MINIMUM FIRE SIZE FOR HYDROGEN STORAGE TANK FIRE TEST PROTOCOL FOR HYDROGEN-POWERED ELECTRIC CITY BUS DETERMINED VIA RISK-BASED APPROACH

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ABSTRACT

As part of the United Nations Global Technical Regulation No. 13 (UN GTR #13 [1]), vehicle fire safety is validated using a localized and engulfing fire test methodology and currently, updates are being considered in the on-going Phase 2 development stage. The GTR#13 fire test is designed to verify the performance of a hydrogen storage system of preventing rupture when exposed to service-terminating condition of fire situation. The test is conducted in two stages – localized flame exposure at a location most challenging for thermally-activated pressure relief device(s) (TPRDs) to respond for 10 min. followed by engulfing fire exposure until the system vents and the pressure falls to less than 1 MPa or until "time out" (30min. for light-duty vehicle containers and 60 min. for heavy-duty vehicle containers). The rationale behind this two-stage fire test is to ensure that even when fire sizes are small and TPRDs are not responding the containers have fire resistance to withstand or fire sensitivity to respond to a localized fire to avoid system rupture.

In this study, appropriate fire sizes for localized and engulfing fire tests in GTR#13 are evaluated by considering actual fire conditions in a hydrogen-powered electric city bus. Quantitative risk analysis is conducted to develop various fire accident scenarios including regular bus fire, battery fire, and hydrogen leak fire. Frequency and severity analyses are performed to determine the minimum fire size required in GTR#13 fire test to ensure hydrogen storage tank safety in hydrogen-powered electric city buses.

1.0 BACKGROUND

From year 2018, the South Korean government established a roadmap to develop an industrial ecosystem for hydrogen economy based on two main areas – hydrogen electric vehicles and fuel cells. Based on this plan, innovative growth in the South Korean hydrogen economy will be offered by 2040, creating 43 trillion won in value added annually and 420,000 new jobs in total. However, to achieve this goal, issues of securing safety in the entire hydrogen cycle and establishing a stable and economical hydrogen production and distribution systems are needed to be addressed.

Considering the safety problems related to hydrogen buses, a research team led by Korea Automobile Testing & Research Institute (KATRI) was formed in 2020. This research is conducted to develop vehicle and component safety assessment technology and/or equipment for preventing secondary accidents (e.g., fire and explosion) and to verify performance of multi-power parallel drive systems targeted for hydrogen bus operation and possible accidents. From this research, local hydrogen bus safety testing protocols will be proposed.

Among the various test protocols for checking safety issues related to hydrogen buses, this work focuses on investigating the contents of fire testing of a compressed hydrogen storage systems (CHSS) for hydrogen buses. Currently, this test protocol follows the same procedure indicated in the United Nations

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Global Technical Regulation No. 13 (UN GTR #13) [1]. GTR#13 Phase 1 was established in 2013 and now Phase 2 is being developed to cover some of the new items originally not addressed in the previous regulation. The research members are actively involved in the Phase 2 working groups to support its efforts of updating the newer version of this regulation.

This paper addresses research efforts to evaluate appropriate fire sizes used in fire testing of compressed hydrogen storage systems (CHSS) for hydrogen-powered electric city buses via risk-based approach. As shown in Figure 1, GTR#13 fire test utilizes the temperature curve measured at the location between the bottom of the tank and the burner surface. The test is conducted in two consecutive stages – localized fire stage where temperatures are between 450 and 700˚C and engulfing fire stage where temperature are above 600˚C. The targeted fire sizes per unit area of the burner proposed to achieve these temperature ranges are 320 kW/m^2 for localized fire stage and 685 kW/m^2 for engulfing fire stage. In this work, quantitative risk analysis is conducted to develop various fire accident scenarios where frequency and severity analyses are performed to determine the minimum fire size required in GTR#13 fire test to ensure hydrogen storage tank safety in hydrogen-powered electric city buses.

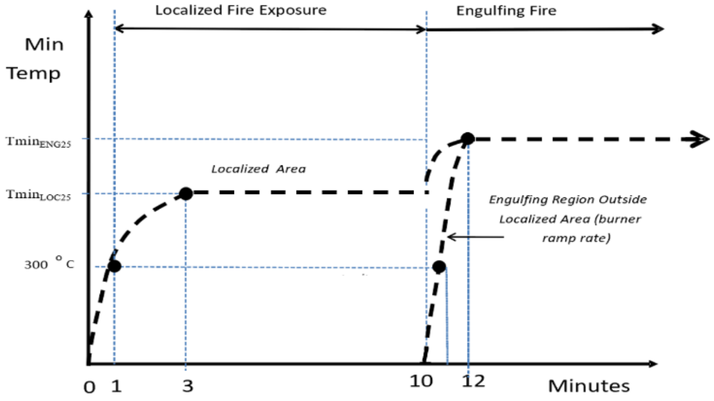

Figure 1. Temperature profile of fire test in UN GTR#13 Phase 2 working draft

2.0 ROLLOVER TEST OF HYDROGEN BUS

To identify possible hazards in case of a hydrogen bus accident, mock-up test of a rollover crash was conducted following the UN R 66 Rollover Test [2] with a hydrogen-powered electric city bus (see Figure 2). This test was highly instrumented with acceleration /angular sensors, hydrogen gas sensors, micro-high-speed cameras, and touch/force sensors to acquire data for future modelling validation work. The test conditions are as follows:

- Each hydrogen fuel tank is filled to 95% of service pressure with hydrogen.
- All fuel valves are in open position and all electric systems are in operation position.
- Angular velocity of tilt platform used in rollover test shall not exceed 5˚/s.

Based on this test, several findings were reported:

- Direct contact between the pressurized fuel systems (fuel lines and valves) and vehicle side wall was observed during the rollover test. High accelerations of 60 ~ 80 g were measured in terms of impact severity of fuel tanks; however, no leak of hydrogen gas was reported.
- Direct contact between the Rechargeable Energy Storage System (REESS) and vehicle side wall during rollover test was observed, i.e., failure of high voltage isolation. 65~90 Ω/V were measured from the test (UN R 100 regulation [3]: equal or over 500 Ω/V(A/C))

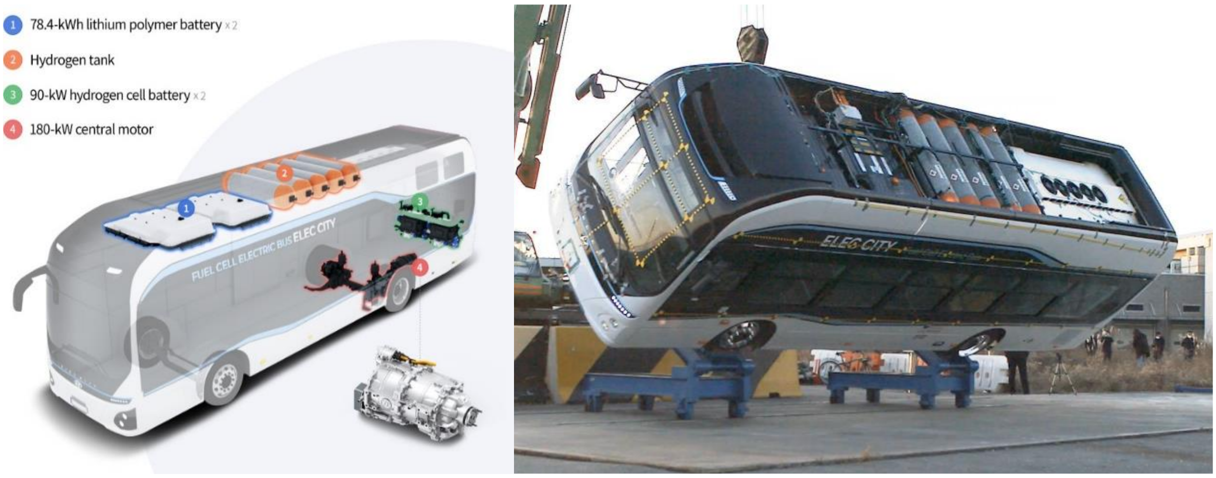

Figure 2. Rollover mock-up test of hydrogen-powered electric city bus conducted at KATRI [4]

Conducting this test led to consider three different types of fire initiating events in the hydrogen-powered electric city bus: (1) fire starting from the batter pack located at the bus deck near the front-end (see (1) in Figure 2); (2) fire starting from underneath the compressed hydrogen storage system (e.g., fires from crash accidents, etc.); (3) fire starting from a leak from the compressed hydrogen storage system.

3.0 QUANTITATIVE RISK ANALYSIS

Quantitative risk analysis is conducted in two parts – frequency analysis and severity analysis – as quantifying risk requires estimation of both results. Frequency analysis is conducted using an event tree analysis, identifying each protection layers in series, to determine which fire conditions are of importance to this study, i.e., of high frequency level so that it cannot be considered as a negligible risk level ($> 10^{-6}$ event per year level). Severity analysis is conducted to check the effectiveness and integrity of TPRD activation protection layer applied in the frequency analysis. This is determined via fire testing defined in the GTR#13, evaluating the performance of a hydrogen storage system (including TPRD) of preventing rupture when exposed to service-terminating condition of fire situation. Three fire scenarios are simulated to estimate the thermal threats received by the tank surfaces and the results are compared to those in the fire test.

3.1 Fire Scenarios

As aforementioned in the previous section, three initiating events in a hydrogen-powered electric city bus are considered in this risk analysis: battery fire, bus fire, and hydrogen leak fire. The fire-starting locations are shown in the figure below in red (see Figure 3).

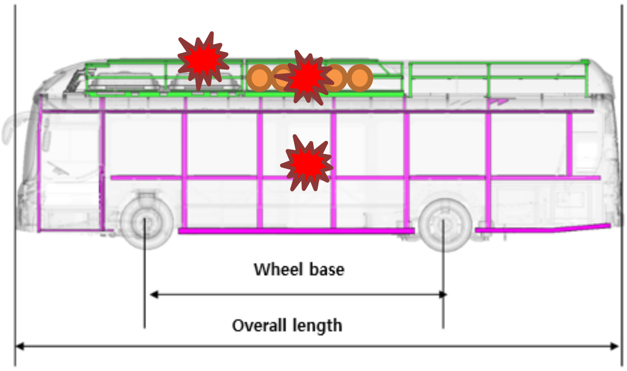

Figure 3. Three fire initiating events: battery fire, bus fire, and hydrogen leak fire

3.2 Frequency Analysis

To conduct frequency analysis, event tree analysis is applied for the three top initiating events. The three events are independent; hence, they will be considered separately. The outcome frequency (OF) is calculated using the following equation:

$$OF = IF \times P_1 \times P_2 \times \cdots \times P_n \tag{1}$$

where IF is the initiating even frequency and P_n is the conditional probability of nth protection layer.

First, event tree analysis of a battery fire initiating in the hydrogen-powered electric city bus is conducted (see Figure 4). The top initiating event frequency was found from Ref [5]. The applied assumptions are: (1) fire occurs when the bus in the upright position (normal position); and (2) thermally activated pressure release device (TPRD) is installed at hydrogen tank to release the pressurized hydrogen from the tank in case of an emergency. The conditional probabilities applied for the protection layer are from Data Table 5.17 of Ref [6]. The resulting cases are: Case 1 – battery fire resulted in heating in the bus deck region; however, TPRD is activated successfully to omit any possible catastrophic tank explosion; Case 2 – battery fire resulted in heating in the bus deck region and TPRD fails to operate properly. From this analysis, it can be shown that Case 2 can lead to catastrophic consequences and the outcome frequency is higher than 10^{-6} event per year, which typically is considered as nonnegligible risk. Also, actual frequency of Case 2 should be calculated by multiplying a factor of 5 to this risk as there are 2 battery packs and 5 identical hydrogen tanks placed within a bus with 2 TPRDs for each tank. This results in 1.9E-05, in the 10^{-5} event per year level. Therefore, careful consideration should be given to Case 2; also, adding Independent Protection Layers (IPLs) to Case 2 should be considered to reduce the outcome frequencies to a negligible risk level. These may be adding a battery fire suppression system within the battery pack, adding a fire barrier between the battery pack area and the hydrogen tank area to prevent flames and heat traveling towards the tanks, or increasing tank integrity to withstand such thermal threats.

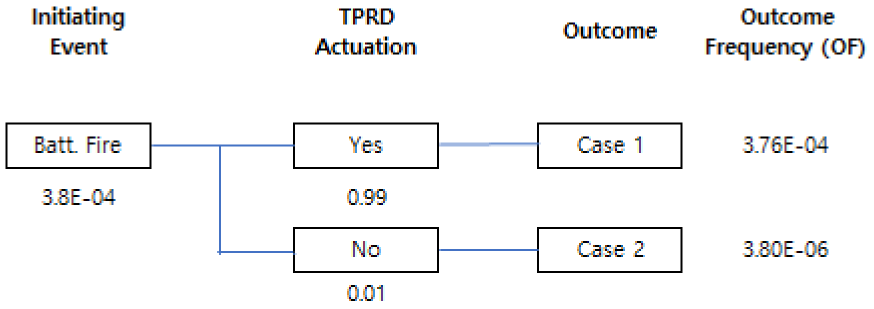

Figure 4. Event tree analysis of a battery fire in a hydrogen-powered electric city bus

Second, event tree analysis of a general bus fire initiating in the hydrogen-powered electric city bus is conducted (see Figure 5). The top initiating event frequency is from car accidents, which was found from Ref [7]. The applied assumptions are: (1) fire occurs when the bus in the upright position (normal position); and (2) thermally activated pressure release device (TPRD) installed at hydrogen tank to release the pressurized hydrogen from the tank in case of an emergency. The conditional probability applied for the protection layer are from Data Table 5.17 of Ref [6]. The resulting cases are: Case 1 – bus fire from a car accident resulted in heating in the bus deck region; however, TPRD is activated successfully to omit any possible catastrophic tank explosion; Case 2 – bus fire resulted in heating in the bus deck region and TPRD fails to operate properly. From this analysis, it can be shown that Case 2 can lead to catastrophic consequences; however, the outcome frequency is in the order of 10^{-7} event per year, which typically is considered as negligible risk. Same as in battery fire analysis, actual frequency of Case 2 should be calculated by multiplying a factor of 2.5 to this risk to account for having 5 identical hydrogen tanks placed within a bus with 2 TPRDs for each tank. This results in 9.7E-07, almost in the 10^{-6} event per year level; hence, there is some possibility to consider this as nonnegligible risk level. Therefore, having additional Independent Protection Layers (IPLs) to Case 2 is recommended to reduce the outcome frequencies to a negligible risk level. Such IPLs are adding a fire barrier to the deck to protect the upper deck area in case of a bus fire or increasing tank integrity to withstand such thermal threats.

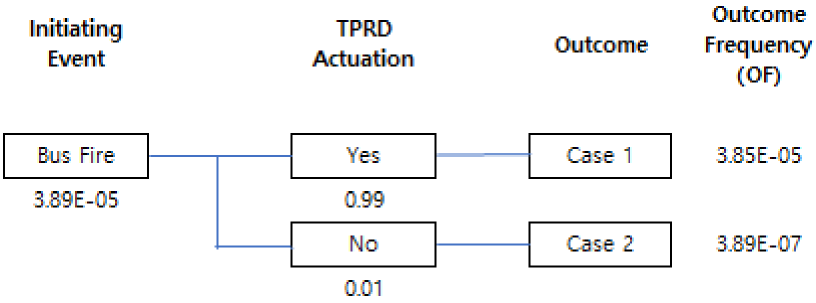

Figure 5. Event tree analysis of a bus fire in a hydrogen-powered electric city bus

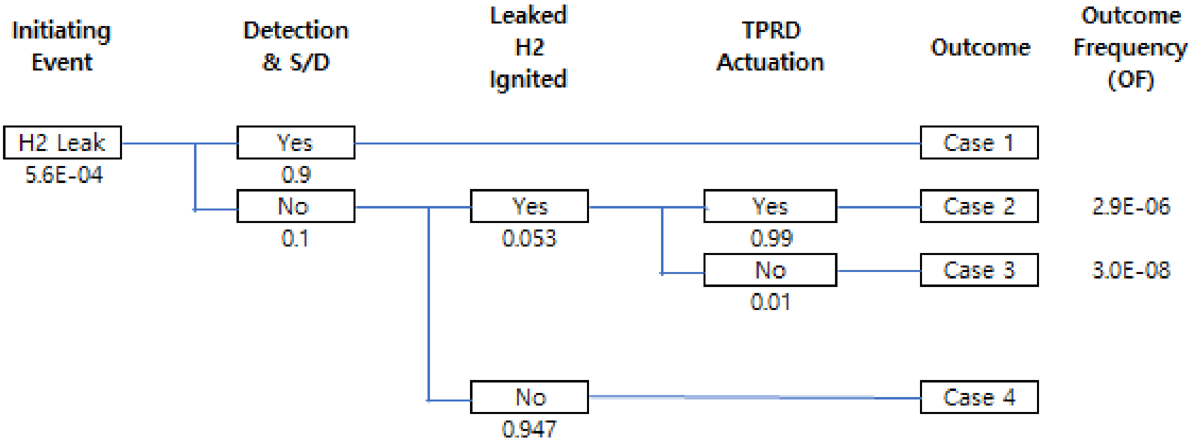

Figure 6. Event tree analysis of a hydrogen leak fire in a hydrogen-powered electric city bus

Third, event tree analysis of a hydrogen leak fire initiating in the hydrogen-powered electric city bus is conducted (see Figure 6). The top initiating event frequency is from car accidents, which was found from Ref [8]. The applied assumptions are: (1) fire occurs when the bus in the upright position (normal position); (2) hydrogen leak is from a 10 mm diameter hole, equivalent to a full rupture of the hydrogen tubings used, releasing from a 700 bar compressed hydrogen storage system; (3) hydrogen sensors are near the leak and safe shutdown is possible; (4) hydrogen leak may not ignite; (5) thermally activated pressure release device (TPRD) installed at hydrogen tank to release the pressurized hydrogen from the tank in case of an emergency; and (6) enough ventilation is offered in the deck area of the bus and therefore any delayed ignition is not considered in the analysis. The conditional probabilities applied for the three protection layers shown in the event tree analysis are from Data Table 5.17 and 5.40 of Ref [6] and Ref [9]. The resulting cases are: Case 1 – hydrogen leak occurs from the compressed hydrogen storage system (CHSS) and is detected followed by a safety shutdown procedure; Case 2 - hydrogen leak occurs; however, detection and safety shutdown fails followed by ignition; therefore, a flame jet occurs but TPRD is activated successfully to omit any possible catastrophic tank explosion; Case 3 -

hydrogen leak occurs and detection & safety shutdown fails followed by ignition; therefore, a flame jet occurs and TPRD fails to operate properly; Case 4 - hydrogen leak occurs and detection & safety shutdown fails; however, ignition does not occur resulting in safe release of hydrogen through venting. From this analysis, it can be shown that Case 3 can lead to catastrophic consequences; however, the outcome frequency is in the order of 10^{-8} event per year, which typically is considered as negligible risk. Even when the actual frequency of Case 3 is calculated by multiplying a factor of 2.5 to this risk to account for having 5 identical hydrogen tanks placed within a bus with 2 TPRDs for each tank, the frequency results in 7.5E-08, almost in the 10^{-7} event per year level, which is still at the negligible risk level. Hence, adding more Independent Protection Layers (IPLs) to Case 3 is not required at this stage.

3.3 Severity Analysis

For the three fire scenarios investigated in this study, severity analyses are conducted with a well-known fire related CFD model, Fire Dynamics Simulator (Version 6.7) [10] developed by National Institute of Standards and Technology, USA and HyRAM [9] developed by Sandia National Laboratories, USA. In any event of hydrogen-powered electric city bus fire, Independent Protection Layer (IPL) of having TPRD activation was considered in the event tree analysis. However, the effectiveness and the integrity of this protection layer is determined and certified with the fire test defined in the GTR#13. Considering that the fire test in the GTR#13 is conducted in two stages, localized and engulfing fire stages, following statements should be true for the fire test to be accurately evaluating the performance of a hydrogen storage system (including TPRD) of preventing rupture when exposed to service-terminating condition of fire situation.

First, the thermal threat received by the hydrogen tank surface prior to TPRD activation in the actual fire scenario should be smaller or equal to that of localized fire stage in the fire test. Additionally, the time at TPRD activation should be less than 10 min. as this is the maximum time duration for the localized fire stage in the GTR#13 fire test. Second, the thermal threat received by the hydrogen tank surface after TPRD activation in the actual fire scenario should be smaller or equal to that of engulfing fire stage in the fire test. If otherwise, the thermal threat applied to the tank surface would be greater than that of the fire tests; and hence, the TPRD activation protection layer and its performance is NOT verified with the given fire test.

To evaluate the appropriateness of the thermal threat level applied in the current fire test of GTR#13 (see Figure 1), three fire scenarios are simulated, and the following model outputs are recorded:

- Time of TPRD activation
- Thermal threat level (max) on tank surfaces at TPRD activation in terms of total heat flux levels
- Thermal threat level (max) on tank surfaces when the fire size reaches its maximum value in modelling.

The fire growth curve used in modelling for the battery fire is from Ref [11] assuming a single battery pack near the tank is involved in the fire. This fire grows to a 1MW fire within the deck area of the bus within 10 min. The fire growth curve for a bus fire simulation is estimated from Ref [12] assuming that the bus is completely consumed in the fire. The fire grows to a 30MW fire underneath the compressed hydrogen storage system within 10 min. The hydrogen leak fire is assumed to occur from a 10 mm diameter hole size pressurized to 700 bar, which is the full rupture of the pipeline case.

The logic behind this exercise is to conduct modelling of the three fire scenarios; and estimate the maximum thermal threat values (in terms of total heat flux levels) on the tank surfaces prior and after TPRD activation. Then compare these values to the thermal threat received in the GTR#13 fire test set-up, also estimated via modelling. By comparing the two thermal threat levels – from actual fire scenario considered in this work and from GTR#13 fire test – the pertinence of the thermal threat level introduced during the GTR#13 fire test evaluated. See Figure 7. Note that for battery fire and bus fire cases, only the upper deck area of the bus is simulated to reduce computational expenses.

The modelling results from the three fire scenarios – battery fire, bus fire and hydrogen leak fire – are summarized in Table 1. As shown in this table, the battery fire case shows that the TPRD is activated at 2 min. after ignition and the maximum thermal threat level, i.e., total heat flux impinging on the tank surface is at 40 to 50 kW/m^2 range and the fire size become approximately 640kW. At 10 min. after ignition, the maximum thermal threat level becomes greater than 60 kW/m^2 and the fire size is at its maximum of 1MW. The severity analysis showed that the Independent Protection Layer (IPL) offered by TPRD activation was appropriately assessed by the GTR#13 fire test protocol as thermal threats experienced by the hydrogen storage tanks in the actual fire scenario is smaller than those experienced in the fire test. Also, TPRD is activated before 10 min. of fire exposure. Note that the maximum thermal threat level applied to the tank surface is in the 50 to 60 kW/m^2 range for localized fire stage and 70 to 80 kW/m^2 range for engulfing fire stage of current version of GTR#13 fire test method (see Table *2*).

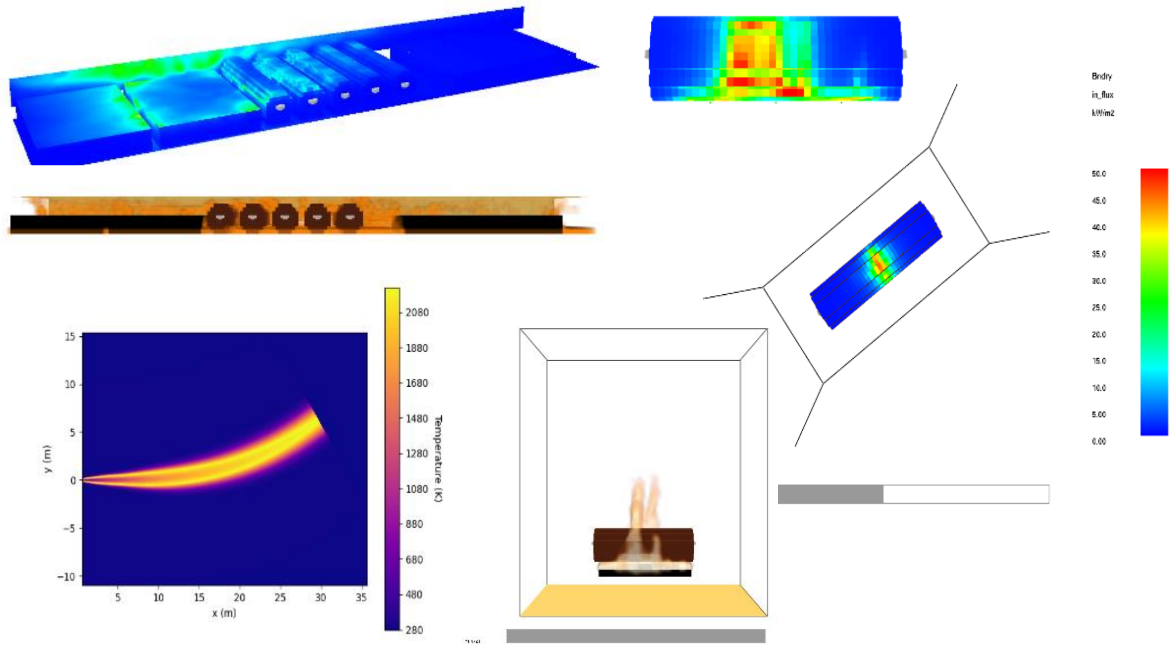

Figure 7. Three fire scenarios – battery fire, bus fire and hydrogen leak fire – are modelled (left) and GTR#13 fire test is modelled with various fire sizes (right) to compare thermal threat levels in each case.

The bus fire case shows that the TPRD is activated at 7 min. after ignition and the maximum thermal threat level, i.e., total heat flux impinging on the tank surface is at 40 to 50 kW/m^2 range and the fire size become approximately 690kW. At 10 min. after ignition, the maximum thermal threat level was not estimated due to numerical instability issue caused by the fire size growing to be too large for the selected computational domain to handle. The maximum fire size set by the user is 30MW, which was obtained from a full-scale bus fire test. Knowing that the fire is at the deck surface area, the fire is burning underneath the tank, which is like the GTR#13 test set-up. Assuming the tanks are placed on top of the burner as in the GTR#13 fire test, the heat release rate per unit area of the burner becomes 40kW/m^2 when TPRD is activated and 1.67MW/m^2 when the fire size reaches its maximum value, 30MW. The severity analysis showed that the Independent Protection Layer (IPL) offered by TPRD activation was appropriately assessed by the GTR#13 fire test protocol only for the localized fire stage as thermal threats experienced by the hydrogen storage tanks in the actual fire scenario is smaller than those experienced in the localized fire stage of the test. TPRD is activated before 10 min. of fire exposure; hence, time duration is properly addressed in the fire test. However, for the engulfing fire stage of the test, the thermal threat experienced by the tank surface would be in the range of 80 to 90 kW/m^2 assuming that the heat release rate per unit area of the burner is 1.67MW/m^2 (see Table *2*). This range is greater than what is being tested in the engulfing fire stage of GTR#13 fire test. Therefore, to adequately assess the CHSS performance (including TPRD) in this bus fire condition, increase in the target heat release rate per unit area of the burner to 1MW/m^2 at minimum is necessary. At 1MW/m^2 level, the maximum thermal threat received by the tank surface is within 80 to 90 kW/m^2 range.

Table 1. FDS and HyRAM simulation results from three fire scenarios

	TPRD Activation Time (min)	Max. Thermal Threat Level on Tank Surfaces at TPRD Activation Time (kW/m^2)	Fire Size at TPRD Activation Time (kW)	Time to Max. Fire Size (min)	Max. Thermal Threat Level on Tank Surfaces at Max. Fire Size (kW/m^2)	Max. Fire Size (MW)
Battery Fire	2	40-50	640	10	60-70	1
Bus Fire	7	40-50	690 (40 kW/m^2 at burner)	10	-*	30 (1.67MW/m^2 at burner)
Hydrogen Leak Fire	-	350 (radiative only)	-	Happens instantly	350 (radiative only)	-

* Modelling aborted due to numerical instability; fire size was too large for the selected computational domain (upper deck area of the bus).

Table 2. FDS simulation results from GTR#13 fire test with different heat release rate per unit area at burner

	Heat Release Rate per Unit Area at Burner (kW/m^2)			
	320 (same as current localized fire stage)	685 (same as current engulfing fire stage)	1000	1670
Max. Thermal Threat Level on Tank Surfaces (kW/m^2)	50-60	70-80	80-90	80-90

For the hydrogen leak fire case, the maximum thermal threat level in terms of radiative heat flux from the flame, which is assumed to be impinging on the tank surface due to such a small space of the upper deck area is above 350 kW/m^2 and this happens instantaneously followed by ignition. The severity analysis showed that the Independent Protection Layer (IPL) offered by TPRD activation was inappropriately assessed by the GTR#13 fire test protocol as thermal threats experienced by the hydrogen storage tanks in this fire scenario is much greater than those experienced in the fire test. Also, TPRD activation may not occur due to the jet flames not being able to reach and heat up the TPRD. Therefore, the Independent Protection Layer (IPL) offered by TPRD activation in Figure *6* should be bypassed, resulting in a possible catastrophic tank explosion outcome frequency of 2.9E-06. By multiplying a factor of 2.5 to this risk to account for having 5 identical hydrogen tanks placed within a bus with 2 TPRDs for each tank, this case results in 7.25E-06, almost in the 10^{-5} event per year level. This indicates that even when a qualified compressed hydrogen storage tank (i.e., passing the GTR#13 fire test) does not ensure fire safety for this hydrogen jet fire scenario. Therefore, to maintain the risk under its acceptable level, additional IPLs should be added. Some examples of IPLs, which may be applied are adding excessive flow valve, adding features to ensure TPRD activation in case of a jet fire, and more.

4 DISCUSSIONS

In this study, quantitative risk analysis is conducted to examine proposed fire sizes in the current working draft of the GTR#13 Phase 2 is appropriate for a hydrogen-powered electric city bus. The fire initiating events are considered from a rollover test conducted at KATRI, which are fire starting from the battery pack located in the upper deck area of the bus, bus fire from a car accident, and a hydrogen leak from the pipelines located near the compressed hydrogen storage system.

Frequency analysis was conducted with event tree analysis considering several Independent Protection Layers (IPLs) – TPRD activation, ventilation (ignition versus dispersion) and detection with safety shutdown. When applying these protection layers, battery fire case with TPRD activation failure was considered as nonnegligible risk with its frequency in 10^{-5} event per year range while other cases resulted in the acceptable range. For bus fire case with TPRD activation failure was considered as at moderate risk level with its frequency approaching 10^{-6} event per year range while other cases resulted in the acceptable range. For the hydrogen leak fire case, all possible cases resulted in the nonnegligible risk range.

To reduce high and moderate frequency risks or to add redundancy to the system, additional IPLs are required to be included in the current hydrogen-powered electric city bus design:

- Add battery fire suppression system within the battery pack;
- Add a fire barrier between the battery pack area and the hydrogen tank area;
- Increase tank integrity/fire resistance to thermal threats (minimum of 1hour for bus fires);
- Add a fire barrier to the deck to protect the upper deck area in case of a bus fire;

Severity analysis of the three fire scenarios was conducted using FDS and HyRAM modelling. The objective of this analysis was to determine the appropriateness of the fire size levels proposed in the current working draft of the GTR#13 Phase 2 – localized fire stage for 10 min. where temperatures are between 450 and 700˚C followed by engulfing fire stage where desired temperature settings are above 600˚C at the tank bottom with targeted fire sizes per unit area of the burner at 320 kW/m^2 for localized fire stage and 685 kW/m^2 for engulfing fire stage. This effort is in other words checking the validity of the TPRD activation protection layer considered in the frequency analysis section.

For the three fire scenarios, maximum thermal threat received by the hydrogen tank in terms of heat flux levels are estimated via modelling prior and after TPRD activation. These heat flux values are compared to simulated thermal threat levels received by the hydrogen tank surface in the GTR#13 fire test set-up. Pre-TPRD activation condition is compared with the localized fire stage in the GTR#13 fire test and post-TPRD activation condition is compared with the engulfing fire stage. For the battery fire case, thermal threats applied to the tank surface during pre- and post- TPRD activation conditions are lower than those in GTR#13 fire test, assuring GTR#13 fire size levels are reasonable. For the bus fire case, thermal threats impinging on the tank surface during pre-TPRD activation condition was lower than that of the localized fire stage in GTR#13 fire test; however, during post-TPRD activation condition thermal threats received from the bus fire exceeded that of the engulfing fire stage. Based on this analysis, increase in the engulfing fire size to 1MW/m^2 burner area is recommended. For the hydrogen leak fire, thermal threats attacking the tank surface was estimated to be much greater than those being tested in the GTR#13 test. Also, TPRD activation may not occur due to lack of heating. Therefore, the Independent Protection Layer (IPL) offered by TPRD activation in the event tree analysis (see Figure *6*) has shown to be ineffective, resulting in a possible catastrophic tank explosion outcome frequency of nonnegligible risk level. To maintain the risk under its acceptable level for this fire scenario, additional IPLs such as adding excessive flow valve, adding features to ensure TPRD activation in case of a jet fire, and more should be applied.

From this work, risk-based decision-making process has been demonstrated for determining the appropriate fire size levels in the GTR#13 fire test. As shown from this exercise, quantitative risk analysis can become a good tool to allow stakeholders to understand why such test conditions are necessary by recognizing the associated risks during the policy making process.

5 ACKNOWLEDGEMENTS

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