19.41 Hydrogen Mixing and Combustion Analysis

19.41.1 Introduction

In the course of a severe accident, a substantial amount of combustible gases can be generated in-vessel from the oxidation of the zirconium and other metals. The AP600 containment is provided with nonsafety-related hydrogen igniters to control the concentration of combustible gases. If the igniters operate, combustion of hydrogen plumes may present a thermal load to the containment. Combustible gas can accumulate in the containment at flammable concentrations if the igniter system fails to function. The AP600 hydrogen analysis quantifies the threat to containment integrity with and without hydrogen igniters.

If vessel failure does not occur, the amount of hydrogen in the containment is limited to the mass generated during the in-vessel core heatup and relocation. If vessel failure occurs with water in the cavity, an additional amount of hydrogen may be generated from ex-vessel fuel-coolant interactions. Furthermore, if the debris layer in the cavity is not coolable or if insufficient water is available in the containment to cool the debris, and subsequent thermal attack of concrete occurs, additional hydrogen and other combustible gas, such as carbon monoxide, will be generated. The AP600 PRA assumes containment failure if vessel failure is predicted, so the evaluation of containment integrity from hydrogen combustion only considers in-vessel hydrogen generation.

Hydrogen combustion is evaluated during two time frames: early (during the in-vessel relocation and hydrogen generation) and intermediate (prior to 24 hours after the onset of core damage). In the early time frame, containment challenge is considered from hydrogen burning as an unmixed plume (diffusion flame) and from local detonation at high concentrations in confined compartments below the operating deck. In the intermediate time frame when the hydrogen is mixed, containment challenge from global deflagration and potential detonation due to stratification of gases is considered. The hydrogen is assumed to burn within 24 hours of core damage.

19.41.2 Controlling Phenomena

The conditions required for combustion in the containment are flammable gas mixtures and the presence of an ignition source. Typically, a spark is sufficient to cause ignition. If the mixture temperature is above ~1000 K, auto-ignition can occur without the presence of an ignition source. The flammability limits are determined by the concentrations and temperature of the combustible gas-air-diluent mixture. Hydrogen and the oxygen in the air are the reactants in the combustion reaction. Steam, carbon dioxide, and excess nitrogen in the mixture act as inertants that may inhibit the reaction.

Hydrogen-air-steam mixtures can burn in several modes: diffusion flames, slow and accelerated deflagrations, and detonations (Reference 19.41-1). Burning of an unmixed hydrogen plume near the source results in a diffusion flame. Diffusion flames are stationary and result primarily in thermal loads on nearby structures or equipment. Deflagrations or detonations are burning of premixed gases. In practical terms, a slow deflagration is a flame that travels at a speed much slower than the speed of sound such that the pressure inside the containment equilibrates during the combustion. No dynamic loads are generated. Accelerated deflagrations travel fast enough to generate shock waves and dynamic loads. Detonations travel at supersonic velocities and also generate dynamic loads. The static loads that result from deflagrations can be predicted and bounded. The maximum dynamic loads from accelerated flames and detonations are difficult to calculate.

Standing diffusion flames on the in-containment refueling water storage tank pool or at the in-containment refueling water storage tank vents can be postulated early into an accident following core uncovery for sequences in which the automatic depressurization system stages 1 through 3 provide a primary depressurization mechanism. A standing diffusion flame at the vent could present a thermal load to the containment steel shell, which is close to some of the vents. If the primary system break is in one of the PXS valve/accumulator rooms which flood with water and submerge the break, diffusion flames can also be postulated at the room exit in the maintenance floor. This location has a direct line of sight with the personnel and equipment hatches, electrical penetrations, and the containment shell, and may present a thermal loading challenge.

The static loads associated with deflagrations are limited by thermodynamics. If all of the chemical energy available in the mixture is converted to temperature and pressure, then the maximum pressure is limited by the adiabatic, isochoric (constant volume), complete combustion (AICC) pressure. The actual pressure would drop over time from this peak because of heat losses to water, structures, and equipment in containment. Dynamic pressure loads are not limited by the adiabatic, isochoric, complete combustion value because the local pressure is due to very rapid, nonequilibrium combustion.

The mode of combustion depends on the mixture concentrations, initial conditions, and boundary conditions (Reference 19.41-1). Near the hydrogen source, hydrogen may not be mixed significantly with the air in the containment. If ignition occurs there, then a diffusion flame may be formed. Further downstream from the hydrogen source, mixing will have occurred and a deflagration or detonation may result, depending on the hydrogen concentration and geometric boundary factors. In some cases, accelerated flames may also develop to detonations, which is called deflagration-to-detonation transition (DDT). The occurrence of flame acceleration and deflagration-to-detonation transition is complex and not completely understood. It is dependent on a number of parameters. These include hydrogen and oxygen concentrations; nature and concentration of inertants; gas temperature and pressure before ignition; ignition source; the size and shape of the compartment in which the combustion occurs; and the number, size, and shape of any obstacles in the compartment.

In AP600, direct initiation of detonation by sufficiently high-energy sources from equipment in containment is unlikely (Reference 19.41-2), but mechanisms to accelerate a flame to a detonation may occur. Deflagration-to-detonation transition is considered the most likely mechanism. Transition to detonation is considered in several sections of the containment for accident sequences that result in hydrogen concentrations greater than 10 volume percent, including the passage connecting the two steam generator compartments, the core makeup tank and equipment bay, in-containment refueling water storage tank gas space, steam generator compartments, and steam generator operating deck.

19.41.3 Major Assumptions and Phenomenological Uncertainties

Because of phenomenological uncertainties, a number of assumptions are necessary in the hydrogen analysis.

19.41.3.1 Hydrogen Generation

The degree to which the cladding is oxidized during the in-vessel phase of the accident sequence and the availability of water to the core determines the rate and the mass of hydrogen released to the containment during the early time phase. The rate and mass of hydrogen produced are important parameters in determining the hydrogen concentration and the flammability limits of the gas mixtures in the containment compartments.

19.41.3.2 Containment Pressure

The containment pressure is an important parameter in the determination of the pre-burn boundary conditions. A higher initial pressure can result in a higher peak pressure, but the increased steam mass can inert the mixture and prevent combustion. If the passive containment cooling system water is not operational, containment pressures are elevated and combustion is steam inerted.

19.41.3.3 Flammability Limits

A flammable condition is determined by flammability limits. Flammability limits of a combustible gas mixture are defined as the limiting gas compositions at a given temperature and pressure in which a deflagration will propagate once ignited. There is information on flammability limits of hydrogen-air-steam mixtures at temperatures less than 149°C. For hydrogen, there are two lean propagation limits considered, upward and downward. At lean upward propagation limits, flames will propagate upward because of buoyancy. At lean downward propagation limits, flames will propagate upward and downward throughout the volume by their own reaction kinetics. Hence, the extent of flame propagation (or combustion completeness) for combustion at lean flammability limits is determined by the hydrogen concentration. This relation is a result from the Nevada Test Site (Reference 19.41-3). The addition of steam or other inert gas has a strong effect on the hydrogen concentration and flammability (Reference 19.41-15).

Combustion initiated by igniters occurs at lean upward flammability limits with a small pressure rise. However, with the failure of igniters, combustion at a hydrogen mixture at a concentration above the lean downward propagation limits may result in much larger pressure and temperature consequences. The global burn considered in the analysis is defined as combustion at or above the lean downward propagation limits. This definition includes the possibility that a global burn becomes a detonation, since the occurrence of a detonation requires a hydrogen concentration much above the lean downward propagation limits.

Combustion regimes and associated adiabatic, isochoric, complete combustion pressure are approximately demonstrated for hydrogen-air mixtures in Reference 19.41-5.

19.41.3.4 Detonation Limits and Loads

A detonation is a supersonic combustion front that produces a dynamic load in excess of the adiabatic, isochoric, complete combustion value. The energy release from the combustion of the hydrogen-air-steam mixture sustains the shock structure that ignites and burns the mixture. The detonation limits cannot currently be predicted by any first-principles theory. Engineering correlations used to predict the limits have been developed based on a measurable quantity called the detonation cell width. For simplified discussion, the detonation cell width can be considered a characteristic length that describes the sensitivity of the mixture to detonation. The smaller the detonation width, the easier it is to get the mixture to detonate and sustain propagation. Deflagration-to-detonation transition is considered, and the method of NUREG/CR-4803 (Reference 19.41-6) is used to evaluate the potential for flame acceleration.

Since the lowest hydrogen concentration for which deflagration-to-detonation transition has been observed in the intermediate-scale FLAME facility at Sandia is 15 percent (Reference 19.41-7), and 10 CFR 50.34(f) limits hydrogen concentration to less than 10 percent, the likelihood of deflagration-to-detonation transition is assumed to be zero if the hydrogen concentration is less than 10 percent.

19.41.3.5 Igniter System

The AP600 nonsafety-related hydrogen igniter system, if operational during a severe accident, will burn hydrogen as soon as the lean upward flammability limits are met. Thus, the concentration of hydrogen is maintained, on average, at the lean upward flammability limits. However, depending on the hydrogen release rate, location and oxygen availability, locally high concentrations may exist in the in-containment refueling water storage tank or in the subcompartment where the pipe break occurs.

The hydrogen igniters are actuated by manual action when core-exit temperature exceeds a predetermined temperature as directed by the emergency response guidelines (ERG). The indication and actuation are done with containment conditions within the equipment qualification limits of the systems used, within the design basis of the plant and systems, and before fission-product releases to the containment, so equipment survivability of the monitoring and actuation systems during the time frame that they are required to perform is supported.

19.41.3.6 Other Ignition Sources

A flammable mixture will not burn without an ignition source unless the temperature of the mixture is sufficiently high (~1000 K) that auto-ignition becomes possible. Hot surfaces or random sparks from equipment or static electricity may be postulated ignition sources. High-temperature gas jets exiting from the reactor coolant system may become an ignition source.

However, the gas stream may not have enough momentum to entrain the surrounding flammable mixture, especially in the depressurized cases.

19.41.3.7 Severe Accident Management Actions

Severe accident management guidance that is considered in the AP600 PRA is the operator action to flood the reactor cavity in the event of core damage. This action often results in the late reflooding of a damaged core due to the time required for the operator to diagnose the problem and take the action. Some events will lead to core reflooding through the natural progression of the accident.

19.41.4 MAAP4 Hydrogen Cases

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19.41.5 Early Hydrogen Combustion

Early hydrogen combustion is defined as burning that occurs during the period the hydrogen is released from the primary system to the containment. During this time, the hydrogen may not be well mixed in the containment and, depending on release locations, may be concentrated in the in-containment refueling water storage tank, PXS valve/accumulator rooms or chemical and volume control system room, steam generator compartments or maintenance floor. If sufficient oxygen is available, the compartments may become locally detonable. If oxygen is not available in the compartment, the plume may travel to a location where oxygen is available and it can burn as a diffusion flame.

19.41.5.1 Hydrogen Generation Rates

Qualitative hydrogen generation characteristics can be inferred from the availability of steam and the availability of overheated, unreacted zirconium in the reactor vessel. Based on the insights from hydrogen generation and mixing analyses, the hydrogen generation can be classified into one of three categories: boiloff generation rate, early-reflood generation rate, and late-reflood generation rate. This section briefly defines each type of hydrogen release in the AP600 hydrogen analysis and the conditions under which they occur.

19.41.5.1.1 Boiloff Hydrogen Generation

Boiloff hydrogen generation occurs as the water inventory in the reactor vessel is depleted by decay heat. The steam generation is limited to the decay heat boiloff in the covered fraction of the core and overheated, unreacted zirconium surface area is limited to the upper regions of the core, which have not relocated below the water line. Core relocation to the lower head may produce a rapid steam generation that produces a brief period of rapid oxidation, but by this time, the core geometry is lost and very little unoxidized zirconium surface area is available for sustained hydrogen production.

19.41.5.1.2 Early-Reflood Hydrogen Generation

Early-reflood hydrogen generation occurs in the event of the reflooding of an overheated, relatively intact core. Quenching of the core provides a large quantity of steam and a large, overheated, unreacted zirconium surface area for oxidation. Shattering of the cladding due to thermal stresses can enhance the oxidation rate. In the early-reflood case, the oxidation of the zirconium is limited only by the degree of core uncovery prior to the reflood. The rate and degree of zirconium oxidation is expected to be greater than the no-reflood case.

19.41.5.1.3 Late-Reflood Hydrogen Generation

Late-reflood hydrogen generation occurs in the event of a reflood after the core has degraded significantly and possibly after relocation to the lower head. Much of the core geometry is lost and little surface area is available for oxidation, even when steaming from quenching debris is available.

19.41.5.2 Hydrogen Release Locations

The hydrogen release locations in the containment determine the hydrogen mixing in the containment and regions of high hydrogen concentration in the event that the igniters fail. The flow paths from release points in confined compartments to the volumes where oxygen is available determine possible locations where diffusion flames may occur.

19.41.5.2.1 Automatic Depressurization System Stages 1, 2, and 3

Stages 1, 2 and 3 of the automatic depressurization system relieve the reactor coolant system pressure from the top of the pressurizer to the in-containment refueling water storage tank. The water level in the in-containment refueling water storage tank at the time of the release determines the steam concentration in the tank. If the spargers are covered, the steam is quenched out of the gas flow and the hydrogen is released to the gas space of the tank. If the spargers are not covered, the steam concentration is high and will drive the air out of the tank. If the igniters are available, diffusion flames may be postulated at the in-containment refueling water storage tank vent exits for large sustained hydrogen releases. If igniters are not available, the possibility of hydrogen detonation is evaluated.

19.41.5.2.2 Automatic Depressurization System Stage 4

Stage 4 of the automatic depressurization system relieves steam and hydrogen from the hot leg of the reactor coolant system to the steam generator compartments in the containment. The steam generator compartments, along with the maintenance floor and the upper compartment, form the major natural-circulation path in the containment. Oxygen starvation of any potential diffusion flames in the steam generator compartment is not expected for low-pressure hydrogen releases from automatic depressurization system stage 4. The containment shell is sheltered from flames in the steam generator compartments by the concrete walls, so diffusion flames at the igniters in the steam generator compartments are not considered to be a threat to the containment integrity. If igniters are not available, good mixing in the compartment mitigates the threat of detonation for the low-pressure releases.

19.41.5.2.3 Break Location

The reactor coolant system break provides a pathway from the reactor coolant system to one of several compartments in the containment. A failure of a component in the reactor coolant system loop (hot leg or cold leg) will relieve hydrogen to the loop compartment. Hydrogen released from the break to the loop compartment will behave similarly to the hydrogen released from stage 4 automatic depressurization system.

A failure of the direct vessel injection line or a break in the chemical and volume control system piping will relieve hydrogen to one of the small compartments under the maintenance floor, the chemical and volume control system room or one of the two PXS valve/accumulator rooms. These compartments are dead-ended and communicate with the maintenance floor through stairway or room vents. The initial blowdown through the break fills the compartment with steam and drives the air out of the compartment. After the blowdown and reactor coolant system depressurization, countercurrent flow between the compartment and the maintenance floor slowly replenishes the air.

Each of the dead-ended compartments has a one-way drain to the containment sump in the cavity. The break flow into a dead-ended compartment will not fill the compartment with water, as the draining and flashing of the break flow can be removed. However, a broken direct vessel injection line in a PXS valve/accumulator room may allow the in-containment refueling water storage tank to drain into the PXS valve/accumulator room if the injection valves open in the broken line. The draining of the in-containment refueling water storage tank water into the PXS valve/accumulator room will fill the PXS valve/accumulator room and spill water over the curb into the maintenance floor.

If the igniters are available, hydrogen released to the dead-ended compartments during the core degradation may burn initially, but may become oxygen starved. The plume then rises through the stairway to the maintenance floor, which is amply supplied with oxygen by the containment natural circulation. A diffusion flame can be postulated at the exit of the dead ended compartments in the maintenance floor. The exterior wall of the maintenance floor is the steel containment shell below the passive containment cooling system annulus, the lower-level equipment hatch, and the personnel hatch. Many electrical penetrations pass through the maintenance floor wall to the auxiliary building.

19.41.5.3 Early Hydrogen Combustion Ignition Sources

For a burn to be initiated, an ignition source is required. Igniters mitigate the threat to the containment integrity from global deflagration and detonation. If a hydrogen plume can produce a diffusion flame, the igniters provide the ignition source.

19.41.6 Diffusion Flame Analysis

An analysis of the threat to the containment integrity from diffusion flames at the in-containment refueling water storage tank vents and PXS valve/accumulator room exits in the maintenance floor has been performed (Reference 19.41-13).

The in-containment refueling water storage tank diffusion flame analysis (Reference 19.41-13) concludes that the operation of stage 4 automatic depressurization system valves reduces the hydrogen release to the in-containment refueling water storage tank and mitigates the formation of diffusion flames at the in-containment refueling water storage tank vents. For a bounding case with 100 percent of the hydrogen released through the in-containment refueling water storage tank, diffusion flames are predicted at the vents and the overflow. The analysis concludes that, for the estimated duration of the flame, containment failure is not predicted, based on a conservative Larson-Miller creep rupture failure assessment.

Even with the actuation of stage 4 automatic depressurization system valves, a diffusion flame is predicted at the dead-ended compartment exits in the maintenance floor for the direct vessel injection break case in which the accumulator room is flooded. The openings from the accumulator rooms and chemical and volume control system compartments that can vent hydrogen to the maintenance floor are either located away from the containment wall and electrical penetration junction boxes or are covered by a secure hatch. The diffusion flame is substantially farther away from the containment wall than in the case of the in-containment refueling water storage tank vents and has a substantially reduced view factor to the containment wall. The transient analysis of the thermal loading on the containment shell, equipment, and personnel hatches, including radiation and convective heat transfer, concludes that the wall, hatches, and electrical penetrations are not threatened by the flame.

19.41.7 Early Hydrogen Detonation

Hydrogen detonation can be initiated from a high-energy ignition source or by deflagration-to-detonation transition during flame acceleration. A review of potential ignition sources in containment concludes that the maximum source is too small to directly initiate a detonation (Reference 19.41-2). Therefore, the occurrence of detonation is related to the potential for deflagration-to-detonation transition in the AP600 containment analysis.

The methodology of Sherman and Berman (Reference 19.41-6) is used to evaluate the likelihood of deflagration-to-detonation transition. The analysis considers the hydrogen release rates to the containment, core reflooding, the containment release locations, and in-containment refueling water storage tank and PXS valve/accumulator room water levels to determine the probabilities.

19.41.8 Sherman-Berman Methodology for Evaluating the Potential for Deflagration-to-Detonation Transition

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19.41.9 Deflagration in Time Frame 3

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19.41.10 Detonation in Intermediate Time Frame

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19.41.11 Safety Margin Basis Containment Performance Requirement

The AP600 containment meets the criteria of the safety margin basis containment performance requirement.

19.41.12 Summary

The major insights of the hydrogen mixing and combustion analysis are as follows:

- No containment failure from hydrogen is predicted if the hydrogen igniters are operational.
- Operation of the stage 4 automatic depressurization system valves releases much of the hydrogen generated in the reactor coolant system to the steam generator rooms where it can be well mixed in the containment to mitigate the threat of diffusion flames from sustained hydrogen released through the in-containment refueling water storage tank.
- The threat of detonation is predominantly due to hydrogen releases to the PXS valve/accumulator rooms below the 107' 2" containment elevation (direct vessel injection line breaks). The compartment is a confined region with little ventilation. Equipment and grating are present to promote turbulence. A break in the compartment induces a high-temperature environment creating good conditions for potential deflagration-to-detonation transition.
- No containment failure is predicted from diffusion flames.
- No containment failure is predicted from deflagration.

Analyses are performed to meet the requirements of 10 CFR 50.34(f). Igniter burning analyses with rapid hydrogen generation and 100-percent cladding reaction conclude that the igniter system maintains the global uniform hydrogen concentration in the containment at or below lower flammability limits. If the stage 4 automatic depressurization system is available, the hydrogen is well mixed in the containment and no excessive concentrations are predicted in the in-containment refueling water storage tank or PXS valve/accumulator rooms. If the stage 4 automatic depressurization system is failed, hydrogen in the in-containment refueling water storage tank and PXS valve/accumulator rooms can reach high concentrations. However, the mixtures are oxygen starved and are not flammable or detonable. The safety margin basis containment performance requirement is met as the loss-of-coolant accident plus

75-percent active cladding reaction hydrogen burn peak pressure provides margin to the ASME Service Level C stress limits.

19.41.13 References

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19.41-16 Deleted.

19.41-17 Deleted.

19.42 Conditional Containment Failure Probability Distribution

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19.43 Release Frequency Quantification

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19.44 MAAP4.0 Code Description and AP600 Modeling

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19.45 Fission Product Source Terms

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19.49 Offsite Dose Evaluation

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19.50 Improtance and Sensitivity Analysis

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19.51 Uncertainty Analysis

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19.52 RTNSS - Focused PRA Sensitivity Study

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19.54 Low Power and Shutdown PRA Assessment

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