Evaluation of Standoff Distances for NPP-Linked Hydrogen Production Facilities through Analysis of Hydrogen Flammable Mass and Explosion Overpressure

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Keywords: Hydrogen, jet, flammable mass, TNT-equivalent mass, overpressure, standoff distance

1. Introduction

There is a growing global interest in clean hydrogen production technologies using nuclear and renewable energy sources to mitigate greenhouse gas emissions. When hydrogen production facilities are integrated with nuclear power plants, significant quantities of high-pressure hydrogen may be produced and temporarily stored near onsite necessitating a thorough risk assessment of associated storage facilities. This paper focuses on assessing the risks associated with hydrogen storage facilities within nuclear power plant premises. We employ scenario-based analysis to model hydrogen gas leakage and determine the flammable mass of leaked hydrogen. Additionally, we calculate the effective TNT equivalent mass to evaluate explosion overpressure scenarios. Our study culminates in the derivation of standoff distances that comply with the regulatory guidelines, particularly US NRC R.G 1.91 based on the calculated hydrogen explosion overpressures.

2. Methodology

2.1 leakage Source Model

Modeling of hydrogen gas leaking due to the rupture of the hydrogen storage is as shown in Figure 1.

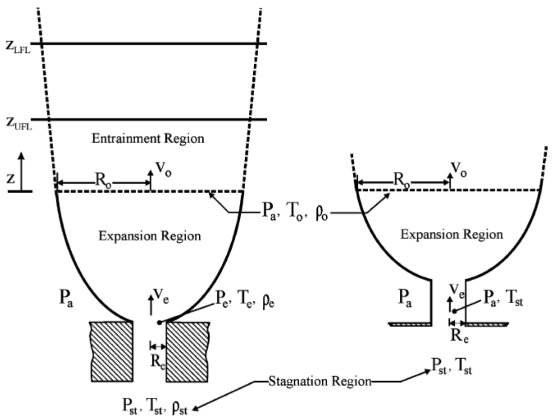

Fig. 1. Jet/plume leak model of hydrogen gas [1]

The choked mass flux of hydrogen through the failure opening is determined by Eq (1) [1].

(1) $$G = C_D\left[\gamma P_{st}\rho_{st}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{1/2}$$

The exit plane properties are related to the stagnation properties of the storage tank via the Eqs (2-4), and the velocity (u_0) in the expansion region of the leaking hydrogen gas jet is calculated using Eq (5) [1]. The radius R_0 is the radius of the hydrogen jet to the end of the expansion region.

(2) $$P_e = P_{st}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

(3) $$\rho_e = \rho_{st}\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}$$

(4) $$T_e = T_{st}\left(\frac{2}{\gamma+1}\right)$$

(5) $$u_0 = \frac{G}{\rho_e} + \frac{P_e - P_a}{G}$$

2.2 Hydrogen Flammable mass

The calculation of the hydrogen flammable mass is outlined in Eqs (6-7) [2][3].

(6) $$m_{flam} = \left(\frac{\pi R_0^3 \rho_0 Y_0}{2E_0}\right)(Fr)^{\frac{3}{5}}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} I_{flam}$$

(7) $$I_{flam} = \frac{5}{4}\left[\left(\frac{Y_0^2}{Y_{LFL}^2} + Fr - 1\right)^{2/5} - \left(\frac{Y_0^2}{Y_{LFL}^2} + Fr - 1\right)^{2/5}\right]$$

The calculation of the Fr number is presented in Eq (8) [3].

(8) $$Fr = \frac{8E_0\,\mu_0^2(\rho_a/\rho_0)^{1/2}}{5g\,R_0\,(\rho_a/\rho_0 - 1)}$$

2.3 TNT-Equivalent Mass

The standard for energy release from TNT is calculated from Eq (9) [4].

(9) $$m_{TNT} = \frac{\Delta H_{comb}\,m_{flam}}{\Delta H_{TNT}}$$

To calculate the overpressure generated by explosions of hydrogen and air mixtures, it is essential to determine the explosion overpressure using the effective TNT equivalent mass. The effective TNT equivalent mass is calculated according to Eq (10).

(10) $m_{TNT,eff} = \alpha \cdot \frac{\Delta H_{comb}\, m_{flam}}{\Delta H_{TNT}}$

2.4 Hydrogen Explosion Overpressure

The maximum blastwave overpressure at a radial distance x from chemical explosions is evaluated by Eqs (11-12) [6].

$$(11)\ \frac{P_s - P_a}{P_a} = \frac{808\left[1+\left(\frac{X}{4.5}\right)^2\right]}{\left[1+\left(\frac{X}{0.048}\right)^2\right]^{1/2}\left[1+\left(\frac{X}{0.32}\right)^2\right]^{1/2}\left[1+\left(\frac{X}{1.35}\right)^2\right]^{1/2}}$$

$$(12)\ \mathbf{X} = \frac{\mathbf{x}}{\mathbf{m}_{\mathbf{TNT,eff}}^{1/3}}$$

3. Analysis

In accordance with US NRC RG 1.91, standoff distances are determined to ensure that the pressure resulting from a hydrogen gas explosion is reduced to a criterion pressure of 1 psi (6.9 kPa) or less, which is deemed safe for nuclear power plants. Consequently, the minimum standoff distance is defined as the radius to the point where the blast wave pressure reaches 1 psi.

3.1 Initial Conditions

The initial conditions for evaluating the hydrogen flammable mass are as presented in Table I [7].

Table I. Initial Condition of Hydrogen Jet

Symbol	variable	initial data
γ	Specific heat	1.41
P_{st}(Pa)	Storage pressure	7.00E+06
T_{st}(K)	Storage temperature	293
R_{id} (J/kgmole K)	Ideal gas constant	8314
P_a(Pa)	Ambient pressure	1.01E+05
T_a (K)	Ambient temperature	293
g(m/sec^2)	Gravitational constant	9.8

3.2 Calculation Results

The calculation results corresponding to the initial conditions outlined in Table I are summarized in Table II.

Table II. Calculation Results of Hydrogen Jet

Symbol	variable	initial data
G(kg/m^2 sec)	Mass flux of hydrogen	3521.3
P_e (Pa)	Pressure at the failure opening plane	3.693E+06
ρ_e (kg/m^3)	density at the failure opening plane	3.645
T_e(K)	Pressure at the failure opening plane	243.8
μ_0 (m/sec)	Velocity of depressurized jet	1986.198

The radius of the expansion region relative to the failure opening radius is as shown in Figure 2.

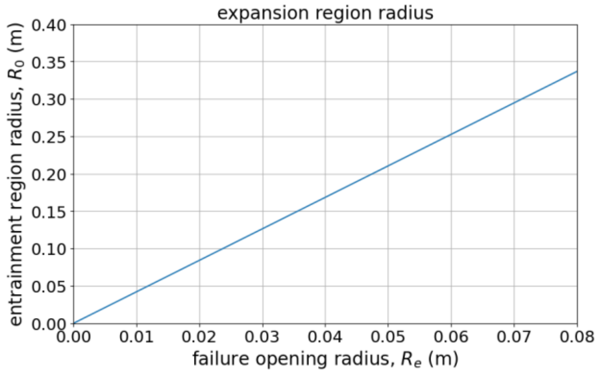

Fig. 2. Radius of the expansion region

The hydrogen flammable mass with respect to the failure opening radius R_e is as shown in Figure 3.

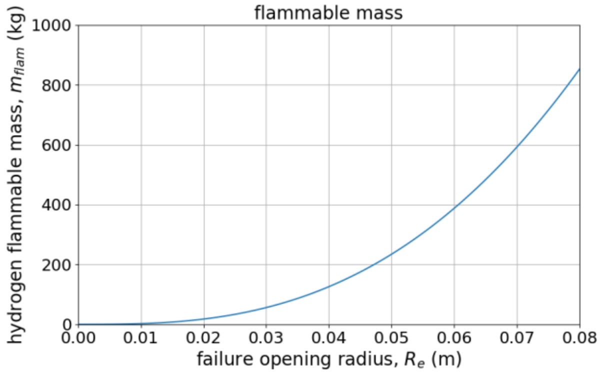

Fig. 3. Hydrogen flammable mass curve

The Effective TNT equivalent mass with respect to the failure opening radius R_e is as shown in Figure 4.

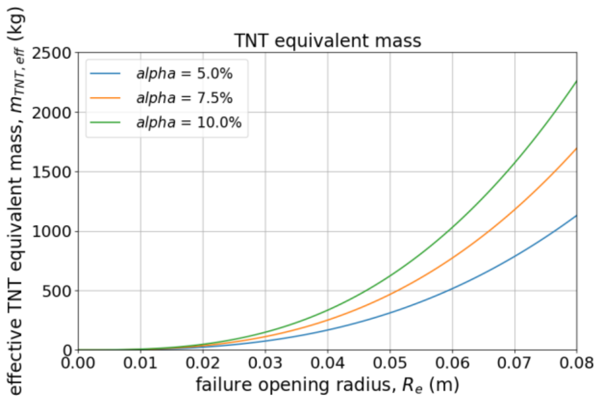

Fig. 4. Effective TNT equivalent mass curve

3.3 Standoff Distance Evaluation

To evaluate the standoff distance, it is necessary to calculate the explosion overpressure radius at which the hydrogen explosion overpressure reaches 1 psi (6.9 kPa). The effective TNT equivalent mass with a 5 % efficiency applied, for failure opening radius of 0.04, 0.06, and 0.08 m are 166.58, 513.91, 1130.25 kg, respectively. The overpressure curves are depicted in Figure 5. The standoff distances for each failure opening radius are presented in Table III.

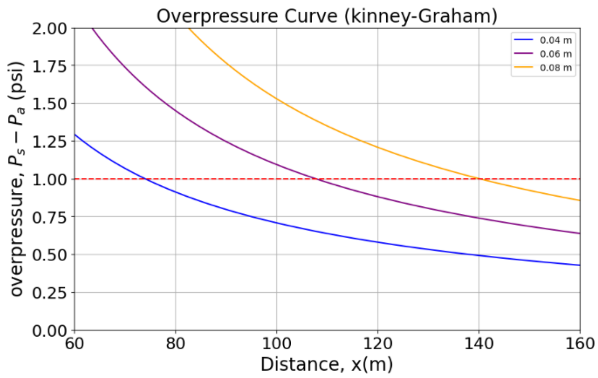

Fig 5. Explosion Overpressure Curve

Table III. Effective TNT equivalent mass with respect to failure opening radius

Failure opening Radius (m)	Effective TNT equivalent mass (kg)	Standoff Distance (m)
0.04	166.58	74.0
0.06	513.91	107.7
0.08	1130.25	140.1

4. Conclusions

To install hydrogen production facilities linked to nuclear power plants, a thorough risk assessment for hydrogen explosions is imperative. Even when these facilities are located near nuclear power plants, they must meet sufficient safety standoff distance requirements to prevent damage from overpressure. US NRC RG 1.91 establishes an overpressure criterion of 1 psi (6.9 kPa) to prevent significant structural damage to nuclear power plant facilities. Accordingly, the paper proposes employing the distance at which the overpressure from an explosion reaches 1 psi (6.9 kPa) as the safety standoff distance. The methodology presented in the paper facilitates the calculation of the hydrogen flammable mass within a hydrogen gas jet and determines the effective TNT equivalent mass based on parameters such as temperature, pressure, and failure opening radius of the hydrogen storage facility. By defining the effective TNT equivalent mass, it becomes feasible to calculate the explosion overpressure as a function of the distance from the explosion origin. This approach is anticipated to contribute to the advancement of clean hydrogen production from nuclear power plants by establishing a rational safety standoff distance that accurately reflects the properties and behavior of hydrogen.

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