THE POSSIBILITY OF AN ACCIDENTAL SCENARIO FOR MARINE TRANSPORTATION OF FUEL CELL VEHICLE -HYDROGEN RELEASES FROM TPRD BY RADIANT HEAT FROM LOWER DECK-

Tamura,Y.[1] and Sato, K.[2]
[1] FC-EV Research Division, Japan Automobile Research Institute,
1328-23,Takaheta, Osaka , Shirosato, Ibaraki , 311-4316, Japan, ytamura@jari.or.jp
[2] Department of Environmental Science, Toho University,
2-2-1, Miyama, Funabashi, Chiba, 274, Japan

ABSTRACT

In case fires break out on the lower deck of a car carrier ship or a ferry, the fuel cell vehicles (FCVs) parked on the upper deck may be exposed to radiant heat from the lower deck. Assuming that the thermal pressure relief device (TPRD) of an FCV hydrogen cylinder is activated by the radiant heat without the presence of flames, hydrogen gas will be released by TPRD to form combustible air-fuel mixtures in the vicinity. To investigate the possibility of this accident scenario, the present study investigated the relationship between radiant heat and TPRD activation time and evaluated the possibility of radiant heat causing hydrogen releases by TPRD activation under the condition of deck temperature reaching the spontaneous ignition level of the tires and other automotive parts. It was found: a) the tires as well as polypropylene and other plastic parts underwent spontaneous ignition before TPRD was activated by radiant heat and b) when finally TPRD was activated, the hydrogen releases were rapidly burned by the flames of the tires and plastic parts on fire. Consequently it was concluded that the explosion of air-fuel mixtures assumed in the accident scenario does not occur in the real world.

1.0 INTRODUCTION

Compressed hydrogen cylinders installed on the FCVs are each equipped with a TPRD--the device designed, at the detection of heat, to release hydrogen gas from the cylinder for its protection from bursting; the hydrogen releases are immediately burned by the flames existing around TPRD. This theoretical process gives an accident scenario shown in Figure 1 for FCVs transported by a pure car carrier or a ferry boat having decks of steel structure. In this scenario, a fire accident breaks out in a lower deck, and heats up the FCVs parked on the upper deck.
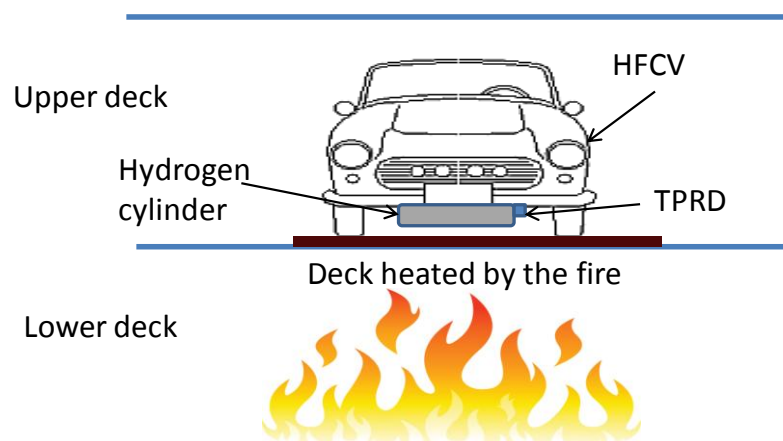

Figure 1. An accident sinario of hydrogen concentrations fire from lower deck

Since FCVs are driven by human drivers onto a car carrier or a ferry, their fuel cylinders contain a certain amount of hydrogen when parked aboard. With the cylinder installed on the underbody portion of the vehicle, the TPRD of the cylinder may be activated by radiant heat in case of a fire accident on the lower deck, resulting in the release of hydrogen from the cylinder.

Accordingly, the following accident scenario was drawn: If, at the time of TPRD activation by radiant heat, no fire is present in the deck where the FCVs are parked, the hydrogen releases will form combustible air-fuel mixtures which may cause explosion; however, if the exterior parts of the FCVs have already been self-ignited and aflame by the radiant heat from lower deck at the time of TPRD activation, the hydrogen releases will be burned immediately by the existing flames, so that explosion will not occur.

The present study was conducted to investigate the relationship between radiant heat and TPRD activation time and the possibility of the accident scenario with or without the spontaneous ignition of FCV exterior parts.

2.0 PERFORMANCE TEST FOR TPRD BY RADIANT HEAT

2.1 Test method

Many researchers have investigated the techniques of predicting the activation time of heat sensors for automatic sprinklers[1,2,3]. Nevertheless, while most of these studies involved heat detectors placed in thermal air currents, there were virtually no studies aimed to predict the heat sensor's activation time under radiant heat. The present study was therefore designed to experimentally determine relations between radiant heat and TPRD activation time. Table 1 shows the specifications of the sample TPRDs; their appearances are shown in Figure 2.

Table 1. Specification of TPRD's

TPRD name	Normal working pressure [MPa]	Type	Nominal activated temperature
#A	35MPa	Fuse metal	104°C
#B	35MPa	Fuse metal	110°C
#C	70MPa	Fuse metal	110°C
#D	35MPa	Glass bulb	110°C

⊗Thermocouple

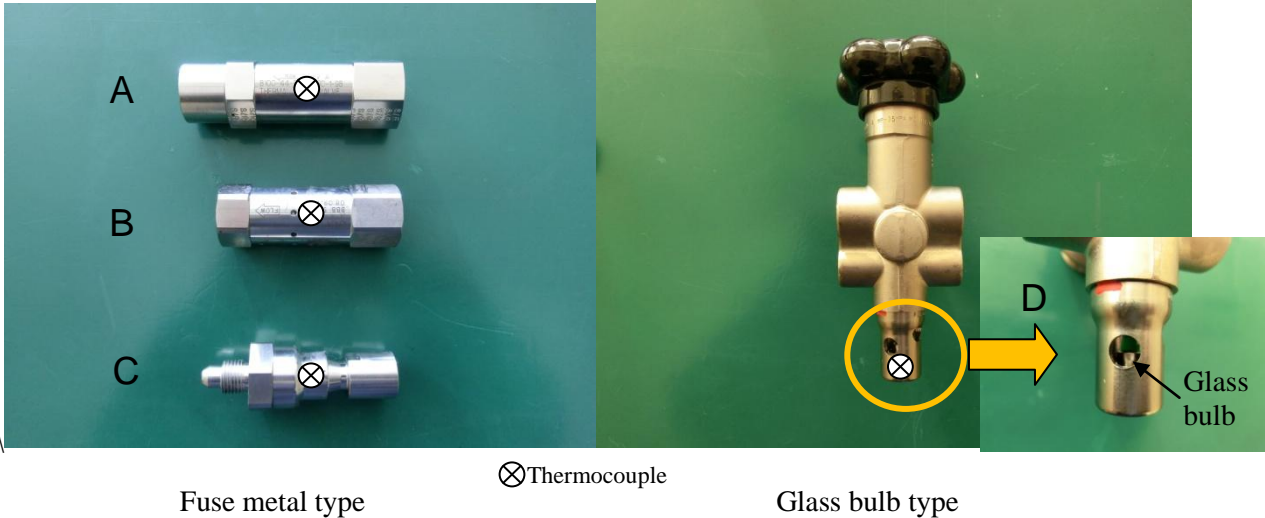Fuse metal type   Glass bulb type

Figure 2. Sample TPRDs

All the four sample TPRDs are types used in automotive compressed hydrogen cylinders. Types A, B and C each incorporate in its stainless steel body a fuse metal that melts at its nominal activating temperature. Type D incorporates a glass bulb which contains a fluid and is ruptured at its nominal activating temperature by the thermal expansion of the fluid. A large portion of the glass bulb is embedded in TPRD's stainless steel body to protect from external impacts. Figure 3 diagrams the test method, and Figure 4 shows a photographic view of the test setup.
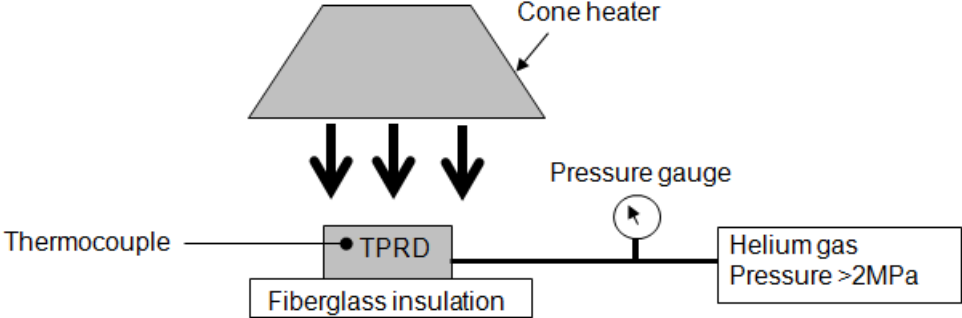

Figure 3. Outline of TPRD performance test

Figure 4. A test situation of TPRD performance test

The TPRD was pressurized by helium gas to more than 2 MPa. Radiant heat was applied to the TPRD from a cone-shaped heater, while the TPRD was thermally insulated from the installation stand by an intervening fiberglass plate. Four intensities of radiant heat was applied: 15, 30, 50 and 75 kW/m^2. The maximum heating duration was set at 1 hour, and radiant heat intensity was calibrated by a heat flux meter before each heat application. The time (t_g) required from heat application to TPRD activation was measured, with the TPRD activation judged by reading the helium gas pressure. Additionally, the surface temperature of the TPRD body was measured by a K-type thermocouple (sheath diameter 0.5 mm) attached to the body surface by a heat-resistant aluminum foil tape.

2.2 Results

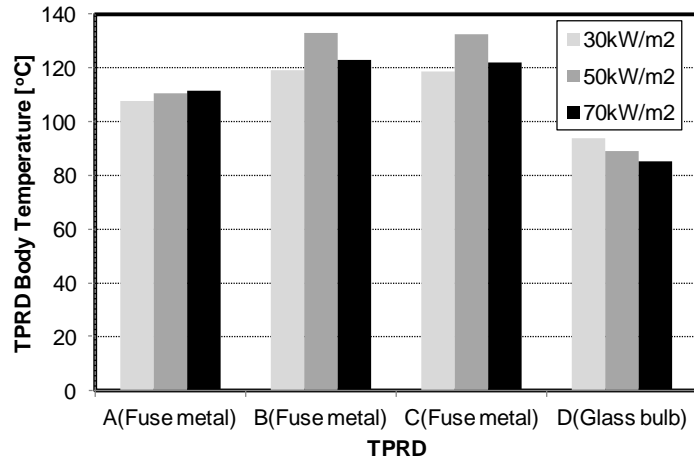Figure 5 shows the surface (body) temperature of TPRD at the time of its activation.

Figure 5. Average TPRD Body Temperature when TPRD activated

The TPRD body temperature at its activation proved to be higher than the nominal activation temperature among the fuse metal type TPRDs, but was lower in the glass bulb type TPRD. This was accounted for that in the fuse metal type TPRDs the radiant heat was transmitted from the TPRD surface to the fuse metal embedded inside the body through heat conduction process, while in the glass bulb type TPRD the radiant heat reached the glass bulb directly from an aperture in the TPRD body.

Figure 6 shows the relationship between the applied radiant flux q_{ac} and TPRD activation time t_{ac}. In the case of a 15 kW/m^2 radiant heat, however, none of the four types of TPRDs was activated during the first 1 hour.
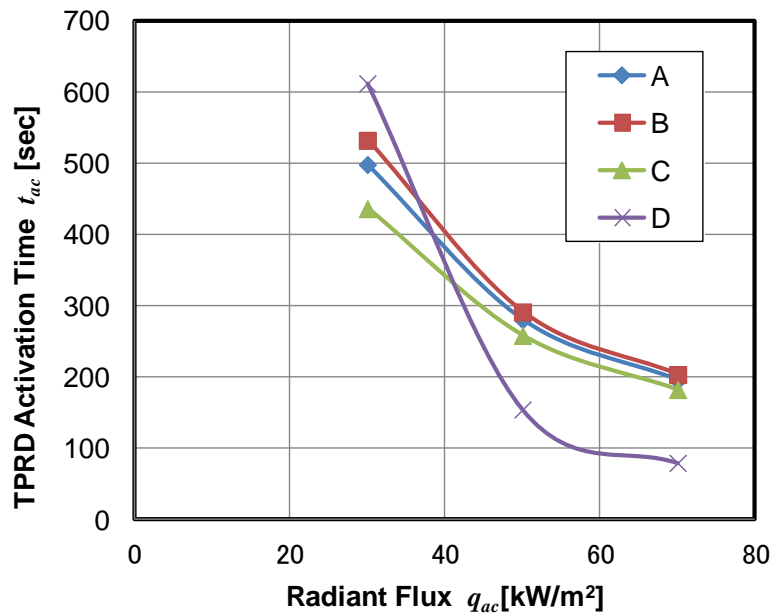

Figure 6. Rerationship with TPRD activation time and radiant flux

The three fuse metal type TPRDs (types A, B and C) proved to have similar curve lines. The comparison of activation time indicated that the glass bulb type TPRD responded with slower

4

activation than did the fuse metal type TPRDs when radiant flux was small, but the activation of the glass bulb type TPRD was faster than the other TPRDs when radiant flux was larger.

Figure 7 shows the relationship between radiant flux and the reciprocal of activation time, where the average activation time of the three fuse metal type TPRDs is also compared.
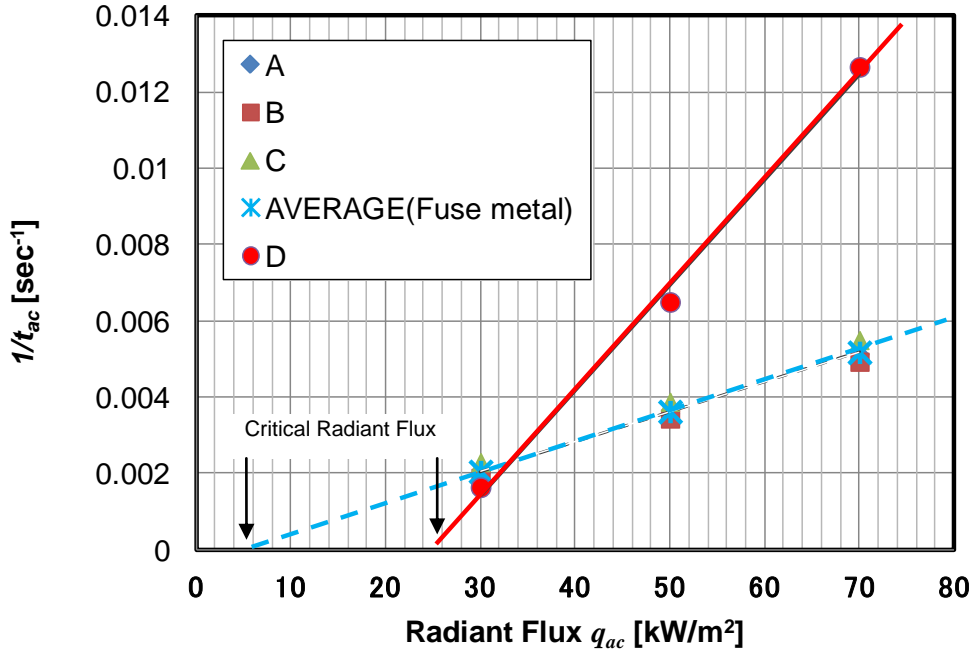

Figure 7. Effects of radiant fluxes on TPRD activation time

As the figure above shows, there was a linear relationship between the reciprocal of activation time and radiant flux; furthermore, the performances of the three fuse metal type TPRDs were plotted virtually on the same straight line. The intersection point of this line and the horizontal axis indicated the maximum radiant heat at which TPRD remained inactive, or the critical radiation q_c. Then, Equation-(1) below holds, where t_{ac} is TPRD activation time, q_{ac} is radiant heat applied, and a is the reciprocal of the line inclination in Figure 6.

$$\frac{1}{t_{ac}} = \left(\frac{1}{a}\right) \cdot (q_{ac} - q_c) \qquad (1)$$

That is, a can be expressed by Equation-(2) below.

$$a = (q_{ac} - q_c)t_{ac} \qquad (2)$$

In Equation-(2), a is the amount of heat required to activate TPRD when applied with radiant heat exceeding the critical radiant flux. In other words, a equals the differential between the total amount of heat generated until TPRD activation ($q_{ac} \times t_{ac}$) and the amount of heat not contributing to TPRD activation ($q_c \times t_{ac}$). Since the value of a excludes the heat applied at the critical radiant flux, the amount of heat not contributing to activation, such as heat dissipations from TPRD, is not calculated.

Table 2 shows the regression formula, critical radiant flux q_c, and total amount a (kWs/m^2) of heat requirement for TPRD activation for each of the four TPRD types.

Table 2. Relationships between TPRD activation time and radiant flux

TPRD	Regression formulae	Critical radiant flux q_c [kW/m²]	a [kWs/m²]
#A (Fuse metal)	$t_{ac}^{-1} = 7.80 \times 10^{-5} \times q_{ac} - 3.72 \times 10^{-4}$	4.77	12820
#B (Fuse metal)	$t_{ac}^{-1} = 7.62 \times 10^{-5} \times q_{ac} - 3.94 \times 10^{-4}$	5.17	13123
#C (Fuse metal)	$t_{ac}^{-1} = 8.55 \times 10^{-5} \times q_{ac} - 4.17 \times 10^{-4}$	4.88	11696
#D (Glass bulb)	$t_{ac}^{-1} = 2.76 \times 10^{-4} \times q_{ac} - 6.85 \times 10^{-3}$	24.8	3623

The value of critical radiant flux proved to be approximately 5 kW/m² for the fuse metal type TPRDs and approximately 25 kW/m² for the glass bulb type TPRD. The lower of the two critical radiant flux values was employed in the rest of the present study in view of greater safety for FCV marine transportation.

The value of a, however, indicated that the total amount of heat required for TPRD activation was larger among the fuse metal type than the glass tube type. This was accounted for that in the fuse metal type TPRDs the radiant heat must be transmitted from the body surface to the embedded fuse metal through the TPRD body having a certain heat capacity, unlike the other TPRD having its glass bulb exposed directly to radiant heat.

3.0 DISCUSSION

Examined below is whether or not the TPRD is activated by radiant heat under the condition of the floor temperature reaching the spontaneous ignition temperature level of automotive exterior parts. First, the amount of heat flux received by TPRD from lower deck when the tire reached its spontaneous ignition temperature was calculated on the basis of the calculation model shown in Figure 8.
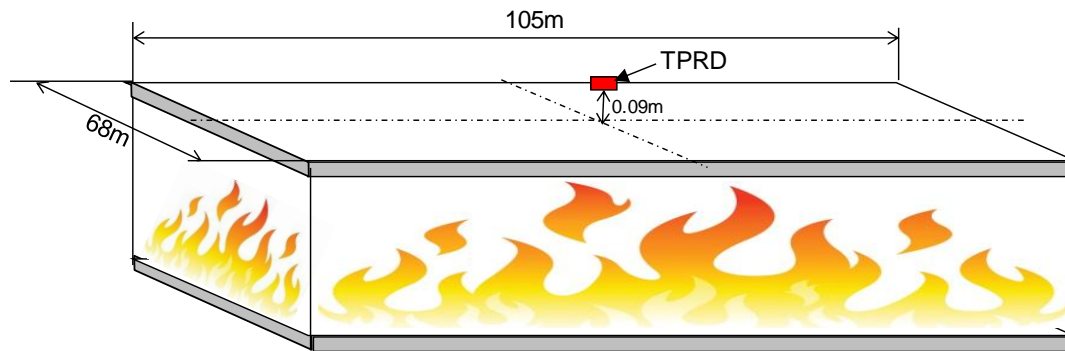

Figure 8. Model

The TPRD was assumed to receive only the radiant heat from lower deck as its heat input. The lower-deck dimensions were set at 105m x 68m on the basis of the actual floor sizes of pure car carrier ships[4]. As Japan's Safety Regulations requires a minimum elevation of 0.09m from floor for TPRDs[5], the TPRD position was set at 0.09m from floor, the closest possible position to the floor, and at the center of the floor in terms of floor length and width. Although the actual TPRDs installed on FCVs are guarded with an undercover for protection against aerodynamic force and splash stones from the ground, the worst case of a missing undercover was assumed. Since the known spontaneous

ignition temperature of tires is 400°C[6], calculations were performed to determine the amount of heat flux received by TPRD when the floor temperature was 400°C.

Compared to the area of the lower deck A_2, the area of the TPRD A_1 is minuscule, so that their configurational relationship can be illustrated as in Figure 9. The view factor F_{12} between A_1 and A_2 can be expressed by Equation-(3) below.
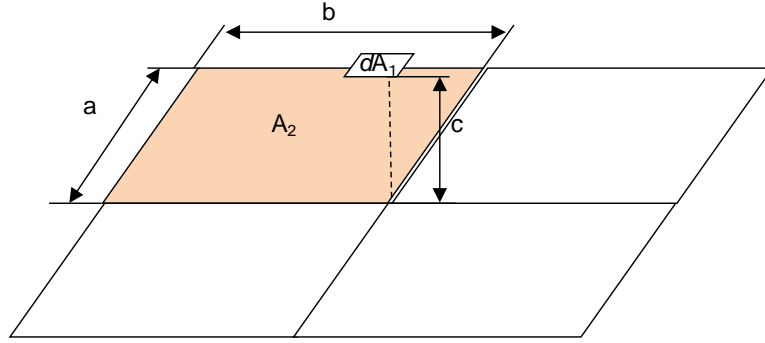

Figure 9. Radiation view factor

$$F_{12} = \frac{1}{2\pi} \left[\frac{X}{\sqrt{1+X^2}} \tan^{-1} \frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}} \tan^{-1} \frac{X}{\sqrt{1+Y^2}} \right] \tag{3}$$

where $X = \dfrac{a}{c}$ and $Y = \dfrac{b}{c}$. When floor length $2a$=105m, floor width $2b$=68m and TPRD elevation c=0.09m are substituted into Equation-(3), the following Equation-(4) holds:

$$F_{12} = 4 \times \frac{1}{2\pi} \left[\frac{583}{\sqrt{1+583^2}} \tan^{-1} \frac{378}{\sqrt{1+583^2}} + \frac{378}{\sqrt{1+378^2}} \tan^{-1} \frac{583}{\sqrt{1+378^2}} \right] = 1.00 \tag{4}$$

As the TPRD body is made mostly of stainless steel, the emissivity ε of TPRD is 0.16~0.35[7,8], whereby 0.35 was selected for calculations. Equation-(5) below was employed to derive the amount of heat flux received by TPRD when the floor temperature was 400°C, the spontaneous ignition temperature of tire rubber.

$$q = \varepsilon\sigma(T_2^4)F_{12} = 0.35 \times 5.67 \times 10^{-11} \times (400+273)^4 \times 1.00 = 4.07 [\text{kW/m}^2] \tag{5}$$

where constant σ is Stefan-Boltzmann $5.67 \times 10^{-11}[\text{kW/m}^2\text{K}^{-4}]$.

From the experimental results reported in section 2, the critical radiant flux necessary for TPRD activation is approximately 5 kW/m². Consequently the calculations indicated that TPRDs would not activate under the floor temperature condition equal to the tire spontaneous ignition temperature.

On the other hand, most of the commercialized FCVs have their hydrogen cylinders guarded by a plastic undercover for protection against aerodynamic force and splash stones from the ground[9]. Accordingly the radiant flux from the lower deck would first heat the undercover before heating the TPRD. With these plastic undercovers made primarily of polypropylene, their softening temperature is known to be 128°C and spontaneous ignition temperature 498°C[9]. When subjected to radiant heat from lower deck, therefore, the polypropylene undercover first softens and drops onto the floor before TPRD activation. Then, given a floor temperature of 500°C (approximately the spontaneous ignition temperature of polypropylene), the radiant heat q_{ac} received by TPRD was calculated to be about 7 W/m² by Equation-(1). This means that, according to the regression formulae shown in Table 1, TPRD

7

needs to be exposed to radiant heat for at least 1.5 hours before its activation to take place. Even if the activation took place and the hydrogen released, the polypropylene undercover fallen onto the floor would have undergone spontaneous ignition, helping the floor temperature to reach the hydrogen spontaneous ignition temperature of 500°C[10]. Therefore, even if TPRD activates, the hydrogen releases will have been burned and the possibility of explosion eliminated.

For the above reasons, the possibility of TPRD activation by radiant heat from lower deck was considered small under the condition of lower-deck temperature reaching the spontaneous ignition temperature of tires or polypropylene exterior parts. Furthermore, even if TPRD was to finally activate due to sustained exposure to radiant heat, FCV exterior parts such as the tires and a fallen polypropylene undercover would have been ignited and burn out any hydrogen releases. Accordingly it is highly unlikely that the accident scenario adopted by the present study will take place in the real world.

4.0 CONCLUSION

In the event of a fire accident on the lower deck of a car carrier ship or a ferry, the TPRDs of FCVs parked on the upper deck may be activated by radiant heat from the lower deck. Assuming TPRD activation without the presence of any flames, the hydrogen releases are considered to form combustible air-fuel mixtures in the vicinity. Yet if FCV exterior parts have already undergone self-ignition, their flames will burn out the hydrogen releases, thus preventing the formation of air-fuel mixtures.

The present study was conducted to examine the accident scenario for FCV marine transportation during which fires may break out in the lower deck and induce TPRD activation in the FCVs parked on the upper deck. The experiment on relationships between TPRD activation time and radiant heat from the lower deck found that it took at least 90 minutes for TPRD to activate under the condition of lower-deck temperature reaching the spontaneous ignition temperature of FCV tires and polypropylene parts; that even if polypropylene parts are melted and self-ignited under radiant heat, hydrogen releases would be burned immediately by the flames present in the vicinity. Accordingly it was concluded that the explosion of air-fuel mixtures assumed in the accident scenario cannot occur in the real world.

REFERENCE

1. Heskestad, G., Bill,R.G.Jr.,Modeling of thermal responsiveness of automatic sprinklers, Proceedings of the second international symposium for fire safety science,pp.603-612,1989.
2. Yukio Yamauchi, Atsushi Mammoto, Masahiro Morita, A Calculation method for predicting heat detector's response, Jornal of Enviro. Eng. AIJNo.603,2006
3. Yukio Yamauchi, A review of literature on fire phenomena related to detection, Bulletin of Japan Association for fire science of engineering, Vol.55,No.2,2005
4. http://www.kline.co.jp/plaza/kline/dairy/1189388_1474.html
5. http://www.mlit.go.jp/jidosha/kijyun/saimokukokuji/saikoku_163_00.pdf
6. Yoshiki Sato, Recycling of Used Tires, Shigen-to-Sozai, Vol.113, pp999-1004(1997)
7. Arthur E.Cote, P.E., Jim L.Linville, Fire progection handbook,Natinal Fire Protection Association, Eighteenth edition, 1997
8. http://www.raytekjapan.co.jp/Raytek/ja-r0/IREducation/EmissivityTableMetals.htm
9. http://newsroom.toyota.co.jp/en/detail/4198334
   John D.DeHaan, Kirk's Fire Investigation, Third Edition, Brady,1990