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.

Refer to Section 3.2 for the seismic and system quality group classifications of 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 pressure differential 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. A pressure differential less than 1 psi is sufficient to burst the rupture and convection foils. Fusible links in the steel frames of the convection foils passively open the flow path at an elevated temperature.

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 separate the air space of the IRWST and the lower part of the annular rooms in containment. Each spring-loaded mixing damper is held closed during normal operation by a solenoid-operated actuator. The mixing dampers open automatically if the differential pressure between operational and equipment rooms is exceeded or if the containment pressure increases slightly above atmospheric pressure. The mixing dampers also open on loss of power to the solenoid-operated actuators and can be opened manually by the operator.

Passive Autocatalytic Recombiners

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. 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 have been subjected to several international testing programs, during which the hydrogen reduction capability was proven for severe accident conditions. Simulated conditions included core melt aerosols and possible catalyst poisons such as tellurium, selenium, antimony, and iodine. Qualification studies, which included the PARs, were conducted that explored the depletion of hydrogen and its relationship with induced convection. Severe accident testing programs are presented in the U.S. EPR Severe Accident Evaluation (Reference 8).

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 unit is located in Safeguard Building 1 and is powered from the Class 1E electrical power supply. 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 the 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 severe accident 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 19.2. The analysis concludes that the hydrogen concentration resulting from a severe accident, including uncertainties, is not a threat to containment integrity.

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 radiolytic hydrogen generation was assumed to come from the entire inventory of RCS and IRWST water plus the radiolysis of Hypalon and PVC jacketed cable in the containment. 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. Figure 6.2.5-9 also shows the hydrogen concentration within containment for various levels of PAR operation. When all PARs are functioning, the hydrogen concentration remains below a level of 1.5 percent, therefore, hydrogen concentration does not threaten containment integrity.

6.2.5.3.2 Severe Accident Hydrogen Concentration

Severe accident evaluations are presented in Section 19.2 including a detailed analysis of combustible gas control. For representative and bounding scenarios, those evaluations show that within the containment atmosphere:

- Hydrogen is effectively distributed throughout containment and is removed as addressed in Section 19.2.4.4.1.3. Figure 19.2-5 illustrates the well-mixed atmosphere with regard to hydrogen concentration.

- The global hydrogen concentration in the containment atmosphere does not exceed 10 percent by volume as shown in Figure 19.2-6, and the hydrogen concentration is reduced to levels below 4 percent by volume before the activation of the severe accident heat removal system as displayed in Figure 19.2-9.

- The containment can withstand a global deflagration without loss of integrity as discussed in Section 19.2.4.4.1.4. Figure 19.2-7 shows the adiabatic isochoric complete combustion (AICC) pressure vs. time, which remains below the ultimate capacity pressure for the U.S. EPR containment.

The containment analysis considers hydrogen generated from fuel cladding oxidation and molten core-concrete interaction (MCCI). The analysis assumes that the hydrogen produced during MCCI is released to the containment and not consumed by auto-ignition. This conservative assumption compensates for unaccounted hydrogen, such as hydrogen generated from cladding oxidation outside the active fuel region, or from the oxidation of zinc-based material coatings and aluminum.

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 mixing dampers to open to the safe position.

The CGCS is capable of operating under the conditions expected during design basis accidents and severe accidents. The PARs are not pressure retaining components and are open at the bottom and the top, therefore, are unaffected by localized pressure increase. The mixing dampers, rupture and convection foils open on pressure differential or temperature differential, therefore, their operation is also not affected by localized pressure and temperature increase due to hydrogen combustion.

The CGCS operates effectively in a steam-saturated atmosphere (steam concentration greater than 55 percent by volume), and will function during and after exposure to the environmental conditions created by the burning of hydrogen, including local detonations. Equipment survivability analyses, described in Section 19.2.4.4.5, 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. 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 seven physically separated areas of the containment. Additionally, the signal processing is carried out by separate channel cards installed within the signal processing unit that is 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).

For operational 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.

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 receive a signal to open automatically on high differential pressure between compartments or on high containment pressure. The mixing dampers can also be opened or closed by manual operator action. Position sensors in the main control room indicate the damper position. The mixing dampers fail open on loss of power.

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 substrate
Small PARs	
• Number of units	6
• Nominal hydrogen reduction rate (per PAR)	2.6 lb^m/hr
• Catalyst	Pt / Pd substrate
Hydrogen mixing dampers	
• Number of units	8
• Approximate opening cross section (total)	64 ft^2
• Nominal actuation pressure	0.5 psid or17 psia
Rupture foils	
• Approximate opening cross section (total)	375 ft^2
• Nominal actuation pressure	0.7 psid
Convection foils	
• Approximate opening cross section (total)	480 ft^2
• Nominal actuation pressure	0.7 psid
• 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	7
• 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.

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

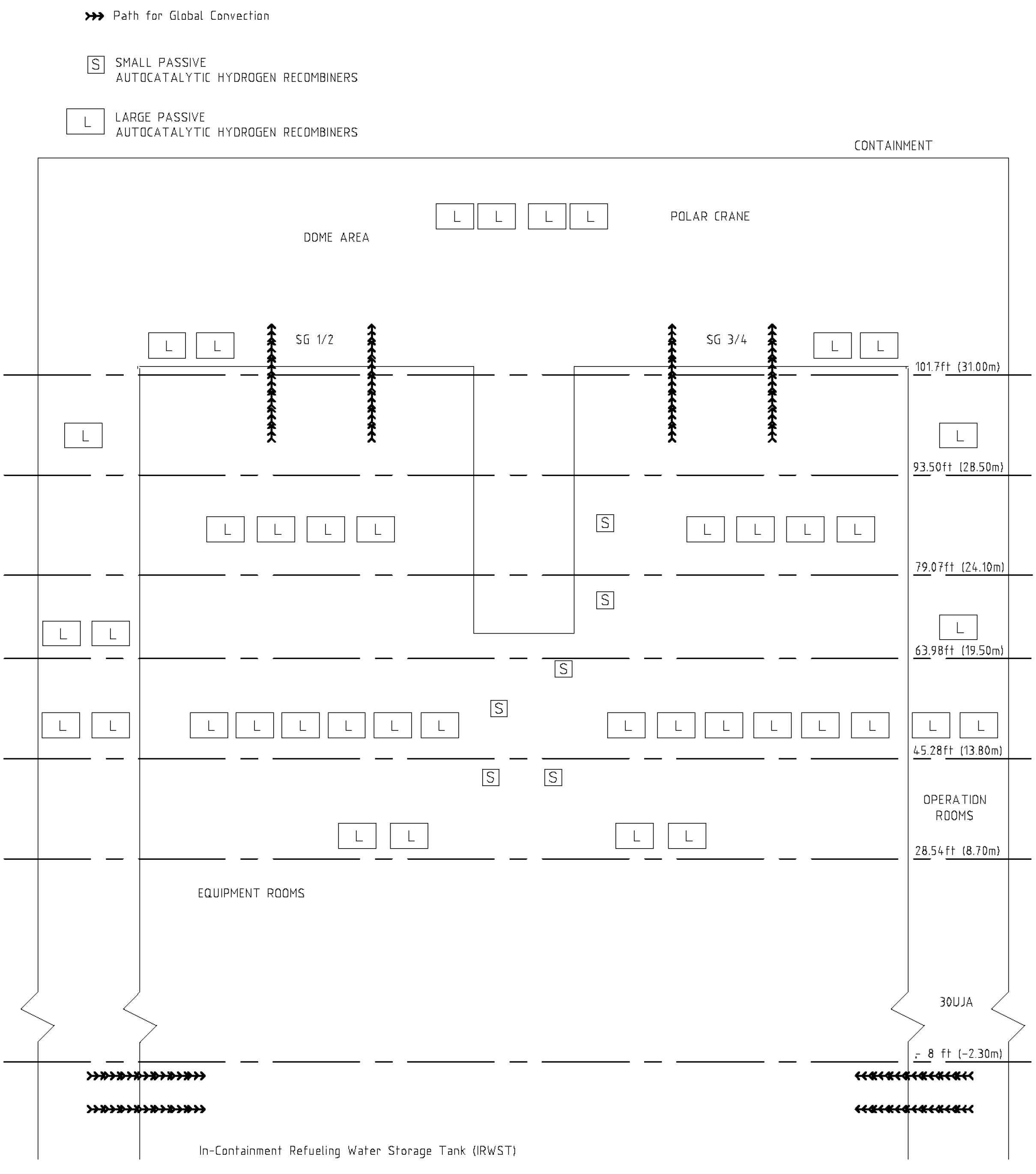


Figure 6.2.5-2—Integrated Production of Hydrogen from 1% Core Oxidation

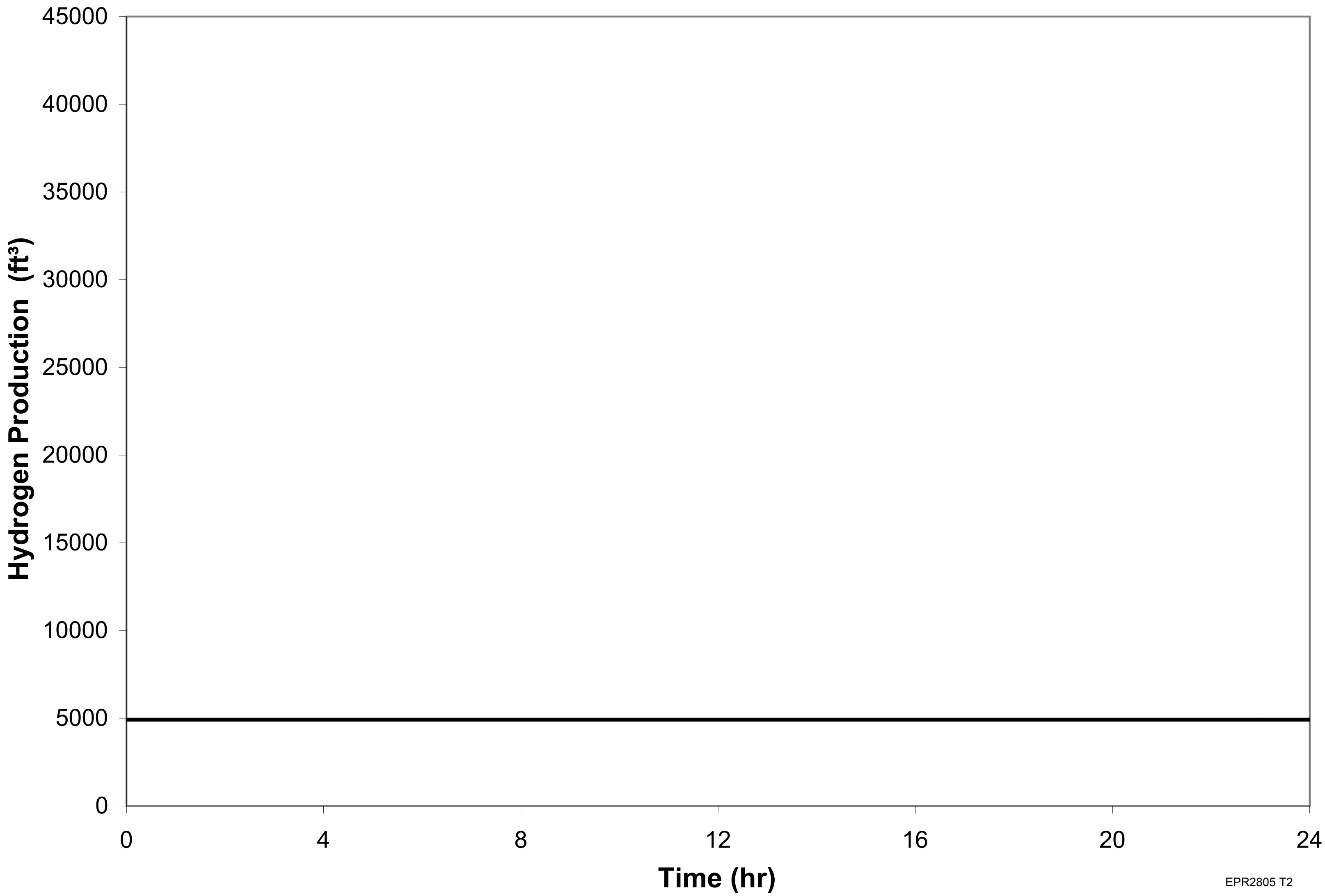


Figure 6.2.5-3—Integrated Production of Hydrogen from Radiolysis

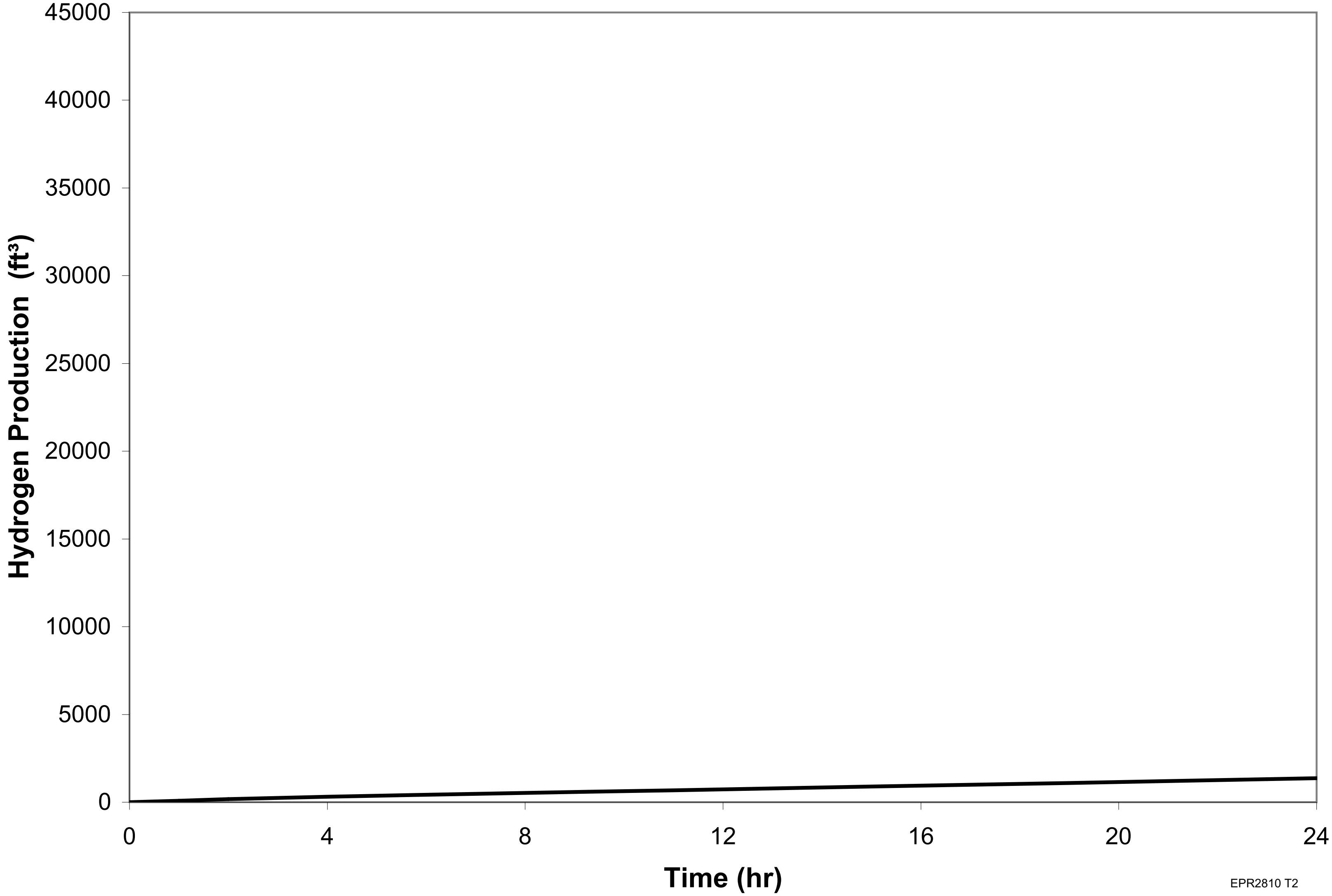


Figure 6.2.5-4—Assumed Hydrogen Generation Rate from Zinc Sources

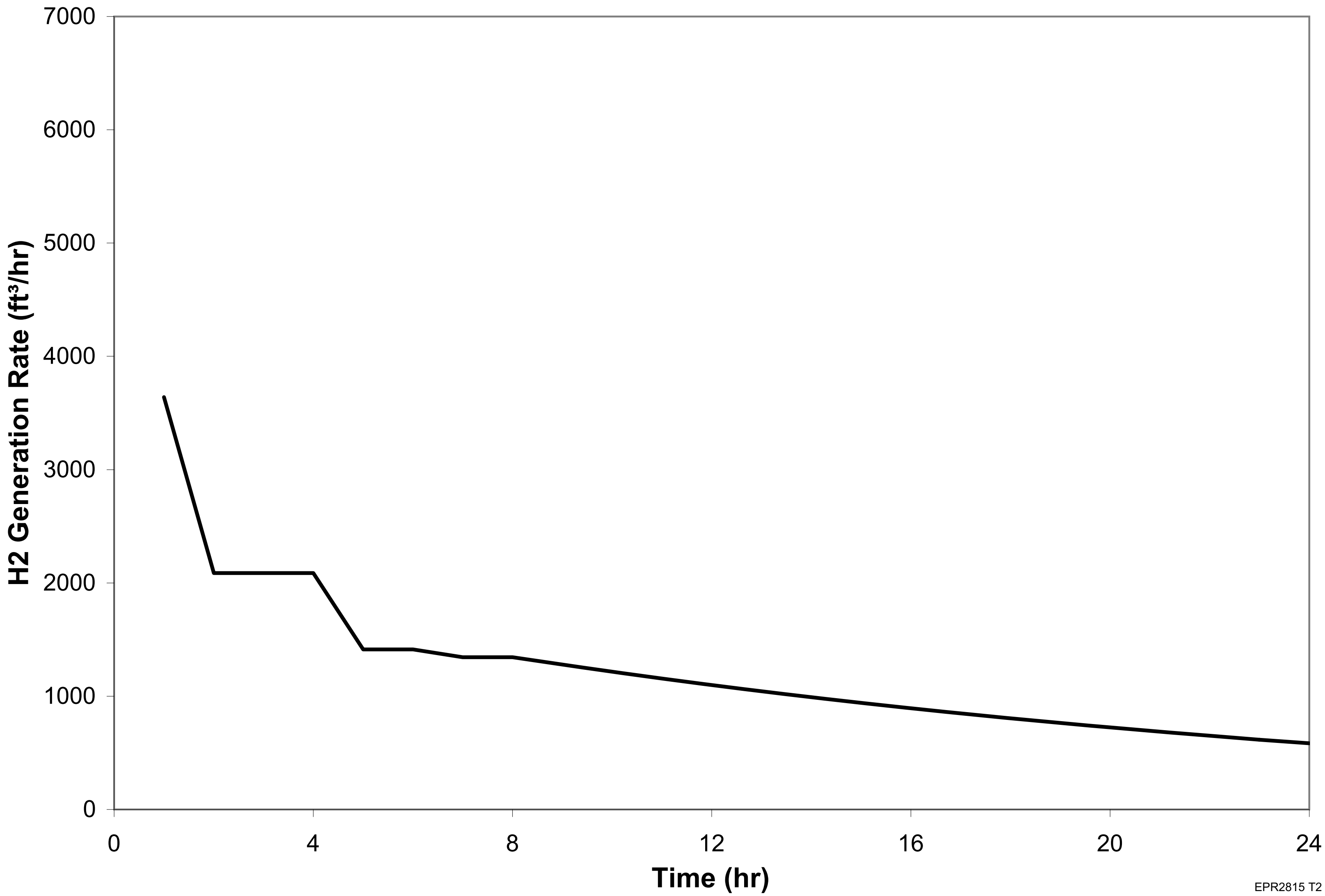


Figure 6.2.5-5—Assumed Hydrogen Generation Rate from Aluminum Sources

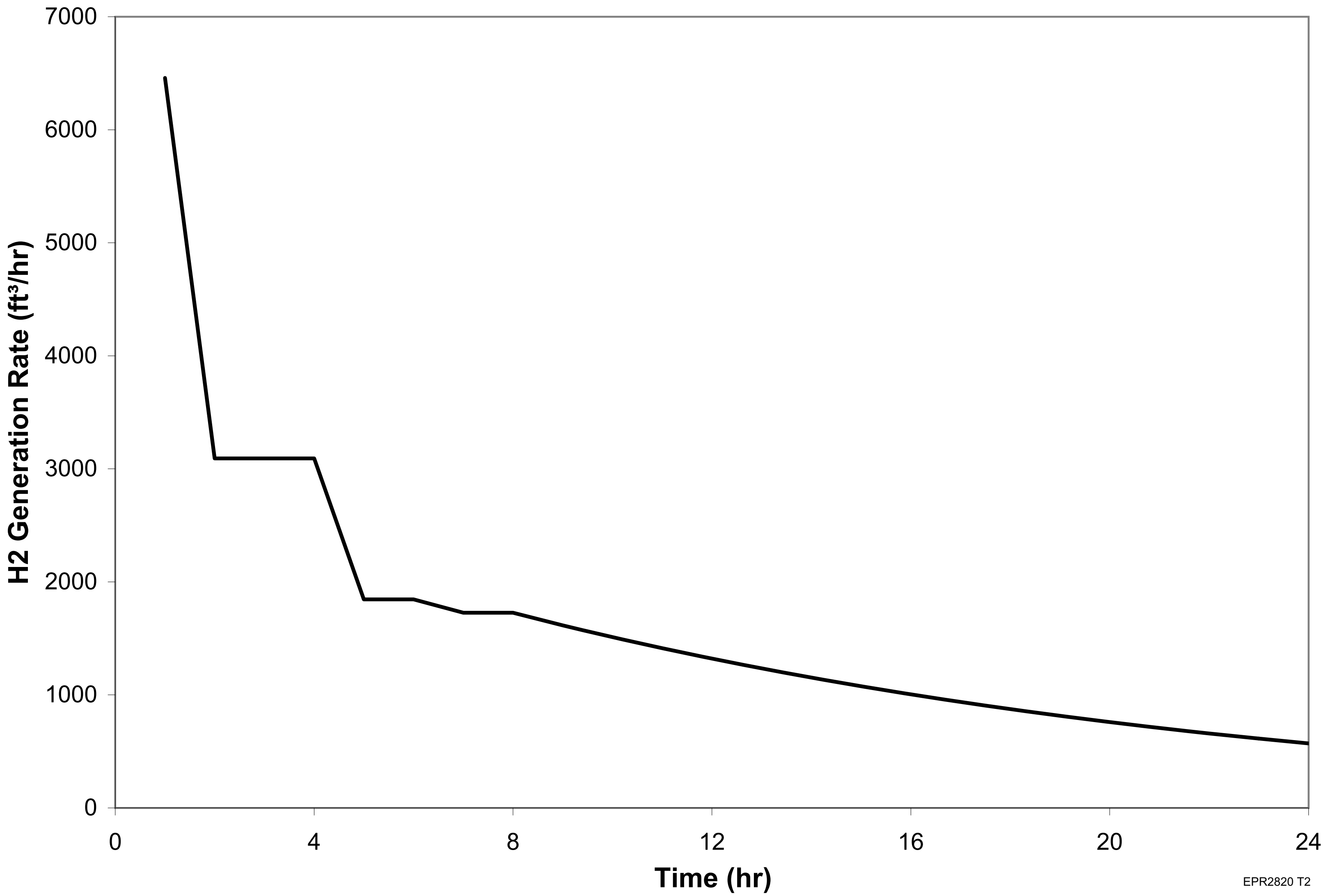


Figure 6.2.5-6—Integrated Production of Hydrogen from Zinc-Based Paint

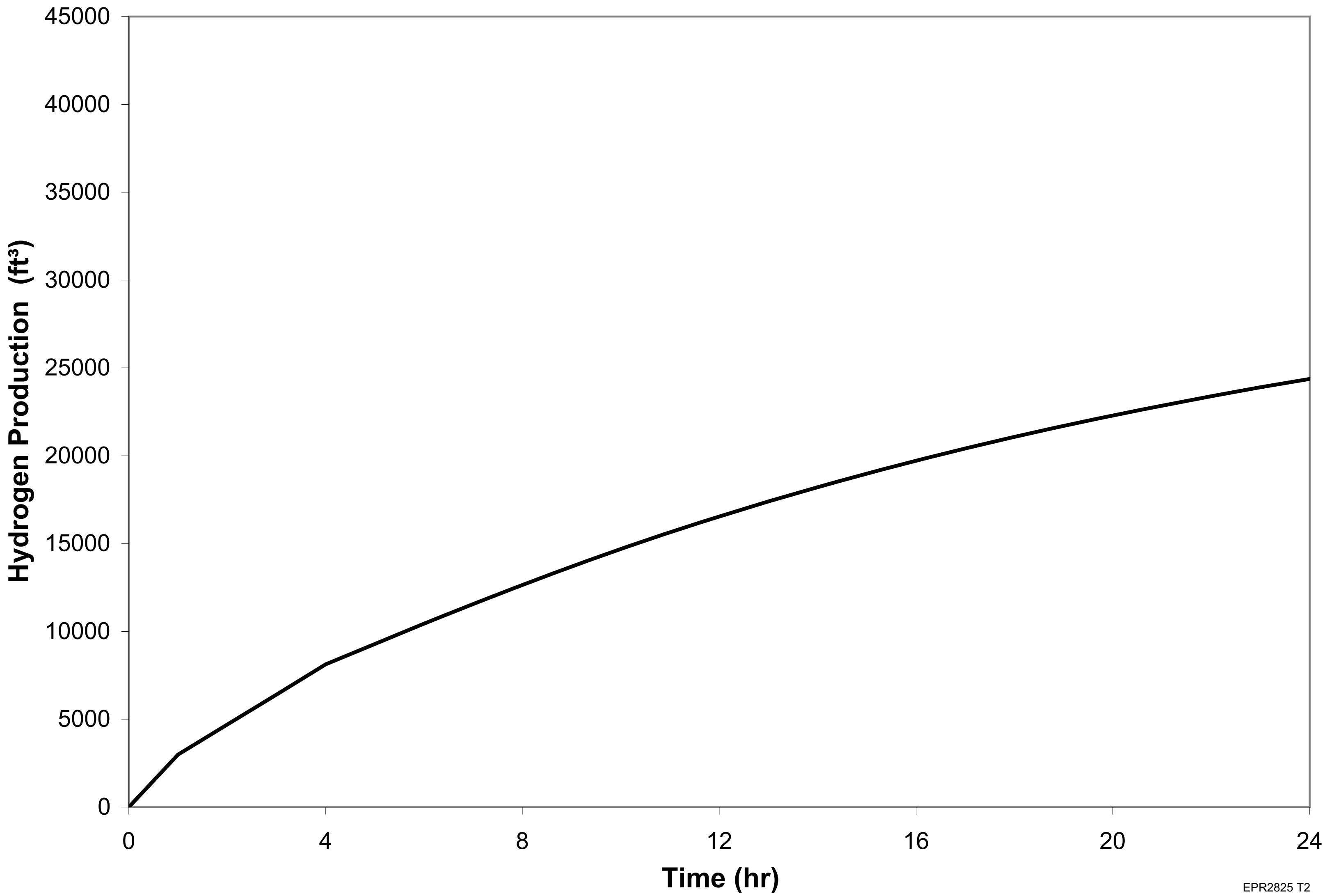


Figure 6.2.5-7—Integrated Production of Hydrogen from Galvanized Steel

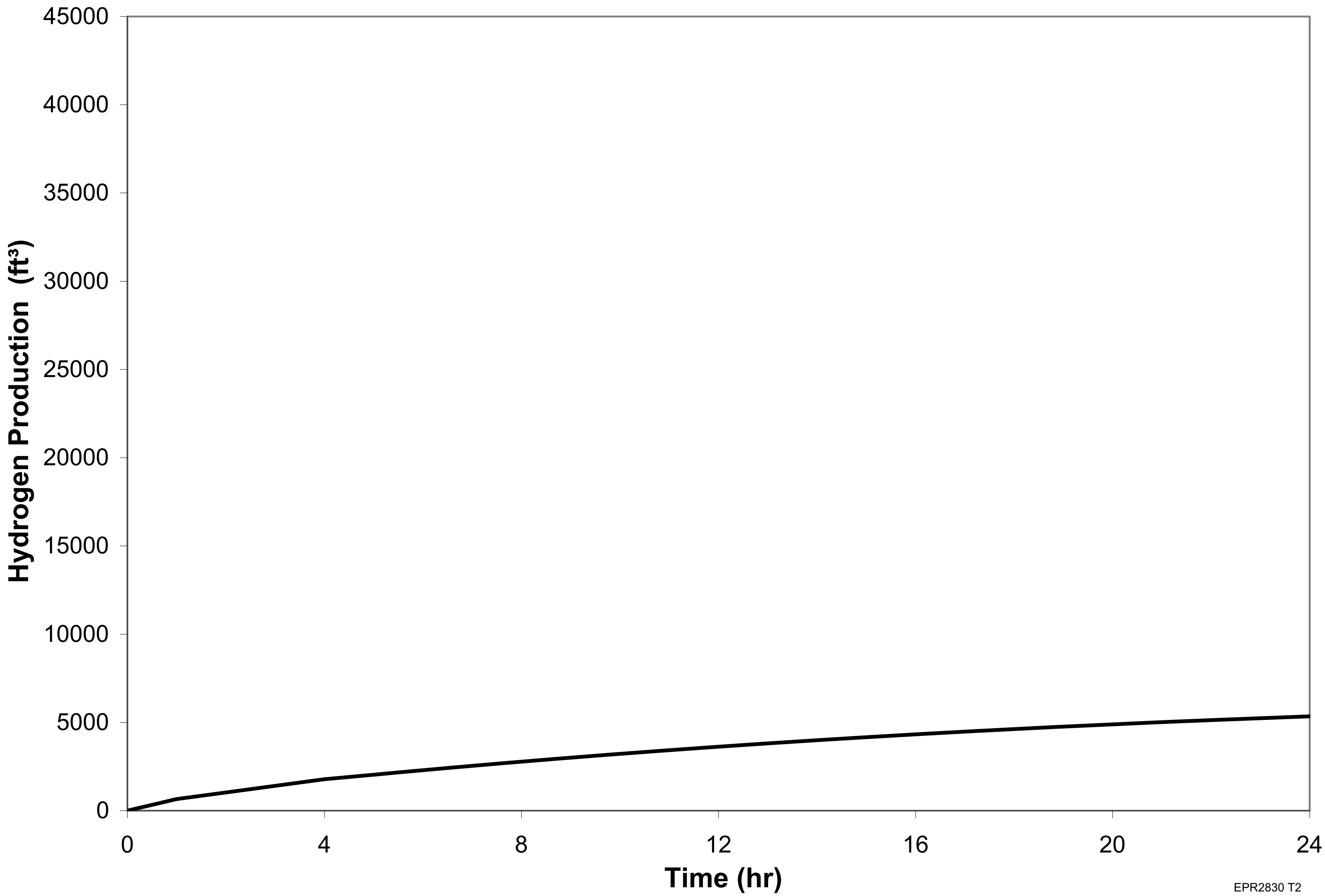


Figure 6.2.5-8—Integrated Production of Hydrogen from Aluminum

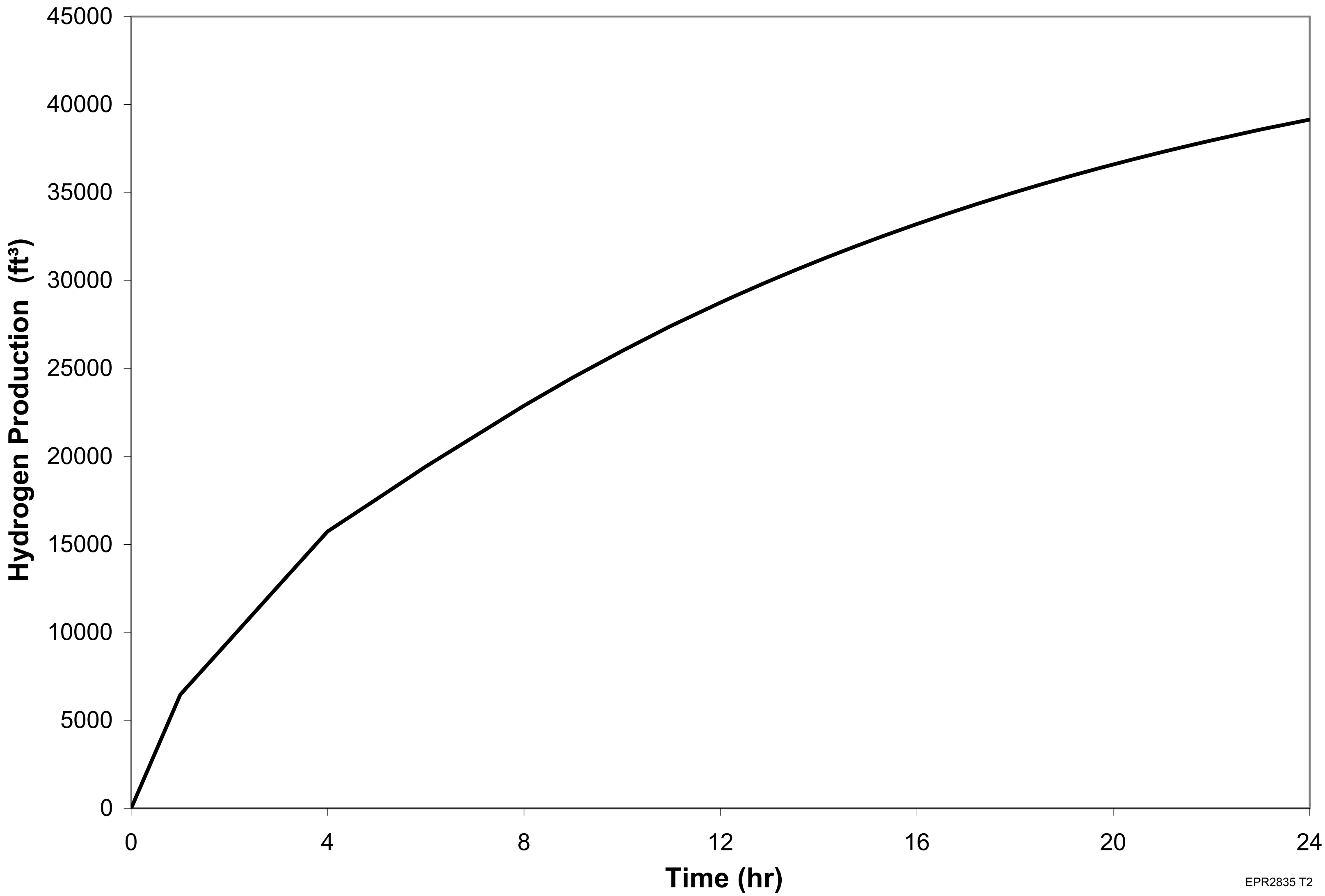
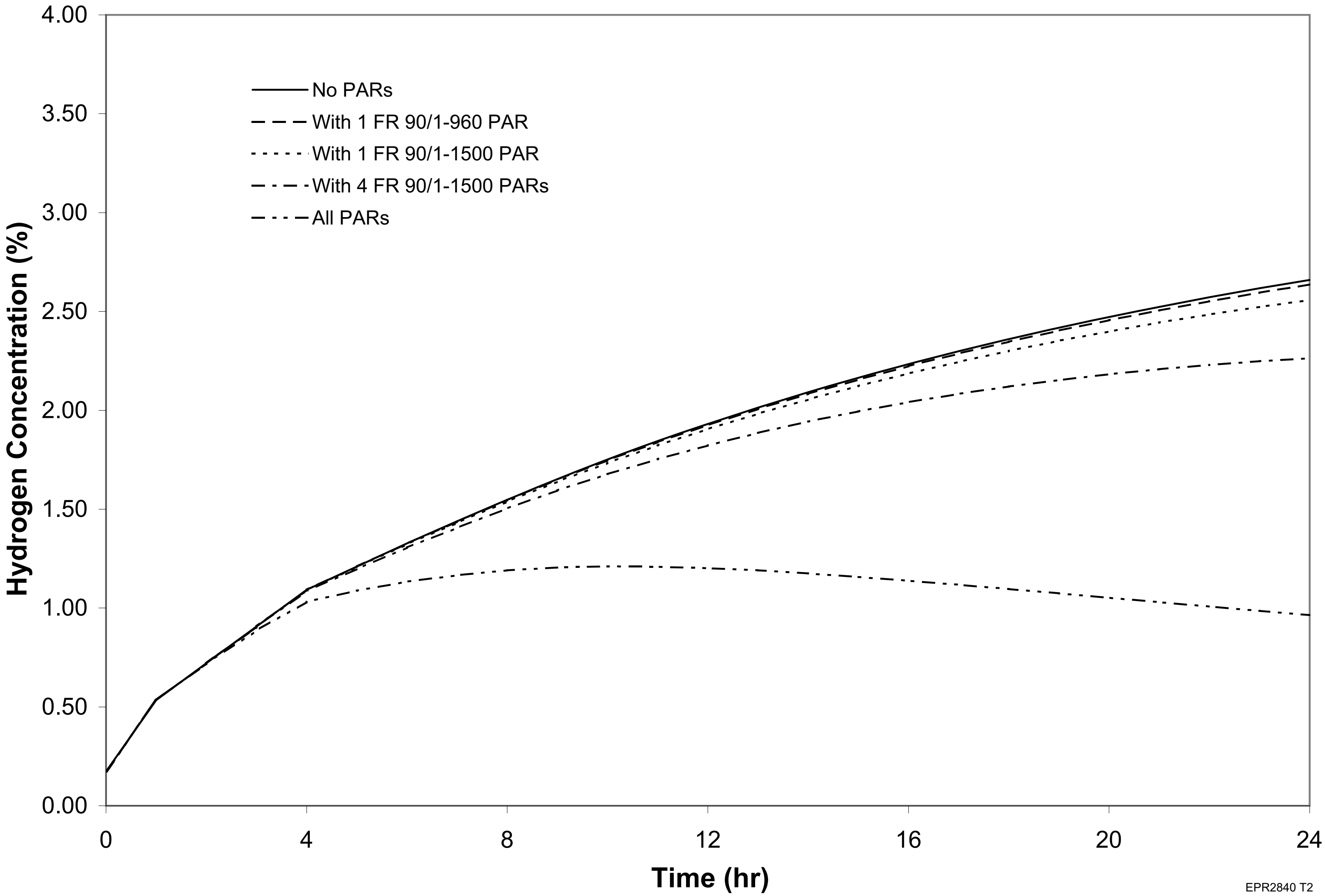


Figure 6.2.5-9—Concentration of Hydrogen in the Containment



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