THE SPREAD OF FIRE FROM ADJOINING VEHICLES TO A HYDROGEN FUEL CELL VEHICLE

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ABSTRACT

Two vehicle fire tests were conducted to investigate the spread of fire to adjacent vehicles from a hydrogen fuel cell vehicle (HFCV) equipped with a thermal pressure relief device (TPRD) : - 1) an HFCV fire test involving an adjacent gasoline vehicle, 2) a fire test involving three adjoining HFCV assuming their transportation in a carrier ship. The test results indicated that the adjacent vehicles were ignited by flames from the interior and exterior materials of the fire origin HFCV, but not by the hydrogen flames generated through the activation of TPRD.

1. INTRODUCTION

In fuel-cell vehicles (HFCV), it is necessary to install the thermal pressure relief device's (TPRD's) in the CFRP（carbon fiber reinforced plastics） hydrogen gas cylinder to prevent rupture from fire heating. The TPRD detects cylinder heating by temperature, and vents the combustible gas from inside the cylinder to the atmosphere before the cylinder can rupture. If the fire comes into contact with the released combustible gas, a hydrogen jet flame is formed around the vent tube discharge opening. In order to evaluate the fire safety of vehicles that use compressed hydrogen as fuel, we conducted fire tests on vehicles that used compressed hydrogen and on vehicles that used gasoline and compared damage to the vehicle and surrounding flammable objects [1,2].

On the other hand, while HFCV are placed on the market, there are possibilities of HFCV as well as other types of vehicles catching fire in vehicle collisions and natural disasters (e.g. earthquakes) or by arsonists. For exsample, in the case of a HFCV fire is caused by a gasoline pool fire, when the TPRD is activated, a fireball more than 10m diameter formed [1], as shown in Figure 1.

Just before TPRD activation　　　　1second after TPRD activation

Figure 1. a HFCV fire test is caused by a gasoline pool fire

However, practically no research reports exist on the flame characteristics to adjacent vehicle. Such data will be necessary for improving the safety against fire of parking lots, tunnels, ferries and car carriers.

As the first step in the study of fire accidents involving HFCV, the authors conducted tests on (1) flame characteristics of an HFCV and a gasoline vehicle parked side by side and (2) flame characteristics of several HFCV assuming their transportation in a carrier ship. This paper reports ignition and fire spread behavior in the presence of one or more HFCV.

2. TEST ON JUXTAPOSED GASOLINE VEHICLE AND HFCV

2.1 Objective

The following scenario was adopted for the first test:

- A gasoline vehicle is parked side by side with a HFCVon the side closest to its TPRD and vent pipe.
- A fire originates from the HFCV's rear tire on the far side from the gasoline vehicle.
- Both gasonline vehicle and HFCV have all their windows closed.

2.2 Test Method

On the basis of the above scenario the test was designed to investigate fire spread behavior, temperatures around the test vehicles, and TPRD activation time. The test setup was as schematized in Fig. 2, where the HFCV was served by a gasoline vehicle (2,000 cc, SUV) whose fuel tank and fuel piping system had been replaced respectively by a compressed hydrogen gas tank and a high-pressure fuel piping system including a TPRD.

The compressed hydrogen gas tank was installed exactly at the position of the removed gasoline tank. Therefore, a big tank was not able to be installed, the tank of 36Litters at a 70MPa starage pressure was installed.

The TPRD was forcibly opened from outside when the measured temperature reached 110°C at the center of a 25 mm aluminum alloy cubic block attached to an end of the HFCV's hydrogen gas tank. The tank had a TPRD vent pipe (inner diameter of 4.2 mm) at its longitudinal end facing the gasoline vehicle, and the vent diection was vertically turned toward the ground. The adjacent gasoline vehicle (1,000 cc, hatchback) had about 10L of gasoline filled in its metallic fuel tank.

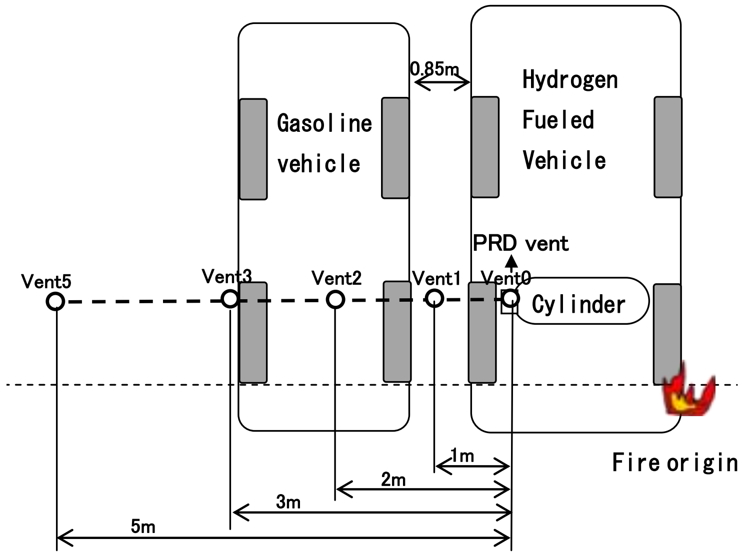


Figure 2. Schematic of test-1 setup

The two vehicles were parked approximately 0.85m apart, with their rear axles aligned. The HFCV's rear wheel opposite to the gasoline vehicle was set as the location of fire origin or ignition. A fire was ignited by operating a propane gas burner for 2 min. Temperatures around the two vehicles were measured using K-type thermocouples (sheath diameter of 1.6 mm). The thermocouples were fixed immediately below the tank's vent pipe opening and at points 1, 2, 3 and 5m away from the vent opening (Vent0, 1, 2, 3, 5) all 1 cm above the ground, see fig.1. Another set of thermocouples were attached to the gasoline vehicle's side surface facing the HFCV as shown in Fig. 3. The test was carried out in the explosion-proof fire test facility of the Japan Automobile Research Institute to preclude influence of the elements.

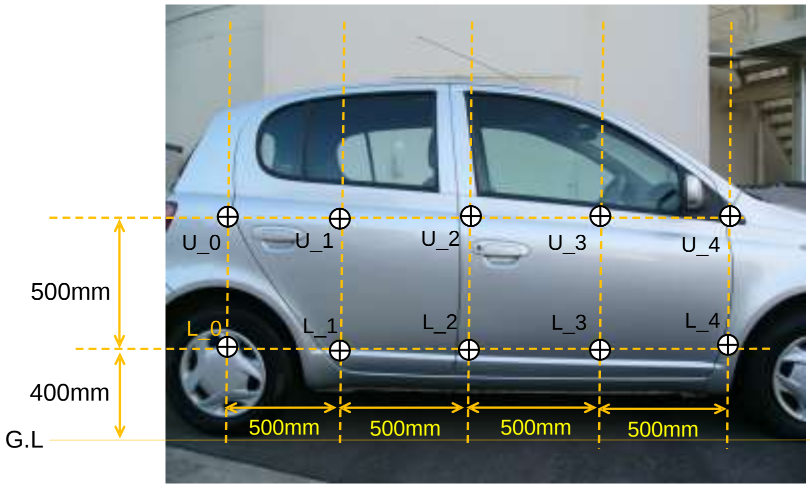
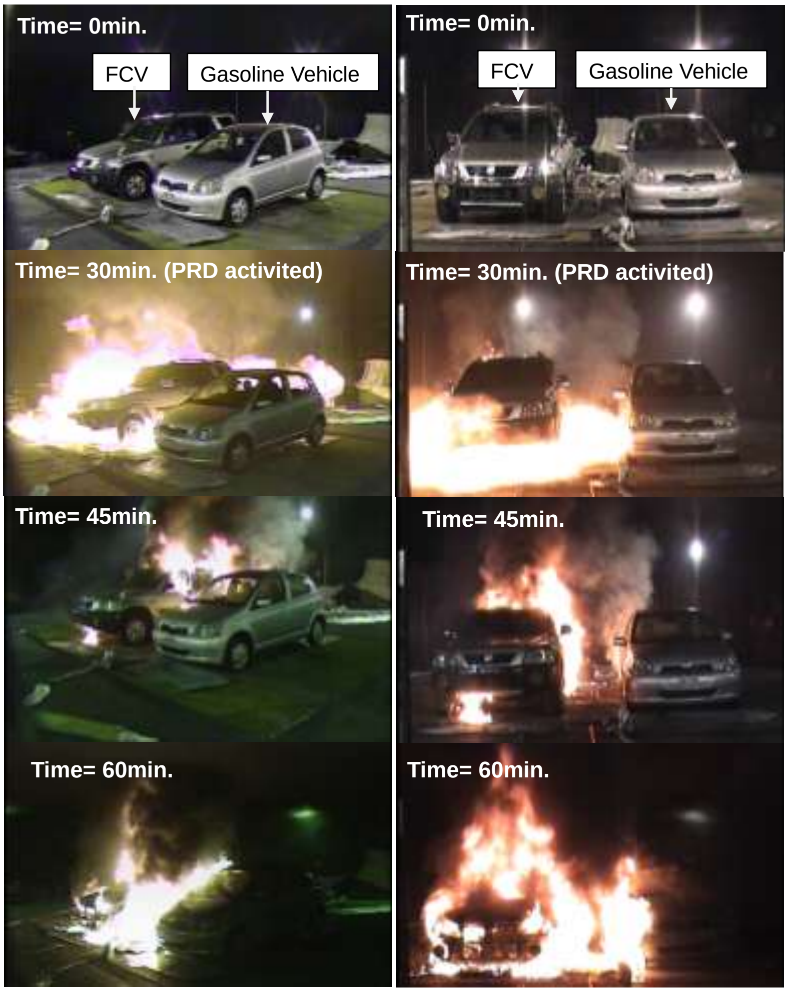


Figure 3. Temperature measurement points of the gasoline vehicle (near side to HFCV)

2.3 TEST RESULTS AND DISCUSSION

Fig. 4 shows the photographic view of how the fire spread in time sequence.

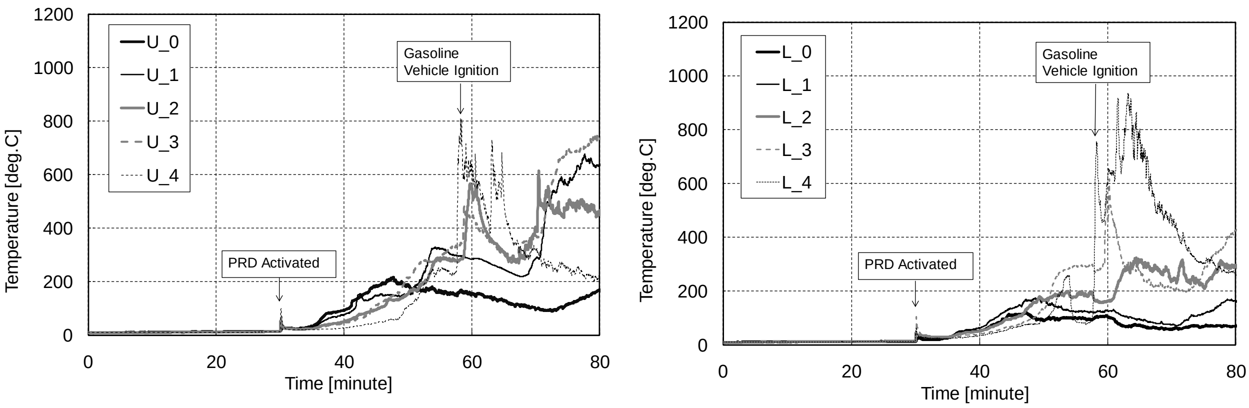


Diagonally to the front of vehicles Front of vechicles

Figure 4. Photographic view of test-1

The HFCV was ignited at time 0 min. from test start. As temperature at the center of the aforementioned aluminum alloy block attached to the tank reached 110°C at time 30 min., the TPRD was opened to release the hydrogen gas through the vent pipe, whereby the fire spread below the HFCV's whole floor. Nevertheless, the gasoline vehicle had yet to catch fire at this point in time.

The gasoline vehicle caught fire at time 57 min. 26 sec. or roughly 28 min. after the TPRD activation of HFCV. Ignition of the gasoline vehicle occurred around the front tire on the near side of the HFCV. At this point the HFCV had already been burned down. Fig. 5 shows the temperature change on the side surface (see Fig.3) of the gasoline vehicle.



(a) Upper side (b) Lower side

Figure 5. Temperatures on gasoline vehicle side

Temperatures on the gasoline vehicle's near side temporarily rose at time 30 min. or shortly after TPRD activation, with the highest temperature measured at 105°C at location L_1 which was closest to the vent pipe. Then the temperatures declined as the release of hydrogen gas completed. It was at time 34 min. that the temperatures resumed their climb. When temperature at location L_4 reached about 400°C, the gasoline vehicle caught fire. Fig. 6 shows the temperatures measured at Vent0, 1, 2, 3 and 5 all 1 cm above ground.

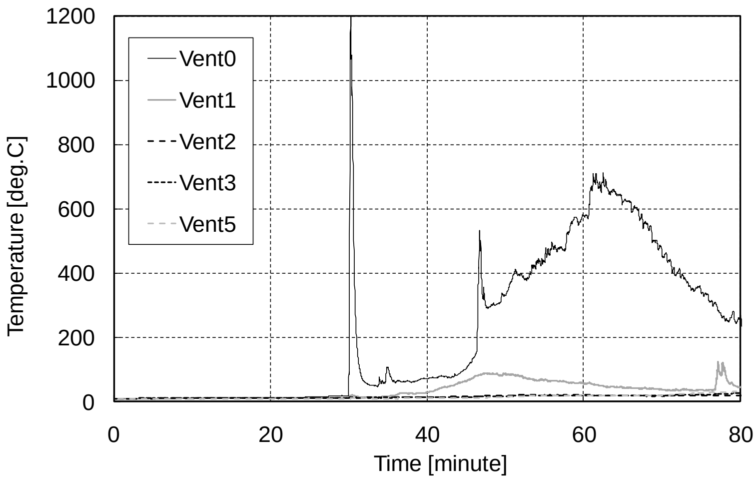


Figure 6. Temperatures at 1cm above ground

Although temperature under the vent pipe (Vent0) measured over 1,200°C at the time of TPRD activation (time 30 min.), temperatures under the gasoline vehicle's floor (Vent1,2,3,5) hardly increased during the initial 30 min. period. Similarly, temperatures around the gasoline vehicle's fuel tank did not notably rise at the time of TPRD activation. This is because, as shown in Fig. 7, the underfloor flames curled up on both sides of the HFCV's body so that it was not possible for the flames to spread across the 0.85m separation into the underfloor space of the adjacent vehicle.

Figure 7. Hydrogen flame following TPRD activation

Consequently the adjoining gasoline vehicle was ignited not by the hydrogen flames generated through TPRD activation but by the HFCV burn-down flames which spread from the exterior and interior fittings of the fire origin vehicle.

3. MULTIPLE-HFCV FIRE TEST ASSUMING A CAR CARRIER

3.1 Objective

The following scenario was adopted for this multiple- HFCV test:

- The transportation of vehicles in a car carrier ship is simulated with regard to aligned vehicle placement, close separations between vehicles, and keeping all the vehicle windows shut.
- A fire accident occurs involving only the vehicles parked on one floor of a car carrier ship.
- The fire origin is on the far side from the adjoining vehicle and near the rear wheel or rear bumper where it takes a longer time to activate the TPRD by heat.
- The test vehicles are station wagons (4.685m long, 1.695 wide, 1.96 high).
- The vehicle windows are all closed.

Unlike the semi-sealed venting condition inside of a ship, however, the test was performed in an open-air condition at the aforementioned explosion-proof fire test facility, because the fire situation cannot be observed.

3.2 Test Method

The setup of this test was as schematized in Fig. 8.

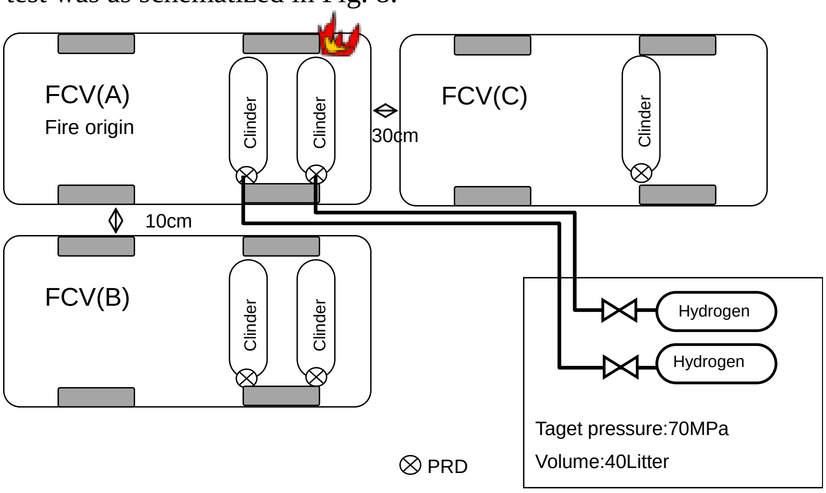


Figure 8. Schematic of test-2 setup

Employed were three test vehicles: HFCV-A which was the fire origin, HFCV-B on the lateral side of HFCV-A, and HFCV-C on the rear side. Following the regular practice in car carrier ships, the test vehicles were parked with a 10 cm lateral and a 30 cm longitudinal separation. The test vehicles were basically gasoline vehicles with their fuel tanks and mufflers replaced with those of HFCV. HFCV-A and HFCV-B respectively had two simulated tanks forward and rearward to the rear axle under the floor, while HFCV-C had only one tank forward to the rear axle. Each of the simulated tanks was made of steel and measured 318 mm in diameter and 800 mm in length with a storage capacity of 40L or more.

These tanks were equipped with a fuse metal TPRD designed to activate at 104°C. The TPRD's activation performance was checked after filling the tank with helium gas to 8~10 MPa. Additionally for HFCV-A, after TPRD activation, hydrogen gas was supplied into its two tanks to 70 MPa in order to check the release of hydrogen gas from a vent pipe (inner diameter of 4 mm). The TPRD vent pipe was designed to release hydrogen gas in the direction of 45° rearward, and its opening was located 30 cm above the ground, see figure 9.

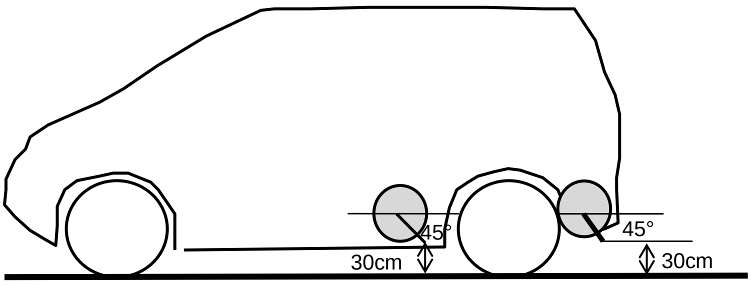


Figure 9. Hydrogen venting direction and location (HFCV-A)

Temperatures were measured at 72 locations under the vehicle floor and around each of the three test vehicles, using K-type thermocouples (sheath diameter of 1.6 mm).

3.2 Test Results and Discussion

Table 1 gives an observation record, Fig. 10 a photographic view, and Fig. 11 a schematic of fire spread to adjacent vehicles prior to TPRD activation in the fire origin vehicle.

Table 1 Fire spread process in test-2

Time(min:sec)	Fire Spread Process
0:00:00	Test start (HFCV-A's rear bumper ignited by burner.)
0:44:35	Explosion noise in HFCV-A ("A") cabin; the rear bumper burning down.
98:36	Flames visible in "A" cabin.
99:31	"A" rear window begins to crack.
99:49	Flames spout from "A" rear tire.
102:10	"A" rear windows crack. RaginHFCV-B ignition g flames arise.
105:24	"A" right rear window breaks.
107:58	"A" left rear window breaks.
109:09	"A" left center window breaks. "B" ignited at its right rear panel.
111:56	Raging flames arise from "A" right rear window.
112:36	Raging flames arise from "A" right rear tire.
114:22	Explosion noise in "A" cabin. "C" ignited at its front bumper and engine hood.
115:59	"B" left rear window breaks; right rear tire bursts.
116:53	Raging flames arise from "B" rear window.
117:15	"A" rear TPRD is activated; start of hydrogen gas release. Hydrogen flames reach "C" front body and "B" rear tire.
117:49	"B" right center window breaks.
117:52	Explosion noise in "A" cabin.
118:46	Hydrogen release from "A" ends. "B" body burns down. "C" front body burns; its front tire bursts.
119:42	"A" right rear tire bursts.
119:47	"B" rear TPRD is activated (2 min. 32 sec. after activation of "A" rear TPRD).
120:43	"B" front window breaks.
122:14	"A" front TPRD is activated (4 min. 59 sec. after activation of "A" rear TPRD). Start of hydrogen gas release from "A" front TPRD.
124:14	Hydrogen gas release ends.

Time =109min. HFCV-B ignition

Time =114min. HFCV-B ignition

Time =117min. Before PRD activation

Time =117min.10sec. PRD activation

Figure 10. Photographic view of test-2

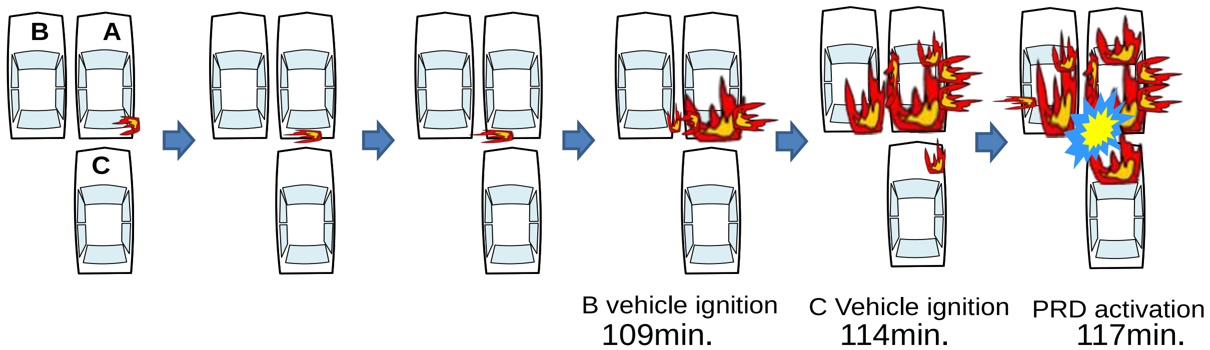


Figure 11. Schematic of fire spread process

The rear bumper of HFCV-A was ignited by a burner at time 0 min from start of the test. Due to fire spread, the ignition of HFCV-B occurred in its right rear side at time 109 min. At time 114 min., HFCV-A practically burned down and the ignition of HFCV-C occurred at its front bumper and engine hood. At time 117 min., the TPRD of HFCV-A's rear tank (filled to 59.1 MPa) activated and hydrogen gas was released from the vent pipe. The fire spread rapidly from HFCV-A to the center area of HFCV-B and to the rear underfloor area of HFCV-C (Fig.9). The release of hydrogen gas ended in 2 min. to a pressure of no more than 1 MPa. At time 119 min. 47 sec., HFCV-B's rear TPRD activated; however, hydrogen gas was not released since the tanks on HFCV-B lacked a release device. At time 122 min. 14 sec., the TPRD of HFCV-A's front tank (filled to 65.4 MPa) activated, releasing hydrogen gas. As a result, all the 3 HFCV burned down. Despite the continuation of the test until time 144 min., HFCV-C's front TPRD did not activate.

Fig. 12 shows the locations of temperature measurement points on hydrogen tanks as viewed from the ground. For data compilation purposes, abbreviations were used. For example, "BTF" means the front tank of HFCV-B and "LowC" means the lower center of a tank.

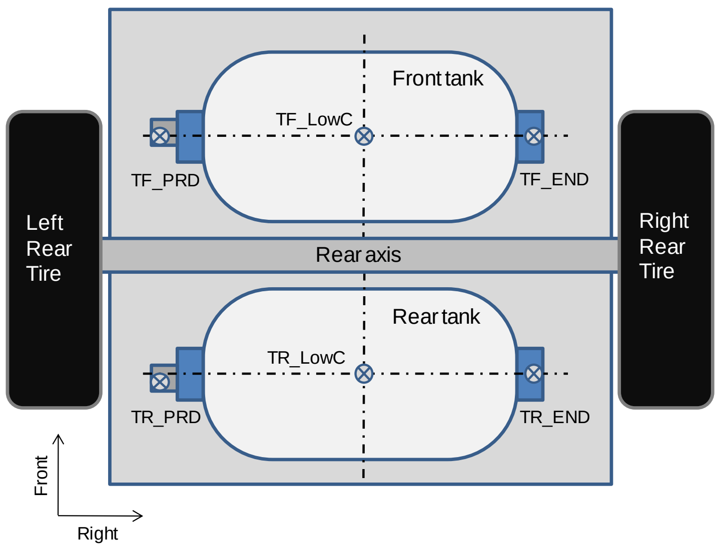


Fig.12 Temperature measurement points on tanks

Fig. 13 shows the temperatures measured around HFCV-B during the interval period from its ignition to rear TPRD activation.

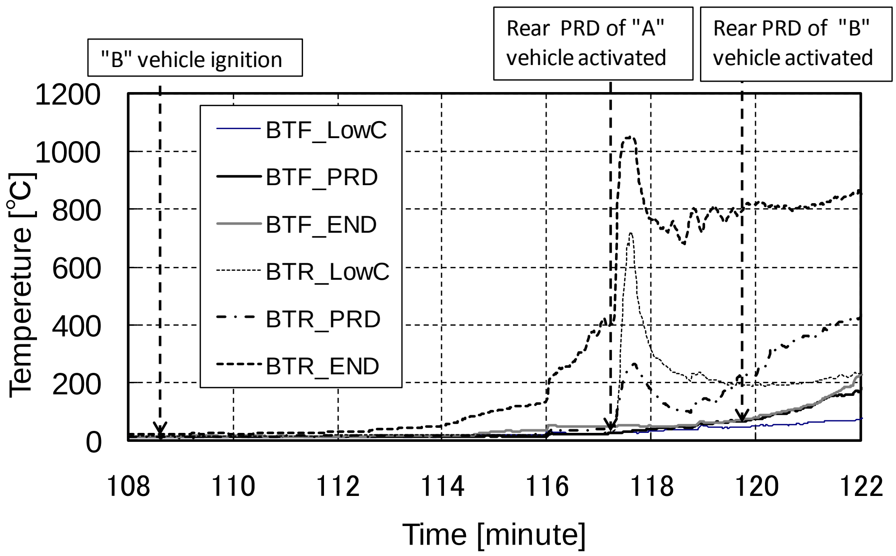


Figure 13. Temperatures on HFCV-B's tanks

After the ignition of HFCV-B, temperature at its rear tank's end plug (BTR_END) gradually increased, and about 117 min. later the temperatures all over the rear tank climbed rapidly, following the activation of HFCV-A's rear TPRD. About 3 min. after this temperature climb, the rear TPRD of HFCV-B activated; however, HFCV-B's front tank was hardly affected by the TPRD activation in HFCV-A.

Figure 14 shows temperatures on the front tank of HFCV-C which was parked behind HFCV-A, when the rear TPRD of HFCV-A activated.

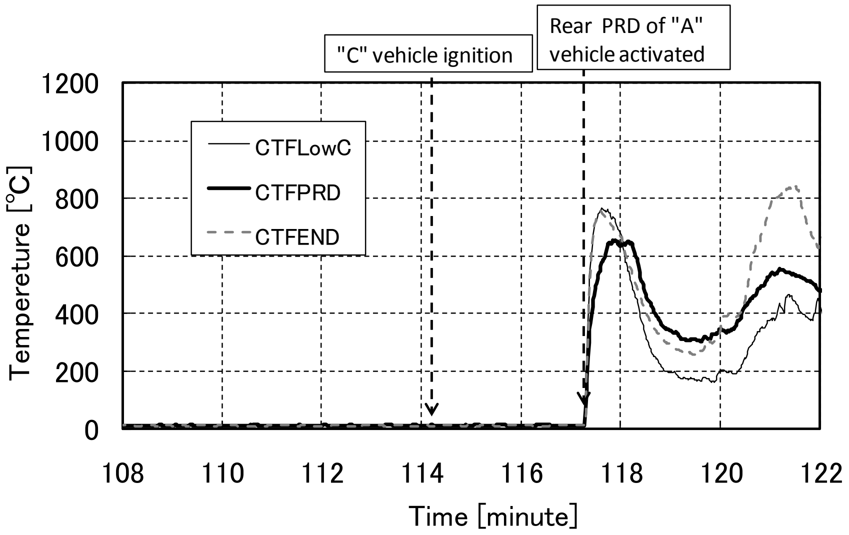


Figure14. Temperatures on HFCV-C's rear tank

Although temperatures on the front tank did not change for some time after HFCV-C's ignition, the temperatures suddenly climbed after the activation of HFCV-A's rear TPRD. These results suggested that under the conditions of the present study, (1) adjoining vehicles are ignited by the flames spreading from the interior and exterior fittings of the fire origin HFCV; (2) subsequently the fire origin HFCV undergoes TPRD activation and thereby generates hydrogen flames, causing the underfloor temperatures of adjoining vehicles to go up and inducing their underfloor TPRD to also activate.

The present test assuming the marine transportation of HFCV was focused on the initial stage of vehicle fire. To investigate the full fire stage, it will be necessary to take into account the conditions inside car carrier ships in greater detail, such as roof structure and venting system.

4. CONCLUSIONS

Experiments were conducted on fire spread behavior in the mixed presence of a gasoline vehicle and an HFCV and in the presence of multiple HFCV assuming the inside of a car carrier ship. The test results indicated that the direct cause of fire spread from fire origin vehicle to adjacent vehicle is the flames spreading from the interior and exterior fittings of the fire origin vehicle – not the hydrogen flames from TPRD activation. However, in car carrier ships and other similar situations with closely parked HFCV, the test results point to the possibilities of a fire in an HFCV to activate its TPRD and thereby to generate hydrogen flames which in turn may cause the underfloor TPRD of adjoining HFCV to activate. To minimize damage by HFCV fire, therefore, it is important to realize early detection and extinguishing of fire before the TPRD activates.

This paper reports the outcome of a study conducted as part of the "Development of Technologies for Hydrogen Production, Delivery and Storage Systems" commissioned by NEDO, the New Energy and Industrial Technology Development Organization in Japan.

REFERENCE

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