

## **Appendix-A**

# **Severe Accident Analysis Report for Hydrogen Issue**

## **TABLE OF CONTENTS**

1.0	Background and Objectives .....	A-1
1.1	Background.....	A-1
1.2	Objectives .....	A-2
2.0	Hydrogen Combustion Phenomena .....	A-3
2.1	Basics of Hydrogen Combustion .....	A-3
2.2	Ignition Source.....	A-4
2.3	Flammability Limits and Combustion Pressures .....	A-4
2.4	Incomplete Combustion .....	A-9
2.5	Flame Acceleration (FA) and Detonation .....	A-17
2.5.1	Deflagrations .....	A-17
2.5.2	Detonations .....	A-17
2.5.3	Deflagration to Detonation Transition (DDT).....	A-18
2.6	Detonation Cell Width.....	A-18
2.7	Correlations for Deflagration to Detonation Transition .....	A-21
2.8	Experimental Database for Flame Acceleration Criterion and Onset of Detonation Criterion.....	A-28
2.9	Effects of H <sub>2</sub> Stratification on Deflagrations.....	A-30
2.10	Hydrogen Mixing and Distribution.....	A-38
2.10.1	Experiments.....	A-38
2.10.2	Code Prediction .....	A-38
2.10.3	Subnode Physics Model in MAAP4.....	A-41
2.11	Passive Auto-Catalytic Recombiners .....	A-45
2.12	Relationship to Containment Failure Mechanisms .....	A-45
3.0	Methodology.....	A-46
3.1	Methodology for Non-Detonative Slow Combustion Evaluation.....	A-46
3.2	Methodology for Local Hydrogen Accumulation Evaluation.....	A-46

3.3	Methodology for DDT Evaluation.....	A-47
3.3.1	Criterion for Flame Acceleration.....	A-47
3.3.1.1	MAAP4 Calculations of Expansion Ratios.....	A-49
3.3.2	Criterion for Deflagration-to-Detonation Transition Potential .....	A-50
3.3.2.1	Correlation for Detonation Cell Width .....	A-51
3.3.2.2	Other Correlation for Detonation Cell Width.....	A-52
3.3.2.3	Detonation Cell Width for CO .....	A-53
3.3.2.4	Characteristic Length of Compartments .....	A-57
4.0	Evaluation and Results Summary .....	A-59
4.1	AICC Pressure Evaluation and Summary .....	A-59
4.2	Local Hydrogen Accumulation Evaluation and Summary .....	A-59
4.3	DDT Evaluation and Summary .....	A-61
5.0	Conclusions.....	A-67
6.0	References .....	A-68

**LIST OF TABLES**

Table 2-1 Experiments Used in Correlations for Flame Acceleration Criterion .....	A-31
Table 2-2 Experiments Used in the $L/\lambda$ Correlation for Onset of Detonations .....	A-33
Table 2-3 References Cited in Tables 2-1 and 2-2 .....	A-34
Table 3-1 Critical Expansion Ratio as a Function of Initial Temperature .....	A-48
Table 3-2 Fitting Equation for Critical Expansion Ratio .....	A-48
Table 4-1 Summary of Locations with DDT Potential and Required Conditions .....	A-64



## LIST OF FIGURES

Figure 2-1 Minimum Ignition Energy for Hydrogen Deflagrations .....	A-6
Figure 2-2 Type of Ignition Source Energies with Sources Required for Detonation by Direct Energy Deposition .....	A-7
Figure 2-3 Comparison of Ignition Source Energies with Sources Required for Detonation by Direct Energy Deposition .....	A-8
Figure 2-4 Flammability Domain for upward Propagation for H <sub>2</sub> -Air- H <sub>2</sub> O vapor mixtures. ....	A-10
Figure 2-5 Comparison of Lower Flammability Limits (LFL) and Upper Flammability Limits (UFL) of hydrogen-air-mixtures as a function of initial temperature .....	A-11
Figure 2-6 Theoretical adiabatic, constant volume combustion pressure ratios of hydrogen-air mixtures .....	A-12
Figure 2-7 Adiabatic, Isochoric, Complete Combustion (AICC) pressures for various containment initial conditions .....	A-13
Figure 2-8 Degrees of Combustion in Hydrogen Air Steam Mixtures .....	A-14
Figure 2-9 Hydrogen concentration during incomplete burning .....	A-15
Figure 2-10 Combustion Completeness for Nevada Test Site Premixed Combustion Tests .....	A-15
Figure 2-11 Comparative pressure profiles for three 8% (nominal) hydrogen combustion tests having different precombustion steam concentrations. ....	A-16
Figure 2-12 Detonation pressure ratios and speed for hydrogen-air mixtures .....	A-19
Figure 2-13 Measured values (McGrill, Sandia) of the detonation cell width ( $\lambda$ ) as a function of hydrogen concentration .....	A-20
Figure 2-14 Detonation Cell Width Data (Sandia HDT) and Predictions (Shepherd Model) .....	A-23
Figure 2-15 Detonation cell width as a function of temperature.....	A-24
Figure 2-16 Deflagration-to-detonation transition (DDT) results from the FLAME facility at Sandia .....	A-25
Figure 2-17 Detonation Propagation and Transmission Correlations for Simple Geometries .....	A-26
Figure 2-18 Illustration of Characteristic Size L for Channels with Obstacles and Varying Blockage Ratio .....	A-27
Figure 2-19 Limits of Flame Acceleration for Hydrogen-Air-Steam Mixtures at 375 K and 1 atm .....	A-35
Figure 2-20 Combustion regime as function of expansion ratio $\sigma$ and Zeldovich number $\beta$ for hydrogen-lean mixtures (i.e., $\beta(\text{Le}-1) < -2$ ).....	A-35
Figure 2-21 Combustion regime as function of expansion ratio $\sigma$ and Zeldovich number $\beta$ for hydrogen-rich (including stoichiometric) mixtures (i.e., $\beta(\text{Le}-1) > -2$ ).....	A-36

Figure 2-22 Expansion ratio and flame acceleration limits of hydrogen-air-steam mixtures at 373 K .....	A-36
Figure 2-23 $L/\lambda$ correlation for onset of detonations.....	A-37
Figure 2-24 Hydrogen distribution and mixing tests.....	A-40
Figure 2-25 Gas temperatures at 0 m floor; comparison of MAAP4 results to HDR Test E11.2 data .....	A-42
Figure 2-26 Hydrogen/helium concentration in the upper dome; comparison of MAAP4 results to HDR Test E11.2 data .....	A-43
Figure 2-27 Hydrogen/helium concentration at 10 m floor; comparison of MAAP4 results to HDR Test E11.2 data .....	A-44
Figure 3-1 Example of Expansion Ratio Calculated by STANJAN Code.....	A-50
Figure 3-2 Calculation Results of Detonation Cell Width from Eq. 3-15 vs. Experimental Data as a Function of Hydrogen Concentrations at Various Temperatures.....	A-54
Figure 3-3 Calculation Results of Detonation Cell Width from Eq. 3-15 vs. Experimental Data as a Function of Steam Concentrations at various hydrogen concentrations .....	A-54
Figure 3-4 Detonation Cell Width (cm) plotted in $[H_2]_{dry}$ - $[H_2O]$ Plane using Eq. 3-15 .....	A-55
Figure 3-5 Comparison of Detonation Cell Width given by Eq. 3-15 and Gavrikov Method .....	A-56
Figure 3-6 Guidelines for Determination of Compartment Characteristic Length .....	A-58
Figure 4-1 Mole Fraction of Hydrogen in the Dome Region for LLOCA .....	A-65
Figure 4-2 Mole Fraction of Hydrogen in the Dome Region for SLOCA .....	A-65
Figure 4-3 Mole Fraction of Hydrogen in the Dome Region for SBO-3way valve .....	A-66
Figure 4-4 Mole Fraction of Hydrogen in the Dome Region for TLOFW-3way valve .....	A-66

## 1.0 Background and Objectives

### 1.1 Background

The potential failure of a nuclear power plant containment due to an energetic hydrogen burn has been a subject of concern for the nuclear regulatory agencies and the nuclear industry worldwide. The concern is that hydrogen, evolved during a core damage event, could accumulate in the containment building and subsequently ignite. If the combustion is energetic enough to fail the containment, the timing and uncertainties in location of the containment shell failure have two potentially important ramifications regarding the radiological source term. First, if the hydrogen burns early and causes containment failure before or shortly after vessel failure, natural fission product deposition mechanisms in the containment do not have sufficient time to significantly affect (reduce) the masses of fission products that could be released through the failure location. Second, fission products carried by gas flows from the failed containment would result in radiological releases to the environment.

The USNRC regulations clearly establish safety requirements related to the potential of hydrogen combustion or detonation as listed below:

#### 10CFR50.34(f)(3)(v)(A)(1)

Containment integrity will be maintained during an accident that releases hydrogen generated from 100% fuel clad metal-water reaction accompanied by hydrogen burning. For concrete containments, containment integrity is maintained by meeting the requirements of the ASME Boiler Pressure Vessel Code, Section III, Division 2 Subsubarticle CC-3720, Factored Load Category, considering pressure and dead load alone.

#### 10CFR50.34(f)(2)(ix)(A) and (B)

The hydrogen control system and associated systems shall provide, with reasonable assurance, that

(A) Uniformly distributed hydrogen concentrations in the containment do not exceed 10% during and following an accident that releases an equivalent amount of hydrogen as would be generated from a 100% fuel clad metal-water reaction, or that the post-accident atmosphere will not support hydrogen combustion.

(B) Combustible concentrations of hydrogen will not collect in areas where unintended combustion or detonation could cause loss of containment integrity or loss of appropriate mitigating features.

#### 10CFR50.44(c)(1),(2) and (3)

(1) *Mixed atmosphere*. All containments must have a capability for ensuring a mixed atmosphere during design-basis and significant beyond design-basis accidents.

(2) *Combustible gas control.* All containments must limit hydrogen concentrations in containment during and following an accident that releases an equivalent amount of hydrogen as would be generated from a 100 percent fuel clad-coolant reaction, uniformly distributed, to less than 10 percent (by volume) and maintain containment structural integrity and appropriate accident mitigating features.

(3) *Equipment Survivability.* Containments that do not rely upon an inerted atmosphere to control combustible gases must be able to establish and maintain safe shutdown and containment structural integrity with systems and components capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen. Environmental conditions caused by local detonations of hydrogen must also be included, unless such detonations can be shown unlikely to occur. The amount of hydrogen to be considered must be equivalent to that generated from a fuel clad-coolant reaction involving 100 percent of the fuel cladding surrounding the active fuel region.

## **1.2 Objectives**

There are three main objectives for this report:

1. To identify the different types of hydrogen combustion that can take place in the APR1400 containment and determine the limiting conditions for combustion.
2. To evaluate how the containment can be affected by the hydrogen combustion.
3. To provide a technical basis for determining whether the likelihood of containment rupture due to hydrogen combustion is big enough to consider it a credible cause of containment failure.

## **2.0 Hydrogen Combustion Phenomena**

This section provides an up-to-date review of current knowledge on hydrogen combustion phenomena in relation to nuclear plant safety during severe accidents. The emphasis of this review is on establishing the technical basis for evaluation of the potential for detonations.

### **2.1 Basics of Hydrogen Combustion**

Hydrogen combustion, or burning, is the result of a chemical reaction between gaseous hydrogen and gaseous oxygen. The products of this reaction are steam and energy; the energy is liberated as light and heat. Necessary conditions for hydrogen combustion are the presence of sufficient amounts of hydrogen and oxygen and the presence of an ignition source or trigger.

With a volume filled with only hydrogen and oxygen gases, minimum concentrations of hydrogen and oxygen are required for hydrogen combustion to occur. A mixture containing too little hydrogen to burn is called "lean", while a mixture containing too little oxygen to burn is called "rich" since there is an excess of fuel. The presence of another gas that does not participate in the combustion reaction (such as steam or nitrogen) acts to inhibit combustion. As the concentration of the inert gas increases, the threshold hydrogen concentration for lean hydrogen combustion increases, while the threshold concentration for rich hydrogen combustion decreases. Extensive research has been performed for numerous combinations of hydrogen, oxygen, and inert gases to map out the hydrogen and oxygen concentrations that are combustible. These maps display the flammability limits.

A trigger is generally necessary to initiate burning of a flammable hydrogen and oxygen mixture. Typically a spark is sufficient to ignite a flammable mixture. The required trigger energy decreases as the hydrogen gas temperature increases, until a threshold temperature is reached. Above this temperature the mixture itself is energetic enough to self-trigger (or auto-ignite). This threshold is therefore referred to as the minimum autoignition temperature.

With a volume containing a flammable mixture of hydrogen and oxygen and a trigger that initiates combustion, the energy release depends on the mass of hydrogen consumed by the chemical reaction. The combustion of one kmole of hydrogen releases 244 MJ of energy. Ignition of gas mixtures with compositions near the flammability limits have too little hydrogen or oxygen for the flame front to propagate throughout the entire volume and consume all of the available hydrogen; such burns are called "partial" burns. As the hydrogen concentration moves away from the flammability limits the associated burns become more complete. When a mixture of hydrogen and oxygen is well within the flammability limit an ignition will cause a complete combustion of the limiting reactant. This is called a "global burn." Global burns yield the maximum energy release that can be obtained by combustion of a given flammable mixture.

Hydrogen-air-steam mixtures can burn in several modes: diffusion flames, slow and accelerated deflagrations, and detonations. Combustion of hydrogen that has not been well mixed with oxygen results in a diffusion flame. Diffusion flames are stationary (standing flames) and the primary consequences are thermal loads on nearby structures and equipment. If hydrogen has mixed well with oxygen, the combustion involves flames moving or propagating through the combustible

mixture. Two types of premixed flame propagation can occur. One is called deflagration, while the other is called detonation. Deflagration is a combustion process in which the flame front moves at subsonic (for slow deflagrations) or sonic (for accelerated deflagrations) velocity with respect to the unburned gas. Detonation is defined as supersonic propagation of the flame front.

It is important to understand how the velocity of the combustion front affects the system. The pressure in a subsonic deflagration cannot exceed the Adiabatic, Isochoric, Complete Combustion (AICC) pressure value, which can be readily calculated by equilibrium thermodynamics. Pressure is then assumed to be uniformly distributed since the flame is moving slowly with respect to the pressure waves. In a detonation, transient overpressures can exceed this AICC value by a factor of three or more, and pressure can vary significantly across the detonation front. Calculating the maximum dynamic loads from accelerated flames and detonations requires a specialized shock wave physics model.

## 2.2 Ignition Source

For any type of combustion, an ignition source is required to provide a minimum amount of energy to a combustible mixture in order to ignite it. Relatively weak sources such as static discharge and sparks can cause ignition. Figure 2-1 presents the minimum ignition energy for hydrogen deflagrations. For the case of 13% by volume of hydrogen in air, approximately 0.07 mJ is sufficient to ignite a hydrogen burn. Figure 2-2 compares various potential ignition sources energies including a simple match. A match burning for one second can release one joule of energy which is over four orders of magnitude more energy than that required to initiate a hydrogen burn. The high energy sources shown in Figure 2-3 are not sufficient to directly initiate shock waves to further drive detonations, but are sufficient to cause a deflagration. As discussed in Section 2.5, a deflagration can develop into a detonation if certain conditions are met.

High temperatures lead to slow volumetric oxidation, and very high temperatures (~960 K) can cause immediate ignition, known as auto-ignition. Auto-ignition is most likely to occur for severe accident sequences that release very high temperature hydrogen-rich gases into non-inerted regions.

## 2.3 Flammability Limits and Combustion Pressures

Flammable conditions are 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 (once ignited) will propagate. There is relatively good information on flammability limits of hydrogen-air-steam mixtures at temperatures less than 149 °C [Reference 19, 32, 3]. At higher temperatures, such information is incomplete. For this reason, a systematic extrapolation of flammability limits to higher temperatures, as well as calculations of flammability limits of different gas compositions such as those used in the MAAP4 code [Reference 17], is a reasonable approach. Classical limits (i.e. derived from practical experience and experimentation) for flammability and AICC maximum equilibrium final pressure are presented in Figure 2-4 and Figure 2-5. In more recent flammability charts [Reference 6], the flammability limits for hydrogen/air/steam mixtures are drawn slightly wider into higher steam concentrations than that in Figure 2-4. The region of concern generally lies below the line of stoichiometric mixtures, where

hydrogen is the limiting reactant. The minimum amount of hydrogen necessary for combustion is slightly over 4% in dry air. The minimum oxygen concentration necessary for combustion is about 5% in dry air, corresponding to about 75% hydrogen. Addition of steam to any mixture of hydrogen and air reduces the hydrogen volumetric concentration and increases the required threshold concentration for combustion.

Figure 2-6 presents the AICC overpressure ratio resulting from combustion of hydrogen in air and indicates classical deflagration and detonation limits [Reference 52]. However, the detonation limits shown in this figure are too simplistic for reactor applications because detonation limits depend on a number of parameters in complex and incompletely understood ways.

The effect of steam on post-combustion pressure is quantified for various initial saturation conditions as a function of hydrogen concentration in Figure 2-7. In this figure, the initial pressure is calculated by adding the partial pressure of hydrogen and steam to a humid air mixture originally at 1.0 atm total pressure and 300 K.

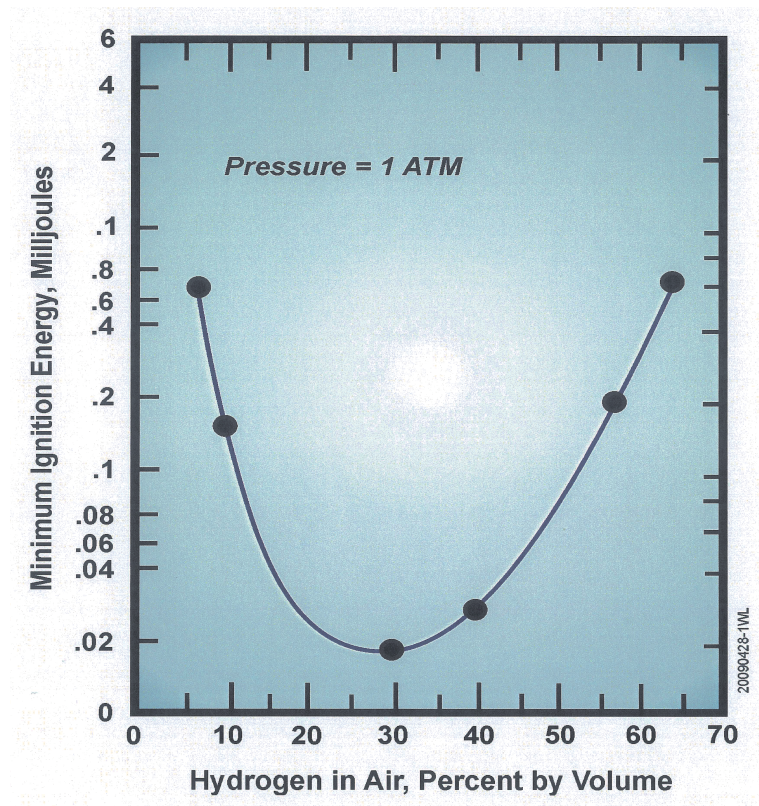


Figure 2-1 Minimum Ignition Energy for Hydrogen Deflagrations [Reference 7]



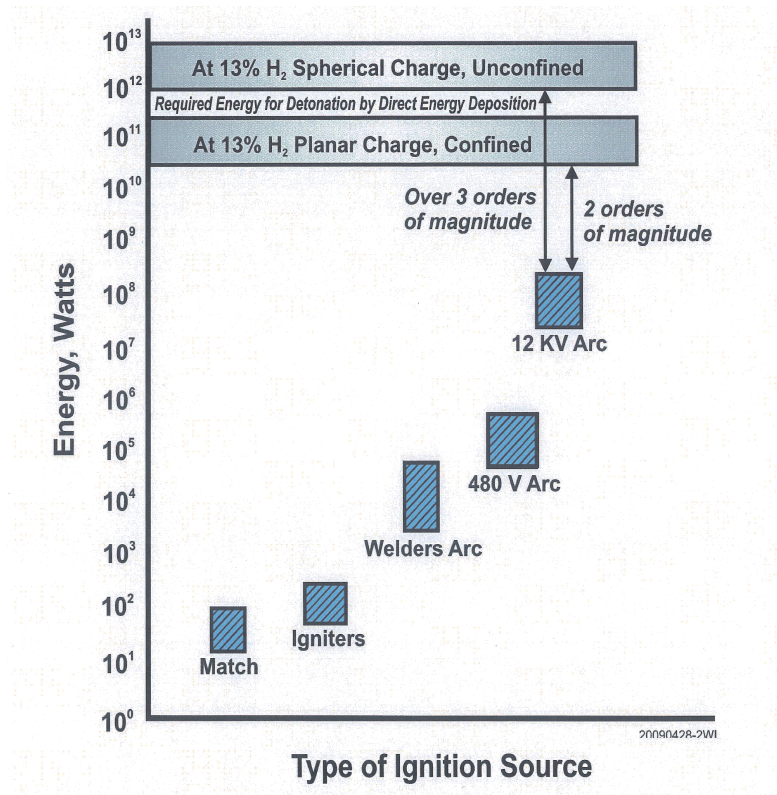


Figure 2-2 Type of Ignition Source Energies with Sources Required for Detonation by Direct Energy Deposition [Reference 16]

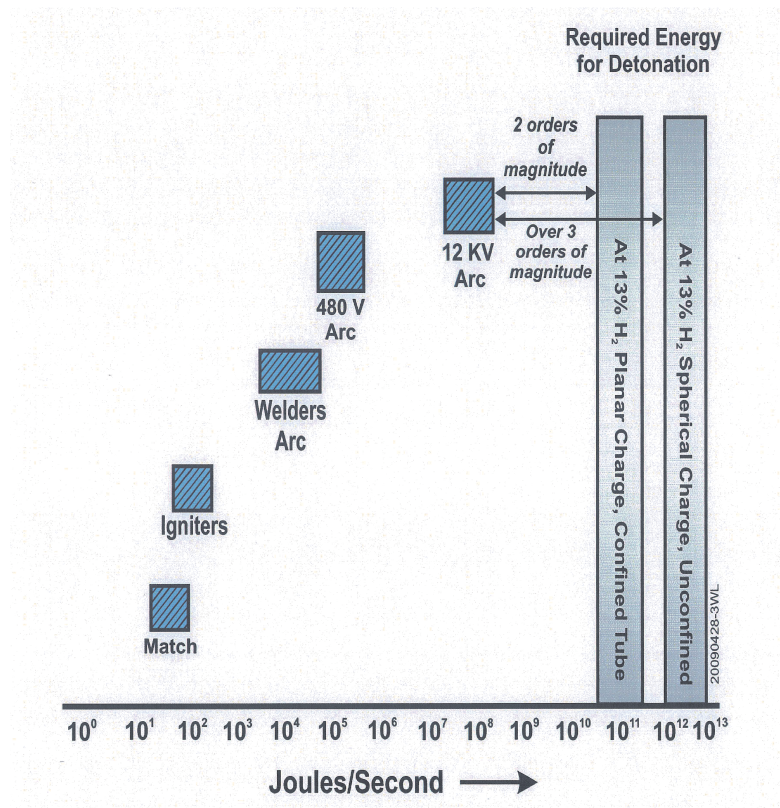


Figure 2-3 Comparison of Ignition Source Energies with Sources Required for Detonation by Direct Energy Deposition [Reference 16]