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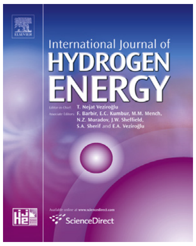

Leakage-type-based analysis of accidents involving hydrogen fueling stations in Japan and USA

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ABSTRACT

To identify the safety issues associated with hydrogen fueling stations, incidents at such stations in Japan and the USA were analyzed considering the regulations in these countries. Leakage due to the damage and fracture of main bodies of apparatuses and pipes in Japan and the USA is mainly caused by design error, that is, poorly planned fatigue. Considering the present incidents in these countries, adequate consideration of the usage environment in the design is very important. Leakage from flanges, valves, and seals in Japan is mainly caused by screw joints. If welded joints are to be used in hydrogen fueling stations in Japan, strength data for welded parts should be obtained and pipe thicknesses should be reduced. Leakage due to other factors, e.g., external impact, in Japan and the USA is mainly caused by human error. To realize self-serviced hydrogen fueling stations, safety measures should be developed to prevent human error by fuel cell vehicle users.

Introduction

Hydrogen fueling stations are essential elements for operating fuel cell vehicles (FCVs). Alazemi et al. reported that by 2013, there were 224 working hydrogen stations distributed over 28 countries and that some 43% of these stations were located in North and South America, 34% in Europe, 23% in Asia, and none in Australia [1]. In Japan, in March 2010, the Fuel Cell Commercialization Conference of Japan proposed the rollout

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Abbreviations: FCV, fuel cell vehicle; HIRD, hydrogen incident reporting database; HIAD, hydrogen incident and accident database.

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of commercial FCVs and hydrogen fueling stations in 2015 and recommended ways to popularize them by 2025 [2]. In March 2016, the Japan Ministry of Economy, Trade and Industry announced its aim to construct 320 hydrogen fueling stations by 2025. Moreover, a Japanese motor corporation has been selling commercial FCVs since December 2014, and other companies are poised to enter the FCV market as well. Therefore, it has become increasingly necessary to establish hydrogen fueling stations.

Hydrogen fueling stations have the following two safety issues [3]: (i) The hydrogen pressure encountered in Japanese stations is very high at 82 MPa. (ii) Explosion and fire are very likely to occur due to hydrogen's inherent characteristics: hydrogen is likely to leak because of its low density, large flammability range, and low minimum ignition energy. In addition, hydrogen embrittlement must be taken into consideration to ensure safety. Therefore, it is very important to assess the risk of hydrogen fueling stations.

Many studies have focused on risk assessment and analyses with respect to hydrogen and hydrogen fueling stations from different points of view [3–13]. These studies include research on hydrogen explosion and fire [4–8], hydrogen compatibility of materials [9–12], and the identification and analysis of hazardous scenarios in hydrogen fueling stations using hazard and operability studies, a hazard identification study, failure mode and effect analysis, fault tree analysis, and other methods [13–28]. Serious hazards in hydrogen fueling stations have also been analyzed in depth [29,30]. Meanwhile, to improve the safety of hydrogen fueling stations by the identification of overlooked incident scenarios, the causes of the incidents have been identified and improvements to prevent such incidents have been suggested [3]. However, only few researches have focused on incident analysis with regard to hydrogen fueling stations.

Table 1 presents the incident and accident database for hydrogen and hydrogen fueling stations. Considering the data for Japan reported in the High Pressure Gas Safety Act Database, Yamada et al. [3] analyzed the incidents using the classification method [31]. The classification method was developed by the present authors. The advantage of this method is that it can categorize the causes of incidents, such as material damage, sealing part problems, human error, and others. The method was adopted as part of the High Pressure Gas Safety Act in Japan. Mirza et al. [32] selected 32 incidents involving hydrogen from the Hydrogen Incident Reporting Database (HIRD), analyzed the incident causes, and suggested safety measures. The Hydrogen Incident and Accident Database (HIAD) [33] describes two accidents involving hydrogen fueling stations in Europe. Thus, accidents involving hydrogen fueling stations in Japan and those involving hydrogen around the world are already being collected and investigated. However, no uniformity exists in the analysis of hydrogen fueling stations around the world. This is because the number of accidents involving hydrogen fueling stations is small considering that the technology is relatively new and it is difficult to compare accidents involving hydrogen fueling stations located in different areas due to regulatory differences [34].

The purpose of this study is to determine common causes of incidents and accidents involving hydrogen fueling stations. To achieve the aim, we extracted incidents and accidents involving hydrogen fueling stations in Japan and the USA from the High Pressure Gas Safety Act Database and HIRD. The method previously proposed by the authors was applied to the incidents, and we succeeded in achieving a uniform classification of incidents involving hydrogen fueling stations in Japan and the USA. Moreover, we analyzed the incidents with regard to the regulations in Japan and the USA.

Classification of incidents and accidents

Method for incident and accident classification

In this study, the incidents and accidents were classified into six categories using our method while referring to the incident response manual of the High Pressure Gas Safety Act [31]: (i) Leakage I: leakage due to the damage and fracture of main bodies of apparatuses and pipes (including welded parts). (ii) Leakage II: leakage from flanges, valves, and seals (including deteriorated nonmetallic seals). (iii) Leakage III: leakage due to other factors, e.g., human error and external impact. (iv) Explosion and fire. (v) Burst and fracture. (vi) Others.

The collected data include the incidents and accidents involving several types of hydrogen fueling stations. In Japan, the types of hydrogen fueling stations considered in this study are onsite-type hydrogen fueling stations using natural gas and other resources and offsite-type hydrogen fueling stations, which receive gaseous hydrogen and liquid hydrogen from other locations and store them. In the USA, some hydrogen fueling stations considered in this study are of the offsite type using liquid hydrogen and the type of the other stations is unknown.

It should be noted that considerable differences exist between the data for Japan and the USA, e.g., in terms of the duty of accident reporting and the standard of accidents. Moreover,

Table 1 – Database of hydrogen incidents and accidents.

Database name	Country/area of incident occurrence	Number of incidents (number of hydrogen fueling station incidents)	Database administrator
High Pressure Gas Safety Act Database	Japan (2005–2014)	(21)	High Pressure Gas Safety Institute of Japan
HIRD	USA (2004–2012)	216 (22) 2016/2/23 access	Pacific Northwest National Laboratory, USA
HIAD	Entire world	271 (2) 2016/2/24 access	European Commission's Joint Research Center, Petten, Netherlands

it should be noted that not all of the real incidents and accidents have been reported for inclusion in the database.

Comparison of incidents and accidents between Japan and the USA

Table 2 presents the classification of incident and accidents involving hydrogen fueling stations in Japan based on the High Pressure Gas Safety Act Database. The total number of incidents and accidents in Japan from 2005 to 2014 is 21. Leakage II was the most frequently reported type of leakage in hydrogen fueling stations in Japan with 14 cases. Most of the leakage II incidents were caused by inadequate torque and sealing. Table 3 presents the classification of the incidents and accidents involving hydrogen fueling stations in the USA based on the HIRD data. The total number of incidents in the USA from 2004 to 2012 is 22.

With regard to leakage I in Japan and the USA, the apparatus and part of leakage differ depending on the incidents and accidents; however, the common cause is mainly design error, that is, poorly planned fatigue. More precisely, the vibration fatigue of piping joints and the fatigue of filling hoses caused the leakage incidents in Japan. On the other hand, the fatigue of filling hoses, fatigue of welded parts of pipes, use of nonconforming material for pressure relief valves, and poor maintenance of filling hoses caused the leakage incidents in the USA. With regard to leakage II in Japan and the USA, the number of leakage II incidents is the largest. It is noteworthy that leakage from screw joints occurs frequently in Japan. The causes of the leakage from screw joints in Japan are inadequate torque, inadequate sealing, and manufacturing error. With regard to leakage III, the cause of all the incidents in the USA is human error. In the USA, one of the incidents involved hydrogen leakage from a filling hose, which was damaged because of an erroneous start by an FCV user. On the other hand, the causes in Japan are human error and a natural disaster.

In the USA, the accidents include two fires at hydrogen fueling stations. Both the fire accidents started because of leakage I. One of them involved the release of approximately 300 kg of hydrogen over 2.5 h at the AC transit hydrogen fueling station in Emeryville; this accident has been covered in detail by Harris et al. [35]. They reported that the nozzle subassembly portion of the pressure relief valve failed, causing an immediate release of approximately 30 kg of hydrogen in the first minute. This rapidly released hydrogen mixed with air in the vent tube, and this mixture subsequently ignited, producing a loud “boom,” as reported by eye and ear witnesses. After the pre-mixed gases were consumed, the venting hydrogen produced a jet flame emanating from the outlet of the vent system. The root cause was improper material selection in a sub-component of the pressure relief valve. In the second fire incident, a fire began in the compression skid of a high-pressure hydrogen fueling station. The initial source of fire was likely to be the release of hydrogen from a failed weld on a pressure switch.

Discussion

Fig. 1 shows the tree diagram of the incidents and accidents involving hydrogen fueling stations in (a) Japan and (b) the USA. The cause of leakage I in Japan and the USA is mainly design error, that is, poorly planned fatigue. Regulations regarding fatigue pertain to the rule of material selection. In Japan, the materials that can be used in hydrogen environments are seriously restricted; for example, only steels that have a certain relationship among its nickel equivalent, temperature, and pressure can be used. The National Aeronautics and Space Administration has provided guidelines for hydrogen system design, materials selection, operations, storage, and transportation [36]. Thus, the USA also has regulations regarding materials for hydrogen embrittlement.

Table 2 – Classification of incidents and accidents involving hydrogen fueling stations in Japan from 2005 to 2014.

Incident type	Apparatus & parts	Cause
Leakage I (3)	Piping joint (screw joint)	Design error (fatigue)
	Filling hose	Design error (fatigue)
	Filling hose	Design error (fatigue)
Leakage II (14)	Joint between coupler and filling hose (screw joint)	Inadequate torque
	Joint between coupler and filling hose (screw joint)	Inadequate torque
	Joint in compressor (screw joint)	Inadequate torque
	Joint between dispenser and filling hose (screw joint)	Inadequate sealing
	Joint between compressor and accumulator (screw joint)	Inadequate torque
	Joint (screw joint)	Inadequate torque
	Joint of compressor's outlet (screw joint)	Inadequate torque
	Joint in liquid hydrogen pipeline (screw joint)	Inadequate sealing
	Joint in accumulator (screw joint)	Inadequate torque
	Joint in accumulator (screw joint)	Inadequate sealing
	Joint (flange joint)	Inadequate sealing
	Joint in compressor	Manufacturing error
	Valve between accumulator and dispenser	Inadequate sealing
	FCV's filling port	Inadequate sealing
Leakage III (2)	Joint in accumulator	Human error
	Joint in dispenser	Natural disaster (earthquake)
Explosion (1)	Highly compressed hydrogen energy generator	Design error
Burst (1)	Filling hose	Design error (fatigue)

Table 3 – Classification of accidents and incidents involving hydrogen fueling stations in the USA from 2004 to 2012.

Incident type	Apparatus & parts	Cause
Leakage I (4)	Crankshaft bearing of compressor	Design error (fatigue)
	Welded part of pipe	Design error (fatigue)
	Pressure relief valve	Design error (nonconforming material use)
	Filling hose	Poor maintenance
Leakage II (6)	Joint in filling system	Inadequate sealing
	Joint of cylinder surrounding accumulator (screw joint)	Inadequate sealing
	Joint between LH_2 lorry and LH_2 pipeline (flange joint)	Inadequate sealing
	Valve in LH_2 pipeline	Inadequate torque
	Valve	Inadequate torque
	Valve	Inadequate sealing
Leakage III (3)	Filling hose	Human error
	Flexible hose from LH_2 lorry	Human error
	Valve	Human error
Burst (5)	Emergency detaching coupler	Malfunction
	Emergency detaching coupler	External impact
	Compressor	Manufacturing error
	Compressor head fastener	Design error
	LH_2 lorry	Human error
Others (4)	Filling system – FCV	Human error
	Filling system – FCV	Human error
	Hose	Human error
	Adapter	Manufacturing error

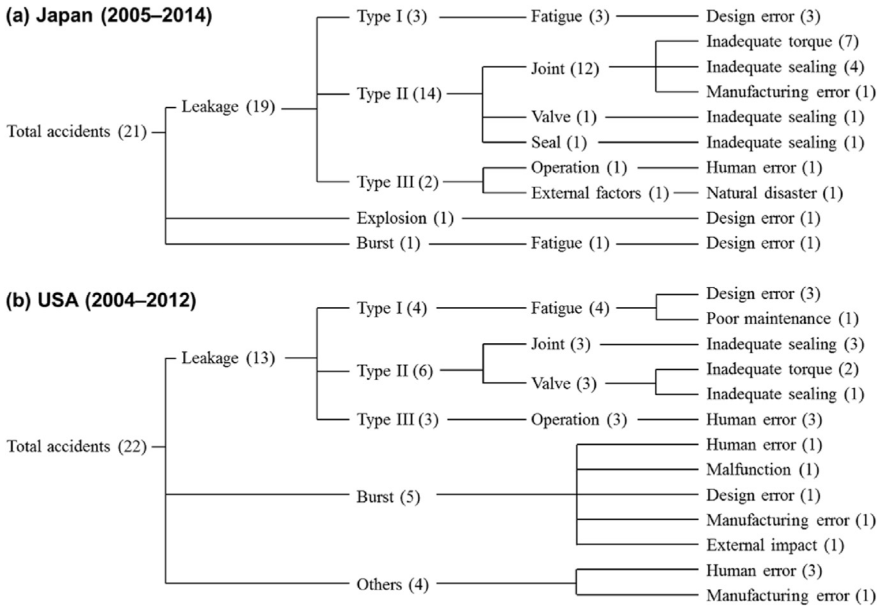

Fig. 1 – Tree diagram of incidents and accidents involving hydrogen fueling stations in (a) Japan (b) the USA.

However, the incidents and accidents occurred because of metal fatigue although materials suitable for hydrogen environments were used. The cause of these incidents and accidents is design error, that is, the misestimation of loads that can be applied to components. Considering the present incidents in Japan and the USA, it is very important to adequately consider the usage environment in the design. However, fatigue-related problems generally appear after long-term use; therefore, it is necessary to continue focusing on the causes of incidents after long-term use.

In Japan, leakage II mainly occurs around a screw joint. A major difference between hydrogen fueling stations in Japan and the USA is the pipe joint method. In Japan, most of the pipes are joined via screw joints; on the other hand, in the USA, most of the pipes are joined via welding joints. Moreover, in general, the number of joints in a hydrogen fueling station in Japan is larger than that in the USA. Japan's High Pressure Gas Safety Act allows the use of welding joints in hydrogen fueling stations. However, Japanese business operators do not use welding joints in hydrogen fueling stations probably because screw joints facilitate easy maintenance and complex layouts might make welding operations difficult. Further, the lack of data on the material strength of welded parts in high-pressure hydrogen environments and the difficulty of ensuring that welded parts have sufficient strength considering the pipe thickness required for carrying hydrogen are the main reasons for the use of screw joints. Actually, the serious fire incident in the USA was caused by leakage from welded parts. Therefore, it might be important to obtain data on the strength of welded parts and develop technology and techniques for reducing the pipe thickness in hydrogen environments.

The primary cause of leakage III is human error. One of the incidents in the USA occurred because of an erroneous start by an FCV user, which subsequently resulted in the filling hose being broken. Incidents due to errors by FCV users have never been reported in Japan. This might be because Japanese regulations prohibit self-serviced hydrogen fueling stations. However, in the near future, self-serviced hydrogen fueling stations might become operational in Japan. Therefore, it might be necessary to provide safety measures to prevent human errors by FCV users. In the initial stage of the spread of compressed natural gas stations in Japan, the number of accidents due to erroneous start by users was large. One of the main causes of the accidents was the nonoperation of the emergency detaching coupler. Therefore, to prevent such accidents, the structure of the coupler used in hydrogen fueling stations has been reformed.

Fig. 2 shows the details of the positions and parts involved in the incidents and accidents at hydrogen fueling stations in Japan and the USA. The facilities, chemical substances, and chemical substance states depend on the type of hydrogen fueling stations. Thus, risk analysis should be performed and safety measures devised for each type of hydrogen fueling station. Most incidents examined in this study occurred in facilities commonly used in all types of hydrogen fueling stations, e.g., joints, compressors, and dispensers. One incident reported in the HIRD was peculiar to a liquid hydrogen fueling station. Here is an excerpt from the database: "In the liquid hydrogen fueling station in the U.S., during transfer of liquid hydrogen from a commercial tank trailer to a receiving vessel, a leakage developed in a bayonet fitting at the trailer/facility connection. The leakage produced liquid hydrogen spray which enveloped the rear of the truck where the hand-operated shutoff valve was located. Emergency trained personnel, wearing protective clothing, except for proper shoes, entered the area and shut off the flow control valve. Reentry personnel suffered frost bite of their feet when shoes became frozen to the water-wetted rear deck of the truck. A loose hose flange connection allowed leakage of cold fluid through the lubricated bayonet seal. This allowed cold fluid to contact and shrink the 'O' ring seal (made of Buna-N rubber), thus permitting liquid hydrogen leakage to the atmosphere." In the case of liquid hydrogen fueling stations, the hydrogen temperature range is larger than that in the case of gaseous hydrogen fueling stations. This is likely to lead to low-temperature embrittlement and thermal fatigue of component materials and may damage the materials. Moreover, liquid hydrogen leakage might induce not only fire and explosion but also frostbite.

Conclusions

In this study, incidents and accidents involving hydrogen fueling stations in Japan and the USA were classified and analyzed considering the regulations in these countries. The findings and conclusions of the study are as follows:

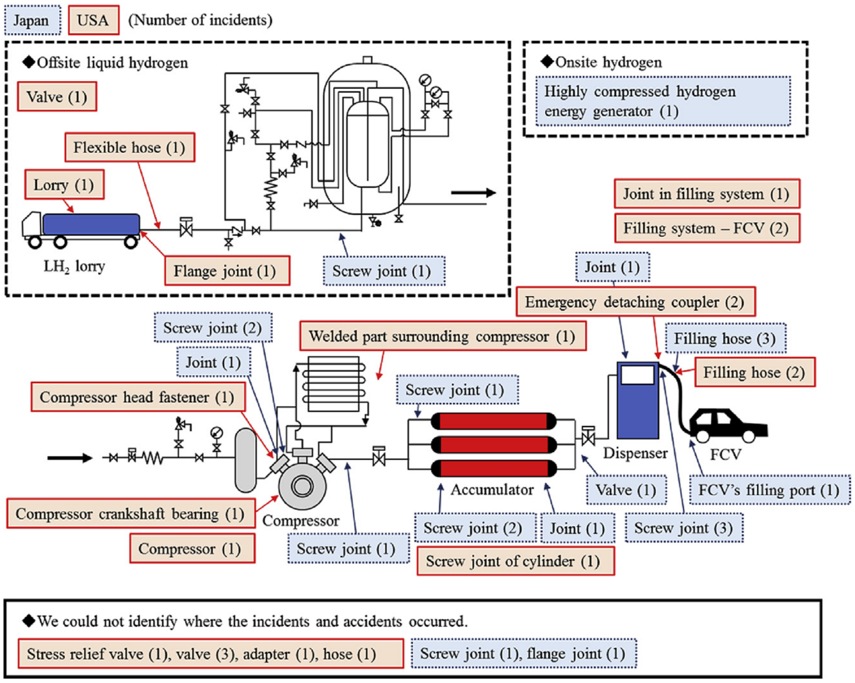

Fig. 2 – Details of positions and parts involved in incidents and accidents at hydrogen fueling stations in Japan and the USA.

1. The main cause of leakage I in Japan and the USA is design error, that is, poorly planned fatigue. Considering the present incidents in Japan and the USA, it is very important to adequately consider the usage environment in the design.
2. In Japan, leakage II is mainly caused by screw joints. If welded joints are to be used in hydrogen fueling stations in Japan, it might be important to obtain data on the strength of welded parts and develop technology and techniques for reducing the pipe thickness in hydrogen environments.
3. The main cause of leakage III in Japan and the USA is human error. To realize self-serviced hydrogen fueling stations, safety measures should be developed to prevent human error by FCV users.

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