Safety on Hydrogen Explosion in Nuclear Power Plants

–Explosion Prevention and Protection Based on the Concept of System Safety–

Nagaoka University of Technology, **Satoshi Kadowaki**

To prevent hydrogen explosions at nuclear power plants, adequate knowledge of hydrogen's combustion characteristics and the types of explosions must be acquired. In particular, an understanding of the following two types of explosions is vital: deflagrations and detonations. Reasonable explosion prevention and protection measures must be sought with reference to the relevant European standards. More specifically, the measures required are the identification of hazard sources, the conducting of risk assessments, and the pursuit of risk reduction. These measures are based on the concept of system safety. Risks should be rationally reduced to ensure safety.

I. Introduction

In March 2011, the Tohoku earthquake triggered hydrogen explosions at the Fukushima Daiichi Nuclear Power Plant, causing severe damage to the surrounding area. This experience was a fresh reminder of how explosion prevention and protection measures are vital for nuclear power plants. It also highlighted the need for the nuclear sector to acquire sufficient knowledge of the combustion characteristics of hydrogen and other flammable gases and the types of explosions.

Against this background, this commentary outlines differences between a deflagration and a detonation as two types of explosions. It explains how flame propagation accelerates during the deflagration process from the perspective of intrinsic instability. In addition, rational measures for explosion prevention and protection based on the concept of system safety are described with reference to the relevant European standards.

II. Explosions

1. Types of Explosions

According to Physics and Chemistry Dictionary 1), "An explosion is a rapid increase or

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release of pressure associated with the rupturing of a container or a rapid expansion of gas accompanied by a blast sound or rupture. Explosions of vacuum flasks, boilers, and volcanoes are physical ruptures, while explosions of gases, dust, gunpowder, and the like are chemical explosions.” According to this definition, the hydrogen explosions experienced at the Fukushima Daiichi Nuclear Power Plant are regarded as chemical explosions. The dictionary further explains that, “Chemical explosions result from intense combustion, decomposition, or other exothermic reactions.” This commentary focuses on chemical explosions to outline the types of explosions.

An explosion can be understood by studying what happens when hydrogen or another flammable gas is premixed with air or another gaseous oxidant. Such a gaseous premixture can explode in one of two ways: deflagrations or detonations. The most distinct difference between these two types of explosions is their propagation velocities in that the former is subsonic while the latter is supersonic.

Table 1 presents the typical characteristics of deflagrations and detonations 2). This comparison assumes a steady one-dimensional flow, wherein M denotes the Mach number (i.e., the ratio of the velocity to that of sound) while u, p, and ρ respectively denote the velocity, pressure, and density. The subscript 1 represents an upstream (unburned) premixture, while the subscript 2 represents a downstream (burned) combustion gas. Table 1 clearly shows that deflagrations and detonations have completely distinct characteristics. Accordingly, the first step is to identify which type of explosion should be subject to close investigation. In general, detonations are considered the more destructive type of explosion.

Table 2 shows the maximum burning velocity for each gaseous premixture 3) at room temperature through a deflagration under atmospheric pressure. Air is employed as a gaseous oxidizer here. Hydrogen deflagration has the highest maximum burning velocity. The upstream and downstream pressures are almost identical since the Mach number of burning velocity is much smaller than 1. Similar to chemical reactions, mass diffusion and heat conduction play important roles in a deflagration.

Table 1 Characteristics of deflagrations and detonations

	Deflagration	Detonation
M_1	0.0001 ~ 0.03	5 ~ 10
u_2 / u_1	4 ~ 16	0.4 ~ 0.7
p_2 / p_1	≈ 0.99	13 ~ 55
ρ_2 / ρ_1	0.06 ~ 0.25	1.4 ~ 2.5

Table 2 Maximum burning velocity in a deflagration

Flammable gas	Maximum burning velocity u_1 (m/s)	Equivalence ratio
Hydrogen	2.912	1.80
Acetylene	1.540	1.30
Ethylene	0.750	1.15
Methane	0.370	1.06
Ethane	0.401	1.14
Propane	0.430	1.14
Butane	0.379	1.13
Carbon monoxide	0.430	2.57

Combustion of a gaseous premixture requires a flammable gas to be concentrated in a certain range within the flammability limits. Such a flammability range is defined by a lower boundary called the "lower flammability limit" and an upper boundary called the "upper flammability limit." This concentration range between these limits corresponds to flammability range. **Table 3** compares the flammability limits (lower and upper) for premixtures of air and different flammable gases 3). Similar to acetylene, hydrogen has a broad flammability range so it needs to be handled with particular care.

Detonations can be further divided into several categories. The most common is CJ detonations, which are named after two scientists, Chapman and Jouguet. **Table 4** presents the stoichiometric characteristics of CJ detonations for different gaseous premixtures 3). Compared to a deflagration, the propagation velocities of CJ detonations are apparently an order of magnitude higher and the pressure of the combustion gases becomes extremely high.

Any detonation of a gaseous premixture requires the concentration of the flammable gas to fit within a certain range (between detonation limits). This range is known to be narrower than the flammability range for any premixture (see Table 3). Any propagation of a deflagration in a gaseous premixture within the detonation limits is accelerated by an increase in the flame surface area to shift further toward a detonation. This phenomenon is called "deflagration-to-detonation transition" (DDT). Many studies have been conducted to investigate this important phenomenon. The transition is usually caused by increased disturbance of a flame surface. The accelerated propagation generates weak pressure waves on the unburned side of the gas. Overlapping each other, these waves produce a strong pressure wave (shock wave) that leads to autoignition and the subsequent detonation of the unburnt gas ahead of the wave 4). The transition to a detonation can take place in open spaces as well, but it is known to take place more easily in pipes since they tend to accelerate propagation velocity better.

Table 3 Flammability limits for a premixture of a flammable gas and air

Flammable gas	Lower limit (vol%)	Upper limit (vol%)
Hydrogen	4.0	75.0
Acetylene	2.5	100.0
Ethylene	2.7	36.0
Methane	5.0	15.0
Ethane	3.0	12.5
Propane	2.1	9.5
Butane	1.6	8.4
Carbon monoxide	12.5	74.0

Table 4 Stoichiometric characteristics of CJ detonations for different gaseous premixtures

Gaseous premixture	u_1 (m/s)	p_2 (atm)	T_2 (K)
Hydrogen + air	1967	15.6	2951
Hydrogen + oxygen	2834	18.8	3682
Methane + air	1801	17.2	2783
Methane + oxygen	2392	29.4	3727
Propane + air	1795	18.2	2819
Propane + oxygen	2360	36.3	3830

2. Acceleration of Flame Propagation

Once a gaseous premixture (e.g., hydrogen and air) is ignited, the premixed flame or deflagration propagates spherically at an accelerating pace. This phenomenon draws attention in the field of explosion safety (combustion safety). The flame propagation velocity of a premixture is the most vital parameter for ensuring safety, so it needs to be adequately evaluated. Conventionally, the propagation velocity of a spherical deflagration has been evaluated based on the burning velocity of a premixed planar flame while taking into account the thermal expansion of the gas. Nevertheless, there are many reports of spherical deflagrations that involve the formation of cellular flame structures and increased flame surface areas, thereby accelerating the flame propagation velocity 5). This formation of cellular structures is particularly salient with respect to a premixture of hydrogen and air due to the intrinsic instability. Propagation accelerates much further in a spherical deflagration inside a vast facility, because the propagation velocity increases with the scale. In the hydrogen explosions that occurred at the Fukushima Daiichi Nuclear Power Plant, giant balls of flames with cellular structures are thought to have grown larger at an accelerating pace of propagation.

For this reason, the acceleration mechanism for flame propagation must be clarified by observing a spherical deflagration triggered by an ignition at the center of an explosion vessel filled with a premixture of hydrogen and air. **Figure 1** shows high-speed imaging of the flame propagation and flame surface shape that was obtained by using the Schlieren method to understand the essential characteristics of hydrogen explosions and obtain the insights necessary to build an acceleration model for flame propagation. The Schlieren method is employed to optically visualize or photograph slight variations in the refraction index in a transparent medium that distorts light beams 1).

Figure 2 shows how a spherical deflagration propagates with an equivalence ratio ϕ of 1.0 (stoichiometric mixture) and 0.5 (lean mixture), initially at room temperature under atmospheric pressure. After the ignition occurs at the center, the deflagration propagates spherically. The propagation is slower with the equivalence ratio of 0.5 because the burning velocity is lower. Cellular flame surfaces are observed with the spherically propagating flame from the gaseous mixture. This shape results from the development of sufficiently small disturbances associated with intrinsic instability. In general, the possible factors behind this intrinsic instability are the hydrodynamic effects generated by the thermal expansion of the gas and the diffusive-thermal effects generated by interactions between the mass diffusion and heat conduction. These effects shape the cellular flames. Markedly uneven cell surfaces are formed with the equivalence ratio of 0.5. In comparison to the results for a ratio of 1.0, the diffusive-thermal effects are more pronounced and they increase the level of instability. It is confirmed

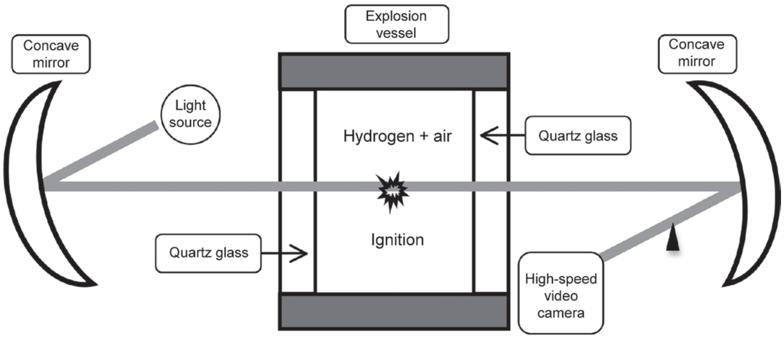

Figure 1 Overview of experimental equipment for investigating hydrogen explosions

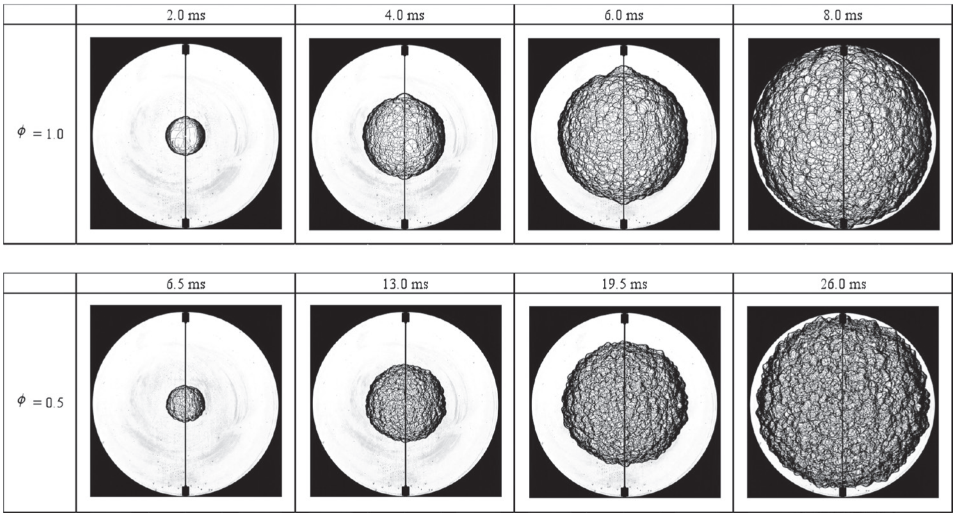

Figure 2 Propagation of a spherical deflagration

that the propagation is visibly accelerated by the increased surface area of the flame.

Experiments on hydrogen explosions will be conducted under various conditions to construct an acceleration model for flame propagation by closely examining how the equivalence ratio, temperature, and pressure influence the acceleration of the propagation velocity. This model is expected to become a useful tool in simulating hydrogen explosions.

III. Safety Standards for Explosion Prevention and Protection

Explosive atmospheres combined with the presence of an ignition source explode and cause harm. In light of this, Europe has established EN 1127-1: 2011, a standard entitled “Explosive Atmospheres—Explosion Prevention and Protection—Part 1: Basic Concepts and Methodology” 6). This standard was established in line with the essential requirements stipulated by EU Directive 94/9/EC (ATEX) and the Machinery Directive 2006/42/EC.

The European standard EN 1127-1: 2011 seeks to reduce risks by pursuing prevention first, then protection, and finally information sharing. The same order is used in the three-step method adopted in ISO12100: 2010, an international safety standard entitled “Safety of Machinery—General Principles for Design—Risk Assessment and Risk Reduction” 7). Japan tends to rely on protective measures using explosion-protected electrical equipment (e.g., IEC 60079-0 8)) and operational information. More properly, risks should be reduced primarily through prevention measures. Other measures should be taken only if the risks cannot be reduced. Ensuring safety by relying on protection and information deviates from the approach adopted in international safety standards. Improvements to address this problem are keenly anticipated.

European standards prescribe the use of zoning classifications based on the quantified probabilities of explosions in explosive atmospheres as well as categories for the equipment, protective systems and components to be deployed in these zones. **Tables 5** and **6** indicate how they correspond to one another, with the former comparing categories and zones from the view of equipment producers and the latter comparing zones and categories from the view

Table 5 Relation between categories and zones (from the view of equipment producers)

Category	Applicable in zone	Explosive atmosphere
1G	0, 1, 2	Gas, steam, or mist + air
2G	1, 2	Gas, steam, or mist + air
3G	2	Gas, steam, or mist + air
1D	20, 21, 22	Dust + air
2D	21, 22	Dust + air
3D	22	Dust + air

Table 6 Relation between zones and categories (from the view of equipment users)

Zone	Applicable category	Explosive atmosphere
0	1G	Gas, steam, or mist + air
1	1G, 2G	Gas, steam, or mist + air
2	1G, 2G, 3G	Gas, steam, or mist + air
20	1D	Dust + air
21	1D, 2D	Dust + air
22	1D, 2D, 3D	Dust + air

of equipment users. These tables indicate which category of equipment can be applicable in which zone and vice versa.

Adequate explosion prevention may even make the deployment of protective equipment unnecessary. This approach is worth considering not only to ensure safety, but also to reduce costs.

IV. Concept of System Safety

System safety is pursued through hardware/software, humans, laws/norms, and various combinations thereof by adopting a system-based approach that applies safety technologies and management methods in an integrated manner. In this process, hazard factors are identified in advance for each stage of the lifecycle, including the designing, manufacturing, and usage stages. The impact of these factors is assessed to implement adequate measures. The definition of "system safety" that is provided in the MIL standard 9) is based on essentially the same concept. Risks must be rationally reduced according to this concept to ensure system safety.

Explosion prevention and protection measures at nuclear power plants should be pursued in accordance with the abovementioned safety standards. More specifically, the required tasks are the following: identification of hazard sources (e.g., the combustion characteristics, ignition requirements, and nature of explosions), risk assessments (e.g., determination of the probability of an explosive atmosphere and the amount, determination of the presence of an ignition source, and assessment of an explosion's impact), and risk reduction (through prevention, protection, and information measures). These measures echo the concept behind system safety. Crucially, safety needs to be ensured by rationally reducing risks.

V. Conclusions

This commentary outlined and contrasted two different types of explosions: deflagrations and detonations. It explained how flame propagation accelerates in a deflagration from the perspective of intrinsic instability. Safety standards for explosion prevention and protection were presented to explain how rational measures are implemented according to the concept of system safety. The author hopes that these rational measures will be taken to ensure explosion prevention and protection at nuclear power plants with adequate preparedness for any explosions.

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