Consequence-based Safety Distances and Mitigation Measures for Gaseous Hydrogen Refueling Stations

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Abstract

With the rapid development of hydrogen vehicle technology and large scale fuel cell vehicle (FCV) demonstration project worldwide, more hydrogen refueling stations need to be built. Safety distances of hydrogen refueling stations have always been a public concern and have become a critical issue to further implementation of hydrogen station. In this paper, safety distances for 35MPa and 70MPa gaseous hydrogen refueling station are evaluated on the basis of the maximum consequences likely to occur. Four typical consequences of hydrogen release are considered in modeling: physical explosion, jet fire, flash fire and confined vapor cloud explosion. Results show that physical explosion and the worst case of confined vapor cloud explosion produce the longest harm effect distances for instantaneous and continuous release, respectively, indicating that they may be considered as leading consequences for the determination of safety distances. For both 35MPa station and 70MPa station, safety measures must be implemented because the calculated safety distances of most hydrogen facilities can not meet the criteria in national code if without sufficient mitigation measures. In order to reduce the safety distances to meet the national code, some mitigation measures are investigated including elevation of hydrogen facilities, using smaller vessel and pipe work, and setting enclosure around compressors. Results show that these measures are effective to improve safety but each has different effectiveness on safety distance reduction. The combination of these safety measures may effectively eliminate the hazard of 35MPa station, however, may be not enough for 70MPa station. Further improvements need to be studied for compressors inside 70MPa station.

Keywords: hydrogen refueling station, consequence modeling, safety distances, mitigation measures

1   Introduction

With the rapid development of hydrogen vehicle technology and large scale fuel cell vehicle demonstration project worldwide, more hydrogen refueling stations need to be built. As a new energy infrastructure for public use, it is always a critical issue to its further implementation whether it could provide enough safety.

Safety distances of hydrogen refueling stations have always been a public concern. "Safety

distances" are always defined to have some space between the hazardous installation and the different types of targets to keep a hydrogen facility or system far enough away from people and other facilities to minimize the effects of an accidental event such as a fire and explosions [1]. There are generally two different ways of characterization of the safety distances. The first one is on the basis of a risk assessment compared with the acceptance criteria. The second one is tied up to the deterministic concept of the maximum consequences likely to occur (the probabilistic terms is never considered). This paper adopts the second approach. In this way the distances estimated are relatively high as they refer to severe accidents.

Based on the second approach, this paper will investigate the safety distances of severe accidents in gaseous hydrogen refueling stations. We do not examine every accident scenario. Instead, we only choose the worst cases to identify the maximum harm effect distances. For example, for the pipe work release, we only choose full bore rupture rather than a given leak diameter. To avoid confusion, "harm effect distance" is used to express distance for a specific consequence (flash fire, jet fire or explosion, etc.) of an accident scenario. A "safety distance" refers to the longest harm effect distance of an accident scenario.

Currently there is only 35MPa hydrogen refueling stations in China. In future, 70MPa stations may be built as the pressure of an FCV tank may increase from 35MPa to 70MPa. Table 1 shows the operating pressure of hydrogen refueling stations and related codes in China, GB 50177 [2].

This code is not specifically designed for hydrogen refueling stations for fell cell vehicles, however, in the absence of specific codes we have to rely on the most relevant one. Table 2 lists the safety distance values in GB50177. We will compare the calculated safety distances with corresponding values in the code, investigate potential mitigation measures and examine whether the measures are effective to reduce safety distances to meet the code.

2 Modeling

2.1 Possible consequences of hydrogen release

Releases of hydrogen can be either instantaneous or continuous. An instantaneous release" is a sudden violent burst of equipment such as the burst of high pressurized hydrogen storage vessel. The result is a depressurization of the hydrogen (physical explosion) and subsequent dispersion of the hydrogen cloud. Ignition of the hydrogen cloud will result in a flash fire (vapor cloud fire). A confined vapor cloud explosion (Confined VCE) may occur if the released hydrogen accumulates in a confined area or if there is a considerable amount of pipe work in the cloud envelope. The consequences of continuous release will depend on the time of ignition. Direct ignition results in a jet fire, while delayed ignition results in a flash fire or an explosion (when released hydrogen piles up in a confined or semi-confined area). A fireball is not likely to occur for gaseous hydrogen, so it is not considered in our consequence calculations. To conclude, four typical consequences of hydrogen release are considered in our modeling: physical explosion, jet fire, flash fire and confined vapor cloud explosion.

Table 1: Operating pressure of hydrogen refueling stations and related codes

	At Present	In Future
Target pressure in FCV tanks	35MPa	70MPa
Maximum allowable working pressure of hydrogen refueling stations	Upper limit = 43.8MPa, actually in engineering practice maximum operating pressure at 41.4MPa in China	87.5MPa
Codes for hydrogen refueling stations in China	GB 50177-2005 is the most relevant one, though not specifically designed for hydrogen refueling station for fell cell vehicles	

Table 2: Safety distances in national code in China

Vulnerable Target	National code GB 50177
Area of important public buildings	50m
Area of civil buildings	25~40m, depending on the inventory of the hydrogen in the station
Equipments such as outdoor substation	25~40m, depending on the inventory of the hydrogen in the station

In the case of a catastrophic rupture of a cylinder, the contents of only one cylinder will be instantly released. It is not expected that several cylinders will rupture simultaneously. The rupture of a cylinder can cause a domino effect. As the peak overpressures are not likely to coincide, the effects of the domino event will not be considerably larger than the effects of a single event [3].

For reasons of conservatism, all continuous releases are assumed to be horizontal. As for the confined vapor cloud explosion, confined volume $1m^3$ is used to calculate the overpressure of the explosion because a hydrogen station should be in good ventilation design and a large congested volume of hydrogen is not likely to occur. To find the worst case for ignition explosions, ignition points are set every one meter distance downwind in modeling. Explosion caused by each ignition point will be calculated separately and then the worst case will be identified.

2.2 Station description and input data

The simplified flowchart of both 35MPa and 70MPa station is shown in Figure 1. In order to get necessary input data for calculation, most data are selected from 35MPa hydrogen refueling station in Shanghai. Hydrogen is brought to the station by road trailer, which consists of eight tubes with a volume of approximately $2.3m^3$ each and contains compressed hydrogen no more than 200 bars (200bar is the upper limit restricted by transportation law in China). The trailer is connected by flexible hose, which is connected to 20m pipe work to compressor. The compressor draws hydrogen from the trailer to fill the buffer storage up to maximum pressure 414bar. The buffer storage is nine interconnected cylindrical pressure vessels with a volume of approximately $0.77m^3$ each. When refueling, hydrogen will be drawn from buffer storage through 20m pipe work to the dispenser, and fill cars to a maximum pressure of 350bars. For 70MPa station, the input data are assumed to be the same except for the operating pressures. All scenarios and input data are shown in Table 3.
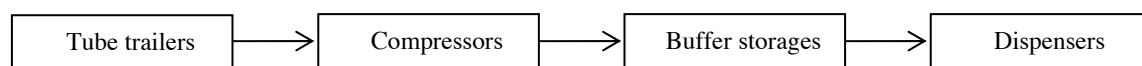
| Tube trailers | → | Compressors | → | Buffer storages | → | Dispensers |

Figure1: Flowchart of hydrogen refueling station

Table 3: Scenarios and data input for consequence modeling

Hydrogen facilities in hydrogen refueling station	Scenario number and descriptions	Release pressure (MPa)		Release hole size (mm)
		35 MPa station	70 MPa station	
Tube trailer	1 Catastrophic failure of tube trailer storage	20	20	N/A
	2 Leak from tube trailer storage	20	20	10
	3 Full bore rupture of flexible hose from tube trailer storage	20	20	13
Pipe work-1, from tube to compressor (20m)	4 Full bore rupture of pipe work	20	20	17
Compressor	5 Catastrophic failure of compressor	43.8	87.5	N/A
	6 Leak from compressor	43.8	87.5	15
Buffer storage	7 Catastrophic failure of storage tube	43.8	87.5	N/A
	8 Leak from buffer storage	43.8	87.5	10
Pipe work-2, from buffer to dispenser (20m)	9 Full bore rupture of pipe work	43.8	87.5	17
Dispenser	10 Catastrophic failure of dispenser	35	70	N/A

2.3 Harm criteria

The thermal, overpressure effects from hydrogen fires and explosions are harmful to people and equipment. According to IGC Doc 75/07/E/rev [4], for harm exposure threshold value to people, it is suggested that a value of $9.5kW/m^2$ is used for radiation from sustained credible fires. 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. Peak overpressure 0.07bar for explosion should be adopted. As for harm to equipment, the thermal radiation $37.5kW/m^2$ and explosion overpressure 0.2 bar are recommended. These values above are used as harm criteria to calculate harm effect distances to people and equipment, respectively.

For reasons of conservatism, all effects are calculated at height 1.5 m instead of on the ground level. 1.5m is considered to be a good average height for exposure to Asian's face and neck, where the body part usually without any cover.

3 Results and discussion

Calculations were carried out with software PHAST6.54 from Det Norske Veritas. This software is applicable for hazardous substances in general and specifically validated for hydrogen release in 2008[5].

3.1 Harm effect distances and safety distance determination

Fig 2 and Fig 3 show the harm effect distances to people and to equipment for all scenarios. For instantaneous release (scenario 1, 5 and 7), physical explosion produces the longest harm effect distances, both to people and to equipment. This indicates that the physical explosion may be considered as a leading consequence to the determination of safety distances for instantaneous release. For all continuous release scenarios, the worst case of ignited explosion produces the longest harm effect distance both to people and to equipment. This indicates that the worst case of ignited explosion may be used as a decisive consequence to the determination of safety distances for continuous release.
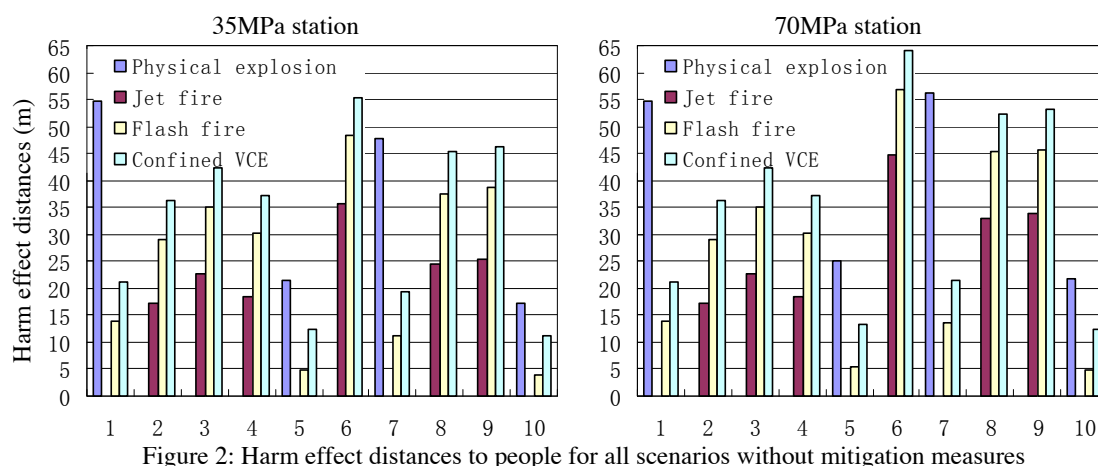

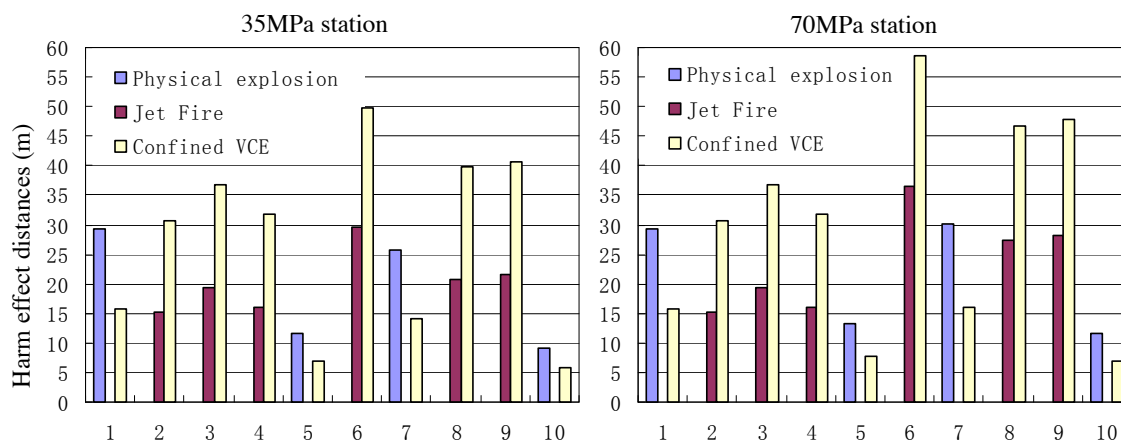Figure 2: Harm effect distances to people for all scenarios without mitigation measures

Figure 3: Harm effect distances to equipment for all scenarios without mitigation measures

3.2 Safety distances comparison with values in national code

Safety distance is defined as the longest harm effect distances and the longest harm effect distances are selected from Figure 2 and Figure 3 to create Table 4.

For 35MPa station, the safety distances to people of most hydrogen facilities are longer than 25 meters, the limit value in national code, expect for dispenser of 17.1 meters. Therefore for the sake of the hazards present at civil buildings, mitigation measures must be implemented on most hydrogen facilities including tube trailer, pipe work, buffer storage and compressor. It is also noticed that safety distances to people of compressor and tube trailer are 55.2 m and 54.7m, respectively, longer than 50 meters, which is the limit value for important public buildings in national code. So for the sake of the hazards present at important public buildings, mitigation measures should be in the first place implemented to compressor and tube trailer.

As for harm to equipment, the safety distances of most hydrogen facilities are also over 25m, the limit value in national code, expect for dispenser of 9.2m. Therefore, for the sake of equipment safety, mitigation measures also must be implemented on most hydrogen facilities including tube trailer, pipe work, buffer storage and compressor.

For 70MPa station, results also show that mitigation measures must be implemented on most hydrogen facilities except for dispenser. One different thing need to be mentioned is that for 70MPa station, besides compressor and tube trailer, buffer storage and pipe-2 also lead to distances longer than 50m, which present hazard to the area of important public buildings.

3.3 Mitigation measures and effectiveness

It is reported in our previous study that elevation of equipment, using smaller vessel and pipe work may be considered as potential mitigation measures [6]. Now we will examine the effectiveness of these measures on safety distance reduction for both 35MPa and 70MPa hydrogen refueling station.

3.3.1 Elevation

Figure 4 shows the safety distances to people and equipment. For 35MPa station with elevation measures, safety distances to people can be reduced from 54.7 to 40.5m (26.0% off) for tube trailer, 37.2 to 17.6m (52.7% off) for pipe between tube and compressor, 55.2 to 35.8m (35.1% off) for compressor, 47.7 to 35.3m (26.0% off) for buffer storage, and 46.2 to 25.2m (45.5% off) for pipe between buffer storage and dispenser. With elevation measures, safety distances of both tube trailer and compressor are reduced to distance lower than 50m. However, compared with 25m for the area of civil buildings in the national code, safety distances of most hydrogen facilities still surpass the value expect for pipe between tube trailer and compressor (17.6m). For the sake of people's safety around civil buildings, further improvements need to be made on tube trailer, compressor, buffer storage and pipe between buffer storage and dispenser.

As for harm to equipment, only the safety distances of compressor (26.9m) can not be reduced to distance shorter than 25m. So, further improvements need to be made on the compressor. One good thing noticed is that safety distance of pipe between tube trailer and compressor can be reduced to zero. Hazard of this pipe work to surrounding equipment can be completely eliminated by elevation.

Table 4: Safety distances of equipment without mitigation measures (m)

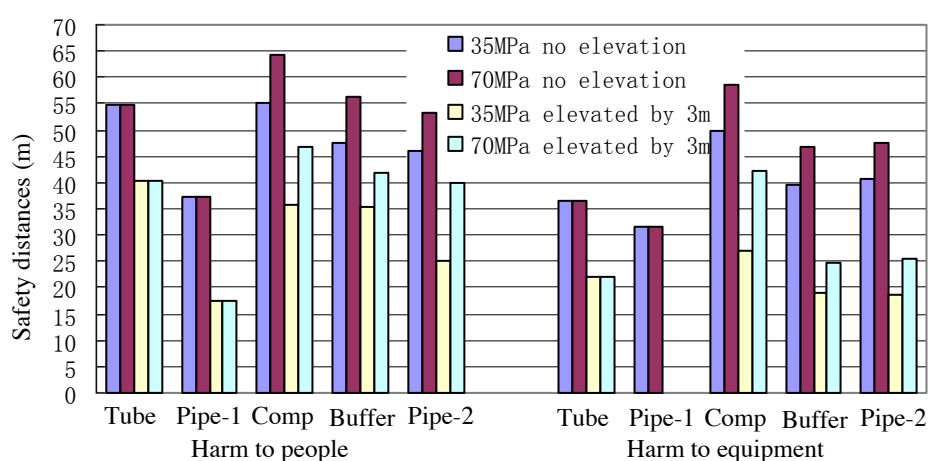| Harm criteria	Harm to people		Harm to equipment	
Station type	35MPa	70MPa	35MPa	70MPa
Tube trailer	54.7	54.7	36.7	36.7
Pipework-1	37.2	37.2	31.7	31.7
Compressor	55.2	64.2	49.7	58.7
Buffer	47.7	56.2	39.7	46.7
Pipework-2	46.2	53.2	40.7	47.7
Dispenser	17.1	21.8	9.2	11.7

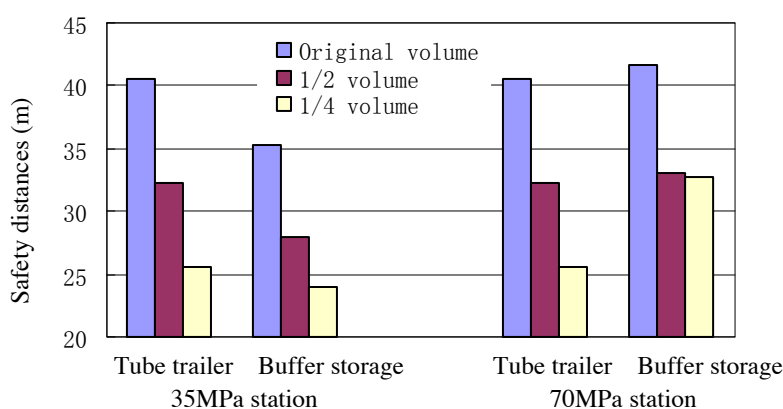Figure 4: Safety distances to people and equipment

Figure 5: Safety distances to people for different storage volume (still with elevation)

For 70MPa station with elevation measures, safety distances to people can be reduced from 54.7 to 40.5m (26.0% off) for tube trailer, 37.2 to 17.6m (52.7% off) for pipe between tube and compressor, 64.2 to 46.9m (26.9% off) for compressor, 56.2 to 41.7m (25.8% off) for buffer storage, and 53.2 to 39.9m (25.0% off) for pipe between buffer storage and dispenser. With elevation measures, safety distances of all hydrogen facilities are reduced to distance shorter than 50m. Hazards to the area of important public buildings are completely eliminated. However, compared with 25m for the area of civil buildings in the national code, safety distance of most hydrogen facilities still surpass this value expect for pipe between tube trailer and compressor(17.6m). For the sake of people's safety around civil buildings, further improvements need to be made on tube trailer, compressor, buffer storage and pipe between buffer storage and dispenser.

As for harm to equipment, safety distances of tube trailer and buffer storage can be reduced to the value smaller than 25m, while safety distance of compressor and pipe between buffer storage and dispenser can not be. For the sake of equipment safety, further improvements need to be made on the compressor and pipe between buffer storage and dispenser. One good thing noticed is that safety distance of pipe between tube trailer and compressor can be reduced to zero. Hazard of this pipe work to surrounding equipment can be completely eliminated by elevation.

To conclude, elevation of hydrogen facilities is an effective measure to reduce safety distance for both 35MPa station and 70MPa station. However, elevation can not reduce all safety distances to values lower than distance limit in national code. For the sake of people's safety, further improvements need to be made on tube trailer, compressor, buffer storage and pipe between buffer storage and dispenser for 35MPa and 70MPa station. For the sake of equipment safety, further improvements need to be made on the compressor for 35MPa station and to the compressor and pipe between buffer storage and dispenser for 70MPa station.

3.3.2 Using smaller storage vessel

In previous section 3.3.1, results show that tube trailer and buffer storage need further improvements even with elevation measure. In this section, decreasing the vessel volume is used as an additional mitigation measure. Figure 5 shows safety distances to people for different storage volume.

For 35MPa station, the safety distance of tube trailer is reduced to 32.2m (20.5% off) and 25.5m (37.0% off) for 1/2 volume and 1/4 volume respectively, compared with 40.5m for original volume (2.3m^3). The safety distance of buffer storage is reduced to 28m (20.7% off) and 24m (32.0% off) for 1/2 volume and 1/4 volume respectively, compared with 35.3m for original volume (0.77m^3). It is noticed that 1/4 volume of tube trailer still produces safety distance longer than 25m, so the volume should be reduced smaller. Based on calculation, only when the volume is smaller than 0.53m^3, can the safety distance be shorter than 25m.

For 70MPa station, the safety distance reduction of tube trailer is exactly the same as that of 35MPa station. The safety distance of buffer storage is reduced to some extent by using smaller vessel but still longer than 25m (33.1m for 1/2 volume and 32.8 for 1/4 volume). Continuous decrease of the volume will not help reduce safety distance. This is because decrease the volume only reduces the harm effect distance of physical explosion but not reduce the harm effect distances of continuous release. When safety distance is determined by the consequences of continuous release, it will be useless to decrease the vessel volume. It seems that 25m in national code may be not suitable for 70MPa station or further improvements need to be investigated to meet the national code.

3.3.3 Using smaller pipe

In previous section 3.3.1, results show that pipe-2 (pipe between storage buffer and dispenser) of both 35MPa station and 70MPa station needs further improvements even with elevation measure. In this section, using smaller pipe is used as a new mitigation measure.

Figure 6 shows the safety distances of elevated pipe-2 with different size. Compared with original pipe (one inch pipe), all safety distances of 3/4 inch pipe can be reduce to the value smaller than

25m, which is the safety distance limit in the national code. Therefore, using 3/4 inch pipe instead of one inch can be considered as an effective migration measure to eliminate hazards both to people and to equipment.
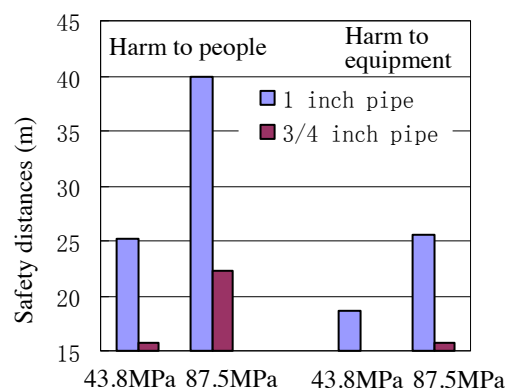

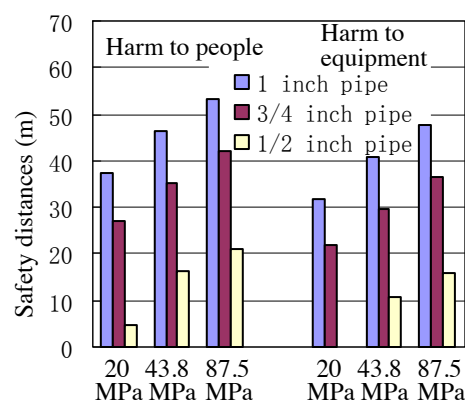Figure 6: Safety distances of pipe-2
(with elevation)

Figure 7: Safety distances of pipe-2
(without elevation)

We also want to find out which size is appropriate for pipe without elevation. Figure 7 shows the safety distances of pipe without elevation. It can be seen that without elevation, using 1/2 inch pipe can reduce safety distance shorter than 25m. Therefore, it may be concluded that both for 35MPa station and 70MPa station without elevation, 1/2 inch pipe instead of others should be used to meet the distance limit in national code.

3.3.4 Compressor with enclosure (solid wall)

In previous section 3.3.1, results show that compressor of both 35MPa station and 70MPa station needs further improvements even with elevation measure. In this section, compressor with enclosure is used as a new mitigation measure. Figure 8 shows the safety distances of elevated compressor with the new measure. For 35MPa station, the safety distance of compressor

with enclosure can be reduced to the value smaller than 25m, both to people and to equipment. For 70MPa station, safety distance to equipment can be reduced smaller than 25m but safety distance to people is still longer than 25m. Further improvements need to be investigated to eliminate compressor hazard to people.
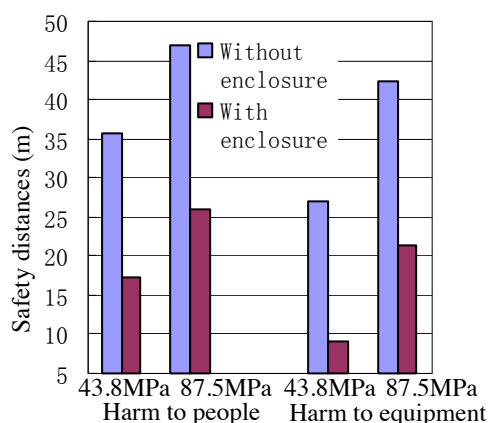

Figure 8: Safety distances of compressor (with elevation)
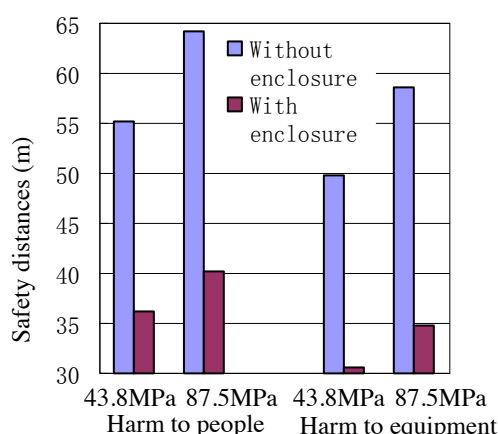

Figure 9: Safety distances of compressor (without elevation)

With enclosure but without elevation (Figure 9), the safety distances of compressor can also be reduced to some extent, but they are still longer than 25m, both to people and to equipment. Therefore, elevation and enclosure should be used together to eliminate compressor hazards to people and to equipment.

4 Conclusions

This paper examines the severe accidents and calculates safety distances of hydrogen facilities in both 35MPa and 70MPa hydrogen refueling station. Mitigation measures are investigated to reduce safety distances to meet the national code GB50177. The major conclusions can be summarized as following.

(1) Physical explosion and the worst case of confined vapor cloud explosion produce the longest harm effect distances for instantaneous and continuous release, respectively, indicating that they may be considered as leading consequences for the determination of safety distances.

(2) For both 35MPa station and 70MPa station without sufficient mitigation measures, safety distances of most equipment are greater than distance limit in national code. Safety measures must be implemented on most hydrogen facilities inside hydrogen refueling stations.

(3) Elevation of hydrogen facilities is an effective measure to reduce safety distances for both 35MPa station and 70MPa station. However, this measure can not reduce all safety distances to values smaller than distance limit in national code. Further improvements need to be made on tube trailer, compressor, buffer storage and pipe between buffer storage and dispenser.

(4) By using appropriate smaller vessel, the safety distances of 20MPa tube trailer and 43.8MPa buffer storage can be reduced to values smaller than the distance limit in national code. By using 3/4 inch pipe with elevation or 1/2 inch pipe without elevation, instead of one inch pipe, the safety distance of pipe work can be reduced to a value smaller than the limit in national code.

(5) Combination of elevation and enclosure is effective to eliminate 438MPa compressor hazards to people and to equipment, while for 875MPa compressor these measures are not enough to eliminate hazards to people. Further improvements need to be investigated in compressors inside 70MPa station.

Acknowledgement

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