6.2.5 Combustible Gas Control in Containment

Combustible gases may be generated following an accident as a result of high temperature reactions between the fuel cladding and coolant, radiolysis of reactor coolant water or emergency core cooling water, corrosion of aluminum and zinc in the containment, or as a consequence of molten core-concrete interaction (MCCI). Hydrogen generation rates from these sources could be sufficient to accumulate combustible mixtures of these gases. The ignition of the combustible sources could breach the containment or damage essential systems and components needed to mitigate an accident.

The U.S. EPR is designed with a number of features to prevent the accumulation of combustible gas mixtures. The containment has sufficient free volume to accommodate the quantity of hydrogen released during both design basis accidents (DBA) and severe accidents and maintain the combustible gas concentration at a safe level. The containment is designed with open-ended compartments to prevent combustible gas buildup and dedicated systems to minimize combustible gas concentration. The combustible gas control system (CGCS) limits the buildup and concentration of gases in the containment to prevent combustible mixtures from occurring.

The CGCS is composed of passive autocatalytic recombiners (PAR), rupture and convection foils, and mixing dampers. In addition, the hydrogen monitoring system (HMS) provides indication of hydrogen concentrations in the containment atmosphere during design basis accidents, and monitors both hydrogen concentrations and steam content in the containment atmosphere during beyond design basis accidents.

6.2.5.1 Design Bases

Design bases for the CGCS and HMS systems include the following:

- The CGCS mixes the atmosphere within the containment (10 CFR 50.44(c)(1)).
- The CGCS limits the hydrogen concentration in containment to 10 percent by volume during and following an accident that results in a fuel cladding-coolant reaction involving 100 percent of the cladding surrounding the active fuel region. (10 CFR 50.44(c) (2)).
- The CGCS remains functional during and after exposure to accident environmental conditions (10 CFR 50.44(c)(3)).
- The HMS measures the hydrogen concentration in containment during and after the accident, and remains functional during and after exposure to accident environmental conditions (10 CFR 50.44(c)(4)(ii)).

- The CGCS maintains containment structural integrity following an accident that releases hydrogen generated from 100 percent fuel clad-coolant reaction accompanied by hydrogen burning (10 CFR 50.44(c)(5), GDC 41).

- The CGCS and HMS are not shared among multiple units (GDC 5).

- The CGCS is designed to permit periodic inspection and testing to confirm the integrity and operability of the systems (GDC 42, GDC 43).

- The CGCS and HMS conform to RG 1.7 to meet the requirements of 10 CFR 50.44.

Table 3.2.2-1 provides the seismic and other design classifications of the components in the CGCS and HMS.

6.2.5.2 System Description

Global convection reduces the likelihood of combustible gas buildup under accident conditions. This is aided by the containment geometry, which provides open-ended compartments and a large total volume (as shown in Figures 3.8-2 through 3.8-13). The CGCS enables the convection of gas mixtures from the lower elevations of the IRWST to the containment dome. This space includes the entire containment volume.

Additionally, the rupture disks of the pressurizer relief tank discharge to the equipment compartments in the lower containment (Section 5.4.11). The release of hydrogen and steam into the lower compartments of the containment drives an upward convection current that promotes mixing of combustible gases.

6.2.5.2.1 Combustible Gas Control System

The CGCS provides for a mixed and homogeneous gas atmosphere in the containment and controls the concentration of combustible gases following an accident that results in a release of hydrogen to the containment atmosphere. The design and performance parameters are listed in Table 6.2.5-1—CGCS Design and Performance Parameters. The CGCS consists of the following components:

- Rupture foils installed in the steel framework above the steam generators open passively on pressure differential to promote global convection and containment atmosphere mixing.

- Convection foils installed with the rupture foils open passively on pressure differential or temperature differential to promote global convection and containment atmosphere mixing.

- Hydrogen mixing dampers installed between the in-containment refueling water storage tank (IRWST) and the annular compartments within containment open passively on receiving a differential or absolute pressure signal or loss of power to promote global convection and mixing. In addition, the mixing dampers can be opened by manual operator action.

- PARs distributed throughout containment recombine hydrogen and oxygen to reduce hydrogen concentrations. The PARs also promote natural convection within the containment.

Rupture and Convection Foils

During normal operation, the rupture and convection foils form a pressure equalization ceiling in each steam generator compartment. The rupture foils consist of a rupture foil frame and burst element. The burst element is designed to open in either direction at a pressure differential of 0.7 psi ± 30 percent. The passive opening of the rupture foil releases no debris that could interfere with the operation of the heat removal system or cause clogging of the sump strainers.

The convection foils consist of two frames connected by hinges on the rear side and a fusible link mounted on the front. The upper frame of the convection foil is installed at the pressure equalization ceiling framework. The lower frame contains the burst element, which is the same as the rupture foil enclosure. For this reason, the bi-directional opening behavior and burst pressure is identical to the rupture foils. The second opening mechanism is the fusible link. It verifies a failsafe and passive opening of the lower frame by gravity. The fusible link design allows a fast opening at a temperature of 176-185°F, within a few seconds. The weight of the lower convection foil frame opens against a slight pressure differential if the ambient temperature exceeds the fusible link opening temperature.

The rupture and convection foils are both safety-related items and are included in the equipment qualification program.

Multiple passive actuation mechanisms fulfill requirements for flow areas and opening times under different loss of coolant accident (LOCA) scenarios. Following a large break LOCA, rupture foils open on differential pressure very early in the accident to create a large free flow area and limit the peak pressure differential in the containment. For a small break LOCA, the mass and energy release may be enough to open only a few rupture foils. However, the large free flow area required for sufficient atmospheric mixing is provided by the convection foils, which open due to the increased temperature.

Apart from breaks in the reactor coolant pressure boundary, hydrogen and steam can be released into containment via the pressurizer relief tank following intentional reactor coolant system depressurization. In this case, a rupture disk opens a path from the tank to the bottom rooms of the steam generator compartments. Reflection of the gas jet on the heavy floor generates a broad plume moving upward in the central part of the containment driven by a density gradient. The resultant opening of the rupture foils enables and promotes global containment convection flows.

Mixing Dampers

Mixing dampers consist of a spring loaded actuator that is held closed during normal operation by an energized solenoid. The second part of the mixing damper is the flap with a horizontal opening axis, similar to a butterfly valve. This design allows the mixing damper to open against a pressure differential. The flap separates the air space of the IRWST and the lower part of the annular rooms in containment. The mixing dampers open if the differential pressure between operational and equipment rooms exceed 0.5 psi; or if the containment pressure exceeds 17.4 psia. The mixing dampers open fail-safe on a loss of power to the solenoid-operated actuators and can be manually opened by the operator.

The mixing dampers are safety-related items and are included in the equipment qualification program.

Passive Autocatalytic Recombiners

The PARs are part of the combustible gas control system. Unlike the rupture foils, convection foils, and mixing dampers, they are not safety-related components; instead, they are designed for severe accident condition applications.

Large and small PARs are arranged in containment to support global convection, homogenize the containment atmosphere, and reduce local and global peak hydrogen concentrations. The location of the PARs is shown in Figure 6.2.5-1—Arrangement and Location of the Passive Autocatalytic Recombiners.

A PAR consists of a metal housing with a gas inlet at the bottom and a lateral gas outlet at the top to promote convection. Numerous parallel plates with a catalytically active coating are arranged vertically in the bottom of the housing. Gas mixtures containing hydrogen are recombined upon contact with the catalyst, with the recombination rate depending primarily on the concentration of hydrogen at the PAR. The PAR recombination efficiencies at different environmental conditions are provided in Supplement 1 to technical report ANP-10299P, Revision 2, "Applicability of AREVA NP Containment Response Evaluation Methodology to the U.S. EPR for Large Break LOCA Analysis," (Reference 15). Technical Report ANP-10322P, Revision 0, "Qualification and Testing of the U.S. EPR Passive Autocatalytic Recombiner" (Reference 28) describes the performed type tests and test results of the AREVA Inc. PAR. In the presence of oxygen, the PARs will start automatically if the threshold hydrogen concentration is reached at the catalytic surfaces. The heat released from the catalyst helps drive gas flow through the PARs, resulting in high recombination efficiency.

The PARs are arranged inside the equipment rooms to promote convection within the containment, and thereby homogenize the atmosphere and reduce local peak hydrogen concentrations. PARs are also located in the containment dome and in the upper part of the annular rooms to support global convection and to prevent gas stratification. The PARs are installed above the floor to provide unobstructed inflow and for easy access to facilitate maintenance. They are located to avoid direct contact with spray water from the severe accident heat removal system, and the PAR cover also protects the catalyst from direct spray and aerosol deposition.

The PARs are designed to withstand severe accident ambient conditions. This includes the capability of reducing hydrogen under severe accident conditions as specified in Table 6.2.5-1. As is the case for other severe accident components, the PARs provide reasonable assurance that the equipment can perform its identified function during the most limiting of the most likely severe accident conditions. The PARs, including the catalytic plates, will be qualified to demonstrate functionality after a seismic event. The PARs are listed in Table 3.10-1—List of Seismically and Dynamically Qualified Mechanical and Electrical Equipment. The most likely severe accident scenarios are determined using the methodology detailed in the AREVA NP Topical Report ANP-10268P, "U.S. EPR Severe Accident Evaluation" (Reference 29). The most limiting severe accident conditions are those that produce the highest global adiabatic isochoric complete combustion (AICC) pressure. These conditions are presented in Section 6.2.5.3.2.

6.2.5.2.2 Hydrogen Monitoring System

Two subsystems of the HMS measure hydrogen concentrations within containment. The low range system measures hydrogen concentrations in the containment atmosphere during design basis events. The high range system measures hydrogen and steam concentrations in the containment atmosphere during and after beyond design basis events. The design and performance parameters for the subsystems are listed in Table 6.2.5-2—HMS Design and Performance Parameters.

The low range system consists of hydrogen sensors arranged in the following containment areas:

- Upper dome.
- Upper pressurizer compartment.
- Upper steam generator compartments 1/2 and 3/4.
- Annular rooms.

The low range HMS signal processing units are located in Safeguards Buildings 1 and 4. They are both powered from the Class 1E electrical power supply. Isolation is provided between power supply and signal processing units. Hydrogen concentrations are measured continuously during plant operation and are available for display in the main control room. A hydrogen concentration measurement that exceeds one percent by volume actuates an alarm in the main control room to indicate a release of hydrogen to the containment atmosphere. A hydrogen concentration measurement that exceeds four percent by volume actuates an alarm indicating that the flammability limit in air has been exceeded. The loss of a measuring channel or failure of a signal processing unit is also indicated.

The high range HMS system consists of two redundant trains of gas samplers and the associated piping running to the process and analysis modules. Information provided by the system regarding hydrogen and steam concentrations is used for accident management measures, for assessing the efficiency of the CGCS, and for estimating the risk of deflagrations in containment. The high range HMS processing equipment is located in Safeguard Buildings 1 and 4 and is powered from the 12-hour uninterruptible power supply. The high range gas samplers are located in the following containment areas:

- Upper dome.
- Upper steam generator compartments 1/2 and 3/4.
- Annular rooms.

The operator starts the high range HMS system manually. Once in operation, the system automatically cycles through the sampling points; samples, processes, and analyzes the containment atmosphere; and displays the results in the main control room.

Alarms in the main control room indicate when the design value for hydrogen concentration has been exceeded at the sampling point, and when the hydrogen concentration required for flammable mixtures has been exceeded. A combined hydrogen and steam concentration alarm indicates a possible threat to containment integrity.

The gas samplers are equipped with throttling orifices downstream of the sampling point to prevent steam condensation. Sampling lines outside the containment are electrically heated, also to prevent steam condensation. After processing, each sample is injected back into the containment to reduce the radiation exposure of the equipment and to limit the dose in the installation compartments.

6.2.5.3 Safety Evaluation

Because the containment environmental conditions and amount of hydrogen released are different for design basis and severe accidents, these two scenarios were evaluated separately. For design basis accidents, there is no hydrogen generation from MCCI. During severe accidents, hydrogen generation from oxidation of fuel cladding and MCCI are many times greater than from other sources. The following sources of hydrogen exist in the containment following a design basis accident or a severe accident:

- Oxidation of the zirconium in the cladding.
- Radiolysis of water (RCS and IRWST) and jacketed cable.
- Corrosion of Zinc from painted surfaces.
- Corrosion of Zinc from steel structures.
- Corrosion of aluminum in containment.
- MCCI (for severe accidents only).

For design basis accidents, a series of bounding assumptions were made for the volume of hydrogen released to the containment from each source. Under these conservative assumptions, it was shown that the hydrogen concentration remains below the threshold for combustion (4 percent) during the first 24 hours following a design basis LOCA with no credit taken for recombination. Based on this analysis, hydrogen generated during and following a design basis LOCA is not a threat to containment integrity.

In the case of severe accidents, a much greater release of hydrogen is analyzed and the release depends more heavily on the scenario-specific phenomena involved. A detailed analysis using the MAAP4 computer code was performed and is discussed in Section 6.2.5.3.2.

6.2.5.3.1 Post-LOCA Hydrogen Concentration

For the post-LOCA hydrogen evaluation, the design basis maximum allowable core oxidation level of 1 percent was assumed. The calculated concentration is displayed in Figure 6.2.5-2—Integrated Production of Hydrogen from 1% Core Oxidation. The analysis assumed this amount of hydrogen to be released in an instant at the beginning of the LOCA transient.

The hydrogen produced from radiolysis is calculated based on the amount of decay heat gamma energy absorbed in the RCS coolant in accordance with Revision 2 of Regulatory Guide 1.7. Hydrogen generation from these sources are shown in Figure 6.2.5-3—Integrated Production of Hydrogen from Radiolysis.

In calculating the hydrogen released from corrosion of zinc and aluminum in the containment, typical corrosion rates were assumed and were applied at the actual design basis accident pressures and temperatures calculated in the containment analysis. These are discussed in Section 6.2.1.3. The surface areas of zinc and aluminum used as input to the hydrogen generation rate equation were developed in a bounding fashion. The entire concrete surface area was assumed to be painted with a zinc-based coating 466,620 ft^2 (43,350 m^2) and the entire surface area of steel was assumed to be galvanized 368,130 ft^2 (34,300 m^2). The use of aluminum materials in the containment is expected to be negligible; a surface area of 10,760 ft^2 (1,000 m^2) was assumed.

The hydrogen generation rates from zinc and aluminum are shown in Figure 6.2.5-4—Assumed Hydrogen Generation Rate from Zinc Sources and Figure 6.2.5-5—Assumed Hydrogen Generation Rate from Aluminum Sources. Applying these corrosion rates to the bounding assumptions for surface areas of each material resulted in the hydrogen generation from zinc and aluminum shown in Figure 6.2.5-6—Integrated Production of Hydrogen from Zinc-Based Paint, Figure 6.2.5-7—Integrated Production of Hydrogen from Galvanized Steel, and Figure 6.2.5-8—Integrated Production of Hydrogen from Aluminum.

Figure 6.2.5-9—Concentration of Hydrogen in the Containment shows the total hydrogen concentration within containment from all sources. The hydrogen remains below the threshold concentration necessary for combustion (4 percent) taking into account no hydrogen recombination from the 47 PARs.

6.2.5.3.2 CGCS Design Basis Severe Accident Hydrogen Concentration

The analysis of the combustible gas control system is based on the results of an enhanced analysis of the most likely severe accident (relevant) scenarios. The purpose of this enhanced methodology is to demonstrate that the CGCS will demonstrate its ability to perform its design functions and to meet the regulatory requirements for:

- Generation of an amount of hydrogen equivalent to the hydrogen produced from the oxidation of 100 percent of the fuel cladding surrounding the active fuel with water.
- Generation of the severe accident design basis hydrogen source prior to vessel failure.
- Demonstration that uniformly distributed hydrogen concentration in the containment does not exceed 10 percent (by volume).
- Demonstration that if post-accident hydrogen concentration exceeds 10 percent by volume that the atmosphere will not support hydrogen detonation.
- Demonstration that hydrogen is effectively distributed throughout containment and is removed (a mixed atmosphere).

Description of methodology

Previous studies, such as those discussed in Section III.A "Hydrogen Generation and Control" of SECY 90-016 "Evolutionary Light Water Reactor (LWR) Certification

Issues and their Relationship to Current Regulatory Requirements" (Reference 30), have shown that it is impossible to force MAAP, a best estimate code, to calculate 100 percent clad oxidation prior to vessel failure. Prior to the introduction of this enhanced methodology, the only way to generate the amount of hydrogen equal to 100 percent oxidation of the cladding surrounding the active fuel was to allow generation of hydrogen by MCCI after reactor vessel failure.

The requirement to show that the CGCS can achieve its design goals with 100 percent of the required hydrogen generated before reactor pressure vessel failure led to the development of a non-traditional approach to release the amount of hydrogen equal to 100 percent oxidation of the cladding surrounding the active fuel. The amount of hydrogen to be released into the primary system before reactor pressure vessel (RPV) failure is defined as that amount that would be generated by the 100 percent oxidation of the fuel cladding surrounding the active fuel length. This amount of oxidation would produce 2996 pounds of hydrogen.

Simulation of 100 percent cladding oxidation before vessel failure

So that this amount of hydrogen is released into the primary system before RPV failure, a hydrogen injection system was created. The injected hydrogen was assumed to be at 1340°F to approximate the temperature of the gases present during core degradation. The goal of the analysis is to simulate the release of the hydrogen from 100 percent oxidation of the cladding surrounding the active fuel length to the primary system at the time in the accident scenario when it is likely to be released.

To achieve this goal, the release of hydrogen into the primary system has the following characteristics:

- The hydrogen injection begins after substantial core degradation has occurred and a majority of the hydrogen has been produced by oxidation of the cladding.
- The hydrogen injection terminates prior to vessel failure.
- The hydrogen injection does not substantially alter the oxidation rate or the progression of the accident.
- The flow rate of the injection is comparable to the hydrogen production from the in core oxidation rate as opposed to a simple step function that may cause a significant change in the melt progression of the accident.

This paradigm avoids two pitfalls of a faster injection process.

- Hydrogen displacing steam, altering the oxidation process.
- The injected hydrogen either heating or cooling the fuel, depending on its temperature, changing the melt progression.

The scenarios analyzed are the most likely severe accident (relevant) scenarios described in Section 19.2.4.2.2. The results of each of the relevant scenarios is examined to determine the amount of hydrogen produced by the MAAP model for that scenario, and the time period the relevant scenario predicts the hydrogen is released. The mass of hydrogen is needed to be injected is the difference between the amount of hydrogen produced by the relevant scenario and the target hydrogen mass of 2996 lbs.

In the analysis, the hydrogen injection is delayed until a majority of the cladding oxidation has occurred. This minimizes the effect of hydrogen injection on the progression of the scenario. The hydrogen injection flow rate for each scenario is chosen to match as closely as possible the natural hydrogen production rate during cladding oxidation.

The hydrogen injection flow rate is adjusted for each scenario so that the target injected hydrogen mass in the vessel is achieved at the time of vessel failure. The result of each analysis is examined so that the target hydrogen mass in the primary system has been achieved.

After vessel failure molten core-concrete interaction (MCCI) is disabled in the MAAP model since the required amount of hydrogen has been introduced into the vessel and containment. Each of the relevant scenarios is continued for at least an hour after vessel failure to demonstrate the adequacy of the CGCS system to allow thorough mixing of the containment atmosphere and to avoid the creation of a combustible mixture in any single containment compartment.

Enhancements made to MAAP's hydrogen distribution model in containment

The hydrogen that is either generated in the core by cladding oxidation or injected from the simulated hydrogen injection system, is released into the containment by:

- Pipe breaks or breaches in the primary system that are modeled as an initiating event.
- Pressurizer relief (safety valves) or depressurization valves via the pressurizer quench tank and tail pipes.
- RPV head failure.

The MAAP containment model should simulate the release of hydrogen from these sources into the containment volumes, the migration and dispersal of the hydrogen, and its recombination of the hydrogen with ambient oxygen in the PARs.

Acceptability of Containment Hydrogen Concentrations in Excess of 10 Percent

The regulatory requirements for the CGCS to limit hydrogen concentration and maintain containment integrity during and following an accident are set forth in the references cited in Section 6.2.5.1. These requirements are a direct implementation of requirements provided in Section I:G "Hydrogen Control" of SECY93-087 (Reference 31).

This section contains the following passage "Additional TMI-related requirements, requires a hydrogen control system that can safely accommodate hydrogen generated by the equivalent of a 100-percent fuel-clad metal water reaction. The system must also ensure that uniformly distributed hydrogen concentrations in the containment do not exceed 10 percent (by volume), or that the post-accident atmosphere will not support hydrogen combustion."

It is important to note that during blow-down by the depressurization system, it is possible that the 10 percent limit will be exceeded for a short time in small compartments as a result of the containment air being replaced by the hot gases from the primary system. The regulatory guidance allows for the acceptability of these transient conditions. Therefore, for scenarios that result in exceeding the 10 percent limit for short periods of time, a determination is made whether the compartment would support hydrogen combustion. The determination is made by comparing the concentrations of hydrogen and oxygen to the Hydrogen Combustion Limits presented in Figure 3.3.5.4-1 of NEA/CSNI/R(2000)7 "Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety," August 2000 (Reference 32).

Results of the Enhanced Analysis

To illustrate the performance of the U.S. EPR containment's CGCS, MAAP was applied to the most likely severe accident relevant scenarios described in Section 19.2.4.2.2. The average hydrogen concentration (assuming uniform hydrogen distribution) for the scenario that results in the highest average concentration is provided in Figure 6.2.5-10. The hydrogen concentration at each node for the most limiting severe accident scenario (the one with highest concentration in any node) is shown in Figure 6.2.5-11 and Figure 6.2.5-12.

The containment nodes represented in Figure 6.2.5-11 are those associated with the normal containment recirculation pattern. During an accident sequence, the U.S. EPR containment is designed so that a natural circulation pattern develops between the two annular compartments. The containment nodes included in this figure are the containment nodes that constitute the natural circulation pattern. The containment nodes shown in Figure 6.2.5-12 are outside this natural circulation pattern and are singled out for separate presentation.

In Figure 6.2.5-11, the hydrogen release through the cycling of the pressurizer relief valves can be clearly observed. This cycling continues for approximately five hours; at which point, the depressurization valves are opened. Upon opening the flow path between the primary system and the lower containment volumes, the steam and hydrogen quickly fills these compartments with a hydrogen and steam mixture, allowing for rapid depressurization of the primary system.

Since this is a rapid depressurization from a full pressure state, the accumulators will also start to inject, pushing more hydrogen and steam out of the primary system into containment. This water also causes a slight increase in the oxidization prior to quenching the core debris.

Because of these factors, the hydrogen concentration in a few containment nodes, exceed the 10 percent criteria as anticipated. Because of the short nature of these peaks, the hydrogen and steam concentrations for these nodes were plotted separately in Figure 6.2.5-13. From this figure, it can be concluded that:

- The peak is extremely short in duration.
- The volumes contain a large amount of steam.

Based on Figure 3.3.5.4-1 of Reference 32, the plot of hydrogen and steam concentrations show that the hydrogen concentration remains significantly below the hydrogen concentration required to support deflagration to detonation transition (DDT). It is therefore concluded that the U.S. EPR containment's hydrogen mitigation system is sufficient to reduce the hydrogen from 100 percent active fuel cladding to a value that will prevent a detonation within containment, (i.e., the 10 percent regulatory requirement).

Containment Performance

The results of the analysis for containment response to a global deflagration show that the containment can withstand a global deflagration without a loss of integrity. Figure 6.2.5-11 demonstrates the well-mixed atmosphere with regard to hydrogen concentration. Figure 6.2.5-14 shows the AICC pressure versus time, which remains below the ultimate capacity pressure for the U.S. EPR containment contained in Table 3.8-6.

Figure 6.2.5-15 shows the containment dome temperature from a realistic hydrogen burn and the global ACC temperature. Note that AICC pressure and temperatures are theoretical values that cannot be reached because actual combustions are not adiabatic, isochoric or complete.

6.2.5.3.3 Design Evaluation

The PARs, rupture and convection foils, and hydrogen mixing dampers of the CGCS are passive devices that do not rely on electrical power to perform their primary functions and are not susceptible to single active failure. Loss of onsite or offsite power has no effect on the PARs and rupture and convection foils, and will cause the fail-safe mixing dampers to fail-safe open.

The CGCS is designed to operate in DBAs with elevated temperature, pressure and radiation. The mixing dampers, rupture and convection foils open early in the accident progression on pressure differential or temperature differential. If the DBA transitions into a Severe Accident, these components have to maintain integrity only. Their operation is not affected by localized pressure and temperature increase due to hydrogen combustion.

The PARs are designed for DBA, as well as SA conditions. For the SA analysis, 100% PAR efficiency is assumed.

The PARs are not pressure retaining components and are open at the bottom and the top, therefore, are unaffected by localized pressure increase. The design covers hydrogen combustion temperature peaks and SA radiation.

The CGCS operates effectively in a steam-saturated atmosphere (steam concentration greater than 55 percent by volume. CGCS equipment required to function during severe accident environmental conditions will demonstrate equipment survivability, including loads resulting from a hydrogen burn as discussed in Section 6.2.5.3.2. Several methodologies to demonstrate equipment survivability are presented in Section 19.2.4.4.5. Based on these two Sections, (6.2.5.3.2 and 19.2.4.4.5), the maximum AICC pressure and temperature are 100.8 psia and 1366°F (from Section 19.2.4.4.5.2). The AICC pressure is a theoretical value that cannot be reached because actual combustion is not adiabatic, isochoric, or complete. The best estimate, limiting pressure, and temperature resulting from a forced hydrogen combustion for CGCS equipment survivability are 76 psia and 796°F. Equipment survivability analyses consider hydrogen concentrations equivalent to that generated from a fuel clad-coolant reaction involving 100 percent of the fuel cladding surrounding the active fuel region using the methodology provided in Section 6.2.5.3.2. The low range and high range HMS systems are capable of operating during design basis accidents and severe accidents, respectively.

The low range hydrogen sensors are located inside the containment and meet the single failure criterion. These sensors are located in physically separated areas of the containment. Additionally, the signal processing is carried out by separate channel cards installed within the signal processing units that are located outside containment. The sensors and cables located inside containment are designed to remain operable during DBAs. The failure of one sensor or cable does not influence the reliability or accuracy of the other sensors.

The high range monitor for the HMS utilizes measuring modules and associated equipment of each independent train. The trains meet the single failure criterion by being physically separated and located in Safeguard Building 1 for train 1 and Safeguard Building 4 for train 2. The gas samplers of each train are installed in different areas of the containment. Each train is equipped with measuring points inside and outside the equipment rooms so that in case a measuring unit is lost, the measuring information can be substituted by the redundant train.

6.2.5.4 Inspection and Testing Requirements

Preoperational testing is performed to verify the design adequacy and performance of the CGCS and HMS system components. Preoperational tests are addressed in Section 14.2 (Test Abstract #013 and #145), while Inspections, Tests, Analyses, and Acceptance Criteria of the CGCS are listed in Section 14.3.

For periodic testing, the PARs have a removable inspection drawer for ease of maintenance and in-service inspection. The catalytic plates are visually examined for scratches, damage, or foreign objects that could limit the surface area for catalysis. The catalytic ability of the plates is tested with special equipment that subjects the plates to a premixed test gas. During outages, the PARs are covered by blankets to avoid direct exposure to dust and fumes generated by local work operations.

Operability of the hydrogen mixing dampers is periodically verified and visual inspections of the dampers are performed to check for obstructions or loose or broken parts that could interfere with their proper operation. The rupture and convection foils are visually inspected for cracks or damage. Significant leakage through the foils is detectable during operation by monitoring of the ventilation system.

The HMS system components are tested periodically during normal plant operating conditions to confirm proper operation.

6.2.5.5 Instrumentation Requirements

The PARs, rupture foils, and convection foils of the CGCS are passive components that do not require instrumentation or controls. The hydrogen mixing dampers (HMD) are safety-related and their operation and actuation logic is controlled by the protection system, safety automation system, and diverse actuation system. There are two sensors per steam generator loop for a total of eight, safety-related delta pressure sensors powered from their respective electrical divisions. This arrangement meets the single failure requirements such that a sensor can be out for maintenance and a single-failure can occur without affecting the HMD control. If two out of eight sensor signals exceed the delta pressure setpoint all eight HMDs receive a signal to open. The delta pressure setpoint is 0.5 psid. The delta pressure is measured across the steam generator pressure equalization ceiling and measures the difference in pressure between the accessible and equipment area. The delta pressure signal accounts for a pressure increase in either of the regions to provide an actuation signal for the HMDs.

In addition, there are a total of four safety-related absolute containment service compartment pressure sensors. Their operation and actuation logic is also controlled by the protection system and the diverse actuation system. For each steam generator loop an associated absolute pressure sensor is located in the accessible area of the containment. If two out of four of the absolute pressure sensors exceed the absolute pressure setpoint of 17.4 psia, the HMDs receive a signal to open. This arrangement and logic also meets the single failure requirements in that a sensor can be out for maintenance and a single-failure can occur without affecting the HMD control. There are no restrictions placed on plant operation if one of the absolute pressure sensors is out of service.

The combination of delta and absolute pressure sensors fulfills redundancy and diversity requirements. Upon loss of power, the HMDs open in a fail-safe position and remain open until power is restored. When power is restored, the HMDs will close automatically unless a high containment pressure condition exists. The plant operator can reset the instrumentation and controls (I&C) interlock function and manually operate the HMDs. Position sensors indicate the HMD position in the main control room. If an HMD opens unintentionally, it can be closed by either the actuator or the mechanical backup closing mechanism. In the unlikely case that a mixing damper remains open, the resulting leakage (cross-sectional area approximately 8 ft^2), compared to the total leakage of penetrations and doors across the in-accessible and accessible rooms, is negligible. HMDs are installed in the accessible area which provides for maintenance access to the component during normal operation. Section 7.3 provides further detail about the I&C logic and logic diagrams of the HMDs.

The redundancy of the eight hydrogen mixing dampers meets FMEA requirements so that one HMD can be out for maintenance and a single failure can occur at a second HMD without affecting the global convection between the equipment and operational rooms (seeTable 6.2.5-3, which lists the CGCS Failure Modes and Effects Analysis).

On-site periodic testing verifies the proper functioning of each installed HMD (see Section 6.2.5.4). The common mode failure is addressed by the qualification program and periodic testing.

High differential pressure at the steam generator pressure equalization ceilings produce an alarm in the main control room.

The HMS monitors hydrogen concentrations in the containment atmosphere during design basis events, monitors hydrogen and steam concentrations in the containment atmosphere during and after beyond design basis events, and monitors the efficiency of the CGCS during and after beyond design basis events. Alarms in the main control room indicate if hydrogen concentration thresholds have been exceeded.

Instrumentation and control systems are described in Chapter 7.

Table 6.2.5-1—CGCS Design and Performance Parameters

Parameter	Value
Large PARs	
• Number of units	41
• Nominal hydrogen reduction rate (per PAR)	11.8 lb_m/hr
• Catalyst	Pt / Pd coating
Small PARs	
• Number of units	6
• Nominal hydrogen reduction rate (per PAR)	2.6 lb_m/hr
• Catalyst	Pt / Pd coating
Hydrogen mixing dampers	
• Number of units	8
• Approximate opening cross section (total)	64 ft^2
• Nominal actuation pressure	0.5 psid or 17.4 psia
Rupture foils	
• Approximate opening cross section (total)	420 ft^2
• Nominal actuation pressure	0.7 psid ± 30%
Convection foils	
• Approximate opening cross section (total)	450 ft^2
• Nominal actuation pressure	0.7 psid ± 30%
• Nominal actuation temperature	180.5°F

Table 6.2.5-2—HMS Design and Performance Parameters

Parameter	Value
Low range HMS in containment	
• Number of sensors	12
• Typical measurement range (hydrogen)	0-10 volume %
• Measurement frequency	Continuous
High range HMS in containment	
• Number of trains	2
• Number of sampling points per train	4
• Typical measurement range (hydrogen)	0-30 volume %
• Typical measurement range (steam)	30-70 volume %
• Approximate measurement frequency	3 min.

Table 6.2.5-3—Combustible Gas Control System Failure Modes and Effects Analysis
Sheet 1 of 3

Component	Component Function	Failure Mode	Failure Mechanism	Failure Symptoms / Effects	Can CGCS Satisfy Success Mission Criteria
Passive Autocatalytic Recombiners (PARs): 30JMT10 AT001 through 30JMT10 AT047 Note: The Passive Autocatalytic Recombiners are severe accident components and not credited for DBAs. They are listed in this FMEA table to cover all Combustible Gas Control System components.	Reduce hydrogen concentration in the containment to maintain containment integrity and promote global convection	Failure to recombine hydrogen	Catalytic	No reduction of hydrogen at PAR location	Yes, the failure only affects the PAR location. Global convection assures a mixed atmosphere and homogeneous distribution of hydrogen in the containment.

Table 6.2.5-3—Combustible Gas Control System Failure Modes and Effects Analysis
Sheet 2 of 3

Component	Component Function	Failure Mode	Failure Mechanism	Failure Symptoms / Effects	Can CGCS Satisfy Success Mission Criteria
Convection Foils: 30JMT20 AB101 through 30JMT20 AB130 30JMT20 AB201 through 30JMT20 AB230 30JMT20 AB301 through 30JMT20 AB330 30JMT20 AB401 through 30JMT20 AB430	Separate the equipment and service compartments during normal plant operation Opens on exceeding the pressure or temperature threshold and transfers the two-room containment into a single volume to promote global convection and atmospheric mixing	a) Open during normal operation	Mechanical	Minor leakage between the equipment and service compartments	Yes, the occurring leakage is negligible compared to the allowed total leakage between the equipment and service compartments.
		b) Failure to open during an accident	Mechanical	No convection at the Convection Foil location	Yes, the blocked free flow area is negligible compared to the total combined opening area of the convection foils.

Table 6.2.5-3—Combustible Gas Control System Failure Modes and Effects Analysis
Sheet 3 of 3

Component	Component Function	Failure Mode	Failure Mechanism	Failure Symptoms / Effects	Can CGCS Satisfy Success Mission Criteria
Hydrogen Mixing Dampers: 30JMT20 AA001 30JMT20 AA002 30JMT20 AA003 30JMT20 AA004 30JMT20 AA005 30JMT20 AA006 30JMT20 AA007 30JMT20 AA008	Separate the equipment and service compartments during normal plant operation by holding the Hydrogen Mixing Dampers closed Opens on exceeding a delta or absolute pressure threshold or loss of power. Transfers the two-room containment into a single volume to promote global convection and atmospheric mixing	a) Open during normal operation	Mechanical / Electrical / I&C	Minor leakage between the equipment and service compartments	Yes, the occurring leakage is negligible compared to the allowed total leakage between the equipment and service compartments.
		b) Failure to open during an accident	Mechanical / Electrical / I&C	No convection at the Hydrogen Mixing Damper location	Yes, the blocked free flow area is negligible compared to the total combined opening area of the Hydrogen Mixing Damper.

Figure 6.2.5-1—Arrangement and Location of the Passive Autocatalytic Recombiners

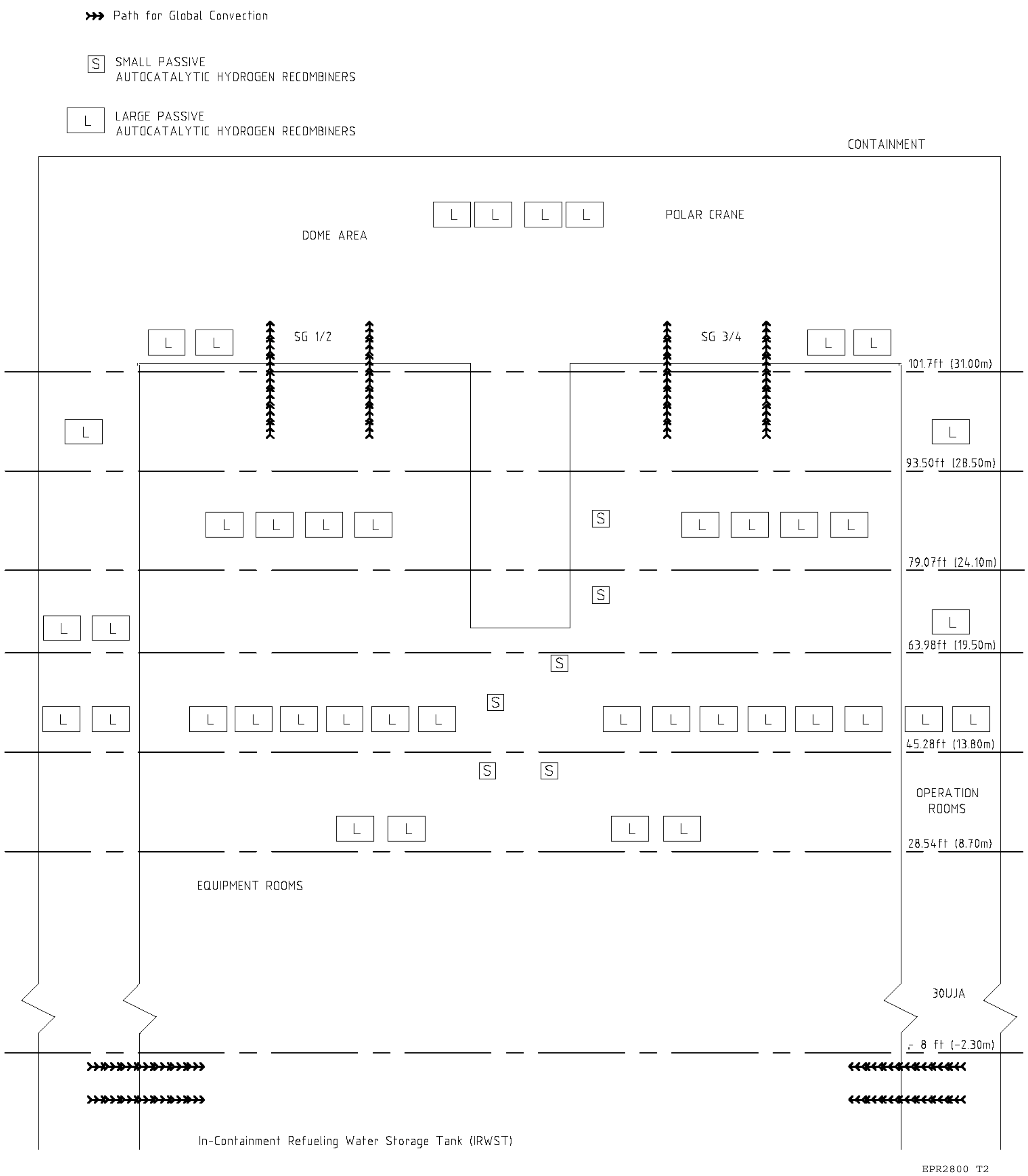

Figure 6.2.5-2—Integrated Production of Hydrogen from 1% Core Oxidation

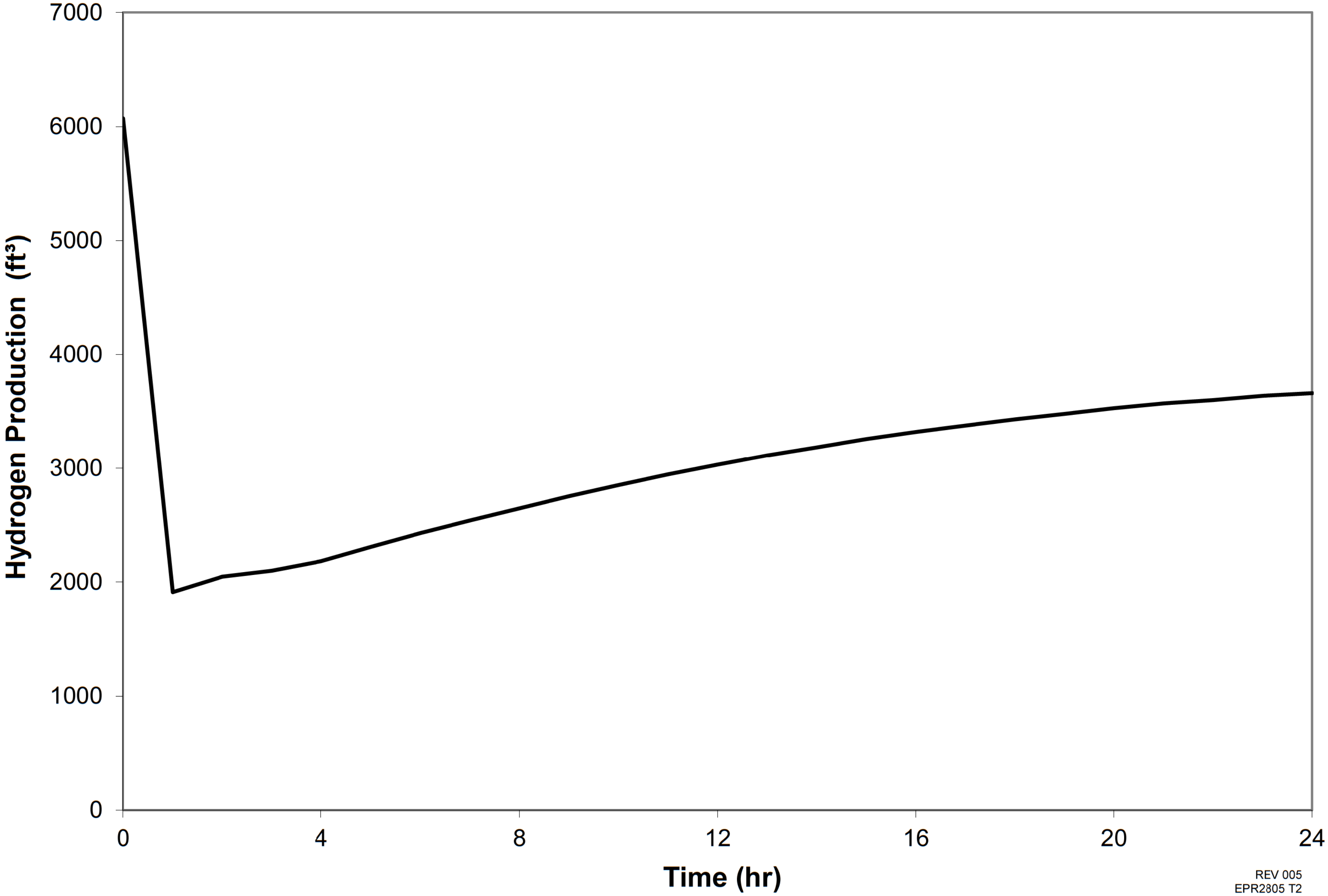

Figure 6.2.5-3—Integrated Production of Hydrogen from Radiolysis

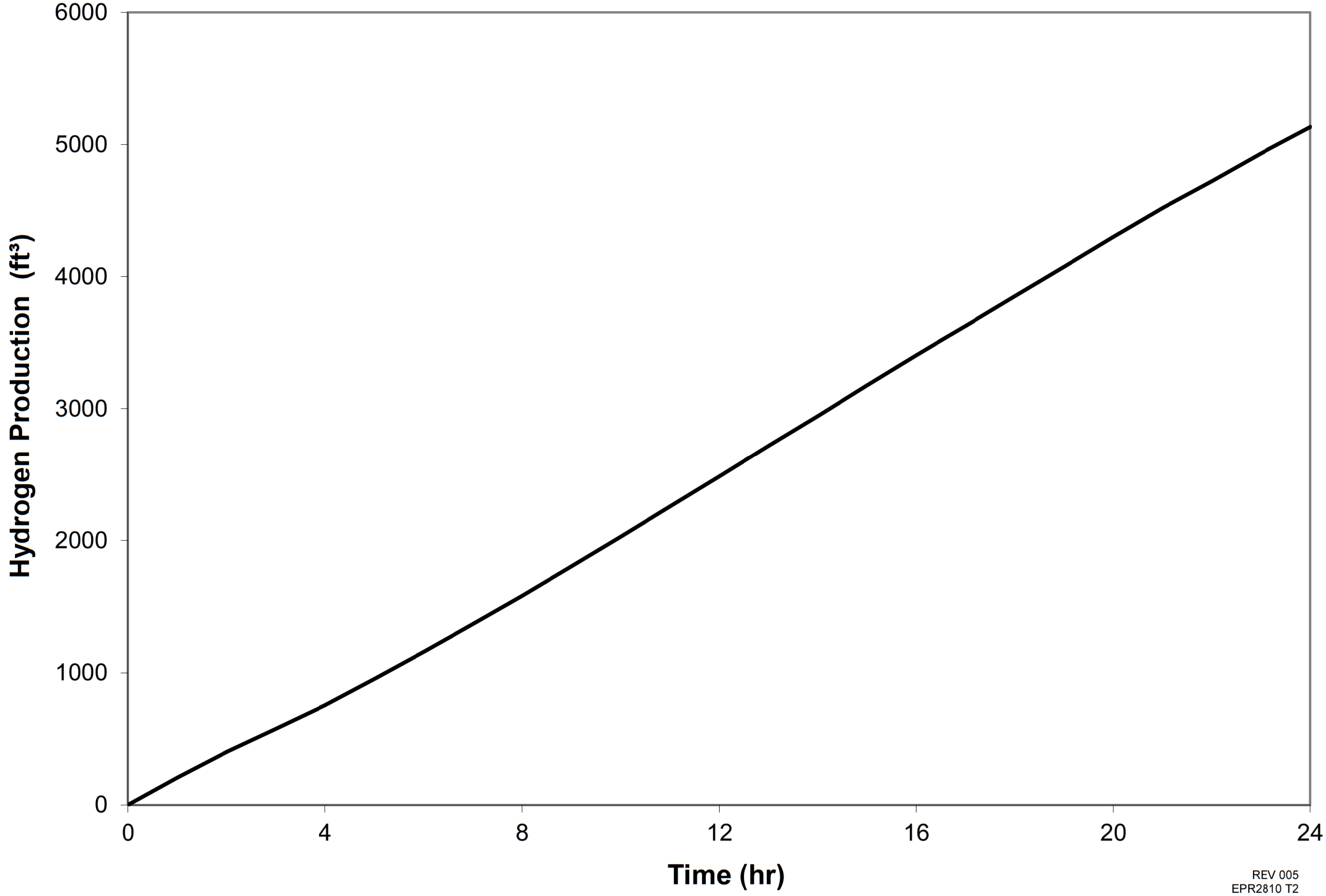

Figure 6.2.5-4—Assumed Hydrogen Generation Rate from Zinc Sources

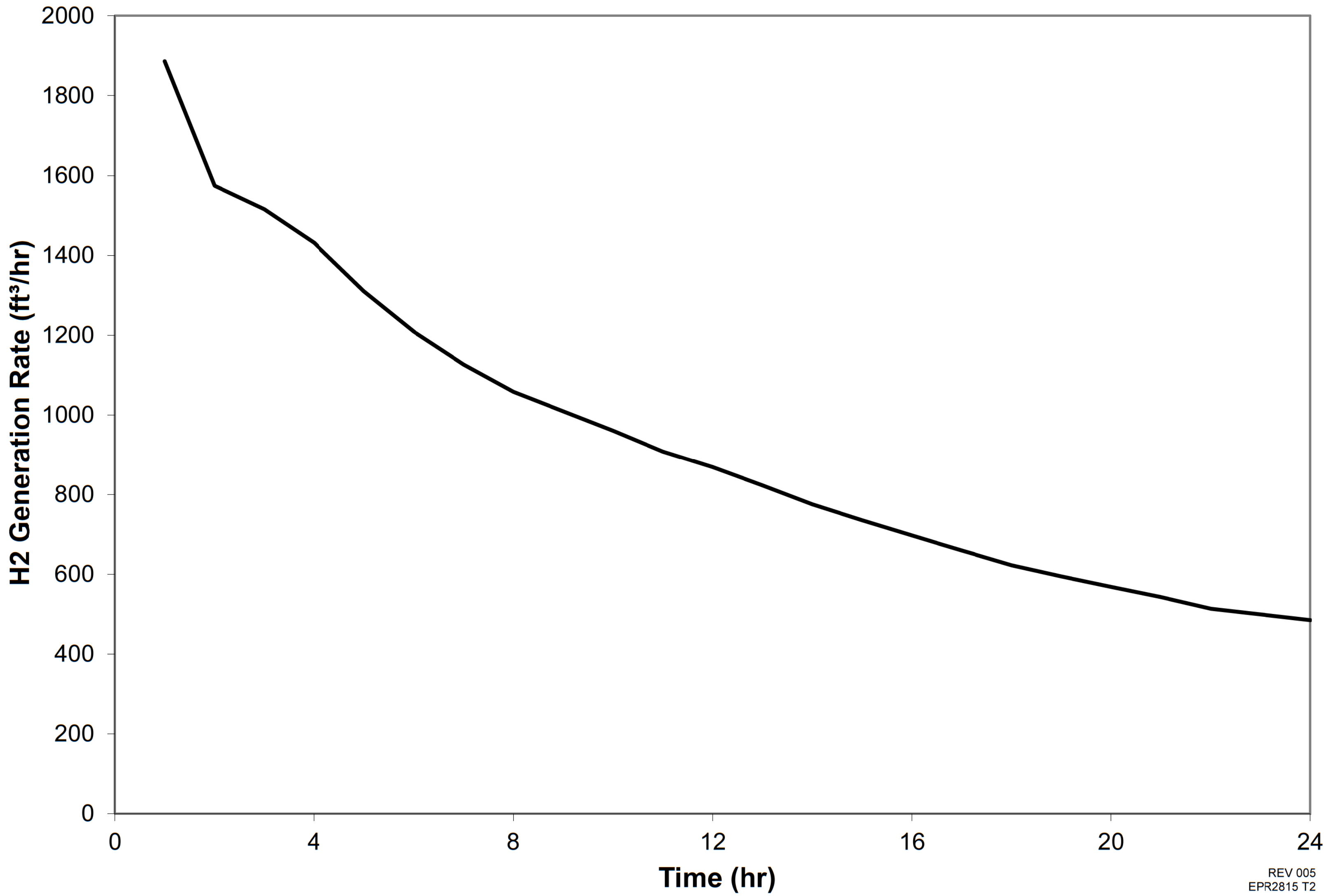

Figure 6.2.5-5—Assumed Hydrogen Generation Rate from Aluminum Sources

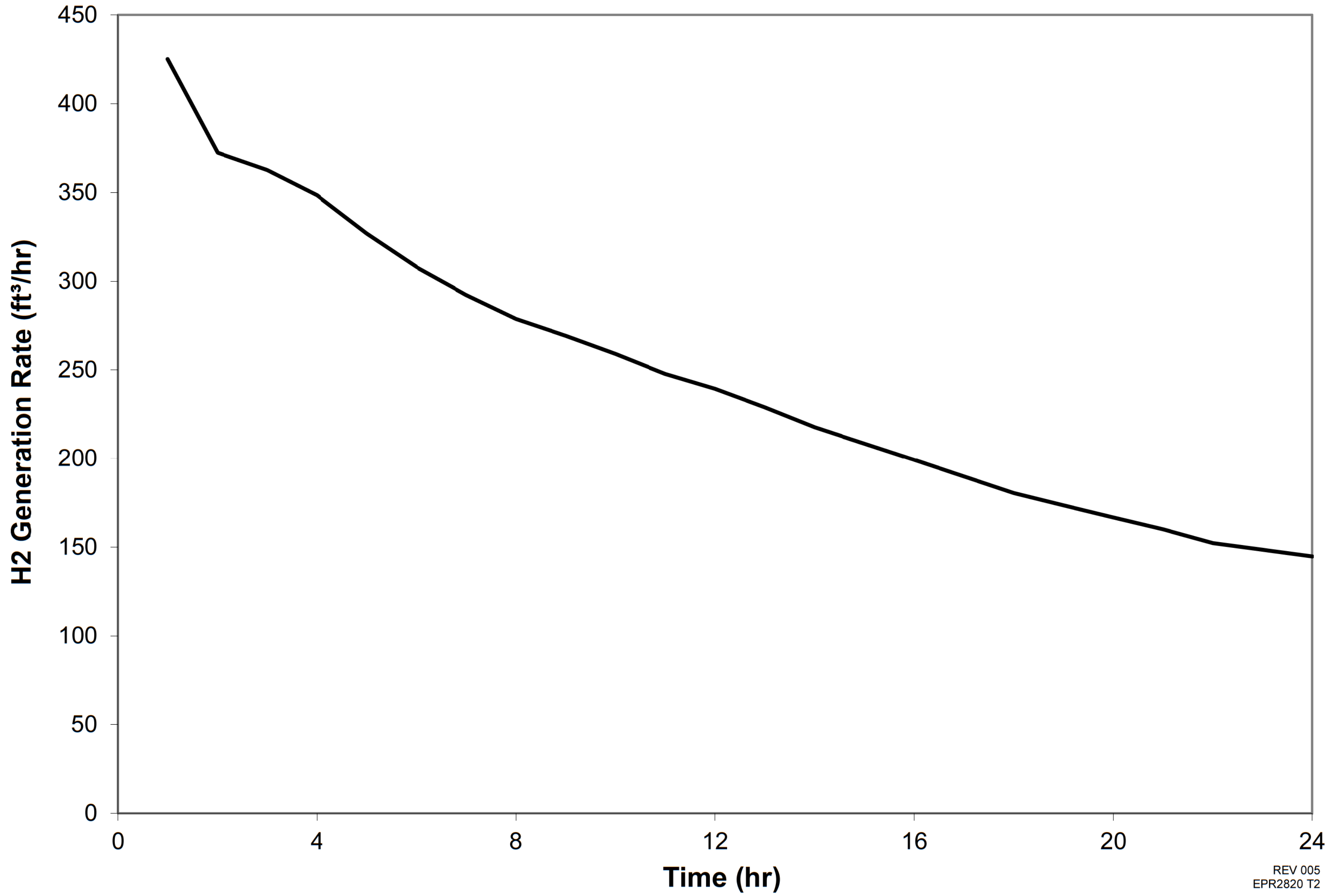

Figure 6.2.5-6—Integrated Production of Hydrogen from Zinc-Based Paint

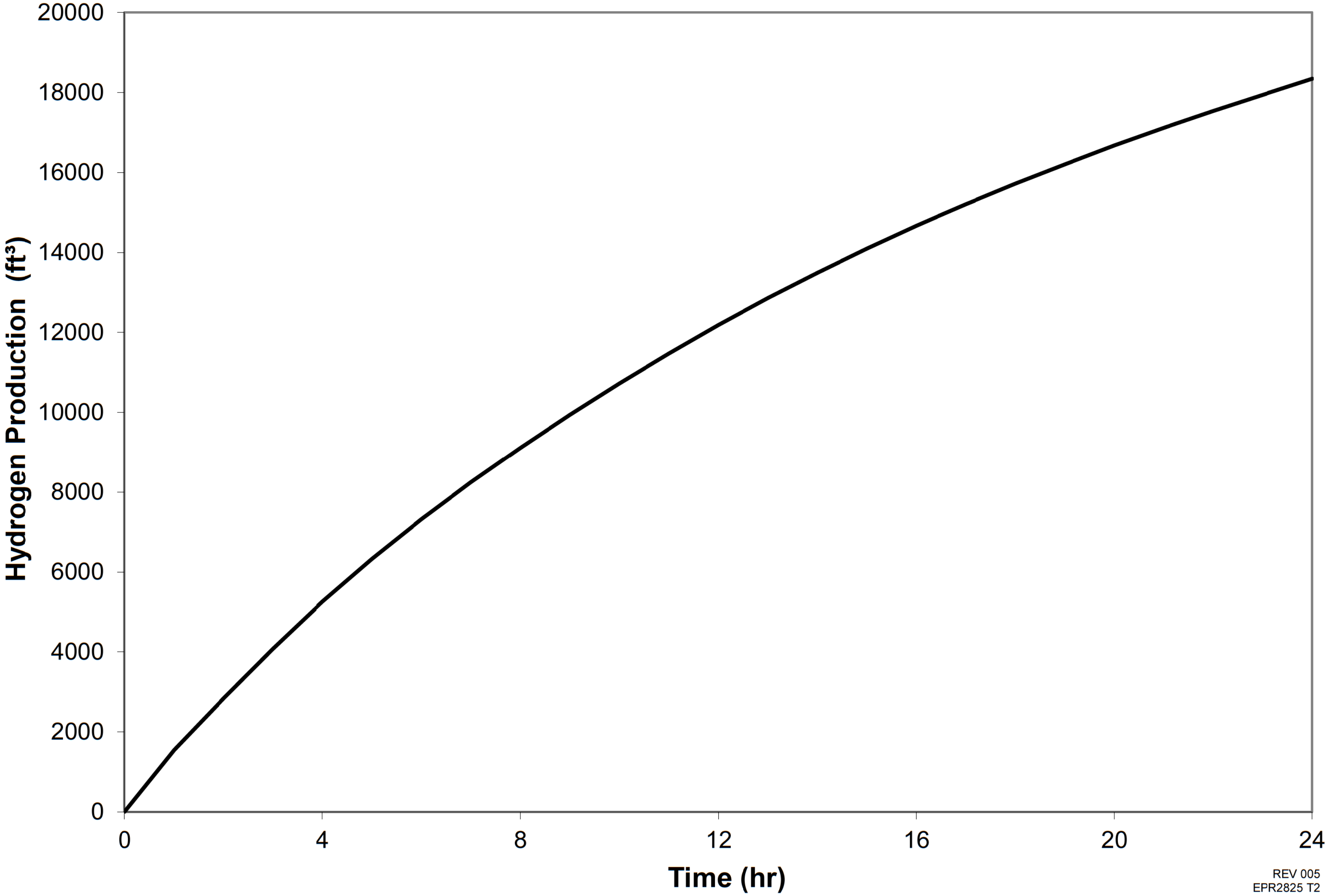

Figure 6.2.5-7—Integrated Production of Hydrogen from Galvanized Steel

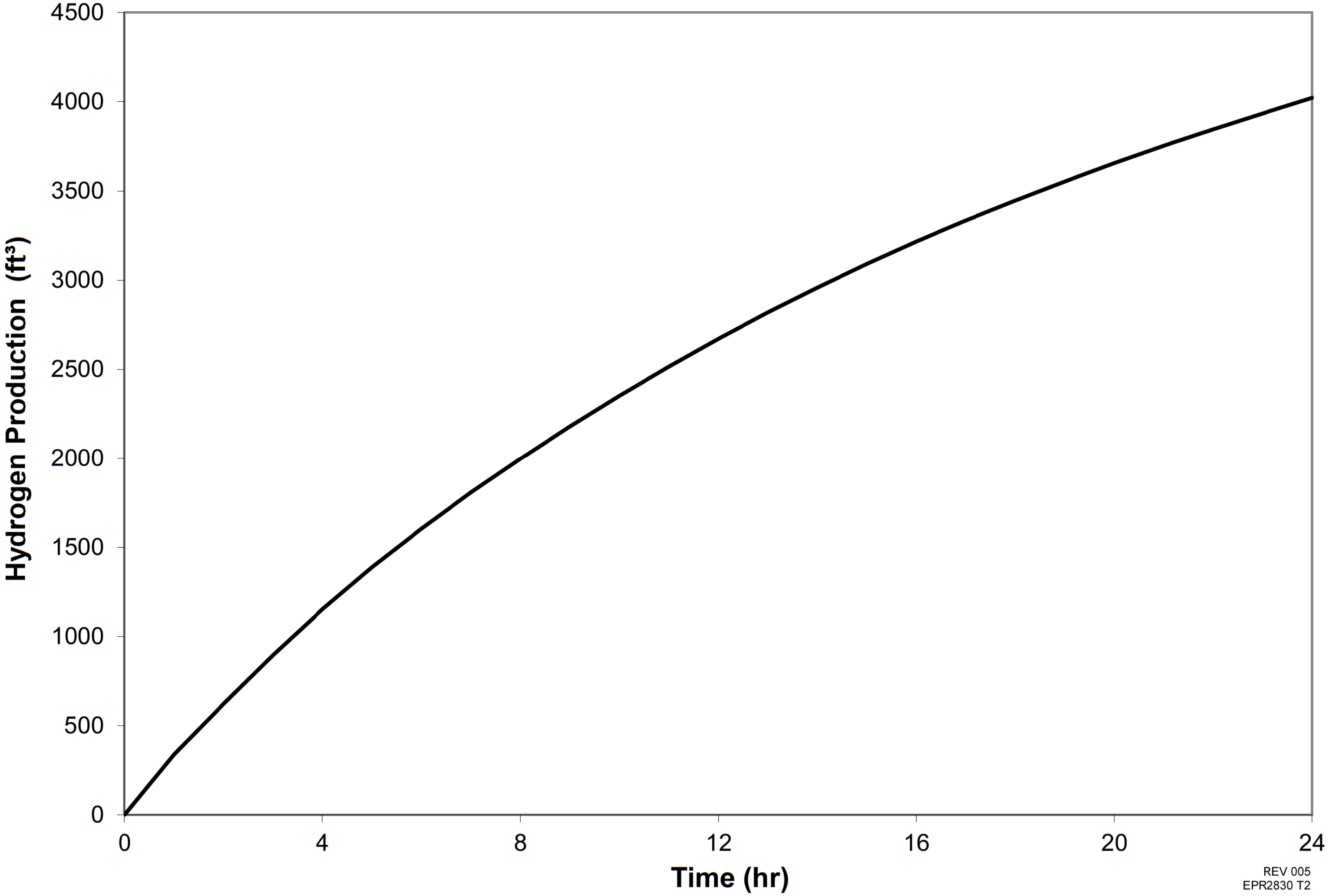

Figure 6.2.5-8—Integrated Production of Hydrogen from Aluminum

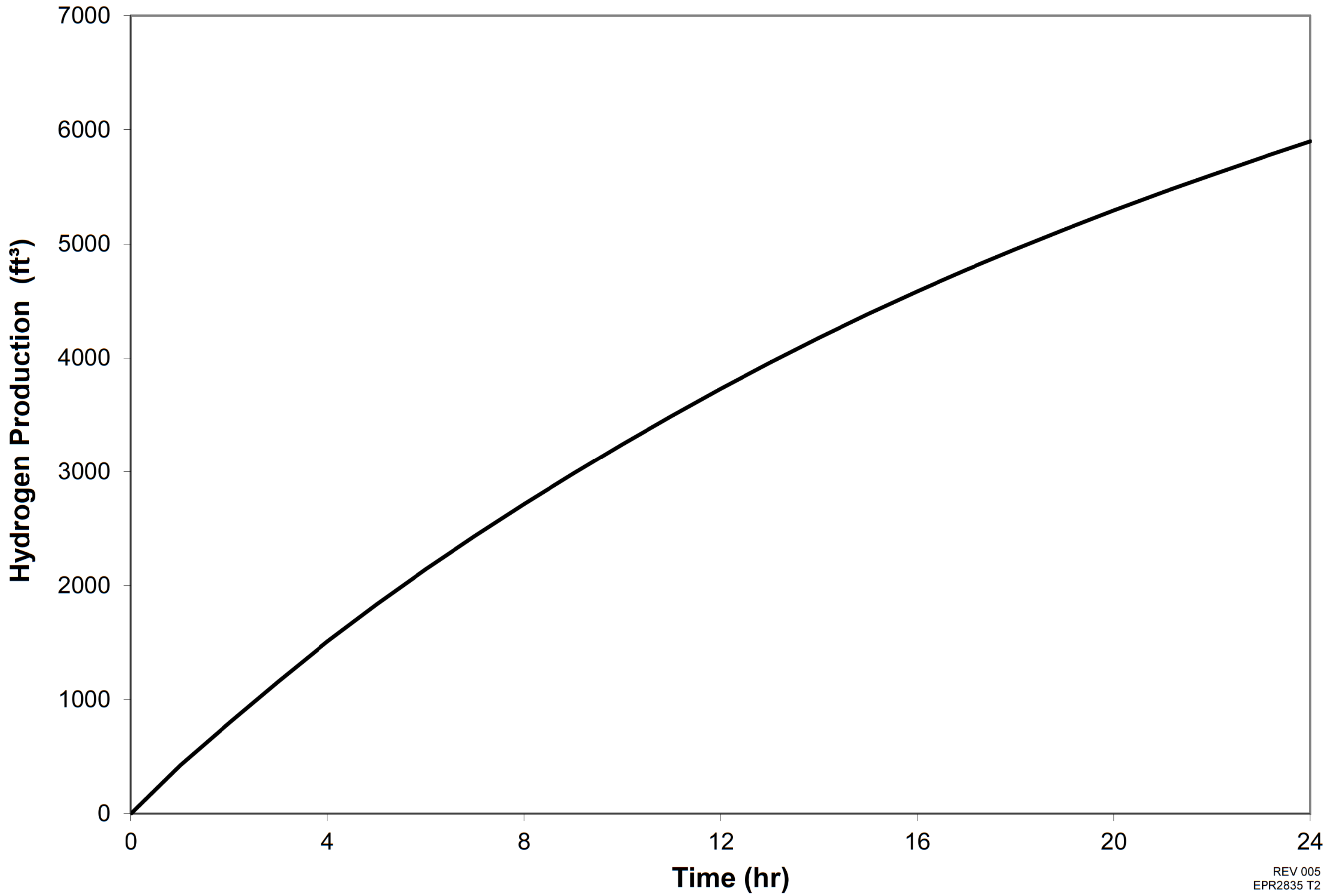

Figure 6.2.5-9—Concentration of Hydrogen in the Containment

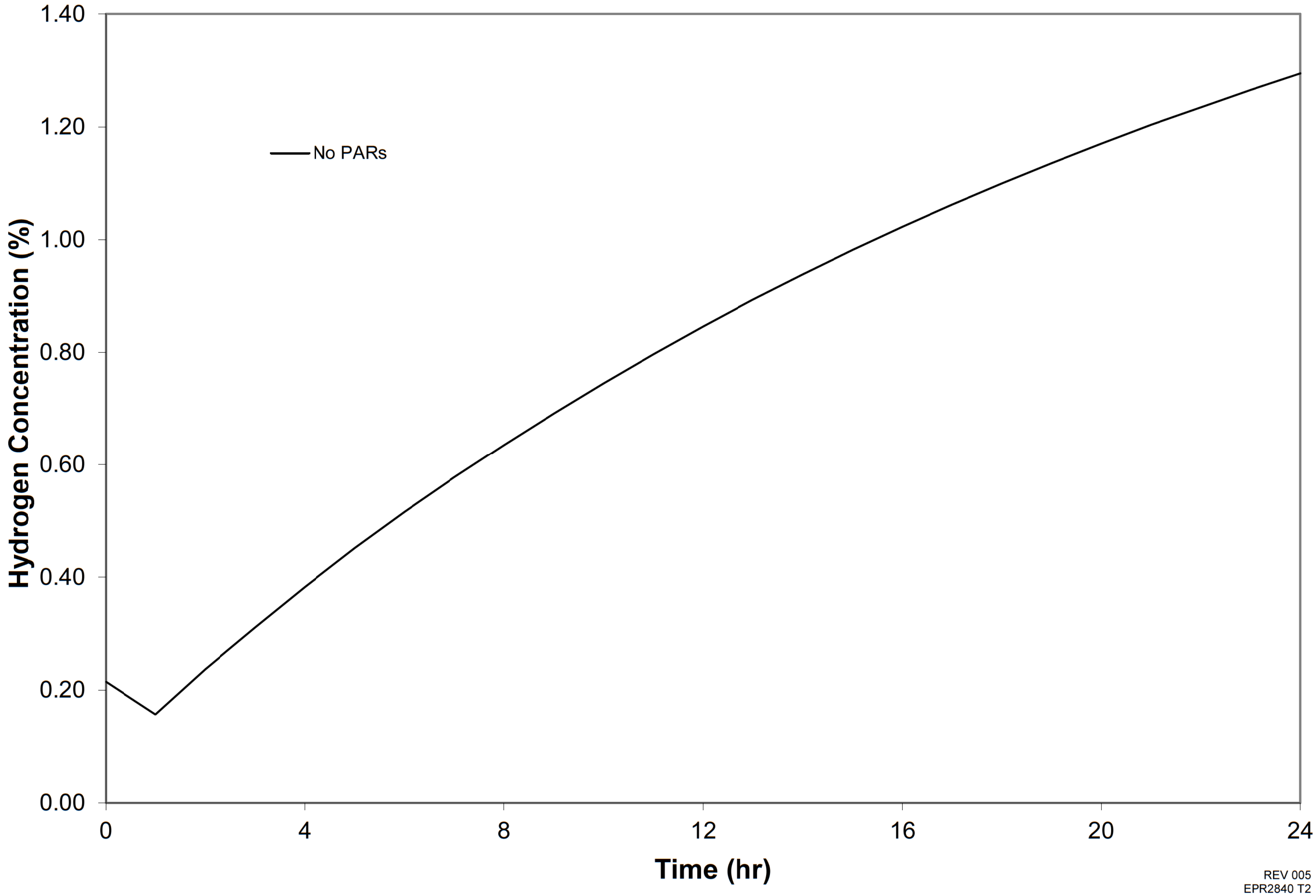

Figure 6.2.5-10—Global Average Hydrogen Concentration within Containment for the Most Limiting Severe Accident Scenario

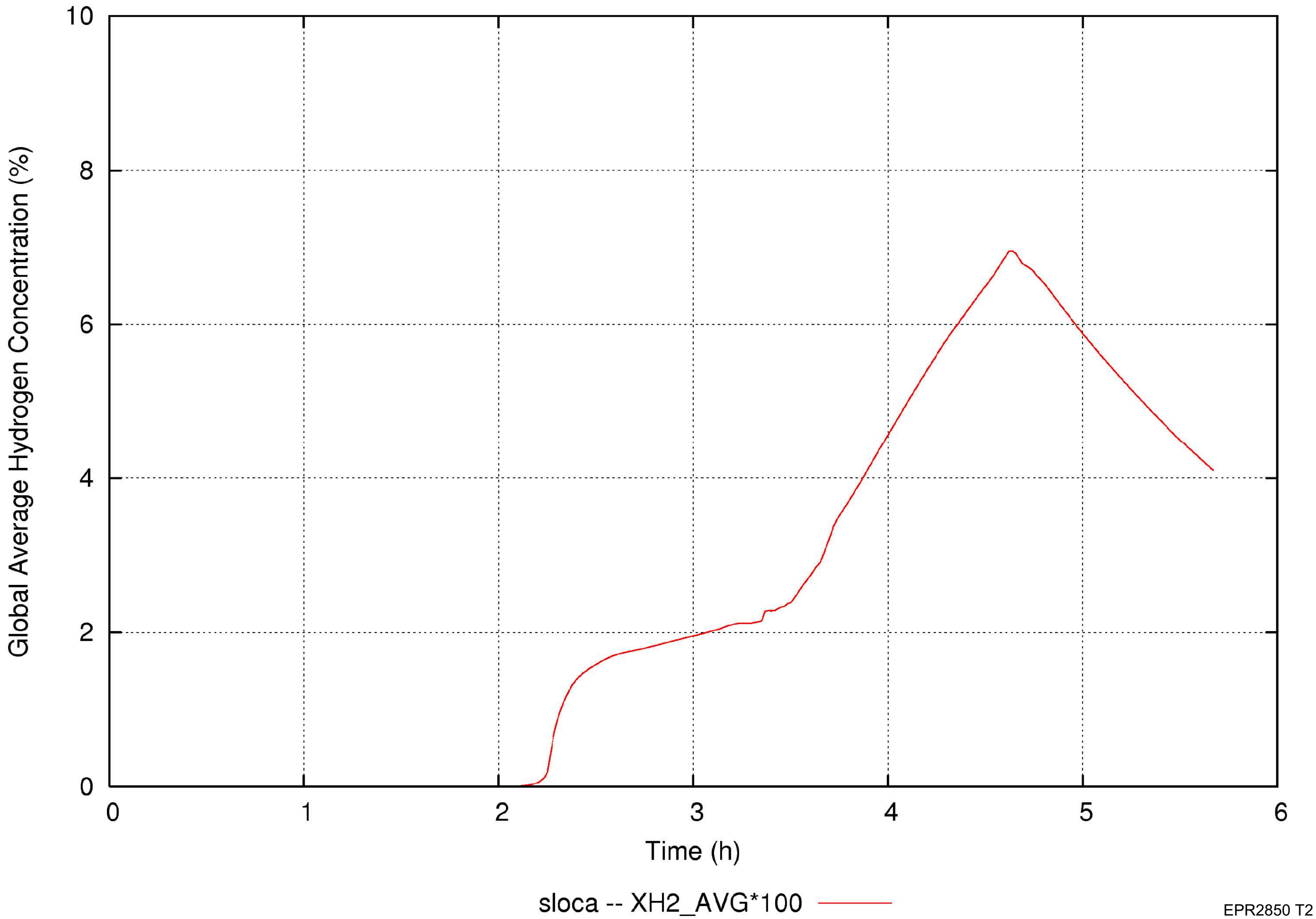

Figure 6.2.5-11—Hydrogen Concentration within Containment for the Most Limiting Severe Accident Scenario

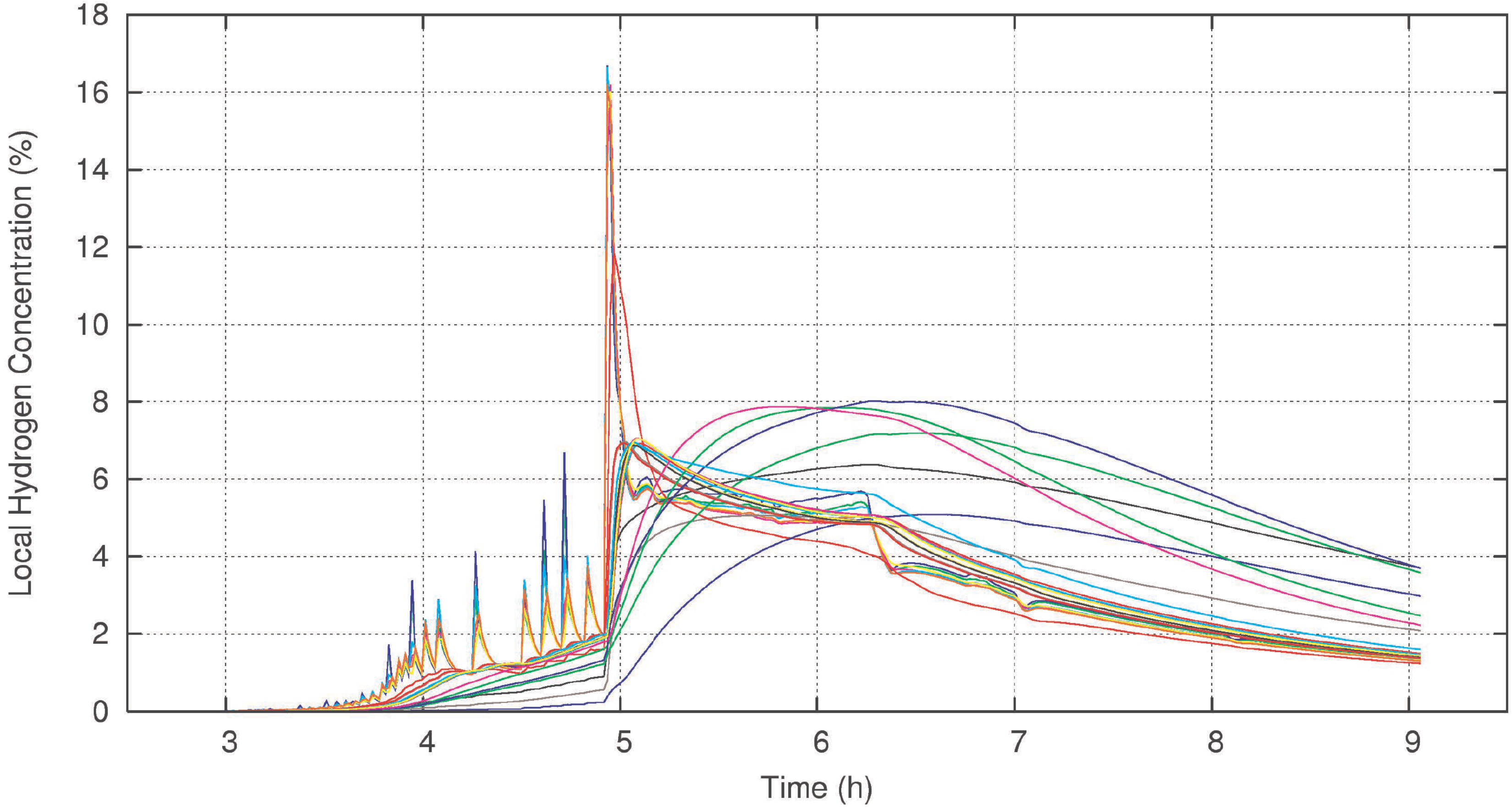

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Figure 6.2.5-12—Hydrogen Concentration in Special Compartments Most Limiting Severe Accident Scenario

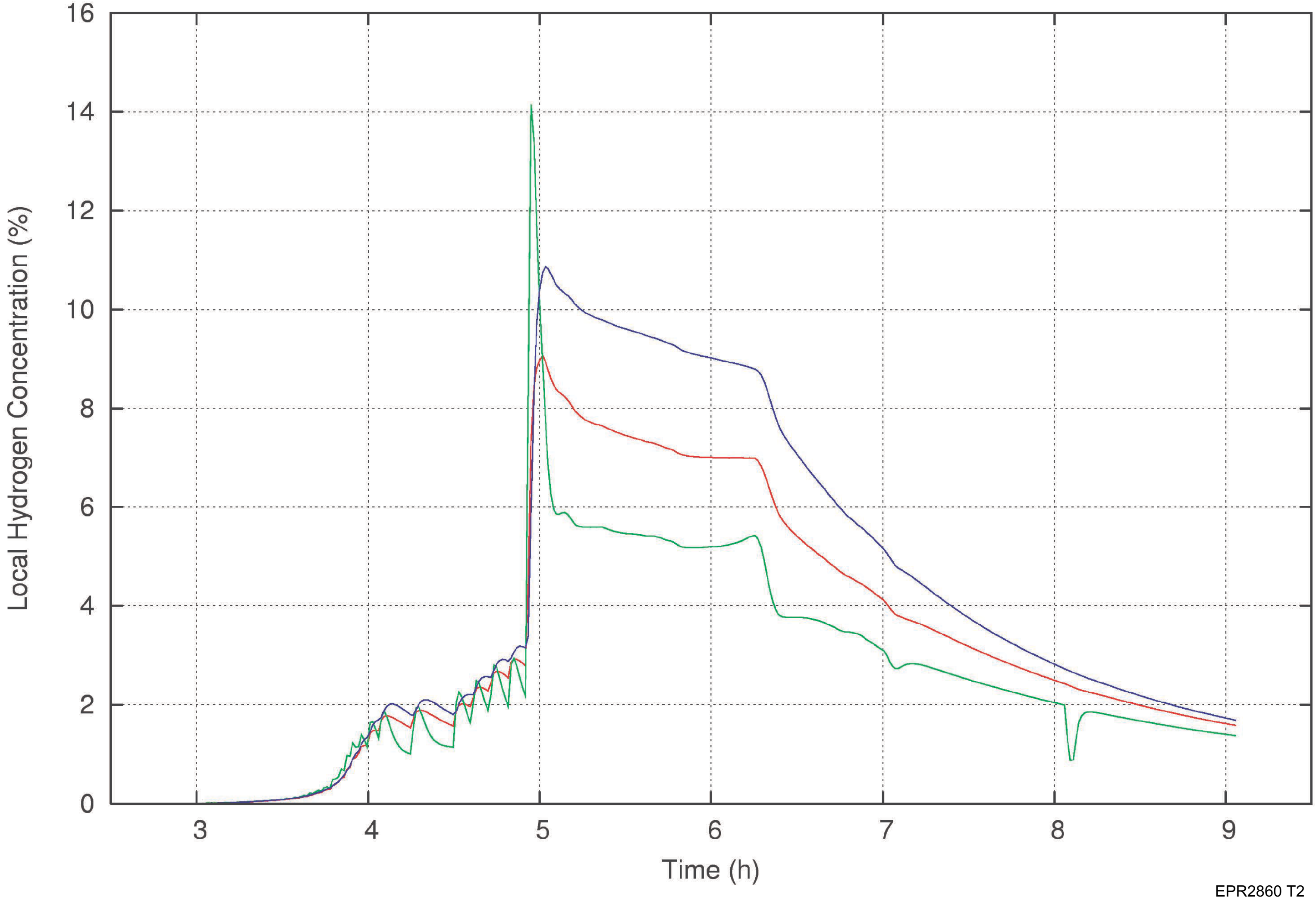


Figure 6.2.5-13—Comparison of High Hydrogen Concentrations to Corresponding Steam Concentrations for Most Limiting Severe Accident Scenario

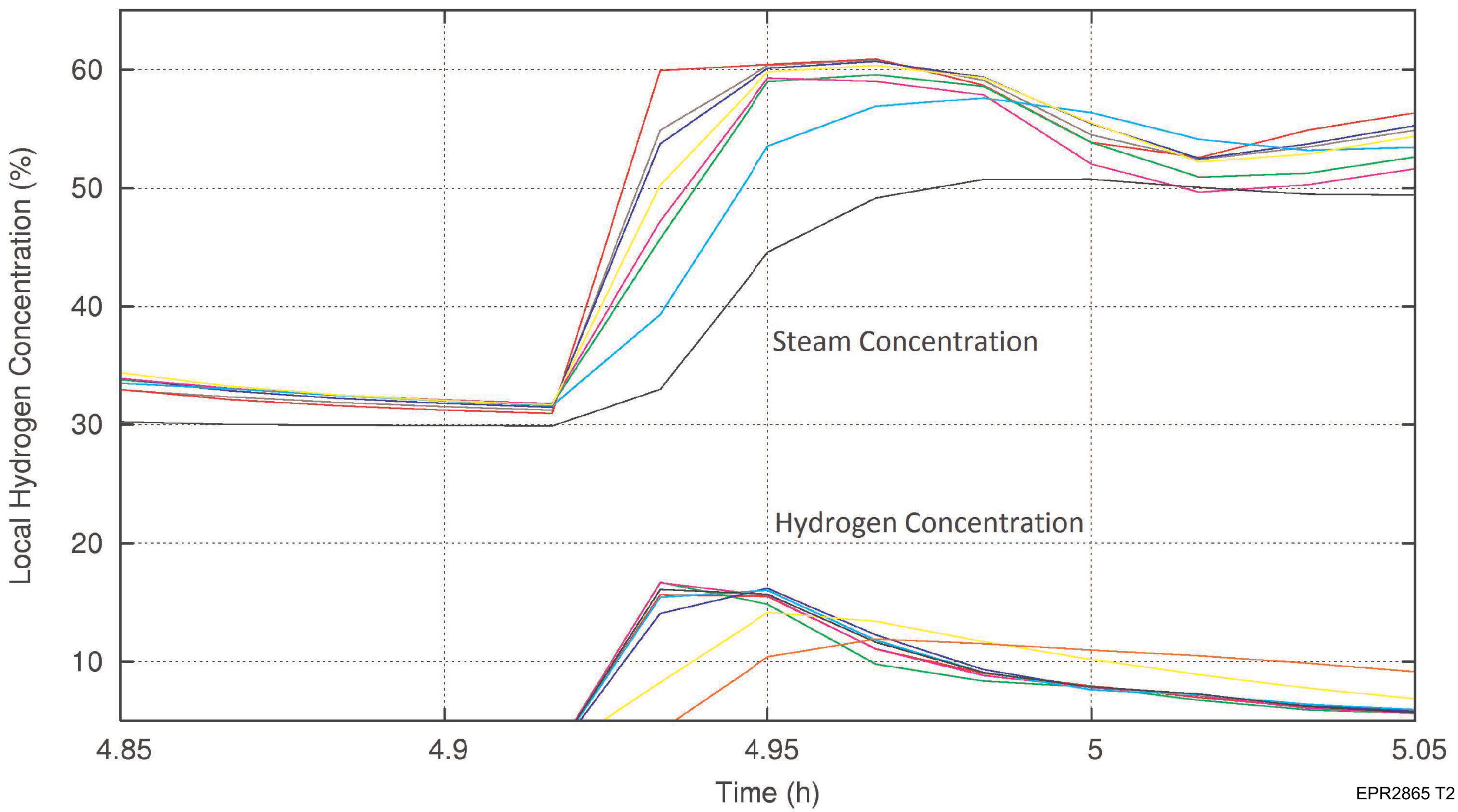


Figure 6.2.5-14—AICC Global Pressure and Containment Pressure for Most Limiting Severe Accident Scenario

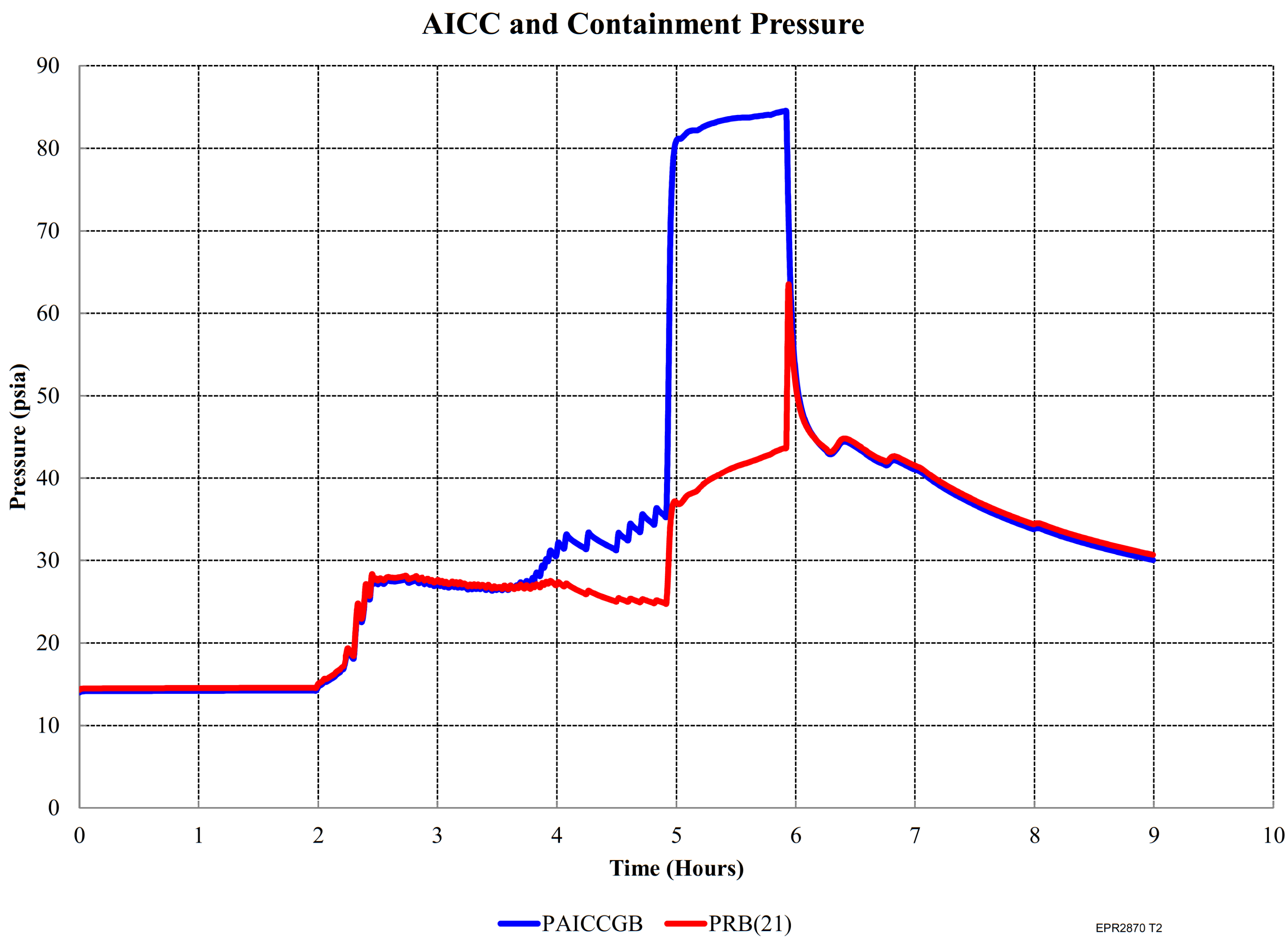
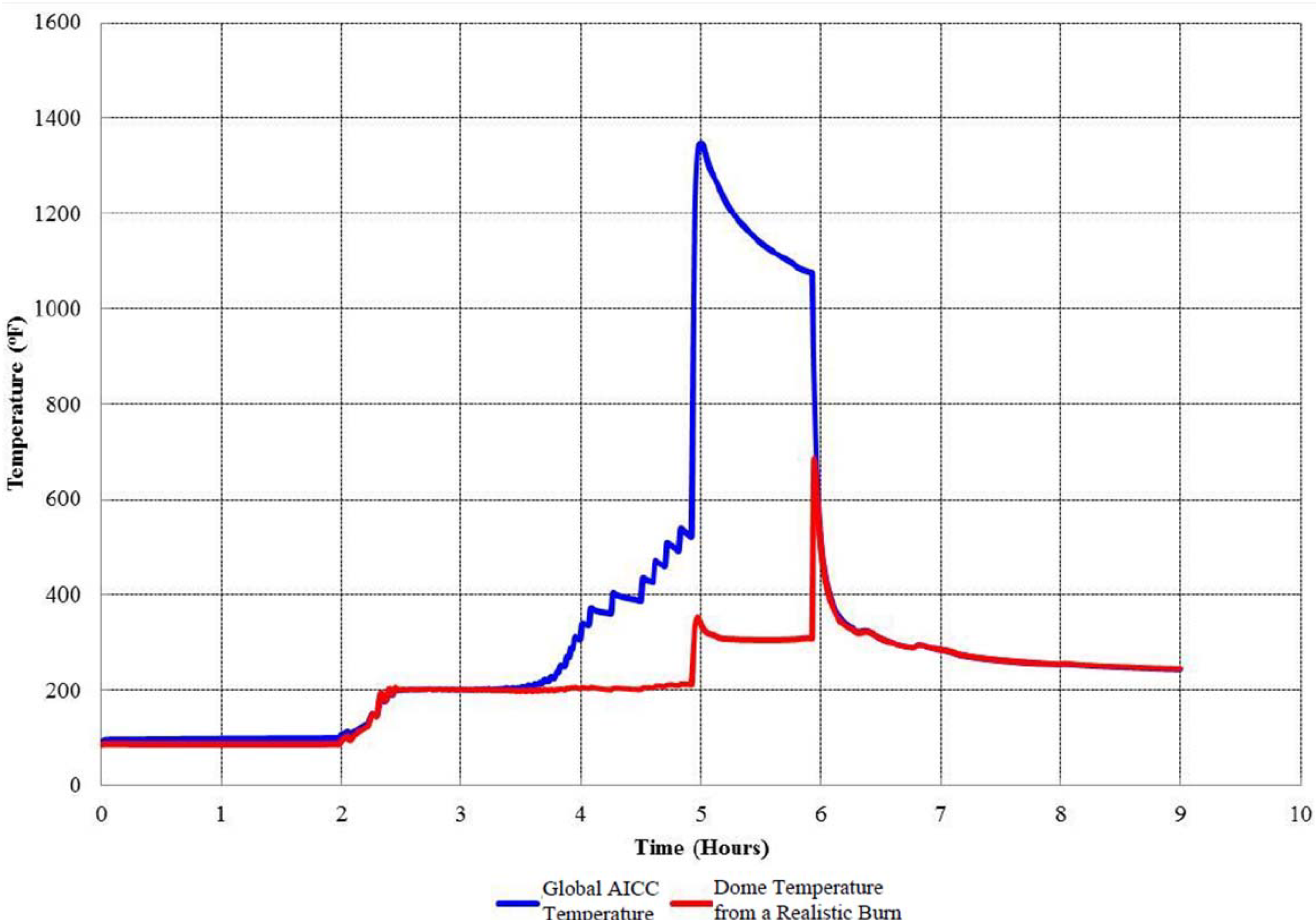


Figure 6.2.5-15—Global AICC Temperature and Dome Temperature from a Realistic Burn



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