

Evaluations of Explosions Postulated to Occur at Hydrogen Production Facilities near NPP

Young-Hun Shin*, Sang-Jin Son, In-Chul Ryu and Kyung-Tae Kim
Korea Electric Power Corporation Engineering & Construction (KEPCO E&C)
269, Hyeoksins-ro, Gimcheon-si, Gyeongsangbuk-do, Republic of Korea, 39660
*Corresponding author: dudgns391@kepc-co-enc.com

***Keywords:** hydrogen production facility, vapor cloud explosion, TNT equivalency, explosion overpressure, safety separation distance

1. Introduction

When an industrial facility, such as a hydrogen production facility, is installed near a nuclear power plant, its potential explosion effects on nuclear safety should be evaluated. NRC RG 1.91 and KINS/RG 1.2 provide guidance for assessing postulated explosions at nearby industrial facilities. These guidelines indicate that no significant adverse impact on nuclear safety is expected when a sufficient separation distance is maintained. Therefore, an appropriate safety separation distance should be determined during the installation of a hydrogen production facility. This study proposes a methodology for determining the safety separation distance between a hydrogen production facility and a nuclear power plant (NPP).

2. Methodology

When a fixed facility, such as a hydrogen production facility, is installed near an NPP, the required safety separation distance is evaluated in accordance with the procedure specified in NRC RG 1.91, as shown in Fig. 1 [1].

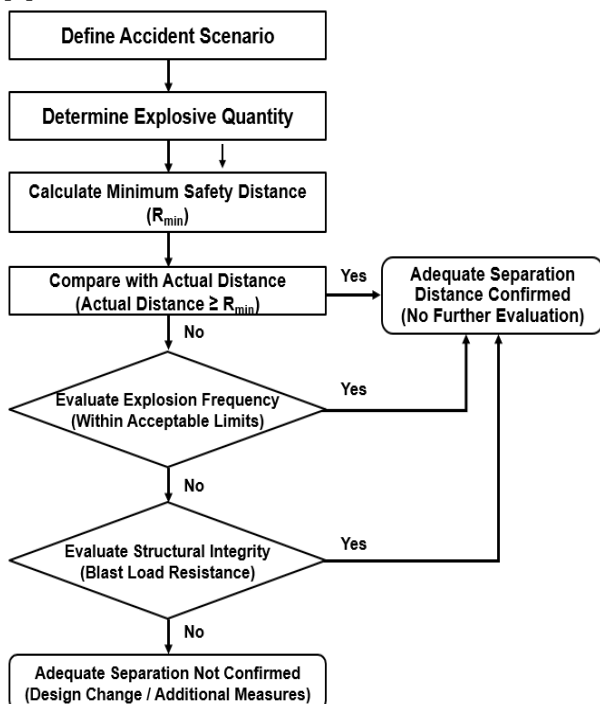


Fig. 1. Evaluation Procedure for Safety Separation Distance

2.1 Accident Scenario and Explosive Quantity

A representative accident scenario for a hydrogen production facility generally assumes that hydrogen released following a pipeline rupture disperses into the atmosphere, forms a flammable vapor cloud, and subsequently explodes. The mass of hydrogen participating in the explosion is determined by applying an appropriate plume dispersion model in accordance with the relevant regulatory guidance.

This study presents a methodology for estimating the mass of hydrogen participating in an explosion using Epstein's top-hat jet/plume model, as illustrated in Fig. 2. The model enables a conservative analytical estimate of the mass of hydrogen participating in the explosion without requiring complex numerical procedures such as CFD simulations.

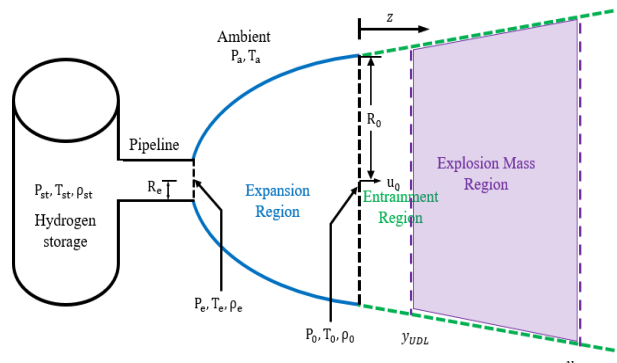


Fig. 2. Epstein's top-hat jet/plume model for hydrogen release from a ruptured pipeline.

In Epstein's top-hat jet/plume model, the jet boundary radius (R) in the entrainment region downstream of the expansion region is expressed by Eq. (1). The mass of hydrogen available for explosion is then evaluated over the region in which the hydrogen concentration lies within the detonable concentration range, as calculated by Eq. (2). In this study, the mass of hydrogen available for explosion is defined as the detonable hydrogen mass. In Eq. (2), the mass fraction of hydrogen (Y) is given by Eq. (3). The hydrogen concentration in terms of volume fraction (y) corresponding to the mass fraction (Y) is calculated using Eq. (4) [3][4].

$$(1) R = \frac{R_0}{Y} \sqrt{\frac{T_a}{T_0} \left[Y + \frac{M_{H_2}}{M_{air}} (1 - Y) \right]}$$

$$(2) m_{exp} = m_{det} = \int_{Z_{UDL}}^{Z_{LDL}} \pi R^2 \rho Y dz$$

$$(3) Y = \frac{u}{u_0} = \frac{1}{1 + \frac{2E_0}{R_0} \left(\frac{\rho_a}{\rho_0} \right)^{\frac{1}{2}} z}$$

$$(4) y = \left[1 + \left(\frac{1}{Y} - 1 \right) \frac{M_{H_2}}{M_{air}} \right]^{-1}$$

The detonable region of the hydrogen jet/plume is determined by considering its geometric characteristics and the criteria for detonation. Specifically, as expressed in Eq. (5), the region where the rate of change in the detonation cell size (λ) with respect to the jet dispersion distance (z) is less than 0.1 is defined as the detonable region [4].

$$(5) \frac{d\lambda}{dz} < 0.1 \text{ (for detonation propagation)}$$

To determine the detonable range of the hydrogen jet, Eq. (5) is further expanded in terms of the hydrogen equivalence ratio (ϕ) and mass fraction (Y) by applying the chain rule. The resulting expression is given in Eq. (6), and its solution provides the range of hydrogen concentrations within the jet that satisfies the detonation criterion.

$$(6) \left(\frac{d\lambda}{d\phi} \right) \left(\frac{d\phi}{dY} \right) \left(\frac{dY}{dz} \right) < 0.1$$

The relationship between the detonation cell size (λ , m) and equivalence ratio (ϕ), and that between the hydrogen mass fraction (Y) and equivalence ratio (ϕ), are given by Eqs. (7) and (8), respectively. In Eq. (7), the coefficients a , b , c , d , and e are -3.96004 , -0.16537 , 2.2608 , -1.18064 , and 0.45823 , respectively [6][7].

$$(7) \ln \lambda = a + b \ln \phi + c (\ln \phi)^2 + d (\ln \phi)^3 + e (\ln \phi)^4$$

$$(8) \phi = \frac{M_a}{0.42 M_{H_2}} \left(\frac{Y}{1 - Y} \right)$$

The TNT equivalency method is commonly used to quantify the magnitude of an explosion by converting the energy of the material participating in the explosion into an equivalent mass of TNT. NRC RG 1.91 provides an equation for calculating the TNT equivalent mass (W_{TNT}), which was applied in this study as given in Eq. (9).

$$(9) W_{TNT} = \alpha \frac{\Delta H_{comb}}{\Delta H_{TNT}} \times m_{exp}$$

In Eq. (9), a value of 1.2×10^8 J/kg was used for the heat of combustion of hydrogen in air (ΔH_{comb}), while a value of 4.5×10^6 J/kg, as specified in RG 1.91, was used for the heat of combustion of TNT (ΔH_{TNT}). The parameter α in Eq. (9) represents the yield factor, which accounts for the fraction of the available combustion energy converted into explosion energy. [1]

In accordance with FM Global Data Sheet 7-42, as referenced in NRC RG 1.91, the hydrogen vapor-cloud explosion was classified as a Class I unconfined vapor-cloud explosion. Accordingly, a yield factor (α) of 5% was applied to a hemispherical Class I unconfined vapor-cloud explosion at ground level [1][8].

2.2 Minimum Safety Distance Calculation

To determine the separation distance from the explosion source for a hemispherical surface burst of TNT, the scaled distance, Z , must first be defined. US NRC RG 1.91 references the CCPS correlation for a conservative evaluation of the separation distance. The explosion overpressure (P) as a function of the scaled distance (Z) is calculated using Eq. (10), and the values of the coefficients a , b , and c used in Eq. (10) are provided in Table I [5].

$$(10) \log P = \sum_{i=0}^n c_i (a + b \log Z)^i$$

Table I. Parameters for the CCPS overpressure correlation.

constant	Overpressure P (kPa) 0.0674 ≤ Z ≤ 40
a	-0.214362789
b	1.3503425
c ₀	2.780769166
c ₁	-1.695898874
c ₂	-0.154159377
c ₃	0.514060731
c ₄	0.098855437
c ₅	-0.293912623
c ₆	-0.026811235
c ₇	0.109097496
c ₈	0.001628468
c ₉	-0.021463103
c ₁₀	0.000145672
c ₁₁	0.001678478

The plot of explosion overpressure (P) as a function of the scaled distance (Z) calculated using Eq. (10) is shown in Fig. 3.

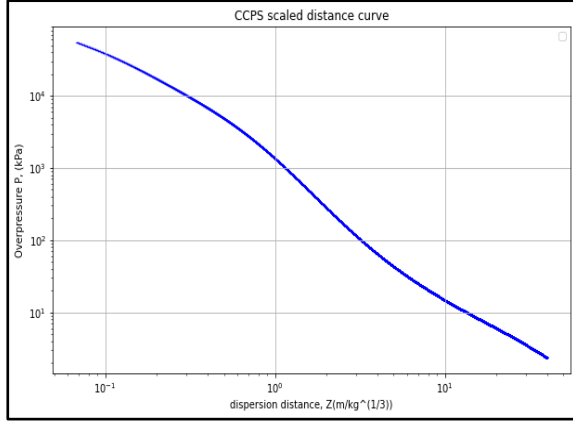


Fig. 3. Plot of Explosion Overpressure versus Scaled Distance (CCPS)

US NRC RG 1.91 considers that an explosion occurring outside the nuclear power plant site does not adversely affect the structural integrity of the reactor building when the peak incident overpressure of the resulting blast wave is limited to 1 psi (6.9 kPa) or less. According to the CCPS correlation, the minimum scaled distance required to satisfy this regulatory pressure criterion is calculated to be approximately $18 \text{ m/kg}^{1/3}$. This value is consistent with the coefficient used in the safety separation distance equations provided in NRC RG 1.91 and KINS/RG 1.2. Therefore, the safety separation distance required to prevent adverse effects on the structural integrity of the reactor building is calculated using Eq. (11), as provided in these guidelines [1][2].

$$(11) L_{\min} = Z \times W_{\text{TNT}}^{1/3} = 18 \times W_{\text{TNT}}^{1/3}$$

3. Example Calculations and Results

Based on the methodology presented in Section 2, calculations were performed for a postulated guillotine break of a pipeline at a hydrogen production facility located near an NPP, and the results are presented in this section.

For the example calculations, the temperature (T_{st}) and pressure (P_{st}) of the hydrogen pipeline were assumed to be 20 °C and 7 MPa, respectively. Under the same temperature and pressure conditions, calculations were performed for pipeline rupture opening diameters of 25, 40, 80, and 100 mm. In calculating the detonable hydrogen mass, the lower concentration bound was set to the hydrogen mass fraction corresponding to the lower detonable limit (Y_{LDL}) calculated for each rupture opening diameter, whereas the upper bound (Y_{UDL}) was fixed at the mass fraction corresponding to 75 vol.% hydrogen, representing the upper flammability limit of hydrogen.

In addition, the lower detonable limit was determined using the criterion given in Eq. (5), and the corresponding minimum detonation cell size ($\lambda_{\min}$) was calculated using Eq. (7). The calculated Y_{LDL} , $\lambda_{\min}$, detonable hydrogen mass (m_{det}), and TNT equivalent

mass (W_{TNT}) for each rupture opening diameter (D_e) are presented in Table II.

Table II. Calculated Hydrogen Explosive Quantities for Different Rupture Opening Diameters ($P_{\text{st}}=7 \text{ MPa}$, $T_{\text{st}}=20 \text{ °C}$).

D_e (mm)	Y_{LDL}	Y_{UDL} (%)	$\lambda_{\min}$ (mm)	m_{det} (kg)	W_{TNT} (kg)
25	1.38×10^{-2}	16.86	128	0.32	0.43
40	1.29×10^{-2}	16.00	192	1.49	1.98
80	1.19×10^{-2}	14.91	356	14.02	18.70
100	1.16×10^{-2}	14.60	436	28.76	38.34

The equivalence ratio (ϕ) at the lower detonable limit and the corresponding detonation cell size ($\lambda_{\min}$) calculated for each rupture opening diameter are shown in Fig. 4.

The top-hat hydrogen jet/plume dispersion models corresponding to each rupture opening diameter are shown in Figs. 5–8. In Figs. 5–8, the lower detonable limit (LDL) and upper detonable limit (UDL) of hydrogen are indicated by red and blue dashed lines, respectively, and the detonable region between these two limits is highlighted in pink.

The explosion overpressure as a function of the separation distance (L) for each rupture opening diameter is shown in Fig. 9. The minimum safe separation distance ($L_{\min}$) was determined as the distance corresponding to the regulatory overpressure criterion of 6.9 kPa(1 psi).

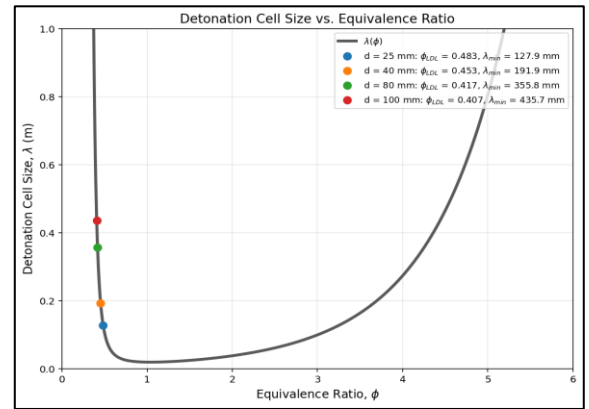


Fig. 4. Minimum detonation cell size versus equivalence ratio for different rupture opening diameters.

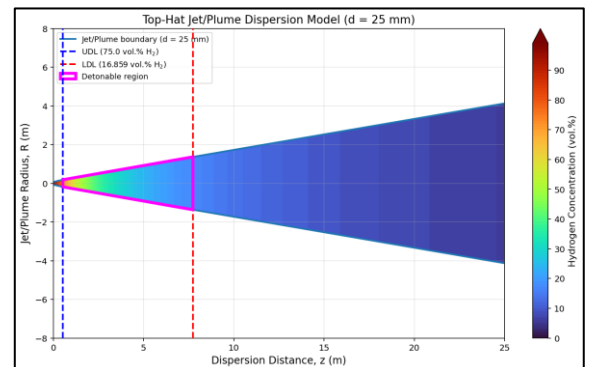


Fig. 5. Hydrogen top-hat jet/plume dispersion model and explosive region ($D_e=25 \text{ mm}$)

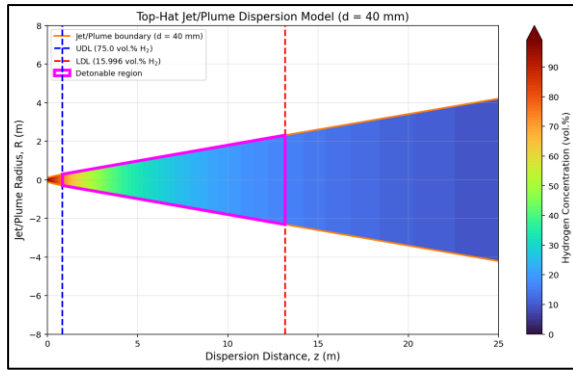


Fig. 6. Hydrogen top-hat jet/plume dispersion model and explosive region ($D_e=40$ mm)

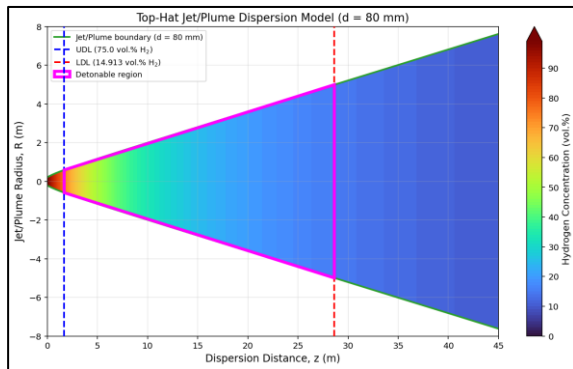


Fig. 7. Hydrogen top-hat jet/plume dispersion model and explosive region ($D_e=80$ mm)

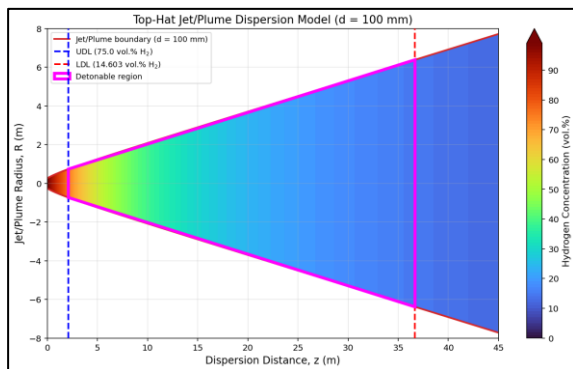


Fig. 8. Hydrogen top-hat jet/plume dispersion model and explosive region ($D_e=100$ mm)

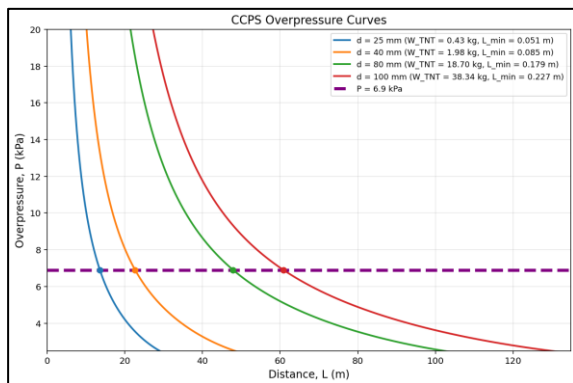


Fig. 9. Explosion overpressure versus separation distance for different rupture opening diameters

As shown in Fig. 9, the minimum safe separation distances (L_{min}) satisfying the regulatory overpressure criterion of NRC RG 1.91 and KINS/RG 1.2 are summarized in Table III.

Table III. Minimum safe separation distance for each rupture opening diameter

D_e (mm)	L_{min} (m)
25	14
40	23
80	48
100	61

4. Conclusions

This study presented a methodology for determining the safety separation distance between hydrogen production facilities and nuclear power plants for postulated hydrogen pipeline rupture accidents. The detonable hydrogen mass was estimated using Epstein's top-hat jet/plume model and the detonation cell-size criterion, converted into a TNT equivalent mass, and subsequently used to calculate the explosion overpressure and safety separation distance based on the CCPS correlation referenced in NRC RG 1.91.

For pipeline conditions of 7 MPa and 20 °C, rupture opening diameters of 25, 40, 80, and 100 mm resulted in TNT equivalent masses of 0.43, 1.98, 18.70, and 38.34 kg, respectively. The corresponding minimum safe separation distances satisfying the 1 psi (6.9 kPa) regulatory criterion were 14, 23, 48, and 61 m. These results demonstrate that the required safety separation distance increases with the rupture opening diameter and the associated explosive quantity. Therefore, the evaluation methodology presented in this study can be applied to assess the potential impacts of postulated explosion accidents at hydrogen production facilities near nuclear power plants and to determine appropriate safety separation distances.

REFERENCES

- [1] U.S. Nuclear Regulatory Commission, Regulatory Guide 1.91, "Evaluation of explosions postulated to occur at nearby facilities and on transportation routes near nuclear power plants" Washington, DC.
- [2] KINS/RG-N01.02, Rev. 4, 원자로시설에 대한 인위적 사고의 영향평가
- [3] Michael Epstein, Hans K. Fauske, Total Flammable Mass and Volume Within a Vapor Cloud Produced by a Continuous Fuel-Gas or Volatile Liquid-Fuel Release, 2007.
- [4] M. Epstein et al, "A Simple Top Hat Jet Model for Prediction of Overpressures Created by an Ignited High-Momentum Hydrogen Jet Release," SSRN Preprint, SSRN Abstract No. 6223751.
- [5] Center for Chemical Process Safety (CCPS), Guidelines for Consequence Analysis of Chemical Releases, American Institute of Chemical Engineers, 1999.

- [6] Kryuchkov, S. I., Dorofeev, S. B., and Efimenko, A. A., 1996, "Critical Conditions for Detonation Propagation Through Mixture with Decreasing Reaction Rate," *Proceeding of the Combustion Institute*, Vol. 26(2), pp. 2965-2972
- [7] Ehrhart, B. D. and Hecht, E. S., 2022, "Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.0 Technical Reference Manual," Sandia National Lab. Report SAND2022-16425 (November).
- [8] FM Global, "Guidelines for Evaluating the Effects of Vapor Cloud Explosions Using a TNT Equivalency Method," *Property Loss Prevention Data Sheets, Data Sheet 7-42*, Factory Mutual Insurance Company, May 2008.