# SAFETY STUDY OF HYDROGEN SUPPLY STATIONS FOR THE REVIEW OF HIGH PRESSURE GAS SAFETY LAW IN JAPAN

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**ABSTRACT**

A safety study of gaseous hydrogen supply stations with 40MPa storage system is undertaken through a risk based approach. Accident scenarios are identified based on a generic model of hydrogen station. And risks of identified accident scenarios are estimated and evaluated comparing with risk acceptance criteria. Also, safety measures for risk reduction are discussed. Especially for clearance distance, it is proposed that the distance from high-pressurized equipment to site borders should be at least 6 meters. As a result of the study, it is concluded that risks of accidental scenarios can be mitigated to acceptable level under the proposed safety measures, with several exceptions. These exceptional scenarios are very unlikely to occur, but expected to have extremely severe consequence once occurred.

## 1.0 INTRODUCTION

In Japan, facilities which deal with high pressurized gas over 10MPa are under the regulation of High Pressure Gas Safety Law. The law requires minimum clearance distance of 11.3m between pressurized equipment and dwellings. If this clearance distance is to be required for hydrogen supply stations, it becomes practically infeasible to diffuse them on commercial basis.

In 2002, the government of Japan released the road map for application and diffusion of Fuel Cell Vehicles (FCVs). In the road map, the reviewing of current regulations was scheduled to be finished by March 2005. Corresponding to the road map, in 2003, Japan Petroleum Energy Center (JPEC), along with partner organizations, initiated a new study to examine the safety requirement for hydrogen supply stations. The study was fully funded by the Ministry of Economy, Trade and Industry (METI). Participants of the study are shown in Table 1.

Table 1. Participants of the study.

| Organization | Task |
|---|---|
| Japan Petroleum Energy Center (JPEC) | General Administration,<br>Risk Assessment |
| Mitsubishi Heavy Industries Ltd. | Experiments/CFD of Diffusion, Explosion, and Jet Fire |
| The Japan Steel Works | Material Test (Stainless steels, Chromium Molybdenum steels),<br>Reliability of compressor |
| Japan Industrial Gas Association | Reliability of piping materials, valves, etc. |
| Iwatani International Corp. | Reliability of liquid hydrogen system |
| Tatsuno Corporation | Reliability of hydrogen gas dispenser |

The purpose of the study is to determine the required safety measures for hydrogen supply stations which are going to be located in the same kind of areas as gasoline stations. Among the safety measures to be discussed, clearance distance is the key issue according to the background of the study. The outcome of the study is intended to be the proposal which would be applied to the review of the High Pressure Gas Safety Law by METI.

## 2.0 METHODOLOGY

A risk based approach, which is shown in Fig.1, is adopted for the study. As a result of this approach, safety measures which are necessary to reduce the risk of hydrogen supply stations to acceptable level would be obtained.

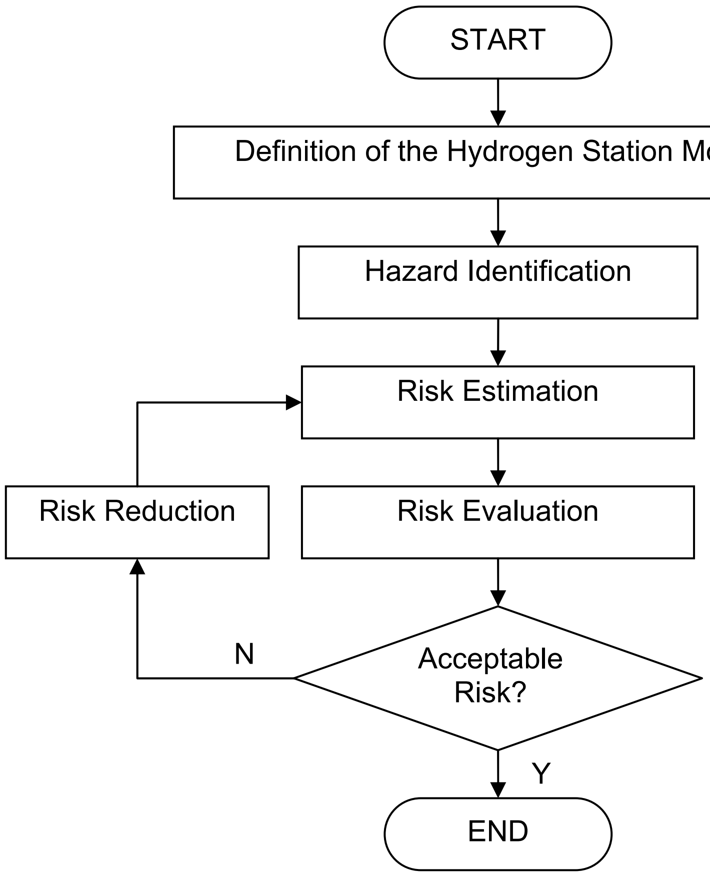


Figure 1. Flowchart of risk based approach

## 3.0 RISK ACCEPTANCE CRITERIA

Risk matrix as acceptance criteria for hydrogen supply stations is discussed and established as shown in Table 2. Risk is produced as a combination of likelihood and consequence, and graded to three categories, which are H, M, and L. The acceptance criteria established by European Integrated Hydrogen Project is referred. [1]

Table 2. Risk matrix.

| | | Likelihood | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| Consequence | | Improbable | Remote | Occasional | Probable |
| 1 | Extremely Severe Damage | H | H | H | H |
| 2 | Severe Damage | M | H | H | H |
| 3 | Damage | M | M | H | H |
| 4 | Small Damage | L | L | M | H |
| 5 | Minor Damage | L | L | L | M |

Detailed explanation of the three risk categories is shown in Table 3.

Table 3. Risk levels.

| Risk Level | Description |
|---|---|
| H (High) | Risk is not acceptable. Remedial actions should be considered to reduce the risk to an acceptable level. |
| M (Medium) | In principle, risk cannot be acceptable. It can be accepted only when risk reduction cannot be achieved by reasonably practical action. |
| L (Low) | Acceptable. Further risk reduction is not necessarily required. |

The likelihood of an identified accident scenario is to be accessed and graded qualitatively to proper likelihood level presented in Table 4. Adoption of quantitative evaluation is avoided considering the lack of enough historical data.

Table 4. Likelihood levels.

| Likelihood Level | | Description |
|---|---|---|
| A | Improbable | Possible, but the probability is extremely low. |
| B | Remote | Unlikely to occur in lifetime of one H2 station. |
| C | Occasional | Likely to occur once in lifetime of one H2 station. |
| D | Probable | Likely to occur several times in lifetime of one H2 station. |

The consequence levels are defined as shown in Table 5. The consequence of the same identified accident scenario is assessed in view of human damage and asset damage.

Table 5. Consequence levels.

| Consequence Level | | Asset Damage | Human Damage |
|---|---|---|---|
| 1 | Extremely Severe Damage | Collapse of nearby dwelling houses | One or more fatalities of pedestrians or dwellers |
| 2 | Severe Damage | Major damage of nearby dwelling houses | One or more fatalities of customers or station workers |
| 3 | Damage | Minor damage of nearby dwelling houses | Injury and hospitalization |
| 4 | Small Damage | Windows broken | Injury and medical treatment |
| 5 | Minor Damage | No damage to nearby dwelling houses | Minor injury |

## 4.0 RISK ANALYSIS

### 4.1 Definition of the Hydrogen Supply Station Model

As a baseline of this study a generic model of a gaseous hydrogen supply station is built, referring to the existing hydrogen supply stations in Japan. The main equipments of the model are a reciprocating compressor, a 40MPa storage system, and dispensers. Even though it is supposed that a reforming unit, which produces gaseous hydrogen, is installed upstream of the compressor, the reforming unit is excluded from the study scope. The spec of these equipments is shown in Table 6. The detail of the model is presented in Fig. 2 and Fig.3.

Table 6. Spec of major unit.

| Unit | Spec |
|---|---|
| Compressor | Type : Reciprocating<br>Capacity : 300Nm$^3$/hr<br>Pressures :0.8MPa(Suction)/40MPa(Delivery) |
| Storage | Pressure : 40MPa<br>Total Storage Volume :1400Nm$^3$<br>Number of Cylinders : 14 |
| Dispenser | Filling Pressure : 35MPa<br>Maximum Flow Rate : 900Nm$^3$/hr |

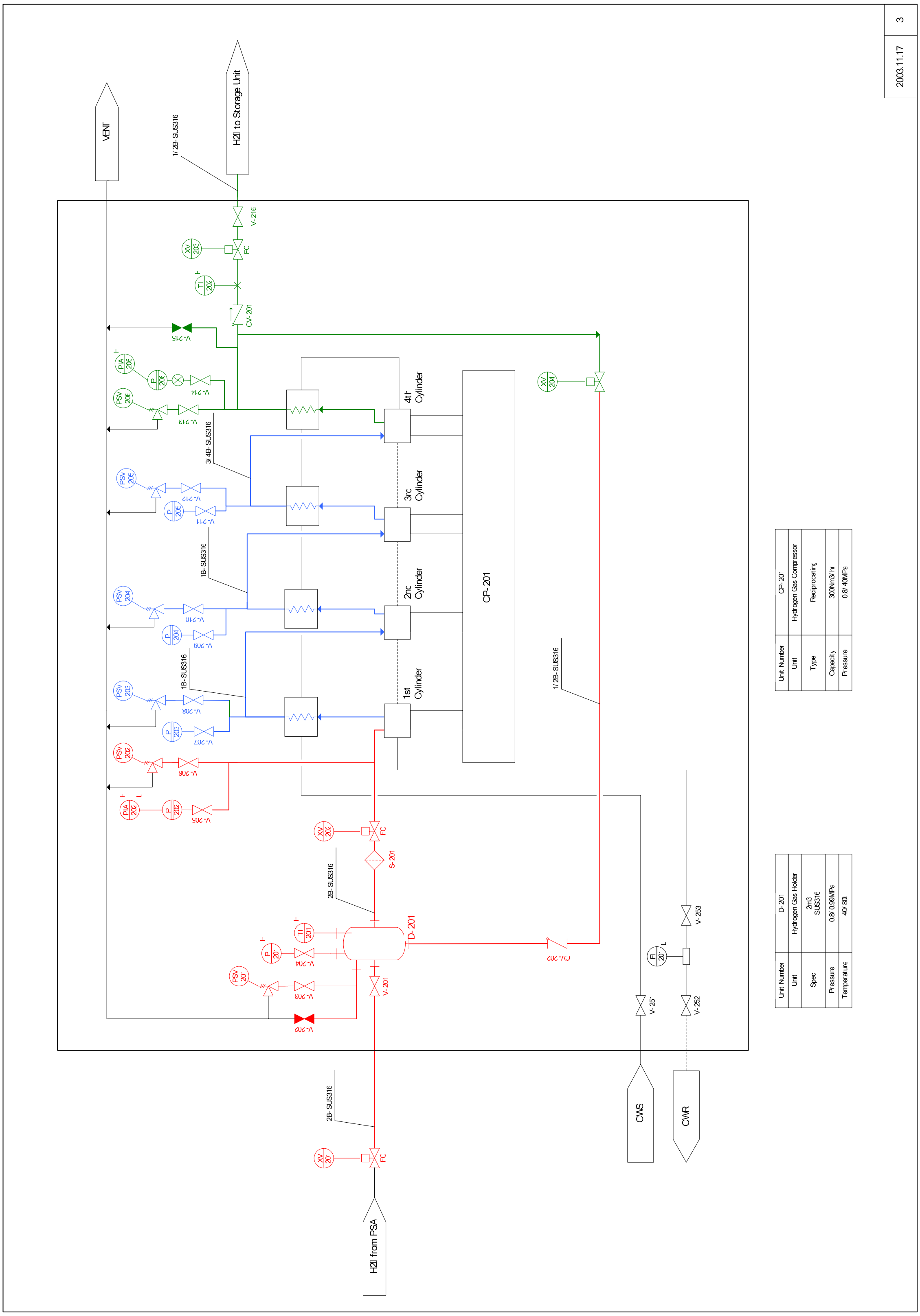


Figure 2. Hydrogen supply station model (1/2).

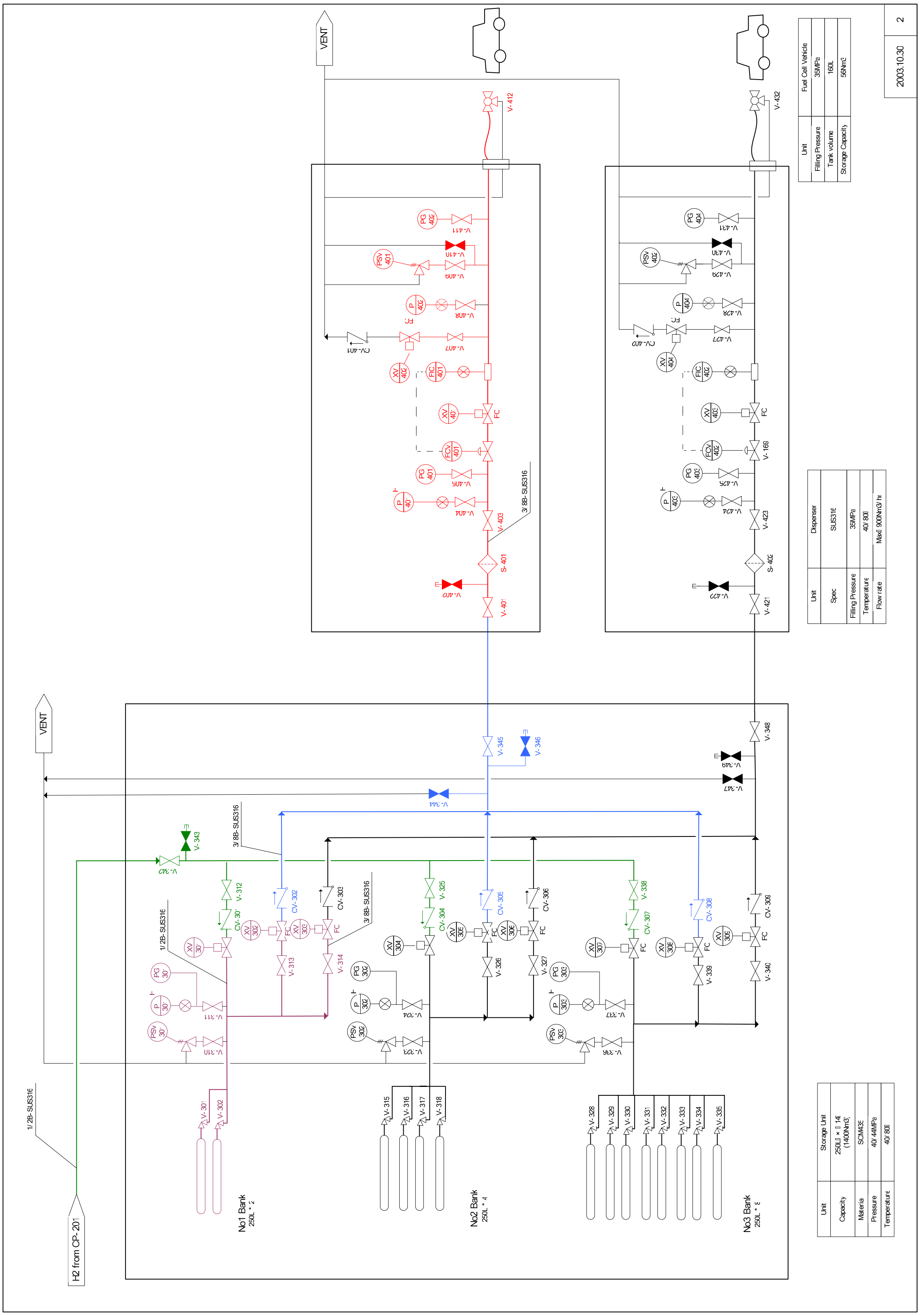


Figure 3. Hydrogen supply station model (2/2).

### 4.2 Hazard Identification

Identification of relevant hazards and accident scenarios, which could occur on operation mode of hydrogen supply stations, is undertaken based on the model. Those on construction and maintenance mode are not discussed in this study. Hazard and Operability Studies (HAZOP) and Failure Mode and Effects Analysis (FMEA) are adopted for the purpose. In the process of hazard identification, it is assumed that safety devices such as safety valves, which are shown on the model, would not function properly when needed. It is in order to ensure exhaustive identification of accident scenarios.

As a result 233 accident scenarios, which might result in explosion or jet fire of released hydrogen, are identified through HAZOP and FMEA. Table 7 shows the list of triggers, which are direct causes of identified accident scenarios. Human factors and natural disasters, as well as failure and deterioration of instruments, are considered.

Table 7. Triggers of identified accident scenarios.

| | Triggers |
|---|---|
| General | Hydrogen embrittlement of piping material (SUS) |
| | Hydrogen embrittlement of cylinder material (SCM) |
| | Stress corrosion cracking on SUS piping |
| | Corrosion on carbon steel and SCM |
| | Looseness of fittings |
| | Sealing material deterioration |
| Valves | Gland packing leakage |
| | Valve seat leakage |
| | Malfunction of automated isolation valves |
| | Malfunction of flow control valve |
| Instrument | Malfunction of pressure indicators |
| | Fatigue of flow meter tube for coriolis type flow meter |
| Compressor | Fatigue of pipe caused by vibration |
| | Malfunction of heat exchanger (gas cooler) |
| Dispenser | Fatigue of filling hose |
| | Wear of filling hose with ground |
| | Deterioration of connective joints of filling hose |
| | Wear of dispensing nozzle |
| | Foreign substance between dispensing nozzle and receptacle of FCV |
| Human factors | Misoperation of hand valves |
| | Drop of a lid of trench on pipe |
| | Collision of a vehicle with a dispenser |
| | False start of FCV while filling hose is connected |
| | Intentional damage on filling hose (mischief of outsider) |
| | Intentional improper operation of hand valves (mischief of outsider) |
| Natural disasters | Earthquake |
| | Strong wind |
| Other | Fire at adjacent building |
| | Direct sunny ray on cylinders |
| | Airplane crush |
| | Collapse of crane |

### 4.3 Consequence Analysis

The consequence of explosion/jet fire of released hydrogen varies depending on such factors as hole size, hydrogen pressure and hydrogen inventory. In this study, the above three factors are discussed in order to estimate the consequence. The identified accident scenarios are investigated and classified into four groups by hole size, from which hydrogen are released out. Classification of hole sizes is shown in Table 8.

Table 8. Classification of hole sizes for accident scenarios.

| Hole Size Class | Representative Value | Description |
|---|---|---|
| *Large* | - | Rupture of a storage vessel. Stored hydrogen is released instantly and it explodes, if ignited. |
| *Medium* | 10mmΦ | Rupture of pipe or filling hose. Massive discharge of hydrogen leads to explosion or jet fire, depending on ignition timing, if ignited. |
| *Small* | 1mmΦ | Relatively small opening such as crack and pinhole on piping and filling hose. Leakage is continuous and it leads to explosion or jet fire, depending on ignition timing, if ignited. |
| *Very Small* | - | Very small opening such as leakage from gland packing of valves. |

For '*Medium*' sized hole which reflects rupture of piping or filling hose, the representative value of 10mmΦ is given considering the size of piping used in the model. As for '*Small*' sized hole, this represents a group of openings generated by various causes. The group includes any cracks on piping and other equipment, loosen fitting, sealing material deterioration, and others. The shape of an opening is generally irregular. And the size of an opening grows larger with the progress of deterioration, starting from quite small opening. However it is determined on engineering judgment basis that a pinhole of 1mmΦ can be the representative for conservative estimation of consequence.

In order to provide basic data for consequence estimation, experimental investigation is undertaken by Mitsubishi Heavy Industries, Ltd.. Some evaluation results based on their investigation are representatively presented below.

Case 1

Applicable Accident Scenario: {*false start of FCV → rapture of filling hose → leakage → ignition → jet fire or explosion*}

The opening is '*Medium*' and the hole size is regarded 10mmΦ. Even though the pressure at storage is 40MPa, the pressure at the opening is reduced to 10MPa considering pressure loss of 30MPa caused by the piping between cylinders and dispenser. In the calculation of pressure loss, it is assumed the connection piping with inner diameter 10mm is 10m long, and straight with no bending and valves. It is experimentally examined that the length of jet fire reaches to 12m at the beginning of the leakage. It implicates that pedestrians and dwellers outside a station would be fatally injured. The consequence level of the accident scenario is graded as level 1 which is 'Extremely Severe Damage'.

Case 2

Applicable Accident Scenario: {*earthquake → rapture of piping between cylinders and a dispenser → leakage → ignition → jet fire or explosion*}

The opening is '*Medium*' and the hole size is regarded 10mmΦ. The pressure is 40MPa. The hydrogen inventory is regarded as 800Nm$^3$ which is the volume of hydrogen stored in the largest bank of cylinders on the model. It is experimentally examined that the length of jet fire reaches to 25m at the beginning of the leakage. As for explosion it is predicted by experiments and computational simulation that the peak pressure of the blast, which is generated by the explosion, reaches up to 150kPa within 10m from the ignition point. This result implicates that dwelling houses near a station would be totally collapsed. The consequence level of the accident scenario is graded as level 1 which is ‘Extremely Severe Damage’.

Case 3

Applicable Accident Scenario: {*fatigue of filling hose at dispenser* → *crack on filling hose* →*leakage* → *ignition* → *jet fire or explosion*}

The opening is ‘*Small*’ and the hole size is regarded 1mmΦ. The hydrogen pressure is 40MPa. As for explosive effect estimation, it is experimentally examined that the peak pressure is 0.2kPa near the ignition point. It implicates that the effect of explosion is harmless for both of human and asset. For jet fire, it is experimentally examined that the length of jet fire is 2.5m. Base on this result it is assessed that station workers and customers within the reach of the flame would die. Thus the consequence level of the accident scenario is graded as level 2 which is ‘Severe Damage’. In addition the effect of hot combustion gas flow after the flame is examined by computational simulation. It is confirmed that persons who are at a distance of 6m from the opening are not harmed by the gas flow.

### 4.4 Likelihood Analysis

Likelihood analysis is undertaken for each identified accident scenario under the assumptions stated below.

- The probability of ignition is not considered, and regarded as 1. It means that released hydrogen always ignites regardless of ignition sources.
- The probability of presence of human beings is assumed as follows. There are always station workers or customers around the equipment of a hydrogen supply station. There are always pedestrians or dwellers beyond the site borders of a hydrogen supply station.

### 4.5 Risk Evaluation

Every identified accident scenario is assessed in terms of its consequence and likelihood, and an appropriate risk level is specified according to the risk matrix. The result of risk evaluation, under the assumption that no safety measure is applied, is shown in Table 9. The format of Table 9 is as same as the risk matrix, and numbers in Table 9 indicate the number of accident scenarios which are assessed to the relevant risk.

Table 9. Risk map before risk reduction

| | | Likelihood Level | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| Consequence Level | 1 | 7 | 2 | 8 | 58 |
| | 2 | 8 | | 13 | 47 |
| | 3 | | | | |
| | 4 | 2 | | 3 | 21 |
| | 5 | 2 | | 6 | 56 |

Safety measures for risk reduction are discussed and distinguished. Principal safety measures adopted in this study are shown in Table 10.

Table 10. Principal safety measures.

| Applied Area | Safety Measure |
|---|---|
| General | 6m of clearance distance between pressurized equipment and site borders |
| | Fire protection wall (h=2m) on site borders which do not face a road |
| | Seismometer and interlock system |
| Material Selection | SCM435 for cylinder material |
| | SUS316L for piping material |
| Compressor Unit | Hydrogen leak detector in an enclosure of a compressor |
| | Ventilation system in an enclosure of a compressor and interlock system |
| | Monitoring of temperature and flow rate of cooling water |
| Dispenser Unit | Breakaway device in the middle of a filling hose |
| | Shock sensor and interlock system |
| | Hydrogen leak detector in a body of a dispenser and interlock system |
| | Hydrogen leak detector at a dispensing nozzle and interlock |
| | Flame detector in dispensing area |
| | Guardrail in front of a dispenser |
| | Piping in trench around a dispenser |
| Storage Unit | Water sprinkler and thermal sensor |
| | Flame detector at header of storage unit |
| | Excess flow valve in an exit pipe of cylinder |

The result of risk evaluation with appropriate safety measures is shown in Table 11. 35 accident scenarios which are included in Table 9 are excluded from Table 11, because triggers of these scenarios can be eliminated by appropriate safety measures.

Table 11. Risk map after risk reduction

| | | Likelihood Level | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| Consequence Level | 1 | 9 | | | |
| | 2 | 58 | | | |
| | 3 | | | | |
| | 4 | 25 | 3 | | |
| | 5 | 58 | 43 | 2 | |

58 accident scenarios in Table 11 are ranked as M (Medium) level, which implies that risk can not be acceptable in principle. All of them are scenarios of which consequence is fatalities of station workers and customers caused by jet fire from '*Small*' opening. An example is shown in the previous chapter of this paper. Reasonably practical safety measures to reduce the likelihood are discussed and specified. It is confirmed that the effect of accidents remains within the premises of a station under the proposed clearance distance. Thus the risks of these accident scenarios are judged to be acceptable.

For 9 accident scenarios, risks cannot be mitigated to acceptable level according to the risk matrix, and are ranked as H (High) level. 6 accident scenarios among them are a result of rupture of piping or filling hose, and triggers of them are as follows; '*false start of FCV*', '*collision of a vehicle with a dispenser*', '*hydrogen leakage at header of storage unit (secondary effect)*', '*earthquake*', '*crash of airplane*', '*collapse of crane*'.

Collapse of the hydrogen tank of a FCV is expected in other 3 accident scenarios, and their triggers are; '*malfunction of flow meter in dispenser*', '*malfunction of pressure indicator in dispenser*', '*malfunction of gas cooler of compressor*'. Safety measures are considered and applied to these 9 scenarios. Even though the likelihood of their occurrence is assessed to be extremely low, the possibility can not be eliminated. Concerning clearance distance, it is practically infeasible to mitigate the consequence of these scenarios by longer clearance distance, because it is supposed that distance of tens of meters is required.

## 5.0 CONCLUSION

The following conclusions are derived from the safety study of a gaseous hydrogen supply station.

- Risks of gaseous hydrogen supply stations can be mitigated to acceptable level, with 9 exceptional accident scenarios remaining.
- Risks of the 9 accident scenarios are assessed to be unacceptable. Their likelihood is '*extremely low*', while the consequence is '*extremely severe*'.
- Safety measures necessary for gaseous hydrogen supply stations are specified.
- Clearance distance is proposed to be 6m between pressurized equipment and site borders.

The result of the study was reported to METI and the High Pressure Gas Safety Institute of Japan, with our recommendation to retain risks of the 9 accident scenarios and not to expand clearance distance further than 6m.

## REFERENCES

1. Norsk Hydro ASA, DNV, Risk acceptance criteria for Hydrogen Refuelling Stations, European Integrated Hydrogen Project [EIHP2], No. ENK6-CT2000-00442