UN GTR#13 IWG SGS meeting

6-7 November 2019, Stuttgart

GTR#13 fire test: research results and text amendments

V Molkov, D Makarov, S Kashkarov

Hydrogen Safety Engineering and Research Centre (HySAFER)
ulster.ac.uk

Outline

- Why GTR#13 “fire test” should **drop maximum temperature requirements** (it is absent in “engulfing fire test”!)?
- What are **real HRR/A** in automobile (gasoline) and other commodities fires?
- Fire resistance rating, **FRR**, as function of specific heat release rate, **HRR/A**
- Reaction of original tank on fires with different HRR/A (no TPRD).
- Re-establishment of engulfing fire test without TPRD (first responders).
- Two simultaneous **thermal requirements** to a burner design:
    - Minimum temperature in defined locations, plus
    - Specific heat release rate (HRR/A) from a burner of area A.
- *Text amendment No.1: “Fire test” and “Engulfing fire test”*
- Effect of wind on a pipe burner prototype (diffusion flame as in real life).
- Do we need localised portion of “fire test” as it stands now?
- Explosion-free in a fire tanks - breakthrough in onboard storage.
- Reaction of explosion-free tank on fires with different HRR/A.
- *Text amendment No.2: TPRD and “other proven safety means”*
- Conclusions

Definitions and abbreviations

Heat release rate (HRR)	- Heat release rate in a fire [kW] or [MW] (can easily be measured by propane flow rate to a burner).
Specific heat release rate (HRR/A)	- Heat release rate in a fire, HRR, divided by area of fire source, A, [kW/m^2] or [MW/m^2]
Heat flux, $\dot{q}''$	- Heat flux on tank surface [kW/m^2] (not the same as HRR/A even the dimension is the same!).
Fire resistance rating (FRR), required by firemen, e.g. EU project HyResponse (cannot be ignored by UN ECE)	- Time from burner ignition until container's rupture in a fire (without or failed TPRD or long localised fire far from TPRD, e.g. smouldering fire)

GTR#13 text amendments marking

The GTR#13 current text is corrected as follows:

- **New added** text – underlined green font
- **Removed current** text – ~~crossed out red font~~

Ulster University

Why GTR#13 “fire test” should drop maximum temperature requirements (it is absent in “engulfing fire test”!)?

Maximum temperature limit in GTR#13:

Localised part: <900°C. Engulfing part: <1100°C

- Real fire temperatures can be higher than GTR#13 requirements for maximum temperature (see Table).
- In reference tests used for GTR#13: (a) the burner design could reduce T by air entrainment; (b) TC was large averaging high flame T and lower T of diluted by air products.
- **Suggestion**: remove the requirement for maximum temperature from GTR#13 “fire test”, i.e. test with localised and engulfing portions (similar to “engulfing fire test” without T limitation).

Fuel	Flame Temperature
acetylene	3,100 °C (oxygen), 2,400 °C (air)
blowtorch	1,300 °C (2,400 °F, air)
Bunsen burner	1,300-1,600 °C (2,400-2,900 °F, air)
butane	1,970 °C (air)
candle	1,000 °C (1,800 °F, air)
carbon monoxide	2,121 °C (air)
cigarette	400-700 °C (750-1,300 °F, air)
ethane	1,960 °C (air)
hydrogen	2,660 °C (oxygen), 2,045 °C (air)
	Methane: 1957°C (in air)
methane	2,810 °C (oxygen), 1,957 °C (air)
natural gas	2,770 °C (oxygen)
	Propane: 1980°C (in air)
propane	2,820 °C (oxygen), 1,980 °C (air)
propane butane mix	1,970 °C (air)
propylene	2870 °C (oxygen)

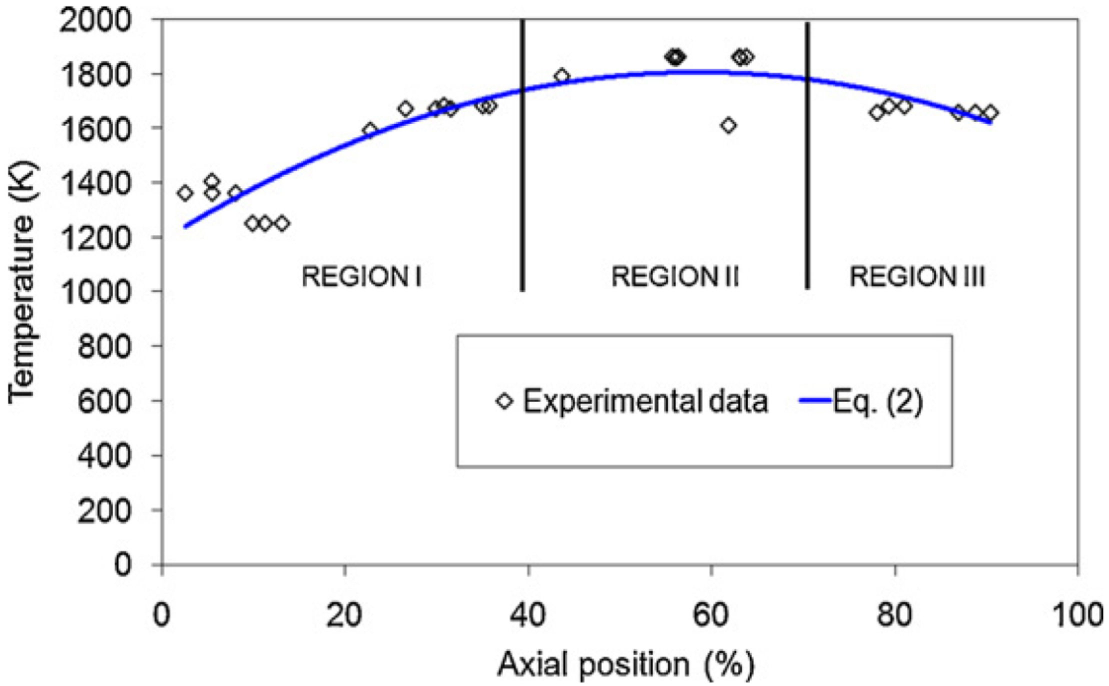
Temperature of propane flame
Agreement of simulated and published data

- For the fire HRR/A=1 MW/m^2 (see further) simulated temperature is 1500-1600^{o}C. It is close (between) the temperature of propane diffusion (not premixed!) flame in air reported elsewhere:
  - **From 1530°C** [M. Gómez-Mares, M. M., and J. Casal, "Axial temperature distribution in vertical jet fires," *Journal of Hazardous Materials*, vol. 172, pp. 54–60, 2009.]
  - **…to 1980^{o}C** [A. M. Helmenstine, "What Is the Typical Flame Temperature for Different Fuels?," *ThoughtCo*. Available: https://www.thoughtco.com/flame-temperatures-table-607307].
- Thus, the requirement to control maximum temperature (900-1100^{o}C) at GTR#13 fire test protocol must be relaxed as it is **prohibitive for the use of fire source representing real automobile fires** (HRR/A≥1 MW/m^2) and don't comply with published data for flame temperature of different fuels.

Example: propane flame

Distribution of temperature along flame axis

- Measured axial temperature as a function of distance (100% - flame tip).
- Reference: Journal of Hazardous Materials 172 (2009) 54-60.

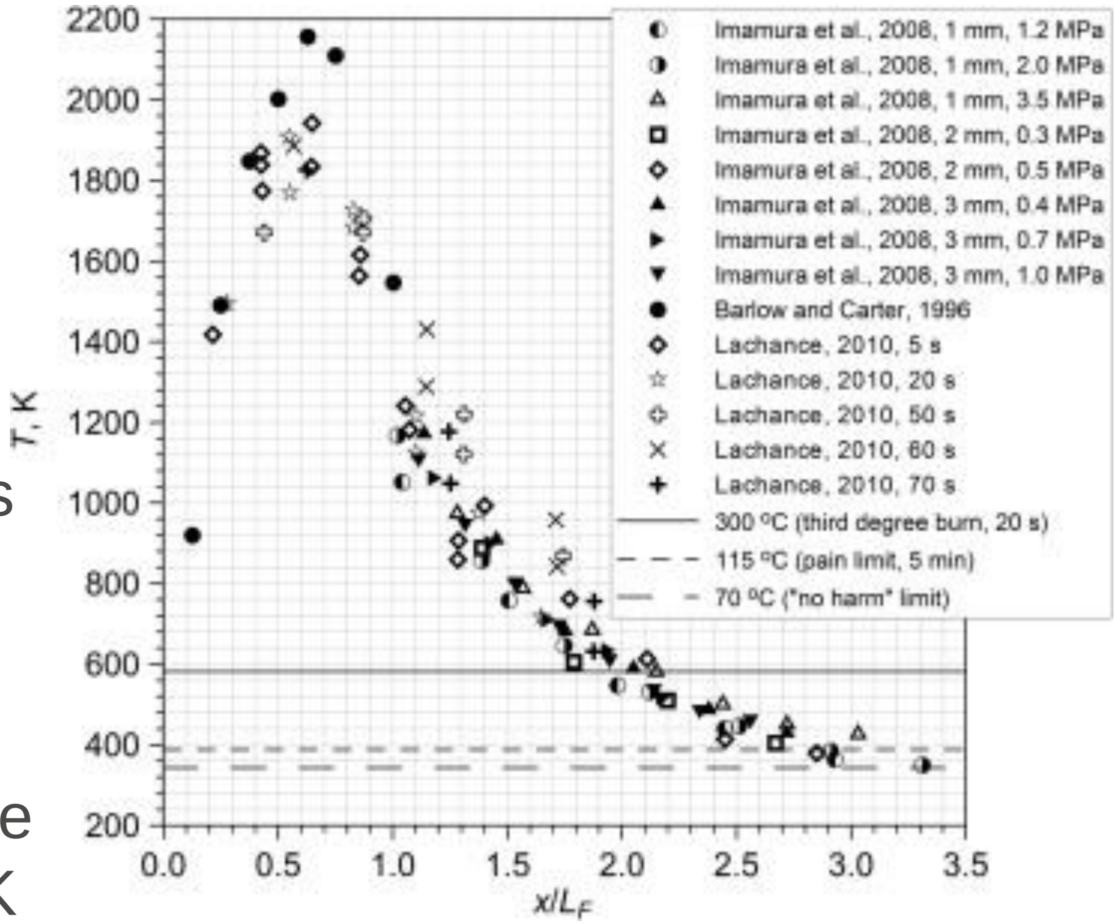


- The maximum centreline temperature reaches about 1900 K (1600 C) at region 60-70% of flame length. This is significantly higher than 900-1100 C in current GTR#13.

Example: hydrogen jet flame

Distribution of temperature along flame axis

- Measured axial temperature as a function of distance expressed in flame calibres.
- Temperature depends where TC is located and on TC size.
- The maximum centreline temperature reaches about 2400 K (2100 C) at the same region 60-70% of flame length. This is even more higher than 900-1100 C in current GTR#13.



Thermal requirements to fire test

Concluding remarks

- **Only temperature control** (without heat flux or correlated with the heat flux specific HRR/A) **is insufficient** to have test reproducibility in different labs. It must be complemented by control of specific heat release rate in a fire source (burner) **HRR/A** to test different **thermal conditions** in variety of real fires.
- **Maximum temperature requirements** in GTR#13 "fire test" (with localised and engulfing parts) **should be relaxed** as:
  - They are below published data on flame temperature of different fuels and thus **enforcing** labs **to use weak fire** source (low HRR/A).
  - Measured temperature depends on thermocouple (TC) size, real flame temperature (could be measured by thin TC) is constant.
  - Cancelling maximum temperature requirement will simplify the fire test protocol and its implementation in different labs.
  - **Yet the issue of fire source with lower thermal load (HRR/A), e.g. at the initial stage of fire must be investigated further.**

What are real HRR/A in automobile (gasoline) and other commodities fires?

HRR/A in automobile (gasoline) fires

Gasoline fires: published data (1976-2017)

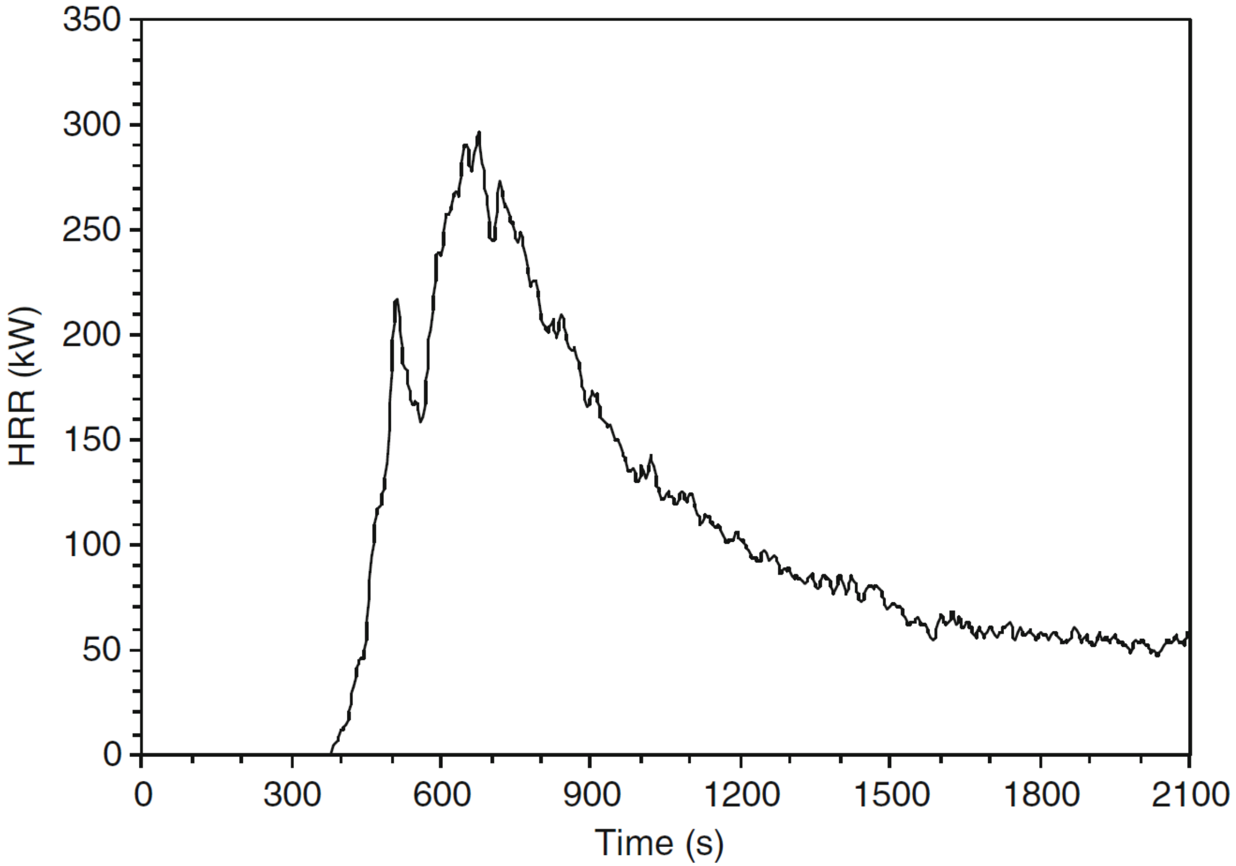
- The automobile fire research over almost half a century demonstrates that HRR/A in **gasoline fires** is **1-2 MW/m²**:
  - On road: **HRR/A=2 MW/m²** *(A. Heselden, Proceedings of the 2nd International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Cambridge, UK, 23-25 March 1976, pp. J1-1–J1-18).*
  - On road: **HRR/A=2 MW/m²** *(S. Liew, D. Deaves, Proceedings of the First International Conference on Safety in Road and Rail Tunnels, Basel, Switzerland, 23rd–25th November 1992, pp. 227–237).*
  - Pool fire equation by Babrauskas for gasoline spill: **HRR/A=2.2 MW/m²** *(V. Babrauskas, Heat release rates, The SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, USA, 2002, 3-1–3-37).*
  - On concrete: **HRR/A=0.8-1.0 MW/m²** *(H. Ingason, Y.Z. Li, Fire Safety Journal, 91, 2017, 399–406).*
- GTR#20: Korean LPG burner with HRR/A=**0.8 MW/m²**.

Conclusion: to be realistic the GTR#13 fire tests must be carried out at HRR/A>1 MW/m² (including localised part!!!)

Realistic HRR/A in real product fires

Example: air conditioner

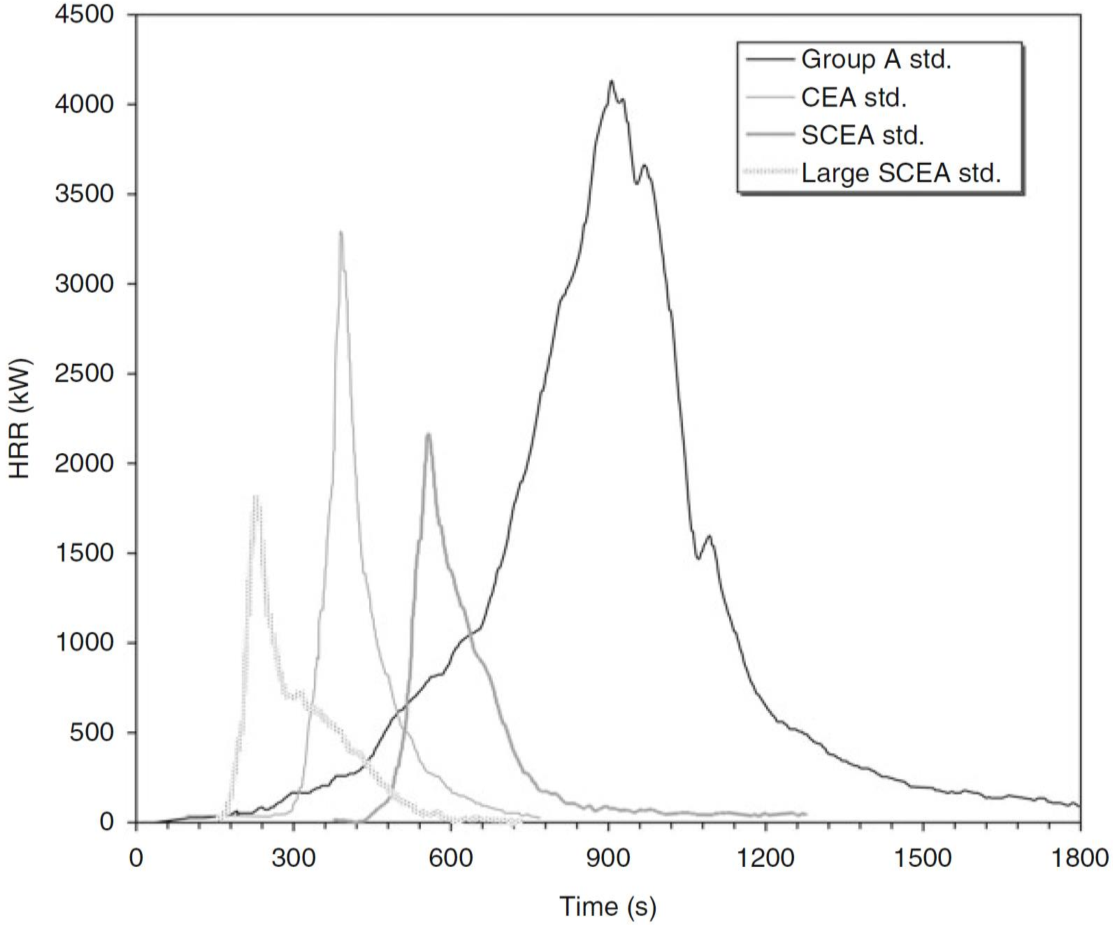
- HRR of a small European in-room air conditioner with a plastic housing (LxWxH=466x406x855 mm). A=0.19 m^2. Only 9 kg of fire load.
- Thus for 10 min HRR/A will be in the range from 1 to 1.5 MW/m^2.



Realistic HRR/A in real product fires

Example: single pallet of various commodities

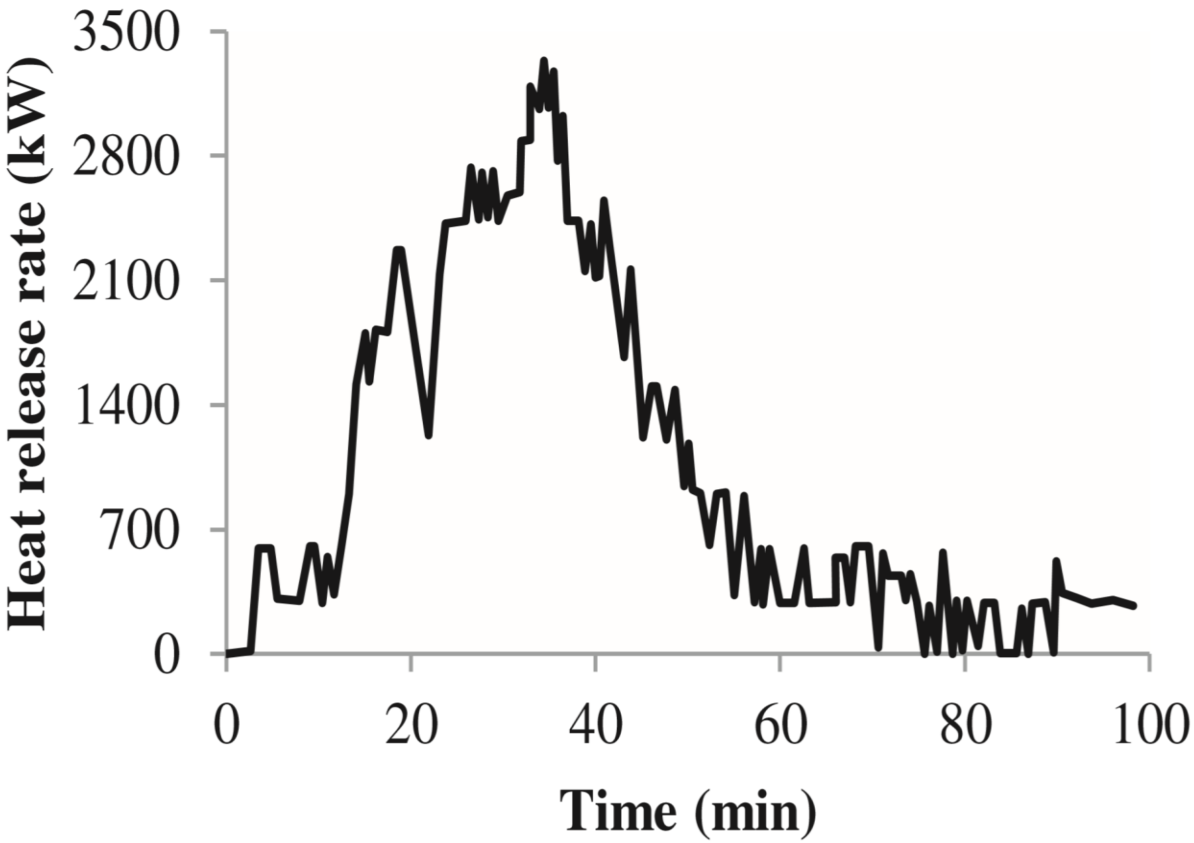
- Different commodities on a pallet of area about 1 m^2.
- Peak HRR/A is in the range 1.8-4.2 MW/m^2.
- HRR/A≥1 MW/m^2 could be as long as 20 minutes.



Realistic HRR/A in passenger car fire

Example: test with fire duration 1 h 40 min

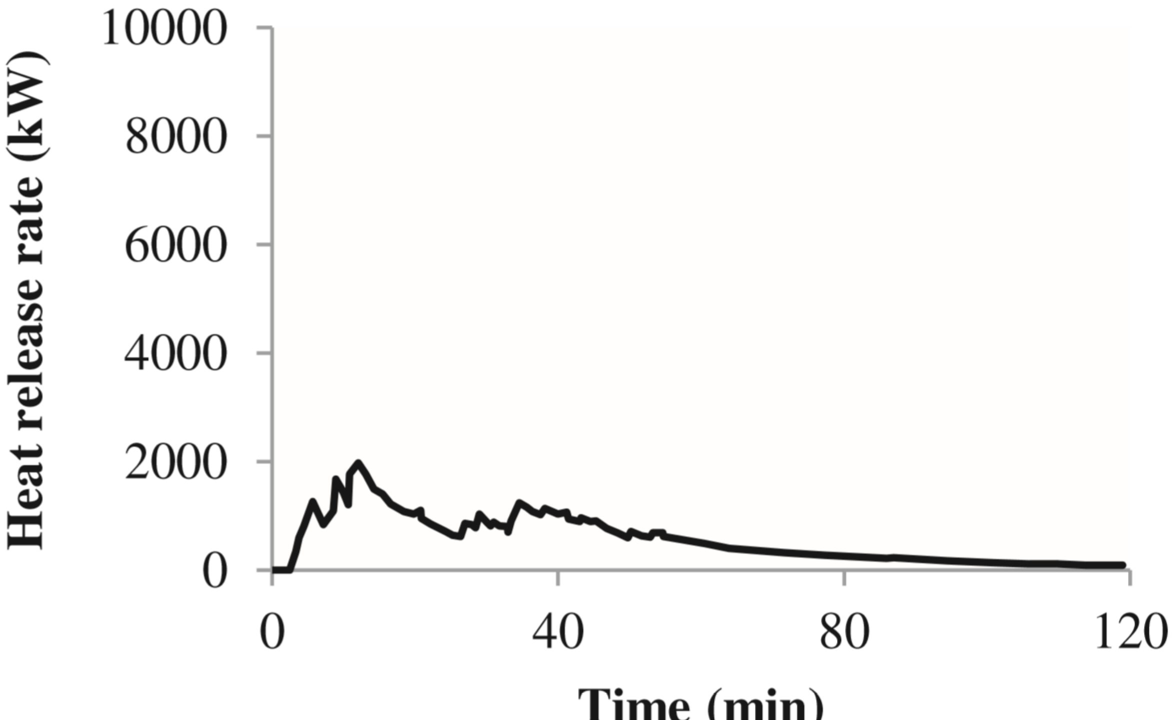
- Car with curb weight 1920 kg. Driver and passenger windows rolled down 10 cm. Ignition source: cloth soaked with methanol. Ignition location: driver's seat.
- Fire duration 1 h and 40 min.
- HRR/A for 4.7x1.7 m car ($A=8\ m^2$) is below $0.43\ MW/m^2$ (scenario with parking of one car over another)



Realistic HRR/A in passenger car fire

Example: test with longest fire duration 2 h

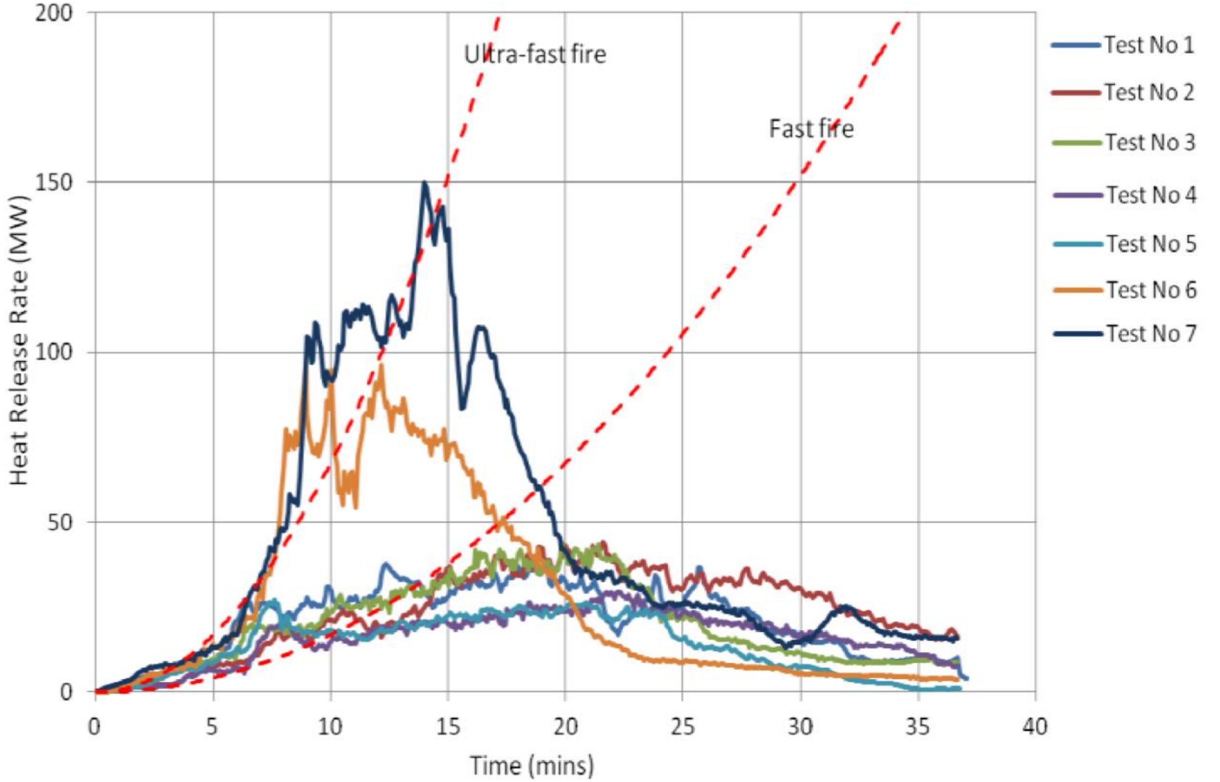
- Datsun 180B Sedan. Curb weight 1102 kg. All doors closed, left front window completely open, other windows rolled down 5 cm.
- Longest fire test duration 2 h. Total mass loss in fire 176 kg.
- HRR/A for 4.7x1.7 m car (A=8 m^2) is below 0.25 MW/m^2.



Realistic HRR/A in HGV fire

Example: HGV fire without/with suppression

- Test 7: free burning; Tests 1-5: deluge system operate at 4 minutes; Test 6: deluge system operate at 8 minutes.
- UK individual truck size 12x2.55 m (A=30.6 m^2).
- Thus, HRR/A≥1 MW/m^2 (up to 5 MW/m^2) will exist longer than 16 min (with no suppression).
- Before 7 min and after 23 min HRR/A≤1 MW/m^2.



Concluding remark

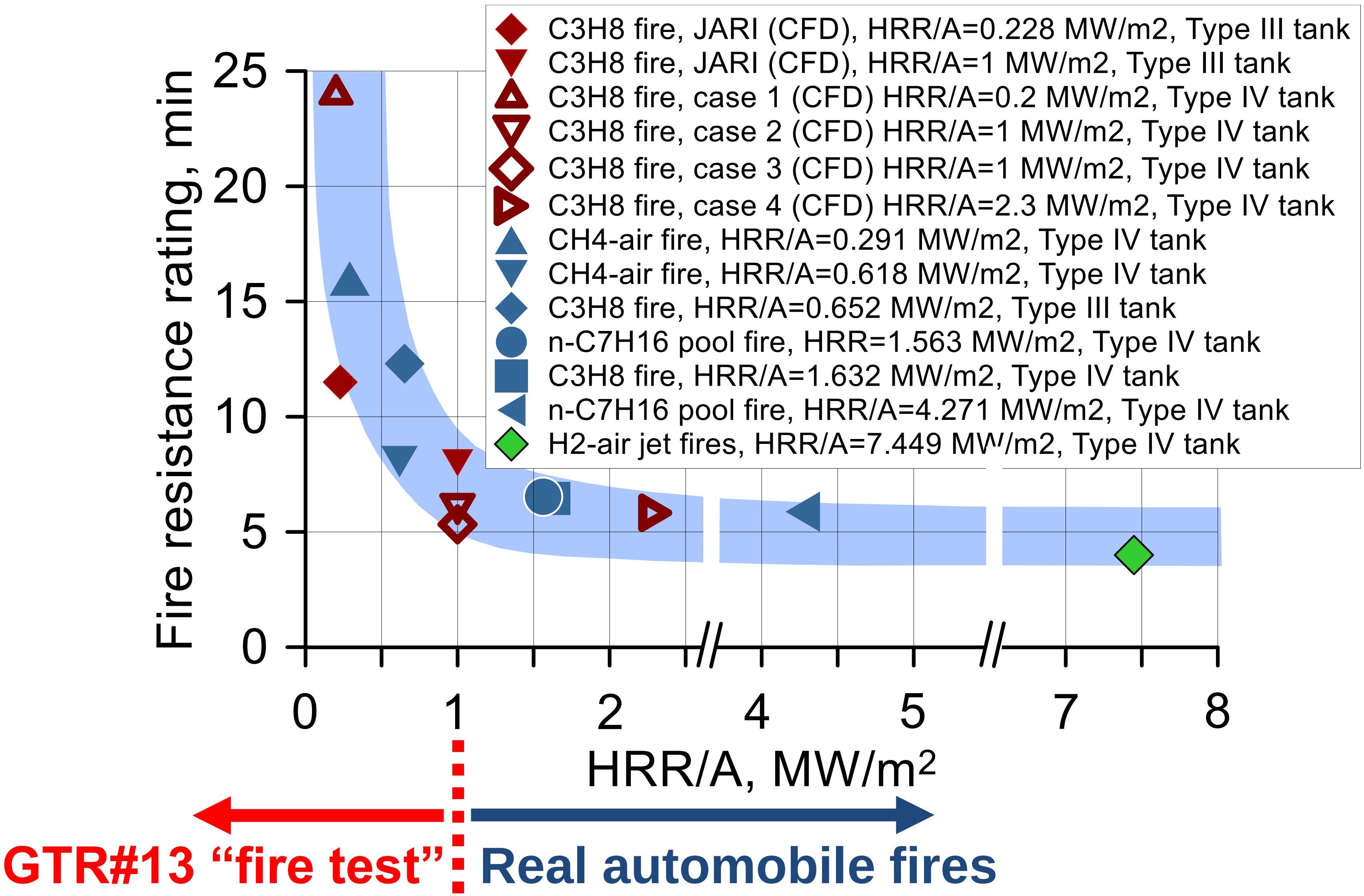
Tank has to withstand any fire condition: gasoline fire (HRR/A=1-2 MW/m^2) and smaller HRR/A fires

!

Dependence of fire resistance rating (FRR) on specific heat release rate (HRR/A)

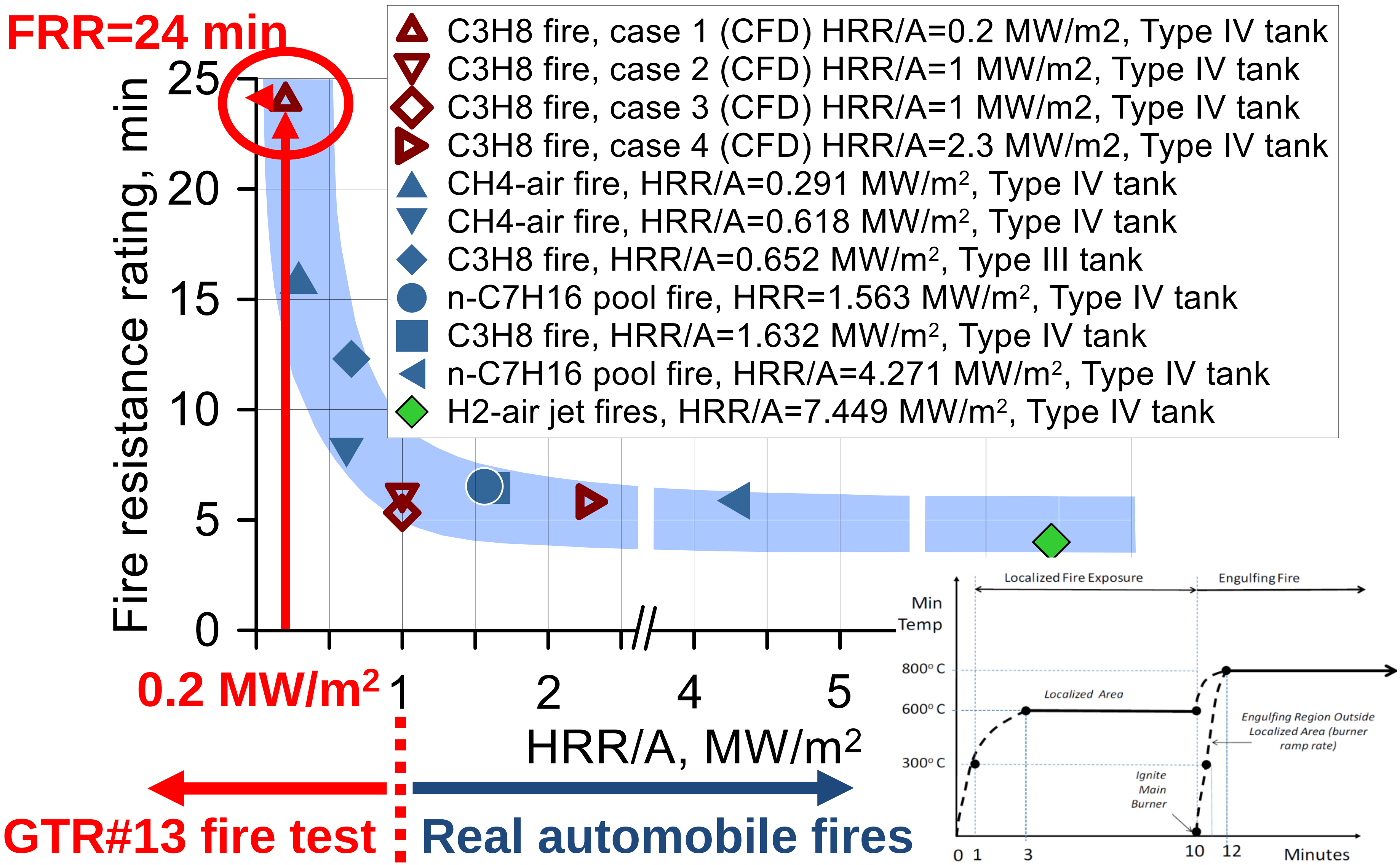
Ulster research result: FRR=F(HRR/A)

Why HRR/A in GTR fire differs from real fires?



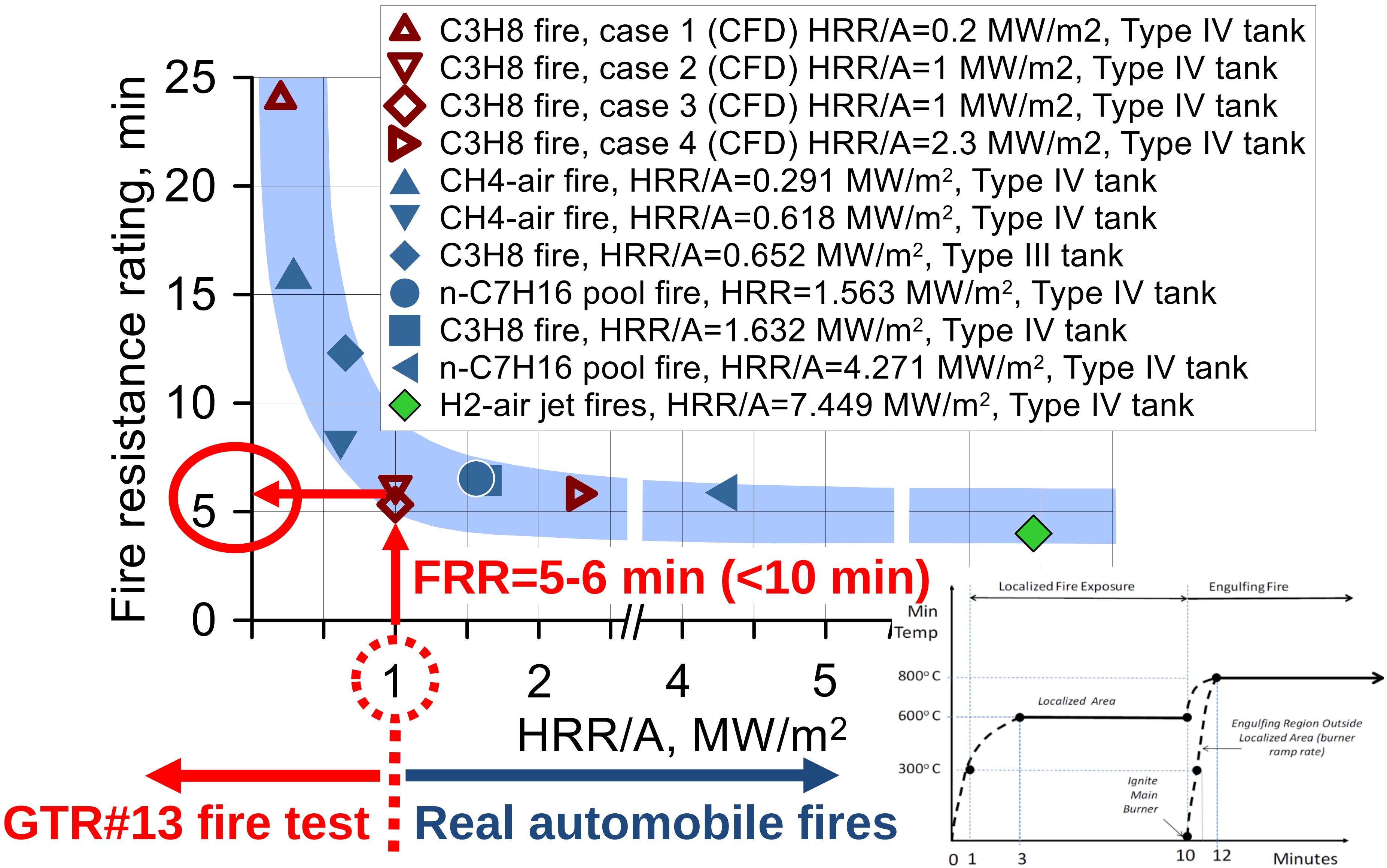
Where is the “game”?

“Use low HRR/A to pass localised part of test”



What is the problem?

Rupture at localised fire time: gasoline HRR/A!



Low HRR/A cannot be used to pass test

Concluding remarks

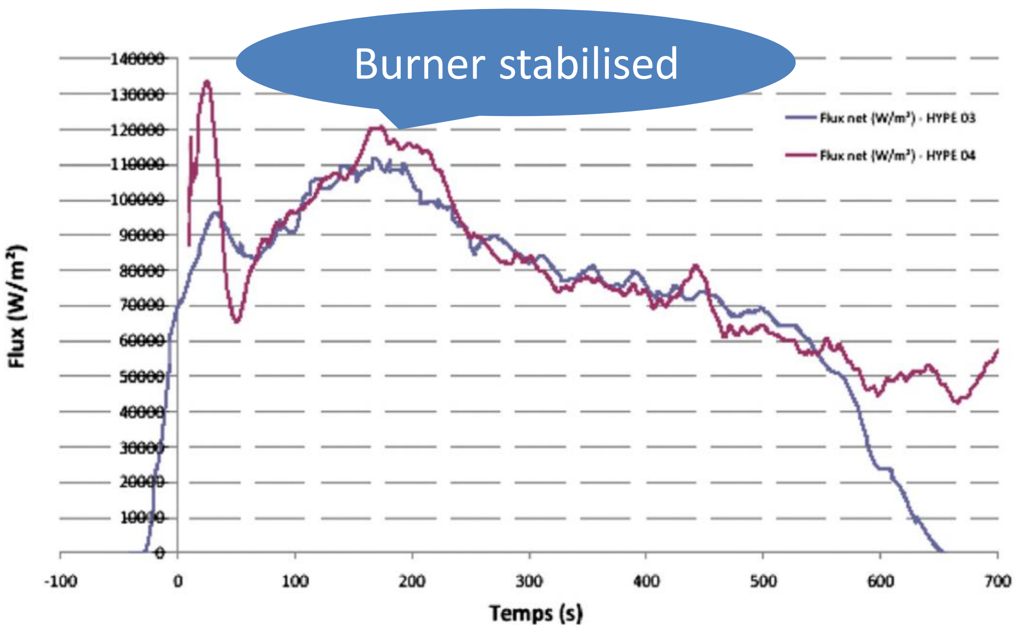
- Literature review gives HRR/A=1-2 MW/m^2 in gasoline fires (applicable to both car and truck scenarios, localised and engulfing fire for scenarios with gasoline spill under vehicle).
- Tank+TPRD system must undergo “fire test” (localised and engulfing portions) at least at real conditions of HRR/A≥1 MW/m^2 (and any other conditions with reduced HRR/A if needed). “Fire test” with only HRR/A below the threshold should be forbidden. It bears a life threat (even GTR#13 fire test would be passed!).
- HRR/A is a key parameter for fire test reproducibility. Easier to measure (flow meter) compared to heat flux to tank $\dot{q}''$.
- HRR/A ≥1 MW/m^2 unambiguously defines FRR (parameter requested by firemen). Engulfing fire test without TPRD must be re-established.
- Tank+TPRD reaction to small HRR/A fires yet to be studied.

Reaction of original tank on varieties of fires with different HRR/A (no TPRD)

Previous study: steel cylinder with air

Heat flux $\dot{q}''$ changes in time (measurements)

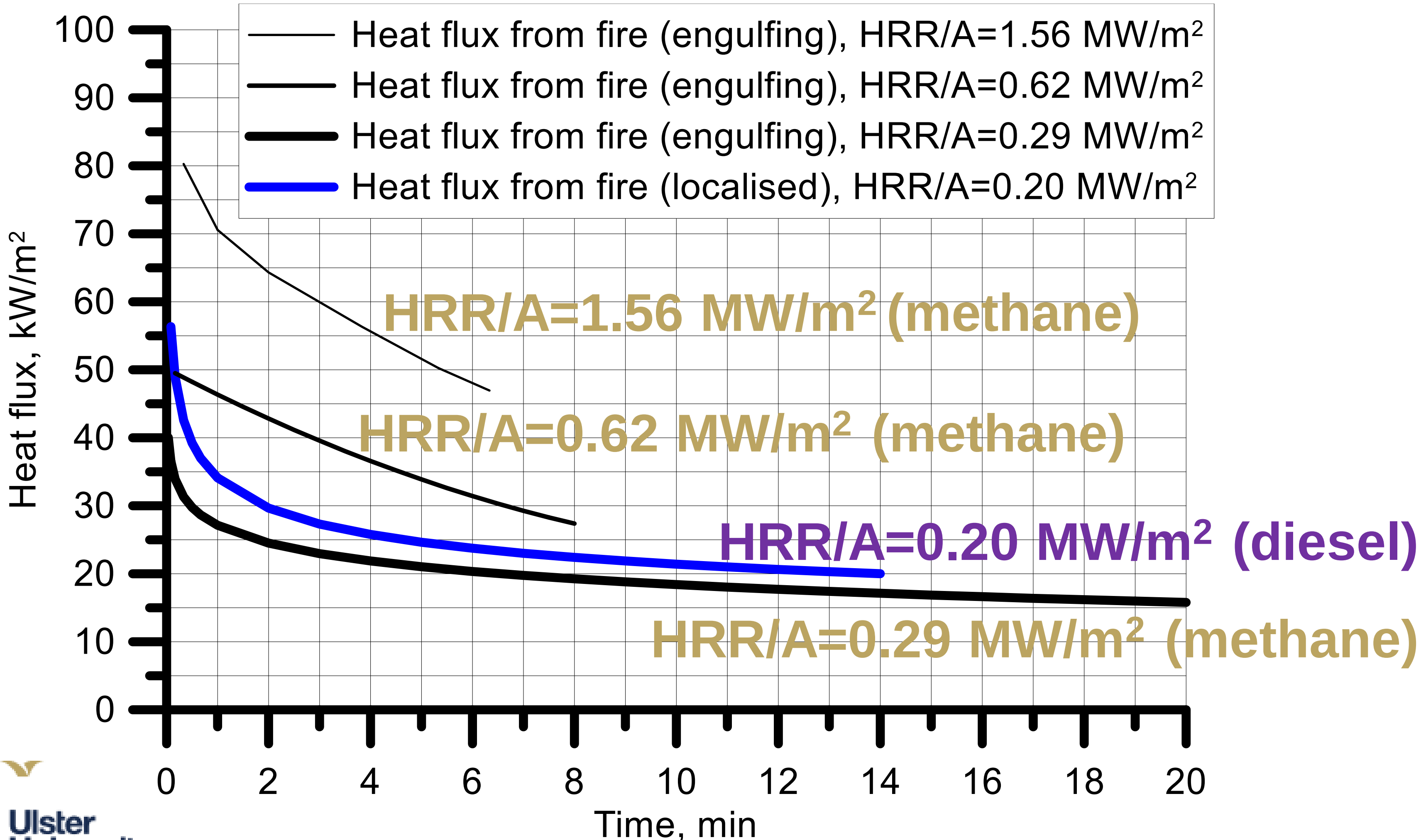
- Two steel cylinder 330x900 mm (12 mm thickness) with air. One ruptured in fire with heptane (HRR=1.5 MW) in pan 0.6x1.2 m, i.e. HRR/A=2.1 MW/m^2 (close to gasoline!).
- The heat flux to cylinder calculated by growth of air temperature and wall temperature. Thermal heat flux is not constant in time but decreases.
- Stabilised burner flame at 200 s (cylinder completely covered).
- Maximum heat flux **110-120 kW/m^2.**



S. Ruban et al., ‘Fire risk on high-pressure full composite cylinders for automotive applications’, IJHE, 2012.

Vehicle fuel and smaller HRR/A fires

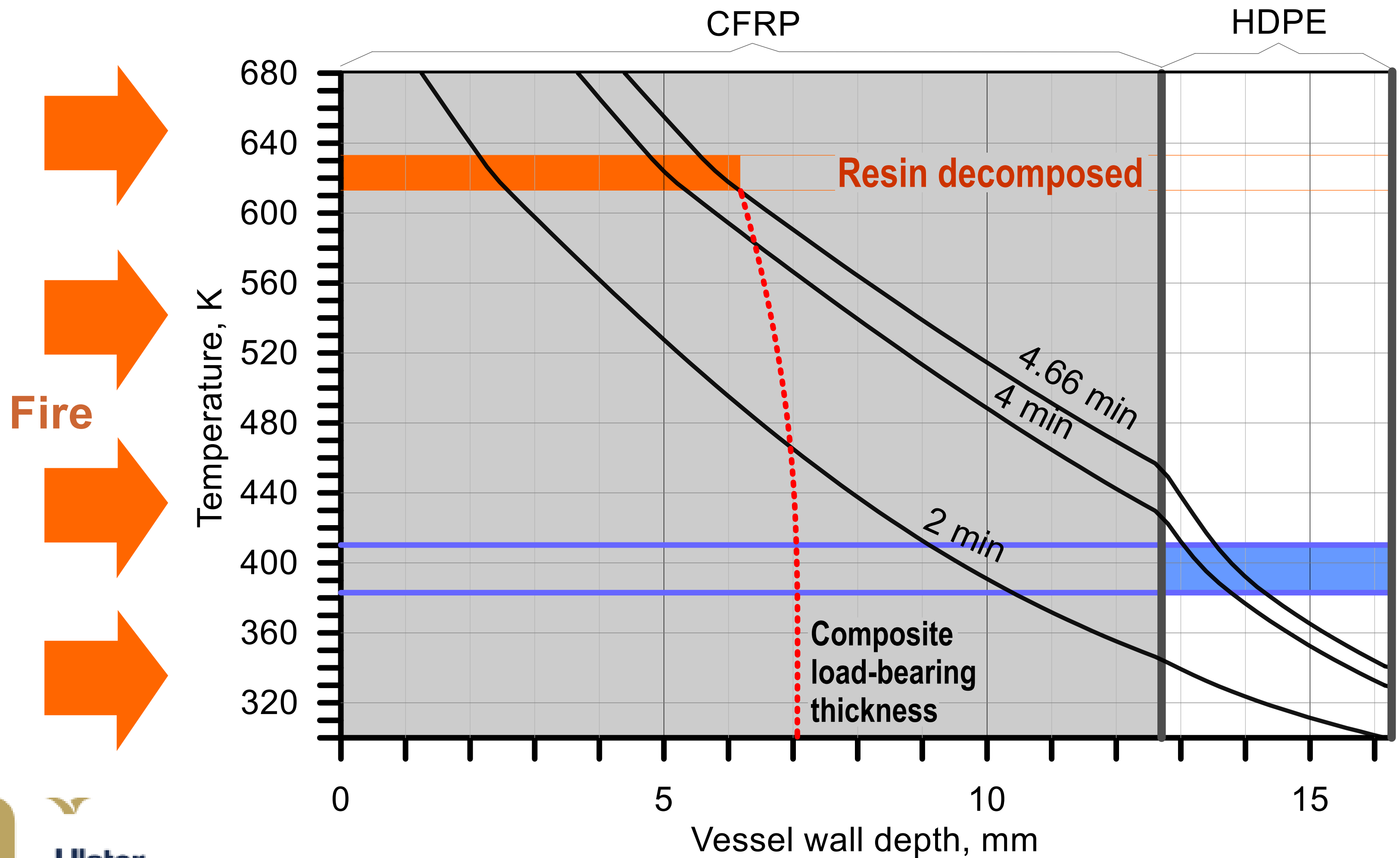
Max heat flux $\dot{q}''$ change in time (simulations)



The higher HRR/A (constant) the higher heat flux to tank $\dot{q}''$ (decreasing)

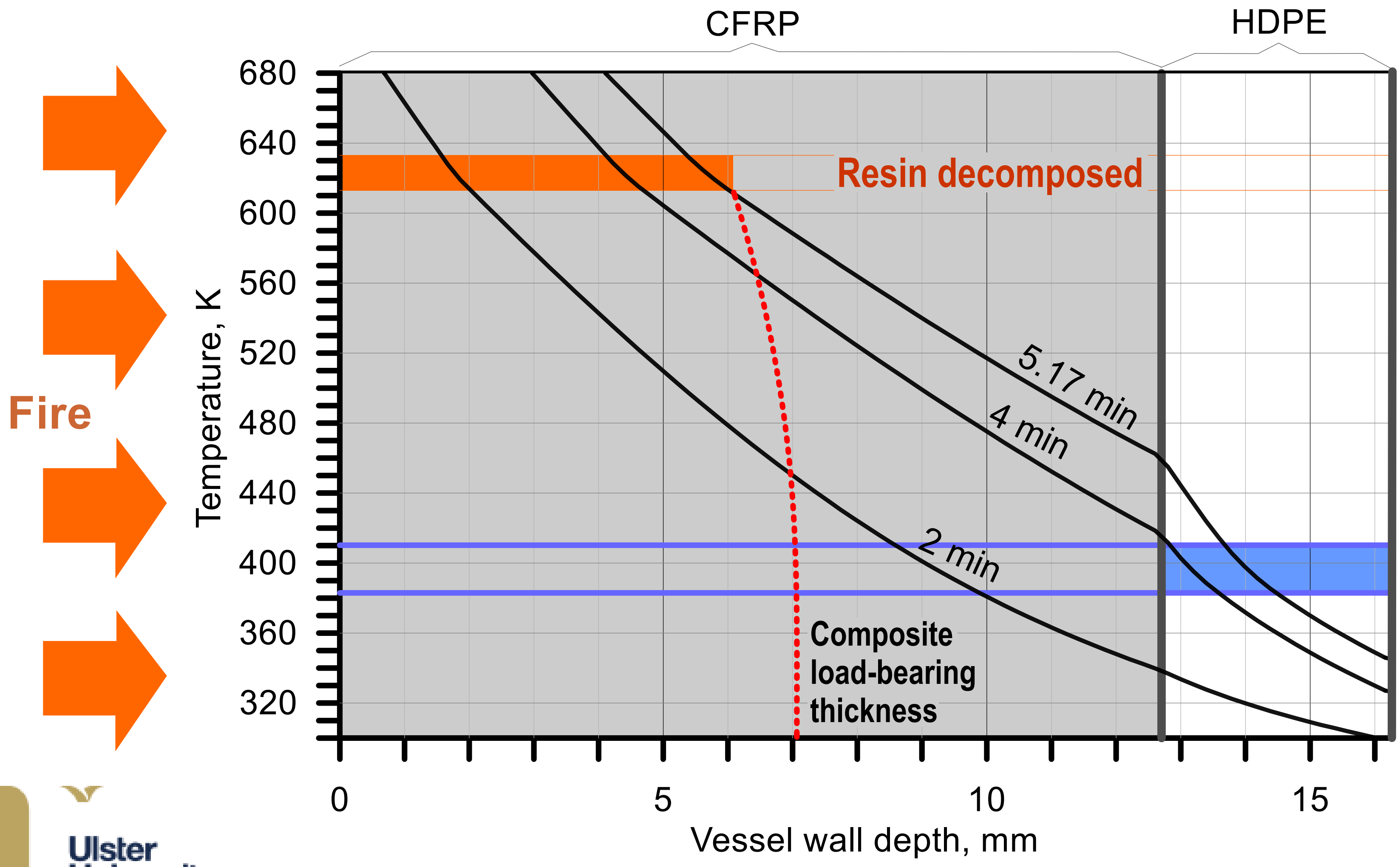
Real HRR/A (gasoline) fire: RUPTURE!

HRR/A=1.56 MW/m^2 (rupture at 4.66 min)



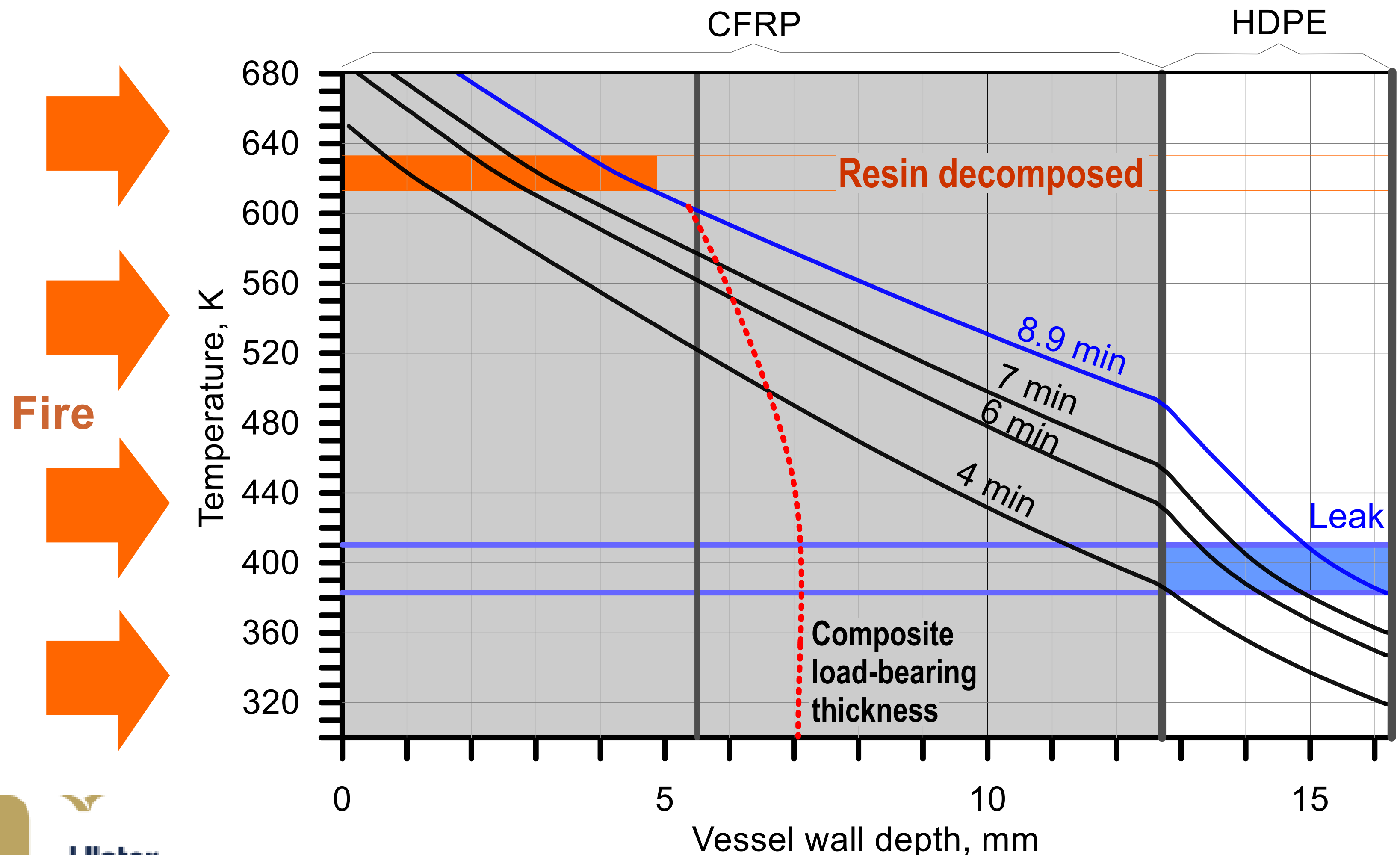
Medium HRR/A fire: RUPTURE!

HRR/A=0.62 MW/m^2 (rupture at 5.17 min)



Small HRR/A fire: LEAK!

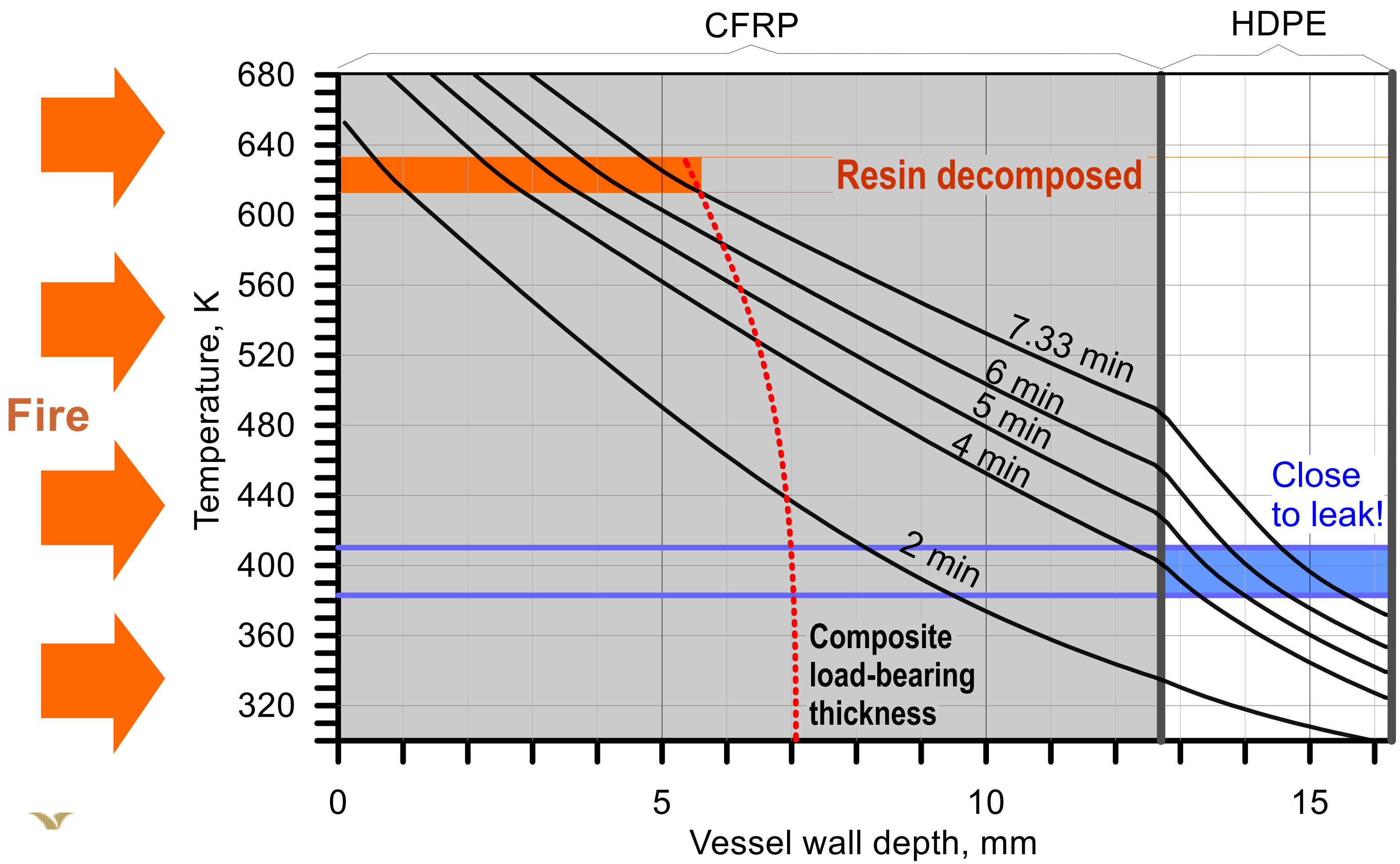
HRR/A=0.29 MW/m^2 (leak at 8.9 min)



Ulster University

Another small HRR/A fire: “RUPTURE”

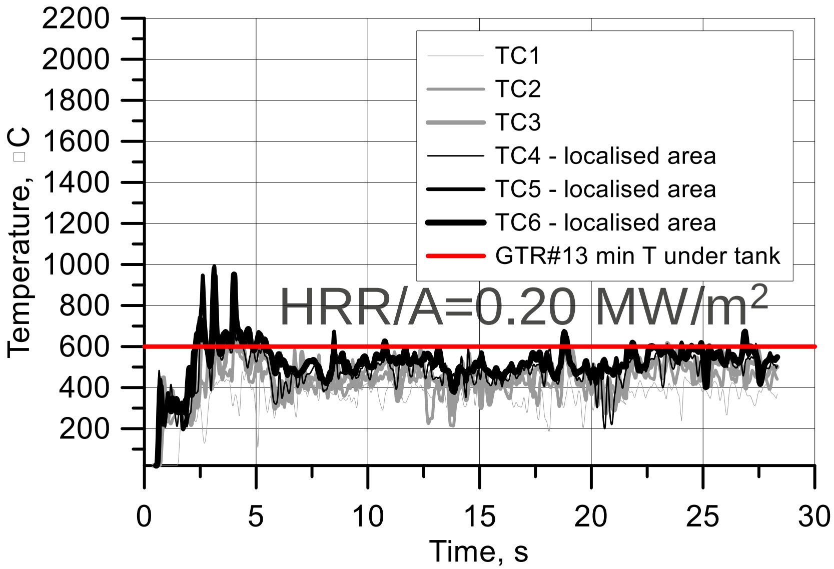
Diesel localised HRR/A=0.2 MW/m^2 (at 7.33 min)

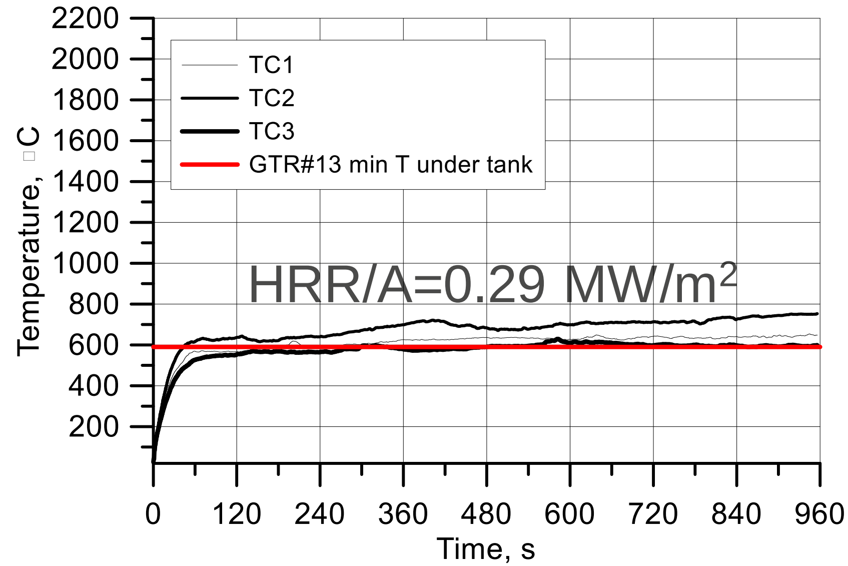


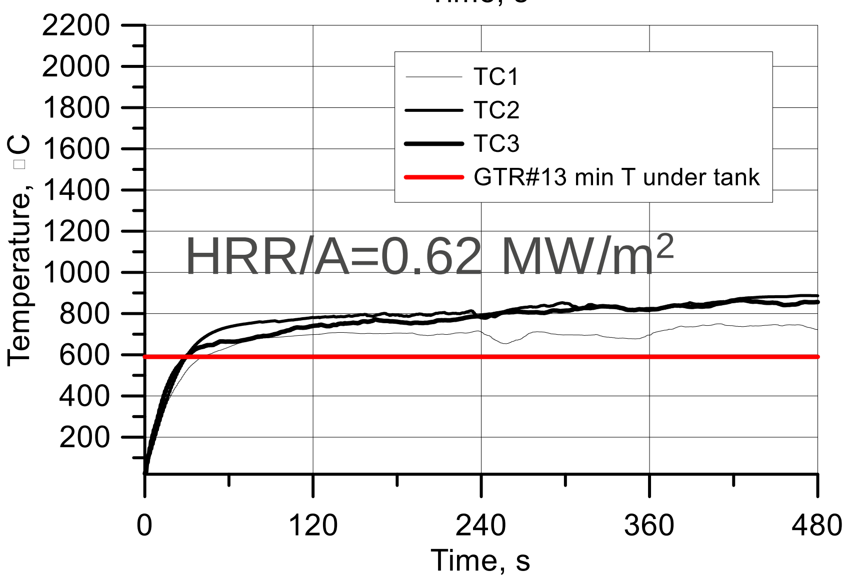
Ulster University

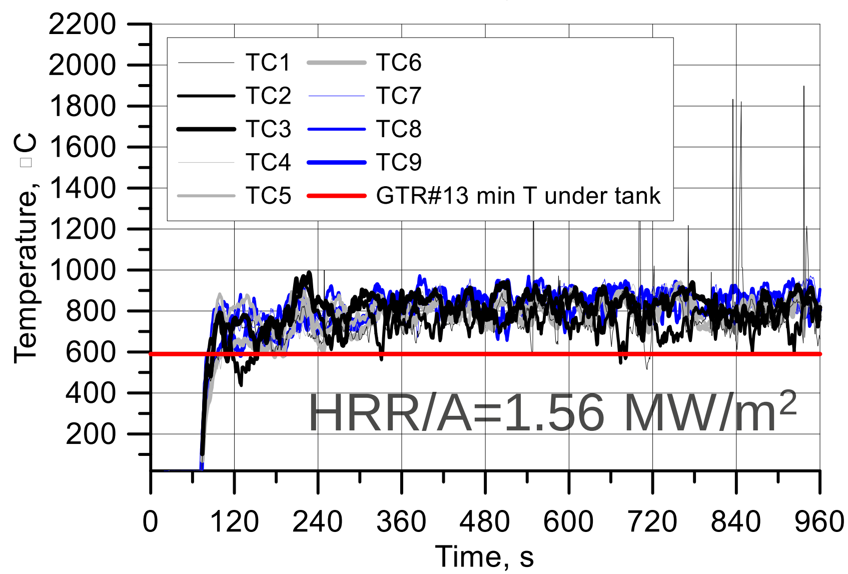
Temperature under tank

Decrease of temperature with HRR/A decrease









Original tank in different HRR/A fires

Concluding remarks on performance in fires

- Non-protected original composite tank of volume 7.5 L and NWP=70 MPa (no TPRD) definitely ruptures in fires with high HRR/A=0.62-1.56 MW/m^2 and leak or rupture at lower HRR/A=0.20-0.29 MW/m^2 in numerical tests.
- The higher is specific heat release rate in a fire, HRR/A (constant in time), the higher is heat flux to the tank, $\dot{q}''$ (decreasing in time).
- Localised in-situ diesel fire with HRR/A=0.20 MW/m^2 generates somewhat higher maximum heat flux to tank surface, $\dot{q}''$, compared to engulfing stand-alone methane fire with HRR/A=0.29 MW/m^2.
- **Rupture issue can be excluded by use of explosion-free in a fire tank (see further).**

Re-establishment of engulfing fire test without TPRD

Low probability high consequences event

Failed to be initiated or blocked in accident TPRD

Fire brigades need to know time to tank rupture in a fire (FRR):

- London fire brigades: first responders arrival time is 5 min 34 s.
- This is comparable to FRR of current tanks of 5-8 min.
- Firemen need to know FRR and parameters of blast wave and fireball to develop intervention strategy and tactics.

Re-establishment of test without TPRD

Concluding remarks

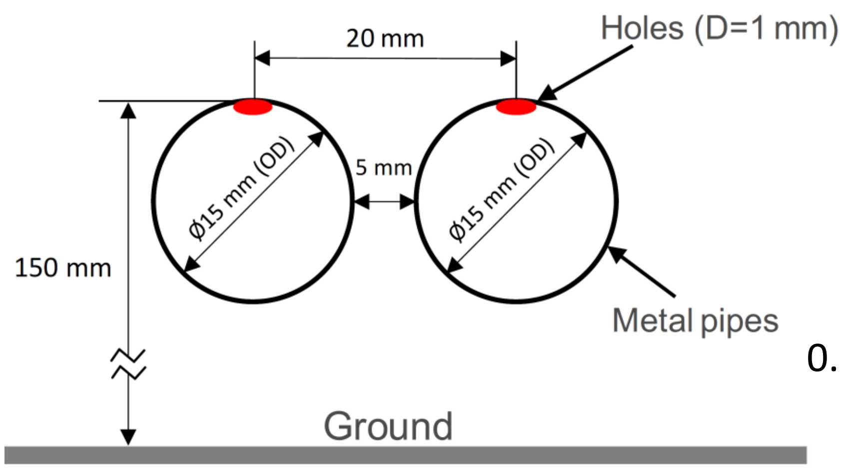
- The statement in TF4 presentation during GTR#13 meeting in Tianjin "*there is one expert that favours a fire resistance test of the container*"…
  should be changed to
  …"*one expert delivered to OICA and other IWG SGS members the message from fire fighters of EU project HyResponse about the need for them to know fire resistance rating of container to develop intervention strategies and tactics*".
- The opinion of IWG SGS is of great importance for fire fighters (engulfing fire test without TPRD must be included into GTR#13 fire tests protocol to underpin inherently safer deployment of the technology and protect life of first responders and the public).
- **Engulfing test without TPRD must be re-established.**

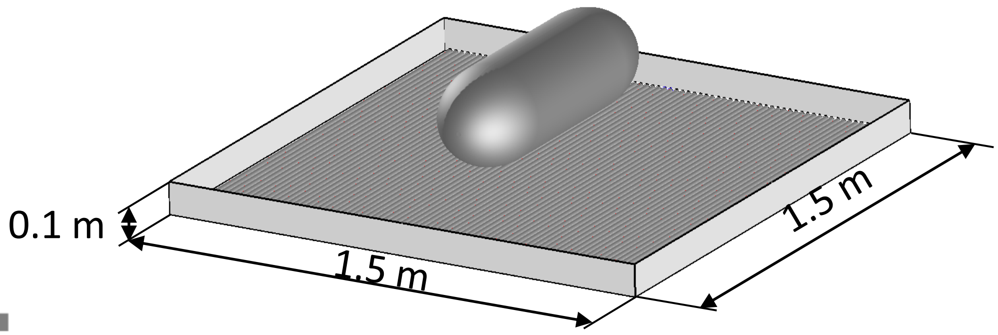
Burner design requirements:
(a) minimum temperature and (b) HRR/A

Example of pipe burner

Details of numerical experiments

- 5600 holes spaced uniformly at 20 mm. Hole D=1 mm.
- Propane injection velocities: 5.3 m/s (HRR/A=1 MW/m^2), 1.2 m/s (HRR/A=0.228 MW/m^2).
- Burner 1.5x1.5 m positioned at 0.15 m above the ground.
- Calculation domain: 6x6x4 m.
- Conjugate heat transfer to Type 3 tank (0.9x0.3 m).

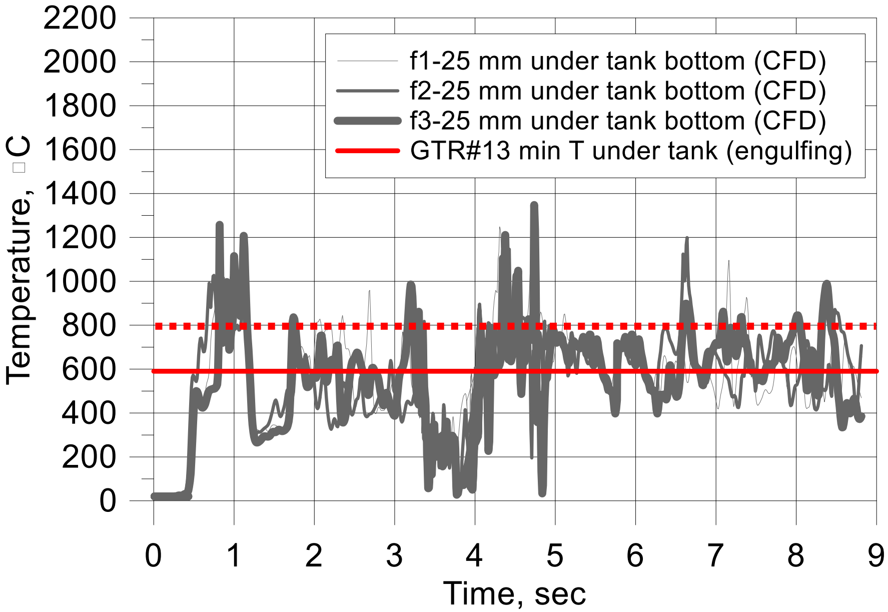




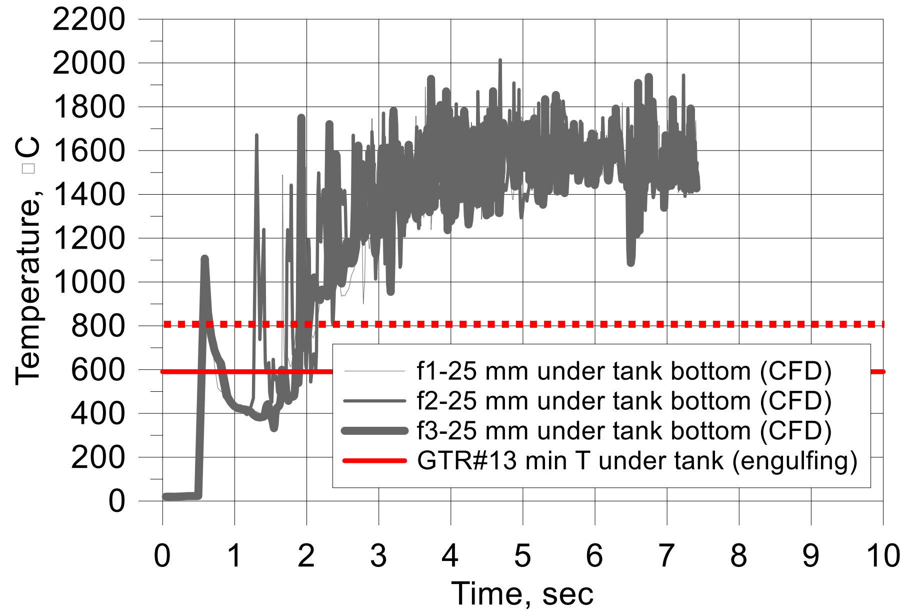
Example of pipe burner

Simulated temperatures under the tank

Case1: HRR/A=0.228 MW/m^2



Case 2: HRR/A=1 MW/m^2

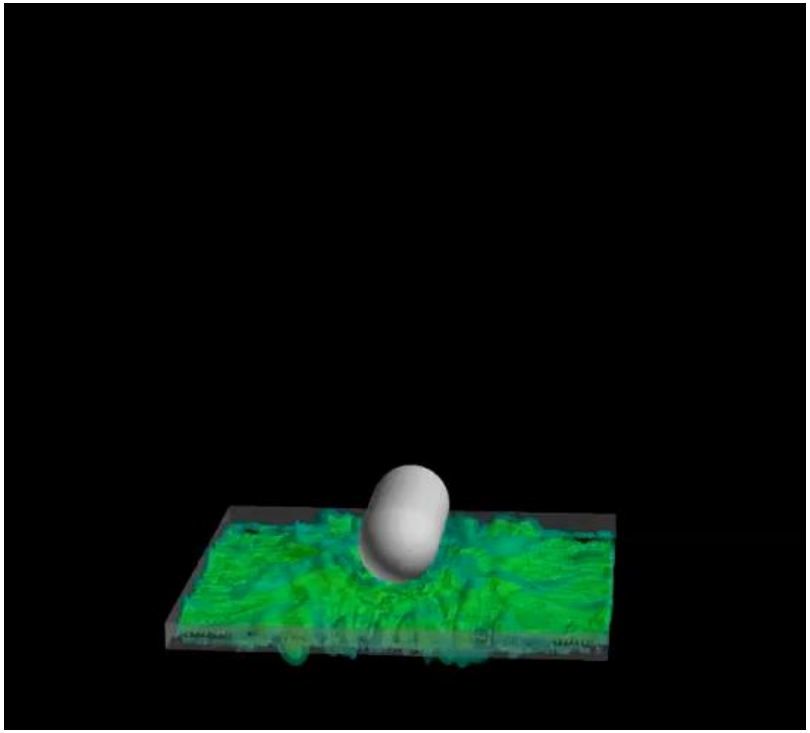


Minimum temperature under the tank is not GTR#13 compliant (<800^{o}C) for HRR/A=0.228 MW/m^2 and GTR#13 compliant (>800^{o}C) for HRR/A=1 MW/m^2!

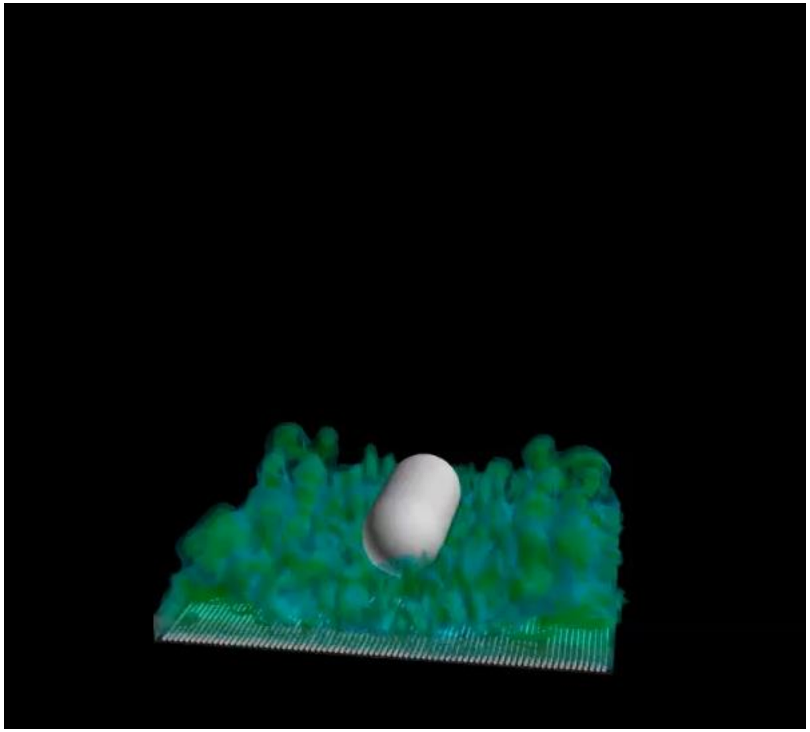
Example of pipe burner

Temperature iso-surfaces

Low HRR/A=0.228 MW/m^2



Real HRR/A=1 MW/m^2



Temperatures:

590°C (GTR#13 min required) 1030°C

Burner design requirements
Concluding remarks

- GTR#13 should regulate two thermal parameters of a burner: minimum temperature and HRR/A. The GTR#13 text could give an example of a burner design but should not prescribe a burner design.
- Simulated prototype of a pipe burner cannot reproduce current (not substantiated enough) minimum temperature requirements of 800^{o}C for engulfing fire in the test with low HRR/A=0.228 MW/m^2.
- Thus, fire testing at HRR/A smaller than 1 MW/m^2 as measured in gasoline fires, e.g. assuming “small” fire between rear seats in a car at initial stage (if we still want to do it) should decrease minimum temperature requirements and link it to the selected HRR/A.

Text amendment No.1:
“Fire test” and “Engulfing fire test”

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.1. Fire test

Localized portion of the fire test

"(c) The fire source consists of ~~LPG~~ gas burners or a pool fire configured to produce the specific heat release rate, HRR/A, at least 1 MW/m^2 and a uniform minimum temperature on the test article measured with a minimum 5 thermocouples covering the length of the test article ~~up to 1.65 m maximum~~ …"

Rationale: To reproduce real conditions of gasoline fire scenario, to ensure fire test reproducibility, to inform first responders about conservative value of time to rupture, and to dismiss current limit for burner and vessel size.

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.1. Fire test

Localized portion of the fire test

"(f) As shown in Figure 7 the temperature of the thermocouples in the localized fire area has increased continuously to at least 300°C within 1 minute of ignition, to at least 600°C within 3 minutes of ignition, and a temperature of at least 600°C is maintained for the next 7 minutes. ~~The temperature in the localized fire area shall not exceed 900°C during this period.~~"

Rationale: The upper temperature limit in the localised fire should be relaxed, as the maximum temperature in a fire may easily exceed 900ºC and vary depending on fuel, burner HRR/A, size of TC. This T limit "helps" to pass current GTR#13 fire test but could create a problem for customers and firemen in real life fire.

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.1. Fire test

Engulfing portion of the fire test

"… The minimum temperature is held at 800°C for tests with HRR/A≥1 MW/m^2 (can be lower for tests at lower HRR/A), and the maximum temperature shall not exceed 1100 °C."

Rationale No.1: The upper temperature limit in the engulfing fire should be relaxed, as the maximum temperature in a fire may exceed 1100°C and vary depending on fuel and burner's HRR/A. This limitation "helps" to pass GTR#13 fire test but could create a problem in real life fire.

Rationale No.2: GTR#20 states that

6.2.4.3.4.6. The Tested-Device shall be exposed to flame for 2 minutes after the averaged temperature reaches 800 °C within 30 seconds. The averaged temperature shall be maintained at 800-1,100 °C for 2 minutes.

Question:

- Why does GTR#13 fire test protocol reduces minimum temperature requirements (and increases time to achieve it) compared to GTR#20 (minimum requirement 800ºC comes into play in GTR#13 test after 12 minutes only, while in GTR#20 in 0.5 minutes)?

Ulster University

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

GTR#13 page: 83

Table 2
Summary of fire test protocol

	Localized fire region	*Time period*	*Engulfing fire region (Outside the localized fire region)*
Action	Ignite Burners	0-1 minute	No Burner Operation
Minimum temperature	Not specified		Not specified
~~Maximum temperature~~	~~Less than 900°C~~		~~Not specified~~
Action	Increase temperature and stabilize fire for start of localized fire exposure	1-3 minutes	No Burner Operation
Minimum temperature	Greater than 300°C		Not specified
~~Maximum temperature~~	~~Less than 900°C~~		~~Not specified~~
Action	Localized fire exposure continues	3-10 minutes	No Burner Operation
Minimum temperature	1-minute rolling average greater than 600°C		Not specified
~~Maximum temperature~~	~~1-minute rolling average less than 900°C~~		~~Not specified~~
Action	Increase temperature	10-11 minutes	Main Burner Ignited at 10 minutes
Minimum Temperature	1-minute rolling average greater than 600°C		Not specified
~~Maximum temperature~~	~~1-minute rolling average less than 1,100°C~~		~~Less than 1,100°C~~
Action	Increase temperature and stabilize fire for start of engulfing fire exposure	11-12 minutes	Increase temperature and stabilize fire for start of engulfing fire exposure
Minimum temperature	1-minute rolling average greater than 600°C		Greater than 300°C
~~Maximum temperature~~	~~1 minute rolling average less than 1,100°C~~		~~Less than 1,100°C~~
Action	Engulfing fire exposure continues	12 minutes - end of test	Engulfing fire exposure continues
Minimum temperature	1-minute rolling average greater than 800°C		1-minute rolling average greater than 800°C
~~Maximum temperature~~	~~1 minute rolling average less than 1,100°C~~		~~1-minute rolling average less than 1,100°C~~

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.1. Fire test

Engulfing portion of the fire test

“The test article is held at temperature (engulfing fire condition) until the system vents through the TPRD and the pressure falls to less than 1 MPa. In a separate fire test **without TPRD** the **fire resistance rating (FRR)** of a tank (**elapsed time from ignition of the fire to the tank rupture**) should be documented to inform first responders’ intervention strategy and tactics (the specific heat release rate, HRR/A, of the fire source should be documented as well).”

Rationale: request of first responders, e.g. in EU HyResponse project.

6.2.5. Test procedures for service terminating performance in fire

6.2.5.2. Engulfing fire test:

"A uniform fire source ~~of 1.65 m length~~ provides direct flame impingement on the container surface across its entire diameter. The specific heat release rate of a fire source, HRR/A, should be at least 1 MW/m^2."

Rationale: To dismiss size limits for burner and vessel, and ensure fire test reproducibility in different laboratories.

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.2. Engulfing fire test:

"The container shall vent through a pressure relief device without bursting. In a separate engulfing fire test without TPRD the fire resistance rating of a tank (elapsed time from ignition of the fire to the tank rupture) should be documented, along with specific heat release rate, HRR/A, of the fire source used in the test."

Rationale: request of first responders (EU HyResponse project).

Effect of wind on a pipe burner prototype

Table of wind velocities

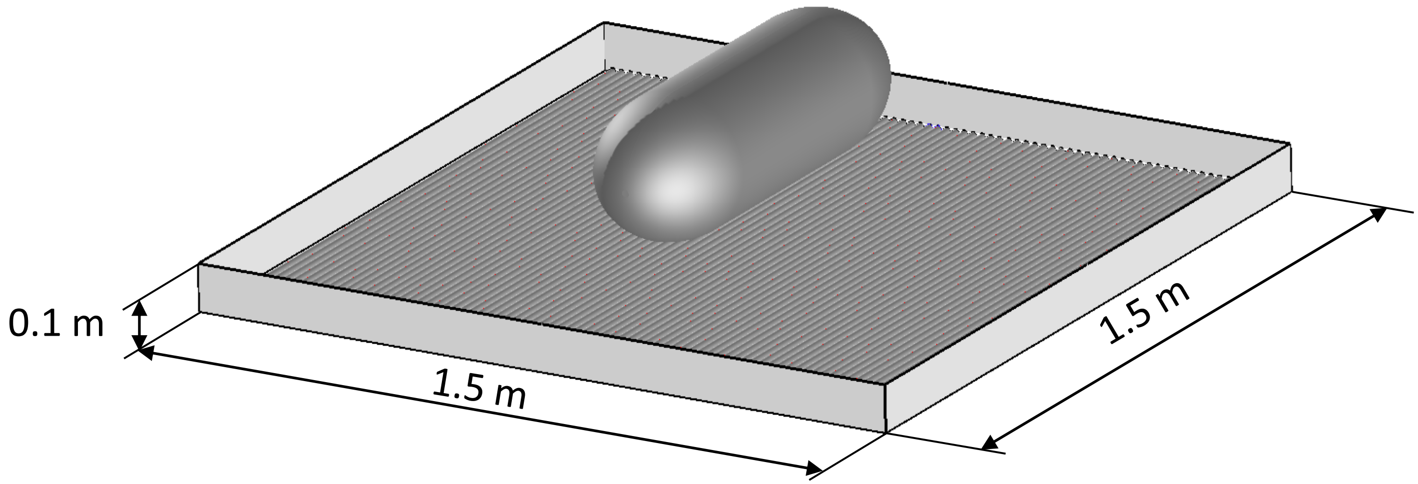
Wind speed	Description
< 1 mph < 0.5 m/s	Calm
1–3 mph 0.5–1.5 m/s	Light air
4–7 mph **1.6–3.3 m/s**	**Light breeze (HSL test, Case 1). Wind felt on face; leaves rustle; wind vane moved by wind.**
8–12 mph **3.4–5.5 m/s**	**Gentle breeze (Case 2). Leaves and small twigs in constant motion; light flags extended.**
13–18 mph 5.5–7.9 m/s	Moderate breeze
19–24 mph **8–10.7 m/s**	**Fresh breeze (Case 3). Small trees in leaf begin to sway; crested wavelets form on inland waters.**
25–31 mph 10.8–13.8 m/s	Strong breeze
32–38 mph 13.9–17.1 m/s	High wind, moderate gale, near gale
39–46 mph 17.2–20.7 m/s	Gale, fresh gale

Source: https://en.wikipedia.org/wiki/Beaufort_scale

Pipe burner performance in a wind

Three different wind speeds

- **Wind 1**: Propane flow rate $\dot{V}$=1589 NL/min, $\dot{m}$=48.54 g/s, HRR=2.25 MW. **HRR/A=1 MW/m²**. **Wind speed 1.8 m/s**.
- **Wind 2**: Propane flow rate $\dot{V}$=1589 NL/min, $\dot{m}$=48.54 g/s, HRR=2.25 MW. **HRR/A=1 MW/m²**. **Wind speed 5 m/s**.
- **Wind 3:** Propane flow rate $\dot{V}$=1589 NL/min, $\dot{m}$=48.54 g/s, HRR=2.25 MW. **HRR/A=1 MW/m²**. **Wind speed 10 m/s**.

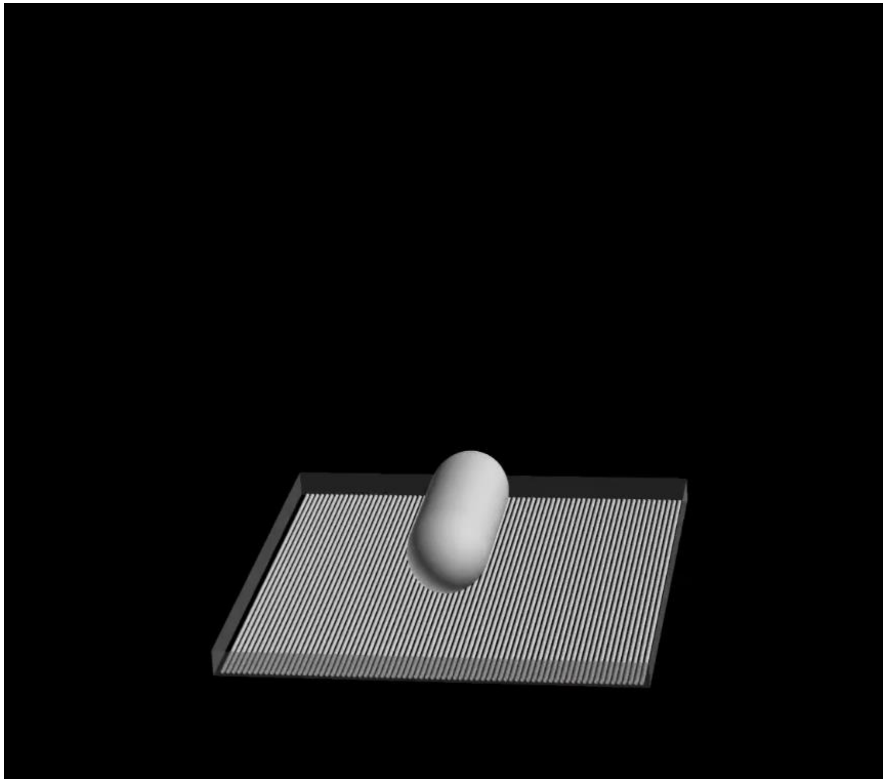


Ulster University

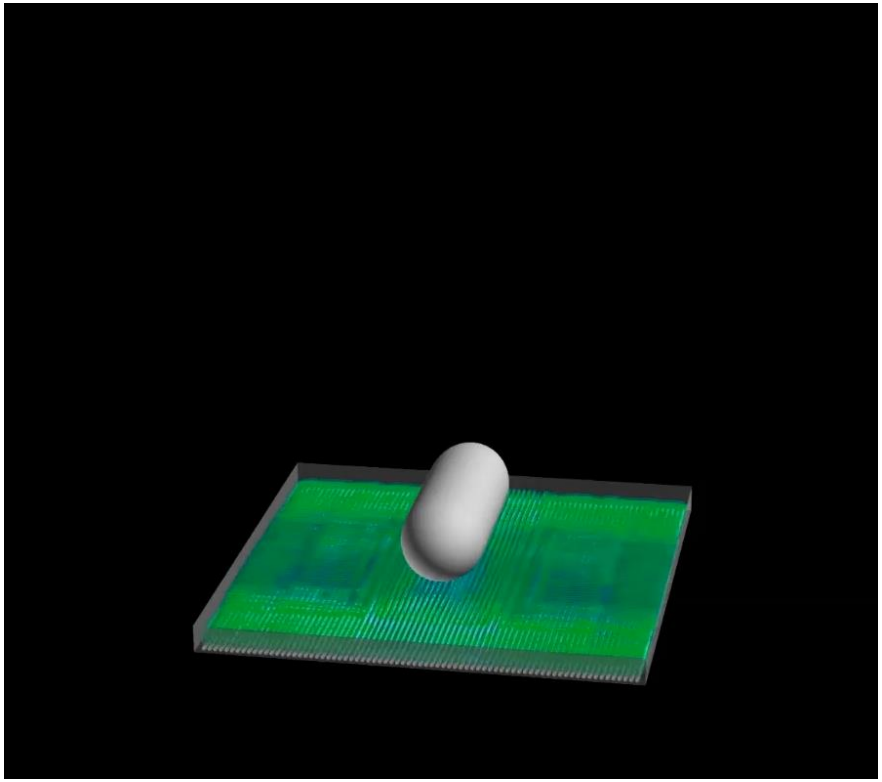
Pipe burner: wind 1.8 m/s (Wind 1)

Temperature iso-surfaces (values – next slide)

Low HRR/A=0.228 MW/m^2



Real HRR/A=1 MW/m^2



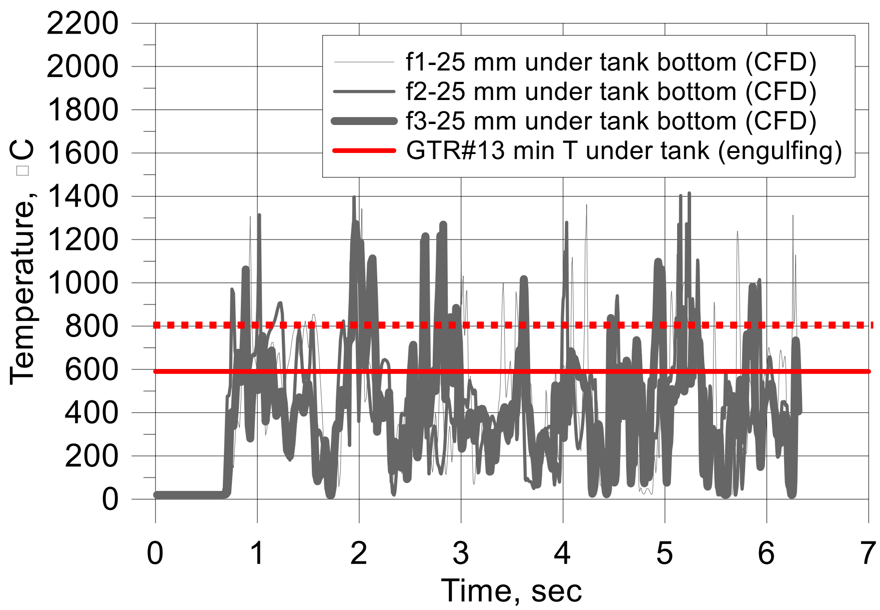
Temperatures:

590°C (GTR#13 min required) 1030°C

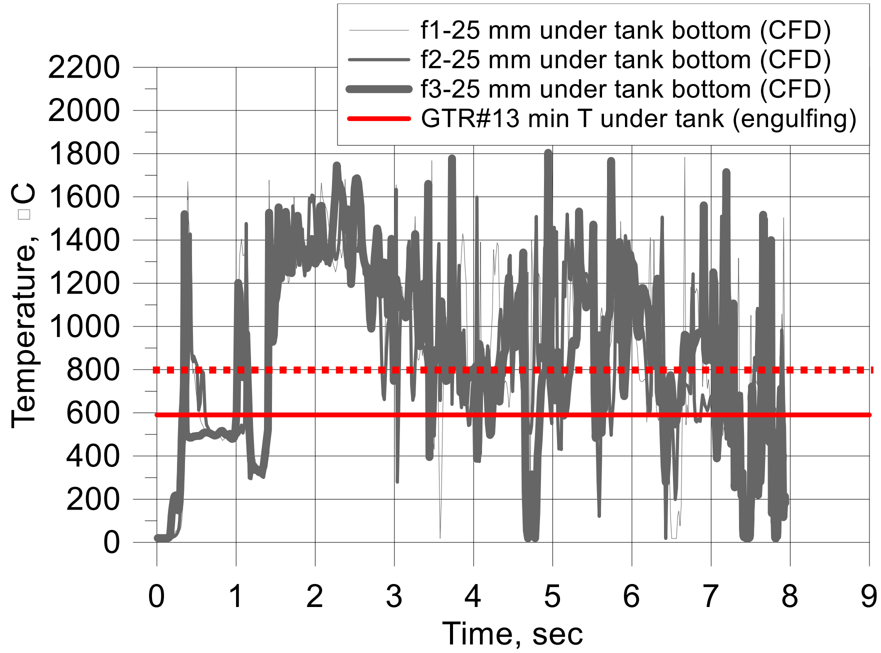
Pipe burner: wind 1.8 m/s (Wind 1)

Temperatures under tank (CFD)

HRR/A=0.228 MW/m^2



HRR/A=1 MW/m^2

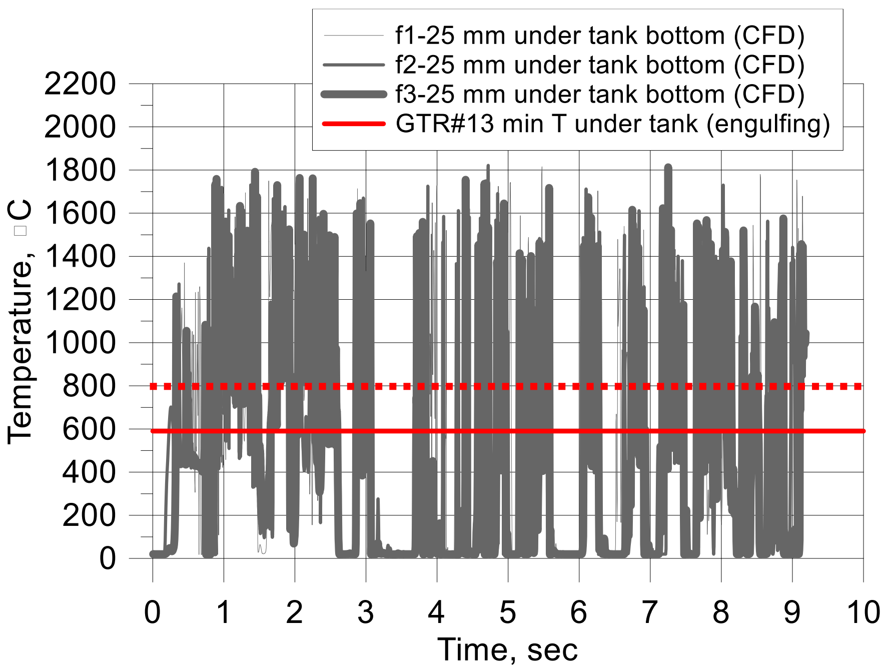


- **GTR#13 (800^{o}C) are not satisfied for HRR/A=0.228 MW/m2 (initial stage). Minimum temperature requirements have to be reduced for HRR/A<1 MW/m^2.**
- **GTR#13 (800^{o}C) are satisfied for HRR/A=1 MW/m^2 (initial stage). Probably minimum temperature requirements can be reduced by wind reasoning.**

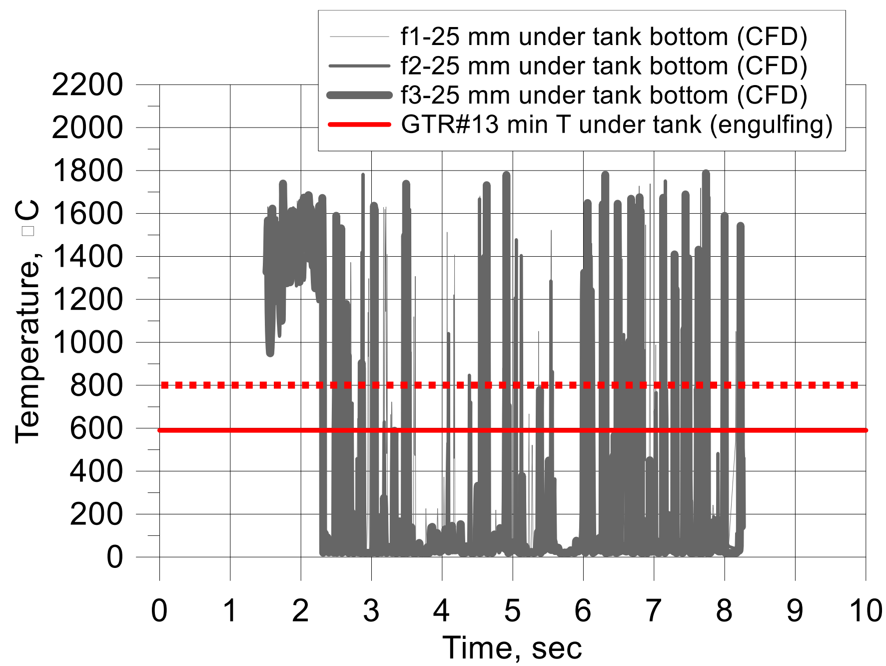
Pipe burner: wind 5 m/s, 10 m/s (CFD)

Temperatures under tank, HRR/A=1 MW/m^2

Wind 2: 5 m/s



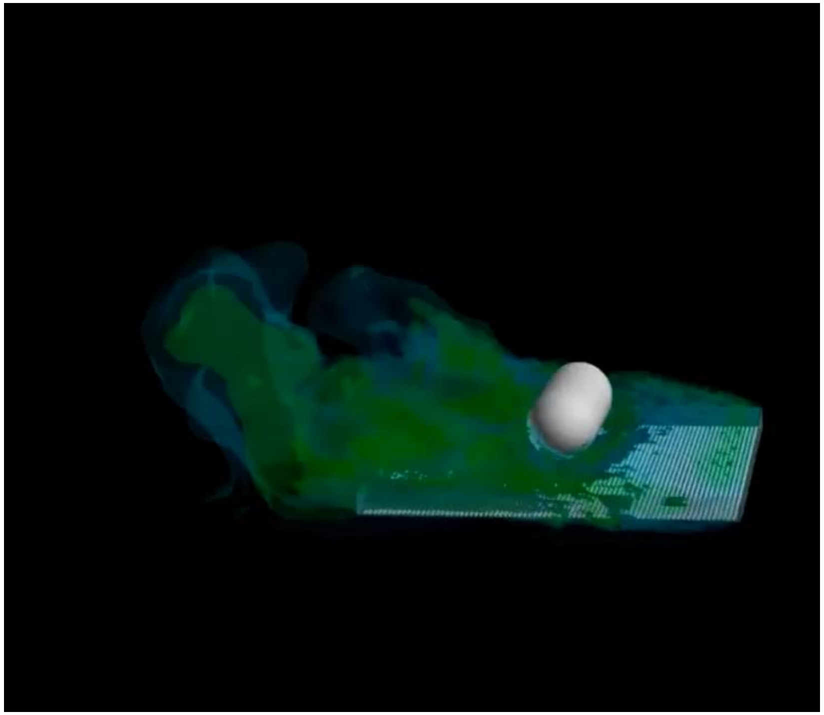
Wind 3: 10 m/s



- **GTR#13 (800°C) are nearly satisfied for wind 5 m/s (concluded by initial stage).**
- **GTR#13 (800°C) are not satisfied for wind 10 m/s (concluded by initial stage).**

Pipe burner: wind 5 m/s and 10 m/s
Temperature iso-surfaces

Wind 2: 5 m/s



Wind 3: 10 m/s

Ulster University

Temperatures:

590°C (GTR#13 min required) | 1030°C

The pipe burner prototype with wind
Concluding remarks

- The pipe burner prototype reproduces GTR#13 minimum temperatures requirements with HRR/A=1 MW/m^2 and wind velocity 1.8 m/s (“light breeze”), and 5 m/s (“gentle breeze”). It does not reproduce required temperatures at wind velocity 10 m/s (“fresh breeze”).
- To satisfy GTR#13 minimum temperature requirements for engulfing fire test the pipe burner prototype (1.5x1.5 m) can be successfully used for wind velocities up to 5 m/s (tank size up to 0.9x0.3 m).
- The use of lower HRR/A in fire test would require reduction of minimum temperature requirements.

Do we need localised portion of “fire test” as it stands now?

Four localised fires under a vehicle

Range: A=0.2-1.9 m^2, HRR/A=0.2-2.3 MW/m^2

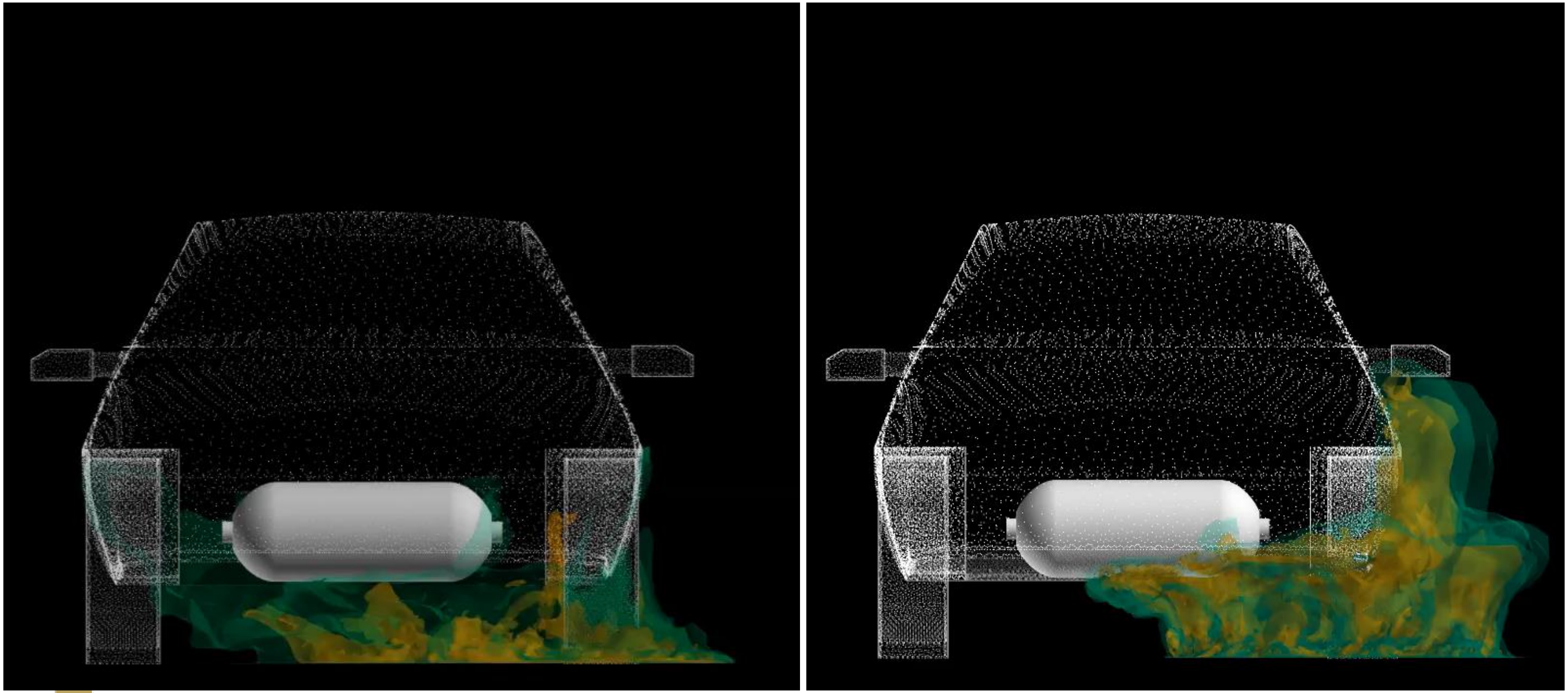
- **Fire 1:** *surrogate fuel*, C_3H_8 equivalent $\dot{m}$=8.2 g/s. Burner A=1.9 m^2, HRR=0.38 MW: **HRR/A=0.2 MW/m^2**.
- **Fire 2:** *surrogate fuel*, C_3H_8 $\dot{m}$=41 g/s. Burner **A=1.9 m^2**, HRR=1.9 MW: **HRR/A=1 MW/m^2**.
- **Fire 3:** *diesel* $\dot{m}$=4.72 g/s(*), C_3H_8 $\dot{m}$=4.31 g/s. Burner **A=0.2 m^2**, HRR=0.2 MW: **HRR/A=1 MW/m^2**.
- **Fire 4:** *diesel* $\dot{m}$=103 g/s(*), C_3H_8 $\dot{m}$=94.5 g/s. Burner A=1.9 m^2, HRR= 4.38 MW: **HRR/A=2.3 MW/m^2**.

(*) **Obtained using** D. Drysdale, An introduction to fire dynamics, 3rd ed., 2011.

In-situ fire dynamics: Fire 1 and Fire 2

Temperature iso-surfaces

Fire 1: HRR/A=0.2 MW/m^2 Fire 2: HRR/A=1 MW/m^2



Ulster University

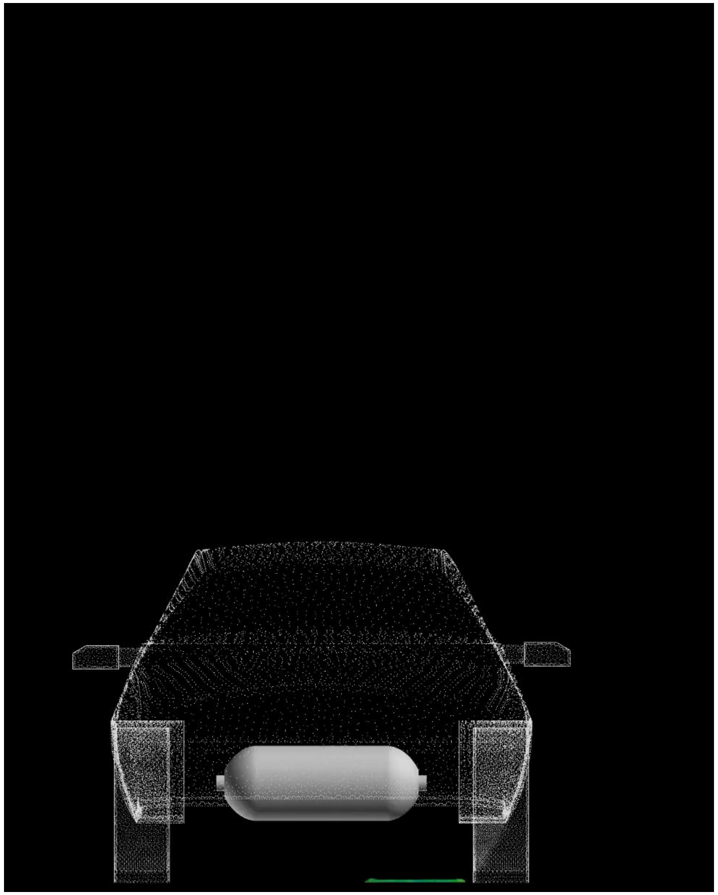
600°C (GTR#13 min required)

1030°C

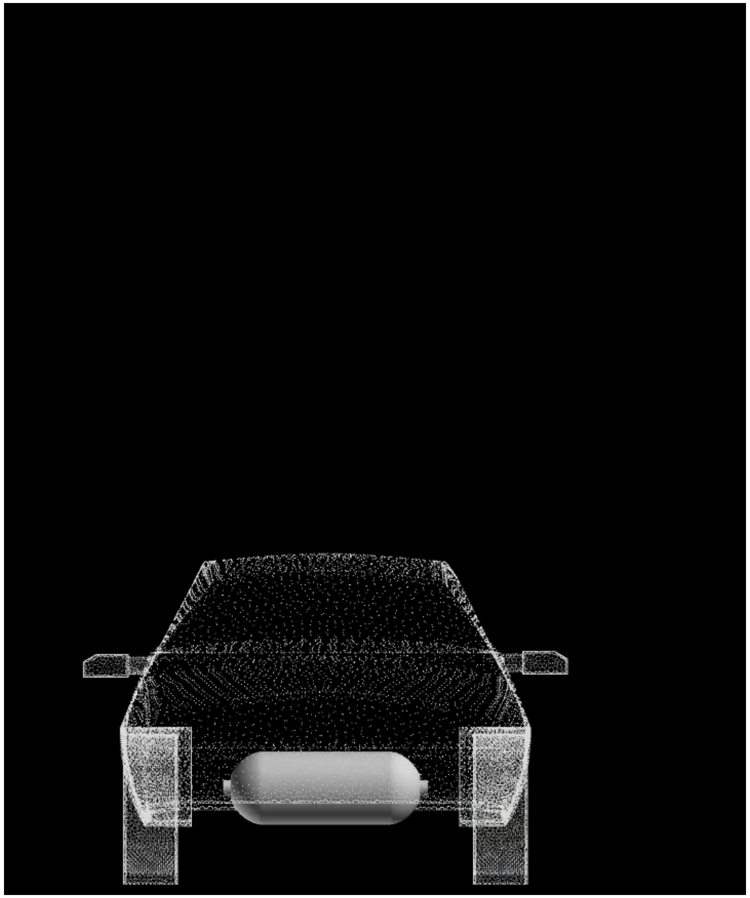
In-situ fire dynamics: Fire 3 and Fire 4

Temperature iso-surfaces

Fire 3: HRR/A=1 MW/m^2



Fire 4: HRR/A=2.3 MW/m^2



600°C (GTR#13 min required) 1030°C

In-situ localised fires: Qs & As

- Would localised fires with specific heat release rate, HRR/A, in the range 0.2-2.3 MW/m^2 provide agreement with GTR#13 temperature requirements?
  Answer: Yes but only for HRR/A > 1 MW/m^2.

- How different will be heat flux to a tank from a fire for different HRR/A?
  Answer: $\dot{q}''$=50 kW/m^2 (HRR/A=0.2 MW/m^2);
  $\dot{q}''$=90 kW/m^2 (HRR/A>1 MW/m^2)

- If GTR#13 fire test temperature requirements are fulfilled, but the heat flux to the tank is different – would this affect the fire resistance rating of a tank?
  Answer: Yes.
  FRR=20-25 min (HRR/A=0.2 MW/m^2).
  FRR=5-6 min (HRR/A=1.0-2.3 MW/m^2).

Do we need localised fire as it stands?

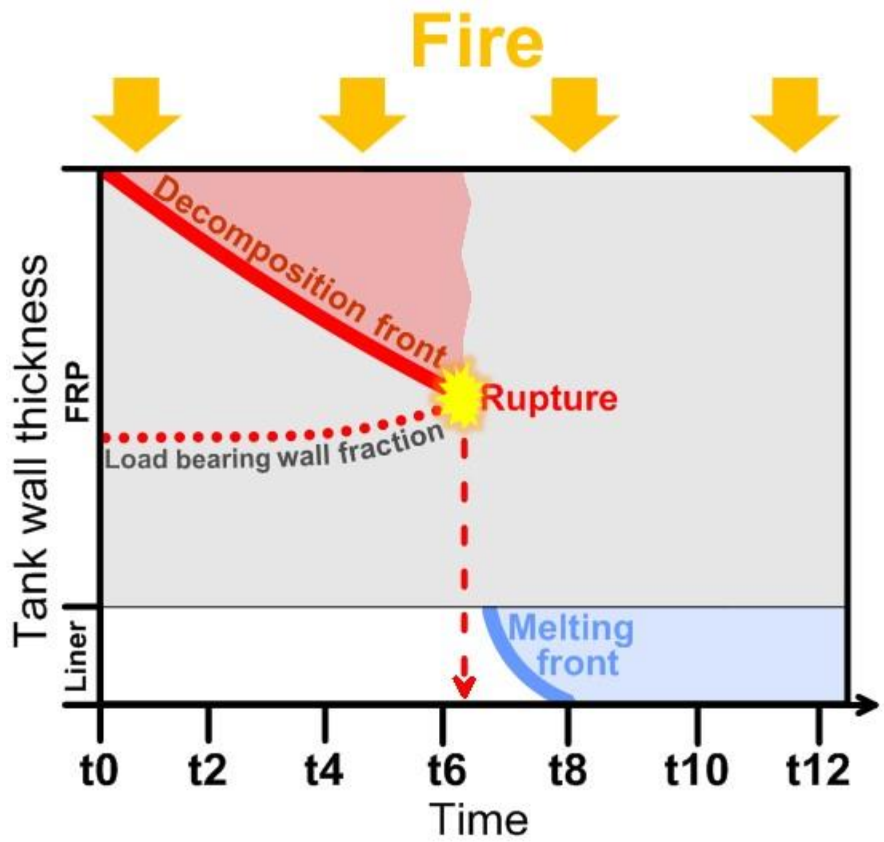
Concluding remarks

- There is high probability that with "gasoline fire" scenario (HRR/A>1 MW/m^2) a tank will rupture at localised portion of test.
- In-situ fire test differs from current "fire test":
  - Flow dynamics is quite different.
  - TPRD location area is affected immediately (making localised test unnecessary).
- In-situ localised fire test satisfies GTR#13 temperature requirements only for HRR/A>1 MW/m^2. For "smaller" fires with HRR/A<1 MW/m^2 we must reduce minimum temperature requirements for selected HRR/A (control of thermal conditions, i.e. temperature and HRR/A, is needed).
- Consider changing "Localized portion of the fire test" for stand-alone tank as it stands now to in-situ fire testing of actual vehicle design.

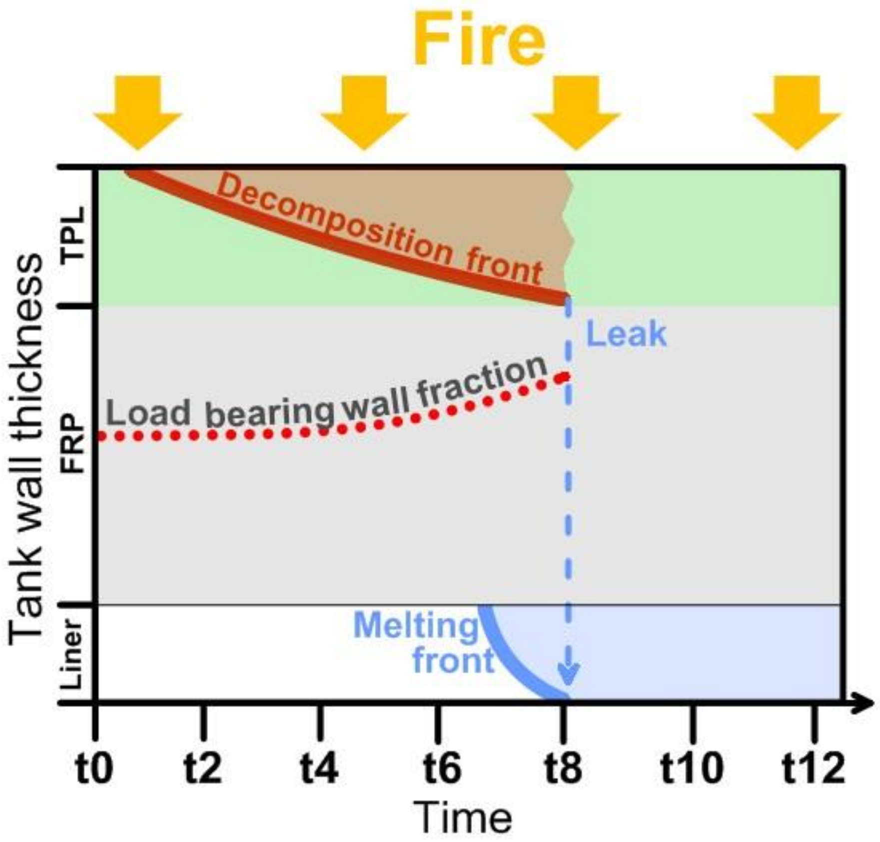
Explosion-free in a fire tanks

Explosion-free in a fire tank: concept
Original (left) and explosion-free (right) tank

Original tank: **rupture**



Explosion-free in a fire tank: **no rupture!**



First prototypes fire testing

Tanks parameters

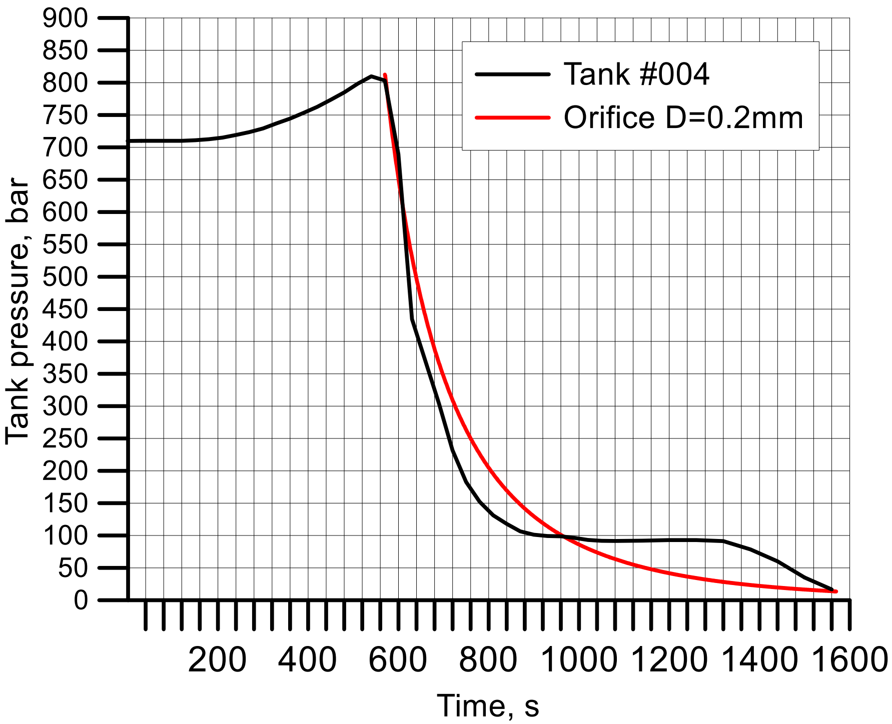
ID	OD of liner, in	OD of finished part, in	FRP#1 thickness, in	FRP#2 thickness, in	Weight, lb
#4	6.334	8.178	0.450	0.472	27.5
#5	6.336	8.465	0.366	0.699	32.3

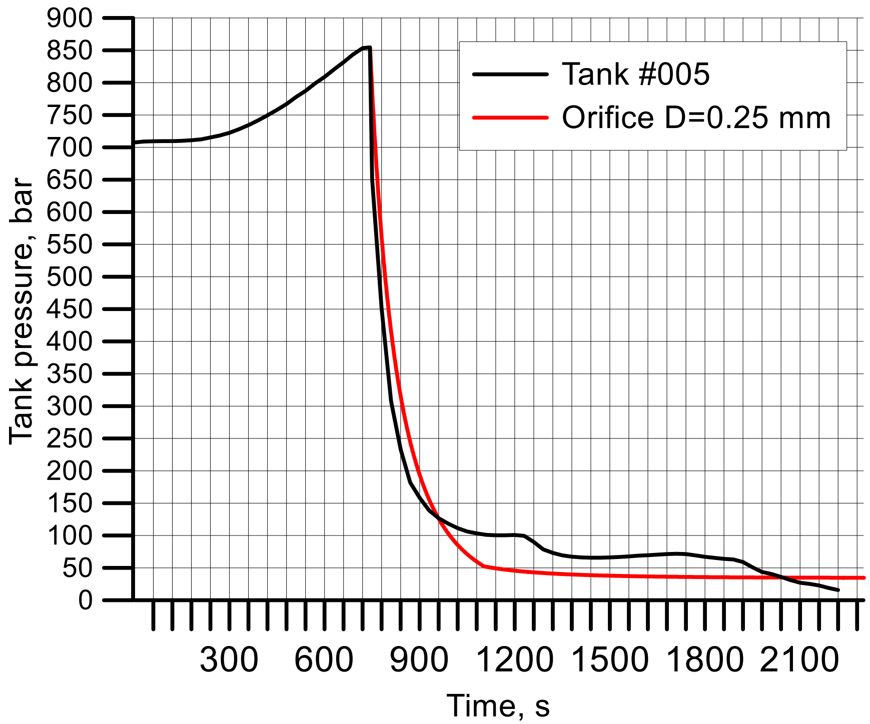
Fire test results

ID	Charge pressure	Vent pressure	Leak starts	Leak duration
#4	700 bar	812.4 bar	9m 27s	16m 29s
#5	700 bar	854.5 bar	12m 23s	14m 37s

Explosion-free in a fire tank testing

Insignificant wall leak: equivalent D=0.20-0.25 mm

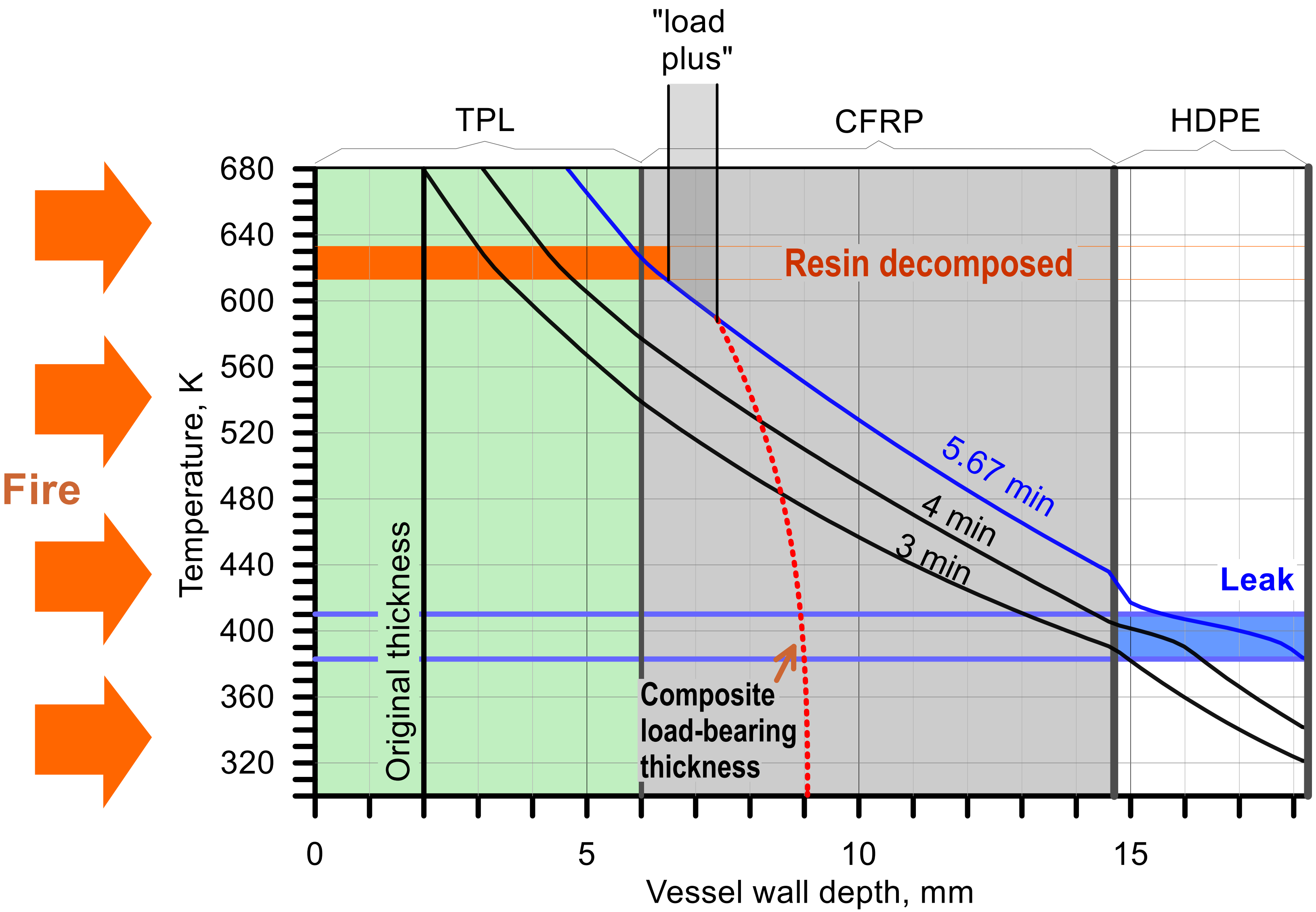




Next 4 slides demonstrate simulated performance of a second prototype of explosion-free in a fire tank at different HRR/A in the same range as original non-protected tank (shown previously). Wall thickness in increased just from 16 mm to 18 mm (insignificant 12%).

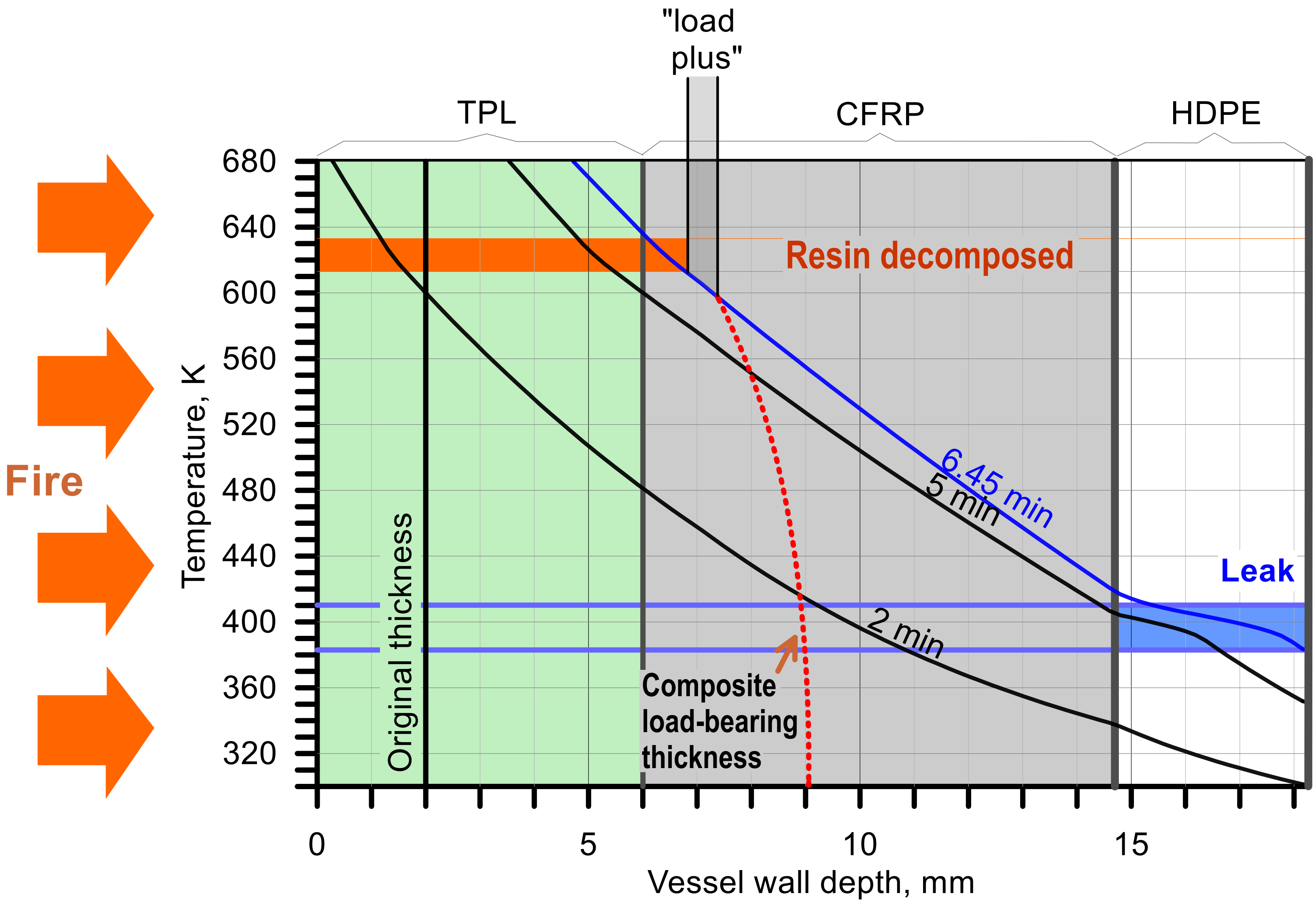
Real HRR/A (gasoline) fire: Leak!

HRR/A=1.56 MW/m² (leak at 5.67 min)



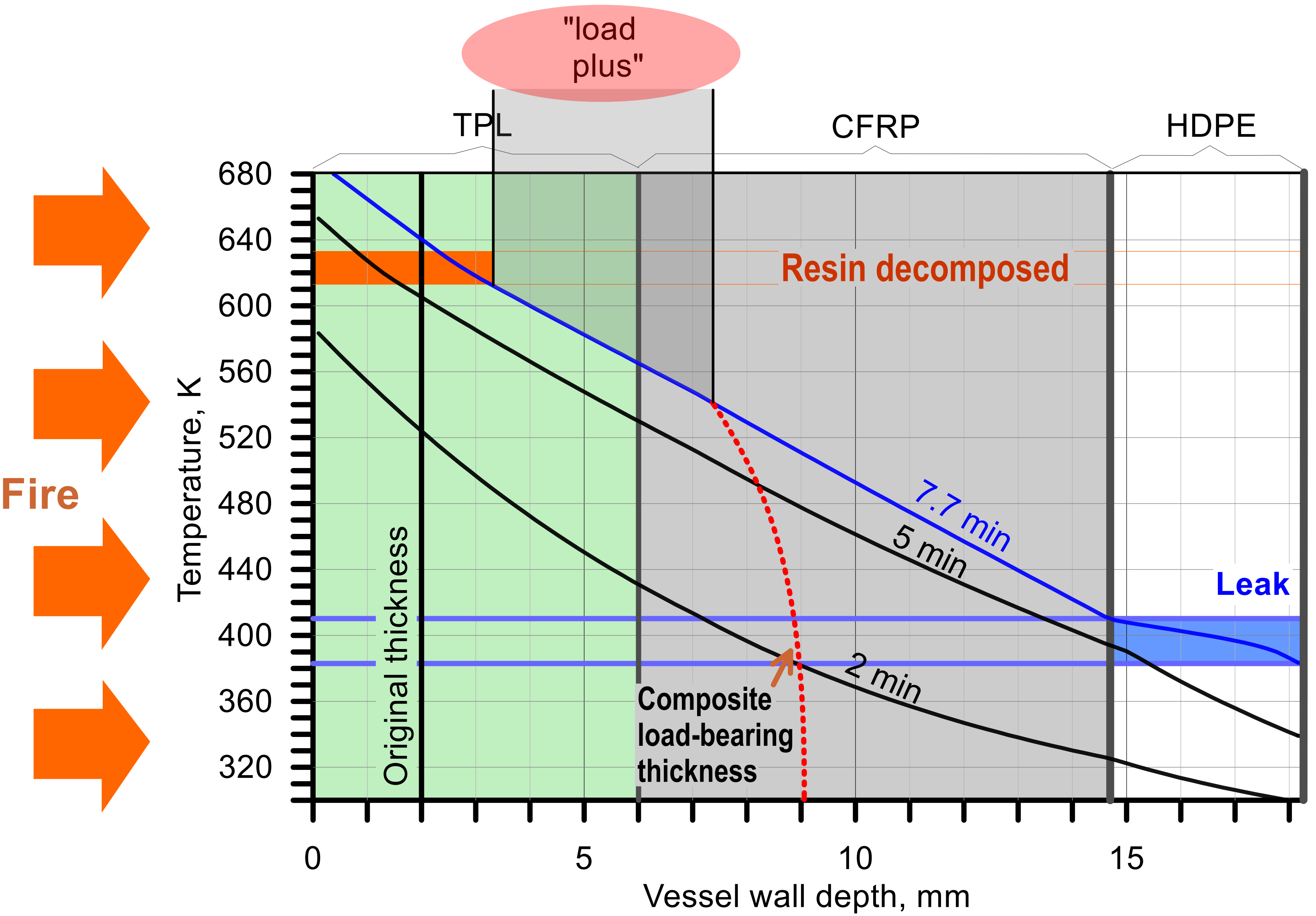
Medium HRR/A fire: Leak!

HRR/A=0.62 MW/m^2 (leak at 6.45 min)



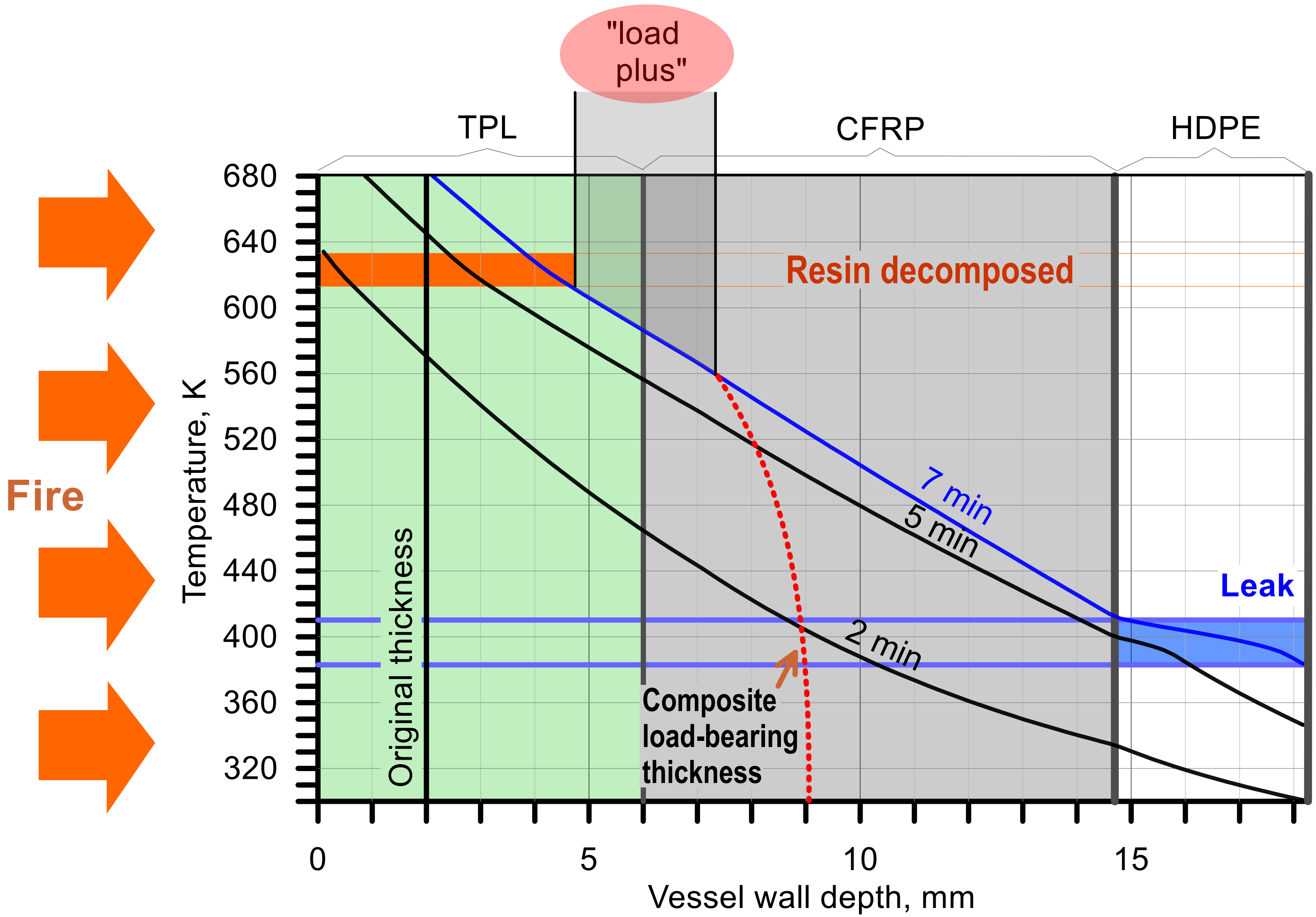
Small HRR/A fire: Leak!

HRR/A=0.29 MW/m^2 (leak at 7.7 min)



Another small HRR/A fire: Leak!

Diesel localised HRR/A=0.2 MW/m² (at … min)



Explosion-free in a fire tanks

Second prototype testing

VIDEO

Explosion-free in a fire tanks

Concluding remarks (1/2)

- The first and second prototypes of explosion-free in a fire composite tanks are manufactured and successfully tested.
- Explosion-free in a fire tanks leak in the whole range of fires HRR/A=0.20-1.56 MW/m^2 (numerical tests).
- Explosion-free in a fire safety technology has larger safety margin for lower HRR/A. Thus, fire testing should be focused on scenarios with high HRR/A (gasoline).
- The devastating consequences and associated risks of hydrogen vehicles could be eliminated with the use of explosion-free in a fire tanks:
    - No blast wave!
    - No fireball!
    - No projectiles!
    - No long flames!
    - No pressure peaking phenomenon!

Explosion-free in a fire tanks
Concluding remarks (2/2)

- Explosion-free in a fire tank, manufactured using leak-no-burst (LNB) safety technology, closes safety issues of any hydrogen vehicle in confined spaces like:
    - Garages
    - Tunnels
    - Underground parking
    - “Isolated” marine and aviation applications, etc.
- Testing confirmed that the customers could have hydrogen vehicles with explosion-free in a fire onboard storage tanks.

Ulster University

Text amendment No.2:
TPRD and “other proven safety means”

C. Description of typical HFCVs
3. Hydrogen storage system

(a) Compressed hydrogen storage system

“19. ...Most high pressure hydrogen storage containers used in fuel cell vehicles consist of two layers: an inner liner that prevents gas leakage/permeation (usually made of metal or thermoplastic polymer), and an outer layer that provides structural integrity (usually made of metal or thermoset resin-impregnated fibre-reinforced composite wrapped over the gas-sealing inner liner).” In a fire test an insignificant leak through tank wall is allowed if it is a part of a tank safety design.

Rationale: GTR#13 should be open to innovations and further improvement in provision of life safety and property protection. Hence, other than TPRD (or in addition to TPRD) proven means for safe release of hydrogen in a fire to exclude tank’s rupture should be allowed.

C. Description of typical HFCVs
3. Hydrogen storage system

(a) Compressed hydrogen storage system

“22. In the event of a fire, thermally activated pressure relief devices (TPRDs) or/and other proven means provide a controlled release of the gas from the compressed hydrogen storage containers before the high temperatures in the fire weaken the containers and cause a hazardous rupture. TPRDs ~~are~~ should be designed to vent the entire contents of the container~~ rapidly.~~” excluding its rupture during blowdown. TPRD design should exclude the pressure peaking phenomenon in confined spaces like garages, etc.

Rationale: GTR#13 should be open to innovations and further improvement in provision of life safety and property protection. Hence, other than TPRD (or in addition to TPRD) proven means for safe release of hydrogen in a fire to exclude tank’s rupture should be allowed.

E. Rationale for paragraph 5…
2. Vehicle fuel system requirements…

(a) In-Use Requirements

(viii) Recommended features for design of a hydrogen fuel system

"(a) The hydrogen fuel system should function in a safe and proper manner and be designed to minimize the potential for hydrogen leaks, (e.g. minimize line connections to the extent possible). The flow of hydrogen through TPRD or other proven means to control release in conditions of a fire should be minimised too with exclusion of a possibility of tank rupture;"

Rationale: GTR#13 should be open to innovations and further improvement in provision of life safety and property protection. Hence, other than TPRD (or in addition to TPRD) proven means for safe release of hydrogen in a fire to exclude tank's rupture should be allowed.

5. Performance requirements

5.1. Vehicle fuel system

5.1.4. Verification test for service terminating performance in fire

A hydrogen storage system is pressurized to NWP and exposed to fire (para. 6.2.5.1. test procedure).

"A ~~temperature~~ thermally-activated pressure relief device or other proven means shall release the contained gases in a controlled manner without rupture" and accounting for the pressure peaking phenomenon in confined spaces like garages.

Rationale: GTR#13 should be open to innovations and further improvement in provision of life safety and property protection. Hence, other than TPRD (or in addition to TPRD) proven means for safe release of hydrogen in a fire to exclude tank's rupture should be allowed.

5. Performance requirements

5.2. Vehicle fuel system

5.2.1.3. Hydrogen discharge systems

5.2.1.3.1. Pressure relief systems…

…

“(b) Storage system TPRDs…

(c) Other pressure relief devices (such as a burst disk)…”

(d) Other proven safety means for pressure relief from a storage container in a fire.

Rationale: GTR#13 should be open to innovations and further improvement in provision of life safety and property protection. Hence, other than TPRD (or in addition to TPRD) proven means for safe release of hydrogen in a fire to exclude tank’s rupture should be allowed.

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.1. Fire test

“The test article is held at temperature (engulfing fire condition) until the system vents through the TPRD or other proven safety means and the pressure falls to less than 1 MPa… the storage system shall not rupture”. The design of TPRD or other proven safety means should exclude confined structure demolition by the pressure peaking phenomenon.

Rationale: GTR#13 should be open to innovations and further improvement in provision of life safety and property protection. Hence, other than TPRD (or in addition to TPRD) proven means for safe release of hydrogen in a fire to exclude tank’s rupture should be allowed.

6. Test conditions and procedures
6.2. Test procedures…for hydrogen storage

6.2.5. Test procedures for service terminating performance in fire

6.2.5.1. Fire test

Documenting results of the fire test

“The results include the elapsed time from ignition of the fire to the start of venting through the TPRD(s) or other proven safety means, and the maximum pressure and time of evacuation until a pressure of less than 1 MPa is reached.”

The fire resistance rating of a tank (elapsed time from ignition of fire to tank rupture) should be defined in a test without TRPD and documented, along with the specific heat release rate, HRR/A, of a fire source.

Rationale: Fire test protocol should include requirement for determination of fire resistance rating (FRR) of the container to inform first responders for development of their intervention strategies and tactics.

Conclusions (1/5)

- **Only temperature control is insufficient** to have test reproducibility in different testing laboratories around the globe. It must be complemented by **control of specific heat release rate in a fire source (burner) HRR/A** to test different **thermal conditions** in variety of real fires.
- **Maximum temperature requirements** in “fire test” (with localised and engulfing parts) **should be relaxed**
- **HRR/A** is easy to measure parameter (fuel flow meter) compared to the measurement of heat flux to tank $\dot{q}''$.
- **Tank must withstand any fire condition without explosion.** Tank must undergo fire test at gasoline spill fire scenarios with HRR/A=1-2 MW/m^2 and, if needed, at smaller HRR/A, e.g. for scenario of localised fire between rear seats, smouldering fire scenario and similar scenarios (if this indeed reflects the reality).

Conclusions (2/5)

- Fire resistance rating, FRR, is a function of specific heat release rate, HRR/A. Lowering HRR/A cannot be used to pass "fire test", which must include (among others if needed) localised part of fire test with HRR/A=1-2 MW/m^2 (characteristic for gasoline spill fire scenario).
- Engulfing fire test without TPRD must be re-established.
- Heat flux $\dot{q}''$ changes in time (measurements and 3D simulations) for fire source with constant HRR/A.
- **Original** composite tank of volume about 10 L and NWP=70 MPa (no TPRD) **ruptured** in all numerical fire tests with **HRR/A in the range 0.29-1.5 MW/m^2**. **Explosion-free in a fire tank didn't rupture** in all tests at the same HRR/A range.

Conclusions (3/5)

- GTR#13 could give an example of a burner design but **should not prescribe** a burner design. Diffusion combustion burner is preferable to closer reflect the reality.
- The **pipe burner prototype** reproduces GTR#13 minimum temperatures requirements with **HRR/A=1 MW/m^2** and wind velocity 1.8 m/s (“light breeze”), and **5 m/s** (“gentle breeze”). However, it does not reproduce required temperatures at wind velocity 10 m/s (“fresh breeze”).
- Consider changing “Localized portion of the fire test” for stand-alone tank as it stands now to **in-situ fire testing of actual vehicle design**.
- The first prototypes of explosion-free in a fire composite tanks are manufactured and successfully **tested**. Explosion-free in a fire tanks **leak** in the **range of fires HRR/A=0.20-1.56 MW/m^2** (numerical tests).

Conclusions (4/5)

- The **devastating consequences** and associated risks of hydrogen vehicles could be eliminated with the use of **explosion-free in a fire tanks**:
  - No blast wave!
  - No fireball!
  - No projectiles!
  - No long flames!
  - No pressure peaking phenomenon!
- Explosion-free in a fire tank, manufactured using leak-no-burst (LNB) safety technology, **closes safety issues of any hydrogen vehicle in confined spaces** like:
  - Garages
  - Tunnels
  - Underground parking
  - “Isolated” marine and aviation applications, etc.

Conclusions (5/5)

- Based on performed experimental, theoretical and numerical studies the amendments are proposed to the following GTR#13 sections:
  - 5. Performance requirements
  - 6. Test conditions and procedures
  - C. Description of typical HFCVs, and
  - E. Rationale for paragraph 5…
- GTR#13 text is amended to account for the **pressure peaking phenomenon** (following requirements of ISO 19882 “Gaseous hydrogen – Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers”).

Ulster University

THANK YOU

Ulster University