an elevation of at least 98 ft prior to the onset of the steady–state heat flux to the vessel wall from the debris to produce the driving head required to enhance the critical heat flux on the vessel surface. The operator action to flood the cavity has been moved to the first step of the emergency operating procedures to provide adequate flooding.

19.39.13 References

19.39-1 Theofanous, T.G., et al., “In-Vessel Coolability and Retention of a Core Melt,” DOE/ID-10460, July 1995.

19.39-2 Theofanous, T.G., et al., “Lower Head Integrity Under In-Vessel Steam Explosion Loads,” DOE/ID-10541, June 1996.

19.39-3 AP600 PRA Report, GW-GL-022, August 1998.

19.39-4 Theofanous, T.G., and S. Angeli, “Natural Convection for In-Vessel Retention at Prototypic Rayleigh Numbers,” Nuclear Engineering and Design, 200, 1-9 (2000).

19.39-5 Angelini, S., et al., “The Mechanism and Prediction of Critical Heat Flux in Inverted Geometries,” Nuclear Engineering and Design, 200, 83-94 (2000).

19.39-6 AP600 Emergency Response Guidelines.

TABLES 19.39-1 THROUGH 19.39-3 NOT INCLUDED IN THE DCD.
FIGURES 19.39-1 THROUGH 19.39-15 NOT INCLUDED IN THE DCD.

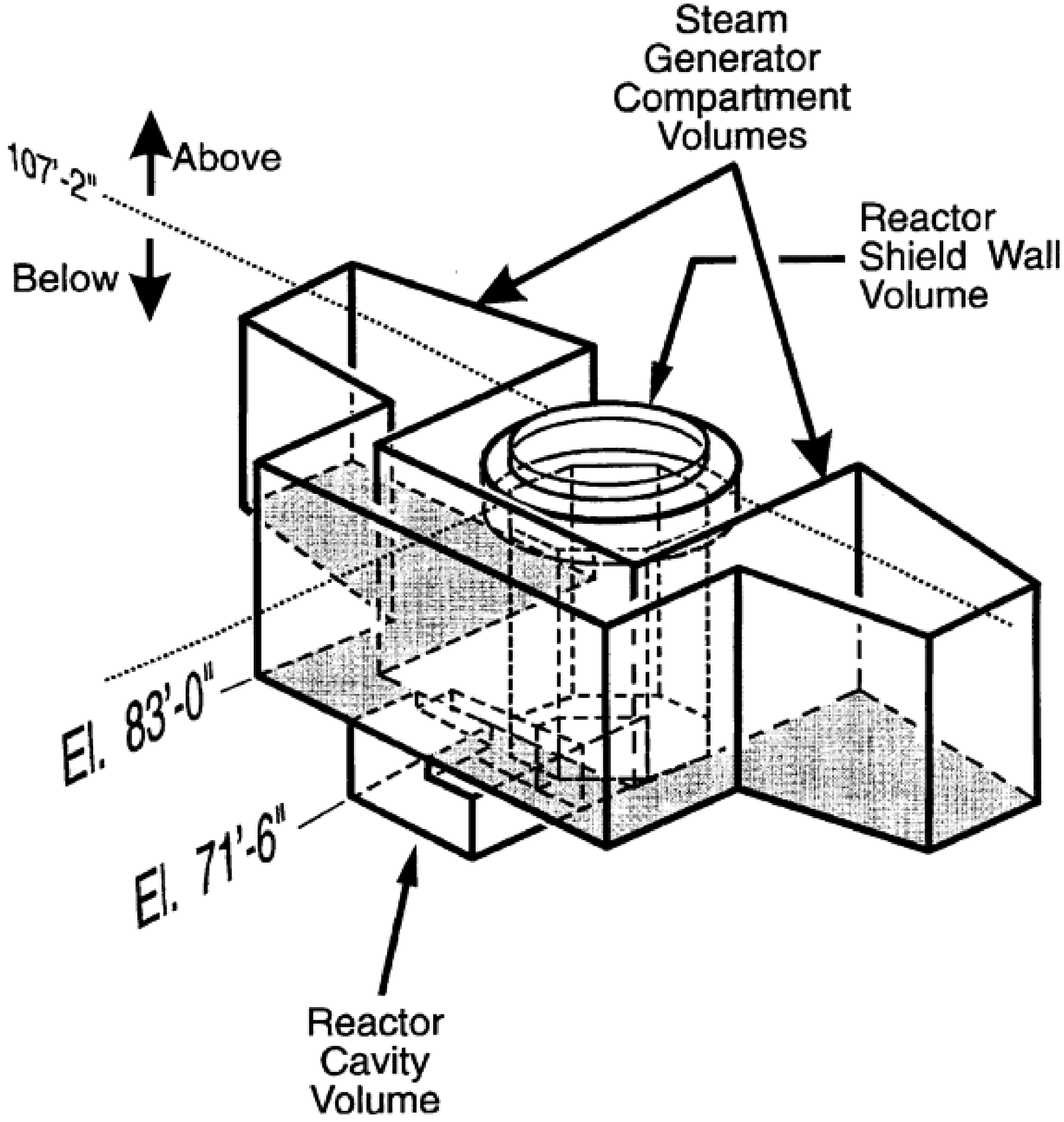

Figure 19.39-16

Containment Floodable Region

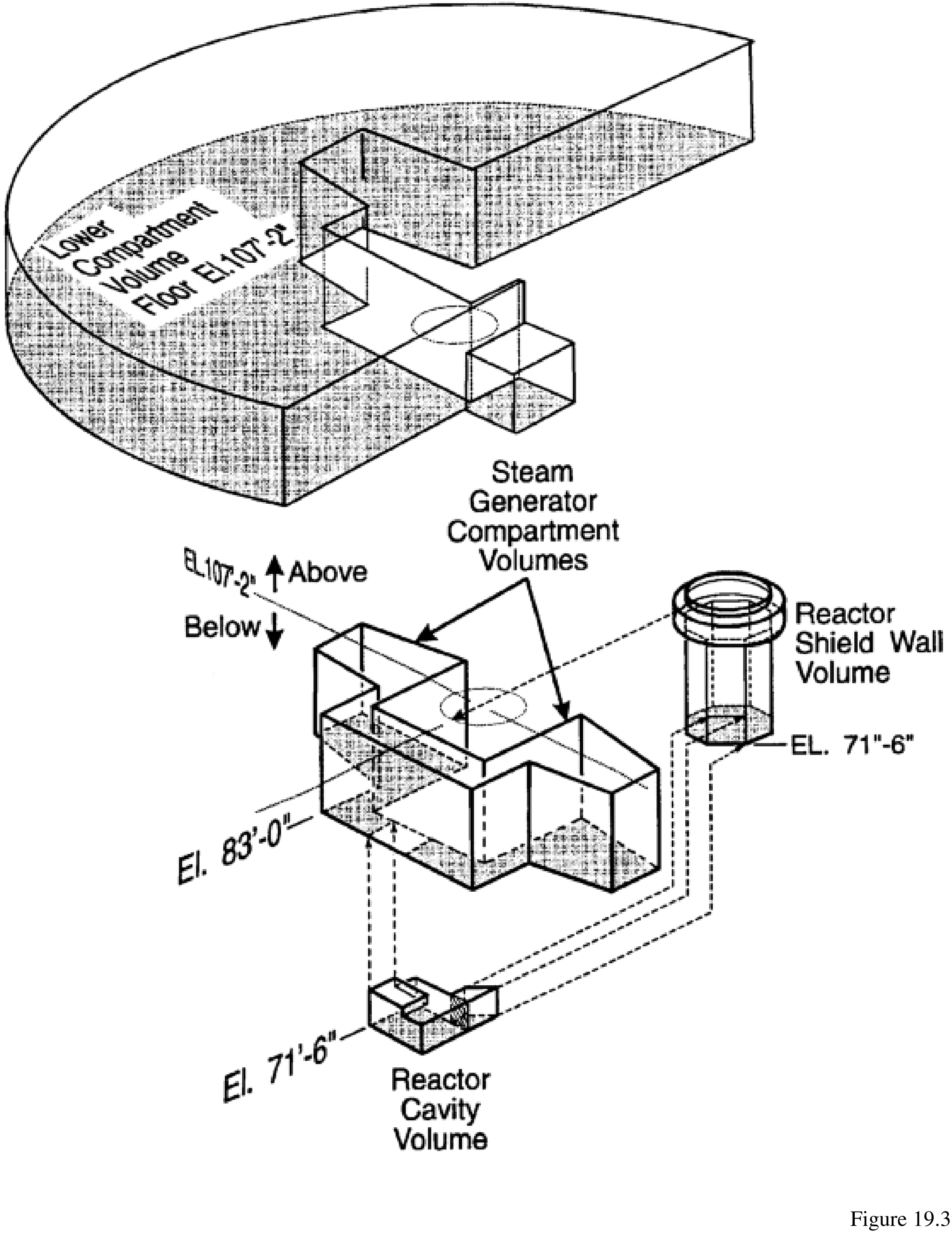

Figure 19.39-17

Containment Floodable Region – Expanded View

FIGURES 19.39-18 AND 19.39-19 NOT INCLUDED IN THE DCD.

19.40 Passive Containment Cooling

The Nuclear Regulatory Commission (NRC) containment performance goal for advanced containment systems is to provide a leak-tight barrier to fission product release for 24 hours following an accident, and to remain as a barrier against uncontrolled releases following that time. The AP1000 containment is cooled via the passive containment cooling system (PCS). Barring hydrogen combustion and ex-vessel phenomena that are addressed elsewhere in the AP1000 containment event tree analysis, the AP1000 containment is not expected to exceed the design-basis pressure during a severe accident. No threat to the containment integrity from long-term overpressurization is predicted.

In the event that design-basis cooling fails, the containment pressure will exceed the design basis, although containment failure within 24 hours is predicted to be highly unlikely. After 24 hours, the operator may vent the containment to prevent uncontrolled failure of the containment per the severe accident management guidelines. Once vented, the steam concentration in the containment will increase and improve the heat removal capacity of the passive cooling such that no further venting would be required.