The Concept of Hydrogen Safety Underlying the Japanese Standards

1. Foreword

A. Since hydrogen is a gas that diffuses extensively and has a wide range of flammability (4%–75%), its unique properties need to be accounted for to ensure safety. (Different from the liquid fuel gasoline.)

B. The development of hydrogen fuel vehicles is relatively new in the history of automobiles, and various issues that are not covered by the provisions for gasoline vehicles must be also addressed.

C. Nevertheless, it is not desirable to set out detailed or complicated provisions that would frustrate the development of new technologies.

Based on the principles A, B, and C above, it is reasonable to design the overall structure of standards, with a view to granting vehicle approvals, as follows:

a. They should be performance requirements, wherever possible.

b. In the case of regulatory items for which it is difficult to specify performance requirements, and for those structures, equipment, and functions to be used as the base to meet the performance requirements, the minimum installation and functional requirements on fuel piping system should be laid out.

c. Individual part certification should be at the minimum necessary level.

2. Structuring of Standards

2.1. Division in the fuel piping system

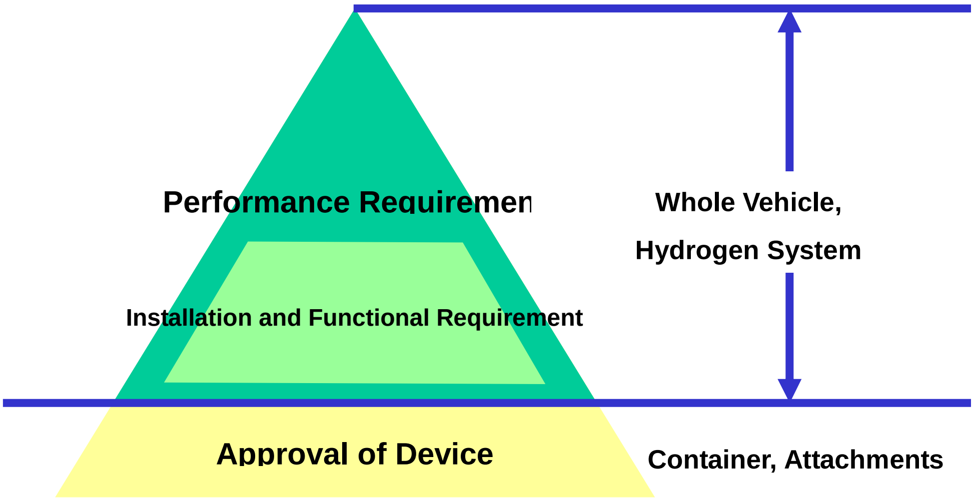
In general, the fuel piping system for fuel cell vehicles is operated by reducing the pressure of hydrogen from the high-pressure container. While the multilevel pressure-reduction structure is also possible, the system is generally divided into two levels: high-pressure part and low-pressure part. Since gas becomes more dangerous when it leaks at high pressures, it is more important to ensure safety at high pressures. Hence, based on the above-mentioned principle C, it is thought to be reasonable to set out provisions for the high-pressure part in addition to standards that cover the overall hydrogen system.

2.2. Reasoning behind the structuring of standards

Due to its low molecular weight, hydrogen leaks more easily than other gases. Also, because it diffuses extensively, there is a risk of explosion when hydrogen-air mixtures that are within the flammable range accumulate in an enclosed space. For these reasons, the Japanese standards were designed to prevent the hydrogen leakage or limit hydrogen leaks to the minimum level so that dangerous situations would not arise by focusing on the following three targets: (1) whole vehicle, (2) hydrogen system, including the fuel piping system, and (3) parts. The standards were then drafted by studying these three objects under different vehicle operational conditions (e.g., parked, idling, running, gas filling, collision, etc.). Furthermore, two things that do not apply to the existing natural gas vehicles were studied: (1) the ability of the fuel (i.e., hydrogen) to embrittle metals and (2) the use of hydrogen gas without odorization.

In drafting of the standards, it was considered necessary, for the purpose of ensuring safety of the whole vehicle and hydrogen system, to establish performance requirements accompanied by test procedures as well as installation and functional requirements on devices.

The specific requirements and the rationales behind them will be explained below.



3. "No Hydrogen Leakage"

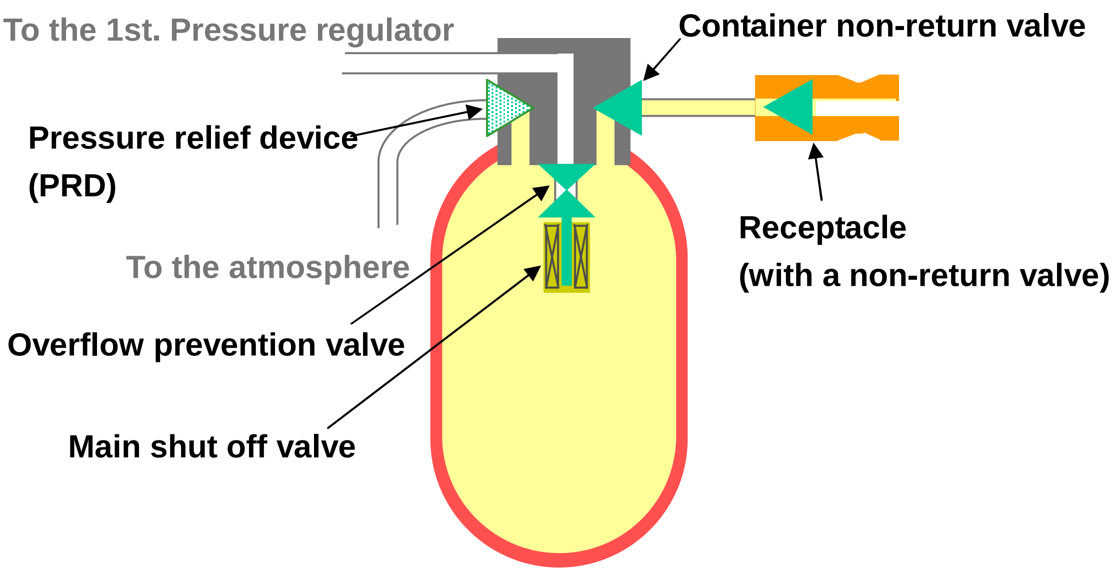
3.1. Hydrogen system

The Japanese standards state that there must be no gas leakage in the hydrogen system. Specifically, they contain the performance requirement to check for gas leakage at critical locations in the hydrogen system by valve check or gas detector.

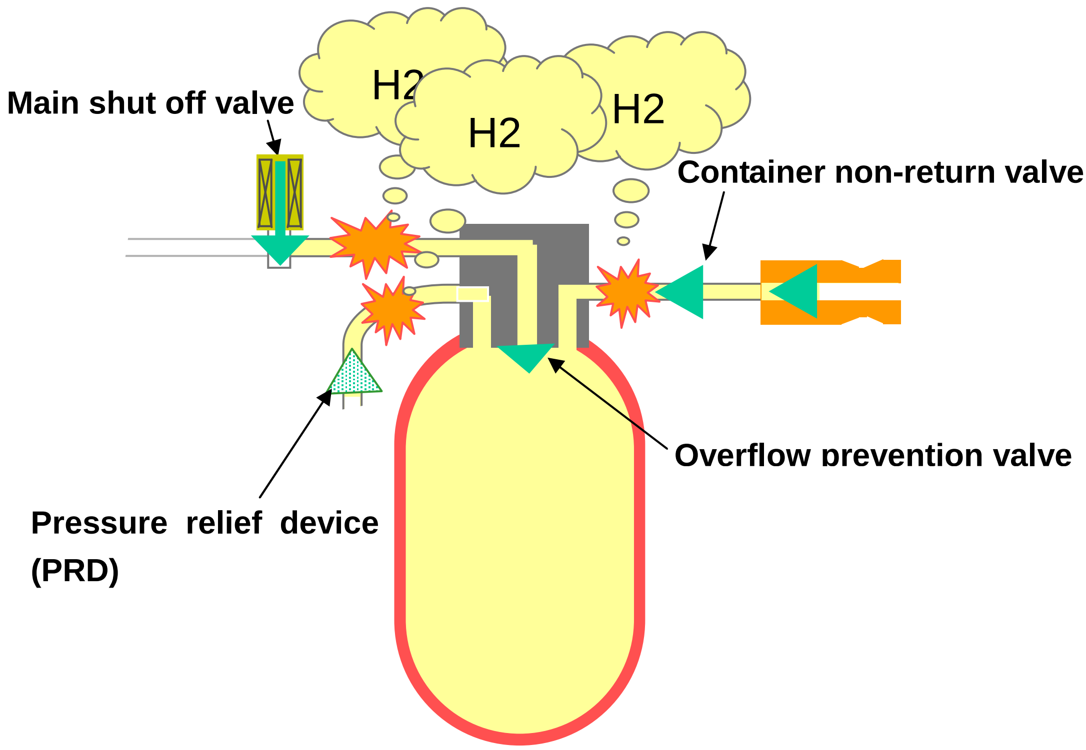
Furthermore, if parts for the high-pressure system are installed at inappropriate locations, even with the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen, described below, operating normally, it cannot stop hydrogen leakage that occurs during the normal use in the real-world situation. For this reason, the Japanese standards include the installation requirement to "install the main shut off valve, PRD, and container non-return valve directly on the container".

In this stage of drafting, the permissible amount of hydrogen leakage in collisions is going to be specified; however, the collision test conditions (speed, collision point, collision direction) are representative of the conditions that are statistically the most probable among those encountered in various traffic accidents nationwide, and so they do not cover all the accidents. It is therefore possible that hydrogen exceeding the permissible rate specified for the collision test will leak when vehicles collide at a speed higher than the test collision speed or at a point different from the test collision point even if the collision speed is lower. In order to minimize the risk of hydrogen leakage that would occur in such real-world collisions as much as possible, the Japanese standards include the installation requirement to "install the main shut off valve, PRD, and container non-return valve directly on the container" (Figure 1).

It should be acknowledged that performance requirements cannot address all the safety issues encountered in the real world. We should consider the real-world safety as the most important matter, and in cases where the performance requirements are not effective enough for ensuring such safety, they should be supplemented by some effective measures in the installation and/or functional requirements, if any.



With the installation requirement to "install the main shut off valve, PRD, and container non-return valve directly on the container"



Without the installation requirement to "install the main shut off valve, PRD, and container non-return valve directly on the container"

Figure 1 With and Without Installation Requirement to "Install the Main Shut Off Valve, PRD, and Container Non-Return Valve Directly on the Container"

The Japanese standards also include the installation requirement that specifies the positional relationship between the first pressure regulator and the main shut off valve.

Since the pressure regulator has a hole or pathway to the atmosphere to function, it must not be installed upstream of the main shut off valve. If the pressure regulator installed upstream of the main shut off valve fails and causes hydrogen leakage into the atmosphere, the leakage cannot be stopped even if the main shut off valve is closed.

It is possible that situations that cannot be dealt with by the system for detecting hydrogen gas leaks/shutting off the supply of hydrogen will occur. Besides, leakage that would occur in parked vehicles with their functions disabled can only be prevented through structural requirements. For these reasons, the requirement to “install the first pressure regulator downstream of the main shut off valve” is important.

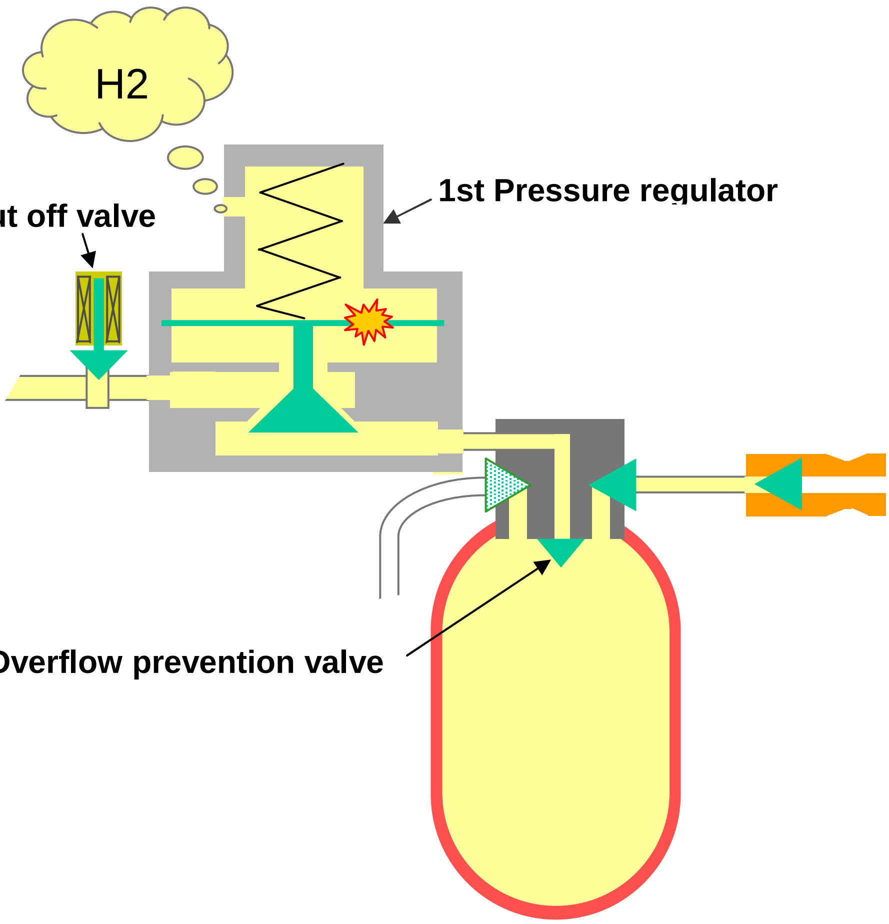


Figure 2 Prohibition to Install the First Pressure Regulator Upstream of the Main Shut Off Valve

In addition, to make sure there will be absolutely no hydrogen leakage in places where there are occupants, the Japanese standards have the basic structural requirement prohibiting the installation of the container, piping, and gas filling unit or receptacle in the passenger compartment and luggage compartment.

As explained above, for the purpose of ensuring there will be no hydrogen leakage or minimizing the hydrogen leakage risk, the three requirements to "install the main shut off valve, PRD, and container non-return valve directly on the container", to "install the first pressure regulator downstream of the main shut off valve", and to "prohibit the installation of the container, piping, and gas filling unit or receptacle in the passenger compartment and luggage compartment" are important and basic requirements that supplement the performance requirements in situations where safety cannot be sufficiently ensured by performance requirements alone from the standpoints of real-world vehicle operational conditions (i.e., parked, idling, running, collision, etc.).

3.2. Fuel container

As described in the previous section, while the provision on the installation of these three parts, i.e., the main shut off valve, PRD, and container non-return valve, is indispensable, it is also essential for the prevention of hydrogen leakage that these three parts operate normally throughout the vehicle's life. Since failures of these three parts and the container would lead to hydrogen leakage that cannot be stopped by the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen, described below, the standards must ensure that these three parts and the container have the necessary function and performance, including the required durability. Therefore, for these three parts and the container, the safety is guaranteed through type certification of individual parts.

In addition, needless to say, when the driver has turned off the ignition switch in the event of some trouble, or when the battery power has gone off due to failure, the main shut off valve must not open; otherwise the hydrogen supply would not be shut off. Accordingly, the Japanese standards also contain the functional provision that "the main shut off valve shall be closed automatically."

Even when the vehicle is parked and thus the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen is off, there must be no hydrogen leakage. For this to be achieved, while the vehicle is parked, it is best to keep the gas inside the high-pressure container only. For this reason, the Japanese standards require the parts that are positioned immediately next to the high-pressure container (both upstream and downstream of the container) to be installed directly on the container (as described in the previous section), instead of being located along the piping. This requirement applies to these three parts: main shut off valve, PRD, and container non-return valve.

4. "Limiting Hydrogen Leaks to the Minimum Level to Prevent Dangerous Situations"

4.1. Purge

Japanese Safety Regulations for Road Vehicles, Attachment 100 ("Japan 100") contains the performance requirement under which the hydrogen concentration must be kept at 4% or below inside the vehicle exhaust system. In the following, the rationale behind the setting of such hydrogen concentration standard will be given.

Naturally, in order for hydrogen fuel cell vehicles to be used widely, it must be ensured that the exhaust gas generated during purging of the installed fuel cells will not cause any danger to the surroundings. In addition, it must not cause those vehicles to be restricted from being parked in residential garages, underground parking lots in cities, etc.

In general, 100%-concentration hydrogen gas is used in purging of fuel cells installed in vehicles, and Japan 100 requires it to be lowered to the level where it does not cause any danger in vehicles (e.g., by means of dilution) when it is discharged from vehicles.

The flammability range of hydrogen is usually 4%–75%. Hydrogen concentration of 75% or above will be within the combustion range when hydrogen diffuses in the atmosphere after being discharged from vehicles, and therefore it is out of the question.

As long as hydrogen concentration in gas is diluted to 4% or below while it is still on board vehicles and then discharged, it will not cause combustion even if fire is set intentionally. Therefore, it will neither cause any danger to the surroundings nor break vehicles.

Next, the reasons why the provision on the discharged hydrogen concentration of 4% or below is appropriate even in terms of safety at garages and parking lots will be explained below.

IEC 60079-10 defines **hazardous area** as an "area in which an explosive gas atmosphere is present, or may be expected to be present, in quantities such as to require special precautions for the construction, installation and use of apparatus..." and **explosive gas atmosphere** as a "mixture with air, under atmospheric conditions, of flammable substances in the form of gas or vapour in which, after ignition, combustion spreads throughout the unconsumed mixture".

If the hydrogen concentration in gas generated during purging of fuel cells to be discharged is required to be 4% or below, no air/gas mixture producing **explosive gas atmosphere** will be discharged. Thus, garages and parking lots will not be considered as hazardous areas that would require special precautions for ventilation or detonation prevention, and hydrogen fuel cell vehicles can be treated the same way as the existing vehicles at those garages and parking lots.

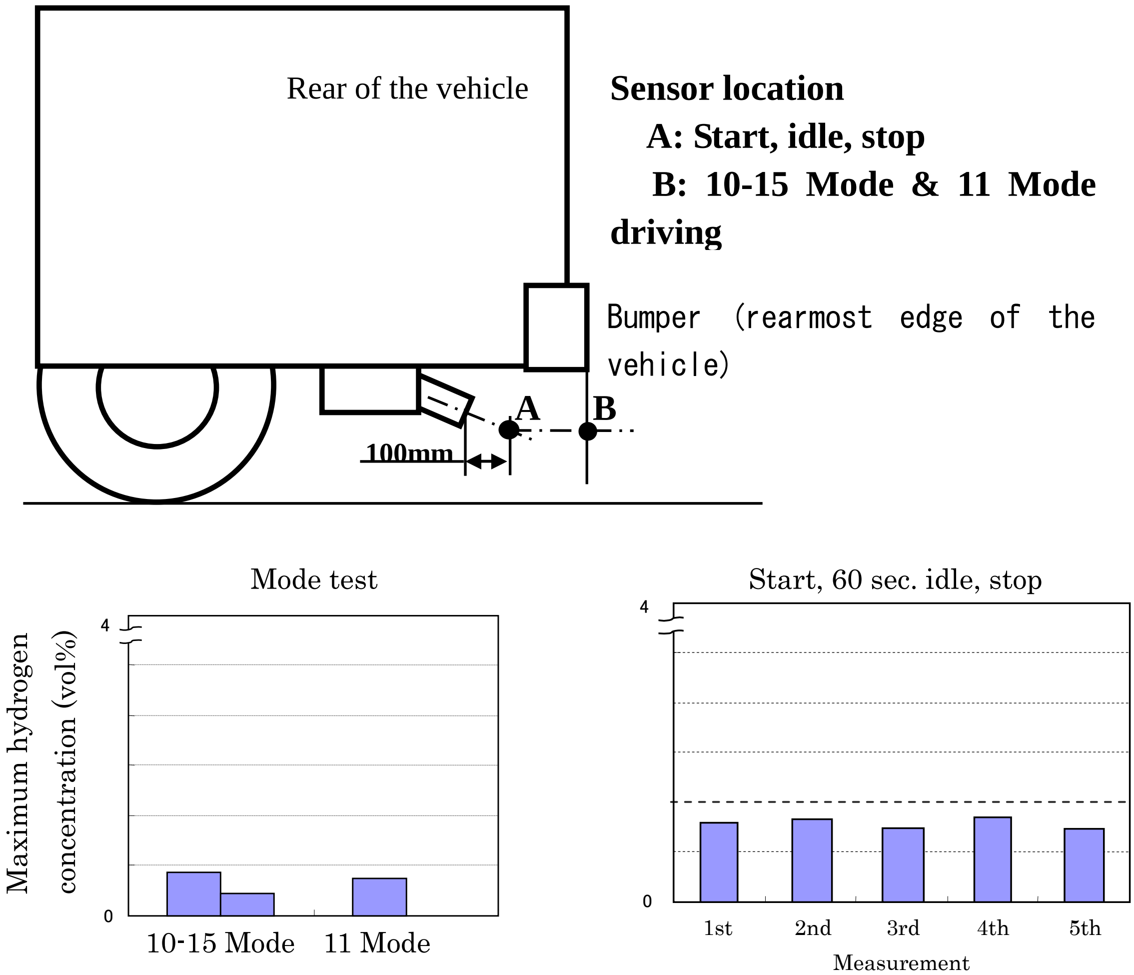
It should also be noted that SAE J2578 requires, for vehicles that discharge gas whose hydrogen concentration is 4% or above, the demonstration that the hydrogen concentration will be 1% (25% LFL) or below in a space simulating a garage with a specific ventilation rate while the vehicle is at idle in such space. This requirement is appropriate in the light of IEC 60079-10 as well.

Paragraph 3.8.1. of Japan 100 states that "in fuel cell vehicles that discharge gas containing hydrogen purged from the fuel cell system into the atmosphere, the purged gas in excess of 4% of hydrogen concentration shall not be discharged or leak to the atmosphere". This provision does not specify any environmental or vehicle operational conditions. This means that no purged gas in excess of 4% of hydrogen concentration must be discharged or leak to the atmosphere under *any* environmental or vehicle operational condition. For the purpose of preventing the hydrogen concentration in purged gas from exceeding 4% when it is discharged into the atmosphere, if dilution is chosen as the method, for example, the dilution rate is to be set for various vehicle operational conditions (cold engine, warm engine, start, idle, acceleration/deceleration, cruising, stop, etc.). This will be the work of engineers of vehicle manufacturers.

Paragraph 3.8.2. of Japan 100 states that "in fuel cell vehicles that discharge gas containing hydrogen purged from the fuel cell system into the atmosphere, as for the hydrogen concentration of the purged gas at time of discharge into the atmosphere, the maximum hydrogen concentration obtained according to the method specified in

Attached Sheet 2 ‘Measurement of Hydrogen Concentration of Purged Gas at Time of Discharge’ shall not exceed 4%”, and Attached Sheet 2 specifies the operational conditions of start with warm engine, idle, and stop. These operational conditions were selected for the following two reasons:

1. When Japan 100 was developed, a fuel cell vehicle was driven according to the 11 Mode (start with cold engine, followed by mode-driving) and 10-15 Mode (start with warm engine, followed by mode-driving) in the Japanese emissions test procedures, and the hydrogen concentration in the discharged gas was measured. As a result, it was demonstrated that, by setting the dilution rate for various vehicle operational conditions (cold engine, warm engine, start, idle, acceleration/deceleration, cruising, stop, etc.), engineers of vehicle manufacturers are able to ensure that no gas in excess of 4% of hydrogen concentration will be discharged into the atmosphere (Figure 3).
2. The discharged gas containing hydrogen would pose most danger to the surroundings not during the vehicle’s running, such as acceleration/deceleration or cruising, but during the following three operations: engine start in the stationary state, idling, and stopping. This is because pedestrians can approach the vehicle during these three operations. And, during these operations, the engine is warm most of the time.



Maximum hydrogen concentration at the rearmost edge of the vehicle (10-15 Mode & 11 Mode)

Maximum hydrogen concentration near the hydrogen discharge point (Start, 60 sec. idle, stop)

Figure 3 Results of Tests to Check Hydrogen Concentration in Discharged Gas

At present, there is a proposal to use, as the hydrogen concentration in discharged gas, the average concentration in any moving 3 seconds time interval. However, no discussion on using the 3-second moving average arose from the results of measurement in the fuel cell vehicle conducted when the Japanese standard was developed (Figure 3).

4.2. System for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen

Because the odorless hydrogen is used, humans cannot detect gas leaks by smell. Therefore, for addressing the hydrogen leakage, the vehicle needs to be equipped with the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen. The Japanese standards contain both the installation requirement for the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen and the performance requirement for testing its normal operation through spraying the actual hydrogen gas onto the system.

We recommend the test procedures of Japan 100 for the following two reasons:

Japan 100 graphically shows the location to install the system for detecting hydrogen gas leaks. However, this is only a guideline. As for actual installation locations, the optimum location will be determined by each vehicle manufacturer in the vehicle development stage through generating leaks at various flow rates from the actual piping, etc.

The testing of the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen in the procedures currently proposed by OICA is similar to the development work performed by vehicle manufacturers in the vehicle development stage, and therefore it is not appropriate as a test for vehicle approval or vehicle inspection. Furthermore, the testing is dangerous and so it is not appropriate as a test for vehicle approval or vehicle inspection from the standpoint of safety, either.

4.3. Collisions

For the purpose of limiting hydrogen leaks to the minimum level so that dangerous situations would not arise in the event of collisions, the Japanese standards have the performance requirement where the permissible amount of hydrogen leakage under the existing crash test conditions is specified.

4.4. Damages to the piping system due to external causes

For when the vehicle is actually running, it is necessary to consider external causes for damage, such as small rocks thrown at the vehicle or big rocks hit by the vehicle. Among hydrogen leakages due to cracks or holes made by these external causes, those that occur in the container cannot be stopped by the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen. Therefore, the Japanese standards require the installation of covers on the container and piping for the prevention of damages due to the external causes. Since the Japanese standards require the main shut off valve, PRD, and container non-return valve to be installed directly on the container, we could exclude the piping from the scope of the "cover for the prevention of damages" requirement and apply the requirement to the container only. We would like to include this subject in the gtr discussions.

5. "In the Event of Abnormally Large Leaks"

For harmonization with the general standards for high-pressure gases, the Japanese standards require the installation of a safety device that limits or shuts off the hydrogen gas flow, i.e., overflow prevention valve or overflow prevention function, in the event of abnormal increase of the gas flow from the container due to some cause.

In the case of CNG vehicles, because the fuel gas is odorized, a gas leak can be detected by smell, and so by switching off the ignition the driver himself/herself can prevent any further gas leak. In the case of hydrogen fuel cell vehicles, since the odorless hydrogen is used as fuel, the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen is installed, and so hydrogen leaks are automatically detected and shut off for preventing any further leak. (As JARI explained at Tokyo Meeting in October 2005, this system can detect hydrogen leaks at the speed equivalent to or higher than human detection by smell and in the leak amount equivalent to or smaller than human detection by smell.)

As described above, a major difference between hydrogen fuel vehicles and CNG vehicles is in the way they detect and shut off gas leaks. In CNG vehicles, whether a gas leak can be stopped or not depends on the situation of and action taken by the driver. Because of this characteristic of CNG vehicles, the requirement to install the overflow prevention valve or overflow prevention function is indispensable for CNG vehicles. On the other hand, in the hydrogen fuel vehicles equipped with the system for detecting hydrogen gas leaks, giving alarms, and shutting off the supply of hydrogen, the overflow prevention valve or overflow prevention function is a redundant function and therefore the requirement to install such valve or function is not indispensable.

When the standards for hydrogen and fuel cell vehicles were developed in Japan, the standards for CNG vehicles were used as the base, and then the characteristics unique to hydrogen fuel vehicles and fuel cell vehicles were added to them. For this reason, no discussion was held on the indispensable requirement for CNG vehicles becoming a redundant requirement for the new technology, as explained above. Hence, we would like to include this subject in the gtr discussions.

6. Overpressure Prevention

For harmonization with the general standards for high-pressure gases, the Japanese standards require the installation of a safety device that prevents the hydrogen system from bursting by releasing the increased gas pressure, such as pressure relief valve or overpressure prevention function, in the event of abnormal increase of the gas pressure in the hydrogen system downstream of the main shut off valve due to failure of the pressure regulator or some other cause.

7. Exclusion of Other Risks

In general, high-pressure gas containers are required to have provisions for preventing the container temperature from rising above a specified level with regard to its storage. The purpose of this requirement is to prevent the container from bursting, etc. by suppressing internal pressure increase caused by a rise in temperature. It is basic to require the installation of a sun shade, etc. for the preventing of temperature rises in the container due to direct sunlight when the vehicle is parked, and it also accords with the general standards for high-pressure gas containers. Since the container's internal pressure that is increased as the temperature rises cannot be lowered through hydrogen consumption when the vehicle is parked, the structural requirement is the only way to prevent such pressure increase. For this reason, the Japanese standards require the installation of a sun shade that blocks the direct sunlight.

In order to prevent hydrogen leakage during the course of gas filling procedures, it is important to install the non-return valve on the receptacle. Without the non-return valve on the receptacle, high-pressured hydrogen gas in the piping to the inlet of the container would burst out after the filling. Therefore, the Japanese standards require the installation of the non-return valve.

It is also important to be able to open and close the main shut off valve at driver's seat, just like the fuel pump can be turned on and off by ignition switch operation in the case of conventional internal combustion engine vehicles. In the event of trouble, hydrogen vehicles must not require drivers and rescue workers to perform any operation that differs from that in the conventional vehicles. Hence, the Japanese standards contain the functional provision that "the main shut off valve shall be operatable at the driver's seat.”

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