QUANTITATIVE RISK ASSESSMENT OF THE MODEL REPRESENTING LATEST JAPANESE HYDROGEN REFUELING STATIONS

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ABSTRACT

Current safety codes and technical standards related to Japanese hydrogen refueling stations (HRSs) have been established based on qualitative risk assessment and quantitative effectiveness validation of safety measures for more than ten years. In the last decade, there has been significant development in the technologies and significant increment in operational experience related to HRSs. We performed a quantitative risk assessment (QRA) of the HRS model representing Japanese HRSs with the latest information in the previous study. The QRA results were obtained by summing risk contours derived from each process unit. They showed that the risk contours of 10^{-3} and 10^{-4} per year were confined within the HRS boundaries, whereas those of 10^{-5} and 10^{-6} per year are still present outside the HRS boundaries. Therefore, we analyzed the summation of risk contours derived from each unit and identified the largest risk scenarios outside the station. The HRS model in the previous study did not consider fire and blast protection walls, which could reduce the risks outside the station. Therefore, we conducted a detailed risk analysis of the identified scenarios using 3D structure modeling. The heat radiation and temperature rise of jet fire scenarios that pose the greatest risk to the physical surroundings in the HRS model were estimated in detail based on computational fluid dynamics with 3D structures, including fire protection walls. Results show that the risks spreading outside the north-, west-, and east-side station boundaries are expected to be acceptable by incorporating the fire protection wall into the Japanese HRS model.

1.0 INTRODUCTION

Hydrogen refueling stations (HRSs) are essential for fuel cell vehicles (FCVs); they are widespread in Japan. Japanese Ministry of Economy, Trade, and Industry has set a target of approximately 320 HRSs by 2025 and 900 by 2030 [1]. However, many accidents in HRSs have been reported in accident databases worldwide [2]. Therefore, many researchers have performed quantitative risk assessments (QRAs) to estimate and evaluate the risks of HRSs. For example, Ham et al. [3] conducted a benchmark risk assessment exercise for HRS to identify the differences and similarities in risk assessment approaches, including QRA. Furthermore, Matthijsen et al. [4] obtained safety distances for a compressed HRS using quantitative risk and compared the results with those for a gas station, a compressed natural gas refueling station, and a liquefied petroleum gas refueling station. Moreover, LaChance et al. [5,6] proposed an approach for the risk-informing permitting process for HRSs using QRA techniques to establish a reasonable safety distance. Zhiyong et al. [7–9] performed QRAs for various compressed HRSs and discussed safety distances. Tsunemi et al. [10] estimated the risks for certain scenarios—a hydrogen leak from some components of the accumulator and dispenser unit in an HRS. Gye et al. [11] conducted a QRA for an HRS in an urban area. Furthermore, Sandia National Laboratories [12–14] estimated the leak frequencies of each component used in hydrogen facilities and developed a software toolkit to perform consequence analysis and QRA.

Current safety codes and technical standards related to Japanese HRSs have been established based on the results of a risk assessment implemented as a part of the ‘‘Establishment of Codes & Standards for Hydrogen Economy Society – Study on the Safety Technologies of Hydrogen Infrastructure’’ conducted by the New Energy and Industrial Technology Development Organization (NEDO) from 2005 to 2009. This work identified the risk scenarios for a compressed and liquefied HRS model, assessed them using a qualitative method, and quantitatively verified the effectiveness of the safety measures [15–17]. In the decade since this risk assessment, there has been significant development in the technologies of the components or facilities used in domestic HRSs; moreover, much operational experience (and knowledge) regarding the safe use of hydrogen in HRSs has been gained through years of commercial operation. Therefore, we previously conducted a QRA and visualized the individual risks of an HRS model that is assumed to be located in an urban area representing Japanese HRSs to include up-to-date information and identify the most significant scenarios that pose the greatest risks to the physical surroundings [18]. Based on the results, we concluded that jet fires show the highest contribution to the risks outside the station. Additionally, the contours of 10^{-5} and 10^{-6} per year covered approximately the entire station and were not within the HRS boundaries. Therefore, it is necessary to consider risk mitigation measures to prevent jet fires. Such measures include shortening the hydrogen release time to prevent continuous jet fires or the use of fire protection walls to reduce the heat radiation outside the HRS. Our QRA had already considered some measures to prevent continuous jet fires, such as excess flow valves, gas and flame detection, and shut-off valves. However, even if these risk mitigation measures were considered, it was shown in the previous paper that the most significant risk was the jet fire that occurred during the 12 s before the shut-off valve was activated. The HRS model in the previous study did not consider any 3D structures, such as fire and blast protection walls or fences, which could reduce the risks of jet fires. These walls or fences have demonstrated their effectiveness in actual accident cases [19]. Therefore, we conducted the detailed risk analysis using a 3D structure model with fire and blast protection walls as passive risk mitigation measures to reduce the risk of jet fires to the outside station.

There have been some studies on the consequences and risk analysis of the hydrogen accidental phenomena, such as hydrogen diffusion, vapor cloud explosions (VCE), or jet fires, using computational fluid dynamics (CFD) that can estimate the hydrogen concentration, overpressure, and heat radiation with 3D structures [20][21]. Additionally, many experimental examples, including low to high-pressure conditions, numerical model development, and evaluation of flame length and heat radiation, have been reported regarding jet fires involving hydrogen [22–24].

This study aims to conduct a detailed risk assessment of a latest Japanese HRS model. First, we identified the scenarios from which units had the greatest risk to the area outside the station. Second, we conducted the detailed consequence and risk analyses with 3D structures, especially fire protection walls, using the FLame ACceleration Simulator (FLACS) code [25]. The 3D model of the HRS based on the current safety codes and standards related to Japanese HRSs was constructed. Finally, we calculated the heat radiation and temperature caused by the jet fires from the Trailer and Cylinders units and estimated the individual risks contributing the most at each risk ranking point in the previous study.

2.0 DETERMINATION OF THE SCENARIO ANALYZING IN DETAIL

In this section, we determined the scenarios that should be conducted a detailed consequence analysis with 3D structures such as fire and blast protection walls.

We conducted a QRA of an HRS model representing Japanese HRSs and identified the most significant scenarios that pose the greatest risks to the physical surroundings in the HRS model in the previous paper [18]. First, we defined the HRS model for conducting a QRA and identified hazards and accidental scenarios, such as hydrogen leakage from components causing jet fires, flash fires, or VCEs. Next, we assessed frequencies of the scenarios estimated using event tree analysis (ETA) and consequences calculated by some analytical models of final events. Finally, we estimated individual risk (IR), which is the frequency of an individual dying due to loss of containment events and indicated as a risk contour around the facilities.

The risk displayed as the sum of the individual risks derived from all the units obtained in the previous paper was divided into separate risk contours for each unit. Figure 1 shows the risk contours displayed for each unit. The 10^{-6} risk contour derived from the Trailer unit and the 2-inch-pipe unit extended far outside the station on the west and north sides, indicating the necessity of risk reduction. On the other hand, for the Compressor unit, a part of the 10^{-6} risk contour reached outside the station, but most of it was contained within the station boundary. Additionally, the 10^{-6} risk contours derived from the Intermediate cylinders unit and the Cylinders unit extended far beyond the station on the north and east sides; furthermore, a part of the 10^{-6} risk contours derived from the Cylinders unit extended beyond the station on the south side. A part of the 10^{-6} risk contour derived from the Dispenser unit reached outside the station, but most of it was contained within the station boundary because its hazards were lower than those of other facilities. In the previous paper, it was revealed that the most significant risk scenario among the risks derived from each unit was a jet fire that lasts for 12 s until the Rupture and Major leak was stopped by a shut-off valve activated by a gas detector or a flame detector. Thus, installing the fire protection walls for jet fires at the station boundaries can be effective to mitigate the risks extended outside the station. Therefore, the consequences of the jet fire scenarios from the Trailer unit, the Intermediate cylinders unit, and the Cylinders unit should be analyzed in detail, considering a fire protection wall. However, since the operating pressure of the Intermediate cylinders unit is lower than that of the Cylinders unit, we decided to show the effectiveness of the fire protection wall for the jet fires from the Intermediate cylinders unit by a detailed analysis of the scenarios from the Cylinders unit.

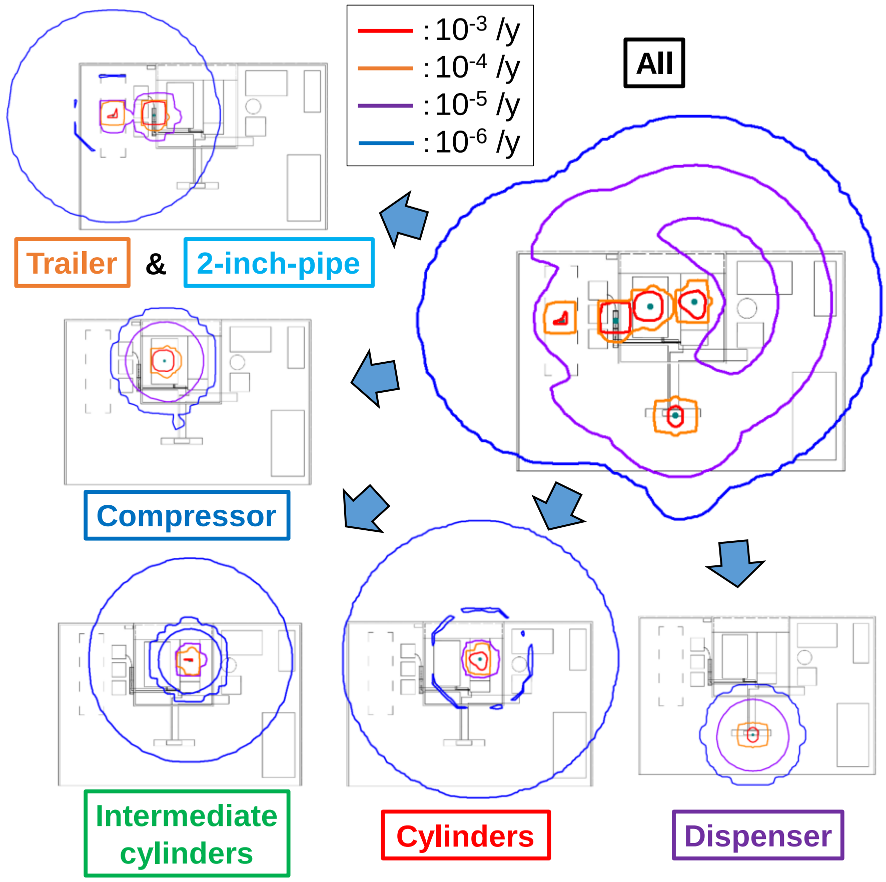

Figure 1 The risk contours displayed for each unit.

3.0 3D MODEL CONSTRUCTION

Figure 2 illustrates the geometry model used for simulations for the HRS with the protection wall. The sizes and layouts of various facilities in the HRS, such as compressors and cylinders, were arranged to construct representative models of the current HRSs in Japan. Current safety codes and technical standards require that a fire protection wall of at least 2 m is erected at the station boundary, except for the boundary facing public roads where vehicles enter and exit the HRS. Therefore, fire protection walls that meet these codes and standards were installed on the three boundaries of the HRS model except for the south side. The fire protection walls are installed to reduce the heat radiation effect to the outside of the station due to jet fires that occur inside the HRS. Moreover, they are also installed to reduce the heat radiation effect to the facilities inside the HRS due to fires that occurred outside the HRS. Additionally, facilities that handle high-pressure hydrogen, such as tube trailers, cylinders, and compressors, are required to maintain a distance of at least 8 m from the station boundaries or to erect blast protection walls ensuring equivalent safety as maintaining the distance. This study assumes that an urban HRS has relatively narrow station areas. Therefore, the option of erecting a blast protection wall was chosen instead of securing the 8-m distance between the facilities and the station boundaries. The blast protection walls were installed to reduce the overpressure effect to the outside of the station due to vapor cloud explosions that occurred inside the HRS. Moreover, it is required that a blast protection wall should also serve as a fire protection wall; therefore, the structure of the blast protection walls was designed, as shown in Fig. 1, with a common part as the fire protection wall in per the current codes and technical standards. Additionally, a blast protection wall with a 2-m height was added because the wall should be installed between the Cylinder and the Dispenser unit.

4.0 SETTING THE SIMULATION CONDITIONS

Table 1 shows the simulation conditions for each scenario, and Table 2 shows the simulation conditions common to all the scenarios. Each condition was determined with the same conditions used in the QRA of the previous paper. The simulations with two types of leakage diameters—Rupture and Major—were performed. The leakage coefficient was assumed to be 1.0 for the conservative analysis. Moreover, the leakage direction was assumed to be in the direction of the station boundary near the representative leakage point of each unit. Furthermore, the ignition time was set to 0.1 s, and the analysis time was set to 12 s from the start of leakage until the shut-off valve was closed. Monitor points, shown in Figure 3, were set at 1, 2, 3, 4, and 5 m from behind the fire protection wall on the extension of the leakage direction. Other monitor points were also set at a 2 m and 3 m height at a distance of 1 m from behind the fire protection wall.

Table 1 The simulation conditions of each jet fire scenario.

Parameters	No.	1	2	3	4	5	6
Unit	-	Cylinders	Cylinders	Trailer	Trailer	Trailer	Trailer
Volume inventory	m^3	0.3	0.3	9	9	9	9
Initial pressure	MPa	82	82	45	45	45	45
Initial temperature	^oC	25	25	25	25	25	25
Leakage diameter	mm	6.3	2.0	6.3	6.3	2.0	6.3
Leakage direction	-	North	North	North	North	North	West
Protection wall	-	X	X	N/A	X	X	X

Table 2 The simulation conditions common to all the scenarios.

	Value	Unit
Atmospheric pressure	0.1013	MPa
Atmospheric temperature	9.85	^oC
Flow coefficient	1.0	-
Leakage height	1	m
Ignition time	0.1	s

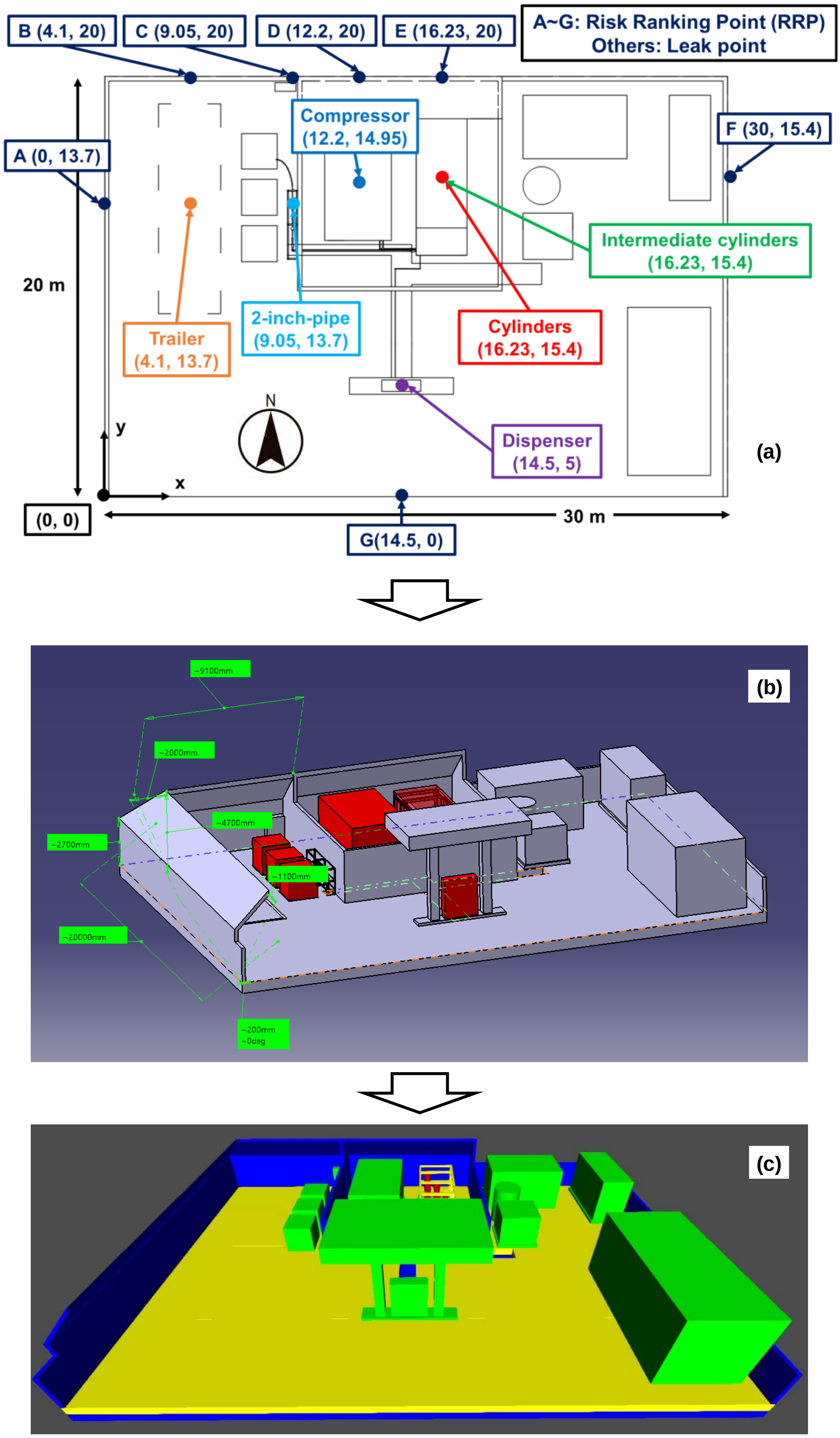

Figure 2 The HRS model (a) layout model with representative leakage points for each node and risk ranking points, (b) 3D model of the facilities in the HRS and the fire and blast protection walls, and (c) the imported 3D structures in FLACS-Fire.

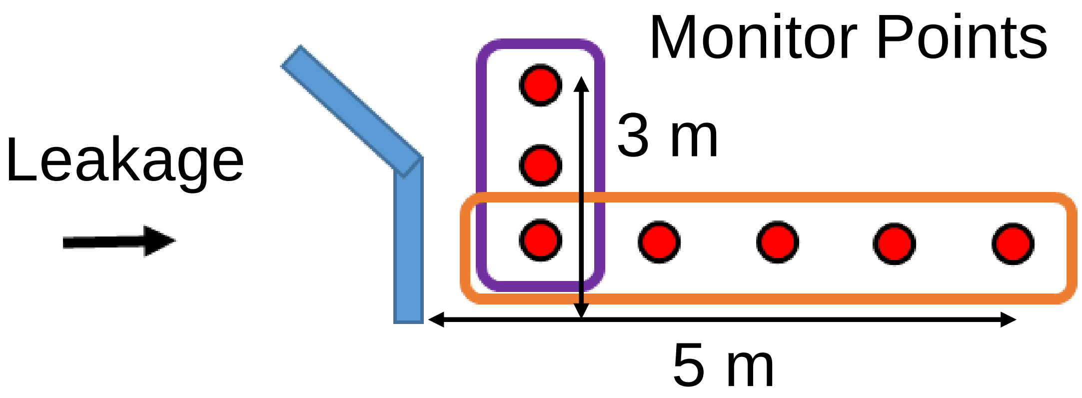

Figure 3 The location of the monitor points.

5.0 RESULTS AND DISCUSSIONS

The jet fires were analyzed for each of the scenarios shown in Table 1. Figure 4 shows the cross-sectional temperature distribution at the leakage point of the jet flame for each scenario. Scenario 3 assumed no fire protection wall. Furthermore, high-temperature area in Scenario 3 extended to the outside of the station, and the temperature of 2000 K extended to 5 m from the station boundary. On the other hand, in Scenario 4, which assumes a fire protection wall, the temperature outside the station did not rise. This indicates that the fire protection wall defends the heat radiation effect of the flame outside the station.

The temperature distribution in Scenario 1, which assumed horizontal leakage from the Cylinders unit, showed that the flame struck the fire protection wall, and the high-temperature area spread over the flame. The temperature rise inside the fire protection wall is particularly significant. Figure 5 shows the value of the heat radiation outside the station over 20 s. Figure 5 shows that the heat radiation at the monitor point located just behind the fire protection wall at 1 m height—directly behind the firewall—is approximately zero. The farther the monitor point is from the fire protection wall, the greater the heat radiation. However, the maximum heat radiation estimated in this simulation was approximately 3.0 kW/m^2 at 3 m height just behind the fire protection wall. Moreover, the lethality was estimated to be approximately 0 % using the Probit function [26], used in the previous paper. Therefore, the fire protection wall has a significant risk mitigation effect on heat radiation because it can significantly reduce the consequence of jet fires outside the station. The estimated heat radiation tends to become larger the further away from the fire protection wall or the higher the height of the monitor point at 1 m from behind the wall; this is because the impact of heat radiation generated by flames spreading along the fire protection wall is larger than that of heat radiation to just behind the fire protection wall. It should be noted that there must be a point where the heat radiation reaches its maximum value because the heat radiation becomes zero at a point infinitely far from the jet flame.

The temperature distribution of Scenario 2, in which the leakage diameter of Scenario 1 was changed to 2.0 mm, shows that the size of the flame is smaller than in Scenario 1 due to the smaller leakage diameter. Therefore, the value of heat radiation outside the station is also considered to be significantly small, as well as the value of Scenario 1.

The temperature distribution in Scenario 4, which assumed leakage to the north direction from the Trailer unit, was similar to that in Scenario 1, which assumed leakage from the Cylinders unit. Moreover, the high-temperature area also spread along the fire protection wall. The heat radiation at the monitor point located just behind the fire protection wall at 1 m height, directly behind the firewall, was estimated to be almost zero (as in Scenario 1). The maximum heat radiation estimated in this scenario was only 0.030 kW/m^2 at a 5 m distance from behind the fire protection wall in the horizontal direction. This value is significantly lower than the value estimated in Scenario 1 and the lethality was also approximately 0 %.

The temperature distribution of Scenario 5, in which the leakage diameter of Scenario 4 was changed to 2.0 mm, shows that the flame's size is smaller than in Scenario 4 due to the smaller leakage diameter (as in the change from Scenario 1 to Scenario 2). Therefore, the value of heat radiation outside the station was also considered to be significantly small, as well as the value of Scenario 4.

As for the temperature distribution of Scenario 6, which assumes horizontal leakage to the west direction from the trailer unit, the flame spreads along the fire protection wall (as in Scenario 5); therefore, the value of heat radiation is also expected to be small.

Therefore, if the fire protection wall is not destroyed and keeps its function to defend the flames, it is possible to reduce the heat radiation effect outside the station by defending the jet fire flame generated from the HRS facilities.

Applying the results of heat radiation reduction by fire protection wall, the consequence of the scenarios with the most significant risks at each risk ranking point obtained in the previous paper can be reduced and the individual risks outside the station can also be reduced approximately one-hundredths. These risks are lower than the risk criteria for the safety of compressed HRS [27] and are acceptable. Although Japan does not have the regulation related to the risk criteria for hydrogen refueling stations, there is the typical separation distance (8 m to the public road) based on current hazard management law (the High-Pressure Gas Safety Act of Japan). The assessment implies that the risks re-estimated in this study are within the separation distance. Therefore, the risks spreading outside the north-, west-, and east-side station boundaries are expected to be accepted by considering the fire protection wall into the Japanese HRS model.

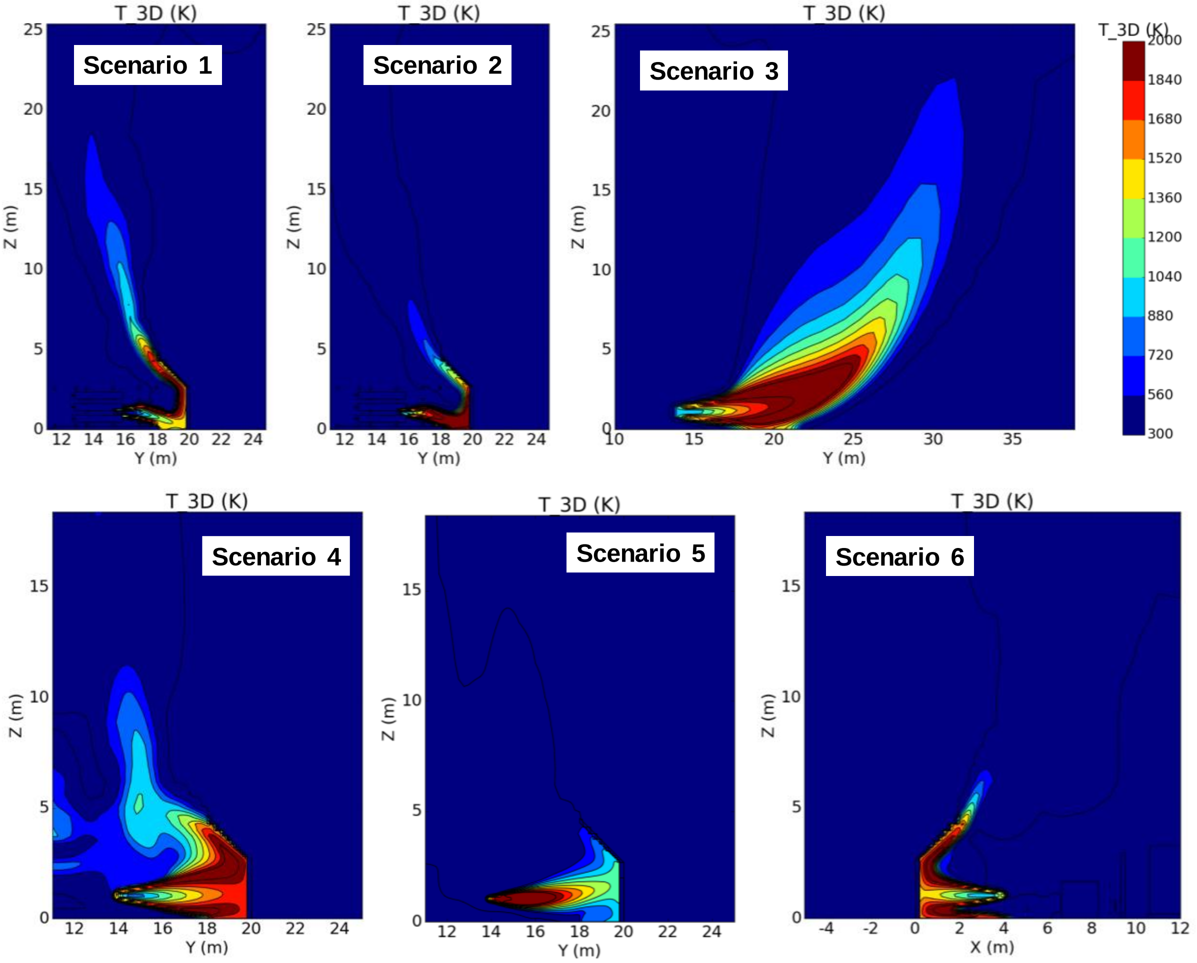

Figure 4 The temperature distribution at the leakage point of the jet flame for each scenario.

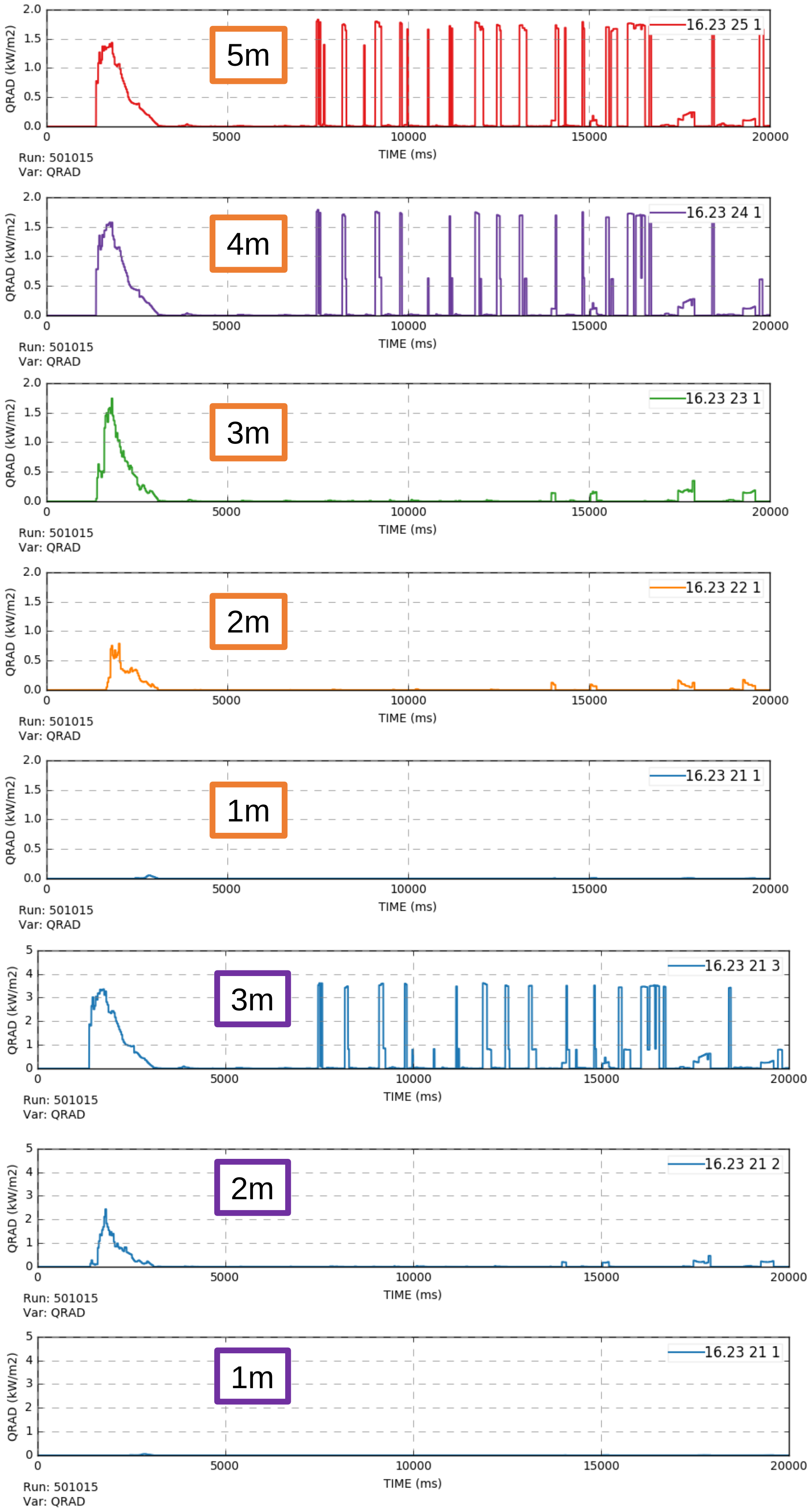

Figure 5 The values of the heat radiation outside the station over time during 20 s in Scenario 1 (in orange: distance, in purple: height).

6.0 CONCLUSION

We analyzed the summation of risk contours derived from each unit and identified the scenarios with the largest risk outside the station. Moreover, we conducted detailed risk analyses of the identified scenarios using the 3D structure model. The heat radiation and temperature rise of jet fire scenarios that pose the most significant risk to the physical surroundings in the HRS model were estimated in detail based on computational fluid dynamics with 3D structures, including fire protection walls. The results indicated that the fire protection wall defends the heat radiation effect of the flame and temperature rise outside the station. Therefore, if the fire protection wall is not destroyed and maintains its function to defend from the flames, it is possible to reduce the heat radiation effect outside the station by containing the jet fire flame generated from the HRS facilities. Eventually, the risks spreading outside the north-, west-, and east-side station boundaries are expected to be acceptable by incorporating the fire protection wall in the Japanese HRS model.

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