

Probabilistic risk assessment of a hydrogen refuelling station explosion in a semi-urban environment using Monte Carlo simulation

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Abstract. Hydrogen is increasingly recognised as a viable clean energy carrier, yet its storage and handling at high pressures raise significant safety concerns, particularly in densely populated areas. This study presents a probabilistic risk assessment of a potential explosion at a hydrogen refuelling station located in a semi-urban environment, involving 100 kg of hydrogen stored at 700 bar. A Monte Carlo simulation approach was employed to model the dispersion of explosive energy and evaluate the consequences on human safety and infrastructure. Key variables included the stochastic efficiency of energy conversion into an explosion (ranging from 10% to 30%) and the random spatial distribution of individuals within a 50-meter radius. Over 10,000 simulations, the likelihood of at least one casualty exceeded 88%, with total impact on all exposed individuals occurring in 43% of cases.

Additionally, structural damage to a nearby building located 30 meters from the epicenter was observed in 67% of scenarios. These results underscore the critical need for revised safety distances, enhanced protective measures, and rigorous failure probability management in the design and regulation of hydrogen refuelling facilities.

The simulation was developed and executed using Python, allowing for efficient modeling and reproducibility.

The methodology proposed offers a robust framework for quantifying the consequences of low-probability, high-impact events in urban energy infrastructure.

1 Introduction

The growing global demand for green and sustainable energy solutions has led to a significant expansion in hydrogen-based technologies. With its high energy density and zero-emission potential, hydrogen is becoming an increasingly attractive option, particularly as a fuel source for transportation, notably in fuel cell electric vehicles (FCEVs). Hydrogen Refuelling Stations (HRS) are essential for the future success of hydrogen-powered mobility. These

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stations are designed to store, compress, and dispense hydrogen fuel to FCEVs safely and efficiently. The deployment of a reliable HRS infrastructure is essential to support the expanding fleet of hydrogen vehicles and to boost user confidence. As of the mid-2020s, several countries, including Japan, South Korea, Germany, and the United States, have substantially invested in expanding their hydrogen refueling networks as part of broader national hydrogen strategies. Figure 1 shows a schematic diagram of a common HRS.

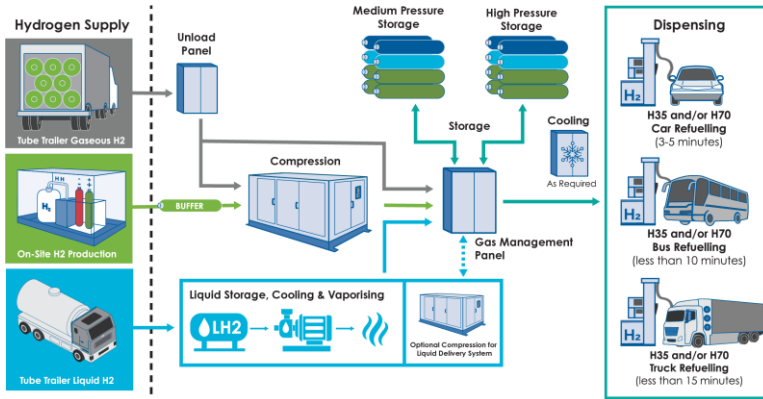


Fig. 1. Schematic diagram of a Hydrogen Refuelling Station [1]

Despite these advancements, the widespread adoption of HRS faces several challenges. However, storing and distributing hydrogen at high pressures – typically up to 700 bar – poses significant safety challenges, particularly in urban environments. These include the need for standardization in refueling protocols and station design, limited hydrogen production and supply chains, as well as high capital and operational costs. Among the most critical concerns, however, are the safety issues associated with hydrogen storage and handling.

One of the most critical hazards associated with hydrogen infrastructure is the potential for explosive releases resulting from equipment failure, human error, or external events. While the probability of such accidents is relatively low, their consequences can be catastrophic. Incidents, such as the 2019 hydrogen station explosion in Sandvika near Oslo, Norway, and hydrogen storage tanks in South Korea, have highlighted the need for robust risk assessment frameworks and spurred a renewed focus on safety regulations and engineering controls [2, 3]. The international scientific community has conducted multiple studies to characterize blast effects, assess mitigation measures, and propose design guidelines for hydrogen refuelling stations (HRS). Li et al. [4] proposed a Bayesian-based dynamic risk model for urban HRS operations, incorporating accident cascades and domino effects to update risk levels over time. Lee and Kang [5] used PHAST and Monte Carlo simulation to quantify the domino explosion risks at urban HRS. Yang et al. [6] conducted a 3D quantitative risk assessment for a major HRS, identifying critical zones using spatial risk visualisation. Shi et al. [7] present some methodological improvements in the risk analysis of an urban HRS, while LaFleur et al. [8] applied quantitative risk assessment (QRA) to demonstrate how probabilistic thresholds can inform HRS site-specific safety protocols and regulatory flexibility. Patel et al. [9] performed CFD-based explosion modeling, emphasizing the effect of blockage ratios and wind conditions on blast intensity at hydrogen stations. Genovese et al. [10] reviewed key engineering measures – grounding, emergency shutoff systems, and intelligent leak detection – emphasizing their effectiveness in mitigating probabilistic risks in dense environments. These studies collectively reinforce the need for hybrid modeling frameworks—combining empirical data, probabilistic simulation, and

regulatory thresholds—to design safer hydrogen infrastructures. They also validate the methodological direction taken in this chapter, specifically the use of Monte Carlo approaches to quantify high-impact explosion consequences in semi-urban environments.

Moreover, bodies such as the European Hydrogen Safety Panel and international standards (e.g., ISO 19880-1:2020) emphasize the importance of probabilistic risk-based methodologies in supporting the safe deployment of hydrogen technologies.

The Joint Research Centre (JRC) of the European Commission developed the *Hydrogen Accidents and Incidents Database (HIAD)* within the context of the European Network of Excellence HySafe. The Joint Research Centre (JRC) maintains HIAD with the financial support of the Clean Hydrogen Partnership [10].

Safety Issues in Hydrogen Refueling Stations

Hydrogen is a highly flammable gas with a wide flammability range (4-75% in air) and a low ignition energy. Key safety issues include:

- Leak detection and prevention: Due to its small molecular size, hydrogen is susceptible to leakage through seals, valves, and connectors. Sensor-based early detection systems are essential for preventing accumulation and potential ignition [11].
- Explosion and fire hazards: Hydrogen can form explosive mixtures with air. Appropriate ventilation, spark-proof equipment, and safe distances are crucial in mitigating explosion risks [12].
- High-pressure systems: storage and dispensing pose risks related to mechanical failure, pressure surges, or improper handling.
- Material compatibility: Prolonged exposure to hydrogen can lead to material degradation, such as hydrogen embrittlement in metals, compromising structural integrity.
- Emergency response and risk assessment: Comprehensive risk assessments and well-rehearsed emergency protocols are crucial in minimizing damage and ensuring public safety in the event of an accident [13].

Despite the efforts, comprehensive quantitative models that integrate uncertainty in explosion energy, human presence, and environmental conditions remain limited [14, 15]. Thus, quantifying the risk associated with hydrogen refueling stations requires a probabilistic approach that can capture the uncertainty and variability in both system behavior and environmental conditions.

This study addresses this gap by applying a Monte Carlo simulation framework to evaluate the consequences of a hypothetical explosion at a refueling station in a semi-urban setting. The analysis considers the release of 100 kg of hydrogen stored at 700 bar and investigates the resulting effects on human safety and nearby infrastructure. By incorporating stochastic parameters such as the efficiency of explosive energy conversion and the spatial distribution of individuals, the model provides a comprehensive probabilistic profile of the incident's impact. This work contributes to the broader effort to ensure the safe deployment of hydrogen technologies in modern urban environments.

2 Methodology

Monte Carlo simulation is a type of probabilistic simulation that relies on repeated random sampling and statistical analysis to compute the result. The simulation method is very closely related to random experiments, for which the specific result is not known in advance. In this perspective, Monte Carlo simulation can be regarded as a systematic approach to doing what-if analysis.

When simulating a physical process, the Monte Carlo approach is based on the following steps:

- **Static model generation.** Every simulation starts with the formulation of a deterministic model that closely reflects the real situation. This model employs the most likely values, or the base case, of the input parameters. Mathematical relationships are then applied to the input parameters, transforming them into the desired output.
- **Input distribution identification.** When the deterministic model is satisfactory, the risk components are added to the model. Since the risks have a stochastic nature related to the input variables, the underlying distribution that governs these variables has to be determined. Standard statistical procedures are applied to identify the input distributions.
- **Random variable generation.** After identifying the underlying distributions for the input variables, a set of random numbers (random variates or random samples) is generated from these distributions. One set of random numbers (one value for each input variable) will be used in the deterministic model to generate one set of output values. This process is repeated by generating more sets of random numbers and collecting different sets of possible output values – the core of the Monte Carlo simulation.
- **Analysis and decision making.** This step involves applying statistical analysis to the collected samples of output values from the simulation, thereby providing statistical confidence for the decisions that may be made after running the simulation.

Monte Carlo simulation has multiple applications in multidisciplinary fields, including mathematics and statistical physics, as well as various engineering disciplines (mechanical, electrical, circuit design, computer science, and software engineering). It is also used for financial analysis, portfolio evaluation, and other types of financial instruments.

In all modern computer-based risk assessment models, particularly when discussing fire and explosion phenomena, Monte Carlo analysis, along with Event Tree and Fault Tree analysis, plays a crucial role in quantitative risk evaluation [14].

2.1 Case study: hydrogen explosion in a semi-urban context

To assess the potential consequences of a hydrogen explosion in a semi-urban location, a probabilistic simulation model was developed using the Monte Carlo method. The scenario evaluated involves a hydrogen refuelling station storing 100 kg of compressed hydrogen at 700 bar (2620.62 l), with a nearby building located 30 meters from the storage unit and 10 individuals randomly distributed within a 50-meter radius. The goal was to estimate the probability and severity of casualties and infrastructure damage, taking into account the key physical parameters and uncertainties.

Simulation setup

The simulation was run over 10,000 iterations, each representing a possible incidence of an explosion event. The random sampling of the explosion efficiency taken into account was:

$$\eta \sim \text{Uniform}(0.10, 0.30) \quad (1)$$

We will use a uniform distribution in this range, which means that any value between 0.10 and 0.30 is equally likely.

The explosive energy of hydrogen can be estimated by conversion to TNT equivalent:

$$E_{TNT} = \eta \cdot m_{H_2} \cdot \frac{\Delta H_{H_2}}{\Delta H_{TNT}} \quad (2),$$

where: E_{TNT} - TNT equivalent explosion energy;
 η - explosion efficiency;
 m_{H2} - the mass of hydrogen implied in the explosion [kg];
 ΔH_{H2} - Hydrogen specific Heat of combustion (120 MJ/kg);
 ΔH_{TNT} - TNT Heat of combustion (4.184 MJ/kg).

For our explosion efficiency range, the TNT equivalent for 100 kg of H2 is between 286.80 and 860.42 kg of TNT.

To estimate the shockwave effects, the scaled Sachs model is applied:

$$\Delta P = P_0 \cdot 0.67 \cdot \left(\frac{E_{TNT}^{1/3}}{R} \right)^{1.5} \tag{3}$$

where: ΔP - overpressure [bar], P_0 - atmospheric pressure (1 bar), R - distance from epicenter [m].

Radius for a given overpressure threshold results from the following formula:

$$R = 1.7 \cdot E_{TNT}^{1/3} \cdot \Delta P^{-0.4} \tag{4}$$

This formula expresses the impact distance as a function of overpressure, providing a simplified formula for quick calculation that is applicable in the rapid evaluation of explosions in free spaces.

For higher precision and more general applicability, the Kingery-Bulmash model adapted to spherical explosion in free spaces, can also be applied. The Kingery-Bulmash model is a widely used empirical model for predicting blast wave parameters from explosive detonations. When adapted for spherical explosions in free space, it provides relationships for key blast parameters as functions of scaled distance. This model was developed based on extensive experimental data from the U.S. Army Corps of Engineers and offers polynomial curve fits for blast wave parameters. For spherical explosions in free space (hemispherical surface bursts), the model predicts: the peak overpressure (ΔP), positive phase duration (t_+), positive impulse (I_+), peak dynamic pressure (q), and shock wave arrival time (t_a).

The fundamental parameter in the model is the scaled distance Z :

$$Z = \frac{R}{W_{TNT}^{1/3}} \tag{5}$$

The peak overpressure is expressed as a function of scaled distance through polynomial fits: $\frac{\Delta P}{P_0} = f_1(Z)$, where P_0 is atmospheric pressure and $f_1(Z)$ is a polynomial function, fitted to experimental data.

The model is based on extensive experimental validation, is widely accepted in blast engineering, covers a broad range of scaled distances, and is relatively simple to implement.

In the Monte Carlo simulation, the following limitations and corrections were used:

- The efficiency factor (η) was considered, randomly, between 10% (slow deflagration) and 30% (complete detonation). The obstruction correction is: $\eta_{eff} = \eta \cdot (1 + 0.5 \cdot Obstruction\ factor)$
- The humidity correction – reduced explosion effects in humid air: $\Delta P_{wet} = \Delta P_{dry} \cdot (1 - 0.15 \cdot RH^{0.3})$, where RH – Relative humidity [%].

In the presented study, a typical scaled distance for the injury threshold $Z = 4\ m/kg^{1/3}$ was considered to calculate the effect radius of the explosion. The building was assumed to be affected if $R_{effect} \geq 30m$. Each person was assigned a random distance from the explosion center, ranging from 0 to 50 meters. Any individual within R_{effect} was considered injured.

Although the annual probability of a catastrophic failure was not directly simulated, it was assumed to be:

$$P_{failure} = 1 \times 10^{-4},$$

value that can be used post-simulation to calculate annualized risk metrics when combined with the consequence probabilities obtained from the Monte Carlo outputs.

2.2 Tools and Environment

The simulation was implemented in Python 3.11, using the NumPy and Matplotlib libraries for numerical processing and visualization. The code structure allows for the integration of more complex dispersion or overpressure models (e.g., CFD or blast wave decay curves) in future research. A sample code is presented in Table 1.

Table 1. Sample Python code for implementing Monte Carlo probabilistic simulation

```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd

# Simulation parameters
num_simulations = 10000
mass_H2 = 100 # kg of hydrogen
energy_H2 = 120 # MJ/kg
energy_TNT = 4.184 # MJ/kg
building_distance = 30 # meters
num_people = 10
person_radius = 50 # meters

# Pressure injury thresholds in bar (1 bar = 100 kPa)
THRESHOLD_MINOR = 3.5 / 100
THRESHOLD_SEVERE = 7.0 / 100
THRESHOLD_FATAL = 35.0 / 100

# Logistic model parameters
P0_kpa = 35.0 # kPa, midpoint of logistic curve
k = 0.25 # slope of the logistic curve

# Step 1: Random explosion efficiency
efficiencies = np.random.uniform(0.10, 0.30, num_simulations)

# Step 2: Calculate TNT equivalent energy
E_TNT = efficiencies * mass_H2 * energy_H2 / energy_TNT

# Step 3: Calculate effect radius using scaled distance  $Z = 4 \text{ m/kg}^{(1/3)}$ 
Z_injury_threshold = 4
effect_radius = Z_injury_threshold * (E_TNT**(1/3))

# Step 4: Assess building damage
building_affected = effect_radius >= building_distance

# Step 5: Random person positioning
people_distances = np.random.uniform(0, person_radius, (num_simulations, num_people))
injured_people = (people_distances < effect_radius[:, np.newaxis]).sum(axis=1)

# Step 6: Overpressure estimation (simplified spherical Sachs model)
P0 = 1 # bar
Z0 = 1
scaled_distances = people_distances / (E_TNT[:, np.newaxis]**(1/3))
```

```

overpressures = P0 * (Z0 / scaled_distances)**3
overpressures_kpa = overpressures * 100

# Step 7: Logistic model for fatality probability
P_fatal = 1 / (1 + np.exp(-k * (overpressures_kpa - P0_kpa)))
random_draws = np.random.rand(*P_fatal.shape)
simulated_deaths_logistic = (random_draws < P_fatal).sum(axis=1)

# Average and histogram
average_fatalities_logistic = simulated_deaths_logistic.mean()
fatalities_distribution = pd.Series(simulated_deaths_logistic).value_counts().sort_index()

# Print results
print(f"Probability building is affected: {np.mean(building_affected):.2%}")
print(f"Probability at least one person is injured: {np.mean(injured_people > 0):.2%}")
print(f"Probability all people are injured: {np.mean(injured_people == num_people):.2%}")
print(f"Average number of fatalities (logistic model): {average_fatalities_logistic:.2f}")

# Plot
plt.figure(figsize=(10, 6))
plt.bar(fatalities_distribution.index, fatalities_distribution.values, color='darkgreen',
edgecolor='black')
plt.xlabel('Number of Fatalities (Logistic Model)')
plt.ylabel('Frequency of Simulations')
plt.title('Logistic-Based Fatality Distribution in 10,000 Simulations')
plt.grid(axis='y', linestyle='--', alpha=0.7)
plt.tight_layout()
plt.show()
    
```

3 Results and discussions

- The total explosive energy available (without losses) resulting from the simulation is:

$$E_{total} = 100 \text{ kg} \times 120 \text{ MJ/kg} = 12,000 \text{ MJ}$$

- The TNT equivalent (with a random efficiency between 10% and 30% is equal to 286.8 – 860.4 kg of TNT.

Table 2 presents the overpressure thresholds for impact assessment, based on explosion safety literature (US Department of Defense, Baker-Strehlow, Kingery-Bulshman, HSE UK data). This overpressure model was used in conjunction with Monte Carlo simulation to compute peak pressure values at random distances and at the location of the nearby building. The values provided a more accurate estimation of potential injury and structural damage zones for each scenario iteration.

Table 2. Overpressure thresholds for Impact Assessment

Overpressure ΔP [bar]	Human Effects	Structural Effects
0.02 – 0.03	Startle response, discomfort	Minor glass breakage (e.g., windows)
0.05 - 0.07	Potential eardrum rupture	Light structural damage (e.g., ceiling tiles)

0.1 – 0.2	Injuries from flying glass, severe discomfort	Moderate damage to house walls
0.3 – 0.5	High risk of fatal injuries	Structural failure of non-reinforced walls
0.7 – 1.0	Near-certain fatality (within proximity)	Heavy structural damage to small building
> 1.0	Fatal at close range, catastrophic trauma	Complete destruction of ordinary buildings

Affected Individuals Distribution

The histogram in Fig. 2 illustrates the frequency distribution of the number of individuals affected by the explosion in 10,000 simulations.

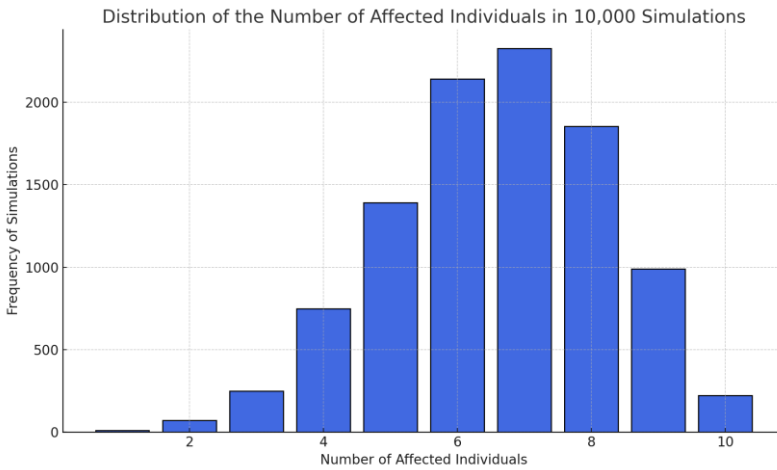


Fig. 2. Number of affected individuals in the Monte Carlo simulation

Pressure Threshold Analysis and Injury Severity

Based on explosion overpressure effects, the following thresholds were used to classify injury severity:

- Minor injuries: ≥ 3.5 kPa (0.035 bar)
- Severe injuries: ≥ 7.0 kPa (0.07 bar)
- Fatalities: ≥ 35.0 kPa (0.35 bar)

After running the simulation, the following results can be mentioned (Figure 3):

- Minor injuries: 1.02 individuals
- Severe injuries: 1.66 individuals
- Fatalities: 2.36 individuals

The fatality threshold of 35 kPa (0.35 bar) used is in accordance with the values recommended by the US DoD and the Kingery-Bulmash model. It can be used in urban-risk scenarios and Monte Carlo simulations. We can use a more realistic, dynamic alternative, namely the fatality probability curve, a logistic probability curve, instead of a fixed pressure threshold. The probability of fatality for each individual was calculated, in this case, as:

$$P_{fatal} = \frac{1}{1 + e^{-k(\Delta P - P_0)}} \tag{6}$$

where P_0 – is the threshold at which 50% of the individuals are dying (35kPa), and k is the slope parameter (between 0.2 -0.5, in this case 0.25).

The average number of fatalities using this logistic model was 2.39 individuals per simulation (Fig. 4).

The difference is slight, but the logistic model represents more realistic the transition from injury to death. Because it permits intermediate probabilities at pressures close to the threshold, it is preferred in scientific studies on probabilistic urban risk.

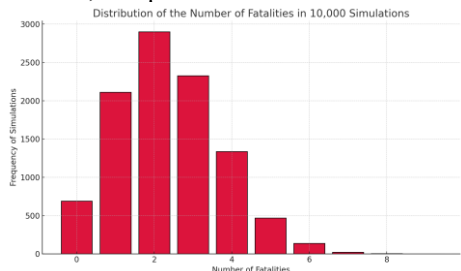


Fig. 3. Histogram of the distribution of fatalities

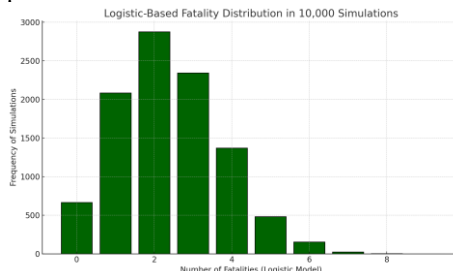


Fig. 4. Histogram of the distribution of logistic-based fatalities

The Monte Carlo simulation also shows that the probability of at least one person being injured is about 100%. These findings suggest that, given the large radius of damage (> 50 m in many cases), it is virtually impossible for all 10 people to be outside the impact zone. It suggests that the safety distance for people is much greater than 50 m in such an incident.

The likelihood that all 10 people are affected is only 2.23%, a low but significant probability that all the individuals are in the critical zone. This result is influenced by the uniformly random distribution of the position of individuals and the variable size of the blast effect (Fig. 5).

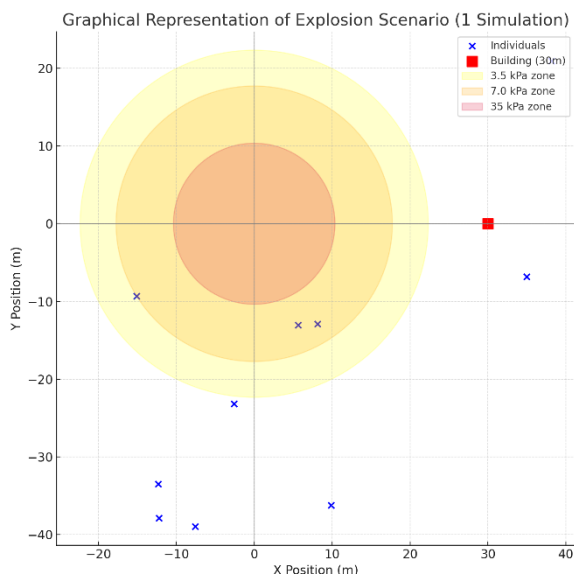


Fig. 5. Graphical representation of the explosion scenario (randomly taken between 10,000 simulations)

Regarding the distribution of the number of affected individuals, the analysis shows that most of the simulations implied 2 to 7 affected persons, with frequency peaks in the range of 5 to 6 affected persons, indicating an area of medium-extended risk.

The probability that the building at 30 m to be affected is high, 76.99%. This threshold corresponds to an estimated shockwave pressure between 0.3 and 1.0 bar, which can lead to significant structural damage.

Based on the findings of this study, the following recommendations are proposed to enhance safety in the context of high-pressure hydrogen storage and refueling infrastructure:

1. **Safety Distance Reassessment:** Regulatory bodies should consider revising minimum safety distances for hydrogen refueling stations, particularly in semi-urban and urban environments, to reflect probabilistic blast impact zones.
2. **Probabilistic Risk Integration:** Risk assessment protocols should incorporate stochastic modeling methods such as Monte Carlo simulations to better capture real-world uncertainties in explosion behavior and human exposure.
3. **Infrastructure Siting and Shielding:** Strategic placement of critical infrastructure and implementation of physical barriers or blast shields can significantly mitigate the consequences of high-energy accidental releases.
4. **Sensor and Control Systems:** Enhanced detection technologies and automated shutdown systems should be deployed to reduce the likelihood of catastrophic failure or to minimize hydrogen release durations.
5. **Emergency Planning and Public Awareness:** Clear, data-driven emergency response plans and public education regarding hydrogen station risks should be integrated into urban planning frameworks.
6. **Further Multiphysics Simulation:** Future work should extend this model with CFD-based dispersion analysis and coupling with fire propagation and structural failure models for a more holistic risk profile.

4 Conclusions

This study demonstrates the applicability and importance of Monte Carlo simulation in evaluating the risk posed by hydrogen refueling stations in semi-urban environments. Despite the low annual probability of catastrophic failure, the simulation results reveal that the consequences of a high-pressure hydrogen explosion can be severe in terms of both human casualties and structural damage. The likelihood of affecting nearby individuals and buildings remains high even under conservative assumptions, indicating a clear need for stricter safety protocols.

The key conclusions drawn from this analysis suggest that current safety distances and urban planning standards may not be sufficient to mitigate risk in case of a hydrogen explosion. Thus, the following recommendations are proposed:

Future work should focus on enhancing the physical realism of the model by incorporating computational fluid dynamics (CFD), analyzing the effects of partial release scenarios, validation with Process Hazard Analysis Software Tool (PHASt) software, and leveraging real-world incident data for calibration. The simulation framework developed here offers a transparent and adaptable tool for decision-makers aiming to balance innovation in hydrogen technology with public and environmental safety.

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