

Effects of Enveloping Pool Fires on LNG tank Containment Systems

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1 Abstract

The increased trade of LNG over the past decade has led to discussion of possible major fire hazards associated with both marine accidents and intentional acts and this is becoming an increasing part of public awareness. Recent studies have tried to evaluate the possible consequence of such events on the areas surrounding the fire but not the vessel itself. Considering major hazard scenarios assuming pool fires around LNG tankers GL, ABS and Moss Maritime together with two German university institutes evaluated the response of a Moss type LNG containment system to an enveloping pool fire. The evaluations include a finite element buckling analysis of the tank cover, an extensive CFD simulation of the insulation system and tank supports and an overall thermodynamic analysis of the major effects of the heat flux caused by a fire. The paper summarizes the results of these extensive evaluations and explains the conclusions and limitations.

2 Introduction

A fleet of more than 300 LNG carriers is currently being used for the transport of natural gas around the world. According to the SIGTTO database, there are about 23 LNG export (liquefaction) terminals and ca. 79 import (re-gasification) terminals worldwide. It is estimated, that the LNG consumption will increase over the next years. [6, 7]

In view of the increasing trade of LNG possible major hazards are in the focus of public discussion. Many studies have been conducted to assess the consequences and risks of LNG spills as a result of marine accidents or intentional acts. Most of such studies have focused on the risk to the population in the vicinity of the terminal. Also damage to the ship structure as a result of contact with the cryogenic LNG has been evaluated in several studies.

A major area of concern has been ignition of a spill, pool fires and possible subsequent overpressure of an intact tank. A tank failure caused by overpressure can cause further damage to the ship structure and / or failure of other tanks. The evaluation of consequences of a Moss containment system under fire exposure is examined below.

For the evaluation of the response of the spherical tank system it is assumed, that the hull is completely engulfed by the fire. There are considerable uncertainties about the realistic flow behaviour and consequently about the emissive power of an LNG pool fire. Experiments have measured maximum local heat fluxes of 300 kW m^{-2} at the outer surface of the fire. Inside the fire ball the combustion is incomplete due to the shortage of air which results in lower temperatures and therefore lower heat fluxes.

Investigations, as to the bases for the IGC Code Chap. 8.5, related to pressure relief valve sizing, have established that the criteria uses a constant average heat flux of 108 kW m^{-2} in the case of fire [4]. It should be noted that this has been considered a good value to use even for fires with much higher local maximum heat fluxes. This value is the standard value used in refinery industry and liquefied gas transport. [1, 3, 10]

Therefore the following investigations to evaluate the heat transfer into the spherical tank system consider the interval of 88 kW m^{-2} up to 300 kW m^{-2} as the emissive power of an LNG pool fire. The fire itself has not been modelled instead simplified scenarios are used to model the heat flux into the ship structure above the waterline.

The Moss containment system is characterized by a spherical tank design, which is supported by a single cylinder, the skirt with a steel weather cover welded to the main deck. cp. Fig. 1.

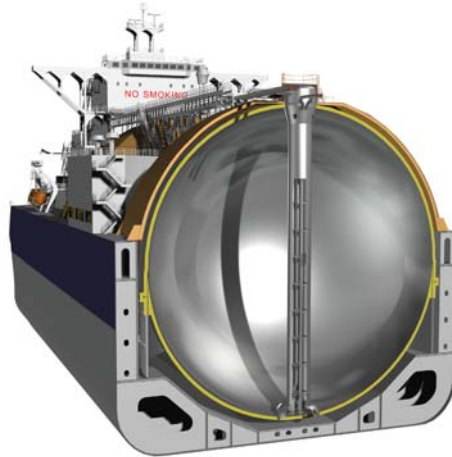


Fig. 1 Spherical tank system

Regarding the heat fluxes into the spherical tank system the air gap between weather cover and insulation is of particular importance. Compared to solids, in which only heat conduction occurs, all three phenomena of heat transfer take place inside the air gap. Depending on the surface configuration heat radiation occurs within this transparent medium. In addition the heat flux into the air will cause differences in density which results in buoyancy forces and consequently natural convection. Due to interaction of thermal conduction and natural convection heat is also transferred by convective heat transport. The investigations on the basis of a simplified steady state 1-D model, which consider the mentioned physical phenomena, are examined below. All of the following results were calculated with no consideration given to the cooling effect of the deluge system which is required to be provided on the tank dome in accordance with IGC.

3 Simplified steady state 1-D model

Within the study [5] heat transfer calculations have been done on the basis of a simplified steady state 1-D model of the LNG tank. The model consists of flat plates instead of spherical walls, which is due to the large radius of the sphere a good approximation. The model is illustrated in Fig. 2

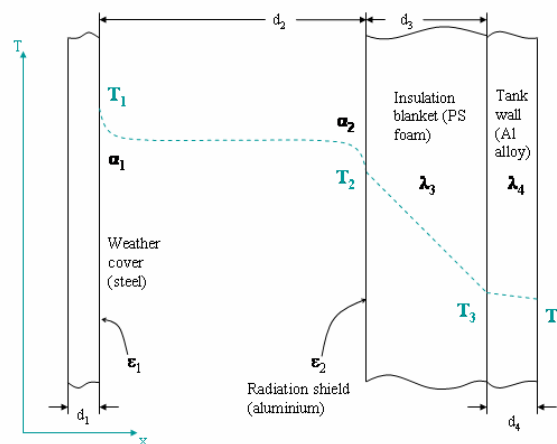


Fig. 2 Model of the spherical tank system, [5]

The model consists of the weather cover (steel), the air gap between weather cover and insulation (polystyrene foam), the vapour barrier (aluminium), the insulation and the inner tank wall (aluminium) cp. Fig. 2. Various insulation materials are used in general, but the polysterene material is selected in this case due to the lowest melting temperature. The material properties are given in Tab. 1, which are used for the following heat transfer calculations.

	Density	Thermal conductivity	Heat capacity	Emission coefficient	Melting temperature
Si-unit	kg m ⁻³	W m ⁻¹ K ⁻¹	J kg ⁻¹ K ⁻¹	-	K
Aluminium	2700	70	904	0.07	873
Insulation	26.5	0.038	1045	-	473 – 573
Air at 0°C	1.27	0.02436	1006.1	-	-
Steel	7850	44.5	475 (at 20°C)	0.7	1023

Tab. 1 Material properties of the spherical tank system

In addition to the material properties the temperature boundary condition are determinable, so that the temperature distribution can be calculated for a profile of the containment system.

The main heat of the engulfing fire is transferred via radiation and absorbed by the weather cover. Based on the equation for radiation the flame temperature depending on the emitted heat flux can be calculated by eq. 1.

$$T_0 = \left[\frac{\dot{q}}{\sigma} + T_1^4 \right]^{\frac{1}{4}} \quad (1)$$

3.1 Possibility of Film Boiling

An issue of concern is the possibility of film boiling cp. Fig. 3. As the weather cover starts heating up if there was no insulation on the tank the LNG would start to boil. Up to the point of film boiling the tank wall is almost at the temperature of the cargo. If a transition occurred to film boiling then a film of methane vapour would separate the tank wall from the cooling LNG. This separation by vapour will cause the tank wall to heat up above the boiling temperature of the liquid and as a consequence cause tank collapse.

For temperature estimation of the inner tank wall the heat transfer properties of methane in pool boiling have been evaluated. Methane is expected, as the main component of natural gas, to represent the properties of LNG within an insignificant deviation. Fig. 3 shows the heat fluxes for nucleate and film boiling as a function of the heat flux into the fluid and the temperature difference $T_{\text{Wall}} - T_{\text{Saturation}}$. The maximum possible heat flux into the fluid is limited by the critical heat flux, which occurs at the transition from nucleate to film boiling. The critical heat flux is reached when vapour bubbles form a closed layer on the heated surface, which lead to the insulation affect described above. The heat flux into the fluid decreases and the surface temperature increases, which can lead to the burn out of the heated surface.

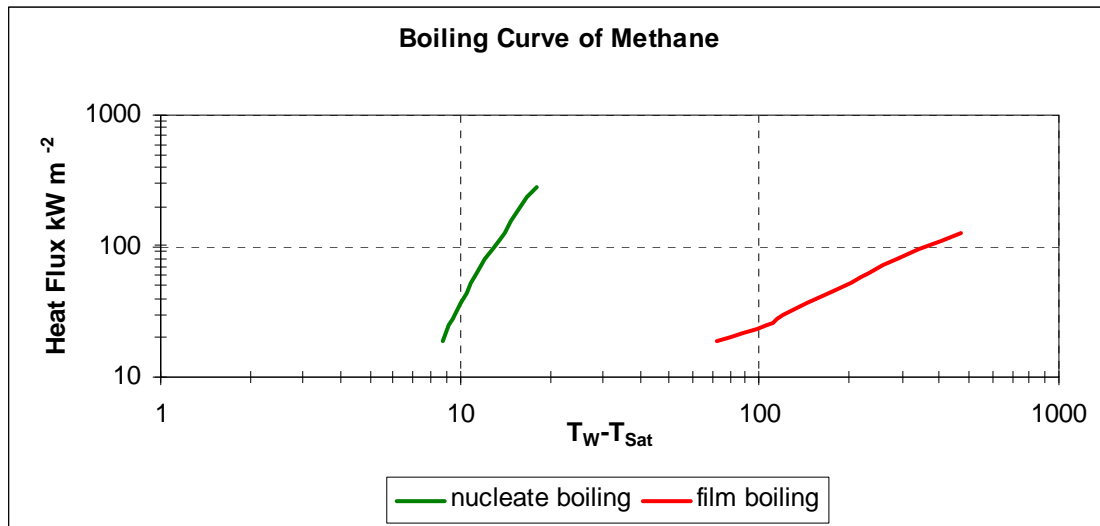


Fig. 3 Boiling curve of methane, [9] modified

For the spherical tank system the critical heat flux constitute 300 kW m^{-2} with a temperature difference of about 15 K. For a heat flux of 20 kW m^{-2} up to 300 kW m^{-2} into the fluid the wall temperature will adjust between 7 K and 15 K above saturation temperature of the fluid. Even considering the worst case scenario that there is no insulation left on the tank surface the heat flux can not reach 300 kW m^{-2} into the LNG. Consequently there is no chance of film boiling. The limitation for the heat flux is explained in ch. 3.2.

3.2 Different Phases of the incident

The heating up of the spherical tank system by an engulfing pool fire can be divided into three different phases. The first phase represents the temperature increase of the tank weather cover structure until the melting point of the insulation is reached, cp. Tab. 1. The second phase range from the beginning of the melting to the complete deterioration of the insulation. The third phase describes the heating up of the cargo tank without insulation, which forms the worst case scenario due to the high expected heat transfer into the LNG.

Fig. 4 shows the emissive power of the LNG fire as a function of the receiving wall (tank weather cover) temperature cp. eq. (1). The two different initial heat fluxes 108 kW m^{-2} and 300 kW m^{-2} , which complies with a radiation source of 1500 K, are considered in the diagram. In addition the hypothetical heat flux into a completely un-insulated tank is illustrated by the green line. The possible maximum heat flux in steady state can be found at the intersection of curve 3 with curve 1, respectively curve 2.

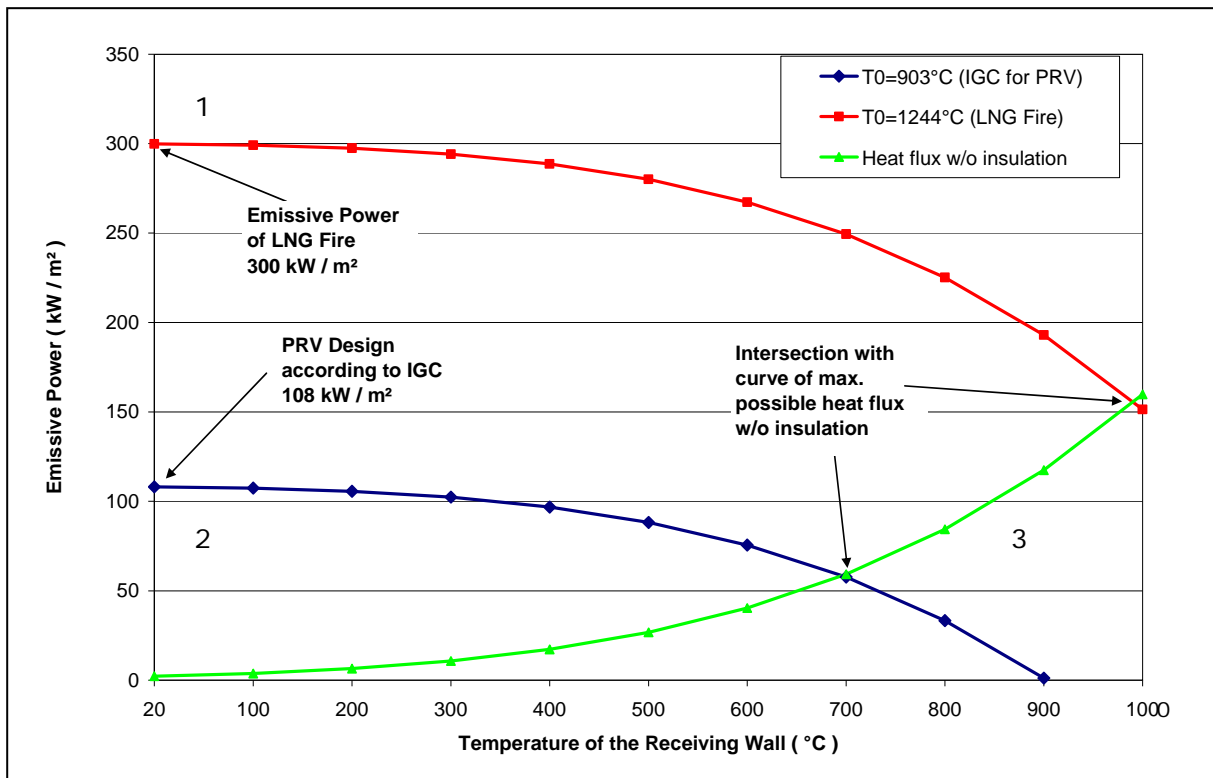


Fig. 4 Maximum heat flux into the tank [5]

Regardless of the initial heat flux assumed even with no insulation at all the maximum heat flux into the cargo tank is about half of the initial emissive power of the fire as is illustrated in Fig 4. Interestingly, this seems to substantiate the use of a Fire Factor, $F = 0.5$, for un-insulated independent tanks in cargo holds. As a consequence of the heat flux limitation film boiling can not occur.

3.3 Burning insulation

Assuming that the cargo hold is filled with ambient air when the fire is initiated, the amount of insulation, which can be burned by the available oxygen, has been evaluated. The air in the cargo hold is only able to supply oxygen for burning 21 m^3 of the insulation. This equals combustion of 5 mm of the insulation, if the burning of the insulation is uniform. The insulation system on a typical moss type LNG carrier is about 290 mm thick. The reduction in insulation thickness and the additional heat of combustion can therefore be neglected. In practice it seems likely that local fire will burn "holes" into the insulation. As the above explanation shows such "holes" will be of limited sizes and therefore their effects can be neglected. [5]

4 CFD-calculations

The CFD method has been used to perform transient analysis of the response of the LNG containment system under fire exposure. Contrary to the steady state calculations the transient heating up of the structure can be illustrated.

The three physical effects of the heat transfer mentioned previously can be simulated by the software CFX 11. Contrary to fluids only thermal conduction is considered inside solids.

The use of CFD methods requires the discretisation of the solution domain. For the analysis of the response of the spherical tank system under fire exposure a 2-D model has been used, which is shown in Fig. 5.

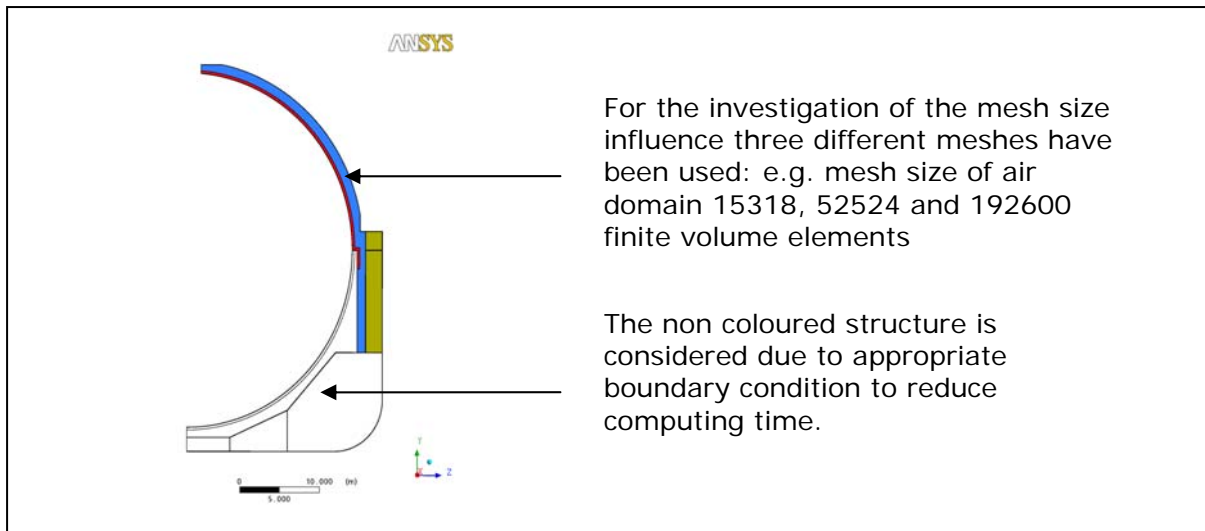


Fig. 5 Model of the solution domain, [8] modified

4.1 Finite Element and Computational Fluid Dynamics analysis for heating up of the weather cover

Independent from the CFD-Analysis carried out by GL, ABS performed a fully coupled Finite Element (FEA) thermal stress analysis of a moss LNG tank weather cover when subjected to varying levels of heat flux from an external fire. This study was carried out just to determine the earliest possible point of buckling.

Since part of GLs CFD study [8] is the examination of the heating up of the weather cover, a comparison was made of these results with those determined by the ABS analysis. The ABS FEA provided the location and time of thermal structural collapse (buckling) as determined by a large local deformation. Such would occur with an abrupt drop in the Young's modulus which occurs in the steel cover at a temperature of around 1023 K.

Very conservative boundary condition were assumed in the ABS study by applying a constant heat flux, independent of the weather cover temperature, to the entire external area of the cover and with no heat transfer into the air gap or insulation (adiabatic case). The bottom of the cover, at the connection to the main deck, constitutes a heat sink with the temperature held at 373°K. Failure of the cover is predicted around the connection of the cover sheet and top platform cp. Fig. 6.

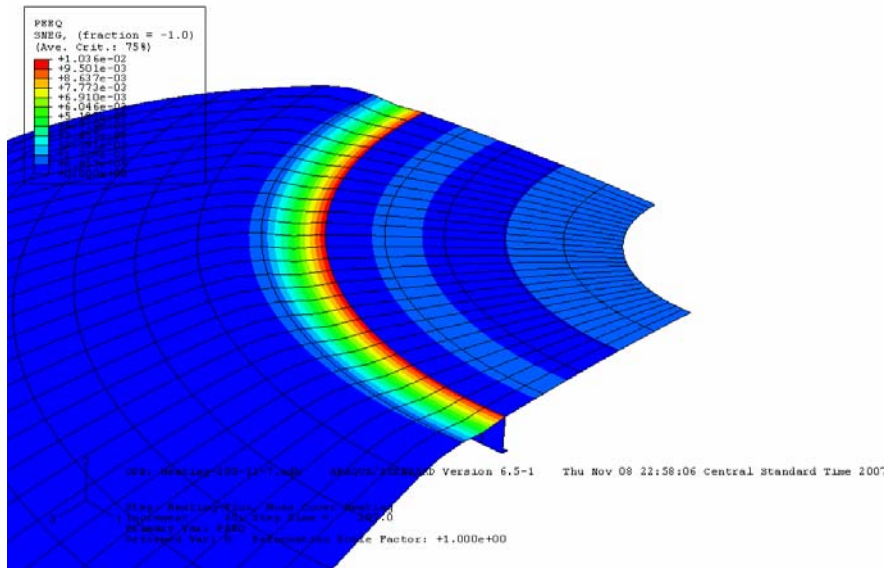


Fig. 6 Location of the thermal collapse (buckling), [2]

Initial calculations have been carried out by GL for the weather cover with the same boundary conditions as used by ABS (steady state heat flux, adiabatic wall). The results of ABS (curve 1) and GL (curve 2) for a heat flux of 88 kW m^{-2} are shown in Fig. 7. Both graphs have the same progress. With these boundary condition the cover takes 798 s to heat up to 1023°K (ABS: 755 s). The differences in time are due to the different kind of models used. The calculations carried out by GL confirmed the results of ABS and vice versa.

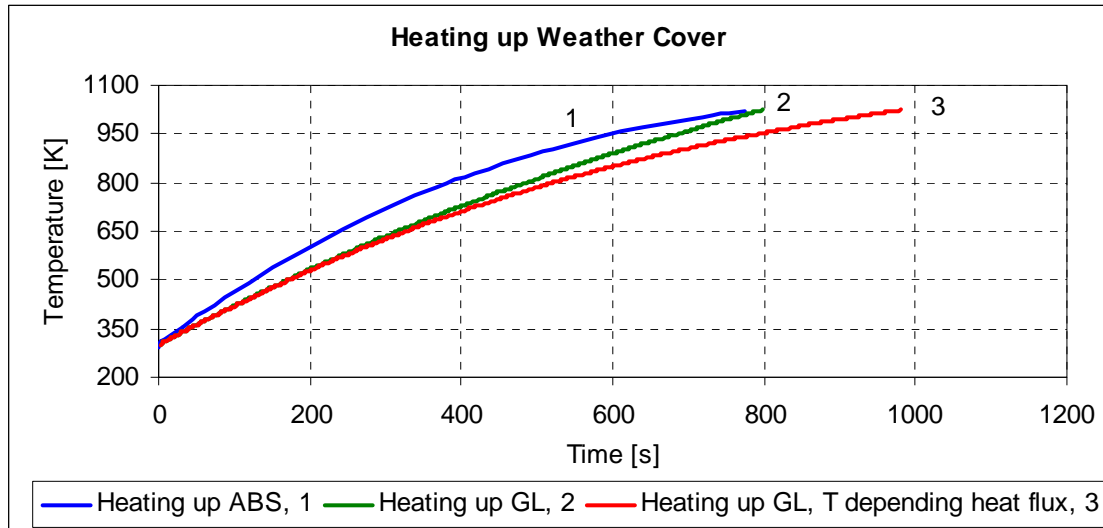


Fig. 7 Comparison heating up the weather cover ABS / GL

In the actual case, the weather cover heats up as a result of heat radiation. On the basis of the heat transfer equation for a black body, cp. eq. (1), the heat flow decrease due to the heating up of the cover.

For each time step the heat flux into the domain is calculated depending on the temperature (previous time step) of this component. The time based heat flux is shown by curve 3. The cover takes 980 s to heat up to 1023°K , which extend the buckling of the structure by approximately 200 s cp. Fig. 7.

4.2 Transient results

Primarily the model has been tested regarding quality aspects of the simulation results. The influence of three different meshes of the fluid and solid has been investigated, whereas the size of the finite volumes has been decreased continuously. Also the effects of different convergence and model criteria, e.g. two different models for the heat radiation, have been analyzed. Furthermore the requirement of a turbulence model for the natural convection has been identified. The following transient calculations use the Shear Stress Transport turbulence model. Due to this initial analysis the configuration has been determined, which assure the significance of the CFD calculations. [8]

4.2.1 Heating up Weather Cover / Insulation

Within the transient simulations a complete heating up of the weather cover is simulated until buckling of this component occurs. The transient calculations are related to the first two phases of the incident cp. ch. 3.2. All calculations have been set up with the normal operation conditions regarding to temperature distribution inside the containment system and ship structure. This temperature distribution has been calculated assuming -163°C inside the tank and an ambient temperature of 20°C . For the simulations a fully liquid wetted inner tank wall and empty ballast water tanks are considered. The transient calculations have been necessary to simulate the natural convection with a sufficient convergence.

Depending on the initial heat flux as boundary condition, which range between 88 kW m^{-2} and 300 kW m^{-2} , the heating up of the weather cover and insulation is shown in Fig. 8.

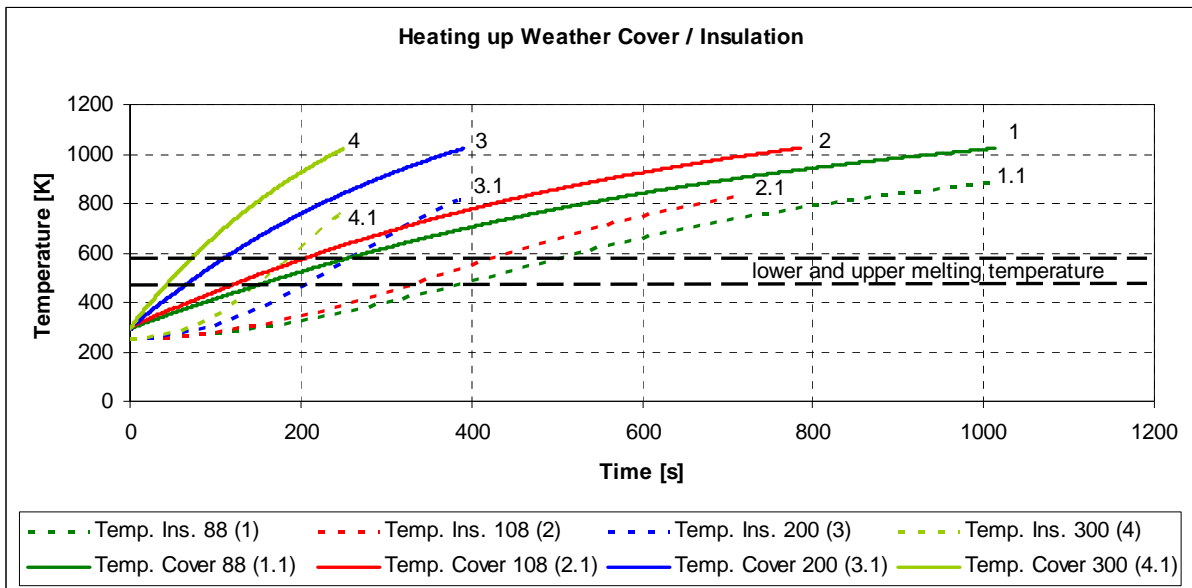


Fig. 8 Heating up of the weather cover and insulation, [8] modified

In Fig. 8 the solid lines represents the heating up of the weather cover and the dashed lines the heating up of the insulation. The gradient of the curves depend on the initial heat flux, which is absorbed by the weather cover. The increase of the temperature on the surface of the insulation follows the corresponding temperature increase with a time delay.

4.2.2 Characteristics of the insulation during incident

Furthermore the different rates of the total heat flux (curve 1) into the insulation are shown in Fig. 9 at the interface between air and insulation domain for the initial heat flux

of 108 kW m^{-2} . Compared to the heat load on the weather cover due to the engulfing fire the total heat flux into the insulation is small. The diagram represents the heat fluxes due to convection (curve 3) and radiation (curve 2), which differ explicitly regarding the gradient. The radiation has the main rate of the total heat flux in the air gap. The negative algebraic sign indicates the direction of the heat flux at the domain interface between air gap and insulation. The negative sign identifies the absorption of radiation on the surface of the insulation (leaving the air domain). The convective heat flux is directed from the surface of the insulation into the air domain.

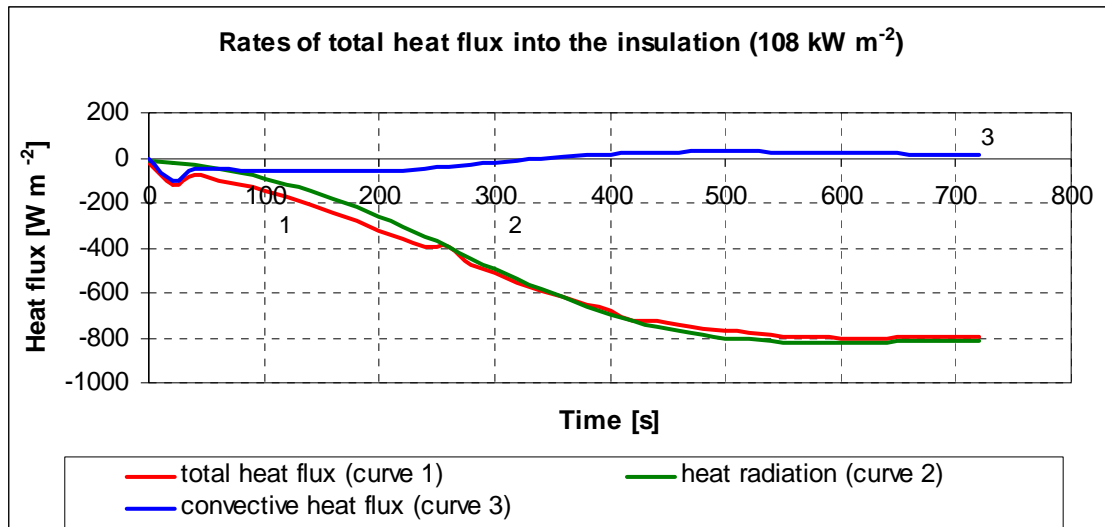


Fig. 9 Rates of the heat flux into the insulation, [8] modified

The heat on the surface of the insulation caused by absorbed radiation can not be conducted into the insulation due to the heat transfer characteristics cp. Fig. 10. Therefore the heat from the surface, which is warmer than the adjacent air, is transferred via convective heat transport back into the cooler air domain.

Via the transient calculations the detailed heat transport into the insulation has been calculated. As a result the temperature distribution in a cross section of the insulation is shown in Fig. 10 for different initial heat fluxes. The position $x = 0 \text{ m}$ corresponds with the position of the tank wall.

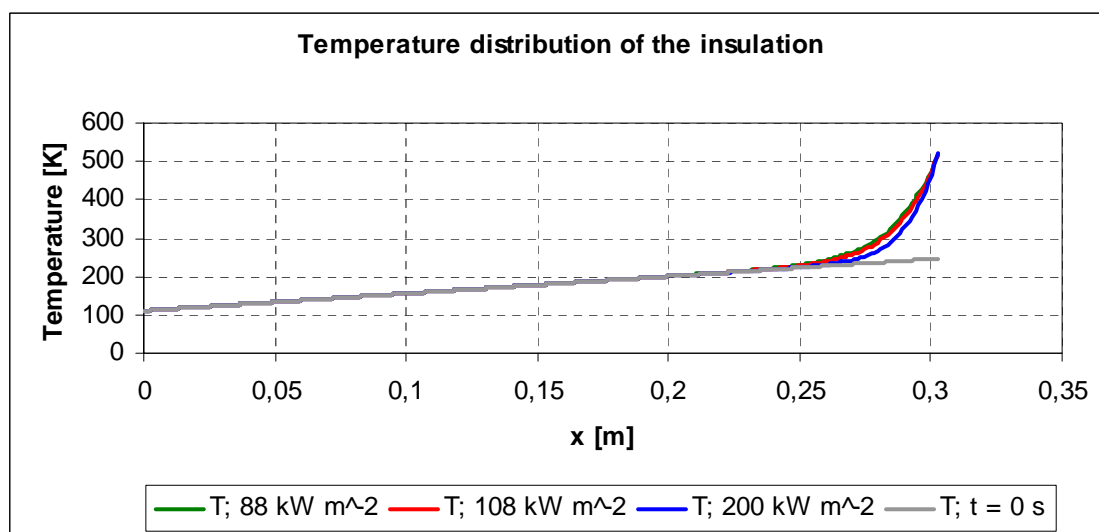


Fig. 10 Temperature distribution inside cross section of the insulation, [8] modified

The grey graph shows the temperature distribution under normal operation condition. The other coloured graphs illustrate the temperature distribution in the cross section of the insulation at the beginning of melting on the surface. Independent of the initial heat flux only 4 cm of the insulation thickness are affected. Even a ship engulfing fire will not lead to initiate heating up of the insulation. Because of the low heat transfer characteristics cp. Tab. 1 it is not possible to heat up the rest of the insulation until the surface of the insulation reaches its melting temperature. Consequently there is no increased heat transfer into the LNG containment system until the insulation is completely destroyed.

4.2.3 Temperature distribution during incident

Fig. 11 shows the temperature distribution at the beginning of the insulation melting (left side) and at the thermal caused buckling of the weather cover (right side).

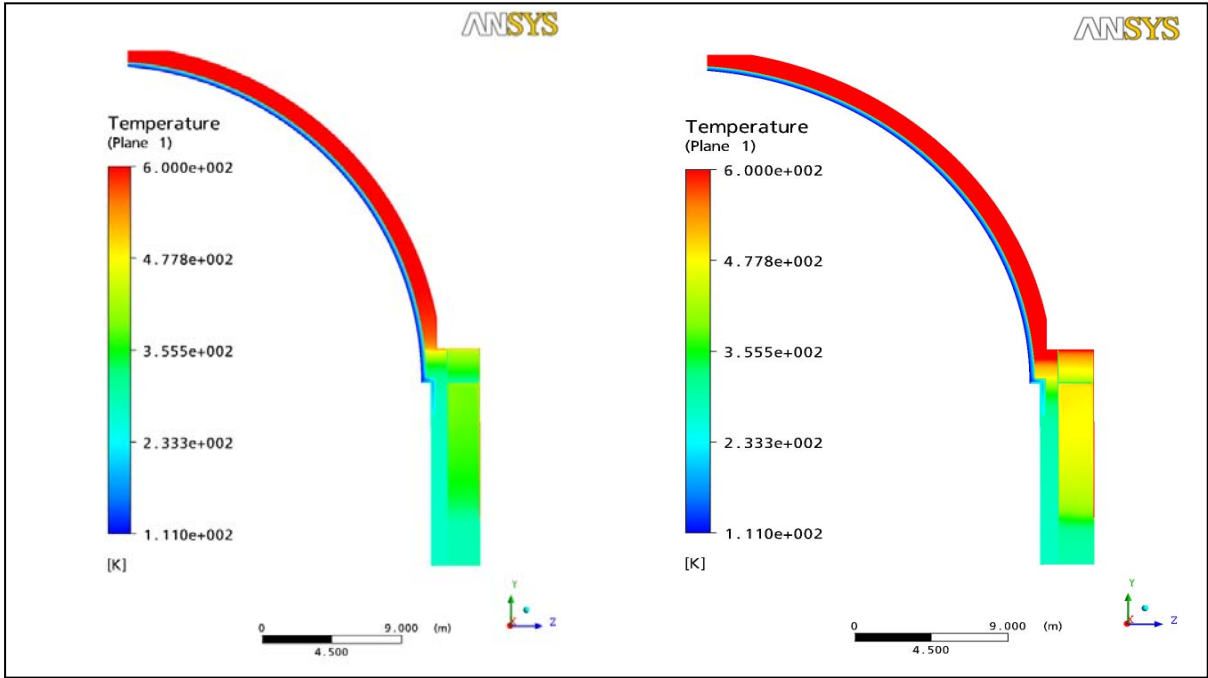


Fig. 11 Temperature distributions in the sphere, [8]

At both time steps (beginning of insulation melting and thermal caused buckling of the cover) there is independent of the initial heat flux a temperature layering in the air gap between weather cover and insulation and also inside the ballast water tanks. In the area of the sphere the maximum temperature can be determined. Because of this clear separated temperature layers the development of a natural convection between sphere and skirt is not possible, which transports the heat to the lower and cooler parts of the air gap.

As shown in Fig. 11 the skirt area does not reach high temperatures compared to the upper sphere. The calculation indicates that the skirt area will not be heated to critical temperatures with regard to structural integrity. The skirt is protected by the ballast tanks, which have been assumed to be empty for the calculations (case of a fully laden vessel). Failure of the support structure can be excluded even for very high heat fluxes into the cover.

Furthermore the critical area concerning structure integrity is the sphere due to the thermal load as verified by [2, 8]. As shown in Fig. 9 the heat radiation has the main influence on the heat transport inside the air gap, which depends on the isotropic emissive coefficients of the surfaces. Due to the rotational symmetry of the sphere the two-dimensional calculations are sufficient for the study presented.

4.3 Relation of CFD calculation results to pool fire burning duration according to SANDIA report

The study [7] has investigated the hazards of large-scale LNG spills over water. The spill can be assumed to be the result of the failure of one tank according a collision or an intentional act.

The calculations have been done under the assumption that the hull is completely engulfed by the fire. The diameter of the LNG spills dependent on the breach size is indicated in [7]. For breaches sizes smaller than 3 m² the pool diameter is calculated to be less than 300 m. The ship length overall of a moss LNG carrier is approximately above 300 m, so that the initial assumptions are very hypothetical.

Dependent on the tank breach size the average burning duration is indicated in [7] (tables 10 and 14 for accidents and intentional acts accordingly). Fig. 12 below relates the temperatures for buckling of the weather cover to the tank breach sizes and consequently the fire durations. The duration of the fire is indicated by the full size of the bars in Fig. 12. The Sandia report uses 5 m² hole as the most likely hole size for very severe intentional acts. Collision will lead to holes up to 2 m².

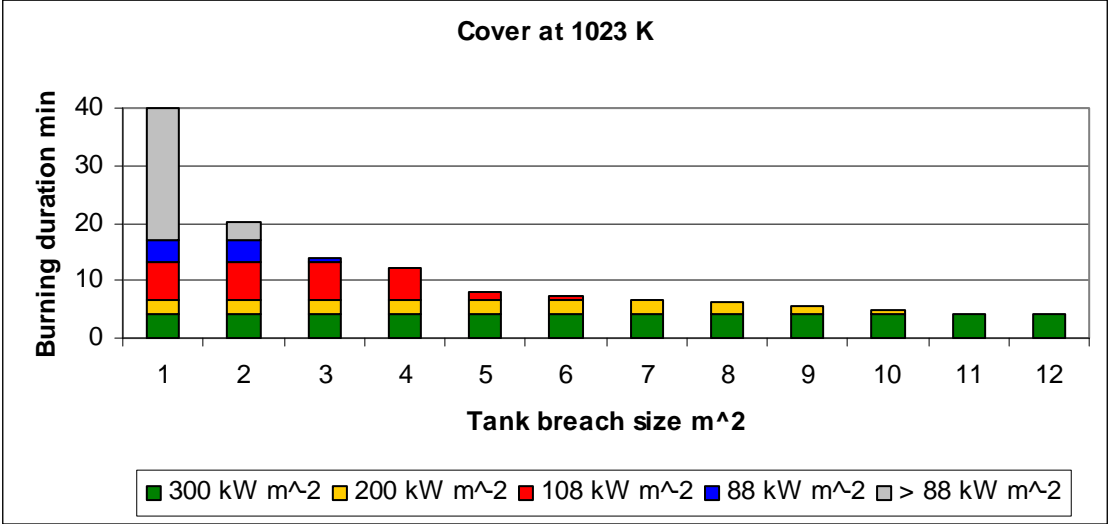


Fig. 12 Heating up of the weather cover and tank breach size, [7, 8] modified

The height of the bars indicates the duration of the fire according to [7]. The colour specifies the required time to heat up the weather cover to the temperature when buckling starts. The different colours indicate different heat fluxes.

The green colour represents the initial heat flux of 300 kW m⁻². The other colours indicate the additional time for the lower heat fluxes to reach the buckling temperatures.

For an initial heat flux of 300 kW m⁻² 4.16 min are needed to heat up the weather cover to the buckling temperature. Compared to the fire durations depending on the breach sizes the heating up of the weather cover to 1023 K affects only holes smaller than 10 m². The time (green plus yellow) of 6.51 min to reach the buckling temperature is required for a fire with an initial heat flux of 200 kW m⁻². This burning time is available for LNG spills caused by a breach size smaller than 6 m². For hole sizes above 3 m² the weather cover can not reach the buckling temperature due to a fire with an initial heat flux of 108 kW m⁻² (green, yellow plus red). Due to heat fluxes lower than 108 kW m⁻² (green, yellow, red, plus blue) caused by breach sizes less than 3 m² the weather cover can reach the melting temperature.

Furthermore Fig. 13 shows the minimum time related to the tank breach size until the deterioration of the insulation starts. The used fire load of 108 kW m^{-2} corresponds to the basic assumptions of the IGC-Code and API-520.

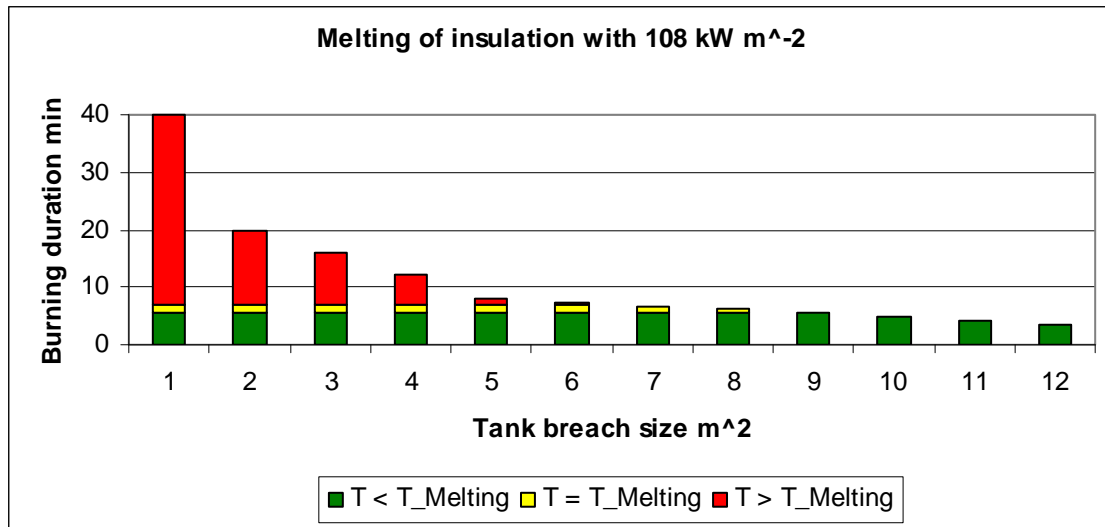


Fig. 13 Melting of insulation caused by a heat flux of 108 kW m^{-2} , [7, 8] modified

The green bar indicates the time required to reach the minimum assumed melting temperature of 473 K. The yellow bar indicates the heating up from 473 K to 573 K, which is the upper value of the melting range. The red bar displays the period which remain for deterioration of the insulation until the fire is expired. Only hole sizes with a red bar will create a fire which will affect the insulation system. This means that fires from hole sizes above 5 m^2 are expired before the insulation is affected.

Study [8] has pointed out, that at the beginning of insulation melting the surface has only reached the melting temperature. In addition to energy for melting heat for the temperature increase to this temperature is required. The total time to increase the temperature of the insulation to the melting temperature can be calculated by use of the complete insulation thickness. For polysterene with a thickness of 0.29 m the heating up from an average temperature of 273 K to the interval of melting requires the two- to threefold of the energy, which is necessary for melting. This additional time is not included in Fig 13.

In the case of an initial heat flux of 108 kW m^{-2} a continuous heat flux of 1 kW m^{-2} , cp. Fig. 9, into the surface is computed. Therefore a melting rate of 2.1 cm min^{-1} is calculated. This rate results from the quotient of the heat flux and the product of density and latent heat of fusion, which constitute 105 kJ kg^{-1} for the foam. Due to this melting rate 14 min are necessary to melt the insulation and at least 28 min to heat up the polysterene to the melting temperature. (In the case of an initial heat flux of 300 kW m^{-2} a melting rate of 3 cm min^{-1} is calculated which result in 9 min for melting and 18 min to heat up the insulation to 1023 K)

The heat flux into the spherical tank system will increase if the insulation is nearly completely deteriorated. Not till then will the LNG start boiling and consequently the pressure inside the tank will increase and cause the pressure relief valves on the tank to open. But additional to the period, when the melting of the insulation starts, the period for heating up the rest of the insulation and melting has to be considered. For an initial heat flux of 108 kW m^{-2} the complete deterioration of the insulation will last at least 47.5 min. (In the case of an initial heat flux of 300 kW m^{-2} the complete deterioration of the insulation will last 29.5 min.)

The investigations do not include further response of the spherical tank system after the insulation is deteriorated and the pressure will increase. Two safety aspects should be noted, that unless the critical flow is not reached, the PRV valves have considerable additional relieving capacity during pressure rise well above the capacity related to the design conditions. Furthermore the tanks will also normally sustain considerable overpressure in moderate sea conditions without exceeding acceptable design response criterion.

5 Conclusions

1. The analysis has demonstrated that there is no risk of film boiling which could cause failure of the tank.
2. The heat flux into the containment systems, assuming all the insulation has been removed, is approximately half the initial heat flux from the fire as long as the weather cover is able to provide radiation shielding. This is true regardless of the initial heat flux. This confirms the value of 0.5 used for the fire factor F , in 8.5 of the IGC for an un-insulated tank inside a cargo hold.
3. The available oxygen inside the cargo hold will only support the combustion of 21 m³ of insulation. If the burning is uniform this would be only about 5 mm out of a total thickness of 290 mm.
4. The CFD model for the weather cover used by GL in the study was calibrated, with very good correlation, against a buckling analysis which had been carried out by ABS. The first sign of local deformation is predicted at the connection of the upper cover sheet to the top platform and with a heat flux of 108 kW m⁻² will occur more than 13 min after the fire starts.
5. There is no increase in heat flow into the cargo tank until virtually all the insulation is destroyed, which will be between 29 and 38 minutes after the fire is started even if the fire load is 300 kW m⁻² (lower fire loads give longer time periods).
6. The heat flux of 108 kW m⁻² is not able to heat up the weather cover to the buckling temperature if the nominal leak size of 5 m² or a greater hole is assumed. The heat flux related to the pressure relief valve sizing is able to heat up the weather cover above 1023 K only for leak sizes smaller than 3 m² cp. [4].
7. The heat flux of 108 KW m⁻² does not burn long enough even with a hole size of 1 m² to completely destroy the insulation system.
8. All of the above results were predicted with no consideration given to the cooling effect of the deluge system which is required to be provided on the tank dome in accordance with IGC.
9. Unless the critical flow is not reached, the PRV valves have considerable additional relieving capacity during pressure rise well above the capacity related to the design conditions.
10. Normally the tanks will also sustain considerable overpressure in moderate sea conditions without exceeding acceptable design response.

6 References

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