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TNO report

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Heat load resistance of cryogenic storage tanks – Results of LNG Safety Program

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List of abbreviations

ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road
BAM	German Federal Institute for Materials Research and Testing
BLEVE	Boiling Liquid Expanding Vapour Explosion
CEN	European Committee for Standardization
CFD	Computational Fluid Dynamics
FEM	Finite Element Method
HAZID	Hazard Identification study
ISO	International Organization for Standardization
JIP	Joint Industry Program
LIN	Liquid Nitrogen (LIN_2)
LNG	Liquid Natural Gas
LOX	Liquid Oxygen
LPG	Liquefied Petroleum Gas
MAWP	Maximum Allowed Working Pressure
MLI	Multi-Layer Insulation
NEN	Netherlands Standardization Institute
PGS	Hazardous Substances Publication Series
PRD	Pressure Relief Device
PRV	Pressure Relief Valve
QRA	Quantitative Risk Assessment
RBM II	Dutch QRA software for hazardous transport
RID	Regulations concerning the International Carriage of Dangerous Goods by Rail
RIVM	Dutch National Institute for Public Health and the Environment
SAFETI-NL	Dutch QRA software for hazardous installations
SC	Steering Committee of LNG Safety Program
SSSC	Small Scale Supply Chain
TEC	Technical Expert Committee of LNG Safety Program
TNO	Netherlands Organisation for Applied Scientific Research

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1 Introduction

1.1 Background

Any tank filled with refrigerated (cryogenic) or liquefied gas is pressurised and susceptible to heat influx, due to the storage conditions and physical properties of the substance inside the tank. Natural gas (methane) has to be refrigerated below its critical point of -82.6°C (at 45 bara) to be liquefied to LNG (approx. -162°C at 1 bara). This is unlike the hydrocarbon gases propane and butane – with their critical points above ambient temperatures – where only pressurisation is sufficient for liquefaction to LPG.

Transport and storage tanks for cryogenic gases[1] (e.g. LNG) are provided with thermal insulation to prevent or at least minimize the heat influx from a source in the surroundings – ambient air, solar radiation, fire exposure – into the liquid. A temperature increase of the liquid will result in a pressure increase in the tank in correspondence with the (saturated) vapour pressure of the substance. Pressures far above the maximum allowed working pressure (MAWP) should be prevented by activation of installed pressure relief devices (PRD). In general, a PRD consists of a spring loaded safety valve or pressure relief valve (PRV). Furthermore, the yield and tensile strengths of the pressurized shell – carbon steel construction – will start to decrease at temperatures above 300°C. Progressive weakening of the shell strength could lead to a (catastrophic) tank rupture below its design and test pressures.

Regulations regarding transport of dangerous goods like ADR/RID – or the EN 13458 standards for stationary cryogenic vessels – comprise several requirements to prevent that a pressure tank will fail during normal operation. In the event of exposure to fire the installed PRV’s are expected to have sufficient delivery capacity and prevent any over pressurization. The LNG transport fleet in the Netherlands is (currently) equipped with double-walled vacuum insulated tanks. Double-walled tanks are considered far more robust, than single-walled tanks with insulation and aluminium cladding. Single-walled tank constructions – considered to be less robust – are not prohibited for LNG in the 2014 ADR/RID regulations [22], but will be in the next regulations.

1.2 LNG Safety Program

LNG is to be introduced in the Netherlands and in other European countries as a new candidate in the traditional fuel mix for truck transport, barges and short sea vessels. The LNG Gate terminal has been refurbished to distribute LNG as a liquid to the Dutch transport fuel markets. The introduction of LNG as a transport fuel requires full understanding of all safety aspects related to the use of it and adjustment of many codes and regulations.

[1] Generally, the term ‘cryogenic’ is used in reference to the liquefaction of permanent gases such as oxygen (LOX), nitrogen (LIN), hydrogen (LH2), and helium (He). These gases phase change from gas to liquid at atmospheric pressure at temperatures called the normal boiling points. The cryogenic region is often considered to be that below approx. 120 K or -153°C. Source: [NIST].

The initiative for the LNG Safety Program was taken by the Netherland's National LNG Platform (private sector) after numerous requests from market parties and Dutch emergency response organisations to enhance and accelerate full development of LNG safety issues. The LNG Safety Program is a joint cooperation with public and private stakeholders (JIP) and is financed by the members of the National LNG Platform, the Ministry of Economic Affairs and the Ministry of Infrastructure and Environment. The overall objective of this JIP is to enhance the knowledge about internal and external safety of small scale LNG supply and the use of LNG as a fuel in trucks, inland-barges and short sea vessels to allow development of innovative and safe distribution and LNG propulsion systems. The program intents to provide necessary knowledge for:
- Regulatory development of internal safety standards such as PGS 33;
- Enhanced methods to calculate external safety risks for QRA models like Safety.NL and RBM II;
- Normative documents via NEN, extended to international CEN/ISO level;
- Local permit granting authorities;
- Guidance for emergency response organisations;
- Guidance for engineering companies to provide safe designs in line with codes and regulations.

The JIP consortium consists – besides the initiating partners NEN (program management), TNO (technical research coordination) and RIVM (governmental policy development participation) – of third party safety experts and public authorities such as the emergency response organisations. The Steering Committee is responsible for the management of the overall progress and quality within the JIP. The SC is chaired by NEN and consists of dignitaries from program participants and governmental organizations. The Technical Expert Committee (TEC) is responsible for the scientific quality of the research programs (progress report to the SC, drafting proposals for projects, experimental set up, verification, e.g.). The TEC – chaired by TNO – consists of program participants and third party specialists.

The main objective for the technical research program within the JIP LNG Safety Program is to validate starting points or assumptions taken in the RIVM risk calculation methodology and PGS 33-1 standard [19], which constitute obstacles in the permitting of small scale LNG in the Netherlands. One program line of the technical research program specifically focusses on stationary storage tanks and mobile transport tanks, and mobile fuel tanks.

1.3 Identified safety issues for tank research

With regard to the deliverables of the tank program line RIVM has requested to provide conclusive evidence, that:
1. Double-walled pressure tanks have – at least – equivalent heat load resistances to those of single-walled pressure tanks fitted with heat resistant coatings. This is an assumption in the RIVM risk calculation methodology for LNG.
2. Double-walled pressure tanks can endure exposure to radiation intensities of 35 kW/m^2 or more without any catastrophic rupture of the tank. This was a starting point in PGS 33-1 for determining the internal safety distances at a fuel station.

The HAZID report [6] has provided an overview of relevant LNG scenarios with safety issues that require consideration or follow-up in the research program. The following made recommendations were relevant to be further investigated in the tank research program line:

- Investigate (e.g. by means of experimental tests) whether a warm BLEVE of the LNG truck and storage tank is credible considering the insulation (vacuum insulated, double-walled) of the tanks and the ability to withstand fire impingement at a certain heat radiation level and exposure duration. Consider also other situations: the truck is not double-walled or otherwise insulated (e.g. coating). Take into account the required design capacity (design case) of the PRV required in relation to the pressure build-up inside the tank to prevent a possible warm BLEVE.
- Consider the relevance of warm BLEVE scenario for mobile stations, considering the placement of trailers with other flammable liquids close to the storage tank. Consider requirements in guideline PGS 33-1.
- Evaluate the relevance and background of the distance between storage tank and filling point (conformity PGS 33-1, minimum 10 meter) considering the outcomes of the investigation into credible fire scenarios that could impinge the tank to a point that it could BLEVE.

Another issue with pressure tanks concerns the current ongoing discussion within the ARD/RID Working Group[2] about (uncertainties of) the heat resistant coatings and pressure relief devices on transport tanks for liquefied gases. The existing uncertainties concern road tanks and rail wagons with liquefied gases (e.g. propane, LPG). However, these uncertainties will also become relevant for LNG when large volumes are going to be transported by road and rail in the Netherlands and across Europe. In case, if there is any heat influx into the liquid LNG is more susceptible to heat than LPG. The Working Group concluded that a PRV hardly delays the time to BLEVE, while a fully coated tank with a PRV delays the occurrence of a BLEVE by approx. 1 to 2 hours. The assumption in transport regulations that only the presence of a PRV can avoid a BLEVE in fire situations was proven wrong by experimental testing. The weakening of the steel as a result of fire exposure was not addressed. The Working Group has advised to evaluate the existing provisions for PRD's in the UN regulations.

1.4 Scope and objective

After consideration of the safety issues relevant for LNG tanks and consultation with members of the TEC the objective of the (thermal) tank research program is to answer to following research questions:

1. Has a double-walled pressure tank – at least – equivalent heat load resistance to those of single-walled pressure tank fitted with heat resistant coating?
2. Can a double-walled pressure tank endure an exposure to radiation intensities of 35 kW/m^2 or more without any catastrophic rupture?
3. What heat load and duration of exposure are necessary to catastrophically rupture a full size double-walled pressure tank (i.e. time to failure)?

[2] Upcoming Joint Meeting of the RID Committee of Experts and the Working Party on the transport of Dangerous Goods; Working Group on the reduction of the Risk of a BLEVE.

This research program intends to demonstrate the heat resistant functionalities of double-walled vacuum insulated tanks as designed. An investigation into the vulnerabilities of tanks due to damage or overturning is not included in the scope. After consultation with the working group members of TEC the focus of the test program was shifted from mobile transport tanks towards stationary storage tanks for LNG[3].

1.5 Limited time frame for preparation and execution

The final agreement on the scope and (re)definition of the tank test program – end November 2014 – was at a relatively late stage of the project time frame. May 2015, TNO was unexpectedly confronted with the ending of the project commitment and participation of a tank manufacturer. After consolation of the TEC and approval of the SC, TNO decided to design and engineer the single walled and double walled tanks itself and supervise the manufacturing of the tanks by Ales Metaaltechniek BV, a metalworking company. TNO was supported by another tank manufacturer – Cryovat BV – with the practical ins-and-outs of designing, instrumentation and manufacturing a double walled cryogenic test tanks, comparable to the ones commercially available.

The whole process from design to manufacture and instrument the two test tanks had to take place in roughly three to four months, in order to meet the last available testing window before winter at BAM Horstwalde. In this process TNO took a pragmatic approach with respect to timing, availability and cost aspects. Because of the time constraints the normal process of consultation, approval, pre-testing, preparation and commissioning could not always be followed and formalised.

[3] Stationary tanks are usually placed in vertical position and consist of two concentric vessels with an austenitic steel inner shell and a carbon steel outer jacket. The interspace between the tanks is filled with perlite powder and evacuated. Unlike the two concentric vessels of mobile transport tanks which only consist of austenitic steel which are nowadays fitted with so-called super insulation (evacuated interspace with multi-layer insulation or MLI). Also the support construction of the inner to the outer vessel differs, whereas manufacturers make their own design choices – allowed within set standards.

2 Approach

The resistance of a pressurised tank against fire exposure cannot be demonstrated by separately testing the elements of the fire protection system. The tank construction (wall thickness, insulation) and its safety accessories (heat resistant coating, double walls, PRVs) need to be tested as a whole and subjected to heat radiation or direct flame impingement in order to bring about stress conditions on materials.

Available data sets for comparison
Heat load tests where the tank is fully engulfed in flames are called bonfire tests. The ability to make a comparison between single-walled tanks with heat resistant coating and double-walled tanks, forms the base for the tank configuration, test conditions and analysis of the data set. The most likely candidate for comparison with LNG tanks are pressurized LPG tanks for which several bonfire tests or test series have been performed the past decades that are well documented in scientific journals [3-16]. The most recent test series were performed by Balke and Heymes. The test setup for LNG tanks was aligned with the test series performed by the Bundesanstalt für Materialforschung und -prüfung (BAM) or Federal Institute for Materials Research and Testing located in Berlin Germany. BAM has connected their experimental test data and in-depth knowledge on tank (fire) behaviour. Within TNO generic models were already available on the thermodynamic processes in a LPG tank and the structural integrity of such tank as a function of temperature of the environment [21].

Providing conclusive evidence
Bonfire tests provide insight into the behaviour of one tank configuration and during one specific fire exposure. Complimentary, series of bonfire tests are then required to validate whether scenarios are realistic or representative. The size of the test tanks and the number of tests are cost determining factors within the test program. TNO intends to extend ─ albeit validated with two tests ─ the insight by tank size scale-up and heat load differentiation. This extension is to be achieved by adaptation of (validated) calculation methods, which were developed by TNO for double-walled cryogenic pressure tanks.

The ‘heat load tolerance’ of a tank is determined by the increase in pressure versus the capacity of the pressure relief valve and remaining pressure containment capacity. The remaining pressure containment capacity is a function of the temperature increase of the pressure wall. TNO has developed a lumped thermal analytical tank model, which calculates the pressure and temperature evolution in time of a double walled vacuum insulated LNG tank, when subjected to heat load [2]. In the lumped approach, the circumference of the tank is divided into limited number segments. The thermal tank model was based on engineering relations between heat transfer through the tank walls and LNG, using a lumped approach. Venting via the PRV was included. In addition to the thermal model, a mechanical tank model was developed taking the pressure and temperature evolution as input and assessing stresses/strains in the tank, and the possibility of a structural failure. Both of these models were parametrised, meaning that the variables such as heat input, geometrical variables and other commonly used factors such as safety and imperfection factors can be changed easily to accommodate different accident scenarios. The combination of the thermal and mechanical models is called the 'TNO tank model'. The development of the TNO tank model was not part of the LNG Safety Program. Therefore, TNO background information related to the tank model used is not in detail presented in this report. The model output, so called foreground information, was initially used to predict the evolution of the two experiments and to optimize the design of experiment. Afterwards, the model theory was validated with the two experimental datasets. One dataset obtained from a single walled cryogenic test tank and the other from a double walled cryogenic test tank. With this approach and validated model, TNO was able to answer the program research questions.

Theoretical basis
The thermal model – that TNO developed prior to the experimental work described in this report – predicts the temperature of the liquid part of the inner tank, temperature and pressure of the vapour part of the tank, the filling level of the tank during the progressing fire, the temperature of the outer tank, the venting behaviour of the PRV. Temperature and pressure information are particularly important for the mechanical model and therefore these are used as input to calculate the structural integrity of the tank in fire.

The model predicts whether the inner tank bursts at the given time after initiation of the fire. An analysis of the material behaviour at high temperatures showed that a fire up to 450°C affects mild steel relatively little. However, beyond 500°C both yield stress and stiffness will be reduced significantly. Strength and stiffness of stainless steel have a more gradual decrease with increasing temperatures compared to the mild or carbon steel. In addition to the analytical model that was developed in MathCad and Microsoft Excel, a numerical model was developed, using the finite element (FEM) program, Abaqus. This FEM-model predicts the deformation of the inner tank at certain inner pressures and temperatures. As expected, the part of the tank which is filled with LNG (or any other cryogenic liquid) was deforming differently from the part that is filled with vapour. The analytical model was validated with the experimental results and used to answer the research questions.

A double walled LNG tank that is engulfed in fire will have an outer tank temperature that is beyond 600°C within minutes from the start of the fire. Mechanical strength of the mild and stainless steel at this high temperatures is poor. Depending on the compressive performance of the insulation layer and the presence (or not) of the stiffening rings on the outer tanks interior, buckling of the outer tank could be observed. Driving force to such event is the vacuum (very low pressure) on the interior face and the atmospheric pressure on the exterior face of the external tank. The subsequent behaviour of the tank depends on the scenario; for instance whether the (properly sized) PRV is working, or whether there is damage on the inner tank, etc. In case of an accidental failure of the outer tank and a consequent loss of vacuum (or any other cause to an increase of the tanks overall thermal conductivity) the LNG at the inner tank will warm up faster than during normal use, and therefore its vapour pressure will increase. Considering such a scenario, the failure mode of the inner tank could be a burst or rupture, at a weak spot due to increase of the inner pressures.

3 Design of experiment

3.1 Tank design and construction

Both design and engineering for test tanks were executed by TNO. Details can be found in Appendix I. The single walled test tank was manufactured by Ales Metaaltechniek. The large sections of the double walled tank were prepared by Ales and assembled by Cryovat. TNO was responsible for the supervision during construction. After construction both pressure vessels were pressure tested at 9 bar and the quality of all the critical welds was verified by means of Non-Destructive Testing (NDT) with radiography.

Configuration and tank sizing
Stationary tanks are generally placed in a vertical position. However, TNO has opted for a more conservative horizontal lying tank configuration. In an intense fire a larger area of vapour part of the horizontal tank will be exposed in comparison to vertical placement. The smaller the test tank size in relation to the heat input, the more conservative the test conclusions will be representative for larger (bulk) volume tanks, i.e. bulk tanks have thicker walls and a (much) lower tank surface area to volume ratio than the test tanks.

TNO made the choice for an identical design of the two pressure test tanks. The single walled tank and the inner tank of the double walled were identical in volume (3 m^3), dimensions and wall thickness. The design of the test tanks was based on the same tank design specifications (DIN 4680-1) used by BAM in their fire tests with LPG tanks. The test tanks were made suitable to contain cryogenic fluids (LIN, LNG, etc.) by constructing them of low temperature resistant stainless steel (type 304) instead of carbon steel. With this setup a straightforward comparison could be made for the behaviour of LPG and a cryogenic fluid in relation to single walled and double walled tanks.

Maximum Allowable Working Pressure (MAWP)
Normally, commercially available cryogenic tank are operated with a MAWP between 10 and 20 bar. Sized tanks in the order of 3 m^3 volume are constructed with wall thicknesses between 6 and 8 mm. In case the tank material is cold stretched during manufacturing the wall thicknesses are reduced.

TNO opted initially for a wall thickness of 6 mm comparable to commercially available tanks. Due to the short time span for completion – as was already explained in paragraph 1.5 – the necessary construction material (stainless steel shell plates and ‘Klöpper’ tank ends) were not available in the opted wall thickness range. For the tank ends only 3 mm was directly available, which then became the choice for the test tanks. Guided by the NEN-EN 13458 design standard for cryogenic vessels, TNO (in house) calculations and a verification by tank manufacturer (Cryovat), the MAWP for the test tanks was set at 7 bar (6 barg). The reduction of wall thickness (6 to 3 mm) and MAWP (10 to 7 bar) had no influence on the validation with the experimental output. Another consequence of the pressure reduction was a shortening of the expected heat-up time to reach the opening pressure of the PRV.

Insulation parameters
The interspace between the inner tank and outer jacket of the double walled tank was determined by the 'Klöpper' tank ends availability of the outer jacket. As a result the interspace had a thickness of 200 mm all around the inner tank, which is comparable to commercially available tanks. The interspace was completely filled-up with expanded Perlite powder and then evacuated. Due to the pending transport deadline to the BAM test facility the interspace evacuation cycles could not be completed. The test tank was put on transport with a low vacuum 200 mbar. Commercially available tanks are normally evacuated to a medium vacuum below 10 mbar.

The single walled tank was initially intended to be fire tested without any insulation for the shell. After deliberations with BAM and made considerations for PRV sizing TNO decided to apply 50 mm Rockwool insulation with cladding all around the tank shell. The insulation needed to prevent the activation of the PRV during the process of conditioning and filling of the tank at the test site.

3.2 Pressure relief valve and other accessories

The objective of the tests is to investigate the structural integrity of the inner tank and outer jacket during full flame engulfment conditions. Any single component failure of attached accessories or piping that could result in a test failure was considered undesirable. Therefore, the PRV, pressure measuring lines and remotely operated block valves were placed behind a fire wall (no fire exposure) by means of extending the vent and fill pipelines. The vent line discharged away from safe area.
Due to material availability the diameter of the extension line was reduced from 38 mm (= 1½ inch) to 25 mm (= 1 inch).

The sizing of the PRV was considered by TNO to be one of the most safety critical elements for the design of experiment. The safety valve has to assure that the pressure inside the tank does not exceed MAWP with more than 110%. The dimensioning needs to be sufficient in order to timely discharge the vapour as a result of heat ingress into the liquid, with due consideration of any backpressure or pressure drop in the vent line. The PRV calculation of the vent opening (orifice) was performed by TNO in accordance with NEN-EN 13648-3 and NEN-EN-ISO 4126 standards with assumed flame temperatures between 900°C and 1000°C. With that it was shown that the minimal orifice diameter for double walled test tank should be 6 mm and for the single walled a minimal orifice 10 mm. TNO decided to maintain a safety factor – factor of two – and install a PRV with a 20 mm orifice diameter. However, during assembly on site the PRV could not be connected to the 1 inch venting line and was connected via ½ inch connection piece. For reasons of safety two PRVs with 20 mm orifices were installed on the vent line.

The calculations showed also that a 1½ inch pipeline would give a negligible pressure drop in vent line in the worst of circumstances. The reduction of the pipeline diameter would self-evident lead to higher flow velocities, increased resistance and higher pressure drops. For the double walled tank the pressure drop in the line could increase to a maximum of 0,2 bar. Such pressure increase in the tank was considered acceptable due to large margins in the tank design (see limit load criteria). However, the pressure inside de single walled tank could increase 1,5 bar due to the pressure drop in vent line, just within the considered acceptable limits. As an additional measure TNO decided to install a second pressure measurement to monitor both static and dynamic pressure during the tests.

3.3 Instrumentation and registration

The required data sets were obtained through sensing of pressure, temperature rise and temperature distribution. The instrumentation setup consisted of the following logged measurements [4]:

- 1 x pressure liquid side inner tank (P2)
- 1 x pressure vent line inner tank (P1)
- 2 x temperature liquid phase inner tank
- 1 x temperature gas phase inner tank
- 7 x temperature wall inner tank
- 7 x temperature wall outer jacket
- 6 x temperature flames
- 2 x temperature PRV exhaust
- 1 x tank mass
- 6 x meteorological conditions
- 5 x videos with view on the test tank
- 1 x video with view on the PRV vent area

The piping and instrumentation diagram is included as Appendix I, Figure 6. The temperature measurements (thermocouple type K) were focussed on the vapour filled part of the test tank to control the experiment via the limit load approach. Too high wall temperatures in relation the actual tank pressure were the cut-off arguments to end a test. Each thermocouple in the double walled tank was positioned via small diameter (in place welded) measuring lines and fixated on the outside of jacket with compression fittings. On the other hand the thermocouples inside the single walled tank were guided to the outside via Conax sealing glands with Grafoil sealant.

There are no thermocouple types which are able to measure the entire range from cryogenic region at -200°C up to the high temperature region at 1200°C. The type K thermocouples were calibrated to measure accurately measure temperatures between 0 and 1200°C. Therefore, the cryogenic temperatures were corrected for the known deviation at the atmospheric boiling point of liquid nitrogen (LIN).

3.4 Protection of tank connections

Any single component failure of attached accessories or piping that could result in a test failure was considered undesirable, as was mentioned before. Therefore, additional measures were taken to protect vulnerable items from the flames, such as sealed thermocouple connections through the wall (single walled tank), flange gaskets and the piping in contact with flames. Therefore, all vulnerable items were selected such that these at least should resist temperatures from the cryogenic

[4] The pressure and temperature measurements for the inner tank of the double walled tank and single walled tank were identical in terms of numbers and location.

region up to 700°C (Rockwool). For both tests ceramic wool insulation (different types; resistant up to 1200°C and 1600°C) was chosen to protect the critical objects directly attached the tanks, thereby also in direct contact with the flames.

3.5 Heat load

The heat load applied to the outside of the test tank is the foremost parameter determining the rate (°C/s) at which the temperature of the tank and its contents (and hence the pressure, strain and stress) increases. With their previous testing BAM has used a heat load of 75 kW/m^2. A narrow array of propane burners provides the controlled heat source during bonfire testing and is therefore reproducible from scientific point of view. The array of burners is not designed to withstand pressure waves of bursting tanks (‘run to destruction’). The limit load approach halts the test before the tank actually ruptures.
In literature typical heat loads of an engulfing hydrocarbon pool fire are in the order of 100 – 140 kW/m^2. However, the clear burning flames of an LNG pool fire produce surface emissive powers (SEP) of 250 kW/m^2 and higher. While jet fire heat loads are above 200 kW/m^2.
A heat load of 75 kW/m^2 is considered realistic for less severe fires that are likely to occur during parking and transport on the road. Full engulfment of a transport tank is possible when parked next to a tank vehicle with a large volume of flammable liquids. TNO proposes to also apply a heat load of 75 kW/m^2 for reasons of comparison. This heat load is considerably larger than 35 kW/m^2 radiation without flame impingement. The duration of exposure needs to be ascertained and is a variable to be tested separately with at least one bonfire test.

3.6 Safety case

Safety was considered as priority above all other items. TNO declared to respect the rules and regulations as stated by BAM, which are clearly specified for guests witnessing the fire test, and for persons doing on-site preparative work.

Driven by a common understanding on safety and feasibility, BAM and TNO made the choice beforehand to use LIN, not LNG for this pioneering bonfire tank tests with cryogenic contents.

Design criteria and safety features
In short, the following risks were addressed during the detailed design process:

- Catastrophic failure of the pressurized tank
- Failure of piping, services valves (flanges, gaskets, and connections)
- Failure of internal connections / tubing / seals of thermocouples and wiring.
- Overfilling of the tanks
- Insufficient capacity of pressure relieve valves
- Failure of pressure relieve valves
- Not measuring (sufficient) data – defect of instruments
- Not meeting representative testing conditions

The main safety features were:

- Broad temperature range of stainless steel
- All pressure, temperature and weigh measurements available during filling
- Oversized safety relief valve(s)
- Remotely operated valves for depressurization
- Safe venting area
- Stand pipe at 50% overflow
- Test tank surrounded by concrete safety wall

The BAM test site, nearby Horstwalde, holds a dedicated ‘bonfire’ unit, which is considered as one of the most advanced ones in the world, certainly in Europe. The facility consists of a grid of large propane burners which can be operated remotely, generating a heat load in a very controlled manner. A wall of protective prefab concrete blocks surrounds the experimental ‘arena’. From several angles different cameras are installed to follow the actual situation during the experiment. Observations are done from the screen or out of the window, in the control room, part of a bunker which is located a few hundred meters away from the event. During the experiment safety was guaranteed by this safe distance.

Safety Session

TNO organised a comprehensive safety review, given the final tank design with additional piping. This session included the tank positioning, the due filling process, as well as the procedures post experiment, for instance how to safely depressurise the vessel and to discharge the remaining LIN. This safety session took place at TNO Utrecht office, September 23rd 2015. A so called ‘WHAT-IF’ methodology was used in order to challenge the experimental set-up and to analyse ‘the script’ of the tests as a whole. Other than TNO, the safety session was attended by representatives of BAM and Cryotainer. Also, one member of project TEC working group ‘Tanks’ took part. Cryotainer was contracted by TNO as supplier of LIN, and is recognised as a knowledgeable party to handle cryogenic substances in a safe way. The company’s standard filling procedure was ‘projected’ to the planned on-site situation, and was verified. Also, the safe depressurisation of the vessel and the due release mode after the experiment was discussed. The recommendations (e.g. with respect to safety wall, vent area and overfilling) were followed-up and implemented.

Limit Load criteria

Given the similar basic experimental design of both the single and double walled test tanks, safe dimensions (lay-out, diameter) of the additional piping and relieve valves (fit for cryogenic purpose, correct set points) were calculated. In short, these calculations included material (steel quality) properties, the due filling grade of the vessel and the expected tank heat transfer capacity (insulation). Also the thermo-dynamic features of LIN and the target heat load, preferably reached during the experiment, were taken into account. The aim of the experiment was certainly not to pursue with fire conditions until the total stress imposed to a tank would lead to a catastrophic failure. In order to avoid such loss of containment, so called ‘limit load criteria’ were set beforehand. Exceedance of the ‘limit load criteria’ (an undesired pressure, temperature combination) should (did) result in an instant abortion of the experiment. Details concerning this limit load approach are outlined in Appendix II. Full commitment of TNO and BAM to obey to the limit load criteria was considered a prerequisite to act, enabling instant judgement of the situation, ensuring a quick decision process during the experiment. Limit load criteria were discussed among parties, were agreed upon and approved.

4 Fire tests and observations

4.1 Double walled vacuum insulated test tank – October 22nd 2015

The double walled vacuum insulated test tank was installed at the dedicated propane burner grid.

Instruments (thermocouples weigh cells and pressure measurement devices) were connected to a data acquisition system; all functionalities/signals were checked before commencing the experiment.

Flanges, gaskets and piping directly connected to the tank, were protected from direct flame contact by wrapping these up (in ceramic wool insulation).

Filling of the test tank with LIN was swift, and successfully performed. Prior to filling, the tank was flushed with nitrogen vapour. Meanwhile, at the point of outflow dew-point measurements were done to be absolutely sure that no traces of water had remained entrapped in the tank interior, pipes and valves. The tank filling process was monitored and controlled by the truck operator (the instrument panel on the truck). In addition to this, one made direct use of the online data generated by the connected pressure meters, thermocouples and weigh cells to follow the filling onto the desired level.

The double walled test tank was filled up with 1400 kg LIN, reaching a filling grade of 66%. The tank was remained to settle for approximately two hours prior to ignition of the fire. During this period, the temperature of the tank was logged, from which insulation performance was concluded (see chapter 5).

Figure 1 An impression of the test site of BAM in Horstwalde.

The total duration of the experiment, time between fire ignition and termination, was approximately 120 minutes.
The initial vapour pressure in the vessel was 1.8 bara, which in two hours time built up to 7.6 bara, then levelled off around this value, on subsequent (re)opening and closing of the (set pressure, calibrated) PRV's. This process continued for approximately 20 minutes until termination of the test. Duplicate pressure measurements were done. Results are shown in chapter 5.

Depending on the location of individual thermocouples, the flame temperatures reached up to 800 - 900^{o}C at bottom of the tank, and varied roughly between 450 and 600^{o}C at the top of the tank (to some extend influenced by wind).
The tank was largely engulfed in fire. Controlling the experiment, BAM used the so called 'BAM curve' as a reference. The intensity of the fire was adjusted to the ambient conditions. This curve is experience based, for a number of comparable tank configurations, and is dedicated to the BAM test-site. The curve compares propane burner mass flow (and weather conditions; ambient temperature, wind speed) to the absolute temperature and the heat radiation established (see Appendix III). The minimum preferred intensity (i.e. heat load larger than 35 kW/m^2) was ascertained, was targeted to 75 kW/m^2.
The (non-insulated) supports of the double walled tank were separately water cooled (sprinkled), to prevent that weakening of these would occur and thereby might destabilise the whole test set up.

4.2 Observations double walled test tank

4.2.1 Video images - Photos

Video images of the tank in fire were taken from three angles. Separately, a fourth video camera was focused solely on the PRV's located outside the fire wall, to study the opening and closure in time. Activation of the PRV's was also monitored by thermocouples placed in both venting-lines, measuring temperature drop.

Figure 2 gives an impression of the control room, which is located in a bunker, a few hundred meters away from the actual testing rig.

Figure 2 Impression of the control room, while monitoring the experiment.

Figure 3 Screenshots, taken from the video registration, showing the double walled test tank fully engulfed in fire.

In a few minutes time a deformation (buckling) of the tank starts to occur, first on the bottom, a few minutes later at the side of the jacket (outer tank). Deformation is induced by the loss of the jackets material strength under thermal stress whereas the driven force pushing inwards is the pressure difference on either side of the outer tank wall, atmospheric (1 bar) against vacuum (low pressure, approximately 200 mbar).

After 1 hour and 49 minutes the vacuum disc popped off, as a result of which some of the Perlite was discharged. In addition to the soot also generated by the propane fire, clearly a sudden release of smoke was observed on the opening of the disc, the complete loss of vacuum (at least, proven by observation).

Whether a vacuum loss really occurred instantly or maybe gradually – for instance starting at a certain point earlier during the experiment cannot be concluded. Loss of vacuum was not one of this projects research questions. Loss of vacuum could have more than one cause, and should be considered as a given (a fact) in such extreme conditions.

Figure 4 Images of the vacuum insulated double walled test tank.

4.2.2 Invasive inspection – double walled test tank.

After transported back to the Netherlands, an invasive tank inspection was performed. The tank was cut open at Cryovat (Nijkerk).

A collapse of the jacket onto the pressure (inner) tank did not occur. This was prevented by some enforcements: welded (vacuum) rings on the jackets interior, or maybe in part by application of supportive (no metal, poor heat conductivity) blocks. The complete separation between inner and outer tank was merely maintained as a result of the presence of Perlite in the annular space.

As shown in the Figure 5, the Perlite filling fully embeds the pressure tank. Perlite remained unaffected by extreme heat exposure. Please note that Perlite does not play a role in the integrity of the tank construction itself (design; with respect to strength, stiffness).

Transport blocks to some extend were affected by the fire, the pressure vessel itself remained completely intact.

Figure 5 Impression of the invasive tank inspection.

4.3 Single walled, Rockwool insulated tank test – October 26th 2015

The single walled, Rockwool insulated tank was installed in the same manner as the double walled vacuum insulated one. Installing of the data acquisition network (connection and testing instruments/measurement devices) was done swiftly and successfully. The filling of the tank occurred at about the same rate as with double walled tank. A filling grade of 65% was achieved, 1420 kg LIN.
Beforehand, it was decided to start the experiment before the set pressure of the PRV's would be reached, limiting the time between filling and the actual ignition of the fire. The filled tank was remained to settle for about 40 minutes.

As expected for a limited insulated single walled pressure tank containing a cryogenic liquid, already during this period a significant pressure build up started to occur. Meanwhile, also some ice formation on the exterior of the tank (metal surrounding the pressure tank with Rockwool) was observed. Measured pressure data results are shown in §5.5.

Water cooling of the tank supports was not considered due to the presence of the additional insulation at the supports. Already, few minutes after ignition of the fire, destabilization occurred and the tank fell over from its support into the fire. The most likely explanation is weakening of steel, not sufficiently cooled – as a result of thermal conductivity (heat bridge). Alternative scenarios, also thought of, were found not plausible.

In the control room quick decisions had to be made, whilst the tank lay in fire. Some of the thermocouples were found offline. Two out of three thermocouples registering the temperature of the head space (vapour phase) were malfunctioning. From the screens in the control room it could not be ascertained from distance that flanges and pipes connected to the tank were still intact or not. In other words, it was not known whether a leakage was part of the system. Also there was no certainty on the accuracy of pressure measurements. Both BAM and TNO agreed, and it was decided to instantly abort the experiment for safety reasons. Thereby one avoided an escalation, a further loss of control – maybe - by exceeding the limit load criteria and consequently a vessel rupture.

Figure 6 Impression of the single walled, Rockwool insulated test tank, before and after the experiment.

4.4 Signal (in)stability of thermocouples

All thermocouple measurements are found stable and reliable in the whole period prior to the experiment, in which the double walled cryogenic test tank stood filled up and acclimatized (2 hours). Using these datasets, for ambient conditions, the performance of the double walled tank with respect to its insulation (its heat transfer capacity) was clearly demonstrated.

All thermocouples, however, those connected to either the tanks jacket (in the vacuum space, onto the inner side of the outer tank) or to the pressure tank (in the vacuum space, onto the outside of the inner vessel) showed to be unstable under fire conditions. The same counts for the three ones in the pressure tank interior (vapour and or liquid phase)

Fortunately, all of these thermocouples measure correct and reliable values, just prior to the start and directly after termination of the experiment. Therefore, by interpolation between beginning and end points, all thermocouple data sets were found useful.

The common cause for this disturbance of the thermocouples and weigh cells as soon as fire was ignited was not found. BAM declared to TNO that they never have had similar problems with (these) thermocouples. Actually, this type of thermocouples was selected and recommended for measuring the whole range between cryogenic and bonfire temperatures. These findings were shared with thermocouple supplier (and manufacturer) Rössel, who was also was asked for an explanation. Some of the thermocouples experimentally used were subjected to tests at the company’s research centre. All proved to be undamaged, and gave correct values when tested either in the cryogenic region or exposed to flame temperature.

5 Data evaluation, modelling and discussion

In this chapter the measured data of the experiment will be evaluated and compared to a model developed by TNO. After a short description of the TNO model, the experiment and the measured data are analysed and the TNO model is validated. Next the validated model is used predict results for LNG and also to extrapolate to larger (real) size LNG (transport) tanks.

5.1 Vacuum insulated tank test – description of TNO model

The model describes the behaviour of a vacuum insulated cryogenic tank subjected to heat [2]. The goal of this thermal tank model is to predict the temperature and pressure evolution of the tank in time, when exposed to a certain heat load, according to several scenarios. Scenarios could be loss of vacuum of the insulation space with associated drop insulation value of Perlite, or the accidently change in tank orientation where the pressure relief valve (PRV) now discharges liquid instead of vapour. The temperature and pressure information could be used in other models to e.g. assess stresses/strains in the tank, and the possibility of structural failure.

Several uncertainties exist with regard to component behaviour and material behaviour at extreme conditions. For example the insulating properties of Perlite insulation at elevated temperatures and pressures is not known, and extrapolated from low temperature and pressure values. Also the behaviour of the PRV at elevated temperatures is not known, nor when e.g. unintentionally liquid is discharged instead of vapour. Also infrared absorption of methane must be investigated in more detail. These topics need to be addressed in order to reduce model uncertainties.

The set of equations describing the behaviour over the large temperature and pressure range is complex and time consuming to solve. Therefore, as a first approximation, LNG properties from a limited temperature and pressure range are used (although these properties are publicly available over a wide temperature and pressure range). Also, it is assumed that LNG consists of methane for 100%. For example constant heat capacities are assumed and ideal gas behaviour of the vapour.

In future, the implementation of real gas properties could be considered, as well as implementation of an extended non-equilibrium model of the tank content, or tilted tank configurations.

This explorative work was not part of the TKI-gas project, but financed with TNO resources in the framework of KIP (Kennis Investering Plan).

5.2 Evaluation of measured data: 3 m^3 tank filled with LIN

5.2.1 Position of thermocouples

The positions of the various thermocouples (TC1, TC2 ,… etc.) are shown in Figure 7 - Figure 10. In the description of the results in the subsequent paragraphs reference is made to these locations.

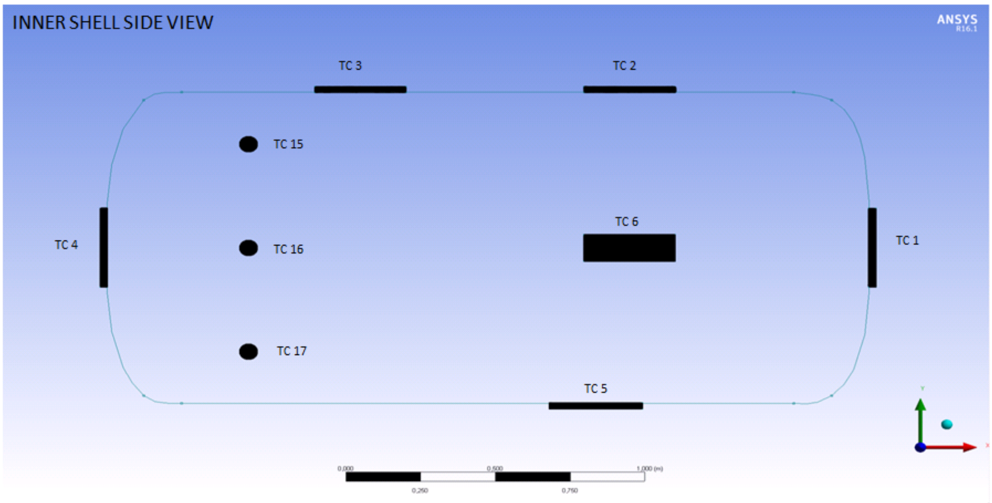

Figure 7 Position of thermocouples on the inner shell wall – side view.
N.B. front view shown in Figure 8 is to the right.

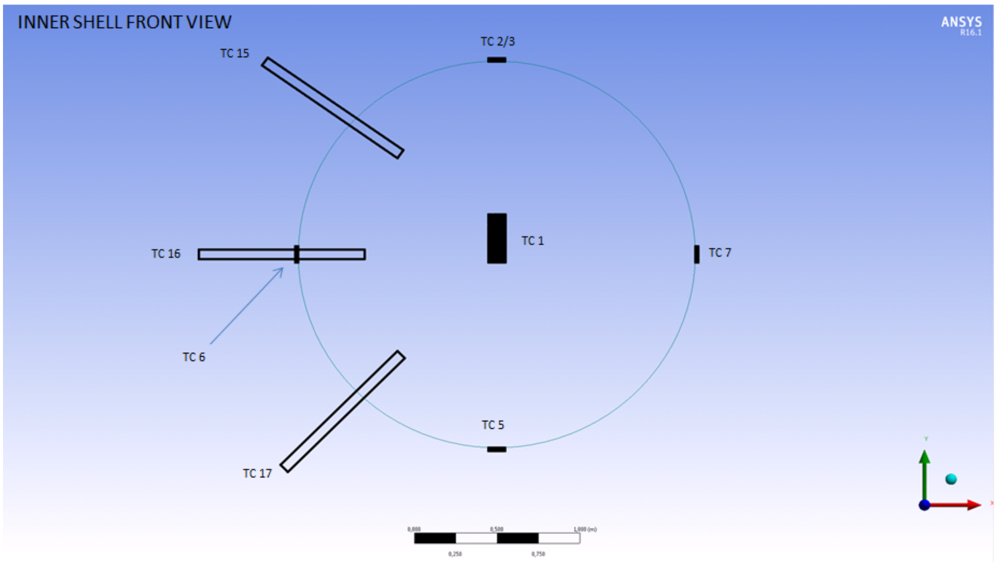

Figure 8 Position of thermocouples on the inner shell wall and inside the tank – front view.
N.B. side view shown in Figure 7 is to the left.

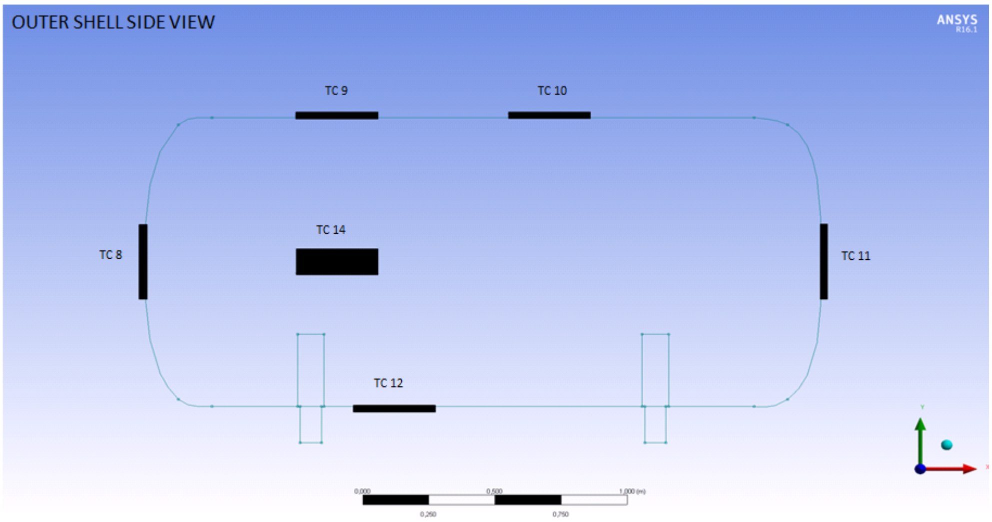

Figure 9 Position of thermocouples on the outer shell wall – side view.
N.B. front view shown in Figure 10 is to the right.

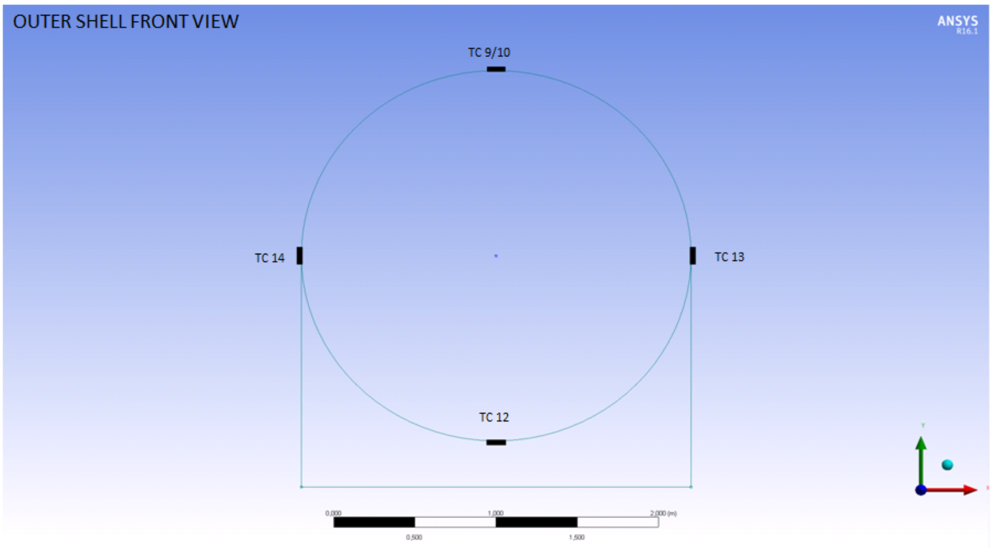

Figure 10 Position of thermocouples on the outer shell wall – front view.
N.B. side view shown in Figure 9 is to the left.

5.2.2 Measured data and the TNO model with default values

In Figure 11 - Figure 22 measured experimental data are shown in blue and results of the TNO model are shown in red. In the legend reference is made to the measurement locations as shown in Figure 7 - Figure 10 above.

The experimental measurements cover a period of approximately 4 hours:

- At t = 0 filling of the LIN tank has stopped and the tank is closed;
- At t = 109 min the fire is ignited;
- At t = 218 min the vacuum disk is released;
- At t = 227 min PRV opens;
- At t = 231 min the fire is stopped, based on the limit load criteria;
- At t = 246 min the experiment is terminated and data acquisition is stopped.

For modelling a 5 hour period is used (Figure 11 - Figure 22).

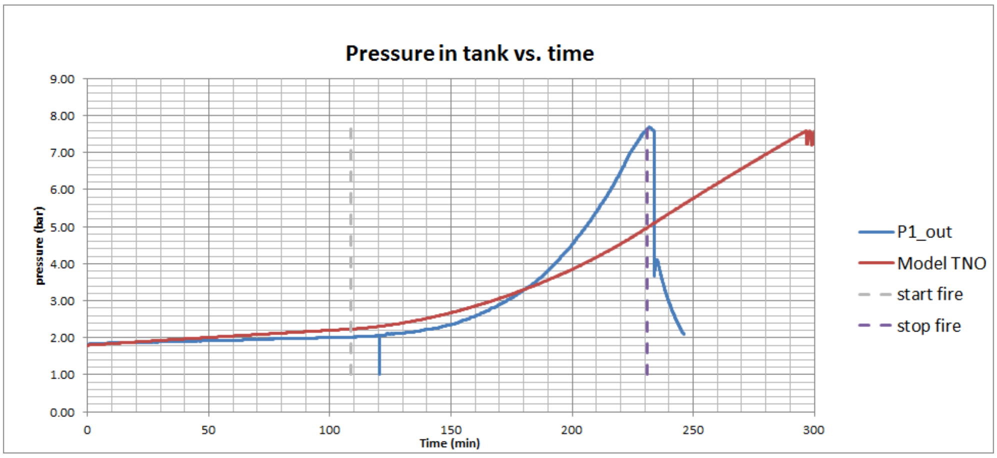

Figure 11 Experimental data at P1, vapour (exhaust) line (blue) and model results (red): Vapour pressure.

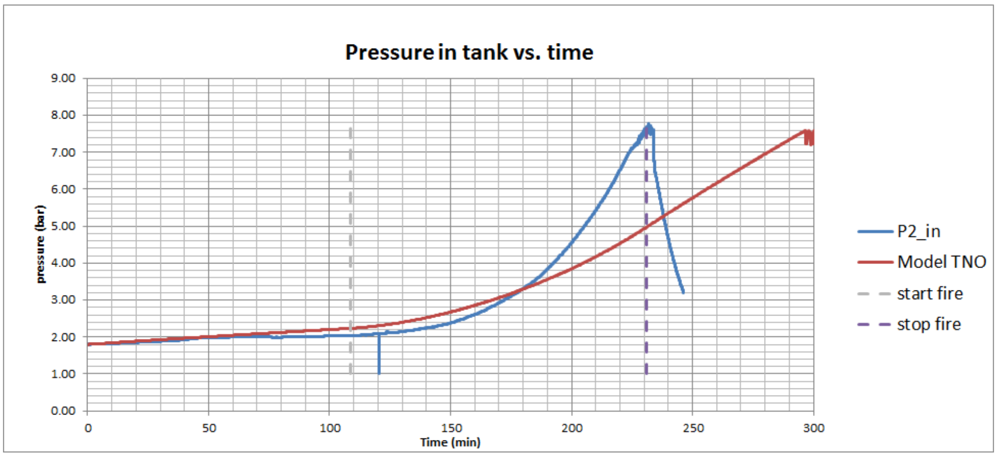

Figure 12 Experimental data at P2 liquid (filling) line (blue) and model results (red): Vapour pressure.

The pressure data are shown in Figure 11 and Figure 12. It can be seen clearly that the TNO-model, when run using the theoretical values that are considered most appropriate, is in poor agreement with the observed data, in particular during the period that the fire is on. Before the fire is ignited, the pressure in the tank rises somewhat slower than predicted. However, after ignition of the fire, pressure rise is faster than predicted.

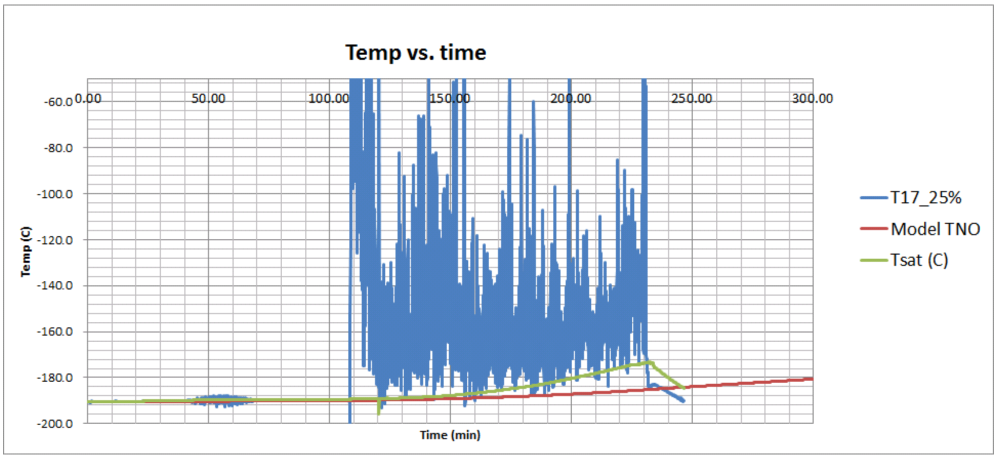

Figure 13 Experimental data (blue) and model results (red): Temperature in the centre of the liquid phase (TC17). Green: calculated (saturation) temperature on the basis of the measured pressure data in Figure 11.

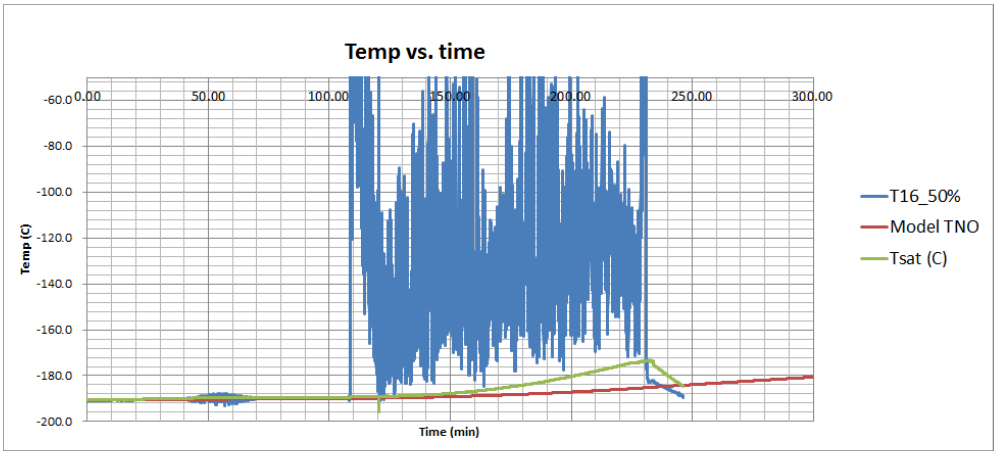

Figure 14 Experimental data (blue) and model results (red): Temperature at the top of the liquid phase (TC16). Green: calculated (saturation) temperature on the basis of the measured pressure data in Figure 11.

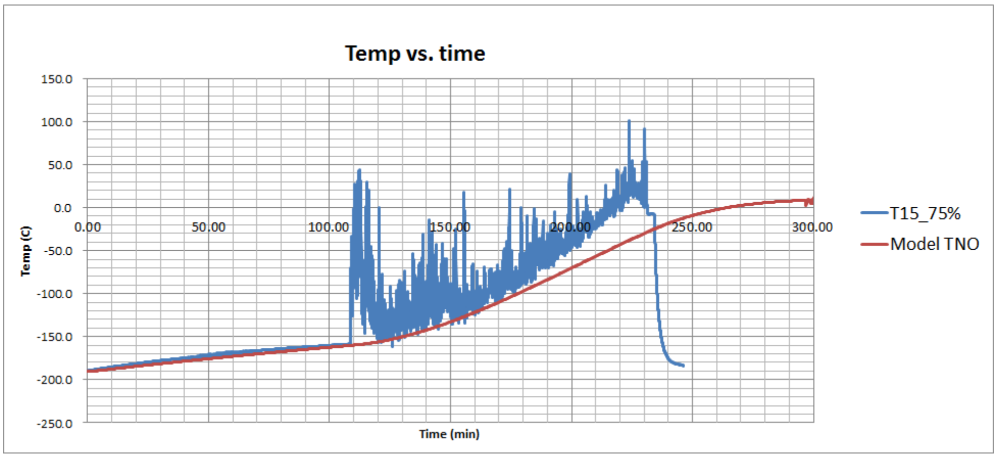

Figure 15 Experimental data (blue) and model results (red): Temperature in the vapour phase (TC15).

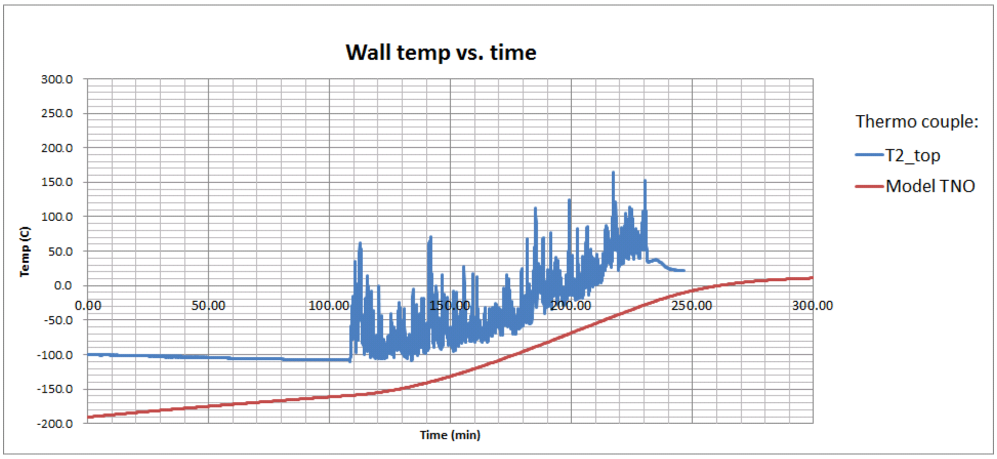

Figure 16 Inner wall temperature at top position TC2 (gas phase).

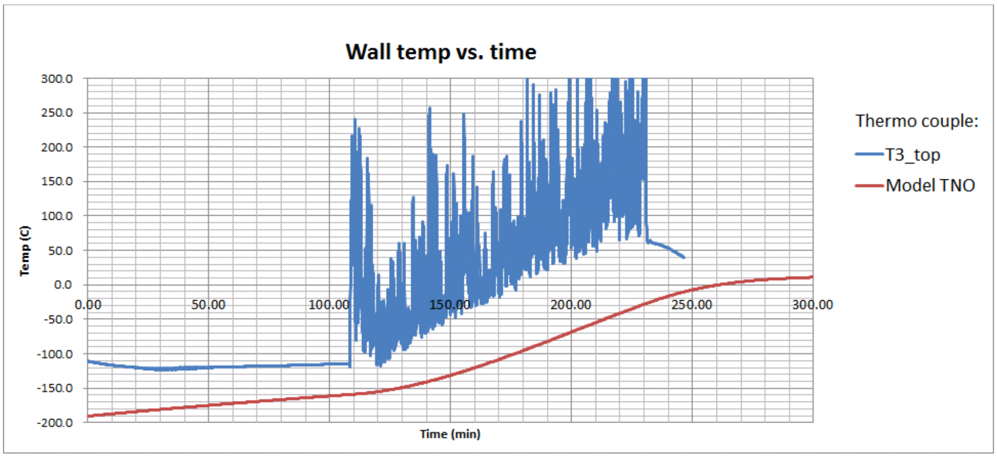

Figure 17 Inner wall temperature at the top position TC3 (gas phase).

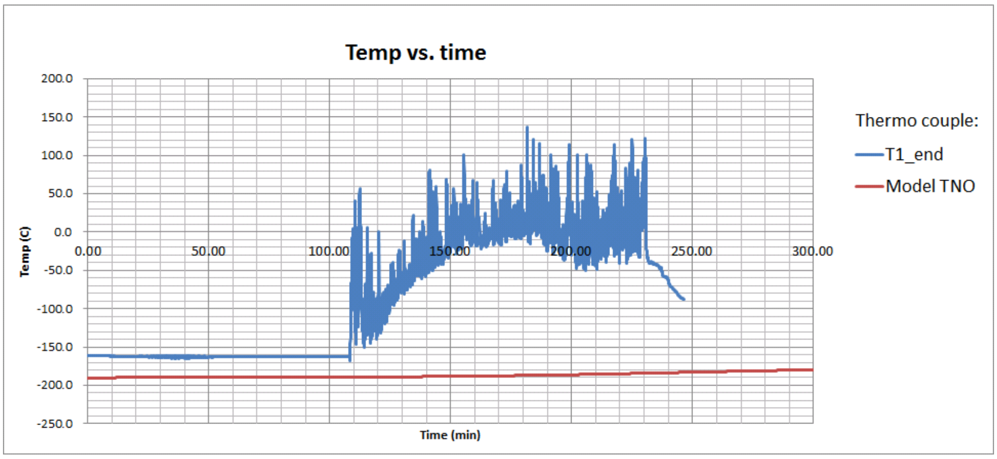

Figure 18 Inner wall temperature at end position TC1.

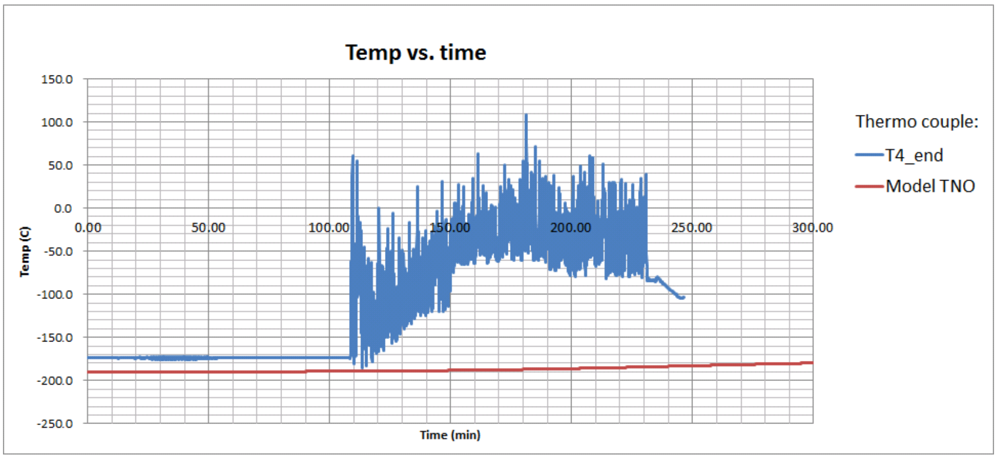

Figure 19 Inner wall temperature at end position TC4.

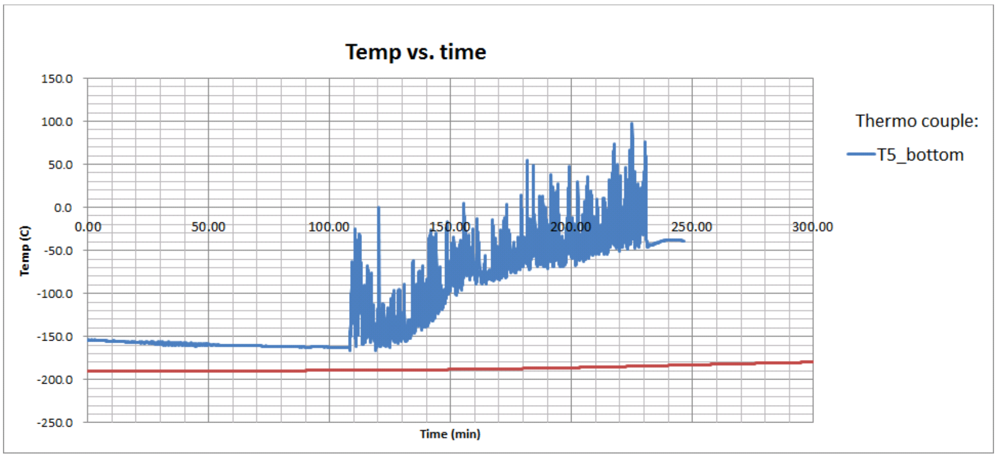

Figure 20 Inner wall temperature at side position TC5.

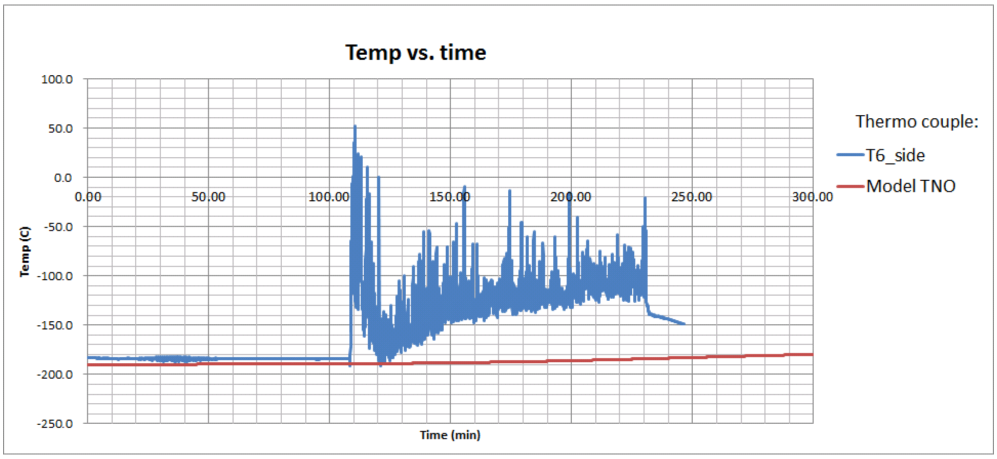

Figure 21 Inner wall temperature at side position TC6.

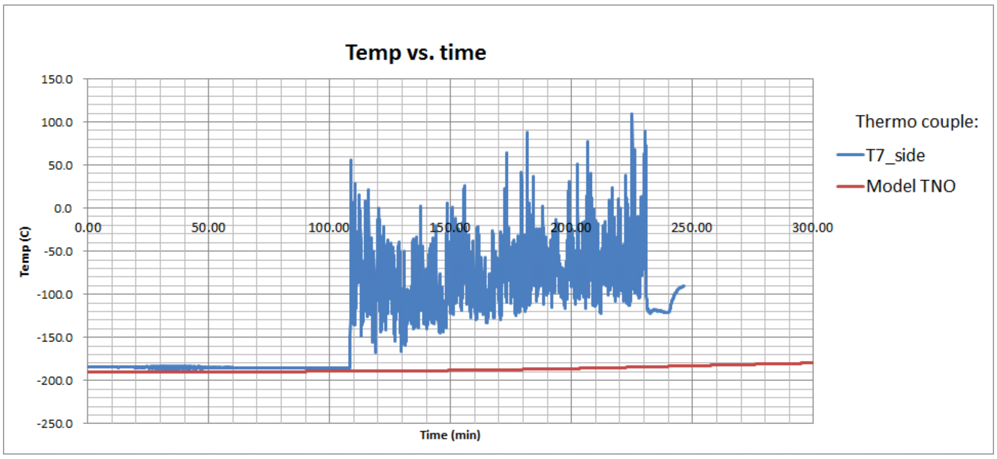

Figure 22 Inner wall temperature at side position TC7.

As outlined earlier, the temperature measurements inside the tank, during the period in which the fire was on, fluctuate heavily and can not be considered reliable, as can be seen in Figure 13 - Figure 15. Only the values before and after the fire are reliable. They are in reasonable agreement with the predicted values of the model. On the basis of the well known saturation pressure – temperature relation (see Figure 24) one can predict the expected temperature of the liquid phase using the measured pressure data. This is shown with the green curves ("T-sat") in Figure 13 and Figure 14.
Also wall temperature data, recorded during the period the fire was on, fluctuate heavily (see Figure 17 - Figure 22). Again they must be considered unreliable. Of the data measured before starting the fire, only the data of thermocouples 6 and 7 (Figure 21 and Figure 22) are in agreement with the model (and with expectations, as one would expect the bottom temperature to be equal to the liquid temperature). Possibly a longer equilibration period than the ca. 2 hours given would have been better. Alternatively suboptimal contact between thermocouple and tank wall may have caused the discrepancy.

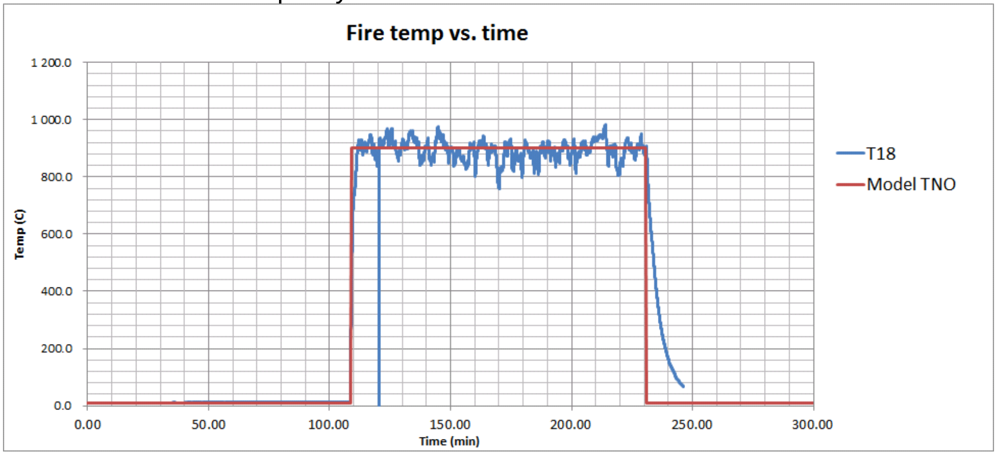

Figure 23 Flame temperature of Thermocouple TC18 and used flame temperature for modelling.

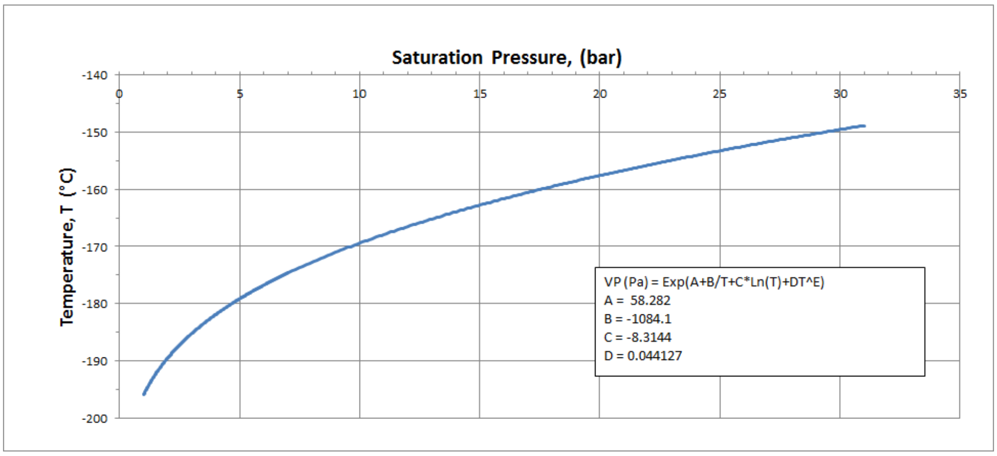

Figure 24 Saturation pressure versus temperature for Nitrogen (DIPPR database [18]).

The thermal conductivity for the Perlite as used in the modelling is shown in Figure 25. These values are based on the equations underlying the frequently used relations as shown in Figure 26. It is furthermore (conservatively) assumed that vacuum of the annular volume is lost at the moment the fire is ignited. The actual moment at which vacuum was lost could not be determined. However the fact that at 1:49 hrs after ignition a vacuum disc was broken was evidence that vacuum was lost at some point during the experiment.

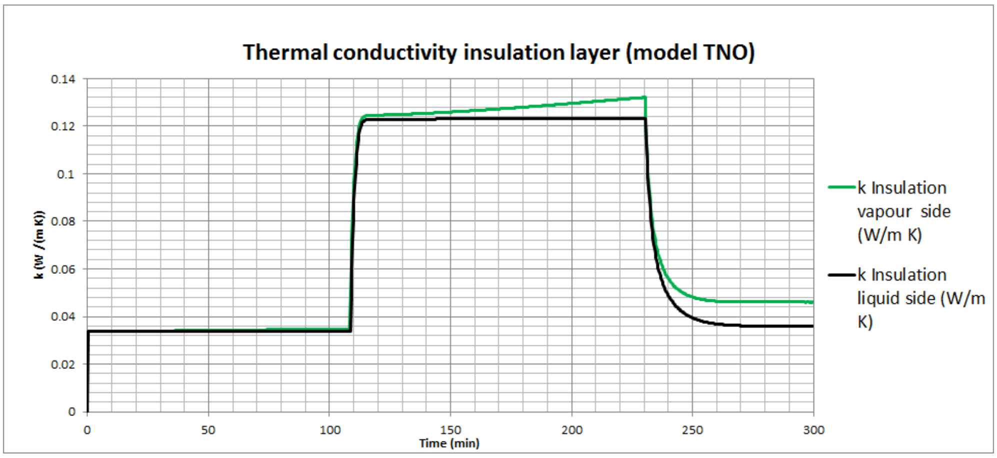

Figure 25 Thermal conductivity as used in the TNO model for liquid (black curve) and gas phase (green curve).

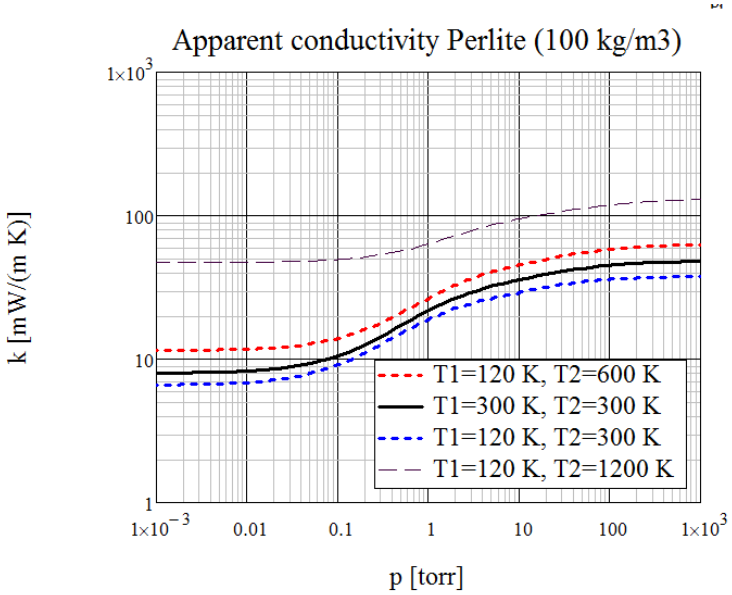

Figure 26 Apparent thermal conductivity (k) of perlite as a function of pressure at a number of temperatures, calculated with the relations according to [17].

From the measured data it can be concluded that it takes approximately 2 hours (from the start of the fire) until the internal pressure has reached the opening pressure of the PRV (ca. 7.6 bara). At that moment the hottest part of the inner wall (at the top near the gas phase) has reached a temperature of approximately 50 °C. This is far from any temperature (at this pressure) at which the structural integrity of the tank could be at risk. According to the TNO model the PRV won't open until approximately 3 hours after ignition. It is not immediately clear what causes this difference. In the next paragraph the thermal conductivity of the perlite used for modelling will be adapted to better fit the actual opening time of the PRV. It should be stressed, however, that it cannot be concluded from the data that this parameter is responsible for the discrepancy between measured and modelled data.

5.2.3 Measured data and the TNO model with adapted values for the thermal conductivity of the perlite

Translating the results from the previous paragraph to LNG and particularly extrapolating them to larger tank sizes can only be done through modelling. In order to improve the agreement between modelled and measured data, the thermal conductivity values of the insulating perlite layer (k_{ins}) used for the modelling were adapted from the default values ($k_{ins(def)}$) used above as follows:

- Cold phase (before the fire was on): $k_{ins(cold)} = 0.6\ k_{ins(def)}$
- Hot phase (during the period the fire was on): $k_{ins(hot)} = 1.45\ k_{ins(def)}$.

The resulting thermal conductivity as a function of time is shown in Figure 27. Modelling results compared to measured data are shown in Figure 28 - Figure 39.

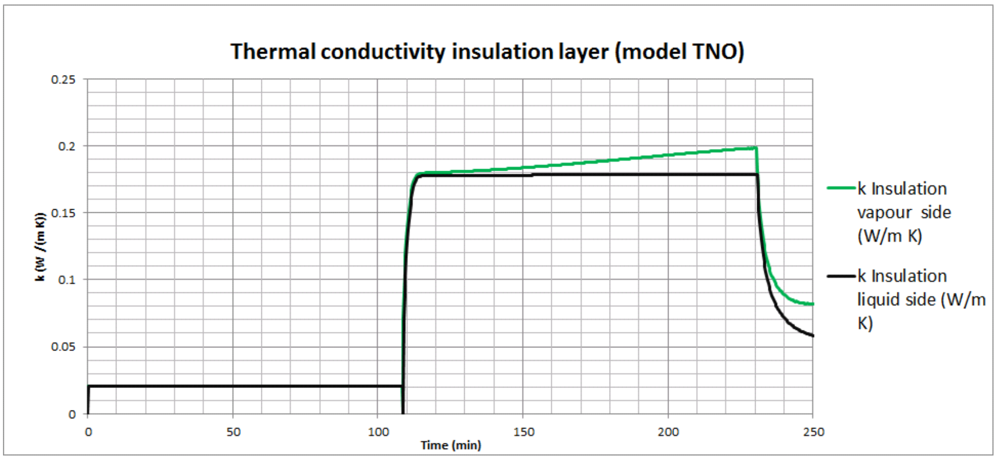

Figure 27 Adapted thermal conductivity values used for better match of modelled with measured data.

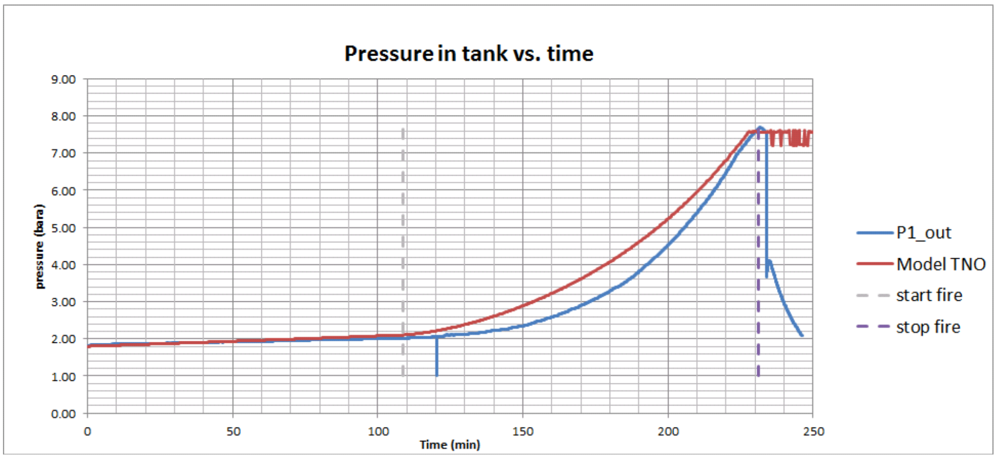

Figure 28 experimental data (blue) and model results (red): Vapour pressure.

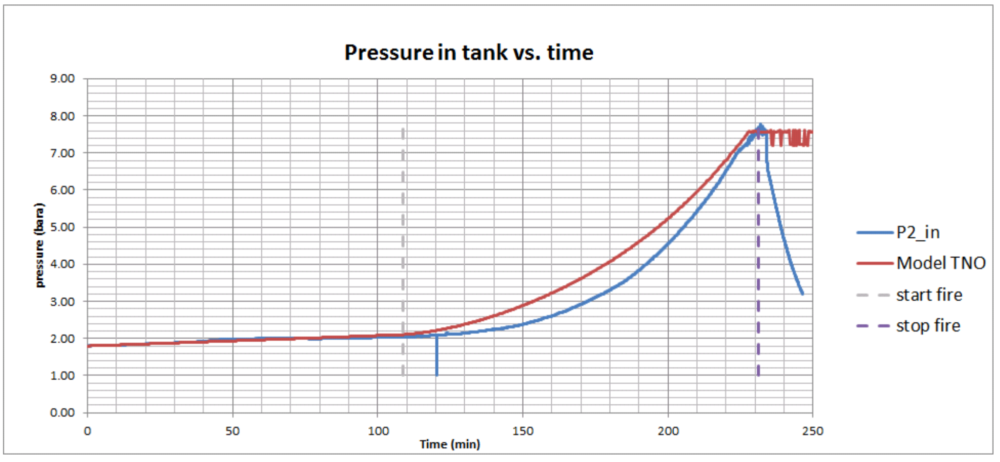

Figure 29 experimental data (blue) and model results (red): Vapour pressure.

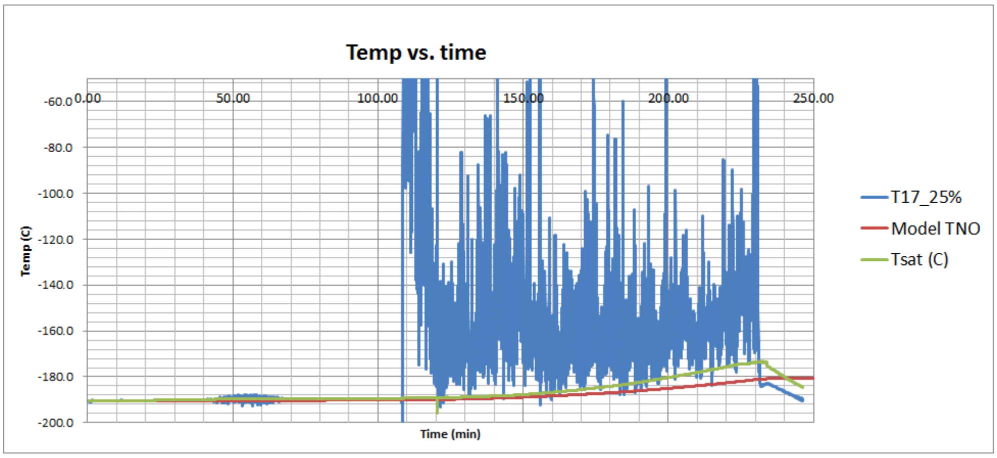

Figure 30 experimental data (blue) and model results (red): Temperature in the centre of the liquid phase.

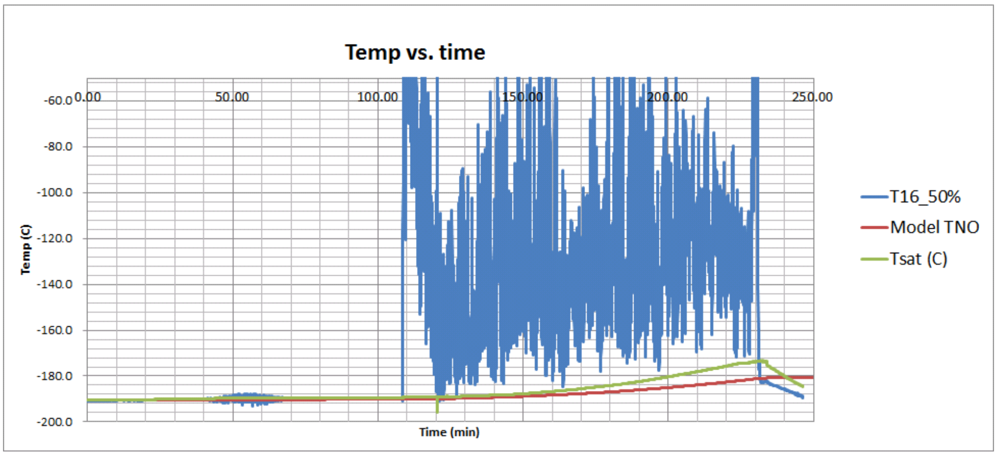

Figure 31 experimental data (blue) and model results (red): Temperature in liquid phase, just below the surface.

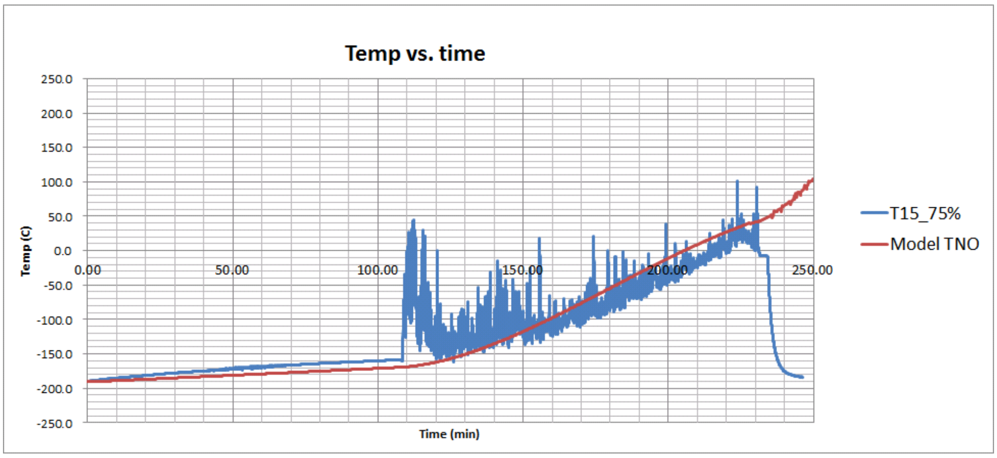

Figure 32 experimental data (blue) and model results (red): Temperature in the vapour phase.

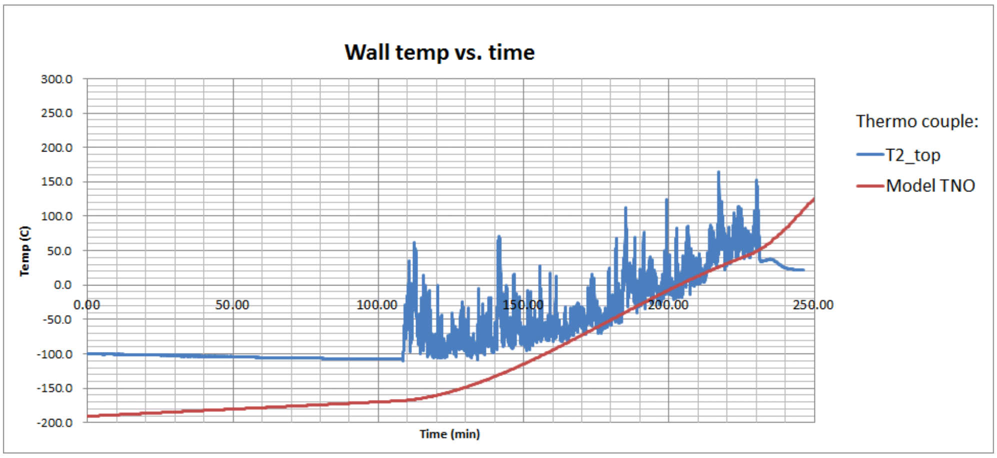

Figure 33 Inner wall temperature at the top position TC2 (gas phase).

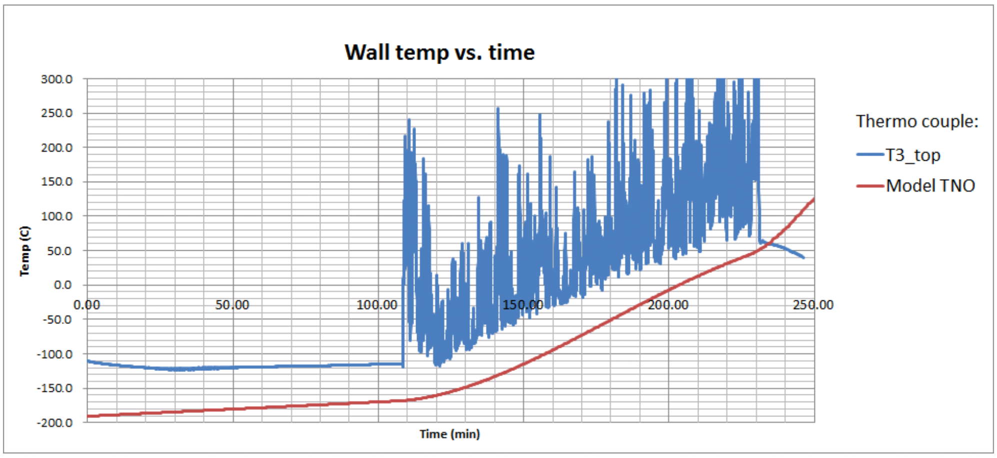

Figure 34 Inner wall temperature at the top position TC3 (gas phase).

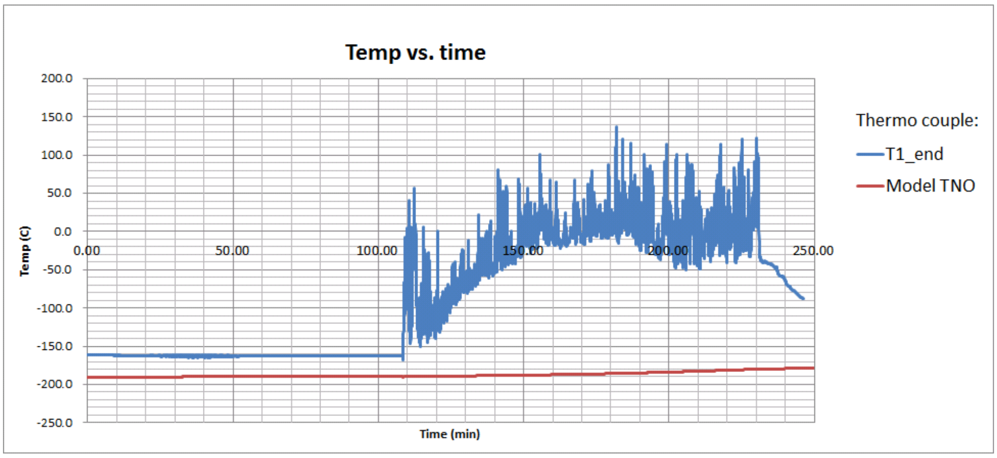

Figure 35 Inner wall temperature at end position TC1.

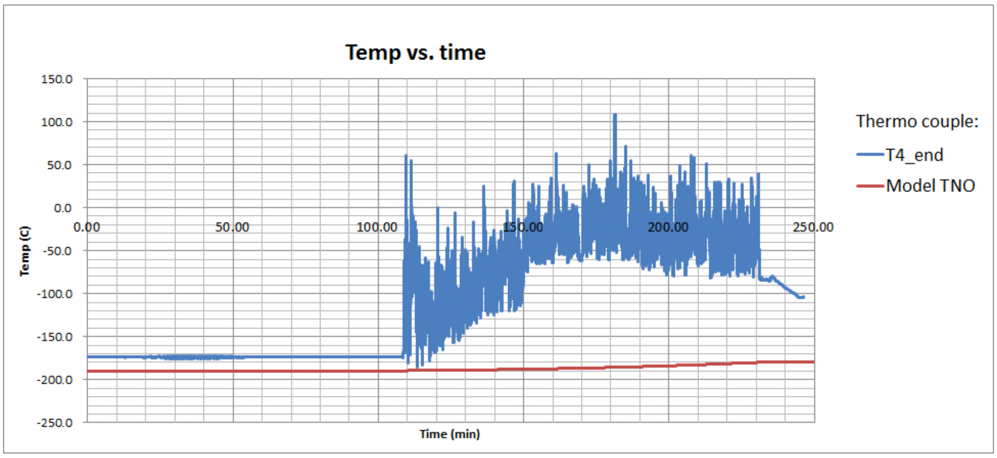

Figure 36 Inner wall temperature at end position TC4.

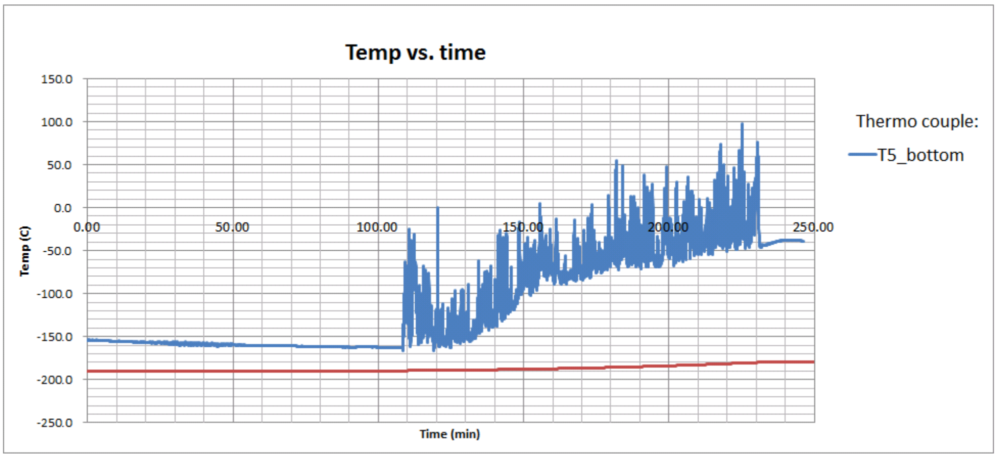

Figure 37 Inner wall temperature at end position TC5.

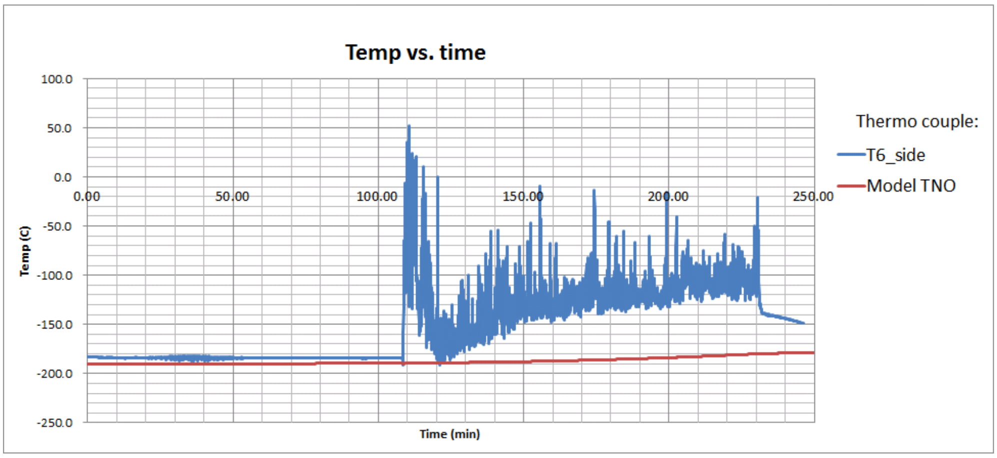

Figure 38 Inner wall temperature at end position TC6.

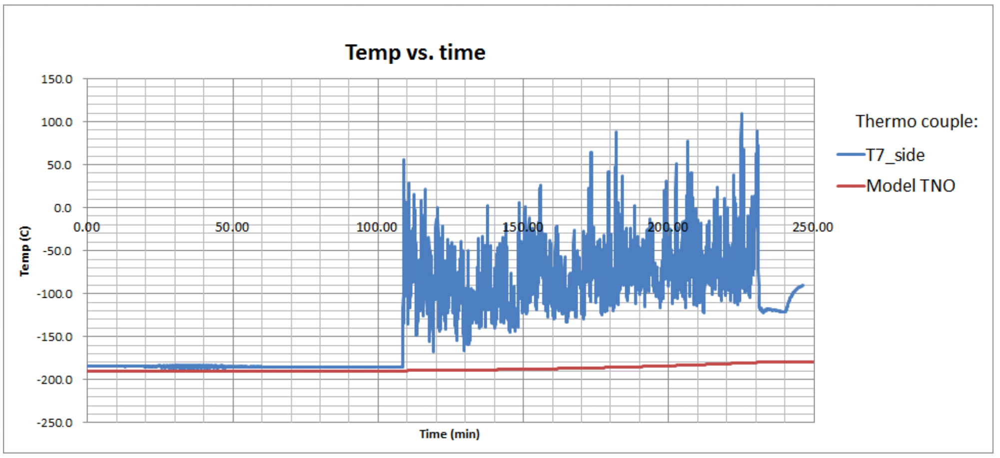

Figure 39 Inner wall temperature at end position TC7.

From Figure 28 and Figure 29 it can be seen that for the cold situation the adapted value of the insulation value gives results that agree well with the measured pressure data. This also applies for the liquid temperature data in this phase (Figure 30 and Figure 31). For the wall temperature the same applies as in the previous paragraph: only the data of thermocouples 6 and 7 (Figure 38 and Figure 39) are in agreement with the model (and with expectations, as one would expect the bottom temperature to be equal to the liquid temperature).
Although the moment of opening of the safety valve is now correctly predicted, it is not possible to find a good agreement between the modelled and measured data for the entire measuring (time) range for the hot period.
Nonetheless in the following paragraphs translation to LNG and extrapolation to larger tanks will be done using the adapted (as well as the default) values for thermal conductivity.

5.3 Vacuum insulated tank: Comparing LIN (3 m^3) with LNG (3 m^3)

In this paragraph the behaviour of a 3 m^3 LIN tank in a fire is compared to that of an LNG tank of 3 m^3.

5.3.1 2 hour fire, insulation as default value in TNO model.

In Figure 40 - Figure 47 predicted results with the TNO model are shown for a fire lasting for 2 hrs. The default value for the thermal conductivity is used. It is also assumed now that vacuum is maintained during the fire.

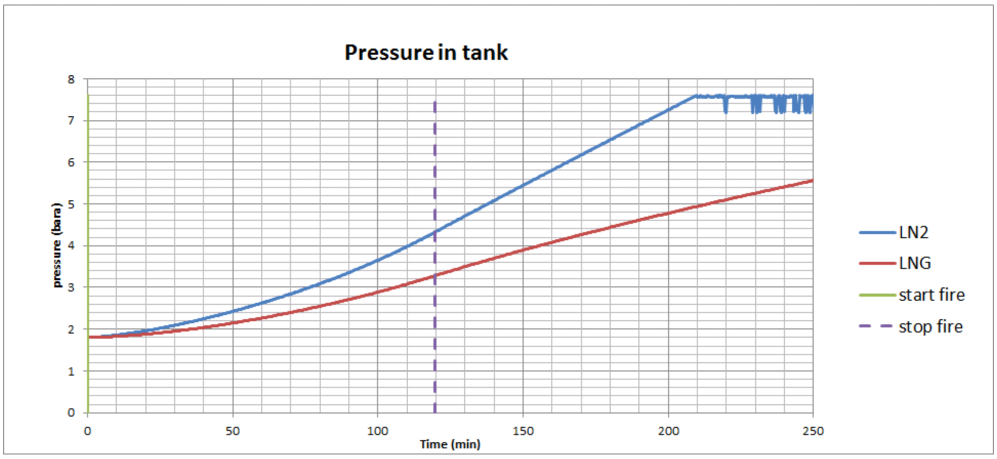

Figure 40 Vapour pressure as a function of time for LNG and LIN_2.

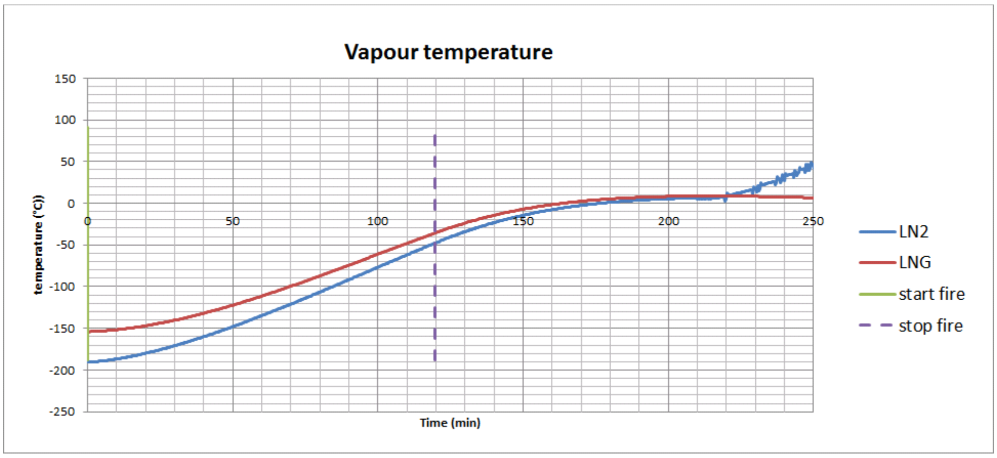

Figure 41 Temperature of the gas phase as a function of time (increase in temperature after 220 min is an artefact of the modelling).

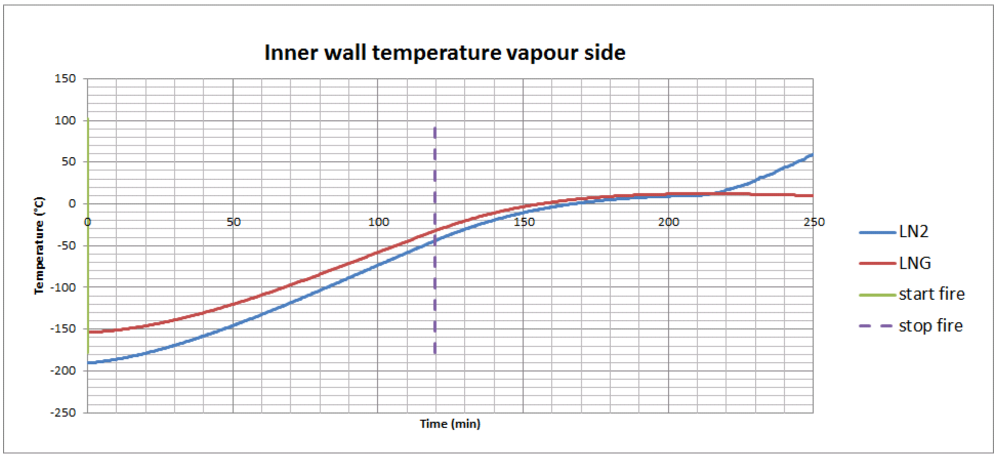

Figure 42 Temperature of the inner tank wall (near gas phase) as a function of time (increase in temperature after 220 min is an artefact of the modelling).

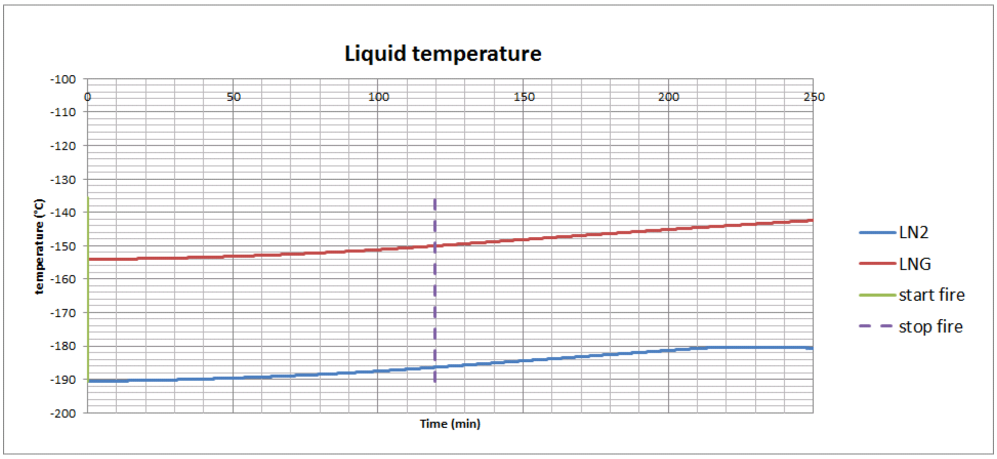

Figure 43 Temperature of the liquid phase as a function of time.

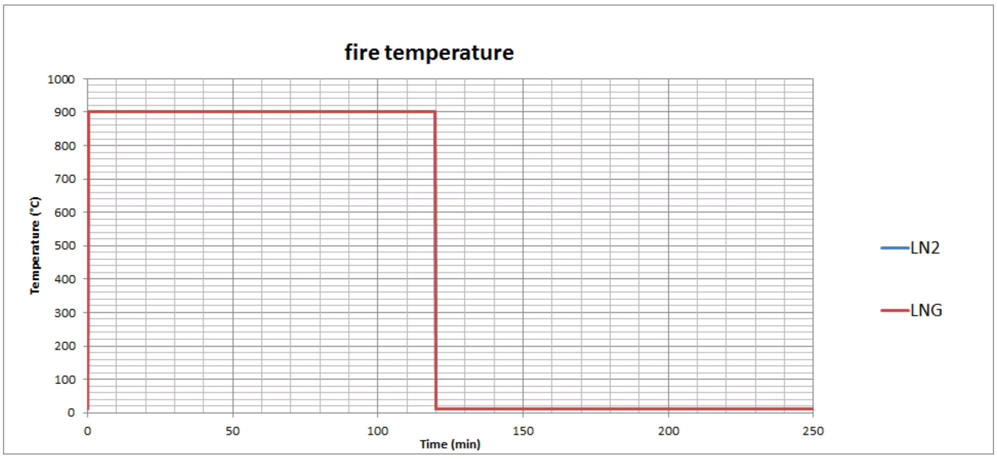

Figure 44 Fire temperature as a function of time as used in the model.

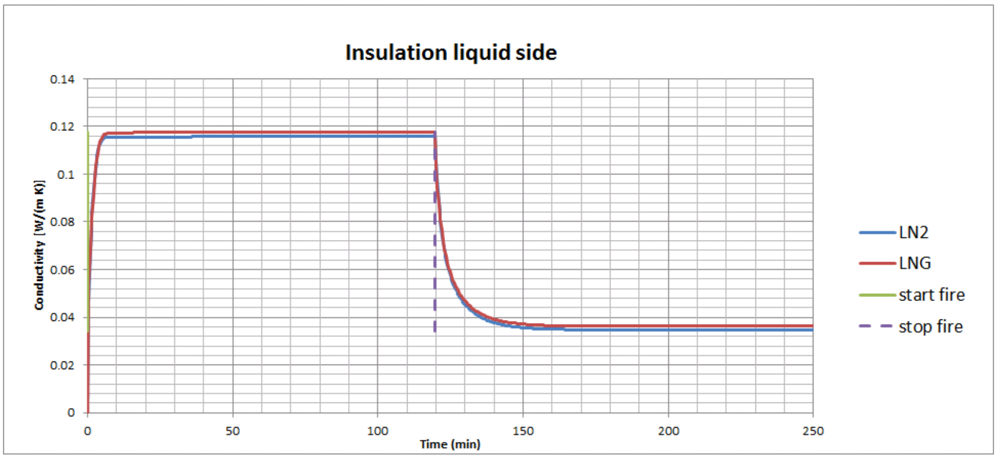

Figure 45 Thermal conductivity of the perlite at the liquid (bottom) side of the tank.

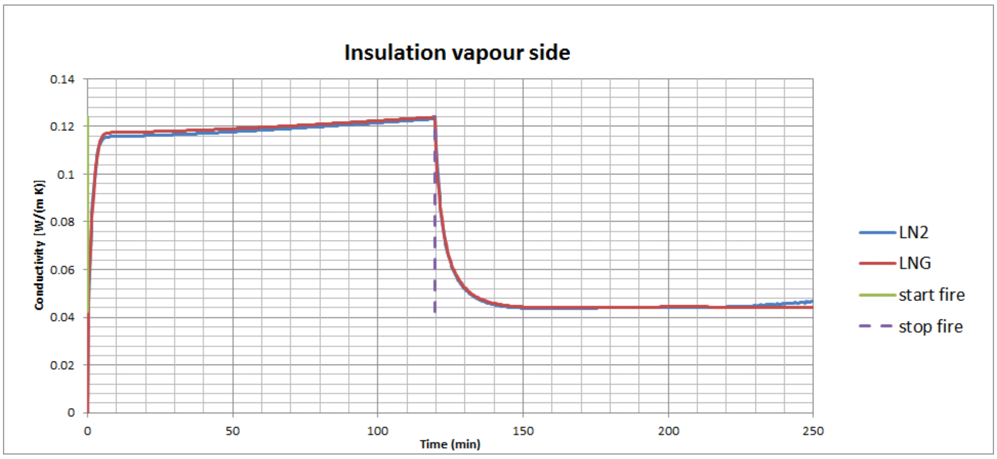

Figure 46 Thermal conductivity of the perlite at the gas (top) side of the tank.

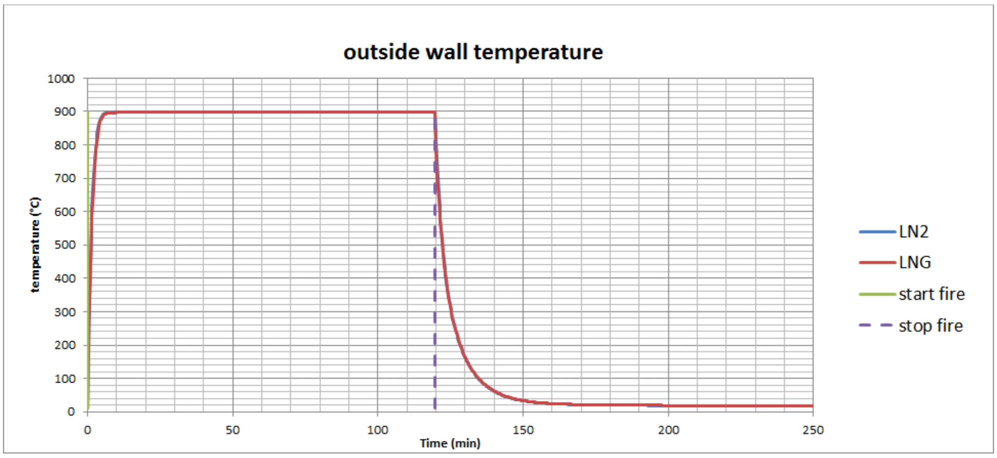

Figure 47 Outside wall temperature as a function of time.

As can be seen from Figure 40 heating of an LNG tank is much slower than a LIN tank. It would take a fire of about 4 hours to reach the set point pressure of the PRV (see Figure 48). Because the heat capacity and heat of evaporation for LNG are larger than of LIN (see Figure 49 and Figure 50) more energy input is required for LNG than for LIN to cause a certain increase in temperature and to evaporate a certain mass of liquid. Therefore the slower increase in pressure (and temperature) can be expected for LNG.

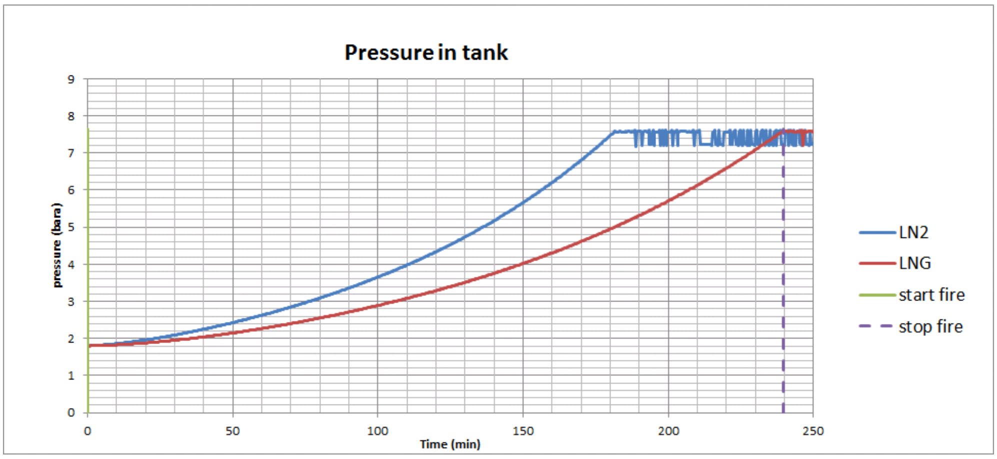

Figure 48 Pressure as a function of temperature for a 3 m^3 LIN_2 and LNG tank in a fire lasting for 4 hrs.

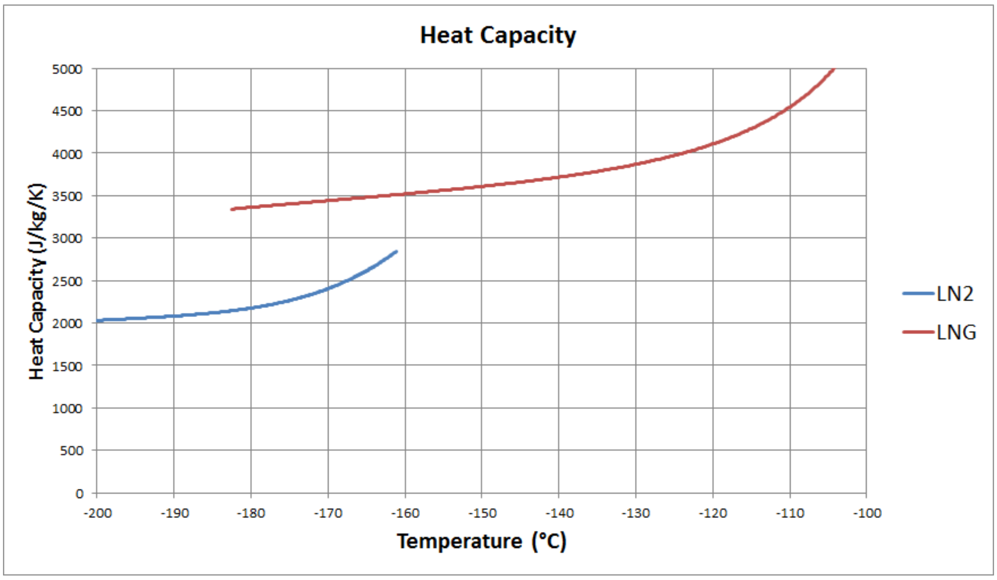

Figure 49 Heat capacities of LNG and LIN_2 (DIPPR database [18]).

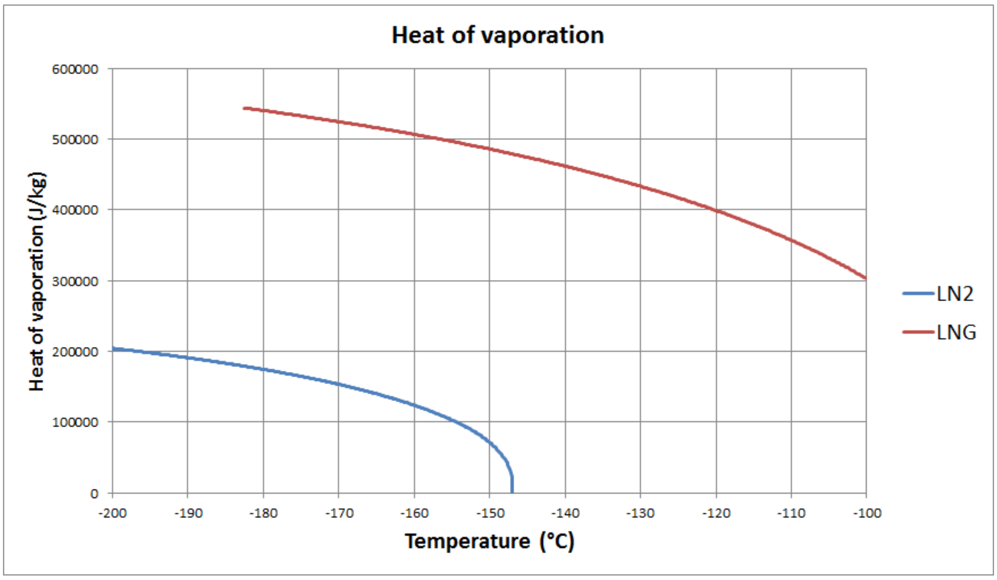

Figure 50 Heat of evaporation of LNG and LIN_2 (DIPPR database [18]).

5.3.2 *2 hour fire, thermal conductivity 1.45 times default value in TNO model.*

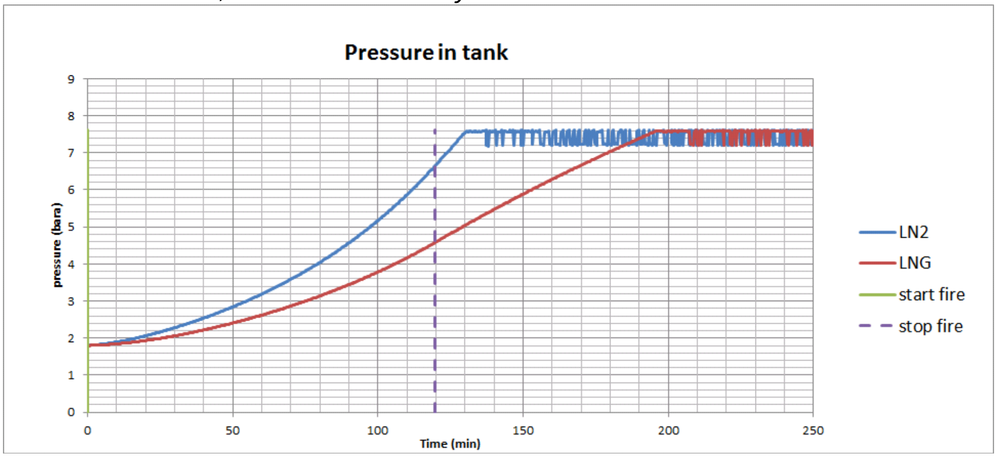

Figure 51 Vapour pressure as a function of time for LNG and LIN_2 with increased value of thermal conductivity.

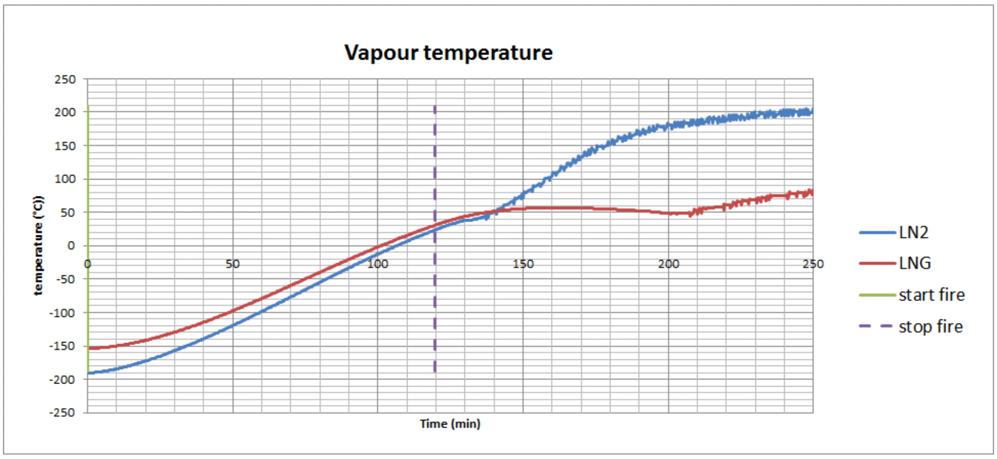

Figure 52 Temperature of the gas phase as a function of time (increase in temperature after 140 min (LIN_2) and 210 min (LNG) is an artefact of the modelling).

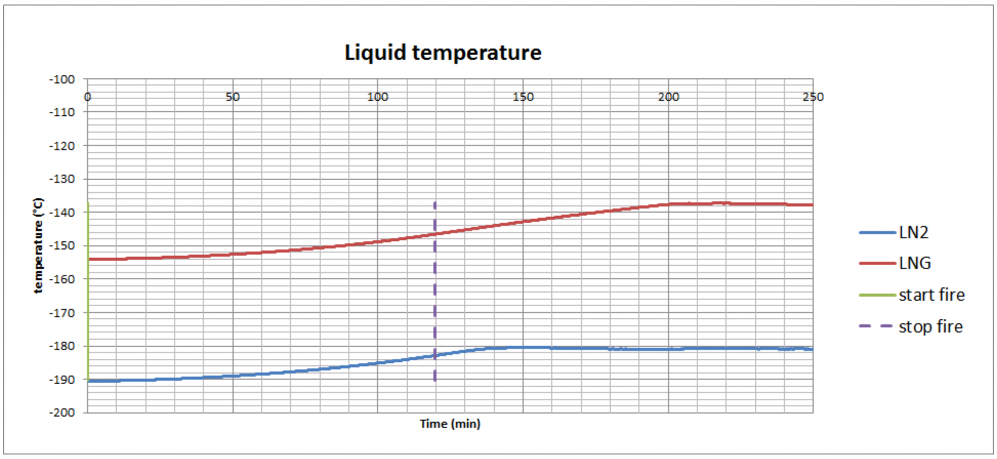

Figure 53 Temperature of the liquid phase as a function of time.

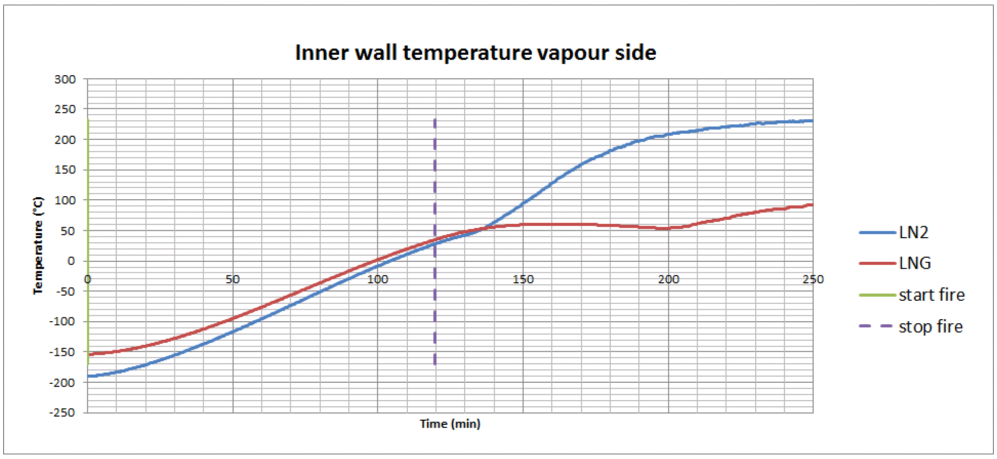

Figure 54 Temperature of the inner tank wall (near gas phase) as a function of time (increase in temperature after 140 min (LIN_2) and 210 min (LNG) is an artefact of the modelling).

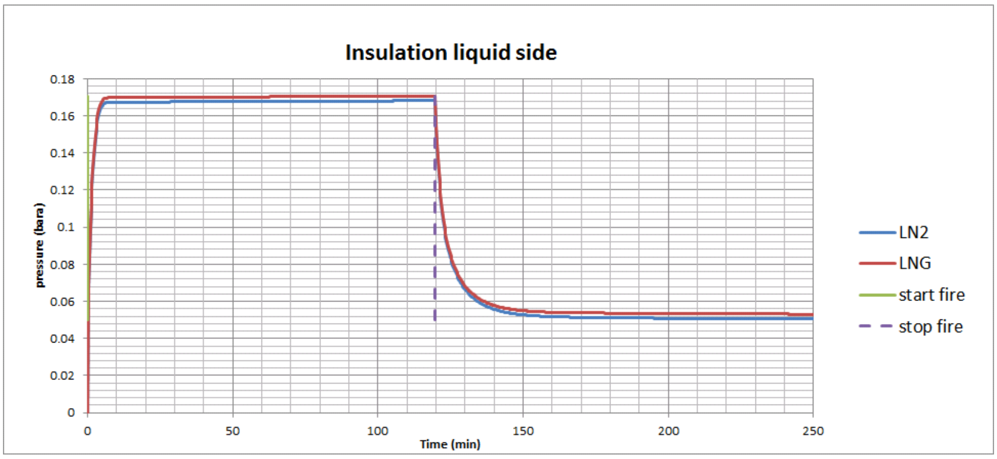

Figure 55 Thermal conductivity of the perlite at the liquid (bottom) side of the tank.

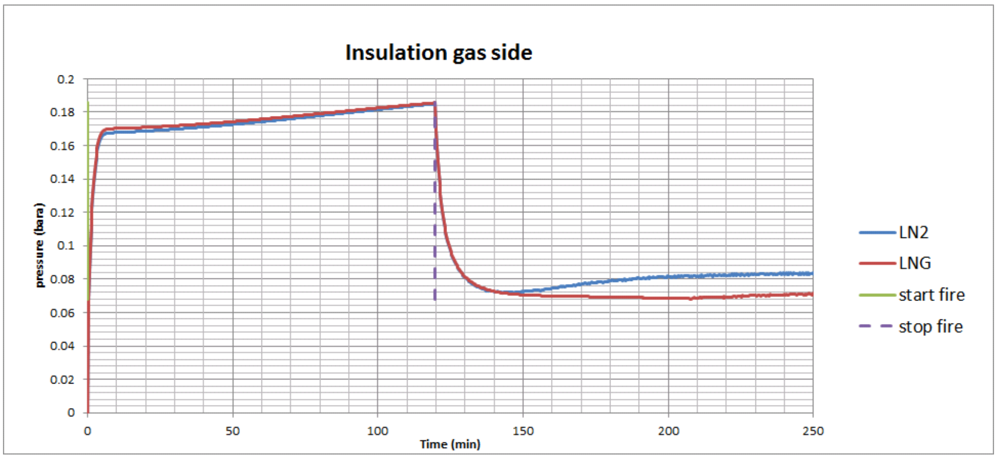

Figure 56 Thermal conductivity of the perlite at the gas (top) side of the tank.

As can be seen from Figure 51 it would take about 50% longer to heat the LNG tank to the set-point value of the PRV than a LIN_2 tank.

5.4 Upscaling: Vacuum insulated tank: Comparing a 3 m^3 with a 45 m^3 real size (transport) tank

Using the TNO model it is possible to predict the behaviour of a real size tank in a fire. The following dimensions were used for the modelling of the transport tank:
- Length inner tank: 13.4 m
- Diameter inner tank: 2.08 m
- Thickness of steel: 6 mm
- Thickness vacuum space: 0.35 m
- Four supports: 1 m x 0.4 m contact area; length = thickness vacuum space.
- PRV diameter:18 mm.

Two cases are calculated:
- LIN: Thermal conductivity 1.45 times default value; 120 min fire duration (Figure 57);
- LNG: Thermal conductivity 1.45 times default value; 120 min fire duration (Figure 58 - Figure 61).

As expected because of the a larger volume to surface area ratio for a larger tank, the temperature and pressure increase for the larger tank is much slower than for the small tank. Hence it will take much longer to reach any critical value for both gas pressure (Figure 58) and wall temperature (Figure 61).

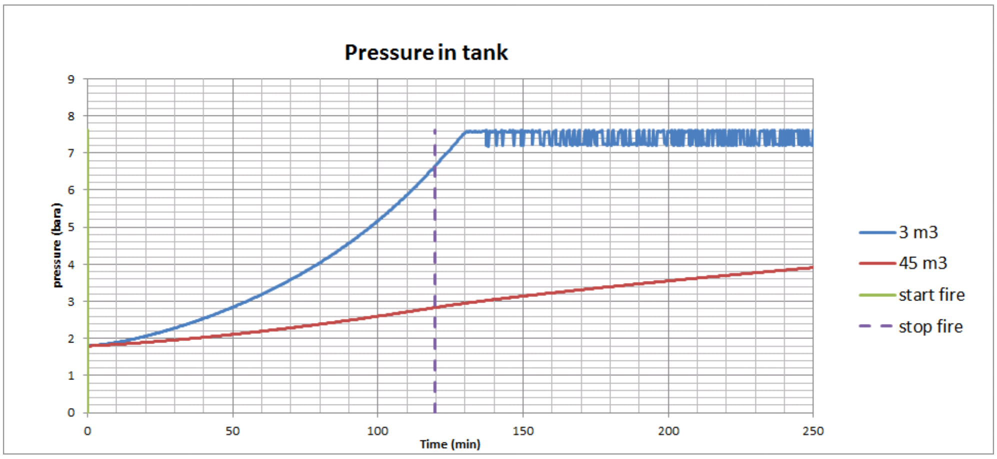

Figure 57: LIN_2: Comparison of pressure in 3 m^3 vs 45 m^3 tank. Thermal conductivity 1.45 times default value; 120 min fire duration.

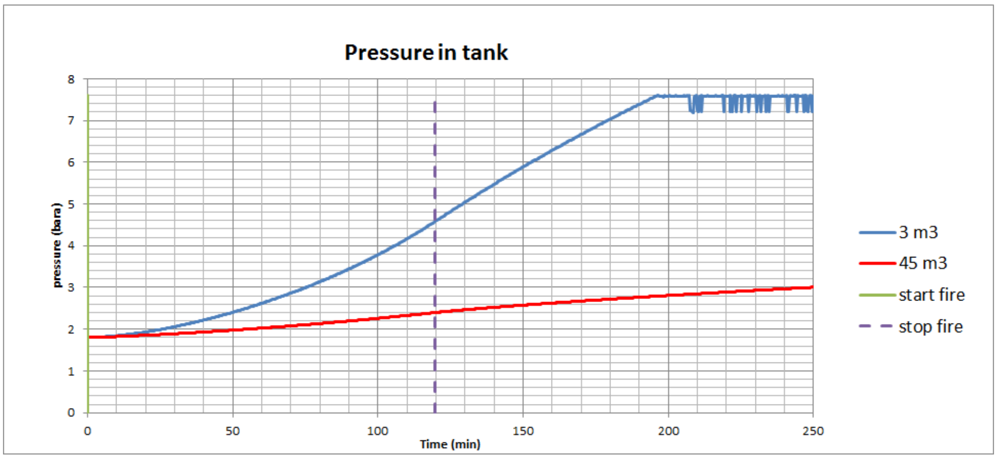

Figure 58 LNG: Comparison of pressure in 3 m^3 vs 45 m^3 tank. Thermal conductivity 1.45 times default value; 120 min fire duration.

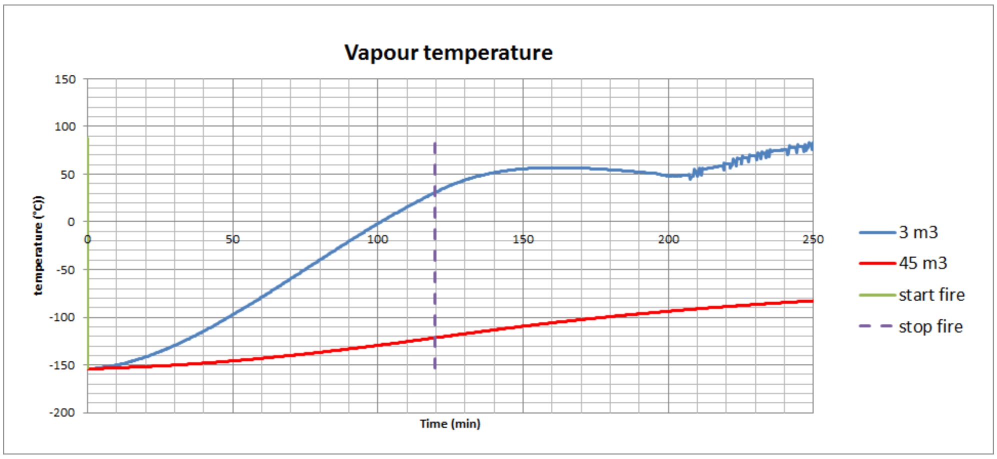

Figure 59 LNG: Comparison of gas temperature in 3 m^3 vs 45 m^3 tank. Thermal conductivity 1.45 times default value; 120 min fire duration (increase in temperature after 210 min in 3 m^3 tank is an artefact of the modelling).

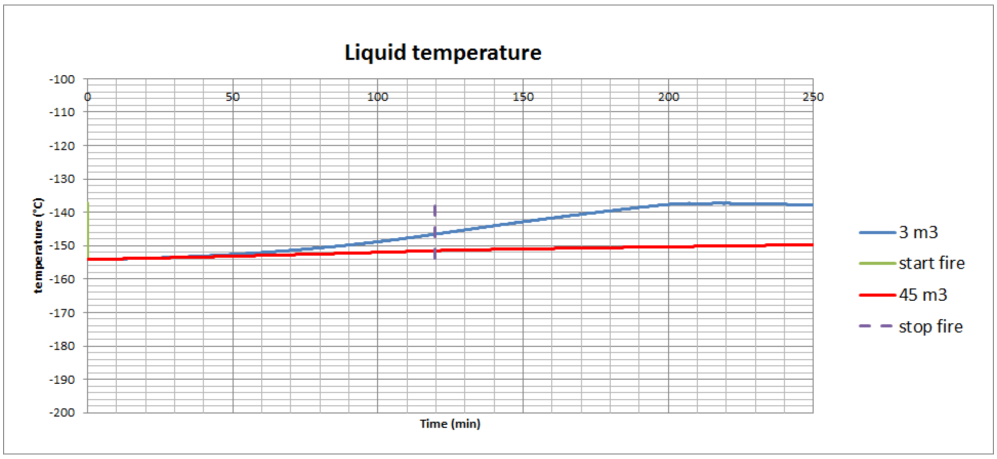

Figure 60 LNG: Comparison of liquid temperature in 3 m^3 vs 45 m^3 tank. Thermal conductivity 1.45 times default value; 120 min fire duration.

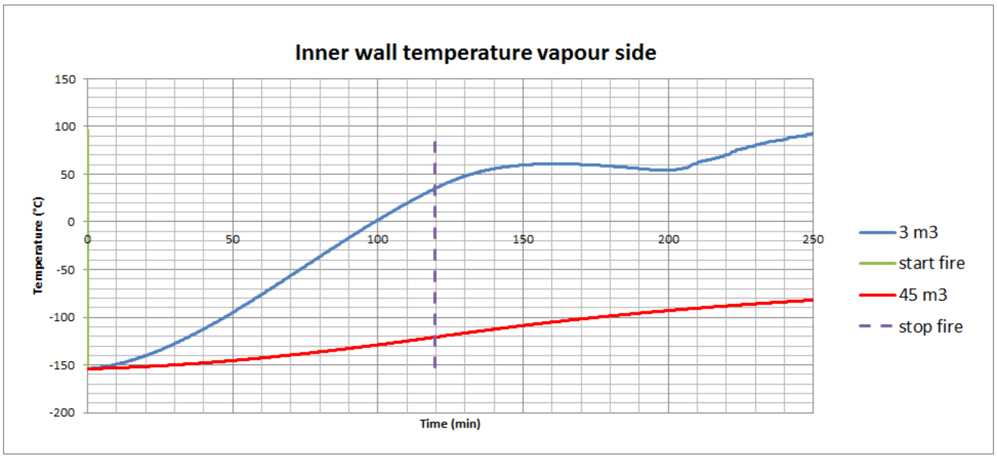

Figure 61 LNG: Comparison of inner wall temperature near gas phase in 3 m³ vs 45 m³ tank. Thermal conductivity 1.45 times default value; 120 min fire duration (increase in temperature after 210 min in 3 m³ tank is an artefact of the modelling).

It would actually take a fire of almost 8 hrs for a full size LNG tank to reach the set point value of a PRV (see Figure 62). At that moment the (inner) wall temperature is still predicted to be well under critical values to cause structural damage (which would be above ca 300°C, see Appendix III).

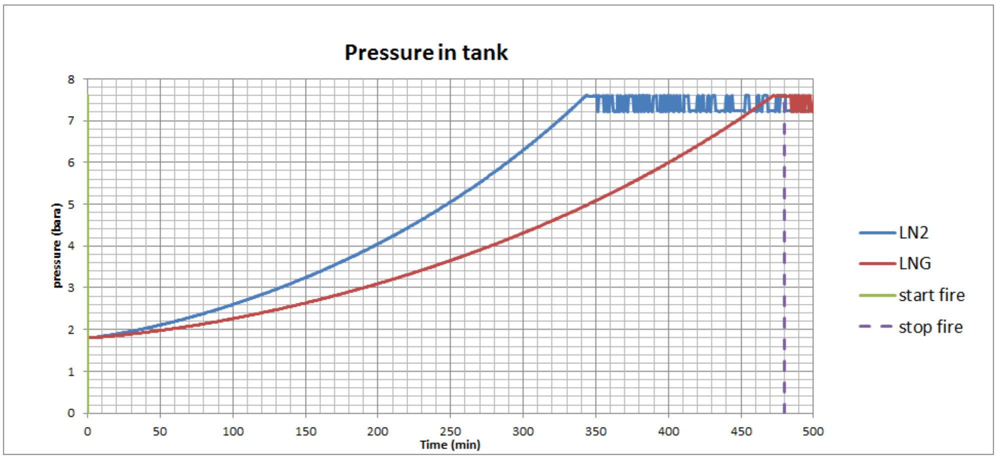

Figure 62 LNG compared to LIN_2 in a 45 m³ tank; thermal conductivity 1.45 times default value; 480 min fire duration.

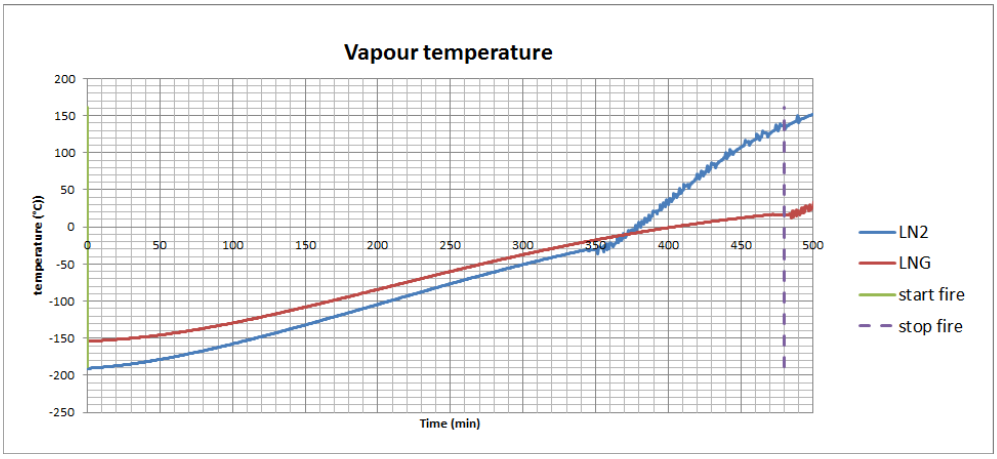

Figure 63 Temperature of the gas phase as a function of time (increase in temperature after 350 min (LIN_2) and 480 min (LNG) is an artefact of the modelling).

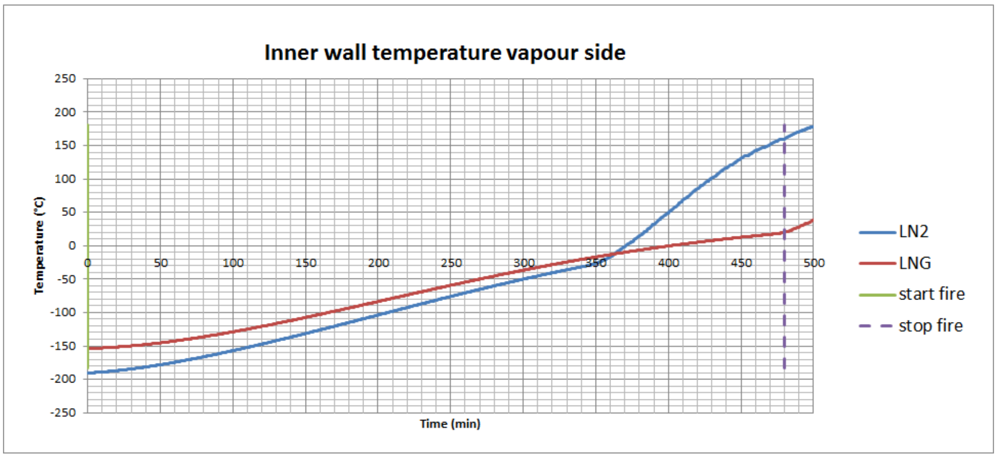

Figure 64 Temperature of the inner tank wall (near gas phase) as a function of time (increase in temperature after 350 min (LIN_2) and 480 min (LNG) is an artefact of the modelling).

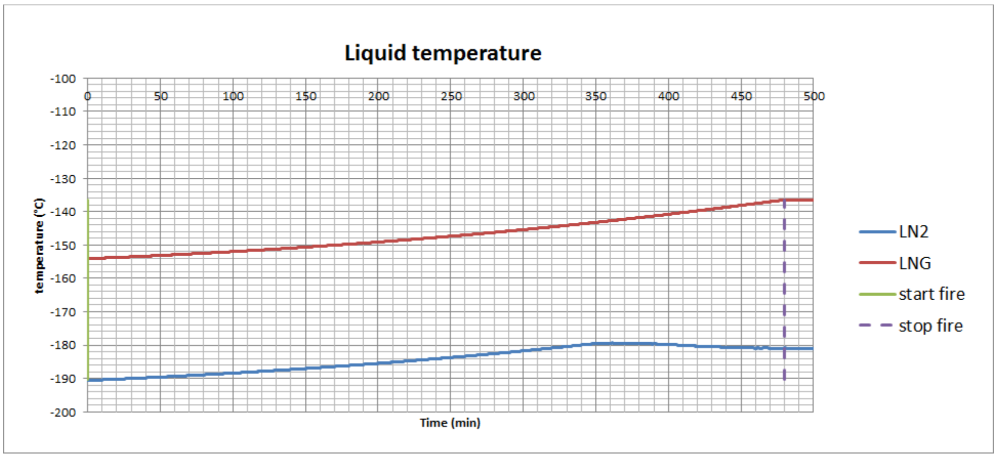

Figure 65 Temperature of the liquid phase as a function of time.

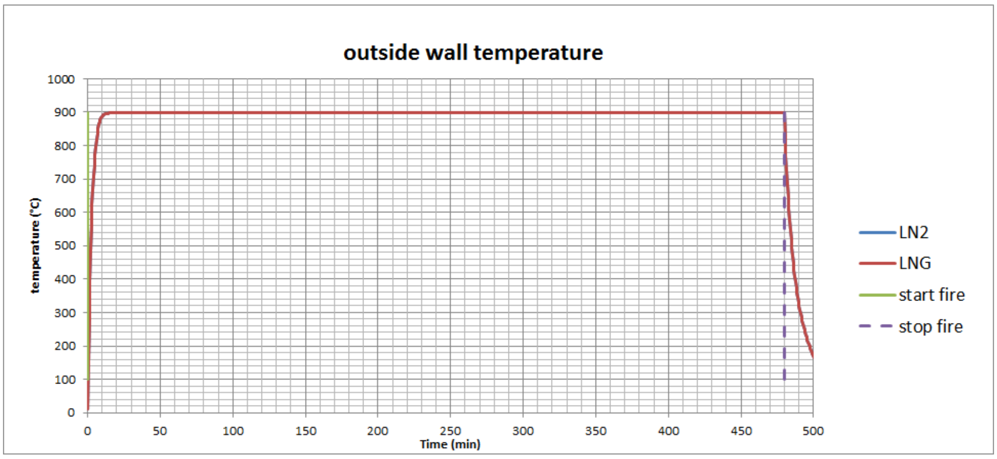

Figure 66 Outside wall temperature as a function of time.

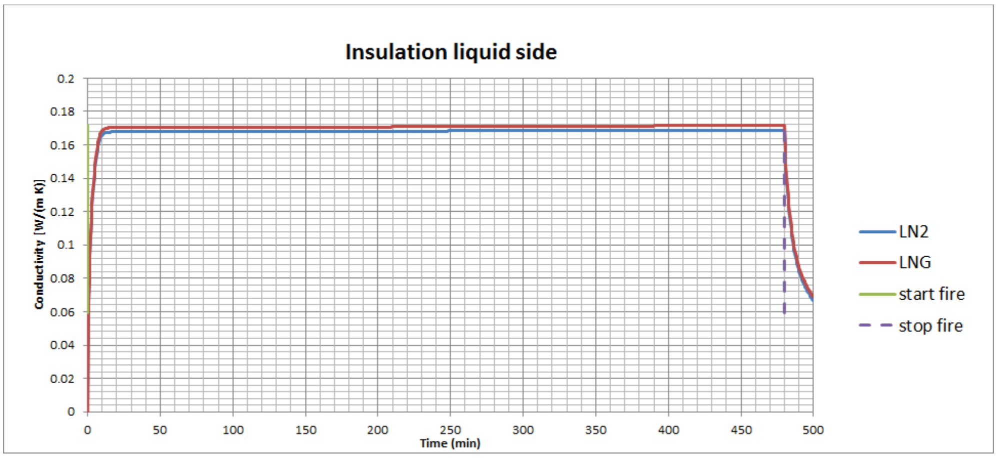

Figure 67 Thermal conductivity of the perlite layer at the liquid (bottom) side as a function of time.

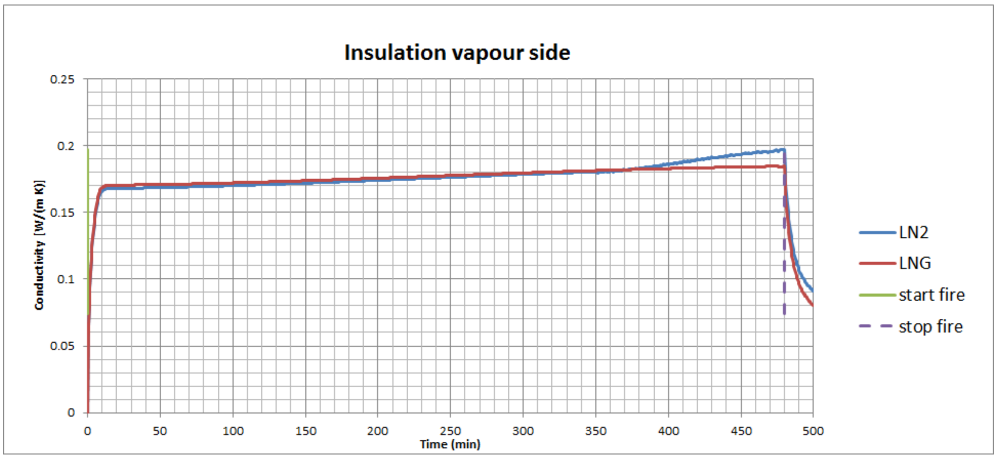

Figure 68 Thermal conductivity of the perlite layer at the gas (top) side as a function of time.

5.5 Single walled tank

For the single walled tank only meaningful results could be obtained for the period prior to ignition of the fire. The experiment had to be terminated a few minutes after

ignition of the fire, as the experimental set-up collapsed, probably as a result of insufficient thermal insulation around the tank supports.
The pressure as a function of time is shown in Figure 69, together with the TNO model result in which the default parameters were used for a 10 cm thick insulation layer consisting of evacuated perlite. As can be seen pressure increases is somewhat quicker than predicted using perlite as an insulator. This indicates that the Rockwool is a poorer insulator (at ambient temperature) than an equally thick layer of evacuated perlite.

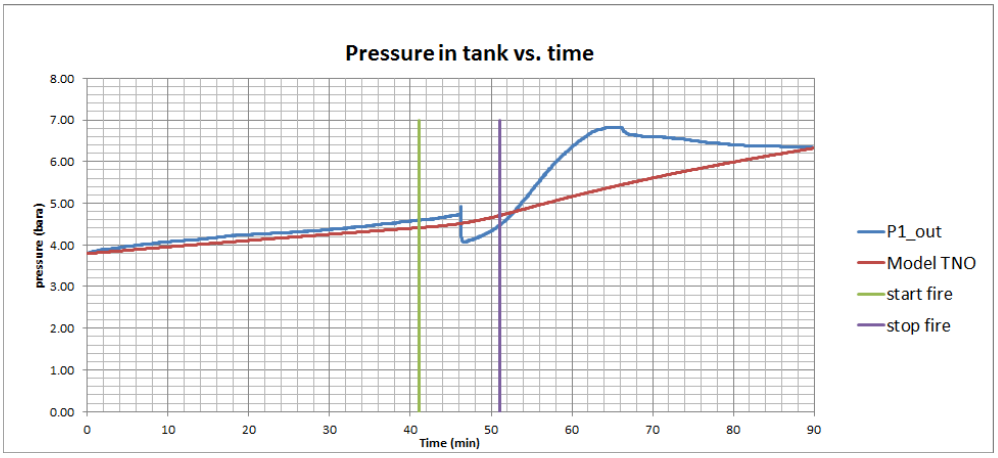

Figure 69 Pressure as a function of time for the single wall tank with 10 cm Rockwool insulation.

6 Conclusions

6.1 Observations

- The double walled vacuum insulated (TNO) test tank proved to be resistant against a representative accident fire scenario, at least for a period of 2 hours. Thereto, the tank was successfully subjected to the heat stress experiment described in this report, reaching an intensity set for75 kW/m^2. Because of wind conditions the average heat load was likely somewhat lower.
- The tank design concept chosen (vacuum rings, blocks, inner tank Perlite embedded, vacuum – low pressure) proved such that a direct contact between pressure tank can be avoided.
- Given the test tank design concept used:
  - Perlite remains unaffected by the experimental conditions (visual inspection).
  - Pressure tank remains unaffected by the experimental conditions.
  - Restricted buckling of the outer tank (jacket) may occur.
  - Supportive blocks (synthetic material) may be affected by the heat.

6.2 Measured data and model analyses

- The pressure data measured during the experiment can be considered reliable. From these data it can be concluded that, for a double walled 3 m^3 tank, for two thirds filled with LIN, it will take approximately 2 hours (from the start of the fire) until the internal pressure has reached the opening pressure of the PRV (ca. 7.6 bar). According to the TNO model the PRV won’t open until approximately 3 hours after ignition, even assuming that vacuum is lost the moment the fire is ignited. Loss of vacuum certainly occurred at some point during the experiment. This was evidenced by the loss of a vacuum disc 1:49 hrs after ignition. It is not immediately clear what causes the difference between modelled and measured data. By adapting the thermal conductivity of the perlite insulation layer in the TNO model an opening time could be predicted that corresponded with the observed data. However the agreement between the measured and modelled pressure - time relations remained far from perfect. It can certainly not be concluded from the data that this parameter (thermal conductivity) is responsible for the discrepancy between measured and modelled data. Nonetheless, for subsequent modelling (i.e. translation of the results to LNG and extrapolation to larger tanks) the adapted thermal conductivity was used, i.e. for the period during which the fire was on, the thermal conductivity was increased by 45% from the default value. The default value was based on well known and frequently used relations in literature.
- The temperature measurements inside the tank as well the measurements of the inner wall temperature, during the period in which the fire was on, fluctuate heavily and can not be considered reliable. Only the values before and after the fire are reliable. Of the data measured before starting the fire, only the data of a few thermocouples measuring the wall temperature at the liquid side (bottom) are in agreement with the model (and with expectations, as one would expect the bottom temperature to be equal to the liquid temperature). It is not clear why the other observed wall temperatures are higher. Perhaps a longer equilibration period than the ca. 2 hours given would have been better. Alternatively

suboptimal contact between thermocouple and tank wall may have caused the discrepancy.

- At the moment the PRV opens the hottest part of the inner wall (at the top near the gas phase) has reached a temperature of approximately 50 °C. This is far from any temperature (at this pressure) at which the structural integrity of the tank could be at risk. For this to occur at this pressure a temperature of about 300 °C would be required.
- Translating the results for LIN to LNG and particularly extrapolating them to larger tank sizes can only be done through modelling. For this the default values for LIN and LNG in the TNO models were used, except for the thermal conductivity of the perlite insulation layer. This value was increased by 45%. It was furthermore assumed that vacuum was maintained during the exposure to fire.
- According to the model it would take about 4 hrs for the 3 m^3 LNG tank to reach the set-point value (7.6 bara) of the PRV. For the LIN tank this would be 3 hrs. Because of the larger heat capacity and heat of evaporation of LNG (i.e. methane) this can be expected.
- The TNO model was also used to predict the behaviour of a real size (45 m^3) LNG tank in a fire. As expected because of the a larger volume to surface area ratio for a larger tank, the temperature and pressure increase for the larger tank is much slower than for the small tank. Hence it will take much longer to reach any critical value for both gas pressure and wall temperature.
- For a full size LNG truck it will take many hours (roughly 8 according to the model) for the pressure to reach the value that the PRV opens (here set at 7.6 bar). The inner wall temperature at the gas phase is then still well below any critical burst value, for which temperatures of ca. 300 °C are required at this pressure.
- However, the outside wall (the shell), in contact with the flames, will have a temperature close to the flame temperature. This will weaken this part, which may result in deformation of the shell. The perlite powder will support the shell. However, vacuum may be lost and the conductivity will rise from appr. 50 mW/m/K (assume vacuum and flame temp appr. 1200 K) to the value of perlite with air at atmospheric pressure: ca. 120 mW/m/K (see Figure 26).
- It should be emphasize here that these predicted are based on a model that still needs optimisation, as the predicted data are not in very good agreement with the measured data. And further optimisation is certainly advised.
  However assuming that the behaviour of the tank in the fire is representative for a “real case”, one can assume that exposure of a real size LNG tank (45 m^3) will result in a slower increase of both temperature and pressure than observed for a 3 m^3 LIN_2 tank, given a certain filling percentage. It should be noted though that lower filling rates will probably reduce the time to opening, as a smaller liquid volume will have to absorb the same heat input.
- Finally it should be remarked that the sudden increase in vapour and wall temperature predicted by the model after opening of the PRV may be a modelling artefact. This needs further investigation.
- From the experiment with the single walled tank with a 10 cm thick layer of Rockwool only data for the phase prior to ignition of the fire were usable. They indicate (as could be expected) that at ambient temperature evacuated perlite is a better insulator than Rockwool.

6.3 Research Objectives – Cryogenic tank integrity

6.3.1 Research question 1 - Has a double-walled pressure tank – at least – equivalent heat load resistance to those of single-walled pressure tank fitted with heat resistant coating?

The heat load resistance of the insulating layer is determined by the thermal conductivity of the insulation layer and the thickness of this layer. LPG tanks are typical single-walled pressure tanks. TNO has performed studies with thermally coated LPG tanks. A typical coating is applied as a 1 cm layer on the outside of an LPG tank. In a fire this coating swells to a thickness of about 5 cm. The thermal conductivity after swelling was found to be approximately 63 mW/m/K [20]. So effectively the energy transfer for the single walled tank with such a coating would be 63/0.05 = 1260 mW/K.
The thermal conductivity of perlite under ambient temperature conditions (300 K) and vacuum can be as low as 9 mW/m/K (see Figure 26). As the layer thickness is typically 20 cm this results in an effective energy transfer ("heat inleak") of 9/0.2 = 45 mW/K. However at 1200 K and when vacuum is lost thermal conductivity may go up to 120 mW/m/K (or even 175 taking the factor 1.45 into account used in the model). Using these values would result in an effective heat transfer of: 120/0.20 = 600 mW/K, or 175/0.2 = 875 mW/K using the factor 1.45.
From this it can be concluded that the heat load resistance of a double-walled pressure tank with a 20 cm thick layer of perlite is – at least – equivalent to the heat load resistance of a single-walled pressure tank fitted with a 1 cm heat resistant (intumescent) coating.

6.3.2 Research question 2 - Can a double-walled pressure tank endure an exposure to radiation intensities of 35 kW/m^2 or more without any catastrophic rupture?

The burners during the test were set to generate a heat load of approximately 75 kW/m^2. This is roughly twice the value of 35 kW/m^2. It can therefore safely be assumed that with a heat intensity of 35 kW/m^2 it would have taken (much) longer than 2 hours for the PRVs on the 3 m^3 tank (for 2/3 filled with LIN_2) to open. Using LNG and larger tanks will further increase this time. Whether or not catastrophic failure will occur (after many hours of exposure to this heat load) cannot be derived from these experiments. It will depend on factors like:

- the set value of the PRV.
- the capacity of the PRV (i.e. will the blow-off capacity be sufficient to prevent an increase in pressure beyond the set value?)
- the (max) temperature of the (inner) tank wall at the gas side. This temperature will determine the strength of the tank
- material properties of the tank (e.g. yield stress)

An experimental assessment will be impractical given the length of time such an experiment would take. Therefore catastrophic failure conditions will have to be determined through modelling. The (TNO-)model used in this study (a so called lumped model) can be used for this purpose with improved and adapted parameters (from small scale experiments). Also CFD models that are being developed by TNO can be used.

6.3.3 Research question 3 - What heat load and duration of exposure are necessary to catastrophically rupture a full size double-walled pressure tank (i.e. time to failure)?

Heat load and duration are, to a certain degree, communicating vessels: a high heat load applied during a short time may cause rupture, as well as a lower heat load during a longer time. The burners at the BAM site were set to generate a heat load of approximately 75 kW/m^2 (although because of the wind the average heat load will have been somewhat lower). As can be seen from Figure 62 it is expected to take many hours for a real size LNG transport tank to heat up to a value where the PRV opens. Whether or not this will lead to catastrophic failure will depend on the parameters mentioned in research question 2. Again only by modelling, in which data from a small scale experiment are extrapolated, this question can be answered realistically.

7 Recommendations

- Pursue with research. Solve the temperature measurements issue and then repeat the fire tests as reported in this document in order to check/ demonstrate reproducibility and generate consistent test data which can be used for calculation model validation purposes.
- The recommendation above, specifically focused on the different (alternative) insulation technologies applied nowadays (e.g. study Perlite embedded, versus Multi Layer Insulation or other).
- The two recommendations above, preferably in combination with the heat resistance of the overall tank construction (e.g. ring enforcement and blocks, versus other designs chosen to connect pressure tank with the outer jacket, the separation distance between inner and outer shell).
- Pursue with research, using a fully equipped (comparable size) commercially available cryogenic tank, filled with LIN (or LNG) to study certain accidental failure modes, potentially others than the scenario ‘tank failure’ by itself.
- Based on the performed experiments tests on real size tanks are not realistic, because of the extremely long times these are predicted to take. However, these predictions are based on a model which is only validated to limited extend. It is therefore paramount that this model should be further developed.
- Pursue with research, specifically studying the behaviour of the pressure relieve valve (PRV) in accidental fire conditions – the effect of the positioning of the PRV, its connection to the tank. In addition to vapour release, also consider (in theory or in practice) the event of possible PRV liquid release.
- Pursue with research on stratification on real size storage tanks. Doing so, the use of Computational Fluid Dynamics is the theoretical exercise to consider. If any, study which implications a stratification may have for the evolvement of an accidental (heat stress) scenario. Still this phenomenon cannot be excluded (for real size, and/or vertical tanks).
- Reconsider the fire intensity (larger than 35 kW/m^2) to which an LNG tank as a whole might be exposed. The bonfire conditions chosen are comparable (and reproducible) to those applied in past thermal heat load tank experiments, single walled, (non)coated, filled with LPG. In future experimental set-ups, one could also consider a jet fire scenario (with heat intensities up to over 200 kW/m^2), thereby possibly inducing a local (undesired) weakening of the tank wall.

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Appendix I Tank design

Introduction

Since it proved to be impossible to procure a suitable and affordable cryogenic vacuum test tank from commercial vendors, it was decided to design and manufacture the tank, under TNO responsibility. The design and manufacturing are reported in this chapter.

Cryogenic vacuum tank

General arrangement
Because of the space required, stationary tanks are often placed in a vertical position. On the other hand horizontal tanks are always used in case of applications in road and rail transport, while in case of fuel tanks on board ships, both concepts are used. Based on these observations deciding for a ‘typical tank’ is not possible. When a cylindrical tank is exposed to an external fire, the exposed area of vertically orientated tank tends to be smaller than the exposed area in case of a horizontally oriented tank. Another feature is the free liquid surface, which tends to be larger in case of a horizontally oriented tank, which implies a larger evaporation rate. Both observations suggest that a horizontally oriented tank is to be considered more vulnerable to an external fire load than a vertically oriented one. Hence a horizontally oriented tanks was decided.

As for the tank size three aspects are relevant;

a. physical phenomena,
b. availability of reference tests,
c. costs.

ad. a. The tank dimensions and scantlings should be chosen such that any physical phenomenon, which will occur in commercially available tanks will also occur in the test tank. Moreover the choice of dimensions and scantling should not introduce any unintended mechanisms.

ad. b. Since fully instrumented fire tests are not carried out frequently, it is important to conducts tests on objects which can be compared dimension wise with tests done in the pasts. In this particular case a reference is made to instrumented fire tests carried out on LPG tanks.

ad. c. Obviously, tank dimensions have a strong influence on costs of manufacturing, handling and testing.

Because earlier fire tests involved a tank with a volume 3 m^3, it was decided to design and build a vacuum tank with the same volume. Compared to most commercially available tanks, this size is rather small. The tank dimensions and scantling, as chosen, can be considered conservative because the ratio between area exposed to heat and tank volume is relatively high compared to bigger tanks, which implies a relatively high heating rate.

Figure 1 shows the tank as designed and built.

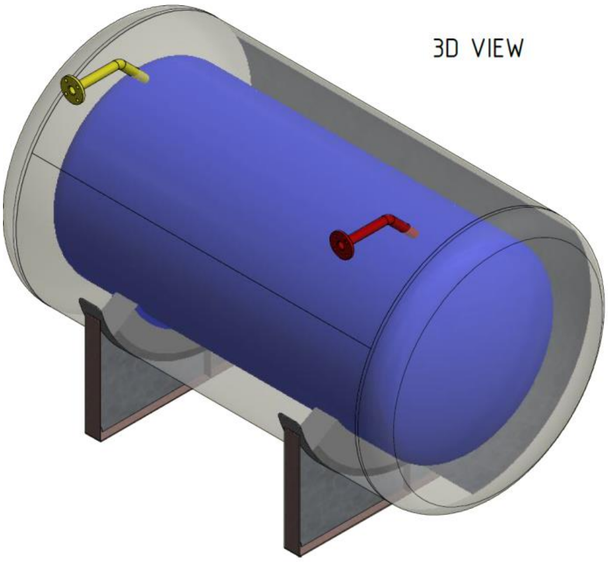

Figure 1 3 m^3 cryogenic vacuum test tank.

Design calculations

The design pressure of the tank has been determined with the simple hoopstress formula;

$$p = \frac{2\,\sigma_y\,\mathrm{t}}{\mathrm{D}}$$

with : p pressure where yield occurs,
σ_y yield stress material,
t plate thickness,
D tank diameter.

With a tank diameter of 1500 mm, a yield stress of 290 MPa and a plate thickness of 3 mm, the pressure at which yield is expected equals 1.16 MPa (11.6 bar). With an arbitrarily chosen safety factor of 1.9 the allowable pressure during tank filling becomes 6 bar.

Please notice that during testing the yield stress of the material is expected to come down. Obviously the safe condition ceases to exist, hence at that stage, personnel is not allowed anymore near the tank. At the test site a safe distance of 400 m is observed during the fire tests.

The outer tanks is designed for buckling. Three methods have used to design for this failure mode;

a. BS EN 13458-2:2002,
b. Rahim,
c. Windenburg Trilling.

The governing formula are:
BS EN 13458-2:2002

$$p_e = \frac{E}{S_k}\left\{\frac{20}{\left(n^2-1\right)\cdot\left[1+\left(n/Z\right)^2\right]^2}\cdot\frac{s-c}{D_a}+\frac{80}{12\cdot\left(1-v^2\right)}\cdot\left[n^2-1+\frac{2n^2-1-v}{1+\left(n/Z\right)^2}\right]\cdot\left[\frac{s-c}{D_a}\right]^3\right\}$$

Rahim

$$P_{cr} = \frac{E\frac{t}{r}}{1+\frac{1}{2}(\frac{\pi r}{nl})^2}\left\{\frac{1}{n^2\left[1+(\frac{nl}{\pi r})^2\right]^2}+\frac{n^2t^2}{12r^2(1-v^2)}\left[1+(\frac{\pi r}{nl})^2\right]^2\right\}$$

Windenburg and Trilling

$$P_{cr} = 2.6E(\frac{t}{2r})^{2.5}\frac{2r}{l}$$

simplified

$$P_{cr} = \frac{2.42E(\frac{t}{2r})^{5/2}}{(1-v^2)^{0.75}[(\frac{l}{2r})-0.45(\frac{t}{2r})^{1/2}]}$$

full

With :

nvr	number of vacuum rings	2	[]
l, lb	buckling length	812.333	mm
n	number of buckling lobes		
D	shell diameter	1600	mm
Da	outside diameter	1600	mm
Di	inside diameter	1597	mm
E	Youngs modulus	2.10E+05	N/mm2
s	min wall thickness	3	mm
c		0	mm
Z	auxiliary value	3.0939	[]
v	Poisson's ratio	0.3	[]
Sk	safety factor	1	[]
K	0.2 % strain stress level	200	[N/mm2]
Z	$0{,}5\pi D_a/l_b$		

With input data as indicated a buckling pressure of 1.75 bar is found. The effect of the assumed number of buckling lobes and the various calculation methods on the buckling pressure is shown in Figure 2.

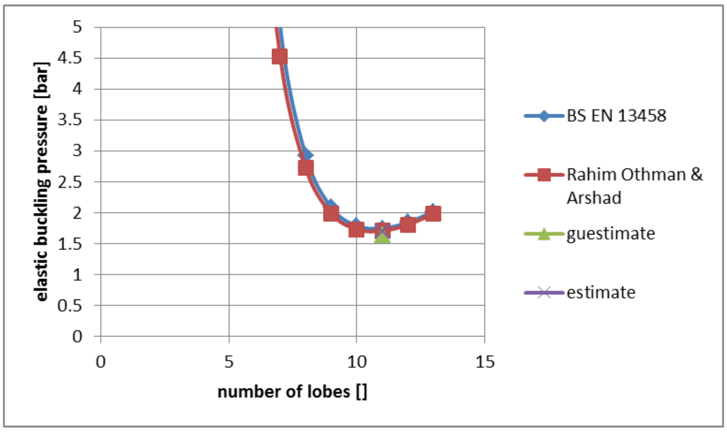

Figure 2 Elastic buckling pressure.

There are two internal ring stiffeners of which the scantlings were chosen according minimum requirements of the BS EN code. The tank design is shown in Figure 3.

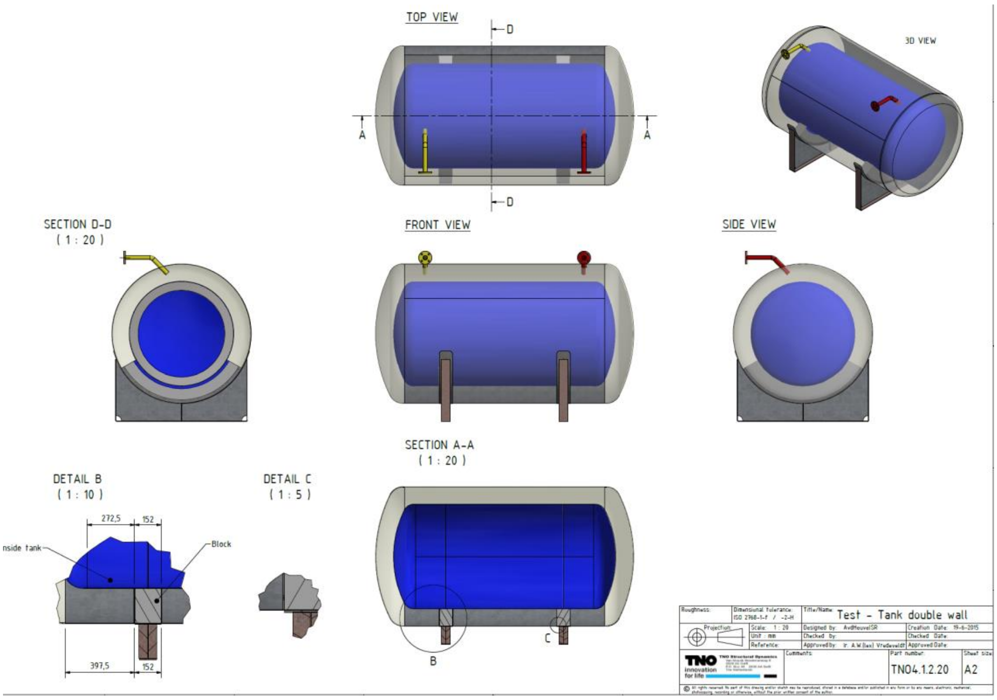

Figure 3 design cryogenic test tank.

Further details can be obtained from Figure 4 and Figure 5. As indicated on the drawings, the outer tank is manufactured of carbon steel S235JR while the inner tank is manufactured from stainless steel 304. Two pipes we fitted in order to gain access to the tank.

6 bar pressure valves were fitted on the both the filling and exhaust lines.

The annular space was vacuumed down to approximately 200 mbar (absolute).
The annular space was filled with perlite powder for reasons of supressing radiation.
Many small diameter tubes were fitted penetrating the outer tank and attached to the inner tank and in three cases penetrating the inner tank. These tubes accommodated temperature gauges.
Pressures were measured in both the filling line and exhaust line.
the piping and instrumentation diagram, relevant for safe operation is shown on.

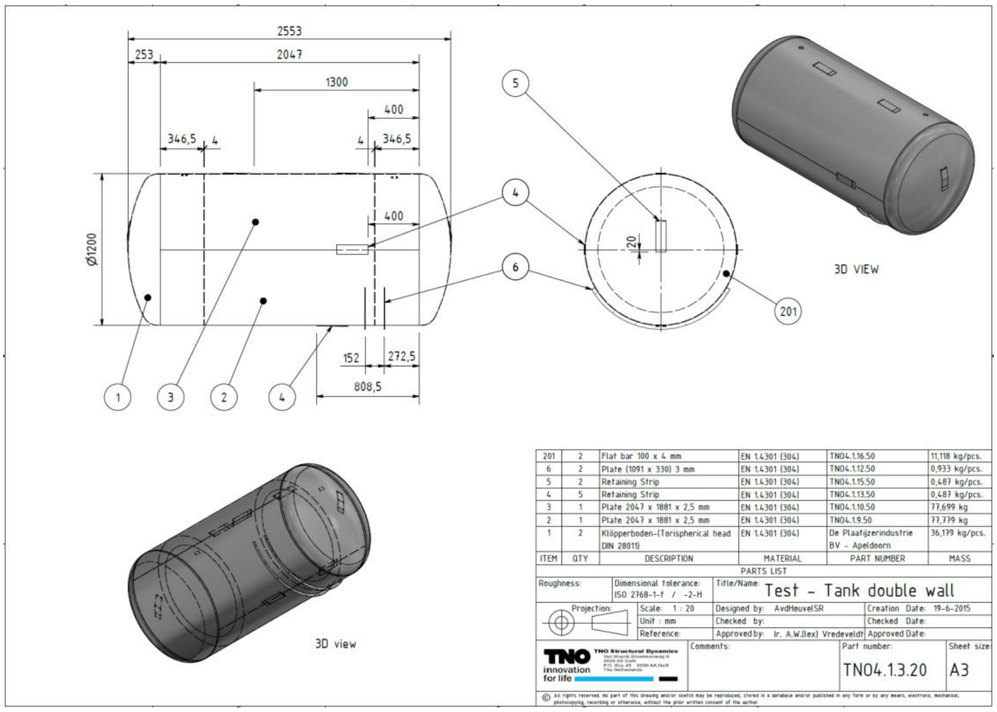

Figure 4 cryogenic vacuum test tank inner tank.

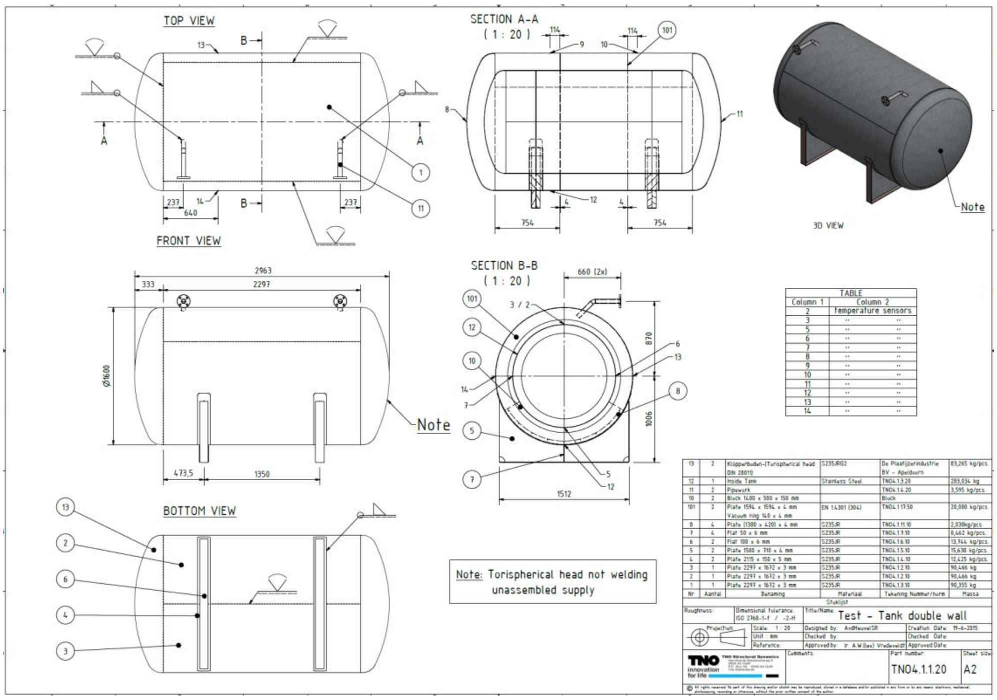

Figure 5 cryogenic vacuum test tank outer tank.

Manufacturing and acceptance tests

Prior to bringing the test tanks to the test site X-ray checks were done which prompted some repairs and adjustments. Moreover a pressure was done prior to putting the tank on transport.

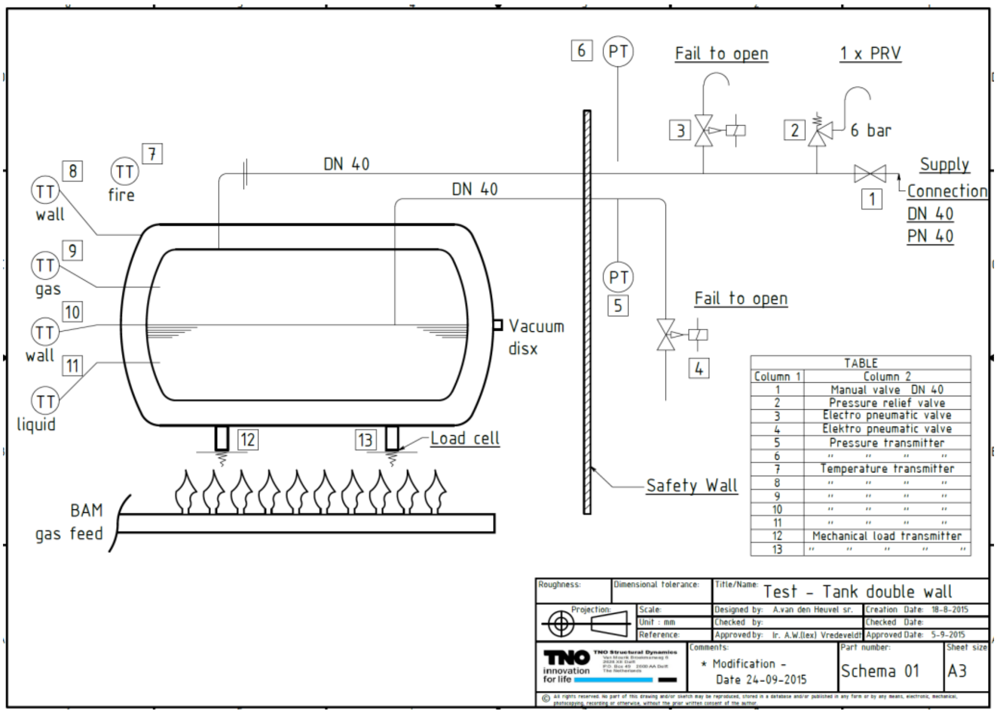

Figure 6 piping and instrumentation diagram for safe testing.

Appendix II Limit load criteria

Introduction

The 3 m^3 vacuum tank subjected to the fire tests is shown in the previous Appendix. The results of the test will be used to validate calculation models which predict temperature and pressure build-up in the inner tank during an exposure to fire.

Scantlings are listed below.

outer tank		
t shell	3	mm
t tank end	5	mm
D	1600	mm
innertank		
t shell	3	mm
t tank end	3	mm
D	1200	mm

The material is stainless steel EN 1.4301 (304).
It is not the intention to bring the tank up to the point of rupture. For this reason a test abort criterion is established which is described in this document.

Background data

One important property of the material is fracture toughness, which needs to be well above 27 J at any temperature in order to avoid any premature rupture. Table 1 shows minimum values according ref. [1]. As can be seen values are at a comfortable level, hence fracture toughness is not considered an issue.

Table 1 fracture toughness values 304 and 404L [1]

Temperature		Charpy V-Notch Energy Absorbed	
°F	°C	Foot-pounds	Joules
75	23	150	200
-320	-196	85	115
-425	-234	85	115

The other important parameter is the yield stress of the material. Various literature references are available on the reduction of material strength at elevated temperatures ([1],[2]). Figure 1 shows strength versus temperature of the material under consideration.

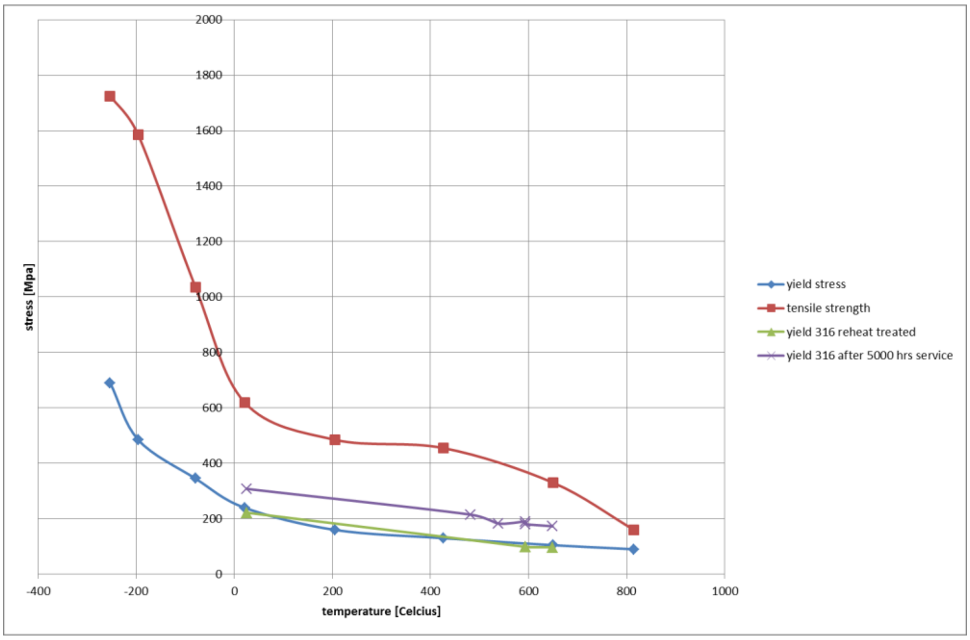

Figure 1 Yield stress and tensile strength versus temperature.

The graph shows that both yield stress and tensile strength reduce significantly at elevated temperature.
For the fire test abort criterion it is proposed to use material yield as the ruling parameter. It basically means that the allowable inner pressure reduces with increasing material temperature. There exists a direct relation between stress in the tank shell and the internal pressure, i.e. the hoop stress and longitudinal stress.

Shell stress

The hoop stress (circumferential) in the cylindrical shell equals;

$$\sigma_c = \frac{p\,D}{2\,t}$$

With : p internal pressure,
D tank diameter,
t shell thickness.

The longitudinal stress in the cylindrical shell equals;

$$\sigma_l = \frac{p\,D}{t}$$

Combining these tresses in a Von Mises stress criterion gives;

$$\sigma_v = \sqrt{\sigma_c^2 - \sigma_c\ \sigma_l\ + \sigma_l^2}$$

It is noted that both stresses are principle stresses.
In this particular case where the longitudinal stress is half the hoop stress, the equation reduces to;

$$\sigma_v = \sqrt{\frac{3}{4}\sigma_c^2}$$

$$\sigma_v = \sqrt{\frac{3}{4}}\sigma$$

With this relation, taking the yield stress as function of temperature (Figure 1) allows to determine the allowable internal pressure as function of temperature. With an additional margin of 10% this gives the figure as shown in Figure 2.

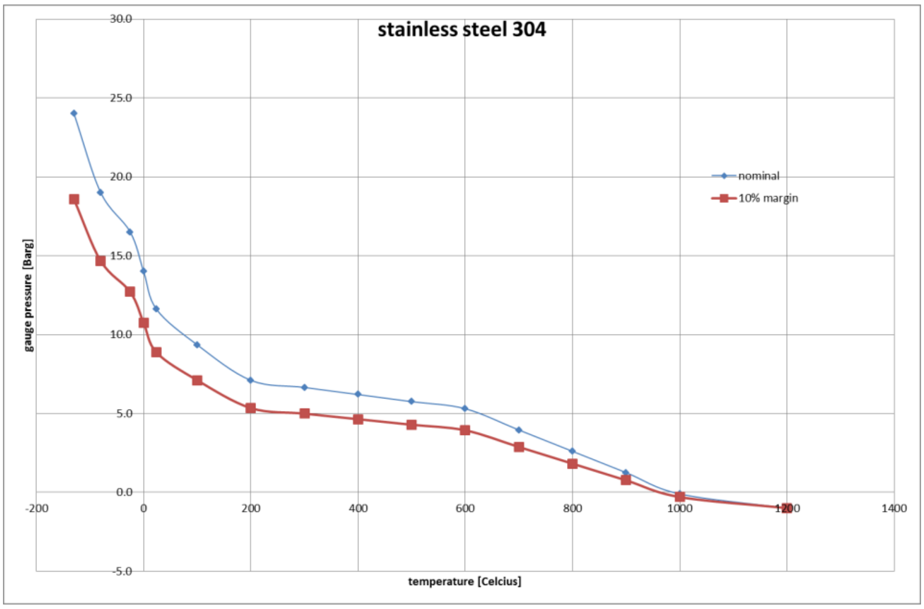

Figure 2 allowable tank pressure versus temperature.

Instrumentation

The sensors which are being used to control the test are two pressure sensors (one at each tube penetration of the tank, indicated with P, see figure below) and four temperature sensors on the tank shell, as indicated with blue arrows in the figure below.
One temperature sensor is situated at the bottom of the tank, one is situated at half height and two are placed at the tank top.

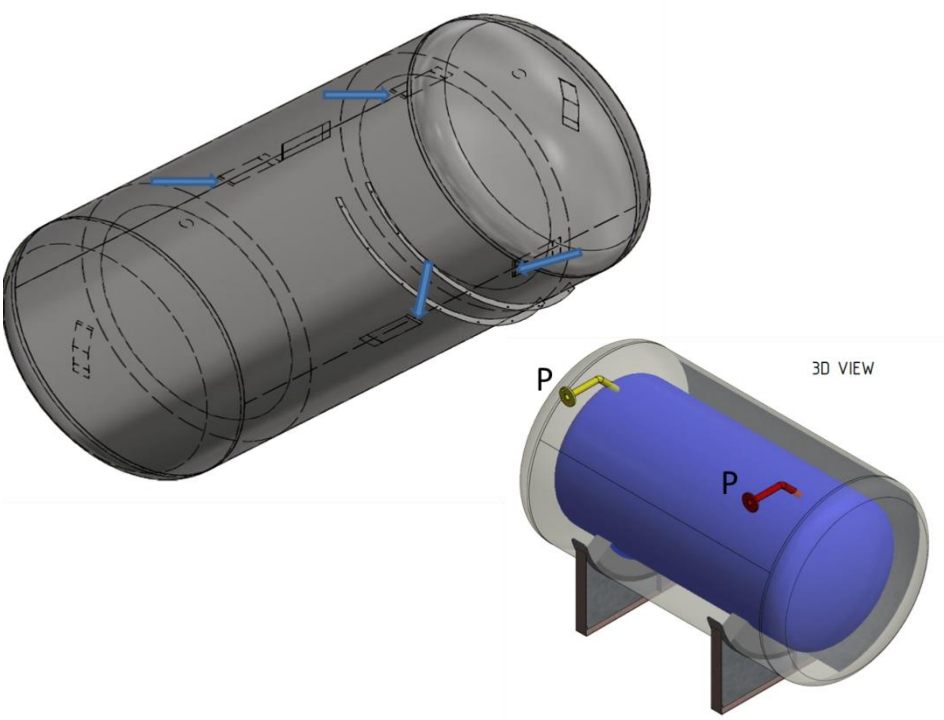

Figure 3 temperature gauges used for test abort.

Abort criterion

According to the reasoning as outlined in the previous sections the test abort can be best based on the graph depicted below.

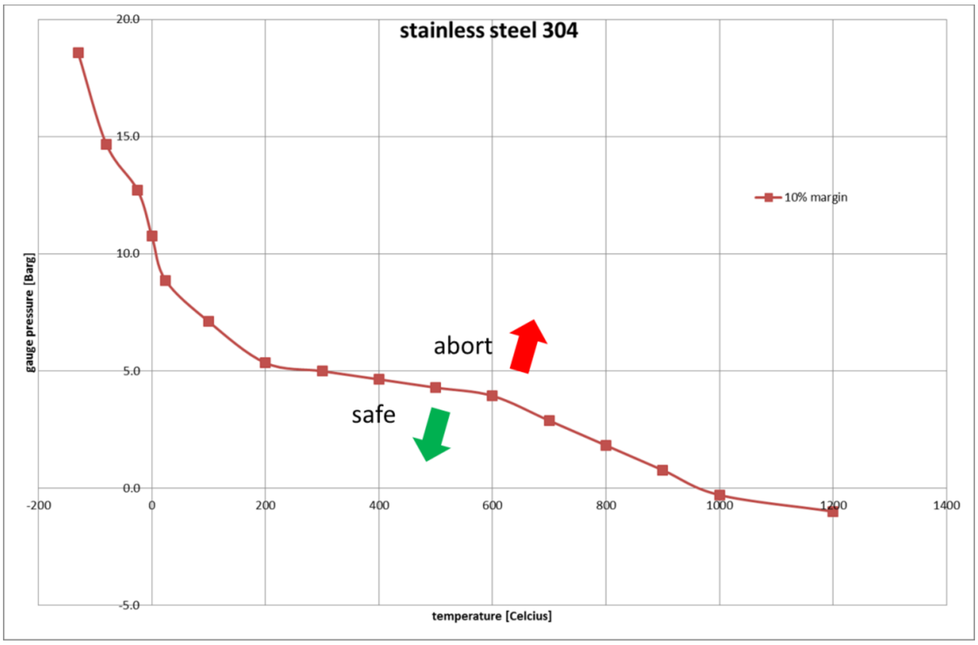

Figure 4 continue – abort graph.

Any pressure-temperature observation, entering the abort is to be used as a test abort criterion.

The abort curve can be described with the formula below;

$$P_{allow} = 5.429\ 10^{-11}\ T^4 - 1.408\ 10^{-07}\ T^3 + 1.194\ 10^{-4}\ T^2 - 4.391\ 10^{-2}\ T + 10.58$$

It is valid only up to 900 Celcius.

The test should be aborted also when the tank wall temperature exceeds 900 Celcius.

References

[1]. Technical Data Sheet AISI 304 AISI 304L, stainless-struturals.com
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Appendix III BAM Curve (Heat Load)

The heat load on the tank was estimated from the propane gas burning rate as shown below.

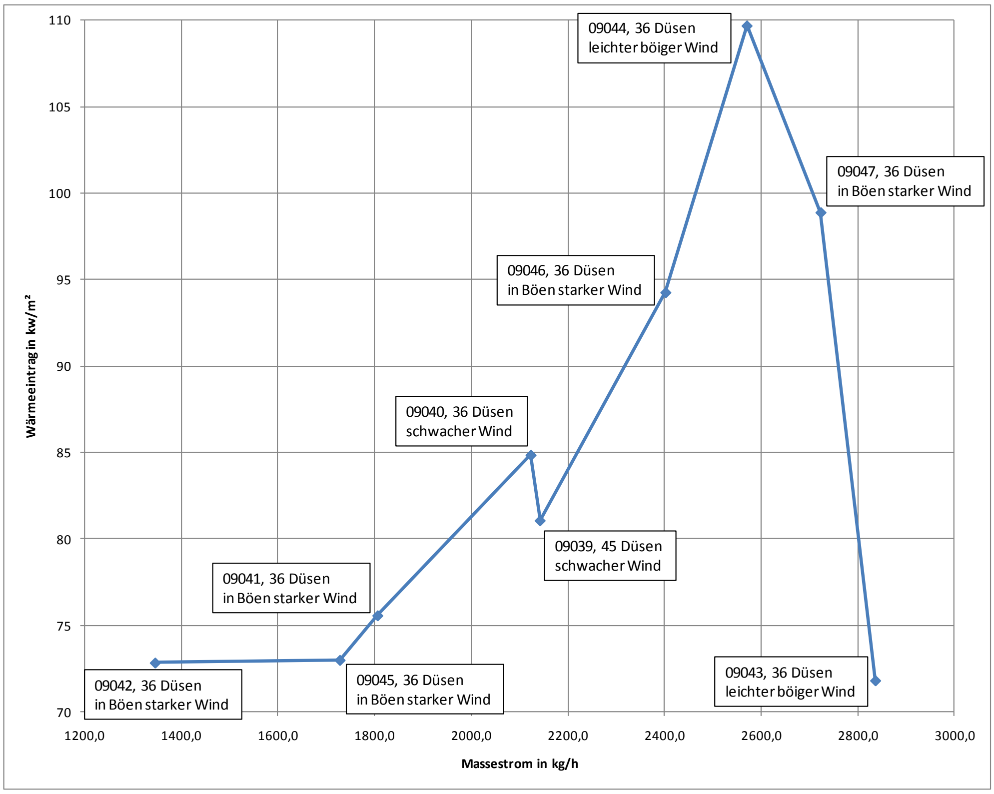

Figure 1 BAM Burner Grid Calibration Curve – Heat Load (kW/m2) versus Propane Flow (kg/hour)