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Simplified approach to evaluating safety distances for hydrogen vehicle fuel dispensers

Authors and Affiliations

Makoto HIRAYAMA *[a, b]

[a] Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, JAPAN

Tel: +81-45-339-3973   Fax: +81-45-339-4011   E-mail: kasai-naoya-pf@ynu.ac.jp

[b] TATSUNO CORPORATION, 1-1, Kasama 4-chome, Sakae-ku, Yokohama 247-8570, JAPAN

Yusuke ITO *[a]

Honami KAMADA *[a]

Naoya KASAI *[a] (Corresponding Author)

Tsutomu OTAKI *[b]

Abstract

As the use of hydrogen as a vehicle fuel becomes increasingly popular, the development and construction of hydrogen fueling stations is significantly increasing as well. However, despite its potential benefits, the flammability of hydrogen creates great safety concerns. In this research, along with various other elements related to such stations, we focused on hydrogen dispensers that are in close vicinity to the general public and developed a simple method to evaluate safety distances. Jet fires, explosions, and flash fires were assumed as undesirable scenarios for evaluating safety distances to third parties. The tools used in our evaluation were an open-access software application and a widely used spreadsheet program that all engineers should be able to access readily. Applying our method to a model hydrogen dispenser, we obtained safety distances of 4.9 m for jet fires, 3.9 m for explosions, and 8.0 m for flash fires. The use of our method and the results obtained in this study contribute to facilitate decision-making when setting safety distances for hydrogen dispensers.

Keyword: Hydrogen dispenser, Risk assessment, Safety distance

1. Introduction

In recent years, the use of hydrogen as an energy carrier has been attracting significant public attention for environmental reasons such as countermeasures against global warming and air pollution. Hydrogen is also becoming more popular as a vehicle fuel and the development of hydrogen fueling stations is significantly increasing. In 2018, the number of such fueling stations in Japan reached a total of 100, which is the largest number for any country in the world. Current plans call for the development of 160 sites by 2020 and 320 sites by 2025. In addition, various progressive plans designed to showcase the practical applications of hydrogen utilization are being implemented in the run-up to the 2020 Tokyo Olympic and Paralympic games. For example, the energy supplied to the Tokyo Olympic Village will be primarily hydrogen-based. In addition, the strategy of the Tokyo Metropolitan Government calls for 35 hydrogen fueling stations to be established within the Tokyo Metropolitan Area before the games, which will make it possible for any driver within the area to reach a hydrogen fueling station in less than 15 minutes. Similar efforts are underway in the European Union (EU), China, and the United States. For example, the Hydrogen Mobility Europe (H2ME) project in the EU calls for the installation of 47 new hydrogen fueling stations in the period from 2015 to 2022. As part of this project, the 50th hydrogen station in Germany was installed in Potsdam in September 2018. However, despite the potential benefits of hydrogen, its flammability creates significant safety concerns. Furthermore, even though the energy density of hydrogen is lower than that of gasoline, which means the amount of radiant heat flux released during combustion is relatively small, hydrogen must be handled at high pressure in order to make the cruising range of a fuel cell vehicle (FCV) equal to that of gasoline-powered vehicles. Therefore, it is essential to properly evaluate these safety concerns and take reasonable and effective countermeasures.

Hydrogen fueling stations are often installed in urban areas facing roads and are readily accessible to everyone. An overview of a typical hydrogen station is shown in Fig. 1. The station model is surrounded by other properties and a road. Hydrogen is transferred from cylinders, pressurized to 82 MPa by a compressor, and then stored in the accumulators. FCVs are then filled with hydrogen through the dispenser. In hydrogen fueling station risk assessments, one point that differs from chemical plants or oil refineries is that such stations are utilized by members of the general public who have not been educated in the safe handling of the fuel. Hence, they cannot be handled in the same manner as plant operators.

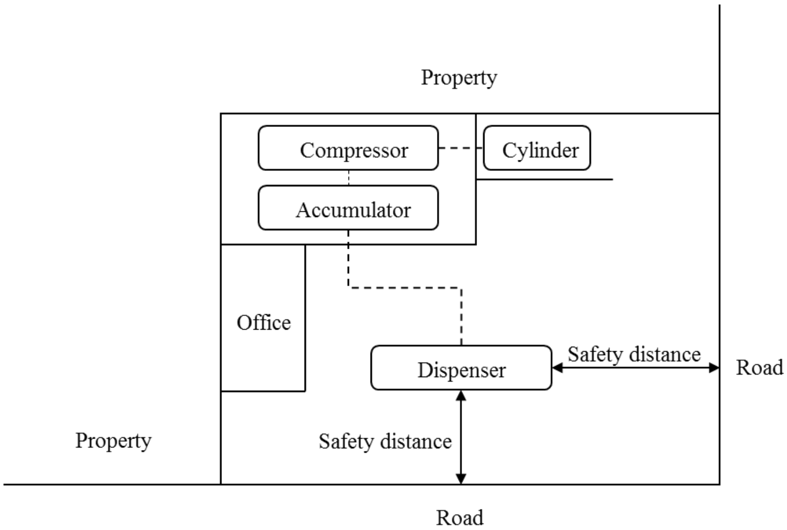


Fig. 1 Hydrogen station outline

In this research, while examining various other fueling station elements, we paid particular attention to dispensers that are in close vicinity to the general public. Although the severity level of an explosion and/or the fire risks involving compressors or accumulators can be controlled to some extent by the installation of firewalls [1–3], it is unrealistic to install firewalls around dispensers that must be readily accessible to vehicle drivers. Furthermore, for driver convenience, dispensers are commonly installed closer to roads than other facilities. Therefore, special attention is required when considering the impact of such fueling stations on third parties, as well as safety measures that can mitigate accidents such as fires or explosions.

Although previous studies on safety issues related to hydrogen fueling stations have focused primarily on compressors and accumulators because of the sizes of their inventories, there have been few studies on dispensers that directly affect the general public. Additionally, while the conventional method of ranking each component by inventory is effective in an initial screening, and while it is reasonable that components containing more fuel should receive more attention, it is necessary to remember that each component is a part of a complete system that is interconnected via pipes. Thus, all the inventory of the entire station is affected in cases where, for example, a shutoff valve between devices does not function correctly. This point must be kept firmly in mind when potential accident scenarios are identified.

There have also been studies related to hydrogen fire and explosion issues. Some of those studies experimentally analyzed the characteristics of such accidents [4–6], while others were based on numerical calculations such as computational fluid dynamics (CFD) [7–18]. However, these studies focused on large-scale facilities such as hydrogen production plants and cannot be directly applied to dispensers due to the unique features of the latter.

There have been other studies that focused on hydrogen fueling stations and examined safety distances [19–25], but the accident scenario assumptions and safety distances varied widely in those studies and gave less attention to dispensers. As a result, no consensus has yet emerged to bridge the gap between international standards and local regulations [26–29]. Furthermore, the schemes presented thus far require the use of expensive software such as FLame ACcelerator Simulator (FLACS) or Process Hazard Analysis Software (PHAST), and expert skills are needed to apply them. In this study, we propose a specialized scheme that can be used to evaluate safety distances for vehicle hydrogen dispensers. Since it is a simple method that is based on open access software and a widely-used calculation application, it can be used readily by any engineer. In the sections below, this method will be applied to a hydrogen dispenser model and its ability to calculate safety distances will be examined.

2. Dispenser model description

Although there are several types of hydrogen fueling stations, their dispenser specifications are approximately the same. A typical hydrogen dispenser model is shown in Fig. 2. As can be seen in this figure, hydrogen from an accumulator enters the dispenser housing through piping and is cooled by a heat exchanger. Then, the hydrogen is transferred into the tank of an FCV through a hose unit mounted outside the housing. The operating pressure is 82 MPa, the flow rate is 5 kg/min, and the volume inside the housing is 2.3 m^3.

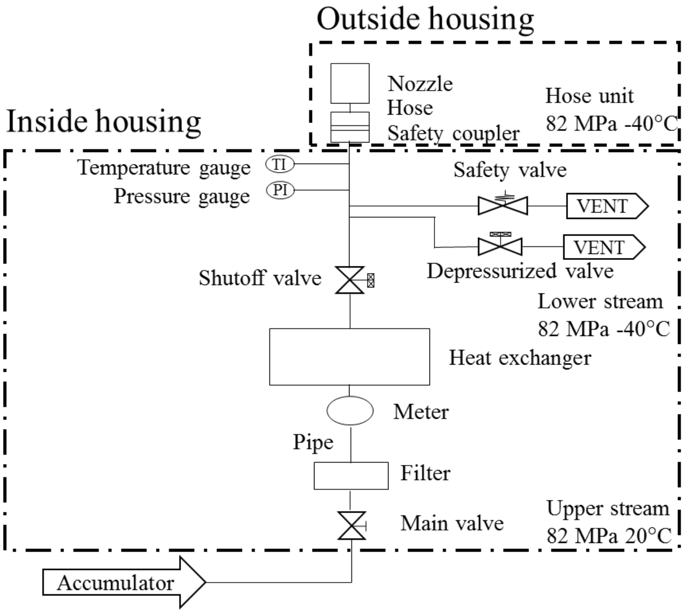


Fig. 2 Hydrogen dispenser model

3. Simplified approach to evaluating safety distances

There are various potential accident scenarios related to hydrogen fuel dispensers. The high-risk scenarios are initiated by hydrogen leakage from various causes, after which the gas is ignited and induces either a fire or an explosion. Figure 3 shows an event tree resulting from high-pressure hydrogen leakage. If the gas is not ignited, there is no effect from the safety assessment point. However, in the case of immediate ignition, a jet fire with a long flame length is generated due to the influence of high pressure, and in the case of delayed ignition, an explosion is generated from the premixed gas. In hydrogen dispensers, leakage from a hose unit outside the housing might form a jet fire, and there is a possibility that an explosion may occur if the hydrogen gas mixes with air inside the housing. In the case of the delayed ignition of a leaked hydrogen cloud from the hose unit outside the housing, a flash fire is generated.

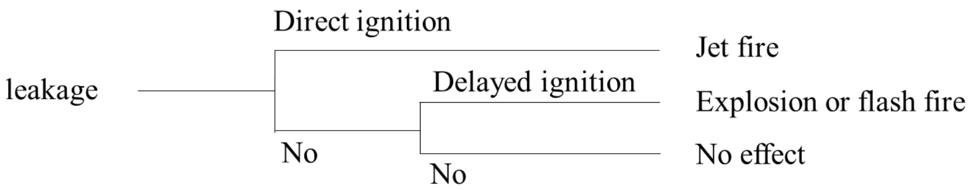


Fig. 3 Hydrogen leakage event tree

Regarding jet fires and explosions, the relationship between the radiant heat flux or blast pressure and the distance from the dispenser are analyzed by simulation software and empirical formulae while assuming leakage and ignition both inside and outside the housing. Then, the influence of radiant heat flux and blast pressure on a third party is examined and derived from the relationship between the fatality probability (FP) and distance. Ultimately, by comparing the results obtained with a risk acceptance criteria, the safety distance from the dispenser can be analyzed. Furthermore, since a reliable calculation model of the severity of flash fires has not yet been established, in our hydrogen dispersion analyses, the distance in which the gas concentration is below the lower flammability limit (LFL) is examined.

3.1 Jet fire analysis

Regarding an accident scenario that involves the leakage of hydrogen from the outside of the dispenser housing, it is assumed that the shutoff valve and the excess flow valve was fully opened without being activated and that hydrogen gas is escaping from the hose unit outside the housing. This scenario presumes the leaked hydrogen ignites immediately and generates a jet fire. Since the main cause of damage, in this case, is radiant heat flux from the flame, the radiant heat flux of the jet fire is evaluated using the Hydrogen Risk Assessment Model (HyRAM) software application [30]. The physics mode is based on the jet fire model in consideration with buoyancy effect and the model was validated by the comparison with experimental data [11]. The coordinates used for the HyRAM simulation are shown in Fig. 4. In this simulation, hydrogen leaks from points (0, 0, and 1) in the x-axis direction and ignites immediately. Next, the relationship between the radiant heat flux from the jet fire and distance is calculated. Calculations are performed for leak hole diameters of 0.05, 0.2, 1.0, and 2.0 mm. The other parameters are shown in Table 1. Assuming that the selection probability of life and death is normal distribution, the FP is calculated from the value of the radiant heat flux obtained by the simulation by using the probit function Y shown below [31]. The equations have been determined by existing experimental data. I refers to the heat flux in kW / m^2, and t is the exposure time in seconds, which is 2 s.

$$Y = -12.8 + 2.56 \ln I^{4/3} t \qquad (1)$$

$$FP = 0.5 \left(1 + \frac{2}{\sqrt{\pi}} \int_0^{\frac{Y-5}{\sqrt{2}}} e^{-t^2}\, dt\right) \qquad (2)$$

Also, assuming that the selection probability of life and death is logistic distribution, the FP is as follows.

$$FP = \frac{e^Y}{1 + e^Y} \qquad (3)$$

Equations (2) and (3) and their probability density functions are shown in Fig. 5. Both have FP=0.5

when Y=5, and these probability density functions (PDF) of normal distribution and logistic distribution have the same value when Y=3.29 and 6.71. It means the values of $I^{4/3}t$ between probit and logit functions are same at these Y values. Therefore, assuming that the form of the logit function is Y=a+b $\ln I^{4/3}t$, the probit function and the logit function are identical. By substituting the equation (1) into the equation (3), the FP is obtained under the assumption that the selection probability of life and death is logistic distribution.

Next, the safety distance is derived so that FP is lower than the acceptance criterion. The acceptance criteria 10^{-8} year^{-1} is used to indicate a negligible level of risk [32]. This value originated in the Netherlands and seems to be universally accepted as it is the most conservative criteria in the EU. Assuming that the frequency of leakage and ignition is 1 year^{-1} and the probability of a shutoff valve failure is 10^{-2}, the allowable FP is 10^{-6}. Since an acceptance criterion of 10^{-8} year^{-1} is used to indicate a negligible level of risk, the safety distance from the dispenser is obtained from the distance where the FP is 10^{-6} or less.

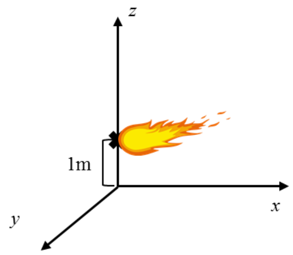


Fig. 4　Coordinates of jet fire simulation

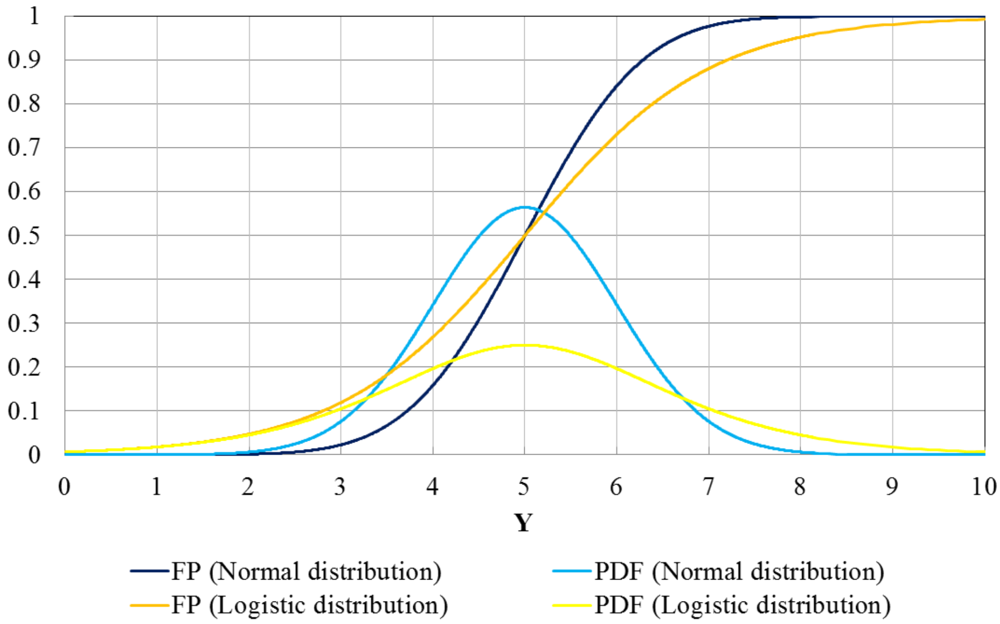


Fig. 5　FP and PDF (Normal and logistic distributions)

Table 1　Input parameters of jet fire analysis

Ambient temperature	15°C
Ambient pressure	0.1 MPa
Hydrogen temperature	-40°C
Hydrogen pressure	82 MPa
Hole diameter	0.05, 0.2, 1.0, 2.0 mm

3.2 Explosion analysis

For an accident scenario that assumes leakage from inside the housing, it is considered that hydrogen has leaked from a joint inside the housing after the shutoff valve closed and is accumulating within the housing. In this scenario, an explosion involving hydrogen premixed with air occurs after delayed ignition. In this case, we focus on the main explosive damage, which is produced by the blast pressure. The following empirical formula is used for the analysis [33]. Since it is assumed that peak pressure is proportional to the cube root of the total energy release, the equation is derived from experimental data for a mixture of 30% hydrogen gas in air as the maximum severity.

$$P=41.5\times W^{\frac{1}{3}}\times R^{-1.1} \quad (4)$$

Here, P is the maximum peak overpressure in kPa, W is the amount of hydrogen in kg, and R is the distance in meters from the ignition point. The volume of hydrogen is set to 0.69 Nm^3 as 30% of the housing volume and is 0.062 kg when converted to weight. From the obtained blast pressure value, the FP is calculated by using the following probit function Y obtained from the Dutch “Green Book” [34], which describes the impact on humans from toxic substance exposure, heat radiation, and overpressure. The equations have been determined by existing data and criteria. The probit function for lung damage is as follows:

$$Y=5.0-5.74\ln S \quad (5)$$

$$S=\frac{4.2}{\overline{P}}+\frac{1.3}{\overline{i}}\ ,\ \overline{P}=\frac{P}{P_0}\ ,\ \overline{i}=\frac{i}{P_0^{\frac{1}{2}}\times m^{\frac{1}{3}}}$$

Here, m is the weight of a person and is assumed to be 60 kg, while P_0 is atmospheric pressure and i is the impulse from the blast. Assuming that the exposure time of the blast is 0.05 s, the impulse is obtained from the following equation:

$$i=\frac{1}{2}Pt$$

The probit function used to determine the probability of survival after impact with the whole body is as follows:

$$Y=5.0-2.44\times \ln S \quad (6)$$

$$S=\frac{7.38\times10^{3}}{P}+\frac{1.3\times10^{9}}{P\times i}$$

The probit function used to determine the probability of survival after an impact to the head is as follows:

$$Y=5.0-8.49 \ln S \quad (7)$$

$$S=\frac{2.43\times10^{3}}{P}+\frac{4.0\times10^{8}}{P\times i}$$

The FP is calculated by substituting the probit function obtained by the above equations into function (2) and (3). The frequency of leakage and ignition is assumed to be 1 year^{-1}. When the acceptable risk criterion is 10^{-8} year^{-1}, the allowable FP is 10^{-8}. The safety distance is taken from the distance where the FP is 10^{-8} or less.

3.3 Analysis of flash fire

In this accident scenario, the leakage is assumed to be the same as that for the jet fire described above. Specifically, a continuous leak from the hose unit caused by a shutoff valve malfunction. Since there are no well-developed models for evaluating the severity of a flash fire, the dispersion of leaked hydrogen is analyzed using the HyRAM software and the point where the concentration is lower than the LFL is evaluated.

HyRAM follows the fast running engineer model created by Houf and Schefer, and the process was simplified by the assumption that the mean velocity profiles are Gaussian [35]. The leaks were considered as unchoked releases in the Froude number range where both buoyancy and momentum are important. It has been verified by comparison with experimentally measured concentration profiles of hydrogen slow leaks. The model determines the trajectory of the buoyant jet and the hydrogen concentration decay. The input parameters are shown in Table 2.

Table 2 Input parameters of dispersion analysis

Ambient temperature	15°C
Ambient pressure	0.1 MPa
Hydrogen temperature	-40°C
Hydrogen pressure	82 MPa
Jet angle	0° (horizontal)
Hole diameter	0.05, 0.1, 1.0, 6.0 mm

4. Result and discussion

The results of the jet fire analysis are shown in Fig. 6. As it was assumed to be a case in which the shutoff valve did not function and the hydrogen leakage continued in a steady state, the value of the radiant heat flux was significant. More specifically, as the leak hole diameter increased, the radiant heat flux value became greater. This result shows that the hole diameter size assumption is a critical component of the risk assessment result.

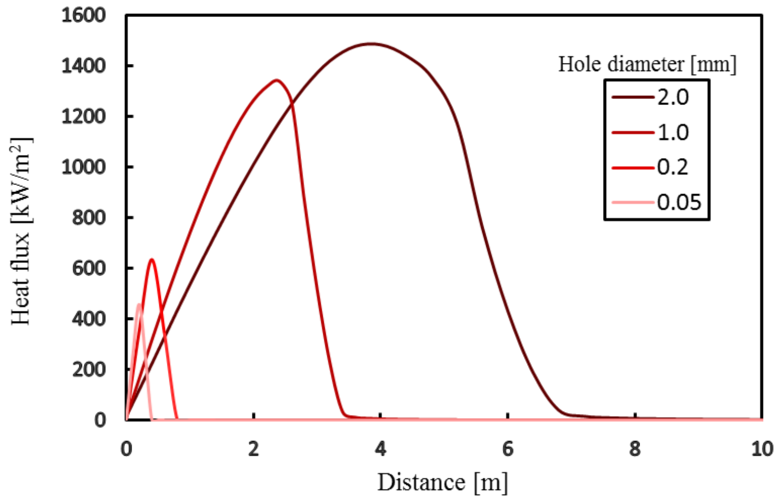
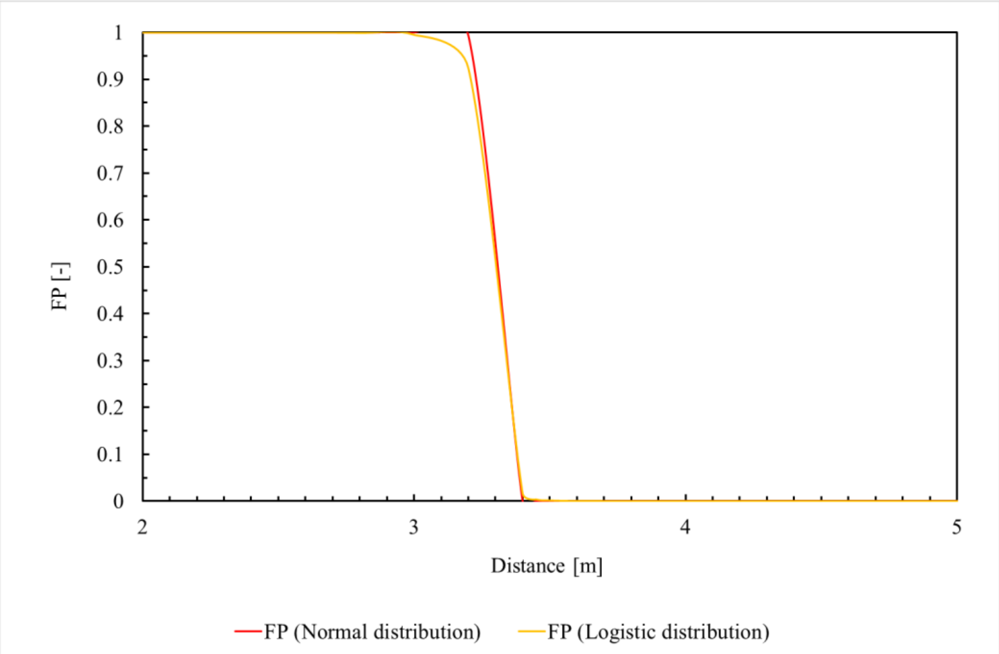
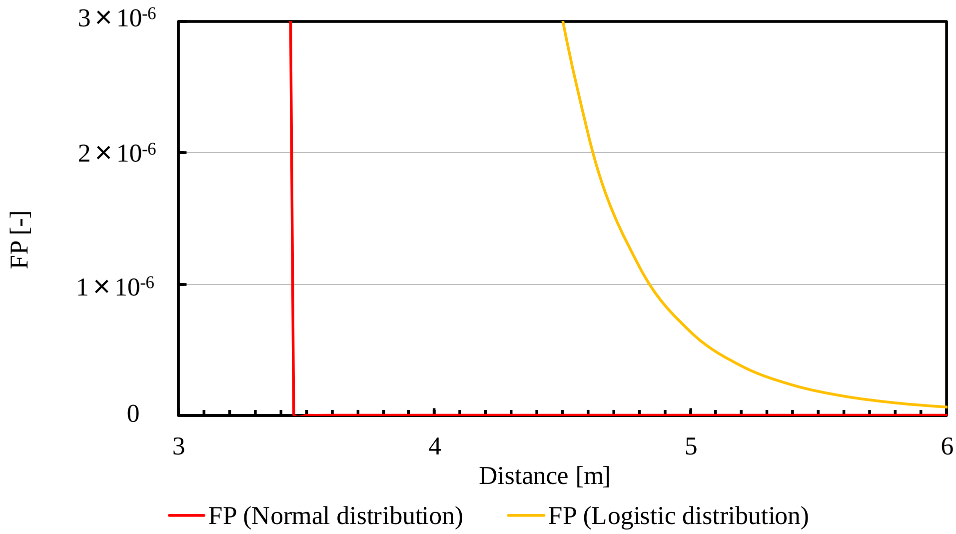


Fig. 6 Heat flux as a function of distance

Figure 7 shows the FP results calculated by using the function (2) and (3) with the radiant heat flux value calculated in a simulation involving a 1.0 mm hole diameter. In the region where the distance was short, the FP was approximately 1 and the value of FP abruptly decreased from a distance of around 3.4 m. Assuming normal distribution, the safety distance from the hydrogen dispenser model for a jet fire was 3.5 m when the allowable FP was 10^{-6}. Assuming logistic distribution, the safety distance is 4.9 m when analyzed similarly. When these results are compared, the logistic distribution has larger variance, so conservative result was obtained.



(a)



(b)

Fig. 7 FP as a function of distance

(a) Overall graph, (b) Enlarged view where FP is around 10^{-6}

The blast pressure obtained from the explosion analysis is shown in Fig. 8 and displays a decreasing exponential. The blast pressure was converted to the three FPs based on impacts to the lung, head, and whole body. Figure 9 shows the relationship between the FPs and the distance from the dispenser. In areas with distances shorter than 0.3 m, head impacts were dominant. From the distance of 0.3 m, whole body impacts became dominant. The shape of the FP graphs had a long tail and the safety distance from an explosion inside the housing was 2.5 m when normal distribution is assumed, or 3.9 m when logistic distribution is assumed as the allowable FP was 10^{-8}. Conservative results were obtained under the assumption of logistic distribution. The impact of flying debris of the housing from an explosion may be greater than the blast pressure itself. However, the actual dispenser has a vent at the top part of the housing for the pressure release. In addition, ANSI / CSA GV4.1 (2013) [36], which is a standard for hydrogen dispensers, requires that a total size of the pressure relief and ventilation opening(s) near the top shall be at least 20 cm^2.

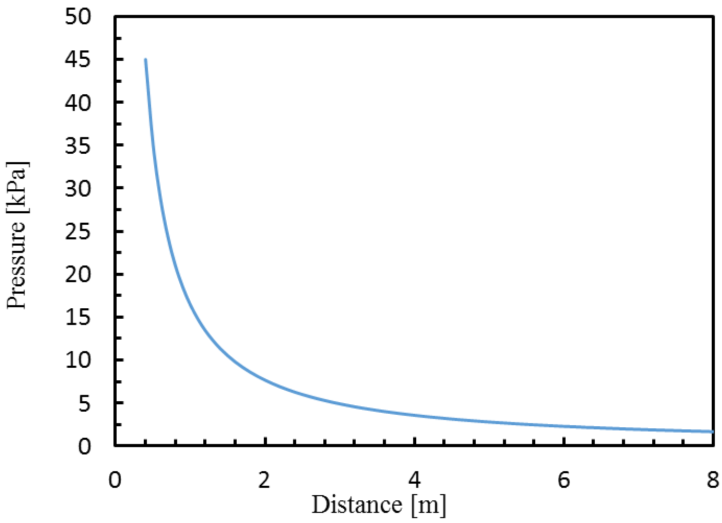
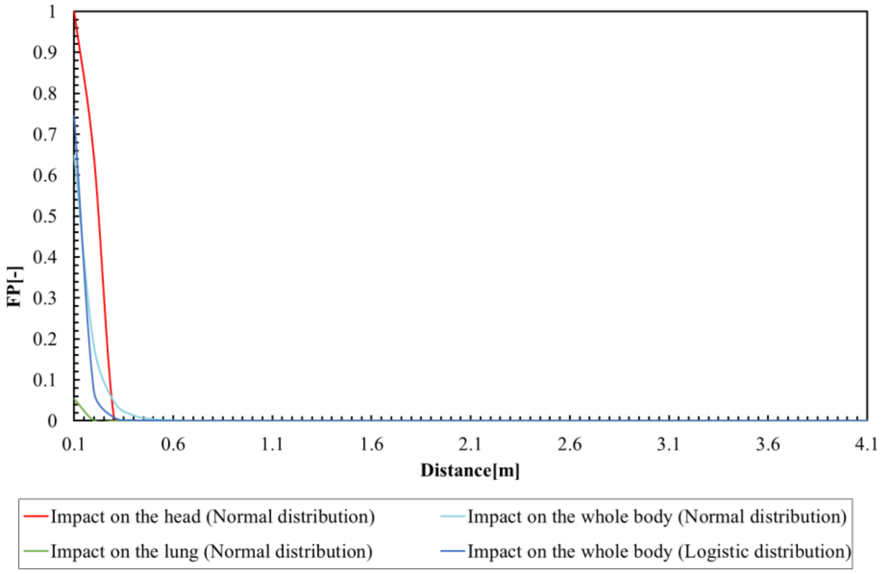
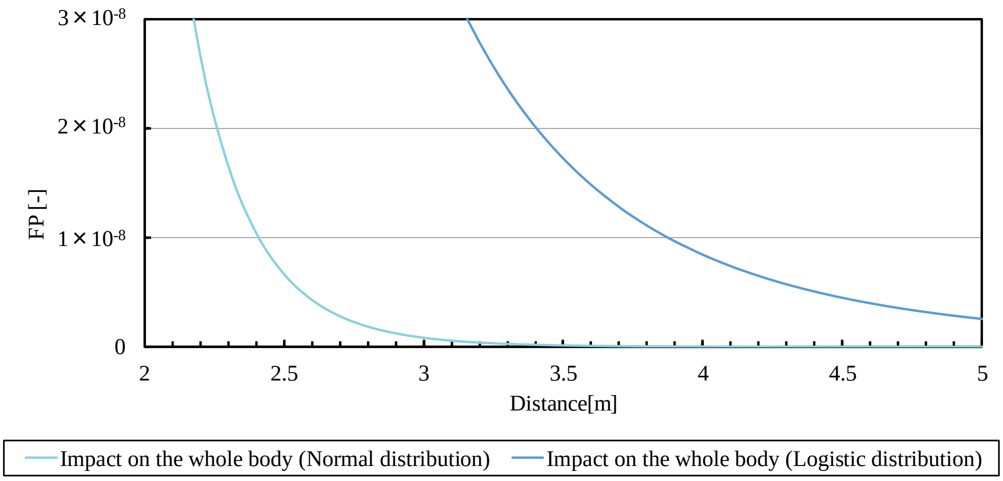


Fig. 8 Pressure as a function of distance



(a)

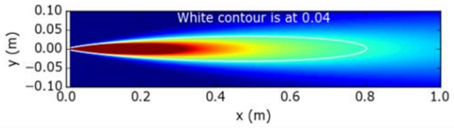
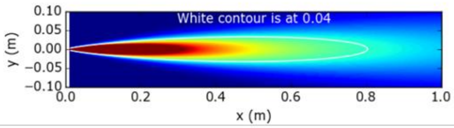
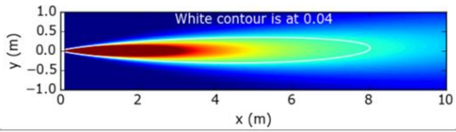
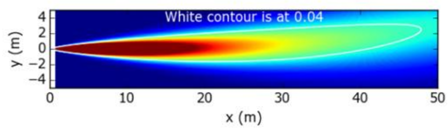


(b)

Fig. 9 FP as a function of distance

(a) Overall graph, (b) Enlarged view where FP is around 10^{-8}

For the flash fire analysis, the simulation result in the case of horizontal leakage is shown in Fig 10. Here, we can see that the diffusion distance was large in the jet direction and that the relationship between the hole diameter and the diffusion distance was linear. Additionally, it was confirmed that when the hole diameter was no more than 1.0 mm, the momentum was dominant, and the effect of buoyancy was negligible. When the hole diameter was assumed to be 6.0 mm, the diffusion range in the horizontal direction was relatively wide due to the buoyancy effect. Although a general hydrogen station has a canopy upward of a dispenser, it has a structure in which hydrogen does not stay. It is required as a safety measure in Japanese regulation. For example, it has openings for the ventilation. Assuming that the opening diameter is 1.0 mm and the hydrogen concentration was 4% or less, the safety distance was calculated at 8.0 m. This level matches current Japanese regulations [37]. It should be noted that only free jet is considered in the simulation model of this study and the distance changes by the effect of obstacles in the environment. Especially, it was reported that the distance from a jet released in close proximity to ground is longer than that from a free jet [38–40].

Hole diameter	Concentration mapping	4% boundary
0.05 mm		0.80 m
0.1 mm		0.80 m
1.0 mm		8.0 m
6.0 mm		48 m

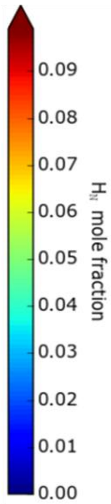


Fig. 10 Concentration mapping and 4% boundary

An overview of results and assumptions are shown in Table 3. The safety distance for a flash fire was 8.0 m, which was the longest. The safety distance for a jet fire is longer than that for an explosion because of the effect of high pressure. In order to reduce the leakage frequency, it is highly effective to select materials and fitting methods properly at the design stage, and to perform periodic maintenance after installation. As for ignitions, the frequency of such incidents can be reduced by improved ventilation and ignition sources removal methods, such as static electricity countermeasures and the use of explosion-proof equipment. However, since it is impossible to completely eliminate leakage and ignition sources, it is necessary to consider safety measures that will reduce the severity of accidents. To reduce the accident consequence severity, widely used safety measures to reduce leakage amounts include temperature and pressure monitoring and the use of shutoff valves. Temperature and pressure are observed in detail in order to satisfy the filling protocol outlined in SAE J2601 [41]. When the value of the temperature or pressure exceeds the criteria, the dispenser shutoff valve will automatically close. One additional established safety measure is safety distance. It is clear that the accident consequence severity of a fire or explosion could be reduced if there is sufficient distance between the site and any third parties. Hence, a safe distance should always be set between a hydrogen fuel dispenser and the site boundary. On the other hand, the sites available for hydrogen fueling stations in urban areas are quite limited, so it is clearly important to define safety distances reasonably in order to facilitate the use of hydrogen-fueled vehicles. Taken together, the results of our study contribute to the decision-making process used when determining proper safety distances for hydrogen dispensers.

Table 3 Results and assumptions

Potential accident scenario	Assumptions	Safety distance
Jet fire (Radiant heat flux)	Hole diameter: 1 mm Exposure time: 2 s Distribution: Normal	3.5 m
	Hole diameter: 1 mm Exposure time: 2 s Distribution: Logistic	4.9 m
Explosion (Blast pressure)	Inventory: 0.062 kg Exposure time: 0.05 s Distribution: Normal	2.5 m
	Inventory: 0.062 kg Exposure time: 0.05 s Distribution: Logistic	3.9 m
Flash fire (Dispersion)	Hole diameter: 1 mm Concentration criteria: 4%	8.0 m

5. Conclusion

In this study, we developed a simple method that is specifically intended for use in the evaluation of safety distances for hydrogen fuel dispensers. Herein, jet fires, explosions, and flash fires were assumed as undesirable scenarios for evaluating the safe distances from the hydrogen dispenser to a third party. The tools used in our analysis were an open access software application and a widely used spreadsheet program that can be accessed by any engineer.

Applying this method to an example of a hydrogen dispenser model, we obtained a safety distance of 4.9 m for jet fires, 3.9 m for explosions, and 8.0 m for flash fires. We believe that our proposed method and experimental results contribute to the decision-making process used to determine proper safety distances for hydrogen dispensers.

6. Acknowledgements

The authors would like to thank TATSUNO CORPORATION and Yokohama National University for the financial support and advice provided.

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Table

Table 1: Input parameters of jet fire analysis

Ambient temperature	15°C
Ambient pressure	0.1 MPa
Hydrogen temperature	-40°C
Hydrogen pressure	82 MPa
Hole diameter	0.05, 0.2, 1.0, 2.0 mm

Table 2: Input parameters of dispersion analysis

Ambient temperature	15°C
Ambient pressure	0.1 MPa
Hydrogen temperature	-40°C
Hydrogen pressure	82 MPa
Jet angle	0° (horizontal)
Hole diameter	0.05, 0.1, 1.0, 6.0 mm

Table 3: Results and assumptions

Potential accident scenario	Assumptions	Safety distance
Jet fire (Radiant heat flux)	Hole diameter: 1 mm Exposure time: 2 s Distribution: Normal	3.5 m
	Hole diameter: 1 mm Exposure time: 2 s Distribution: Logistic	4.9 m
Explosion (Blast pressure)	Inventory: 0.062 kg Exposure time: 0.05 s Distribution: Normal	2.5 m
	Inventory: 0.062 kg Exposure time: 0.05 s Distribution: Logistic	3.9 m
Flash fire (Dispersion)	Hole diameter: 1 mm Concentration criteria: 4%	8.0 m

Figure

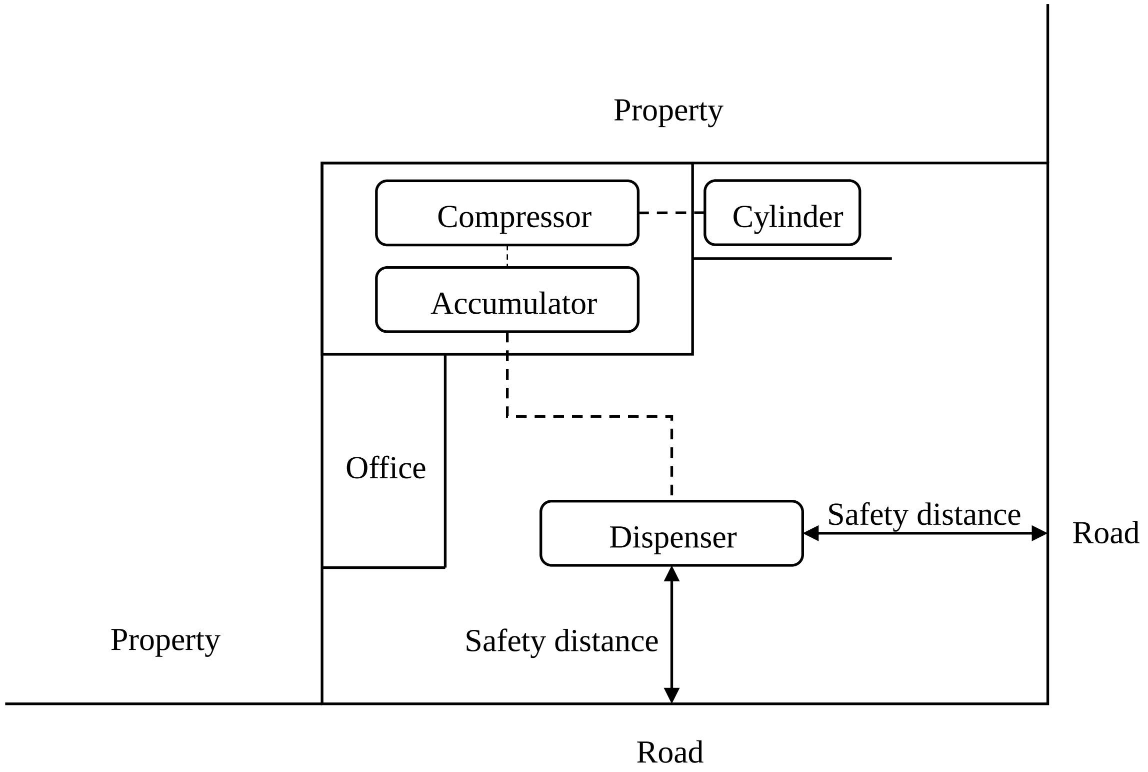


Fig. 1: Hydrogen station outline

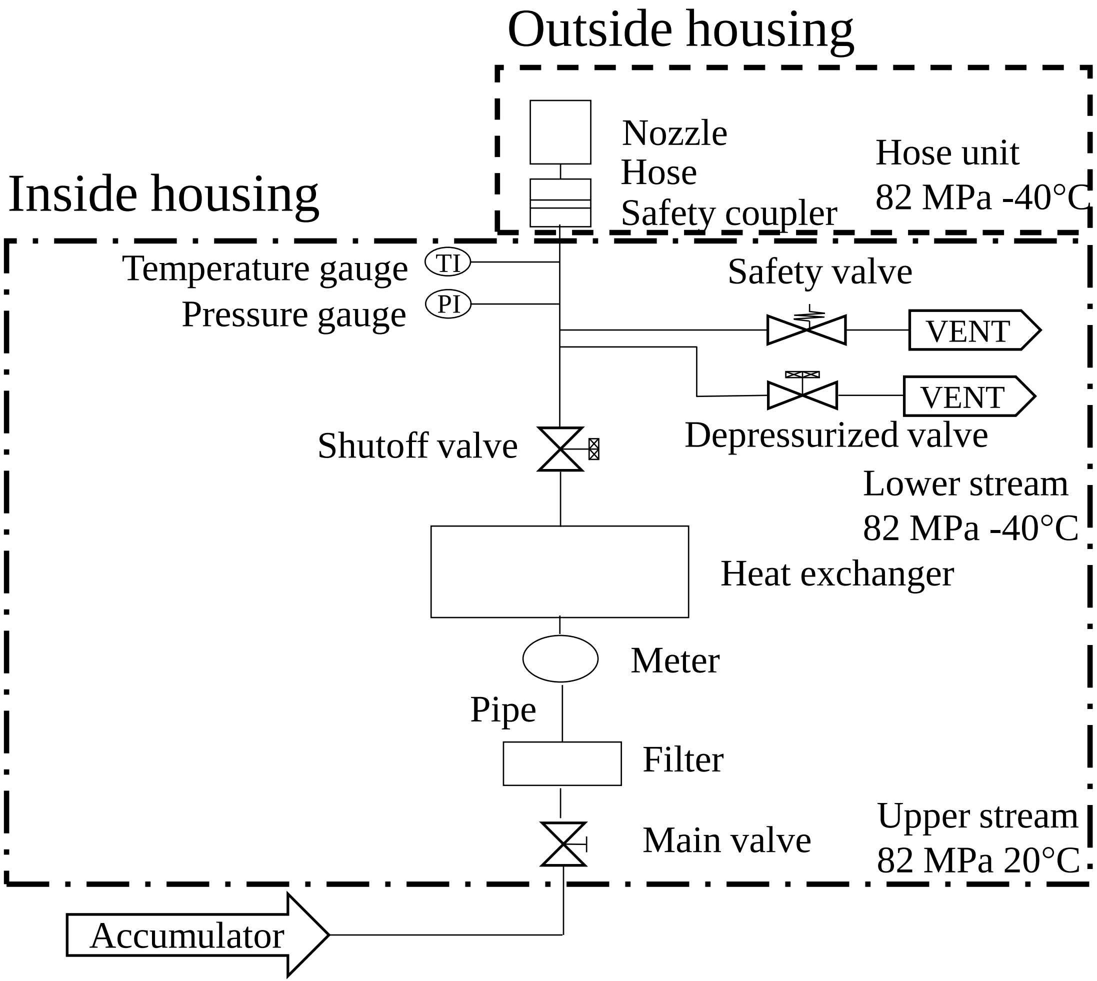


Fig. 2: Hydrogen dispenser model

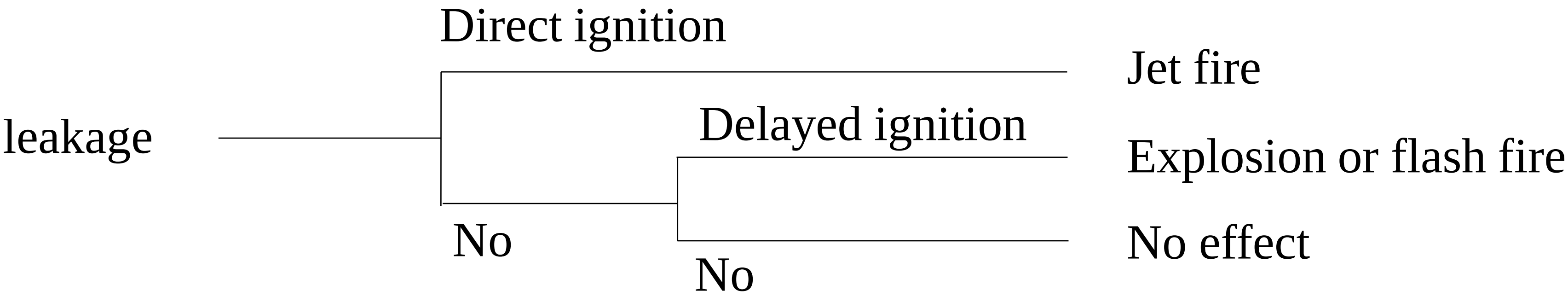


Fig. 3: Hydrogen leakage event tree

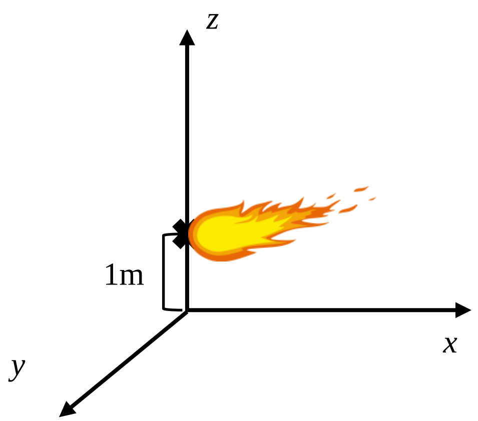


Fig. 4: Coordinates of jet fire simulation

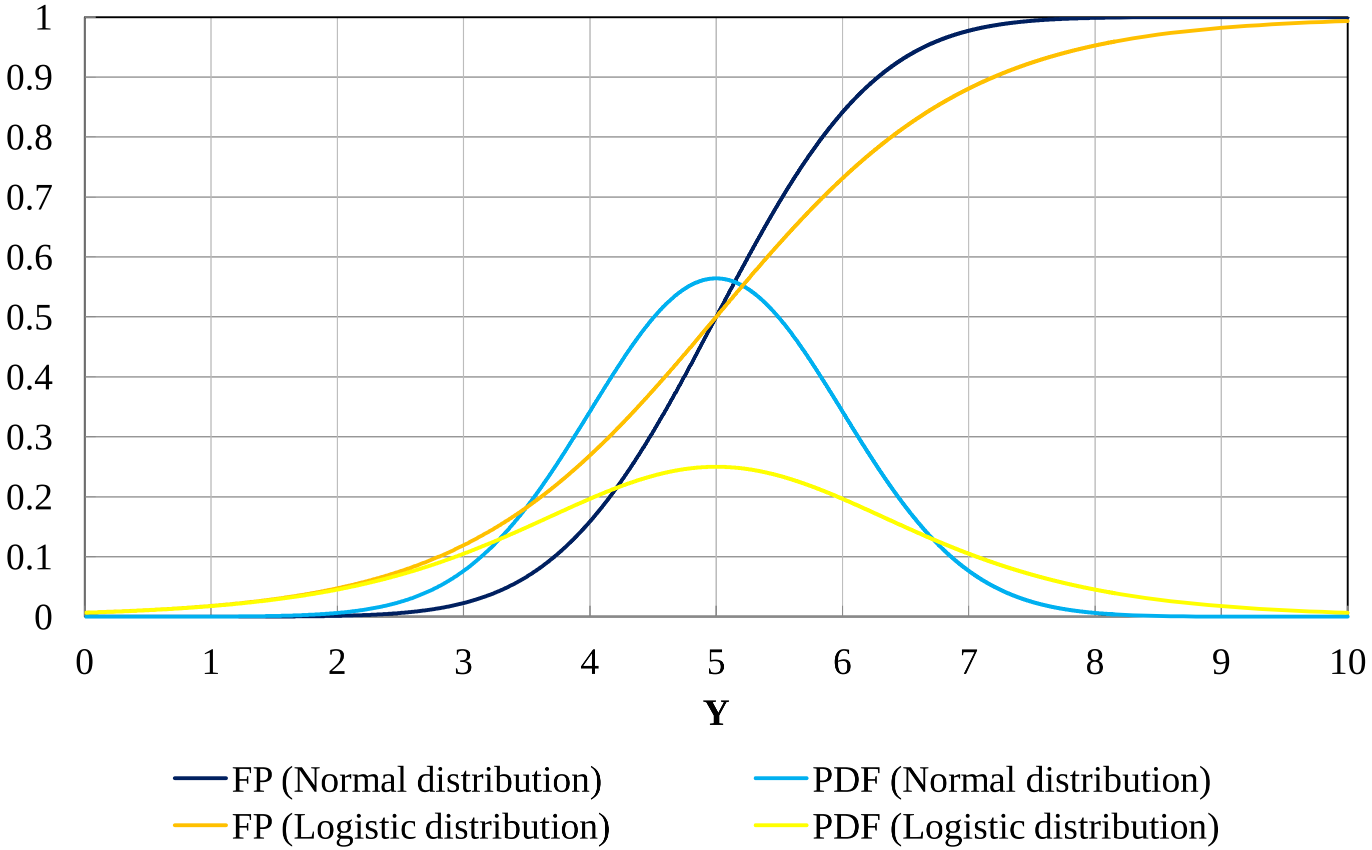


Fig. 5: FP and PDF (Normal and logistic distributions)

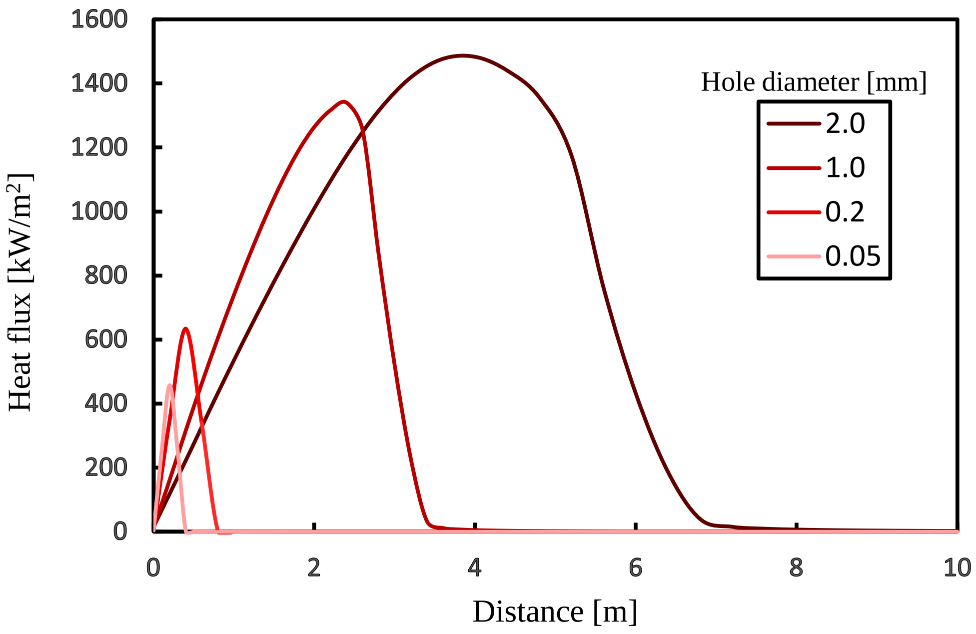
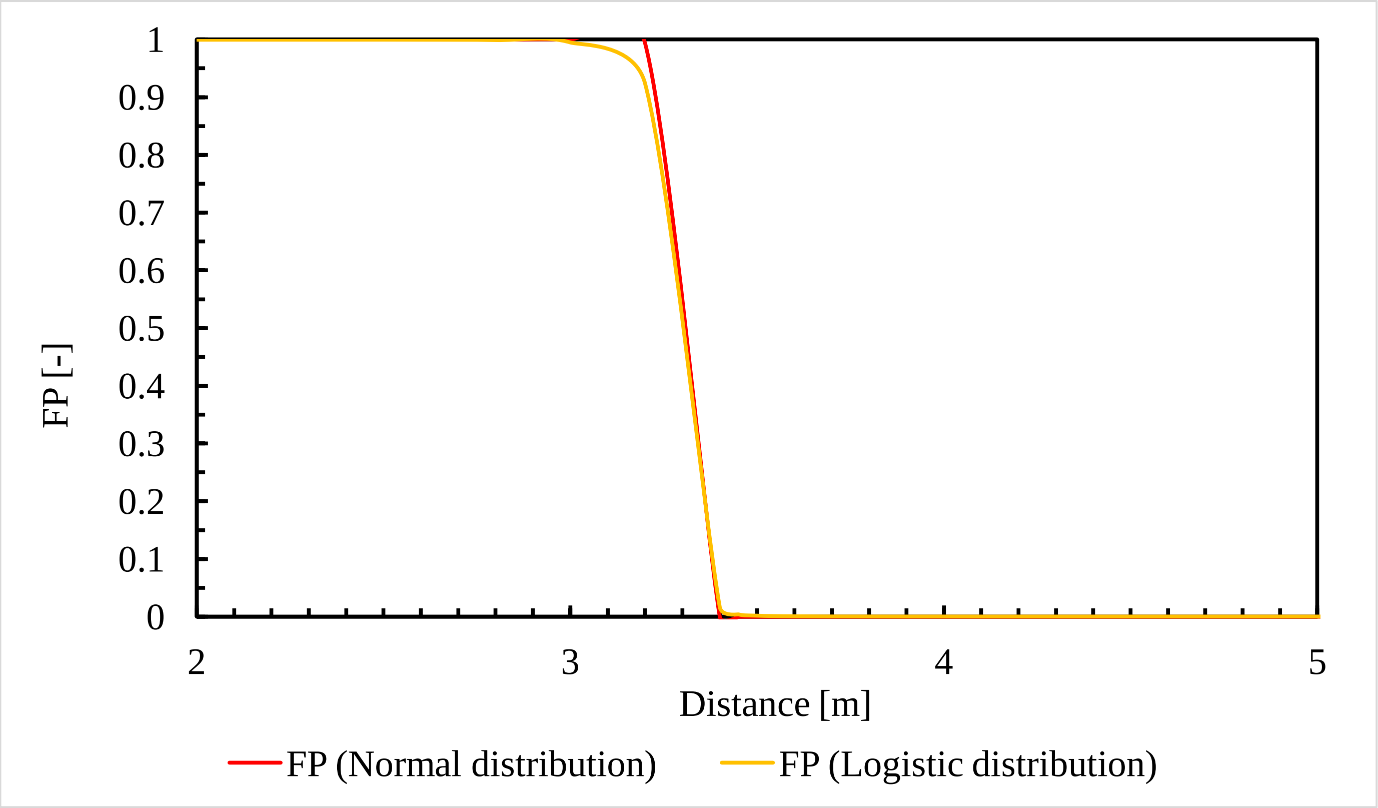
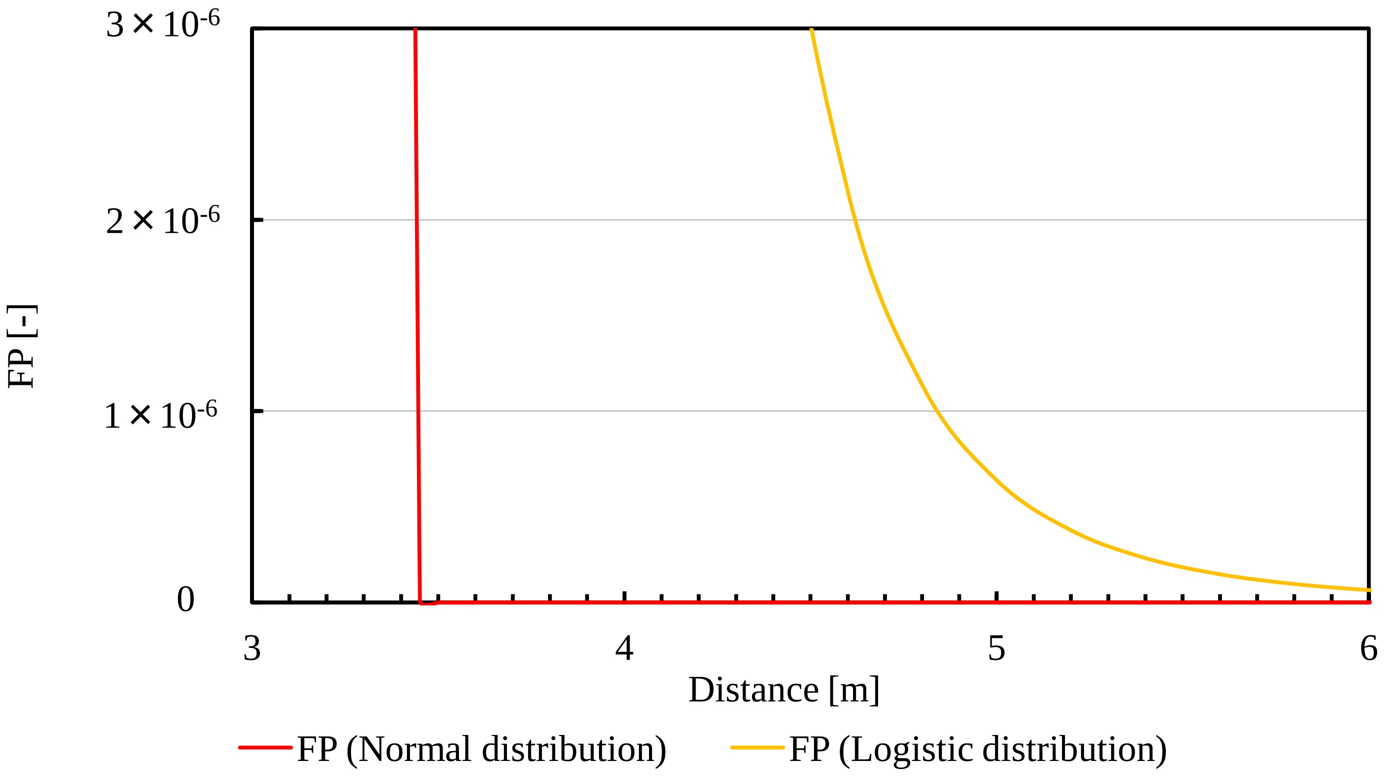


Fig. 6: Heat flux as a function of distance



(a) Overall graph

Fig. 7: FP as a function of distance



(b) Enlarged view where FP is around 10^{-6}

Fig. 7:　FP as a function of distance

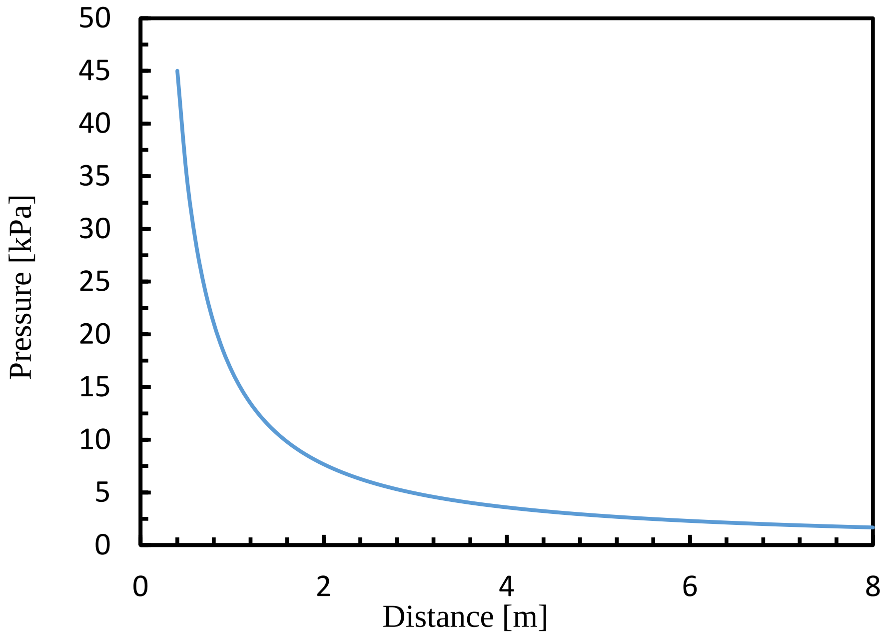
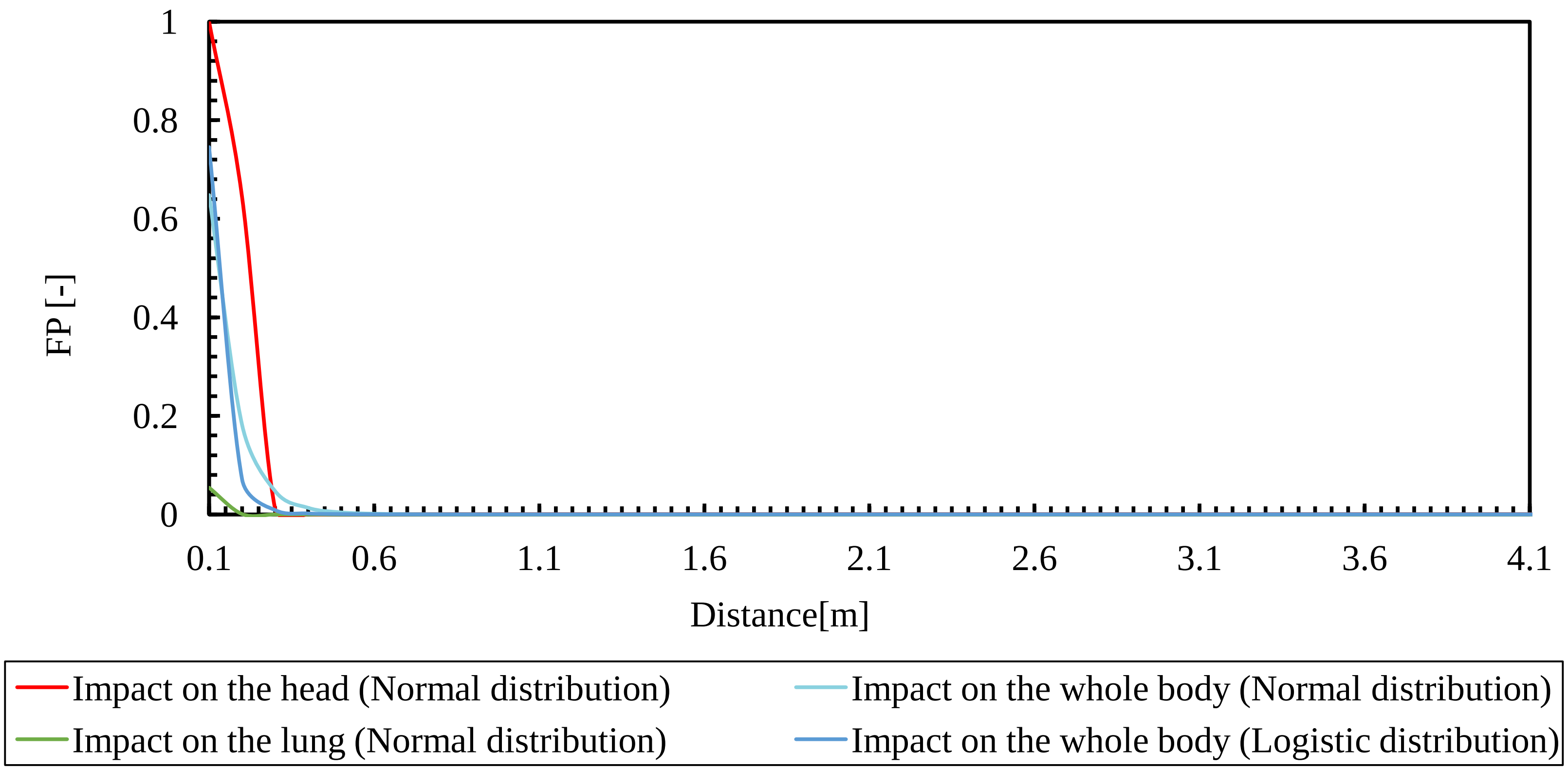
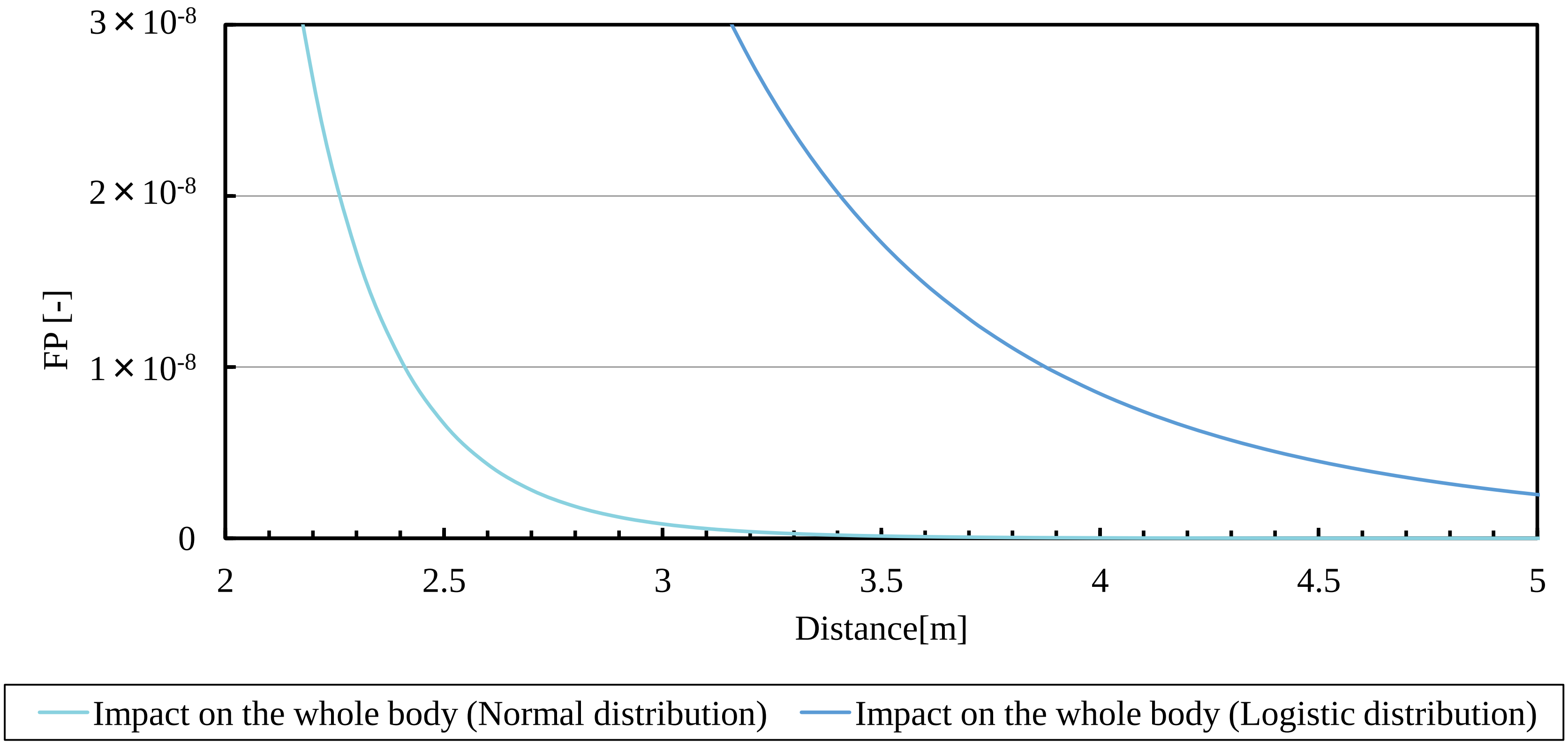


Fig. 8: Pressure as a function of distance



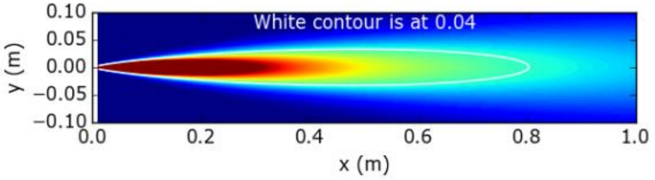
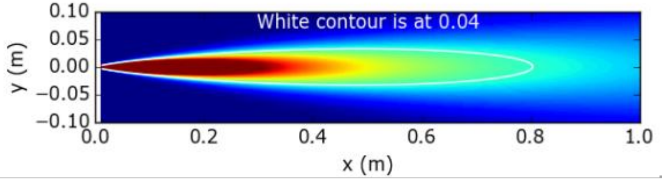
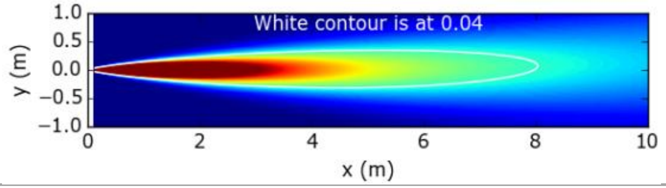
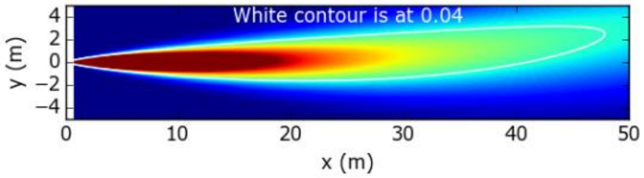
(a) Overall graph

Fig. 9: FP as a function of distance



(b) Enlarged view where FP is around 10^{-8}

Fig. 9: FP as a function of distance

Hole diameter	Concentration mapping	4% boundary
0.05 mm		0.80 m
0.1 mm		0.80 m
1.0 mm		8.0 m
6.0 mm		48.1 m

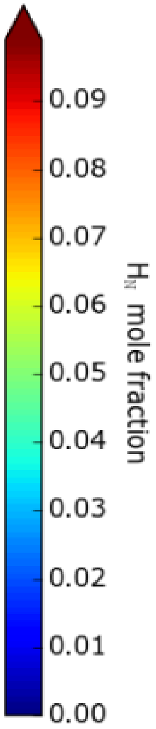


Fig. 10: Concentration mapping and 4% boundary