19.39 In-Vessel Retention of Molten Core Debris

19.39.1 Introduction

In-vessel retention (IVR) of molten core debris through water cooling of the external surface of the reactor vessel is a severe accident management feature of the AP600. 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 AP600 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 the containment. Retaining the debris in the reactor vessel protects the containment integrity by eliminating the occurrence of ex-vessel severe accident phenomena, such as ex-vessel steam explosion and core-concrete interaction, for which there are large uncertainties.

The AP600 is uniquely suited to in-vessel retention because of the following design features:

- The low-power-density fuel produces a low heat flux through the vessel wall.
- The reliable reactor coolant system depressurization 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 design concept provides an engineered pathway for water-cooling the vessel and for venting steam from the reactor cavity.

The Risk-Oriented Accident Analysis Methodology (ROAAM) analysis of the in-vessel retention phenomena (References 19.39-1 and 19.39-2), including the testing and evaluation of the thermal-hydraulic uncertainties of the in-vessel circulating molten debris pool, boiling crisis on the exterior vessel surface, and lower head integrity under in-vessel steam explosion loads, has been performed through the Department of Energy (DOE) Advanced Reactor Severe Accident Program (ARSAP). Given the strong technical basis and dependability of the ROAAM assessment, Westinghouse is using the results of the in-vessel retention ROAAM (Reference 19.39-1) as the basis for the treatment of vessel failure on the AP600 PRA model. Vessel failure is considered to be physically unreasonable (failure probability of zero is assigned in the PRA model) if the following conditions are met:

- The reactor coolant system is depressurized.
- The reactor vessel is submerged.

- Reactor vessel reflective insulation and containment water recirculation flow paths allow sufficient ingress of water and venting of steam from the cavity.

- The treatment of the lower head outside surface (painting, coatings, etc.) does not interfere with water cooling of the vessel.

19.39.2 Summary of In-Vessel Retention ROAAM

The ROAAM phenomenological evaluation provides a technique for resolving the effects of uncertainties associated with severe accident phenomena (Reference 19.39-3). A phenomenon is decomposed and testing and analysis of each sub-phenomenon are performed to determine the range and effect of uncertainties. Bounding analyses were performed to determine the effect of the phenomena on the containment to demonstrate that failure is physically unreasonable. If failure could not be ruled out, accident management strategies were generated to mitigate the phenomenon. The entire process was subject to peer review until all comments are resolved. ROAAM has been used successfully to resolve severe accident containment integrity issues with respect to boiling water reactor liner melt-through and direct containment heating during high-pressure melt ejection events. In the AP600 PRA, ROAAM is used to demonstrate that the reactor vessel will not fail when the reactor cavity is sufficiently flooded.

The in-vessel retention phenomenon is decomposed into the thermal-hydraulic behavior of the molten debris pool inside the reactor vessel and the boiling crisis on the external surface of the reactor vessel. The thermal-hydraulic behavior of the molten pool in the lower head determines the heat flux at the azimuthal locations on the lower head from the bottom of the vessel to the top of the debris pool. The boiling crisis phenomenon determines the heat removal capacity of the water cooling the external surface. Based on a structural analysis of the reactor vessel wall, it is determined that the vessel will remain intact as long as the heat flux at the vessel wall remains below the critical heat flux at each location from the bottom of the vessel to the top of the debris pool.

The ROAAM analysis also investigates transient aspects of core relocation to the lower head and development of the steady-state heat transfer system described above. Investigations of lower head vessel failure due to jet impingement (Reference 19.39-1) and in-vessel steam explosion (References 19.39-2, 19.39-6, 19.39-7, and 19.39-8) have been performed and it is concluded that these phenomena will not fail the vessel. Investigations of the transient development of molten pool conditions conclude that the steady-state heat fluxes bound the transient conditions. Therefore, vessel failure prior to the development of the natural circulating pool and external cooling is physically unreasonable.

The results of in-vessel retention ROAAM analysis have been peer-reviewed by an international panel of 17 experts in the fields of severe accident progression, heat transfer, thermal-hydraulics, and structural mechanics. The conclusion that vessel failure is physically unreasonable under thermal-hydraulic conditions of in-vessel retention is considered to be resolved and is credited in the AP600 PRA, provided that the sequence meets the criteria outlined above.

Based on the results of the ROAAM testing and analysis, vessel failure is concluded to be physically unreasonable in the AP600 PRA provided the following conditions are met:

- The reactor coolant system is depressurized.
- The vessel is submerged above the top of the molten debris pool.
- Reactor vessel reflective insulation allows the ingress of water at the bottom and egress of steam at the top.
- The reactor vessel external surface conditions do not preclude the wetting phenomena identified as the cooling mechanism in the ULPU testing (reference 10.39-1).

Each of these items is discussed below.

19.39.3 Reactor Coolant System Depressurization

Reactor coolant system depressurization is discussed in Section 19.36.

19.39.4 Reactor Cavity Flooding

Reactor cavity flooding is accomplished either through 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 either of the two recirculation lines between the in-containment refueling water storage tank and the containment recirculation sump. The water floods the containment by flowing out of the recirculation sumps, filling the floodable region, shown in Figure 19.39-5, of the containment to the 107' 2" elevation, shown in Figure 19.39-6.

Some accident sequences flood the cavity automatically. Core damage occurs as a result of failure to recirculate water to the core once it is drained from the in-containment refueling water storage tank, or when injection occurs is not sufficient or soon enough to prevent core damage.

Two criteria are used to determine successful reactor cavity flooding: 1) the reactor vessel hemisphere must be submerged prior to relocation of core debris to the lower head; and 2) the water level must be above the top of the in-vessel debris bed prior to full relocation of debris to the lower head.

19.39.5 Reactor Vessel Insulation Design Concept

With respect to in-vessel retention, the purpose of the reactor vessel insulation is to provide an adequate water layer next to the reactor vessel to promote heat transfer from the reactor vessel. This is accomplished by providing:

- A frame that maintains the insulation a minimum specified distance away from the reactor vessel

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

- A means to allow steam generated by water contact with the reactor vessel to escape from the region surrounding the reactor vessel

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

Functional requirements for the design of the reactor vessel insulation and its supports, with respect to in-vessel retention, are defined by conservatively estimating the pressure differential across the reactor vessel insulation panels during the period that the reactor vessel is externally flooded with water and the core is being retained in the reactor vessel through heat removal from the vessel wall accomplished by the water. An analysis of these requirements for the insulation and support system was then completed to verify compliance.

19.39.5.1 Description of Insulation

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

19.39.5.2 Determination of Forces on Insulation and Support System

To investigate the forces, or pressures, that may be expected in the reactor cavity region of the AP600 during a core damage accident in which the core has relocated to the lower head and the reactor cavity is reflooded, data from ULPU tests (Reference 19.39-1) are used. The particular configuration reviewed (Configuration III) closely models the full-scale AP600 geometry of water in the region near the reactor vessel, between the reactor vessel and the reactor vessel insulation. The ULPU tests provide data on the pressure generated in the region between the reactor vessel and reactor vessel insulation. These data, along with observations and conclusions from heat transfer studies, are used to develop the functional requirements with respect to in-vessel retention for the reactor vessel insulation and support system.

Since the reactor cavity region of the AP600 is connected to the larger water pool in the containment through both the vented reactor vessel support blocks and the reactor cavity opening to the reactor coolant drain tank room, the static head of water in the reactor cavity can be calculated from the height of water in the containment. Under core damage conditions in which the reactor coolant system is depressurized via the automatic depressurization system, the level in containment is expected to be at the 107' 2" level. This results in a static head of water above the reactor cavity floor of approximately 35.6 feet of water. This static head acts on the outside of the insulation at all times during the core damage accident scenario. The forces acting on the inside of the insulation are the static head of water (considering voiding) plus the pressure pulses from water boiling at the surface of the reactor vessel.

The path taken by the escaping steam is upward between the insulation and the reactor vessel until the elevation of the steam vent doors. From there, it passes through the baffle in the reactor vessel support blocks and continues through the loop holes in the bio-shield to the larger steam generator compartments. Since the volume occupied by the steam voids in the water between the reactor vessel and the insulation and in the water pool above the reactor vessel nozzle blocks is small compared to the total volume of water in the containment, the overall water level in the containment would not rise significantly during boiling episodes. The collapsed water height for calculating the static pressure between the insulation and the reactor vessel is therefore significantly less than the actual water height in the remainder of the containment.

The following peak loading and deflection criteria for the reactor vessel insulation and support system functional requirements are defined with respect to in-vessel retention:

- The maximum outward (away from vessel) pressure is estimated to be 6.56 feet of water.
- The maximum inward (toward vessel) pressure is estimated to be 12.95 feet of water.
- The maximum inward deflection is designed to be less than 4 inches to maintain a minimum 2-inch gap between the reactor vessel and the insulation to match the minimum flow area of 7.5 ft^2.

19.39.6 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 during shipping and storage. In the PRA, it is assumed that no external surface treatment of the reactor vessel impairs heat removal from the vessel external surface, nor will it inhibit the wettability of the surface.

19.39.7 Reactor Vessel Failure

The reactor vessel is not considered to be failed if debris is maintained in the reactor vessel and relocation to the containment is prevented. Based on the ROAAM 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.

19.39.8 Summary

AP600 is uniquely suited to in-vessel retention of molten core debris. The ROAAM analysis of in-vessel retention phenomena concludes that vessel failure is considered to be physically unreasonable if:

- The reactor coolant system is depressurized.
- The reactor vessel is submerged.

- Reactor vessel reflective insulation and containment water recirculation flow paths allow sufficient ingress of water and venting of steam from the cavity.

- The treatment of the lower head outside surface (painting, coatings, etc.) does not interfere with water cooling of the vessel.

19.39.9 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 Theofanous, T.G., "On the Proper Formulation of Safety Goals and Assessment of Safety Margins for Rare and High-Consequence Hazards," Reliability Engineering & Systems Safety, Summer 1996.

19.39-4 Deleted.

19.39-5 Deleted.

19.39-6 Theofanous, T.G., et al., "Premixing of Steam Explosions: PM-ALPHA Verification Studies," DOE/ID-10504, September 1996.

19.39-7 Theofanous, T.G., et al., "Propagation of Steam Explosions: ESPROSE.m Verification Studies," DOE/ID-10503, August 1996.

19.39-8 Theofanous, T.G., Volume 1 - "Appendices E, F, and G to DOE/ID-10541," and Volume 2 - "Addenda to DOE/ID-10541, -10503, -10504," October 1997, and Volume 3 - "Addenda to DOE/ID-10503, 10504," December 1997.

FIGURES 39-1 through 39-4 and FIGURES 39-7 through 39-9
are not included in the DCD.

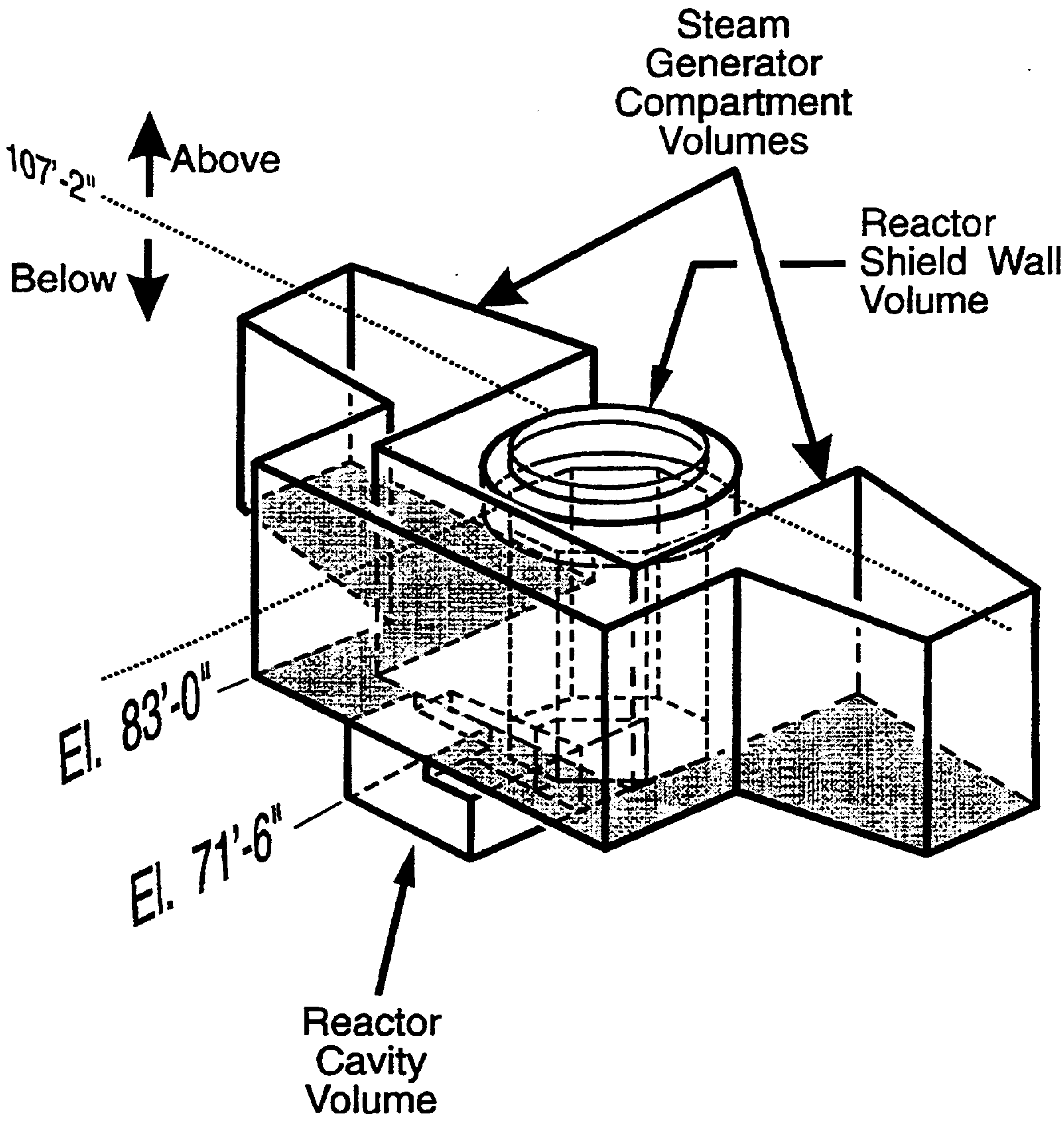

Figure 19.39-5

Containment Floodable Region

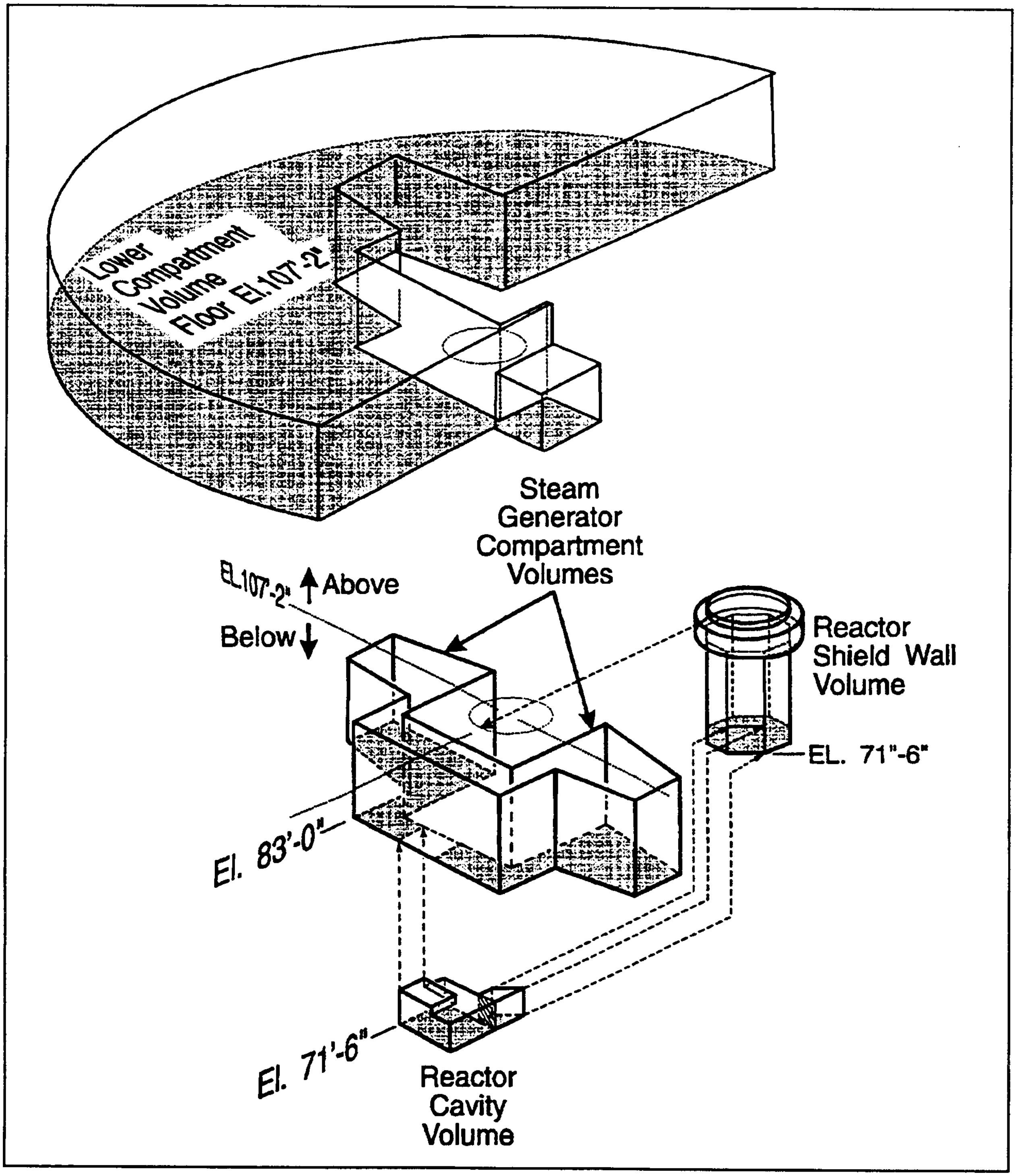

Figure 19.39-6

Containment Floodable Region - Expanded View

19.40 Passive Containment Cooling

Failure of passive containment cooling system (PCS) water being delivered to the containment shell is not considered to be a containment failure mechanism in the PRA because containment cooling with only air limits the containment pressurization sufficiently that the probability of containment failure is very low. Therefore, for consideration of the passive containment cooling system in the PRA model, the only failure mechanism that is assumed is failure of the PCS annulus due to plugging of the annulus drains.

There are two 100-percent drains in the vertical wall of the Shield Building. One drain is sufficient to prevent overflowing of the passive containment cooling system to block the air inlet.

The probability of failure of the passive containment cooling system due to the drain plugging is considered to be a rare event due to the following considerations:

- The annulus is shielded from random accumulation of debris that may potentially plug the drains.
- The drains are located on the Shield Building vertical wall above the annulus floor, and have screens to prevent small animals from entering the drains.