Effect of a heat release rate on reproducibility of Fire test for hydrogen storage cylinders

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Abstract

The paper addresses the reproducibility of the fire test in the United Nations “Global technical regulation on hydrogen and fuel cell vehicles” (GTR#13) and similar fire test protocols in other regulations, codes and standards (RCS). Currently, GTR#13 requires controlling the flame temperature beneath the tank. An original Ulster conjugate heat transfer numerical model was applied to carry out a study demonstrating the dependence of a fire resistance rating (FRR) of a composite hydrogen tank on a fire heat release rate (HRR). No thermally activated pressure relief device was used. The validation experiments conducted afterwards at Karlsruhe Institute of Technology (KIT) plus a former USA fire test have confirmed the Ulster’s conclusion to control not only temperatures, yet the fire HRR. This will improve the GTR#13 fire test reproducibility in different laboratories worldwide. The numerically observed variations of FRR were confirmed by the unique experimental data of the authors’ collaborators: FRR=16-22 min for HRR=79 kW, 7-8 min (HRR=165 kW) – both tests were carried out at KIT with identical 36 litres volume and 700 bar pressure tanks; and 6-7 min (HRR=370 kW), though this test in USA was performed with a larger volume tank of 72.4 litres and 350 bar. The data on pool fire test with significantly higher HRR, i.e. 4100 kW, and tank volume of 100 litres and 700 bar pressure confirmed the “saturation” effect in the dependence of FRR on HRR at HRR above 350kW. The results of the study underpin the suggested amendment to GTR#13 to improve the reproducibility of the fire test and perform tests with onboard storage tanks at HRR>350 kW.

keywords: hydrogen, alternative fuel, onboard storage, fire test, fire resistance rating, heat release rate.

**ABBREVIATIONS**

CFD computational fluid dynamics

CFRP carbon fibre reinforced polymer

CNG compressed natural gas

FRR fire resistance rating

GTR Global Technical Regulation

HGV heavy goods vehicle

HPV hydrogen-powered vehicle

HRR heat release rates

LDV light duty vehicle

MPV multi-purpose vehicle

NWP nominal working pressure

PRD pressure relief device

RCS regulations, codes and standards

SUV sports utility vehicle

TPRD thermally activated pressure relief device

1. introduction

The fire test is mandatory to assess the performance of onboard hydrogen storage tank in fire conditions. This is one of the tests that the hydrogen storage cylinder ought to undergo to be admitted for further exploitation. The authors would like to underline here that the fire test is rather qualification test to compare and assess different tank designs than the guaranty of safety provisions, which is a wider issue. The fire test provides the service-terminating condition and qualifies the system of storage tank with thermally activated pressure relief device (TPRD). However, the test doesn’t answer the question on TPRD failure probability to assess the risk. The TPRD is tested together with the tank to provide blowdown of hydrogen when activated in a fire to avoid tank’s rupture accompanied by devastating blast wave and fireball [1]–[5]. The use of TPRD is currently mandatory requirement for onboard hydrogen storage. There are two tests in the protocol, which reflect the reality, i.e. possibility of localised and engulfing fires. There is a risk of TPRD not to be activated, e.g. due to its failure or in a case of localised fire far from TPRD leaving no possibility for it to be triggered and initiate the gas release. It is worth noting that TPRD technologies are different and such failures may occur if storage is equipped with old or not “properly designed” TPRD [6]. There is no data on onboard hydrogen storage tank rupture in a fire due to currently small number of hydrogen-powered vehicles in operation, but accidents with compressed natural gas (CNG) storage rupture when PRD or TPRD did not work, are widely available, e.g. [7]–[12].

The GTR#13 [6] was the first regulation to introduce the localised fire test. It requires the storage system to be filled with hydrogen at 100% of nominal working pressure (NWP) and then subjected to a fire. No rupture shall occur and the TPRD should release the hydrogen in a controlled way [6]. The temperatures required in GTR#13 “Fire test” section with localised and engulfing parts to be controlled within a specified range 800°C-1100°C. The “Engulfing fire test” section in turn, postulates the need to control the minimum flame temperature only (590°C); this engulfing testing mode falls under the scope of current study.

There have been several studies related to performance of compressed cylinders in a fire [13]–[18] including those showing actual fire resistance rating (time to rupture) of typical values ranging approximately from 6 to 16 min [1], [2], [19]–[23]. Two fire tests with a stand-alone type IV hydrogen tank and an under-vehicle type III tank, both of pressure about 350 bar and without TPRD, were carried out in USA. The propane burner was used and in both tests it was shielded against wind. In the stand-alone tank test the burner was shielded by a metallic pan, and in the under-vehicle tank test it was shielded by mounting the tank between rear wheels replacing a gasoline tank. The decrease of heat release rates (HRR) in these tests from 370 kW to 265 kW, resulted in the increase of fire resistance rate (FRR) from 6 min 27 s to 12 min 18 s respectively [1], [2], [21]. These two tanks differed to some extent in initial pressure (343 / 345 bar), volume (72.4 / 88 L), wind shielding, and probably winding pattern. However, in the authors’ opinion, the increase of FRR in the under-vehicle test is mainly due to the lower HRR and thus lower heat flux to the tank. Indeed, the lower is heat flux the longer is time needed to decompose resin in the outer layers of carbon fibre reinforced polymer (CFRP). Thus, the time to rupture, i.e. time for the resin decomposition front to reach the increasing with internal pressure load-bearing non-decomposed part of the wall, increases.

There are two different suggestions what should be introduced into GTR#13 fire test protocol to improve its reproducibility: HRR or heat flux. These are two related parameters [22]. However, the authors prefer to introduce HRR as it is a constant during the test parameter, which can be easily controlled in any testing laboratory by an existing fuel flow meter. Contrary to HRR, the heat flux into the tank changes in time even if the HRR in the test is constant. This is due to the change of the tank surface temperature in time. Plus, the cost of heat flux meters increases the destructive fire test cost significantly.

In vehicle fires, HRR can change from about 2 MW for a passenger car to 150 MW for heavy goods vehicles and even beyond. Okamoto et al. [24] described car fires lasting for as long as 2 h with a peak HRR as high as 4 MW. Tohir and Spearpoint [25] described the vehicle fires from mini to heavy passenger cars, sports utility vehicles (SUV), multi-purpose vehicles (MPV) etc., as long as 1 hr 40 min, and achieved range of HRRs up to nearly 8.85 MW [25]. In experiments by Mangs and Keski-Rahkonen [26] the peak HRR in a car fire reached about 1.9 MW. The modern car fire experiments [27] demonstrated the peak HRR of 3.8-16 MW. The recent research indicated the HRRs in heavy goods vehicle (HGV) fires reached 100-200 MW [28]–[30] as well as the latter higher value was also mentioned in [31] and [32]. Tarada [31] provides the data on HRR of the fires with HGVs and vehicles with dangerous goods as high as 120 MW; the petrol tanker fuel spill fires can reach 200-300 MW. Tarada [31] also gave the typical HRRs for vehicle fires: passenger car (5-10 MW); light duty vehicles (LDV) (15 MW); coach, bus (20 MW); lorry, HGV up to 25 tonnes (30-50 MW); HGV, 25-50 tonnes (70-150 MW); petrol tanker (200-300 MW). A vehicle fire is known to be especially dangerous at car parks due to possible fire spreads to adjacent vehicles [33]. In spite of this useful data for understanding vehicle fires, they hardly could be applied to formulate requirements to HRR in a fire source following GTR#13 fire test protocol. Indeed, the most of HRR in a vehicle fire would not “directly” affect the storage tank due to its “protected” location under a vehicle, while the most of heat will be released in a plume above the vehicle. Nevertheless, we need to understand how FRR of a tank depends of HRR in the source of fire test.

The requirements in the GTR#13 regarding fire tests were aimed to understand hydrogen tanks behaviour in a fire. It was observed that tanks of the same design had different values of FRR obtained in different laboratories. Each laboratory followed the standard protocol controlling the fire temperatures in designated locations. It was suggested at Ulster that the required control of temperatures only is not sufficient. This is the reason for unacceptable ambiguity of fire test results with different FRR, i.e. by an order of magnitude. This could have serious safety implications on a tank design and finally, the life safety. It was decided to perform a numerical study to estimate effect of HRR in a fire source on FRR and, if the effect is numerically confirmed, to compare it against experimental data. The paper reports results of numerical study of the effect of HRR in a fire source on FRR of hydrogen storage tanks, and its validation by experimental data. The goal of this study is to underpin the reproducibility of the fire test protocol of GTR#13.

1. numerical study of FRR dependence on HRR
   1. Experimental and numerical details

From four validation tests only three were used for comparison with simulations using our conjugate heat transfer model. All tested hydrogen storage cylinders had no TPRD. The details on cylinders used in simulations are presented in Table 1. HRR in Watts (J/s) was calculated as a fuel mass flow rate (kg/s) multiplied by a heat of combustion measured in Joules per kg of fuel.

The experiments with a premixed methane-air fire source were simulated using the geometry of HYKA-A2 KIT facility [34]. The data on the facility and the fire source were available for simulations prior to experiments [ 24]. The fire source comprised three sintered plates releasing the pre-mixture of defined concentration using methane and air flow rate regulators. The maximum fire HRR in the facility was limited to 165 kW. The pre-test simulations of fire test with the maximum HRR=165 kW were performed following the GTR#13 protocol for engulfing fire test [6]. The temperature requirements of GTR#13 were fulfilled in the simulations, i.e. the temperature in three locations under the tank were above 590°C. A series of simulations was carried out to find out the lowest possible HRR at which GTR#13 temperature requirements for engulfing fire test are fulfilled. The determined lowest HRR for this premixed burner was found to be 79 kW. This HRR was recommended as the lowest for the KIT tests.

The third simulation was performed with non-premixed propane burner with HRR=370 kW, in line with the test [1]. This HRR is more than twice higher than the maximum HRR applied at the KIT facility (165 kW). The propane non-premixed fire source comprised perforated pipework structure.

Table 1. Details on experimental cylinders used in the numerical study.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fire tests | Cylinder details | | | |
| Diameter × length, volume | Service pressure | Safety factor | Composite thicknesses |
| CH4-air, premixed | 32.5×91 cm, 36 L | 700 bar | 2.25 | 27 mm |
| C3H8, non-premixed | 41×84 cm, 72.4 L | 350 bar | 2.25\* | 18.2 mm\*\* |

Note: \* authors’ assumption; \*\* deduced in [36] from [1].

The mean flow rate of methane-air mixture in test with HRR=79 kW and HRR=165 kW were =30 g/s and =60 g/s respectively. The flow rate of propane in the test with HRR=370 kW was =8 g/s.

It is worth noting that the tests with 36 L and 700 bar tank had premixed burner dimensions complying with GTR, i.e. length of approximately 1.65 m and width 0.57 m, which was sufficient to cover the entire circumference of cylinder (of width 0.325 m). The test with 350 bar and 72.4 L tank also had the same length of the burner, as the test was performed following FMVSS 304 procedure [37], but with partially isolated perforation.

The 3D geometry of calculation domains for two types of numerical fire tests is shown in Figure 1.

 

Figure 1. Calculation domains for numerical tests with premixed methane-air burner [22] (left) and non-premixed propane burner (right) [1].

The implemented in the simulations material of the bosses was aluminium with the properties =202.4 W/m/K, =2719 kg/m3, and =871 J/kg/K [38]. The properties of the CFRP cylinder overwrap were =1.32 W/m/K [39], =1360 kg/m3, and =1020 J/kg/K [40]. The properties of the HDPE liner were =0.4-0.2 (@293-423 K) W/m/K, =940 kg/m3, and =2000-2600 (@293-423 K) J/kg/K [41].

The Ulster 3D computational fluid dynamics (CFD) model of conjugate heat transfer was applied to simulate the fire tests. The model solves 3D Favre-averaged equations for mass, momentum and energy conservation and species transport. The standard model [42] was used for modelling turbulence, eddy-dissipation model [43] was used for modelling combustion and discrete ordinates model [44], [45] was used for modelling radiative heat transfer. The time from the fire test start until the failure (rupture) of a compressed tank in a fire, i.e. FRR, was estimated in the simulations using the original tank failure mechanism developed at Ulster [46]. The failure mechanism is as follows. For the regulated in GTR#13 safety factor of 2.25 (ratio of burst pressure to NWP) the load-bearing fraction of a composite wall thickness is 1/2.25=0.44 and the remaining fraction of the wall (0.56) is in fact the thickness that can be degraded in fire conditions without tank rupture. During the fire the load-bearing wall thickness increases from 0.44, where  is the wall thickness without liner, to , where is transient pressure. Thus, the load-bearing wall thickness “propagates” outwardly. Simultaneously, the resin degradation front propagates through the composite wall inwardly. When the degradation front reaches the load-bearing wall thickness, the tank fails. The failure model assumes that when resin in CFRP melts, the load-bearing ability of affected layers is lost. This model assumes that the orientation of fibres is optimised by a manufacturer and thus has no effect of the tank failure compared to the role of resin melting on the load-bearing ability of fibres when fibre plies become “loose” without resin.

* 1. Simulation results: dependence of FRR on HRR

The simulations showed that FRR of a high-pressure hydrogen storage tank strongly depends on fire HRR, even if the GTR#13 requirements on the flame temperatures were fulfilled. Let us consider two tests with 36 litre and 700 bar cylinders and use of the premixed burner. In the test with HRR=79 kW the simulated FRR was 21 min 35 s. In the test with about twice higher HRR=165 kW the simulated FRR changed inversely, i.e. it decreased by about 3 times (7 min 30 s). This confirms the authors’ hypothesis about the decrease of FRR with the increase of HRR regardless the fulfilment of the GTR#13 temperature requirements. The risk of hydrogen-powered vehicles strongly depends on fire resistance of compressed hydrogen storage tank, if TPRD failure rate is quite high or in case of localised fire not affecting TPRD, as it is the main parameter along with fire brigade time arrival [47].

The numerical test with the 72.4 L and 350 bar cylinder and a fire with almost double increase of HRR to 370 kW (propane burner) resulted in FRR=6 min 46 s. This demonstrates that the FRR decline became significantly smaller, i.e. by only 9.7% (compared to 3 times change with HRRs 79 kW and 165 kW). This is an indication of the “saturation” in the decrease of FRR with the increase of HRR up to 350 kW, observed in simulations that yet to be proved experimentally.

Despite of different composite thicknesses and probably winding pattern in two types of considered cylinders the strongest dependence of FRR is on HRR. The authors think that for the same HRR the FRR of 700 bar tank will be somewhat higher compared to 350 bar tank due to larger wall thickness if the same safety factor 2.25 is assumed. However, the effect of maximum storage pressure on FRR seems not as strong as the effect of HRR, especially al low values of HRR.

Thus, we revealed in the numerical study that fire test for a storage tank with lower HRR produces longer FRR of the tank. It could easily be misinterpreted as a “provision” of safety. Consequences from using such protocol could be crucial for life safety and property protection.

The variation of simulated FRR as a function of HRR is shown in Figure 2.



Figure 2. Numerically obtained dependence of FRR of composite hydrogen tanks on a fire HRR.

1. Experimental validation of FRR dependence on HRR
   1. Validation domain

Following the numerical study, two validation test were performed at KIT with premixed methane-air burner, one with HRR=79 kW and another with HRR=165 kW [34].

The available in literature test with non-premixed propane burner performed in 2005 in USA [1] was used for numerical study conclusions validation as well. These tests expand validation domain to different fire source HRRs, types of fuel and types of burner. The arrangements of hydrogen tanks in fire tests for premixed and non-premixed burners are shown in Figure 3.

 

Figure 3. Photographs of hydrogen tank fire test arrangements for premixed [22], [34] and non-premixed [1] burners.

* 1. Experimental observations

The pre-test simulations with HRR=79 kW and HRR=165 kW were used as a basis to formulate a testing programme with thermally unprotected and protected tanks [34]. Only the tests with unprotected tanks are analysed in this study. The tests were performed in full accordance with GTR#13 requirements to engulfing fire test. Table 2 compares simulated FRR of Type IV tanks with FRR observed in KIT tests with 36 litre and 700 bar cylinders.

Table 2. Experimental and numerical FRR in premixed burner tests with different HRR.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fire source | HRR | FRR | | Difference\* |
| Test | 3D model |
| CH4-air, premixed | 79 kW [34] | 15 min 56 s | 21 min 35 s | +34.8% |
| 165 kW [34] | 8 min 3 s | 7 min 30 s | -7% |

Note: \* - over-prediction (+) and under-prediction (-) of test data by the CFD model.

The discrepancy of results between 3D model and experiments (+35% in one case and -7% in another) doesn’t negate the revealed correlation between HRR and FRR (see Figure 4 below). The correlation includes results for different heat​ ​release​ ​rates​ and​ ​cylinders. The overprediction of the test data by 35% in simulations can be attributed to several factors that are under continuous investigation of the authors. These could include the effect of selected from literature physical properties of materials, boundary conditions, e.g. temperature of heated sintered plates, turbulence and combustion sub-models, etc.

Table 2 shows that the increase of HRR in experiments from 79 kW to 165 kW results in double decrease of FRR from about 16 min to about 8 min. Such a significant variation indicates a clear problem with reproducibility of the GTR#13 fire test protocol.

Let us further validate the conclusion of numerical study in the saturation of FRR as a function of HRR in a fire source by the experimental data. For this purpose, the experiment with higher HRR=4100 kW in n-C7H16 pool fire and storage cylinder of 100 litre volume and pressure 700 bar was added to the correlation between FRR and HRR (see data in Table 3). This is in addition to the test with HRR=370 kW in non-premixed burner which was simulated in previous section. The summary of two experiments with higher HRRs is shown in Table 3 along with results of the simulation of the test with non-premixed propane burner.

Table 3. Experimental and numerical FRR in non-premixed burner and pool fire tests.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fire source | HRR | FRR | | Difference\* |
| Test | 3D model |
| Non-premixed C3H8 fire | 370 kW [1] | 6 min 27 s | 6 min 46 s | +4.9% |
| n-C7H16 pool fire | 4100 kW [20] | 5 min 53 s | N/A | N/A |

Note: \* - +4.9% is over-prediction of tested FRR by the CFD model.

Table 3 shows that 3D CFD model of conjugate heat transfer reproduces FRR measured in the test with propane burner [1] within 4.9%. Experimental FRR=6 min 27 s in the fire test with HRR=370 kW is by 19% shorter than FRR=8 min 3 s measured in the KIT test with HRR=165 kW, even though HRR is more than 2 times higher. Moreover, Table 3 demonstrates that in the two tests with HRR difference of 11 times, i.e. HRR=370 kW and HRR=4100 kW, the FRR reduces by only 9.6%. The use of pool fire as a fire source expands the validation domain of this study further and underpins the derive in this study correlation of decreasing FRR with increasing HRR, and the “saturation” of FRR dependence on HRR at HRR above 350 kW.

The analysis of heat flux to the surface in the simulation demonstrates that the heat flux changes over the tank surface. This is due to varying in space convective and radiative fractions of the total heat flux. Plus, the convective heat flux changes over time in a location on the surface due to changing in time tank surface temperature. Significant non-uniformity of the heat flux over the surface would hamper its integration without CFD model. However, exactly the integral heat flux to the stored in the tank hydrogen is needed to assess the increase of pressure and thus the load-bearing thickness of the tank wall to apply the failure criterion. In the authors opinion, this makes difficult to consider the heat flux as an easy control parameter to improve the reproducibility of the GTR#13 fire test. Constant HRR per unit area of a burner and thus a tank, which is above the critical value, seems easier to implement method and easy to control parameter compared to changing heat flux.

1. THE CORRELATION BETWEEN FRR AND HRR

The numerical and experimental results are summarised in Figure 4. The reduction of HRR from 79 kW through 165 kW to 370 kW and ultimately to 4100 kW resulted in the monotonic decrease of FRR from 16-21 min to 6-8 min and in the monotonic decrease of FRR derivative. The simulated and experimental FRR show the same trend despite the difference between them for a given HRR. There is “saturation” or “plateau” in the dependence of FRR on HRR for HRR above about 350 kW. The increase of HRR beyond this critical value will have no effect on the determined value of FRR. This requirement to HRR in the GTR#13 fire test protocol would provide the reproducibility of the test in different laboratories around the globe.



Figure 4. The correlation between FRR and HRR for different burners and tanks: 700 bar - 36 litre (premixed methane-air burner), 350 bar - 72.4 litre (non-premixed propane burner), 700 bar - 100 litre (n-C7H16 pool fire) [1], [2], [20], [34].

The level of FRR “saturation” depends on several tank design parameters, including safety factor, which is currently regulated as 2.25, storage pressure, etc. However, the change in the saturation level would not terminate the existence of the “saturation” effect for forthcoming designs of onboard storage tanks. The change of “saturation” level can be studied only when more experimental data are available or validated 3D CFD models are used to derive the value of the level for new tank design. The existence of the correlation between FRR and HRR for different tank design and fire sources is the strength of the study based not on invented reasoning but on the solid experimental data obtained in different testing laboratory.

1. Conclusion

The performed numerical study and follow-up validation tests unveiled the significant dependence of FRR of compressed hydrogen onboard storage tank on HRR in a fire test complying with GTR#13. This dependence is the reason of unacceptably high difference in FRR results obtained in different laboratories due to required control of the temperatures only. The significance of this study is in the provision of evidence that not only the temperature, but also the heat release rate in a fire source are the key parameters that define the reproducibility of GTR#13 fire test protocol for onboard hydrogen storage.

The revealed “saturation” effect in the dependence of FRR on HRR defines the originality of the study, which results in an essential improvement of the GTR#13 fire test reproducibility through introducing the requirement to perform tests with HRR in the fire source at least 350 kW (for the regulated burner length of 1.65 m and burner width close to an onboard tank width).

The rigour of this study is based on the consistency of the derived correlation of FRR on HRR and the proved existence of the “saturation” effect by both, the numerical experiments and the physical tests. The validation domain and the observed phenomena spread over various fire sources, fuels, HRRs and tank designs: premixed methane-air burner, non-premixed propane burner, heptane pool fire, composite hydrogen storage tanks of 36 litre to 100 litre volume and initial pressure 350 bar and 700 bar, HRR in a fire source from 79 kW to 4100 kW. The HRR, which is constant during the fire, and related to HRR but changing in time heat flux to a vessel are the major interrelated parameters affecting the FRR. However, HRR is recommended here as the most practical parameter to provide the GTR#13 fire test reproducibility.

The suggested amendments to the GTR#13 fire test protocol will have an impact on composite tank design and provisions of safety for hydrogen-powered vehicles. The study eliminates the basis for improper fire testing of onboard storage that could have serious safety implications for human life and property protection.

1. Acknowledgements

Funding: This work was supported by EPSRC (UK) through: Hydrogen and Fuel Cells Supergen Hub project and its continuation [EP/J016454/1 and EP/P024807/1]; EPSRC Supergen Challenge project “Integrated safety strategies for onboard hydrogen storage” [EP/K021109/1]; Fuel Cell and Hydrogen 2 Joint Undertaking under grant agreement No.736648 (NET-Tools project) respectively. This Joint Undertaking received support from the European Union’s Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY.

Thanks to Dr Farid Arya (Ulster University, UK) for the measurement of carbon fibre reinforced polymer (CFRP) material properties, and Mr Per Heggem from Hexagon Composites (Norway) for the valuable contribution to the EPSRC Supergen Challenge project. Special thanks to colleagues at Karlsruhe Institute of Technology (Germany), including Dr Andreas Friedrich, Dr Olaf Jedicke, Prof Thomas Jordan and others for experimental fire tests.

REFERENCES

­[1] N. Weyandt, “Analysis of Induced Catastrophic Failure Of A 5000 psig Type IV Hydrogen Cylinder,” Southwest Research Institute report for the Motor Vehicle Fire Research Institute, 01.06939.01.001, 2005.

[2] N. Weyandt, “Vehicle bonfire to induce catastrophic failure of a 5000-psig hydrogen cylinder installed on a typical SUV,” Southwest Research Institute report for the Motor Vehicle Fire Research Institute, 2006.

[3] V. Shentsov, W. Kim, D. Makarov, and V. Molkov, “Numerical simulations of experimental fireball and blast wave from a high-pressure tank rupture in a fire,” presented at the Proc. of the Eighth International Seminar on Fire & Explosion Hazards (ISFEH8), Hefei, China, 2016.

[4] V. Shentsov, D. M. C. Cirrone, D. Makarov, and V. Molkov, “Simulation of fireball and blast wave from a hydrogen tank rupture in a fire,” presented at the The International Symposium on Nonequilibrium Processes, Plasma, Combustion and Atmospheric Phenomena, Sochi, Russia, 2016, pp. 435–442.

[5] W. Kim, V. Shentsov, D. Makarov, and V. Molkov, “High pressure hydrogen tank rupture: blast wave and fireball,” in *6th International Conference on Hydrogen Safety*, Yokohama, Japan, 2015, vol. 243.

[6] United Nations Economic Commission for Europe, “Global technical regulation on hydrogen and fuel cell vehicles. Addendum 13: Global technical regulation No. 13. Global Registry.,” UNECE, Global Registry, 2013.

[7] Hawkes, “US – CNG Tank Explodes on Garbage Truck,” *Hawkesfire*, 12-Feb-2016. [Online]. Available: http://www.hawkesfire.co.uk/36706. [Accessed: 12-Jan-2016].

[8] YouTube, “Car explosion in gas station,” 2013. [Online]. Available: https://www.youtube.com/watch?v=wPHfiwPSDPM. [Accessed: 01-Dec-2016].

[9] YouTube/Disaster Channel, “St. Louis Gas Cylinders Disaster,” *YouTube*. [Online]. Available: https://www.youtube.com/watch?v=EPuTQYHnfoc. [Accessed: 01-Dec-2016].

[10] YouTube, “Must See - Power of Liquid Natural Gas Explosion Accident - Incredible Footage - China,” *YouTube*. [Online]. Available: https://www.youtube.com/watch?v=UI0QWm4TxZU. [Accessed: 01-Dec-2016].

[11] A. Shaukat, “Transport safety: CNG cylinders killed more people than US drones: Report,” *The Express Tribune*, 2012. [Online]. Available: http://tribune.com.pk/story/362282/transport-safety-cng-cylinders-killed-more-people-than-us-drones-report/. [Accessed: 01-Dec-2016].

[12] D. Lowell, “Natural Gas Systems: Suggested Changes to Truck and Motorcoach Regulations and Inspection Procedures,” U.S. Department of Transportation Federal Motor Carrier Safety Administration Office of Analysis, Research, and Technology, Final Report FMCSA-RRT-13-044, 2013.

[13] M. Azuma *et al.*, “Safety design of compressed hydrogen trailers with composite cylinders,” *International Journal of Hydrogen Energy*, vol. 39, no. 35, pp. 20420–20425, 2014.

[14] J. Hu, J. Chen, S. Sundararaman, K. Chandrashekhara, and W. Chernikoff, “Analysis of composite hydrogen storage cylinders subjected to localized flame impingements,” *International Journal of Hydrogen Energy*, vol. 33, pp. 2738–2746, 2008.

[15] J. Zheng *et al.*, “Experimental and numerical studies on the bonfire test of high-pressure hydrogen storage vessels,” *Int. J. Hydrog. Energy*, vol. 35, no. 15, pp. 8191–8198, 2010.

[16] J. Zheng *et al.*, “Heat transfer analysis of high-pressure hydrogen storage tanks subjected to localized fire,” *Int. J. Hydrog. Energy*, vol. 37, no. 17, pp. 13125–13131, 2012.

[17] J. R. Travis and D. Piccioni Koch, “GASFLOW simulations of a Bonfire test,” *International Journal of Hydrogen Energy*, vol. 39, no. 24, pp. 13041–13047, 2014.

[18] J. Zheng *et al.*, “Experimental and numerical investigation of localized fire test for high-pressure hydrogen storage tanks,” *Int. J. Hydrog. Energy*, vol. 38, no. 25, pp. 10963–10970, 21 2013.

[19] S. Ruban *et al.*, “Fire risk on high-pressure full composite cylinders for automotive applications,” *Int. J. Hydrog. Energy*, vol. 37, no. 22, pp. 17630–17638, 2012.

[20] L. Bustamante Valencia, P. Blanc-Vannet, L. Heudier, and D. Jamois, “Thermal history resulting in the failure of lightweight fully-wrapped composite pressure vessel for hydrogen in a fire experimental facility,” *Fire Technology*, no. 52, pp. 421–442, 2016.

[21] R. Zalosh, “Blast waves and fireballs generated by hydrogen fuel tank rupture during fire exposure,” in *5th International Seminar on Fire and Explosion Hazards*, Edinburgh, UK, 2007.

[22] Y. Kim, D. Makarov, S. Kashkarov, P. Joseph, and V. Molkov, “Modelling heat transfer in an intumescent paint and its effect on fire resistance of on-board hydrogen storage,” *International Journal of Hydrogen Energy*, vol. 42, no. 11, pp. 7297–7303, 2016.

[23] Z. Saldi and J. Wen, “Modeling thermal response of polymer composite hydrogen cylinders subjected to external fires,” *International Journal of Hydrogen Energy*, vol. 42, no. 11, pp. 7513–7520, 2017.

[24] K. Okamoto, T. Otake, H. Miyamoto, M. Honma, and N. Watanabe, “Burning behavior of minivan passenger cars,” vol. 62, pp. 272–280, 2013.

[25] M. Tohir and M. Spearpoint, “Distribution analysis of the fire severity characteristics of single passenger road vehicles using heat release rate data,” vol. 2:5, 2013.

[26] J. Mangs and O. Keski-Rahkonen, “Characterization of the Fire Behaviour of a Burning Passenger Car. Part I: Car Fire Experiments,” vol. 23, pp. 17–35, 1994.

[27] Department for Communities and Local Government, “Fire spread in car parks, BD2552.” BRE, 2010.

[28] UPTUN 251, “UPTUN 251: Engineering Guidance for Water Based Fire Fighting for the Protection of Tunnels and Subsurface Facilities,” EU Research Project, 2006.

[29] SOLIT, “Safety of Life in Tunnels – Water Mist Fire Suppression Systems for Road Tunnels,” Final Report, 2007.

[30] J. Jönsson and F. Herrera, “HGV traffic – Consequences in case of a tunnel fire,” presented at the Fourth International Symposium on Tunnel Safety and Security, Frankfurt am Main, Germany, 2010, pp. 125–134.

[31] F. Tarada, “Fires in tunnels – can the risks be designed out?,” *Eurotransport Magazine*, vol. 9, no. 4, pp. 46–49, 2011.

[32] T. McCory, D. Sprakel, and E. Christensen, “Workpackage 2 Fire development and mitigation measures. D251. Engineering Guidance for Water Based Fire Fighting Systems for the Protection of Tunnels and Sub Surface Facilities,” Official deliverable, Sep. 2008.

[33] Y. Tamura, M. Takabayashi, and M. Takeuchi, “The spread of fire from adjoining vehicles to a hydrogen fuel cell vehicle,” *International Journal of Hydrogen Energy*, vol. 39, no. 11, pp. 6169–6175, 2014.

[34] D. Makarov, Y. Kim, S. Kashkarov, and V. Molkov, “Thermal protection and fire resistance of high-pressure hydrogen storage,” presented at the Eighth International Seminar on Fire & Explosion Hazards (ISFEH8), Hefei, China, 2016.

[35] A. Friedrich, “Private communication,” 2015.

[36] S. Kashkarov, “Fire resistance of on-board high pressure storage tanks for hydrogen-powered vehicles,” Ph.D. Thesis, Ulster University, 2016.

[37] U.S. Department of Transportation, National Highway Traffic Safety Administration, “Compressed natural gas (CNG) fuel containers integrity,” Laboratory Test Procedure for FMVSS 304 TP-304-03, 2003.

[38] SAS IP, Inc., *ANSYS Fluent*. 2016.

[39] F. Arya, “Private communication,” 2016.

[40] J. P. Hidalgo, P. Pironi, R. M. Hadden, and S. Welsh, “Effect of thickness on the ignition behaviour of carbon fibre composite materials used in high pressure vessels,” presented at the Proc. of the Eighth International Seminar on Fire & Explosion Hazards (ISFEH8), Hefei, China, 2016, vol. (SUBMITTED).

[41] J. Meyer, “Optimisation of onboard hydrogen storage fire resistance,” Ulster University, UK, 2012.

[42] B. E. Launder and D. B. Spalding, *Lectures in Mathematical Models of Turbulence*. London, England: Academic Press, 1972.

[43] B. F. Magnussen and B. H. Hjertager, “On mathematical models of turbulent combustion with special emphasis on soot formation and combustion,” in *16th Symp. (Int’l.) on Combustion*, The Combustion Institute, 1976.

[44] E. H. Chui and G. D. Raithby, “Computation of radiant heat transfer on a nonorthogonal mesh using the finite-volume method,” *Numerical Heat Transfer*, vol. 23, no. Part B, pp. 269–288, 1993.

[45] G. D. Raithby and E. H. Chui, “A Finite-Volume Method for Predicting a Radiant Heat Transfer in Enclosures with Participating Media,” *Journal of Heat Transfer*, vol. 112, pp. 415–423, 1990.

[46] S. Kashkarov, D. Makarov, and V. Molkov, “Model of 3D conjugate heat transfer and mechanism of compressed gas storage failure in a fire,” presented at the ICHS 2017, Hamburg, Germany, 2017.

[47] M. Dadashzadeh, S. Kashkarov, D. Makarov, and V. Molkov, “Socio-economic analysis and quantitative risk assessment methodology for safety design of onboard storage systems,” presented at the International Conference on Hydrogen Safety (ICHS) 2017, (SUBMITTED), 2017.