

THE NEW FACILITY FOR HYDROGEN AND FUEL CELL VEHICLE SAFETY EVALUATION

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ABSTRACT

For the evaluation of hydrogen and fuel cell vehicle safety, a new comprehensive facility was constructed in our institute. The new facility includes an explosion resistant indoor vehicle fire test building and high pressure hydrogen tank safety evaluation equipment. The indoor vehicle fire test building has sufficient strength to withstand even an explosion of a high pressure hydrogen tank of 260 liter capacity and 70 MPa pressure. It also has enough space to observe vehicle fire flames of not only hydrogen but also other conventional fuels, such as gasoline or compressed natural gas. The inside dimensions of the building are a 16 meter height and 18 meter diameter. The walls are made of 1.2 meter thick reinforced concrete covered at the insides with steel plate. This paper shows examples of hydrogen vehicle fires compared with other fuel fires and hydrogen high pressure tank fire tests utilizing several kinds of fire sources. Another facility for evaluation of high pressure hydrogen tank safety includes a 110 MPa hydrogen compressor with a capacity of 200 Nm³/h, a 300 MPa hydraulic compressor for burst tests of 70 MPa and higher pressure tanks and so on. This facility will be used for not only the safety evaluation of hydrogen and fuel cell vehicles but also the establishment of domestic/international regulations, codes, and standards.

1.0 INTRODUCTION

The early commercialization and popularization of fuel cell vehicles (FCV) requires that sufficient safety be secured. The fuel, that is, hydrogen, easily leaks, is broad in range of flammability, and ignites with even a slight energy by inherent nature. Further, in onboard storage, extension of the distance of travel by a single filling of the hydrogen fuel to a level enabling commercialization requires high density storage by increase of pressure etc. However, up until now there have been few cases of use of hydrogen as a vehicular fuel. Sufficient knowledge for feedback for securing vehicular safety has not yet been obtained at the present. To secure safety for FCVs, test data has to be collected from the viewpoints of 1) high pressure hydrogen safety, 2) collision safety, and 3) fire safety and regulations, codes, and standards have to be formulated. In view of this, the Japan Automobile Research Institute (JARI) has been conducting tests for evaluation of safety required for formulating regulations, codes, and standards for hydrogen and fuel cell vehicles as part of a project commissioned by the Ministry of Economy, Trade and Industry and the New Energy and Industrial Technology Development Organization (NEDO). In this project, JARI constructed a "Hydrogen and Fuel Cell Vehicle Safety Evaluation Facility (Hy-SEF)".

2.0 FIRE TESTS FOR HIGH PRESSURE HYDROGEN TANK-MOUNTING VEHICLES

Before constructing the Hydrogen and Fuel Cell Vehicle Safety Evaluation Facility, JARI conducted fire tests on high pressure hydrogen tank-mounting vehicles as compared with gasoline vehicles and natural gas vehicles. It conducted the tests using the test facility of Canada's Powertech.

Figures 1 to 4 show the states of flames at the time of maximum fire strength in different fuel type vehicles and the results of measurement of the heat radiated near the vehicles. For the sources of the vehicle fires, we ignited solid fuel on the instrument panel ashtrays to simulate natural fires. We measured the heat radiated at distances of 1 m from the sides of the vehicles at heights from the ground of 1.2 m. Figure 1 shows the case of mounting two 35 MPa high pressure hydrogen tanks (internal capacities of 34 liters) in the trunk of a general vehicle and releasing upward the hydrogen released at the time of safety valve operation. The safety valves were actuated 14 minutes and 36 seconds and 16 minutes and 16 seconds after the occurrence of the

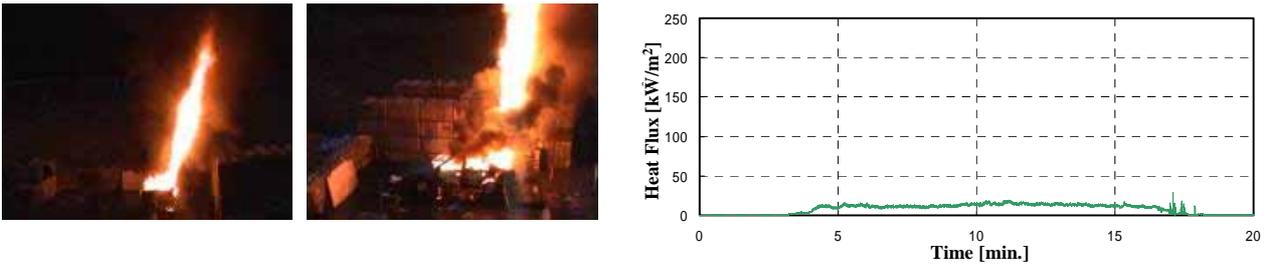


Figure 1 Upward hydrogen flame from a fired vehicle installed two 35MPa, 34 liters capacity cylinders

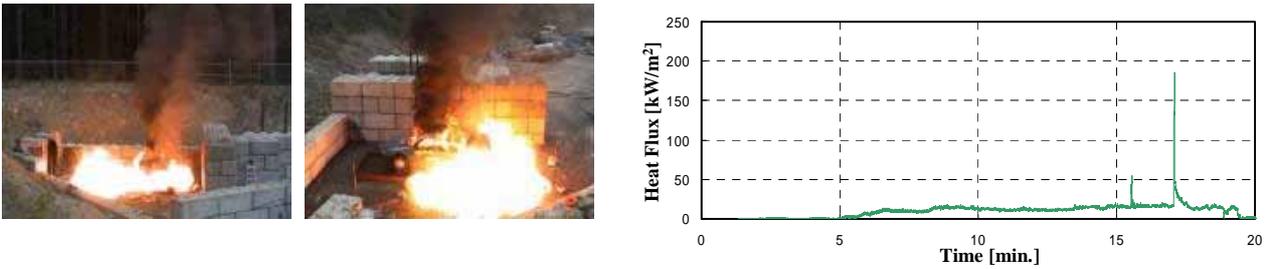


Figure 2 Downward hydrogen flame from a fired vehicle installed two 35MPa, 34 liters capacity cylinders

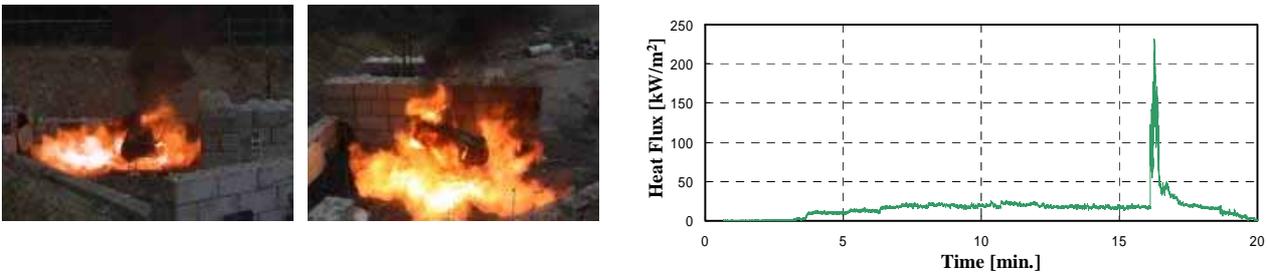


Figure 3 Downward natural gas flame from a fired vehicle installed two 20MPa, 34 liters capacity cylinders

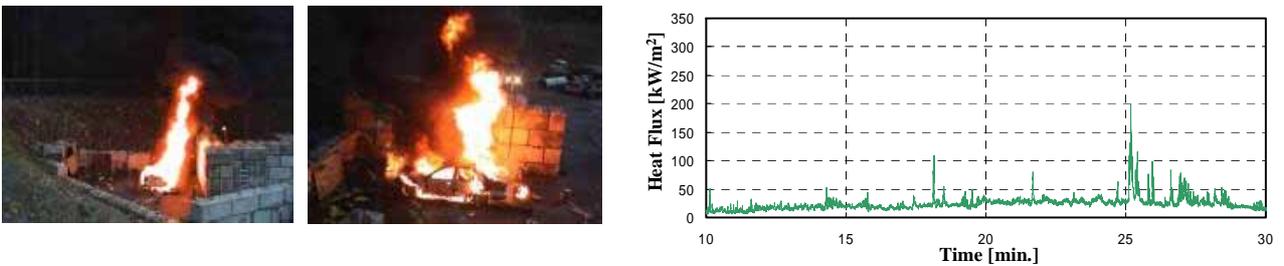


Figure 4 Gasoline flame from a fired vehicle filled with 40 liters

fire. Hydrogen flames were released, but no conspicuous peak of heat radiated could be observed. Figure 2 shows the case of mounting two same 35 MPa high pressure hydrogen tanks and releasing the hydrogen downward. The tank safety valve of the second tank was actuated at 17 minutes and 4 seconds after occurrence of the fire. The peak value of the heat radiated was about 190 kW/m². Figure 3 shows the case of mounting two 20 MPa compressed natural gas tanks and releasing the gas downward. The safety valve of the first tank was actuated after 16 minutes and 27 seconds, while the safety valve of the second tank was actuated after 16 minutes and 53 seconds. The peak value of the heat radiated was found to be about 235 kW/m². Figure 4 shows the case of filling an ordinary steel gasoline tank with 40 liters of gasoline. From about 14 minutes after the start of a fire, gasoline vapor leaking from the seals of the gasoline tank burned and caused intermittent flames. The maximum value of the heat radiated was about 200 kW/m². If comparing the spread of the flames emitted at the time of the maximum strength of the fire in these four types of vehicle fire tests, the hydrogen flames released from the high pressure hydrogen tank-mounting vehicle were short in

time of release, small in effect of the heat radiated to the surroundings, and further the same in extent of spread of flames as gasoline and narrower in range than natural gas. The short time of release is due to the small flow resistance of hydrogen passing through the safety valves. The small effect of heat radiated is due to the fact that pure hydrogen flames do not give off hard to see, that is, strong visible light. The spread of the flames remained in a range narrower than compressed natural gas with a small pressure of 20 MPa due to hydrogen being faster in speed of combustion than natural gas and burning in a short time. From the results of these tests, it can be said that a fire in a 35 MPa high pressure hydrogen tank-mounting vehicle would not be very much higher in hazard compared with the existing vehicle fuels of gasoline and natural gas.

3.0 HYDROGEN AND FUEL CELL VEHICLE SAFETY EVALUATION FACILITY

3.1 Explosion Resistant Indoor Fire Test Building

When evaluating the fire safety of high pressure hydrogen tanks or vehicles mounting such tanks, depending on the tanks covered or the test conditions, bursting of the high pressure tanks, leakage of large amounts of hydrogen, ignition of the leaked hydrogen, explosions, and other hazards and risks may be envisioned. Further, when conducting vehicle fire tests or flame exposure tests on high pressure tanks by pool flames of gasoline or light oil or other liquid fuels, a large amount of smoke is emitted and a large noise is emitted at the time of operation of the tank safety valves, at the time of tank bursting, and at the time of ignition of the leaked hydrogen, and other effects of the tests on the surrounding environment are a concern. Up until now, high pressure tank flame exposure tests and vehicle fire tests have been conducted in the mountains or in the desert away from human habitation. At such outdoor test facilities, the weather or climate at the time of conducting the tests have an effect and therefore obtaining reproducibility of the results of tests was difficult. Further, there were limits on the installation of the measuring equipment required for obtaining precision test data.



Figure 5 The photo of an explosion-resistant indoor fire test building



Figure 6 An image of the test building in cross-section

In view of this situation, we constructed an explosion-resistant indoor fire test building enabling indoor high pressure tank flame exposure tests and vehicle fire tests. The appearance of this facility is shown in Figure 5. Further, an image of the test building in cross-section is given in Figure 6. This test building secures sufficiently large space for measuring the spread of flames emitted when hydrogen is released from high pressure tank safety valves, that is, PRDs (Pressure Relief Devices), and the effects on the surroundings at the time of vehicle fires. The inside diameter of the test building is 18 m and the ceiling height is 16 m.

Further, to give sufficient strength against possible explosions, the 1.2 m thick reinforced concrete protective walls are clad inside with 6 to 12 mm thick steel plate. A design pressure resistance of 320 kPaG is secured even at the structurally most susceptible ceiling exhaust opening and inlet. This pressure envisions the explosion of hydrogen released from a 260 liter, 70 MPa high pressure hydrogen tank (assuming compression coefficient of about 1.4, about 130 Nm³). To confirm this design pressure resistance, we exploded 16 kg of TNT in the test building to generate a shock wave and measured the strain near the ceiling openings. [1] The floor of the center of the test building is made of refractory brick to secure heat resistance for the fire tests. Further, the center floor receives the strongest shock wave at the time of an explosion, so is hardened by 4 m thick reinforced concrete to secure shock proofness and vibration proofness. The test building is provided with two iron doors. One is for loading vehicles etc. and has a size of the opening of 2.4 m × 2.4 m, while the other is for entry of workers and has a size of the opening of 2.0 m × 0.9 m. Further, for the rifle bullet penetration tests stipulated in western tank regulations, a 20 cm inside diameter through hole is provided at a height of 1.0 m from the floor so as to enable a rifle bullet to be fired from outside the test building toward a tank in the test building.

To conduct fire tests in the test building, we formed a donut shape air feed tunnel underground in the surroundings and used an air blower to enable supply of 750 Nm³ per minute of air from 42 air vents. The air vent openings are structured as spring-type check valves to prevent pressure waves at the times of explosions in the test building from traveling back to the air blower side and damaging the air blower. Further, the connection parts between the bottoms of the air vents and the air feed tunnel are provided with flame arresters for preventing entry of hydrogen flames to the air blower side.

In the exhaust system, the large amount of smoke and harmful substances generated at the time of vehicle fire tests etc. are removed by the provision of a reverse cleaning regeneration type (system of regenerating clogged filters by blowing air from the opposite side) ceramic filter and adsorption by a mixed agent (diatomaceous earth + hydrated lime + activated charcoal) in an exhaust treatment facility. Table 1 shows the results of analysis of the harmful components of exhaust before and after the exhaust treatment facility at the time of conducting a fire test on a general passenger vehicle carrying 10 liters of gasoline as compared to Japan's environmental regulations. In the state with the exhausts untreated, the emissions of particulate matter and dioxins were higher than the environmental regulations, but after exhaust treatment, all of the values were reduced to far below the environmental regulations. Further, the effect on the outside of the noise of the release of hydrogen at the time of tank safety valve operation and the noise of explosions occurring in the test building is eased by the provision of a large silencer for reducing the noise pressure level by 80 dB.

Table 1 Results of analysis of the harmful components of exhaust emissions

		Smoke [g/Nm ³]	SOx [ppm]	HCl [ppm]	Dioxins [ng-TEQ/Nm ³]
Japan's environmental regulations	Designed value	0.01	40	430	5
Untreated Exhaust	Measured value	0.21	<1	24	29
Treated Exhaust		0.0027	<1	<4	0.046

The completion of such an explosion resistant indoor fire test building has enabled high pressure hydrogen tank flame exposure tests, tank-mounting vehicle fire tests, etc. to be performed with a high precision and good reproducibility while ensuring the safety of the test personnel and suppressing the effects on the surrounding environment.

3.2 High Pressure Hydrogen Tank Flame Exposure Tests

One of the safety requirements sought in regulations on high pressure hydrogen tanks is clearance by the tanks of a flame exposure test. This test is for confirming that even when a high pressure tank-mounting vehicle becomes involved in a fire, before the tank bursts, a safety valve will operate to release the gas inside the tank and thereby keep the damage due to the accident to a minimum. The method used for the flame exposure test is set down in Japan in its High Pressure Gas Safety Act, while is being discussed in U.S. for

hydrogen gas vehicle (HGV) regulations and in Europe in the European Integrated Hydrogen Project (EIHP), but only general conditions such as the flame dimensions and tank surface temperature have been set. Details such as the types of the fuels for use for the sources of the fires, the methods of shielding safety valves so that they are not directly touched by the flames, the specifications of the thermocouples for measuring the tank surface temperatures, and the surrounding environment at the time of the tests (temperature and wind) have not yet been set. In this research, we focus on the types of the fuels serving as the sources of the fires among these test conditions and evaluate their effects and compare them with flame exposure conditions of high pressure tanks envisioned at the time of vehicle fires. We ran tests by four methods: 1) light oil pool flames, 2) wood flames, 3) propane burner flames, and 4) vehicle fires.

For the light oil pool flames, we used a pool tank of a size of a length of 1,650 mm, a width of 1000 mm, and a depth of 100 mm, used a fuel comprised of light oil in an amount of 40 liters plus gasoline in an amount of 0.6 liter, and added a suitable amount of water for adjusting the height of the liquid surface. For the wood flames, we stacked cedar materials of a width of 40 mm, length of 1,650 mm, a thickness of 20 mm to a height of 440 mm and added lamp oil in an amount of 4 liters and solid alcohol fuel in an amount of 0.3 liter for ignition. For the propane burner flames, we used a burner of a length of 2,000 mm and a width of 300 mm. We conducted the tests under two conditions of propane gas flow rates of 90 liters/min. and 190 liters/min. We caused the vehicle fire by attaching a high pressure hydrogen tank at the location under the trunk from which the gasoline tank was removed and starting the fire from the instrument panel ashtray. The test tanks used were type 3 tanks made of aluminum liners reinforced by carbon fiber-reinforced plastic and with inside capacities of 34 liters, while the tank safety valves were metal fusible plug type pressure relief devices attached inside the tanks. The states of release of the hydrogen flames at the time of tank safety valve operation at the tests are shown in Figures 7(a) to (d). In all of the tests, the high pressure hydrogen tanks did not burst, hydrogen was released from the tank safety valves, and therefore the requirements stipulated in the regulations were satisfied.



(a)



(b)



(c)



(d)

Figures 7 (a) to (d) The state of released hydrogen flames at the time of tank safety valve operation at the tests. (a) light oil pool fire, (b) wood flame, (c) propane burner (190 liters/min.), (d) vehicle fire

Table 2 The difference of the states until tank safety valve operation at the different fire conditions

	Light oil	Wood	Propane (90L/min.)	Propane (190L/min.)	Vehicle fire
Maximum pressure (Filling pressure) [MPa]	35.1(33.6)	36.9(32.8)	40.3(32.9)	35.2(32.7)	39.4(32.9)
Ratio of rise of pressure [%]	1.04	1.13	1.22	1.08	1.20
Pressure rise rate [MPa/min.]	1.01	2.31	1.60	1.49	0.561
The time until the PRD operation [seconds]	90	108	273	99	698
The average tank top surface temperature [°C]	147	207	84.0	188	89.7
The average tank bottom surface temperature [°C]	380	327	775	625	55.9

However, the states until tank safety valve operation at the different test conditions differed as shown in Table 2. With a vehicle fire, it takes time for the flames to spread from the location of the vehicle where the fire started to the location where the tank is mounted, so compared with other tank flame exposure tests, the time taken until tank safety valve operation is remarkably long. Further, the flames at this time are mainly due to the interior materials of the passenger compartment. The flame conditions and temperature conditions to which the high pressure hydrogen tank mounted at the bottom of the vehicle are exposed differ from those of a stand alone tank test using flames from the bottom of the tank. The temperature at the tank surface at the time of tank safety valve operation in a stand alone tank test was a high one of several 100°C at the tank bottom. Further, the tank bottom temperature was higher than the tank top temperature. On the other hand, with a vehicle fire, the temperature at the bottom of the tank was 55.9°C and at the top of the tank was 89.7°C, that is, again the temperature at the top of the tank was higher than the temperature at the bottom of the tank. In this way, at the time of a vehicle fire, a high pressure hydrogen tank can be said to be less directly touched by the flames and instead to be gradually heated by the rise in the surrounding temperature. As a result, the hydrogen filled in the tank rises in temperature and the ratio of rise of pressure at the time of tank safety valve operation (internal pressure at time of safety valve operation/internal pressure at time of start of test) becomes a large 1.20. In a stand alone tank test where the vehicle fire conditions and pressure rise ratio are the closest, we used burner flames with the smallest flame size and a propane flow rate of 90 liters/min.

In this way, flame exposure tests of high pressure hydrogen tanks can give different results depending on the detailed test conditions not stipulated in the regulations. There is a concern that the results of evaluations will differ with each testing authority. In the future, we are planning to evaluate the effects of the flame dimensions, safety valve shields, surrounding environment, etc. and collect test data for proposing a high reproducibility flame exposure test method.

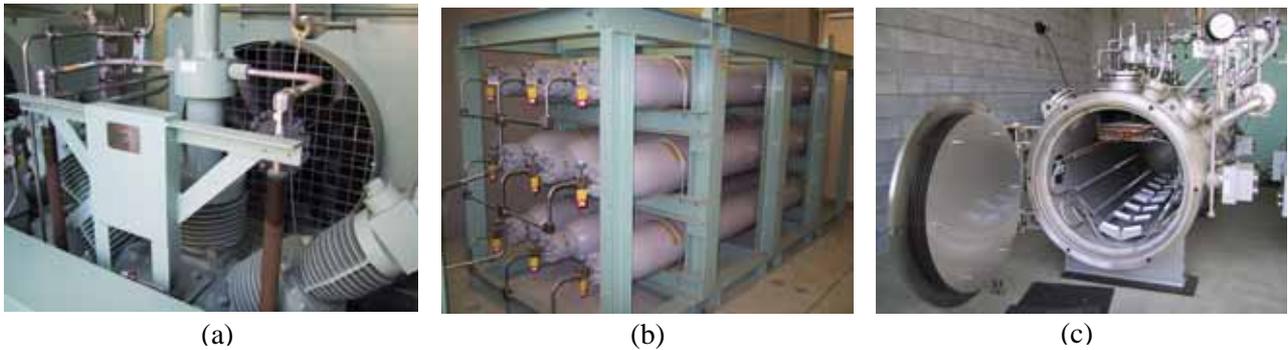
3.3 Other Test Facilities

In our newly constructed hydrogen and fuel cell vehicle safety evaluation test facility, we are introducing various equipment enabling the comprehensive safety evaluation tests stipulated in high pressure hydrogen tank regulations.

3.3.1 High Pressure Hydrogen Filling Test Apparatus

We introduced a high pressure hydrogen filling test apparatus to enable rapid filling tests for high pressure hydrogen tanks, gas cycle tests, gas permeability tests, connector durability evaluation tests, etc. The apparatus is comprised of a high pressure hydrogen compressor, a high pressure hydrogen booster tank bank, a filling control apparatus, air-tight temperature control chambers, gas pits, and hydrogen recovery buffer tank banks. The high pressure hydrogen compressor is a non-lubrication piston type featuring air cooling, a processing capability with five stages of compression of 200 Nm³, and a maximum applied pressure of 110 MPa. These specifications were set to enable hydrogen gas filling cycle tests for large sized, superhigh pressure tanks with usage pressures of 70 MPa and internal capacities of 260 liters. The high pressure hydrogen booster tank bank is comprised of nine connected Cr-Mo-based alloy steel tanks with usage pressures of 110 MPa and internal capacities of 72.5 liters. The hydrogen gas filling control apparatus can be freely set and controlled in filling speed and filling pressure in accordance with the usage pressure and tank

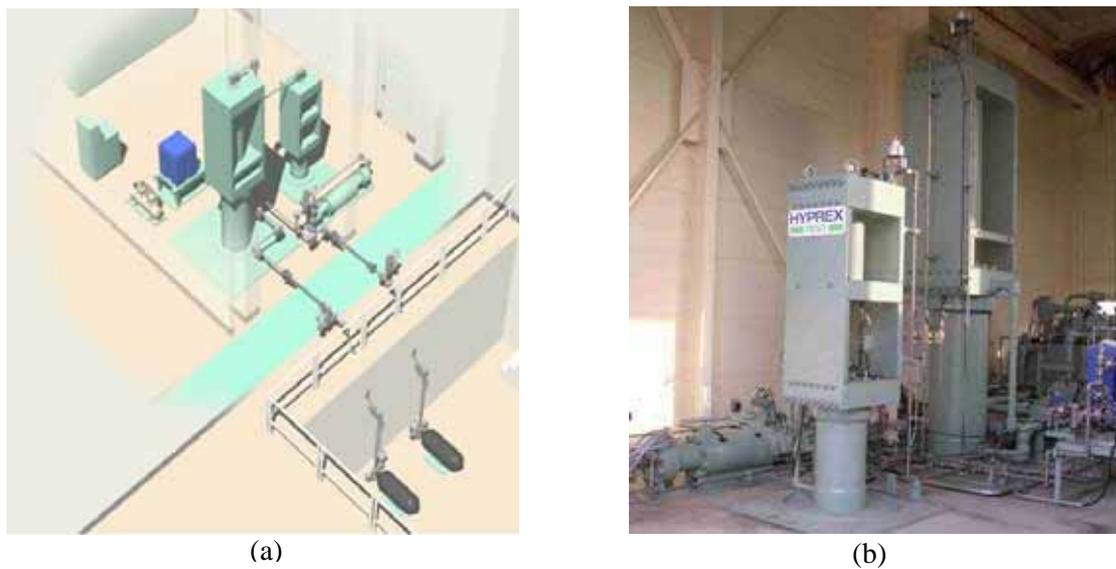
capacity so as to enable rapid filling tests, gas cycle tests, etc. The air-tight temperature control chamber enables the temperature of the environment around a tank to be controlled to -40°C to 85°C and secures a high air-tightness to enable measurement of the speed of permeation of hydrogen gas through a plastic liner tank. The gas pit is for conducting gas filling tests safely, enables accommodation of a large sized air-tight temperature control chamber by being made a size of $6\text{ m(L)} \times 3\text{ m(W)} \times 3\text{ m(D)}$ and is covered at its top by a grating lid. The hydrogen recovery buffer tank bank is used for recovering hydrogen released in a gas cycle test and is comprised of two cadres each comprised of 30 connected tanks of internal volumes of 47 liters and highest filling pressures of 19.6 MPa. Photos of the high pressure hydrogen compressor, high pressure hydrogen booster tank bank, and air-tight chamber are given in Figures 8(a) to (c).



Figures 8 (a) High pressure hydrogen compressor, (b) High pressure hydrogen booster tank bank, (c) Air-tight temperature control chamber

3.3.2 Water Pressure Test Apparatus

We introduced a water pressure test apparatus for measurement of the smallest burst pressure of high pressure tanks and evaluation of the durability by pressure cycle tests. The system used uses an oil hydraulic pump to press a piston and raise the water pressure. For the pressure cycle tests, the maximum pressure was made 120 MPa, the capacity of the tanks covered by the test was made 20 to 260 liters. 1 to 10 cycles of a pressure raising and reduction cycle were performed per minute for each tank capacity. For the burst tests, we introduced an intensifier of a maximum pressure of 300 MPa enabling burst tests of 70 MPa class superhigh pressure tanks. The water pressure tests are conducted by leading a high pressure water pipe to the adjoining burst pit. A lid having a reinforced glass window enabling observation of the behavior at the time of tank bursting was used to cover the pit. A general diagram of the water pressure test apparatus and a photo of the intensifiers are shown in Figures 9(a), (b).



Figures 9 (a) Diagram of water pressure test apparatus, (b) Photo of Intensifiers

4.0 CONCLUSIONS

The vehicular high pressure hydrogen tanks in use are light weight composite tanks of 35 MPa or higher pressures made from carbon fiber-reinforced plastic from the viewpoint of the space and weight restrictions for mounting in vehicles. As regulations for vehicular high pressure hydrogen tanks, in Japan, regulations attached to the High Pressure Gas Safety Act began to be enforced on March 31, 2005. Similar regulations are being formulated in the U.S. by the Department of Transportation (DOT) for hydrogen gas vehicles (HGV) and in Europe by the EIHP (European Integrated Hydrogen Project). Further, international standards are being discussed at the ISO/TC197/WG6. Regulations for vehicles mounting high pressure hydrogen tanks are being established in Japan under the Road Vehicles Act. As international regulations, gtrs (global technical regulations) are scheduled to be formulated at the UN-ECE/WP29/GRPE. Further, there are many regulations and standards which should be established to clarify the requirements for fire-extinguishing facilities for hydrogen vehicles entering underground garages and popularize and promote hydrogen and fuel cell vehicles such as restrictions on high pressure hydrogen tank carrying trucks passing through tunnels. In Japan, the government is taking the lead in establishing and reevaluating such regulations. The public and private sectors have been working together to eliminate obstacles to the initial introduction of hydrogen and fuel cell vehicles. In the future, such regulations are supposed to be established from the perspective of harmonization with international regulations. Comprehensive test data will have to be obtained for risk assessment of accidents and safety confirmation.

The hydrogen and fuel cell vehicle safety evaluation test facility reported in this paper provides the test data necessary for formulation of these regulations and can be used for running the safety confirmation tests stipulated in the regulations and for running certification tests for high pressure hydrogen tanks and hydrogen vehicles.

ACKNOWLEDGEMENT

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REFERENCE

1. Suzuki, J. Watanabe, S. Yamada, T. Sawamoto, Y. Sakaguchi, M. Sawaguchi, S., Performance Evaluation of Explosion-proof Fire Test Dome to the Air-Hydrogen Explosion, JARI Research Journal vol. 27, No.5, (2005.5)