STUDY ON THE HARM EFFECT OF LIQUID HYDROGEN RELEASE BY CONSEQUENCE MODELING

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ABSTRACT

In this paper, the accidental release of hydrogen from cryogenic liquid storage tank and the subsequent consequences are studied including hydrogen cold cloud, fire ball, jet fire, flash fire, and vapor cloud explosion. The cold effect, thermal effects and explosion overpressures from the above consequences are evaluated using IGC and TNO harm criteria. Results show that for instantaneous releases of liquid hydrogen, the sequence of harm effect distances is that vapor cloud explosion>flash fire>cold cloud> fireball. For continuous releases of liquid hydrogen, the sequence of harm effect distances is that vapor cloud explosion>jet fire>flash fire>cold cloud. The vapor cloud explosion is the leading consequence of both instantaneous and continuous releases and may be used for the determination of safety distances of a liquid hydrogen tank. Besides, the harm effect distances of liquid hydrogen tank are compared with those of compressed hydrogen storages with equivalent mass. Results show that the liquid hydrogen storage may be safer than 70MPa gaseous storage in case of leak scenario but may be more dangerous than 70MPa storage in case of catastrophic rupture. It is difficult to tell which storage is safer from a consequence perspective. Further investigation need to be made from a standpoint of risk, which combined both consequences and the likelihood of scenarios.

1.0 INTRODUCTION

In order to make hydrogen-powered vehicles to travel as long distance as the gasoline-powered vehicles, more hydrogen needs to be carried onboard. Liquid hydrogen can be stored and transported in much larger quantities than compressed hydrogen and may be considered as an alternative storage for hydrogen vehicles. Hydrogen vehicles such as buses require longer range capabilities and longer hours of operation and in these applications liquid hydrogen may be considered as an attractive storage. Despite the fact that the high complexity of the storage and refilling systems makes it more suitable for large amounts or long distances, automobile producers like BMW and GM applied liquid storage technology in their hydrogen cars, internal combustion engines and fuel cells, respectively.

Besides issues with hydrogen boil-off, liquefaction, weight, volume and tank cost need to be addressed, safety issue are also a critical concern for use of liquid hydrogen. Compared with compressed hydrogen storage, liquid hydrogen has much lower storage pressure. Thus the risk caused by high pressure can be reduced. However new hazards such as cold effects are introduced by cryogenic hydrogen release with extremely low temperature. The safety issues on cryogenic liquid hydrogen for on-board hydrogen storage need further investigation.

This paper studies the accidental release of hydrogen from cryogenic liquid storage tank and calculates the subsequent consequences such as hydrogen cold cloud, fire ball, jet fire, flash fire, and vapor cloud explosion. The cold effect, thermal effects and explosion overpressures from the hydrogen consequences are evaluated. The harm effect distances of liquid hydrogen tank are also compared with those of 70MPa compressed hydrogen storage with equivalent mass. The term” harm effect distances” used in this paper is based on harm criteria in IGC ref. 75/07/E[1], in which the severity of consequences can be defined at two levels: harm criteria and no harm criteria. As to people, an approximation value of 1% probability of fatality to a general population for “harm” and 0.1% probability of fatality for “no harm” are suggested.

2.0 MODELING

2.1 Possible consequences of liquid hydrogen release

Releases of liquid hydrogen can be either instantaneous or continuous. The instantaneous release is a sudden burst of a storage tank. The result is a release of the entire hydrogen and the subsequent evaporation and dispersion of the hydrogen. Immediate ignition of the released hydrogen may result in a fireball. If without immediate ignition, the released cryogenic hydrogen can cause a significant reduction in ambient temperature, which may cause harm to people. The released hydrogen can rapidly mix with air and form a hydrogen flammable cloud. Ignition of the hydrogen cloud will result in a flash fire (vapor cloud fire). A vapor cloud explosion may occur if the released hydrogen accumulates in a confined area in the cloud envelope. The consequences of continuous release also depend on the time of ignition. Direct ignition results in a jet fire, while delayed ignition results in a flash fire or results in an explosion. Without ignition, the cold cloud may also cause harm to people. To explain more clearly, an event tree is drawn in Figure 1. To conclude, five typical consequences of liquid hydrogen release are considered in modeling: cold cloud, fire ball, jet fire, flash fire and vapor cloud explosion.

The thermal effects including both direct flame contact and heat radiation from immediate ignition consequences are calculated with fireball model by Martinsen, et al [2] and jet fire model by Cook, et al [3], respectively. The explosion overpressure of a vapor cloud explosion is calculated with a Baker-Strehlow method [4].

2.2. Harm effect and harm criteria

The cold effect of cryogenic hydrogen, thermal and overpressure effects from hydrogen fires and explosions are harmful to people. According to IGC Doc 75/07/E/rev [1], for harm exposure threshold value to people, it is suggested that a “harm” criteria for cold effect could be a cloud temperature below -40℃, and for radiation from sustained credible fires a value of 9.5kW/m^2 is used, and for explosion peak overpressure 0.07bar should be adopted. A flash fire of a flammable gas cloud could occur the maximum extent of the cloud to the Lower Flammable Limit (LFL) should be taken.

As the consequences to exposure to radiation are dependent upon both the heat flux and the exposure duration, the thermal dose criteria should also be used. According to TNO Green book [5], a thermal dose of 520 $(kW/m^2)^{3/4}s$ is suggested for harm criterion of 1% probability of fatality, which is in accordance with harm criteria definition in IGC Doc 75/07/E. A review of these criteria is listed in Table 1. These values are used in modeling to calculate harm effect distances to people.

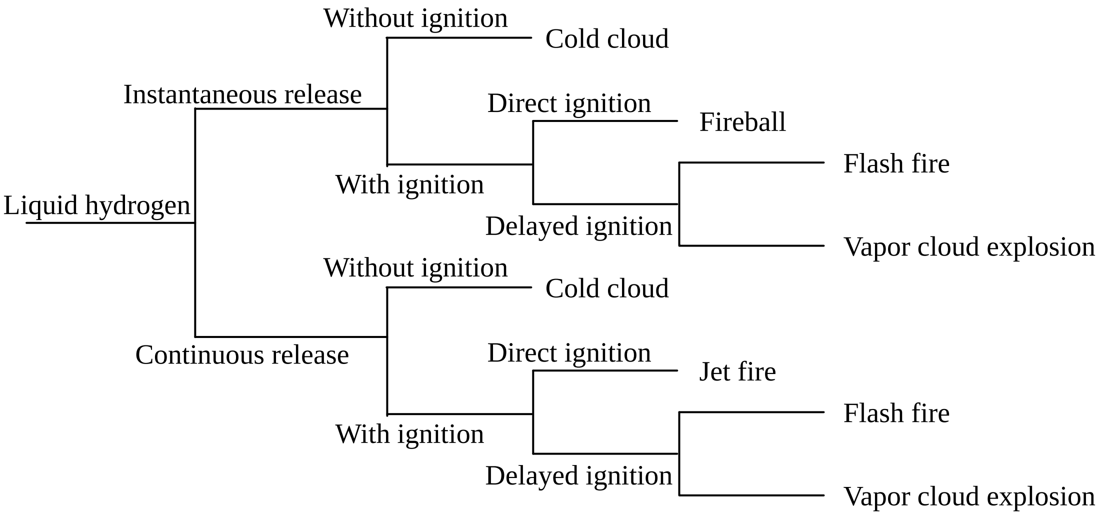

Figure 1 Event tree of liquid hydrogen release

Table 1 Harm criteria used in modeling

Consequences	Harm effect	Harm criteria to people
Cold cloud	Cold effect	-40℃
Fire ball	Flame contact ; heat radiation	Fireball radius; 9.5 kW/m^2（Pain threshold after 8s） or 520 $(kW/m^2)^{3/4}s$
Jet fire	Flame contact; heat radiation	Jet fame length; 9.5 kW/m^2（Pain threshold after 8s） or 520 $(kW/m^2)^{3/4}s$
Flash fire	Flame contact	Lower flammable limit (4%)
Vapor cloud explosion	Overpressure	0.07 bar

All effects are calculated at height 1 m instead of the ground level. 1 m is considered to be a good average height rather than 0 m for exposure to people.

2.3 Other modeling assumptions and parameters

For reasons of conservatism, all continuous releases are assumed to be horizontal and downwind. To find the worst case, delayed ignition points are assumed to be located at the furthest location downwind at which the concentration is equal to the lower flammable limit. As for release pressure, liquid hydrogen is usually transported in cryogenic tank at 10-20psi (approximately 0.7~1.4bar) [6], therefore the medium value one bar is selected as the release pressure in modeling. As to release hole size, the worst case with largest release diameter is not expected to be larger than 10mm, corresponding to the full bore rupture of 9/16 inch pipe or connection parts. The leak from tank are usually occur in connectors, valves and fittings[7] and generally the release diameter is not expected to be larger than the hole size of full bore rupture. The calculated severity of consequences is sensitive to the assumption of release diameter, so several release hole size will be studied and compared.

Table 2 Modeling assumptions and parameters

Item	Catastrophic rupture of tank	Leak from tank
Release inventory(kg)	3.5	
Release pressure（bar）	1	
Release direction	——	Horizontal, downwind
Release hole size (mm)	——	Vary, up to 10mm
Release height(m)	1	
Atmospheric temperature (℃)	15	
Wind velocity(m/s)	5	
Pasquill stability	D(neutral))	
Result output height(m)	1	

Other modeling parameters such as release height and weather conditions are assumed to be the values listed in Table 2. Release height is assumed to be 1 meter height. Atmospheric temperature and Pasquill stability is assumed to be 15℃ and neutral stability (D). Wind velocity is assumed to be 5m/s. A review of all modeling assumptions and parameters are also shown in Table 2.

3.0 RESULTS AND DISCUSSIONS

Calculations were carried out with Process Hazard Analysis Software Tool (PHAST 6.54) from Det Norske Veritas. The software is usually used to assess situations which present potential hazards to life. It is applicable for hazardous substances in general and has not been specifically validated for liquid hydrogen release yet.

3.1 Harm effect distance of each consequence

The harm effect distances for instantaneous release of liquid hydrogen are shown in Figure 2. It can be seen that for catastrophic rupture of liquid hydrogen tank, the cold cloud produces 21.0 m of harm effect distance to people. If with immediate ignition, the direct flame contact of a fireball will result in 3.3 m of harm distance. The heat radiation of 9.5kW/m^2 from the fireball can affect a distance of 11.7 m however the duration of the fireball is only 0.86 second, which results in the thermal dose of only 17.3 (kW/m^2)$^{3/4}$s, much smaller than the harm criterion of 520(kW/m^2)$^{3/4}$s. Therefore the harm effect of the heat radiation from the short-duration fireball may be ignored and the direct flame contact will dominate the harm effect distance of the fireball. If with delayed ignition, the worst case of flash fire or vapor cloud explosion can produce longer harm distance to people, about 34.2m, and 42.2m, respectively.

The overall sequence of harm effect distances for instantaneous release of liquid hydrogen is that vapor cloud explosion>flash fire>cold cloud> fireball. The vapor cloud explosion is the leading consequence of an instantaneous release and may be used for the determination of safety distances in the scenario of catastrophic rupture of liquid hydrogen tank.

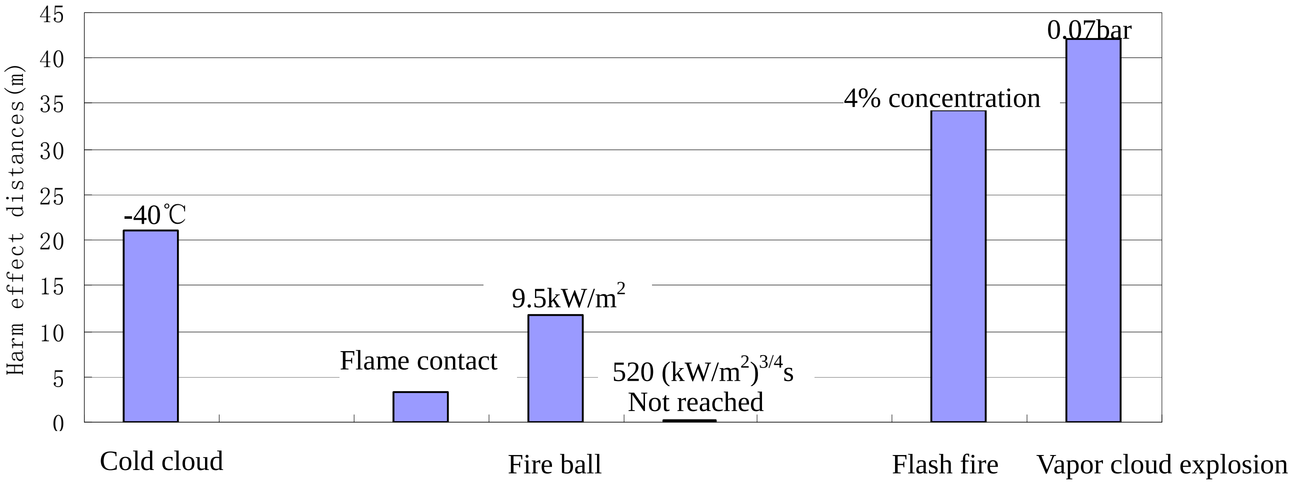

Figure 2 harm effect distances of catastrophic rupture of liquid hydrogen tank

The harm effect distances for a continuous release of liquid hydrogen with a hole size of 10mm are shown in Figure 3. It can be seen that for 10mm leak from liquid hydrogen tank, the cold cloud produces only 1.6 m of harm effect distance to people, much smaller than the cold effect distance (21m) from catastrophic rupture. If with immediate ignition, the direct flame contact of a jet fire will result in 4.3 m of harm distance. The heat radiation of 9.5kW/m^2 from the jet fire can affect a longer distance of 5.9 m. Compared with the heat radiation from direct ignition of an instantaneous release, the radiation of 9.5kW/m^2 from the jet fire can only reach approximately half distance of the fire ball of 11.7m. However, the thermal dose of the jet fire is much larger than that of the fireball because of the much longer duration. As shown in Figure 3 and Figure 2, the thermal dose of 520 (kW/m2) $^{3/4}$s from the jet fire can reach 5.7m, but the thermal dose from the fire ball never reach this level. Consequently, the harm effect distance of the jet fire (5.9m) is longer than that of the fireball (3.3m). If with delayed ignition, the worst case of flash fire or vapor cloud explosion can produce harm distance to people about 5.5m, and 11.0m, respectively, much shorter than those from instantaneous release due to the much smaller mass flow rate of leak scenario.

The overall sequence of harm effect distances for continuous release of liquid hydrogen is that vapor cloud explosion>jet fire>flash fire>cold cloud. The vapor cloud explosion is the leading consequence of a continuous release and may be used for the determination of safety distances in the leak scenario of liquid hydrogen tank.

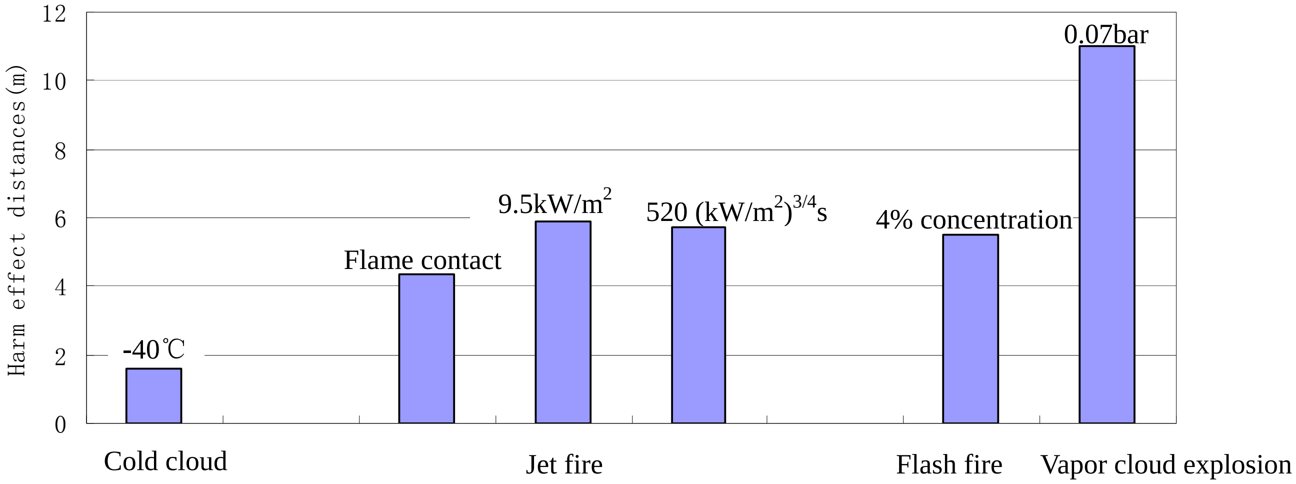

Figure 3 harm effect distances of 10mm leak from liquid hydrogen tank

If make an overall comparison between Figure 2 and Figure 3, it is obvious that the longest harm effect distance of a catastrophic rupture is much longer than that of a leak scenario. The catastrophic rupture is the leading event with larger harm rather than leak scenarios. You might argue that the sudden burst of cryogenic hydrogen tank is not likely to occur unless in some extreme catastrophic event such as car accident, and the leak scenarios are the most frequent events likely to occur. Purple Book [8] usually suggests that the catastrophic failure of pressure vessel is lower than a magnitude of leak frequency and for non-pressure vessel the rupture frequency should be much smaller. Your argument is reasonable and may be right if from a standpoint of risk. However it is not the case from a consequence perspective. From a harm perspective, the catastrophic rupture is the dominate event rather than leak scenarios.

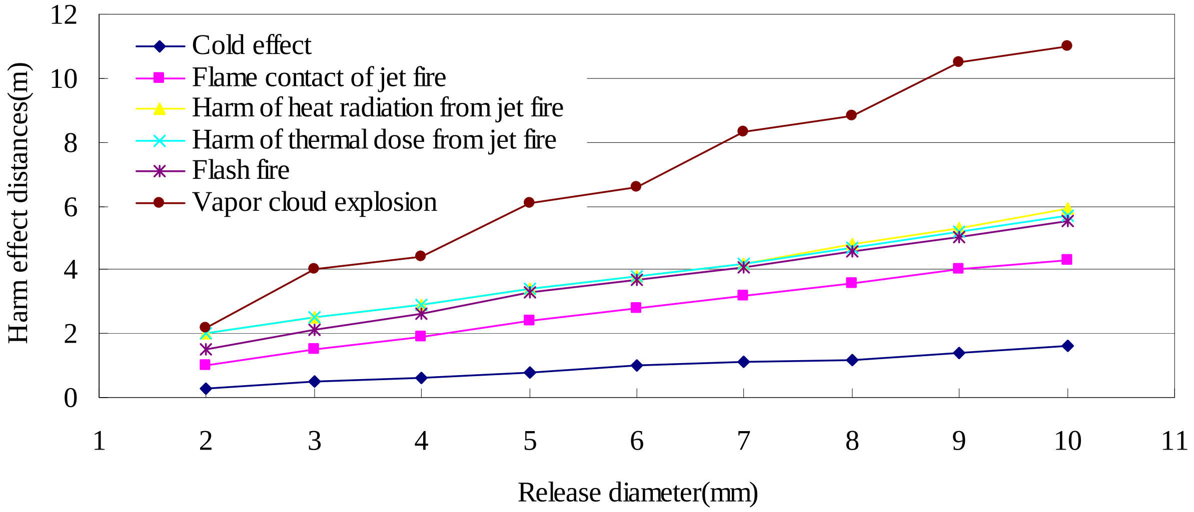

Figure 4 harm effect distances for leak from liquid hydrogen tank with different release hole size

10mm leak is a conservative assumption and in most cases, the actual leak diameter may be smaller. The harm effect distances of leak from liquid hydrogen tank for different release hole size are shown in Figure 4. It can be seen that the harm effect distances increases with the growth of leak diameter.

With the leak diameter changes from 2mm to 10mm, the longest harm effect distances vary from 2.2m to 11.0m with ignition consequences, and only from 0.3m to 1.6m without ignition. The cold effect of liquid hydrogen leakage is quite localized. No matter how release diameter changes, the hazard sequence is still that vapor cloud explosion>jet fire>flash fire>cold cloud. The vapor cloud explosion is always the leading consequence of a continuous release and can be used for the determination of safety distances in the leak scenario of liquid hydrogen tank.

3.2 Comparison of compressed gas cylinder and liquid hydrogen tank with equivalent mass

The consequences of compressed gaseous hydrogen release are physical explosion, jet fire, flash fire and vapor cloud explosion, which was already studied in our previous research [9]. For the reason of conservatism, the comparisons are made under worst condition including catastrophic rupture and worst release diameter of 10mm. The calculated harm effect distances of instantaneous release and continuous release under different storages are shown in Figure 5 and Figure 6, respectively.

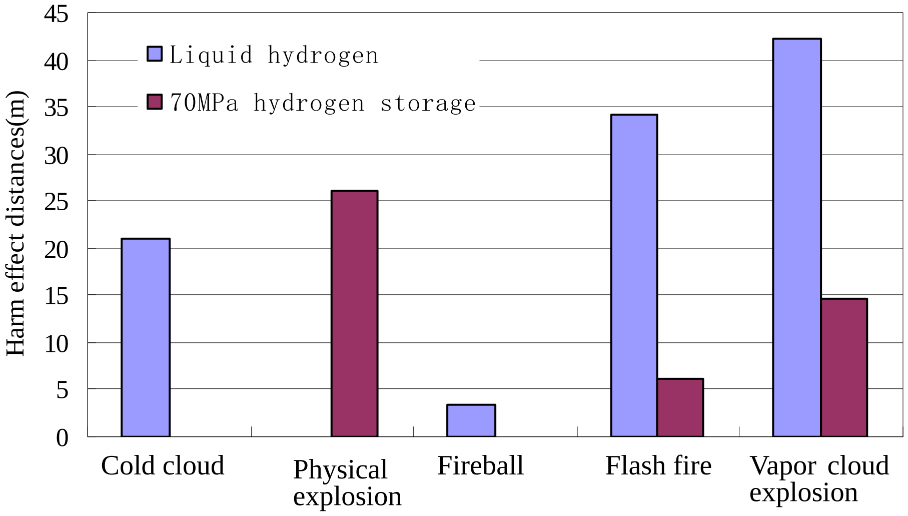

Figure 5 harm effect distances of catastrophic rupture under different storages

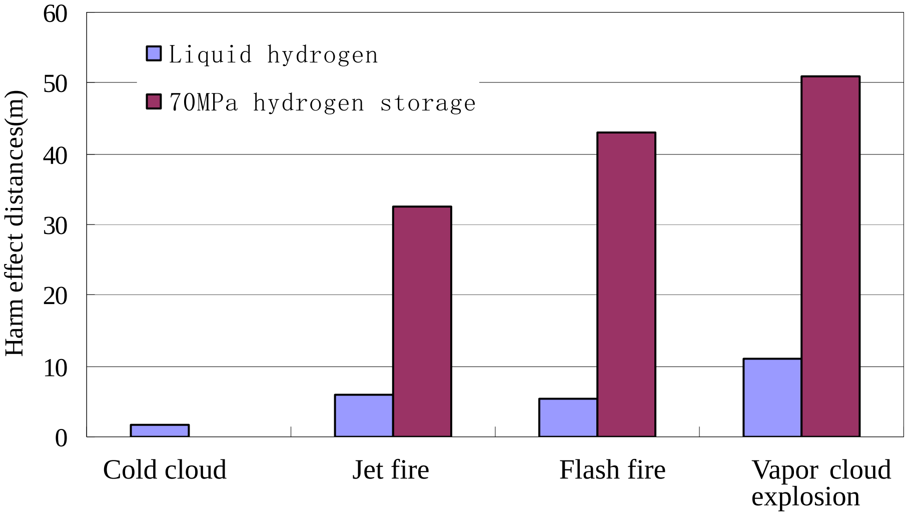

Figure 6 harm effect distances of 10mm leak under different storages

It can be seen from Figure 5 and Figure 6 that for instantaneous hydrogen release, the longest harm effect distance of liquid hydrogen release is much larger than that of 70MPa gaseous hydrogen release. On the contrast, for continuous hydrogen release, the longest harm effect distance of liquid hydrogen release is much smaller than that of 70MPa gaseous hydrogen release. In detail, without ignition, the instantaneous release of liquid hydrogen produce shorter harm effect distance than that of 70MPa gaseous hydrogen, while the continuous release of liquid hydrogen produce longer harm effect distance than that of 70MPa gaseous hydrogen. Oppositely, with ignition sources, the instantaneous release of liquid hydrogen produce longer harm effect distance than that of 70MPa gaseous hydrogen, while the continuous release of liquid hydrogen produce shorter harm effect distance than that of 70MPa gaseous hydrogen.

The results indicate that the liquid hydrogen storage may be safer than 70MPa gaseous storage in case of leak scenario but may be more dangerous than 70MPa storage in case of catastrophic rupture. It is difficult to tell which storage is safer from a consequence perspective. Further investigation need to be made from a standpoint of risk, which combined both consequences and the likelihood of scenarios.

4.0 CONCLUSION

In this paper, the accidental release of hydrogen from cryogenic liquid storage tank and the subsequent consequences are studied such as hydrogen cold cloud, fire ball, jet fire, flash fire, and vapor cloud explosion. The cold effect, thermal effects and explosion overpressures from the consequences are evaluated. Besides, the harm effect distances of liquid hydrogen tank are compared with those of 70MPa compressed hydrogen storages with equivalent mass. The main conclusions can be summarized as following.

1. For instantaneous releases of liquid hydrogen, the sequence of harm effect distances is that vapor cloud explosion>flash fire>cold cloud> fireball. The vapor cloud explosion is the leading consequence of and may be used for the determination of safety distances in the scenario of catastrophic rupture of liquid hydrogen tank.

2. For continuous releases of liquid hydrogen, the sequence of harm effect distances is that vapor cloud explosion>jet fire>flash fire>cold cloud. The vapor cloud explosion is also the leading consequence and may be used for the determination of safety distances in the leak scenario of liquid hydrogen tank.

3. The liquid hydrogen storage may be safer than 70MPa gaseous storage in case of leak scenario but may be more dangerous than 70MPa storage in case of catastrophic rupture. It is difficult to tell which storage is safer from a consequence perspective. Further investigation need to be made from a standpoint of risk, which will combine both consequences and the likelihood of scenarios.

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