19.34 Severe Accident Phenomena Treatment

19.34.1 Introduction

This section describes how the AP1000 containment addresses challenges from severe accident phenomena, and how the challenges are evaluated in the probabilistic risk assessment (PRA). In the PRA, the Modular Accident Analysis Program (MAAP) version 4.04 code (Reference 19.34-8) is used to evaluate severe accident scenarios. Severe accident phenomenological uncertainties are treated with Risk-Oriented Accident Analysis Methodology (ROAAM) (Reference 19.34-2) phenomenological evaluations, with AP1000-specific decomposition event tree phenomenological evaluations, or with assumptions that certain low-frequency severe accident phenomena fail the containment. The objective of these studies is to show, with a high degree of confidence, that the AP1000 containment will accommodate the effects of severe accidents in a range of scenarios for at least the first 24 hours after the onset of core damage. Such evaluations demonstrate the robustness of the containment design.

19.34.2 Treatment of Physical Processes

The following eight issues are identified in Reference 19.34-1 as being representative of the phenomenological issues pertaining to severe accident conditions:

1. Loss-of-coolant accident (LOCA)
2. Fuel-coolant interaction (steam explosion)
3. Hydrogen combustion and detonation
4. Melt attack on concrete structure or containment pressure boundary
5. High-pressure melt ejection
6. Core-concrete interaction (CCI)
7. Containment pressurization from decay heat
8. Elevated temperature (equipment survivability)

The challenge to the containment integrity from a LOCA blowdown is covered in the containment design basis and is not specifically addressed here. Treatment of physical processes affecting the remaining challenges is discussed in this chapter.

19.34.2.1 In-Vessel Retention of Molten Core Debris

In-vessel retention (IVR) of core debris by external reactor vessel cooling is a severe accident mitigation attribute of the AP1000 design; it is discussed in detail in Chapter 19.39. With the reactor vessel intact and debris retained in the lower head, phenomena such as molten core-concrete interaction and ex-vessel steam explosion, which occur as a result of core debris relocation to the reactor cavity, are prevented.

The AP1000 reactor vessel insulation and containment geometry promote in-vessel retention. Engineered design features of the AP1000 containment flood the containment reactor cavity region during accidents, and thereby, submerge the reactor vessel in water.

Chapter 39 of the AP1000 PRA presents an AP1000-specific evaluation to determine the likelihood that sufficient heat can be removed from the outside surface of the submerged reactor pressure vessel lower head to prevent reactor vessel failure and relocation of debris to containment. The methodology used to quantify the margin to vessel failure in Reference 19.34-2 for the AP600 was adapted to the AP1000. For the AP1000 the methodology assumes that:

- The RCS is depressurized.
- The reactor vessel is submerged above the 98-ft elevation in the containment.
- The reflective insulation promotes the two-phase natural circulation in the reactor vessel cooling annulus.
- The reactor vessel external surface is bare metal.

The containment event tree includes a node to ascertain that the reactor coolant system (RCS) is depressurized and a node to determine if adequate water is available in the cavity to achieve two-phase natural circulation. Success at both of these nodes is required to demonstrate that the conditions and assumptions of the IVR analysis are met. The AP1000 design specifies that the reactor vessel insulation is designed appropriately and that the outer surface of the reactor vessel promotes wetability.

Accounting for the uncertainties in thermal-hydraulic parameters, the heat fluxes to the vessel wall and reactor vessel internals from the debris pool are calculated. The results show large margin to failure for the reactor vessel if it is externally cooled by water.

19.34.2.2 Fuel-Coolant Interaction (Steam Explosions)

A steam explosion may occur as a result of molten metal or oxide core debris mixing with water and interacting thermally. Steam explosions are postulated to occur inside the reactor vessel when debris relocates from the core region into the lower plenum and in the reactor cavity if the vessel fails and debris is ejected from it into water in the reactor cavity.

19.34.2.2.1 In-Vessel Fuel-Coolant Interaction

In-vessel steam explosions were studied extensively in the AP600 analyses. A ROAAM analysis of the AP600 reactor vessel lower head integrity under in-vessel steam explosion loading is presented in Reference 19.34-3. Typically, in-vessel steam explosion analyses focus on the α-mode containment failure, which is induced by the reactor vessel upper head failure. The ROAAM analysis focused on failure of the lower head since that steam explosion vessel failure mode would impair the in-vessel retention capability of the reactor vessel. The ROAAM analysis concludes that lower-head vessel failure from in-vessel steam explosion is physically unreasonable with very large margin to failure.

Based on the in-vessel core relocation scenario for the AP1000, the in-vessel steam explosion ROAAM analysis presented for the AP600 can be extended to the AP1000. The mass flow rate, superheat and composition of debris in the relocation from the upper core region to the

lower head is expected to be essentially the same as the AP600. The geometry of the lower head of the AP1000 is the same as the AP600. Therefore, it is reasonable to extend the results of the AP600 in-vessel steam explosion ROAAM analysis to the AP1000.

The results of the in-vessel steam explosion ROAAM can also be extended to containment failure induced by in-vessel steam explosions (α-mode containment failure). The likelihood for vessel failure and subsequent containment failure due to in-vessel steam explosion is so small as to be negligible. This conclusion is in agreement with the conclusions of the U.S. Nuclear Regulatory Commission (NRC)-sponsored Steam Explosion Review Group (Reference 19.34-4).

19.34.2.2.2 Ex-Vessel Fuel-Coolant Interaction

The first level of defense for ex-vessel steam explosion is the in-vessel retention of the molten core debris. If molten debris does not relocate from the vessel to the containment, there are no conditions for ex-vessel steam explosion. In the event that the reactor cavity is not flooded and the vessel fails, the PRA containment event tree assumes that the containment fails in the early time frame.

An analysis of the structural response of the reactor cavity was performed for the AP600 (Reference 19.34-5, Appendix B). As in the in-vessel steam explosion analysis, the results of this AP600 ex-vessel steam explosion analysis are extended to the AP1000. The vessel failure modes for AP600 and AP1000 are the same. The initial debris mass, superheat and composition are assumed to be the same as the AP600. The reactor cavity geometry and water depth prior to vessel failure are the same as AP600. Therefore, the results of the AP600 ex-vessel steam explosion analysis are considered to be appropriate for the AP1000.

19.34.2.3 Hydrogen Combustion and Detonation

A decomposition event tree analysis discussed in Section 19.41 evaluates the potential for hydrogen combustion threatening the containment integrity during a severe accident sequence in the AP1000. The analysis examines diffusion flame burning and local detonation occurring during in-vessel hydrogen generation prior to hydrogen mixing in the containment and global deflagration and detonation, which may occur later when the hydrogen is mixed throughout the containment. Only in-vessel hydrogen generation is considered, since vessel failure and ex-vessel debris relocation is assumed to fail containment.

The AP1000 provides defense-in-depth to address hydrogen diffusion flames that may challenge containment integrity. The first level of defense is the stage four automatic depressurization system (ADS Stage 4) lines from the RCS, which prevent significant hydrogen releases to the in-containment refueling water storage tank (IRWST) and Passive Core Cooling System (PXS) compartments. ADS Stage 4 vents from the RCS hot legs to the loop compartments, which are shielded from the containment shell and have a constant source of oxygen from the natural circulation in the containment. Hydrogen can burn as a diffusion flame in the loop compartments without threatening the containment integrity. If ADS Stage 4 fails, the AP1000 has provided design considerations in IRWST vents to mitigate diffusion flames near the containment walls. Vents from the passive injection system compartments and chemical volume and control system compartment are located away from

the containment shell and penetrations in order to mitigate the threat from hydrogen diffusion flames.

Containment failure from a directly initiated detonation wave is not considered to be a credible event for the AP1000 containment. There are no ignition sources of sufficient energy to directly initiate a detonation in the AP1000 containment. Deflagration to detonation transition (DDT) is considered to be the only likely mechanism to produce a detonation in the AP1000 containment.

The likelihood of DDT in the AP1000 containment is evaluated locally in confined compartments during in-vessel hydrogen generation and globally after in-vessel generation is concluded and hydrogen is mixed in the containment. For a DDT to occur, the combination of the gas mixture sensitivity to detonation and the geometric configuration potential for flame acceleration must be conducive to DDT. Since the hydrogen concentration necessary to form a detonable mixture depends on the size of the enclosure, concentration requirements for DDT in different regions of the AP1000 containment are extrapolated from the FLAME facility data (Reference 19.34-6) using scaling arguments based on the detonation cell width. The geometric requirement is evaluated considering aspects such as the degree of confinement and the extent and type of obstacles present in the postulated flame propagation path. In all cases, DDT is assumed to result in containment failure in the containment event tree analysis.

Global hydrogen deflagration and the potential for containment failure are modeled on the containment event tree. Adiabatic, isochoric, complete combustion (AICC) is assumed, and peak pressure probability distributions are developed for the accident scenarios. The probability of containment failure due to hydrogen deflagration is evaluated from the containment failure probability distribution combined with the peak pressure probability distribution.

19.34.2.4 High-Pressure Melt Ejection

The AP1000 incorporates design features that prevent high-pressure core melt. These features include the passive residual heat removal (PRHR) system and the ADS. These design features provide primary system heat removal and depressurization to prevent high pressure core damage conditions. The consequences from postulated high pressure melt ejection (HPME) are mitigated by the containment layout which provides a torturous pathway to the upper compartment, and no direct pathway for the impingement of debris on the containment shell.

In high-pressure core damage sequences the potential exists for creep-rupture-induced failures of the RCS piping at the hot-leg nozzles, the surge line, the steam generator tubes and, given debris relocation to the lower plenum, in the reactor vessel lower head. Failure of the hot-leg nozzle or surge line prior to failures of other components results in the rapid depressurization of the RCS. Failure of the steam generator tubes results in a containment bypass and a large release of fission products to the environment. Failure of the lower head of the reactor vessel results in the potential for HPME.

Hot-leg nozzle failure is expected prior to steam generator tube failure, but because of large uncertainties, hot-leg nozzle creep rupture failure is not credited with preventing steam

generator tube failure. In the PRA, steam generator tube failure is assumed for high-pressure sequences in the containment event tree analysis unless operator action to depressurize the RCS with the ADS is successful.

19.34.2.5 Core Debris Coolability

In accident sequences where the reactor pressure vessel failure is not prevented, core debris may be discharged into the reactor cavity. The likely vessel failure modes produce a low pressure melt ejection (LPME) to the containment. The AP1000 cavity design provides area for the core debris to spread. Condensate from the passive containment cooling system (PCS) returns to the reactor cavity, thereby providing a long-term supply of water to cool the core debris.

At vessel failure it is very likely that the cavity will be filled with water from the RCS, core makeup tanks (CMTs), and accumulators to at least the 83-ft elevation. There are significant uncertainties associated with debris spreading into a water-filled cavity. Debris-spreading is mainly a function of the highly uncertain vessel failure mode. A large-scale lower-head failure releasing debris at a high rate would enhance spreading, while a localized failure mode would release debris at a slow rate, which would most likely cause the debris to pile up under the reactor vessel and minimize spreading.

Given the uncertainties in the debris-spreading and in non-condensable gas generation and combustion, the containment event tree analysis does not credit containment integrity in the event of failure of the lower head of the vessel and relocation of the core.

A limited set of deterministic analyses of debris spreading and core-concrete interaction in the AP1000 cavity is presented in Appendix 19-B. The analyses show that basemat melt-through is not predicted to occur within 24 hours of the accident initiation. Basemat melt through is predicted to occur before pressurization of the containment by non-condensable gases challenges the containment integrity.

19.34.2.6 Containment Pressurization from Decay Heat

The AP1000 containment is cooled via the PCS (see Section 19.40). Evaporative water cooling of the containment shell provides long term containment cooling and limits the containment pressure to less than the design pressure for all severe accident events except hydrogen combustion (which is addressed separately). Containment water is provided to the top of the containment via redundant, diverse system of valves and lines, including a line that can be connected to an outside water source, such as a fire truck.

In the unlikely event that water cannot be supplied to the top of the containment shell for an extended period of time, air-only cooling by air flowing through the PCS annulus provides significant cooling to the containment. Under the right environmental conditions, the containment is expected to reach an equilibrium pressure that will not challenge containment integrity. However, under nominal-to-conservative environmental conditions, containment integrity by air-cooling alone cannot be assured. In this case, containment failure is predicted to occur more than 24 hours after accident initiation.

A significant amount of time is available for operator action to vent the containment under the severe accident management guidance (SAMG). Containment venting mitigates uncontrolled releases of fission products from a failed containment. The AP1000 can be vented on an ad-hoc basis under the SAMG from a number of containment penetrations. Containment venting also reduces the partial pressure of non-condensable gases in the containment, and thus creates a new containment underpressure failure mode that may occur if containment is cooled after venting.

19.34.2.7 Elevated Temperatures (Equipment Survivability)

Reference 19.34-7 states that equipment identified as being useful to mitigate the consequences of severe accidents must be designed to provide reasonable assurance that it will continue to operate in a severe accident environment for the length of time needed to accomplish its function. Also, 10 CFR 50.34(f) requires safety equipment to continue performing its function after being exposed to a containment environment created as a consequence of generating a quantity of hydrogen equivalent to that from 100-percent cladding oxidation. As the AP1000 design uses thermal igniters to burn hydrogen in a controlled manner, it is necessary to demonstrate that the safety equipment can continue to perform its function in the high-temperature environment created by the hydrogen burning.

The functions of the equipment in containment for which credit is taken in the AP1000 PRA were reviewed to determine if the equipment is required to operate in a severe accident environment and beyond design basis limits. The equipment and the basis for operation are the same as the AP600. Therefore, the results of the AP600 are extended to the AP1000 for equipment survivability.

19.34.2.8 Summary

The potential for and the consequences of severe accident phenomena are evaluated. The preventive and mitigative features of the AP1000 addressing the severe accident phenomena are discussed. This information is applied to the containment event trees and used in the quantification of the large release frequency.

19.34.3 Analysis Method

The design certification of the AP1000 included consideration by the NRC of the topic referred to in this section.

19.34.4 Severe Accident Analyses

The design certification of the AP1000 included consideration by the NRC of the topic referred to in this section.

19.34.5 Insights and Conclusions

The analyses of the severe accident phenomena for the AP1000 PRA highlight the following insights and conclusions:

- The design of the AP1000 reactor vessel, vessel insulation, and reactor cavity; and the ability to flood the cavity after a severe accident reduce the potential challenges to the containment integrity by maintaining the vessel integrity.
- Should a failure of the reactor vessel occur, the design of the reactor cavity enhances the ability to cool any core debris that exits the vessel.
- Lower head vessel failure due to in-vessel steam explosions is physically unreasonable.
- The ADS and PRHR system are design features that can be used to prevent high-pressure core melt in a severe accident.
- A directly-initiated hydrogen detonation in the AP1000 containment is not a credible event.
- The equipment needed to mitigate the consequences of a severe accident is designed to provide reasonable assurance that it will continue to operate during an accident.

19.34.6 References

19.34-1 Letter from D. A. Ward, Advisory Committee on Reactor Safeguards, to K. A. Carr, Chairman, Nuclear Regulatory Commission, "Proposed Criteria to Accommodate Severe Accidents in Containment Design," dated May 17, 1991.

19.34-2 Theofanous, T. G., et al., "In-Vessel Coolability and Retention of a Core Melt," DOE/ID-10460, July 1995.

19.34-3 Theofanous, T. G., et al., "Lower Head Integrity Under In-Vessel Steam Explosion Loads," DOE/ID-10541, July 1996.

19.34-4 NUREG-1116, *A Review of the Current Understanding of the Potential for Containment Failure From In-Vessel Steam Explosions*, 1985.

19.34-5 GW-GL-022, AP600 Probabilistic Risk Assessment, August 1998.

19.34-6 Sherman, M. P., Tieszen, S. R., and Benedick, W. B., *FLAME Facility - The Effects of Obstacles and Transverse Venting on Flame Acceleration and Transition to Detonation for Hydrogen-Air Mixtures at Large Scale*, NUREG/CR-5275, April 1989.

19.34-7 Attachment to letter from D. M. Crutchfield, Office of Nuclear Reactor Regulation, to E. E. Kintner, Advanced Light Water Reactor Steering Committee, "Major Technical and Policy Issues Concerning the Evolutionary and Passive Plant Designs," dated February 27, 1992.

19.34-8 "EPRI MAAP 4.0 Users Manual."

TABLES 19.34-1 THROUGH 19.34-26 NOT USED.
FIGURES 19.34-1 THROUGH 19.34-391 NOT USED.

19.35 Containment Event Tree Analysis

The design certification of the AP1000 included consideration by the NRC of the topic referred to in this section.