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Research Summary – Modelling of a UN-T75 ISO Portable Tank in Fire and Impact Conditions

*Transportation of Dangerous Goods (*TDG) | *Scientific Research Division*

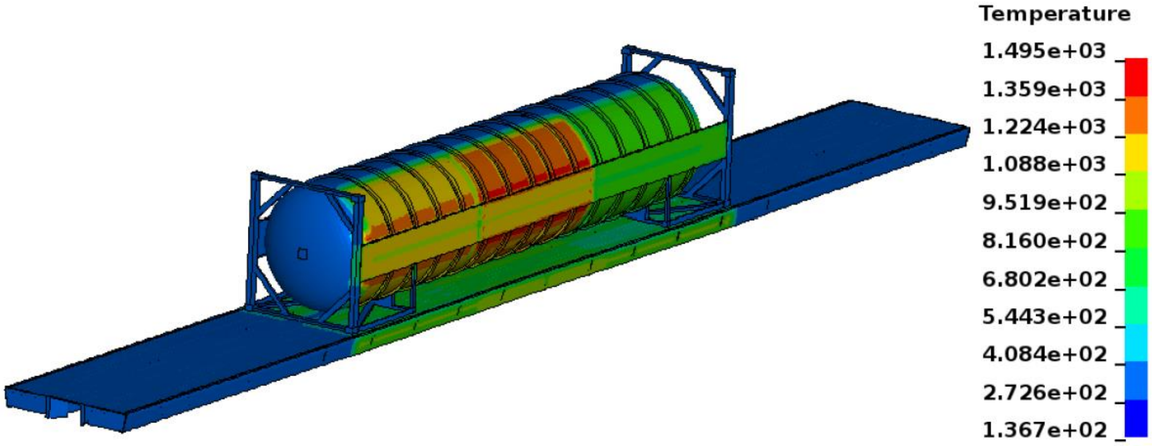

Figure 1:Predicted external tank temperature [K] after 30 min in pool fire

Summary

In this research, Transport Canada created a computer model of a UN-T75 ISO portable tank containing liquefied natural gas (LNG), and used that model to perform a number of evaluations related to fire and impact performance, to understand how these portable tanks perform in different kinds of accident conditions.

BACKGROUND

Liquefied natural gas (LNG) is a Class 2.1 flammable gas, made by cooling natural gas (primarily comprised of methane) below its boiling point so it can be shipped as a liquid. Transport Canada's *Transportation of Dangerous Goods Regulations* currently allows cryogenic LNG to move by rail in Canada in UN-T75 ISO portable tanks transported on flat deck rail cars, as well as in TC-113 tank cars.

Because the safety performance of UN-T75 portable tanks in fire conditions had not previously been verified, the United Sates Department of Transportation Federal Railroad Administration (U.S. DOT FRA) performed full scale fire testing in 2017 and 2022 to obtain pressure, temperature, and heat flux data, and to monitor pressure relief valve (PRV) behaviour. [1, 2] This data was supplied to Transport Canada for the purposes of this study.

OBJECTIVES

Transport Canada's objective in this work was to use the FRA fire test data to support the creation of a finite element (FE) model of the portable tank and its lading, to develop an analytical method of evaluating the fire safety performance of these portable tanks.

METHODS

In previous work for Transport Canada, Friedman Research Corporation (FRC) developed a FE model to simulate the heating of an ISO UN-T75 cryogenic tank 60% full of liquefied nitrogen and used the Fire Dynamics Simulator (FDS) model to replicate the fire conditions and generate a heat flux boundary condition. [3] This current work was based on that FE model, and was organized into six (6) tasks:

Task 1: Modelling of UN-T75 Tank with LNG

Three (3) approaches to model the heating of the LNG lading were considered, with the goal of including the chemical reactions and phase change to accurately simulate how the LNG behaves in a pool fire.

Task 2: Model refinement based on 2nd fire test

Data from the 2022 fire test, which used LNG as a lading, was used to validate the way the modelled portable tank heats up and how its internal pressure increases. Temperatures were recorded using thermocouples submerged in the fluid, in the vapour space, on the interior surface of the internal tank, and on the external surface of the external tank. Incident heat flux was measured using directional flame thermometers (DFTs) on the exterior tank. Internal tank pressure data was collected from an external sensor coupled to the tank via a closed pipe and the tank's pressure gauge. The pressure in the annular space was also monitored. Differences in insulation performance were investigated to attempt to replicate the measured experimental results.

Task 3: Simulating the effects of PRV LNG exhaust

FDS models were used to simulate the flow of LNG through a PRV and subsequent jet fire impingement on a nearby ISO-T75 tank. LNG mass flow rates, flame size, temperature, and incident heat flux were estimated.

Task 4: Predicting a BLEVE event

The computer model was extended past the validated heating and pressurization levels to attempt to predict the characteristics (e.g., time to event, pressure) of a BLEVE (boiling liquid expanding vapour explosion), where the container ruptures when LNG contained above its atmospheric boiling point is rapidly exposed to ambient conditions through the rupture of the container. Four (4) models were used:

- A thermal-structural model with phase change to model the heating to the point of tank failure;
- A thermal-structural model to predict the point of tank failure and subsequent fragmentation;
- A compressible fluid dynamics (CFD) model with phase change to investigate the feasibility of evaluating the near-field response of the fluid immediately post-BLEVE; and
- A CFD model to model post-BLEVE vapour dispersion and ignition.

A test failure matrix was developed to assess different heating, fill, damage scenarios, and the presence of obstacles in the environment on the features of the predicted BLEVEs.

Task 5: Predicting the effects of PRV failure conditions

PRVs that had been in the 1st fire test were installed in a test assembly. The performance of the PRVs when expelling water or liquid nitrogen was investigated, to assess opening pressure and mass flow rate, as well as general performance with a cryogenic liquid. Performance was compared against manufacturer test data, and no testing of an undamaged PRV was performed.

Task 6: Effects of rollover conditions

An FE model was used to estimate damage to a single UN-T75 tank in the following scenarios:

- Rollover from a flat car
- Rollover from a flat car with velocity
- Impact with bridge/tunnel abutment
- Impact with railcar coupler in perpendicular and longitudinal directions

RESULTS

Task 1

The initial setup of the model was successful in using both equation of state (EOS) and chemistry-based material models to simulate the heating and phase change of natural gas.

Task 2

The models were able to predict the external tank temperature within 200 K for most locations, but prediction of the internal fluid temperature (Figure 2) during the closed volume portion of the test (prior to PRV activation) depended on tuning of the insulation conductivity.

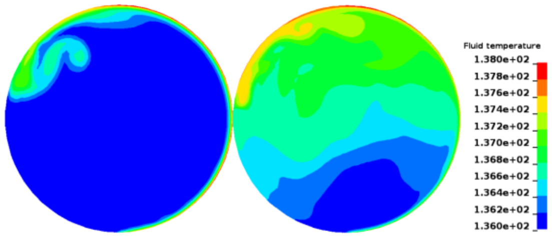

Figure 2: Fluid temperature [K] at 20 s (left) and 6 min (right) showing convective mixing and temperature stratification; centre cross section of tank

After PRV opening, the phase change of the lading was not able to be directly modelled, but predicted temperature and pressure were still comparable to the test data.

Task 3

The observed nitrogen exhaust from the 1st fire test and the calculated methane jet fire (Figure 3) dimensions could be large enough to impinge on other railcars. The model predicted that in a high flow rate scenario, the heat flux was higher and more localized than the heat flux from a pool fire and could be directed towards the piping cabinet of an adjacent tank, which would increase the likelihood of PRV Teflon seal failure.

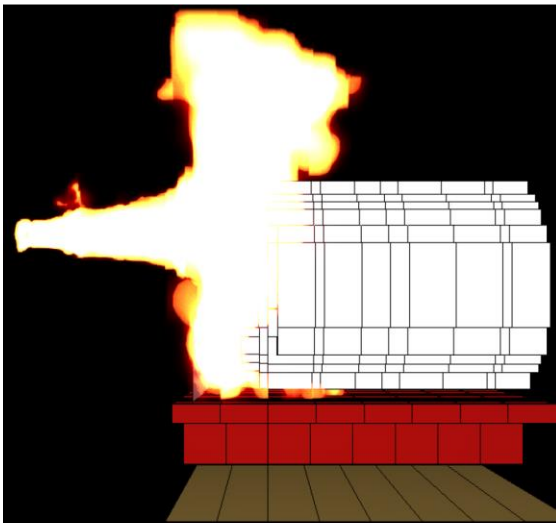

Figure 3: Flame impingement on railcar at 1 m standoff distance, 'high' flow rate

Task 4

Table 1 describes the outcome for predicted BLEVE scenarios, based on a set temperature of the inner tank and the assumed pressure rise from the 2nd fire test. These times are for comparison between runs only and are not necessarily a prediction of the actual time to BLEVE and should be used as a relative comparison between the scenarios. Times shown in Table 1 do not include time to heat the tank to the scenario fire temperature. Scenarios with higher temperature had a decreased time to BLEVE once at their scenario temperature, and a lower failure pressure. The presence of isolated pathways for heat transfer, such as denting of the exterior shell, also decreased the time to BLEVE.

Table 1: Summary of predicted BLEVE data using two (2) pressure rise assumptions (grey indicates lower pressure/earlier time to BLEVE than the median), starting from a heated tank

Scenario	Pressure at failure (normalized)	Time to BLEVE (ave. pressure rise; min)	Time to BLEVE (max pressure rise; min)
COLD_ALL	1.00	125	86
HOT_ALL	0.45	55	43
HOT_HALF	0.30	37	30
MID_HALF	0.53	65	48
COLD_HALF	0.63	78	56
HOT_ISOL	0.75	93	66
MID_ISOL	0.84	105	73
HOT_FULL	0.20	24	22
MID_FULL	0.53	65	48
COLD_FULL	0.65	80	58
HOT_EMPTY	0.45	55	42
MID_EMPTY	0.55	68	50
COLD_EMPTY	0.65	80	58

Generally, the initial point of failure was at the location of greatest temperature gradient in the tank where there was a buildup of strain difference, as shown in Figure 4 for the HOT_HALF scenario.

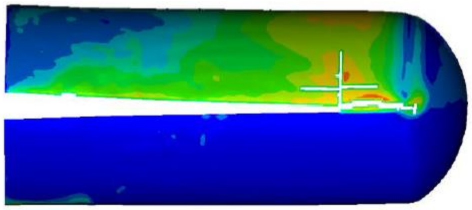

Figure 4: Fragmentation pattern for HOT_HALF scenario

In scenarios where the tank BLEVEs and the gas immediately ignites, the characteristics of the fireball varied based on the mass of LNG available in the tank at time of rupture, and the presence of obstructions on the ground.

The dispersion model predicted that in the event that a tank BLEVEs but the vapour does not immediately ignite, adequate flammable vapour would be present near ground-level to ignite in the presence of some other ignition source.

Task 5
Testing of the PRVs that had been used in the 2nd fire test indicated that thermal damage resulted in a reduced initial opening pressure than the manufacturer data, which could result in releasing vapour at a slightly greater flow rate than intended. When venting liquid nitrogen, the valves were susceptible to ice accumulation in and on the valve during release (Figure 5). As a result, the flow of liquid nitrogen through the PRVs was observed to be extremely unpredictable and transient, while the flow of water occurred in a more predictable way.

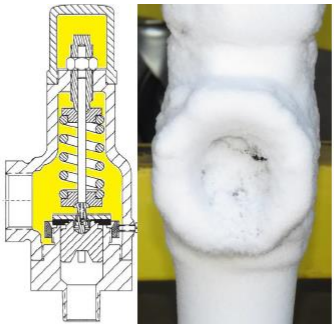

Figure 5: PRV cross section with open volumes at risk of ice accumulation highlighted in yellow (left); iced-over PRV (right)

Testing showed that at colder temperatures, when compared to manufacturer data, the spring constant changed, and a greater pressure was necessary to initiate opening, which could delay time to opening in an incident. The interaction of these effects further leads to uncertainty in the control of pressure in the portable tank during fire events.

Task 6
Tanks were not likely to rupture in rollover scenarios, either with or without longitudinal velocity. Scenarios that included impacts with other objects, such as abutments or tank cars, were likely to lead to failure of the tank (e.g., Figure 6).

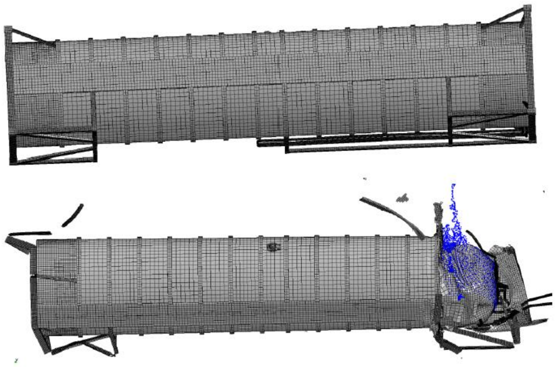

Figure 6: UN-T75 before (top) and after (bottom) impact with abutment (methane release shown in blue)

CONCLUSIONS

An extensive dataset generated from two (2) fire tests of UN-T75 tanks was used to support the development of multiple models which have demonstrated important capabilities. The report highlights the level of confidence for each and identifies the most significant features requiring improvement or additional data.

Some key findings include:

Tasks 1 & 2
- The predicted heat transfer into the LNG from the pool fire depended greatly on the definition of the tank insulation properties. It was also affected by the predicted intensity of convective mixing within the internal tank.

Task 3
- An LNG exhaust jet flame from a venting PRV can result in a greater localized heat flux to a neighboring tank than the pool fire itself.

Task 4
- In BLEVE scenarios, inner tank failure was predicted to occur fastest when the tank was held at higher temperatures, and failure was observed to occur at the location of

maximum temperature gradient.

- Tank failure cases with more localized heating, representative of external-to-internal tank contact from buckling, produced the largest predicted fragment sizes. In these localized heating cases, there was an indication that the tank failed at lower pressures than if a larger proportion of the inner tank was exposed to the same temperatures.
- Fragment velocity increased with internal pressure at failure.
- The post-BLEVE fireball size, heat flux magnitude, and heat flux duration all increased with increasing LNG mass at rupture.
- The predicted post-BLEVE fireball and gas dispersion response is sensitive to the nature of the tank rupture, mass of LNG, and any obstacles that may be present in the environment.

Task 5

- PRV performance could be negatively affected by both the cryogenic and fire environment that it is subjected to. This can potentially result in increased hazards such as improper functioning of the PRV due to ice buildup or changes to the spring constant, when compared to manufacturer data.

Task 6

- The risk of UN-T75 tank failure in derailments increases when derailments involve impacts with fixed objects, terrain features, or other railcars. On its own, a rollover did not result in tank failure, but could result in tank inversion that could potentially degrade or impede PRV performance. In any case, the loss of the external jacket and accompanying insulation would increase the risk of tank failure when exposed to fire in that area.

FUTURE ACTION

Improving the representation of how the heat transfer properties of insulation change at high temperatures would improve the fidelity of the modelling endeavour. Testing of the insulation would be necessary to monitor its degradation and performance under high heat. The model could also be improved by adding the effects of nucleate boiling and heat transfer to the vapour space.

The BLEVE prediction model could be improved by adding tank details such as welds, internal reinforcements, heat affected zone material properties, thermal creep response and other relevant details. The time required to heat the tank to the scenario temperature could also be assessed, to obtain a complete estimate of time in fire until potential BLEVE event. Full validation of the model would require additional test data, obtained through small-scale testing of tank rupture and BLEVE.

Additional studies using the demonstrated models could be undertaken to evaluate the performance of similar tanks in pool fires with other cryogenic fluids or pressurized gasses. This would require changes to both the lading properties and work to account for differences in tank design.

REFERENCES

[1] US DOT FRA, "Fire Performance of a UN-T75 Portable Tank Phase 1: Loaded with Liquid Nitrogen | FRA (dot.gov)", 2020.

[2] US DOT FRA, "Fire Test of an UN-T75 Portable Tank on a Flat Car Phase II | FRA (dot.gov)", 2023.

[3] Friedman, K., & Mattos, G., Friedman Research Corporation. “Analysis of Liquid Nitrogen Test Data”, Unpublished Report for Transport Canada, 2018.

Report: Modelling of ISO [UN-T75] Portable Tank Fire Test (2023)

Authors: K. Friedman and G. Mattos

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CONTACT

To obtain a copy of the report, please contact us:

TDG Scientific Research
TC.TDGScientificResearch-RecherchescientifiqueTMD.TC@tc.gc.ca

KEYWORDS

LNG, UN-T75, portable tank, cryogenic liquid, fire testing, BLEVE, rollover, modelling, simulation, PRV, dangerous goods, transportation, rail