SUMMARY of INVESTIGATIONS

into

The EFFECT of FIREon LNG CARRIER CARGO CONTAINMENT SYSTEMS

Abstract

It has long been considered that the risks associated with transporting liquefied gases by sea have been identified, understood and adequately dealt with in the Rules of the ships classification societies. Furthermore, the “International Code for the Construction and Equipment of ships Carrying Liquefied Gases in Bulk” (IGC), developed by the International Maritime Organization (IMO), has been adopted by virtually all flag states and has served the industry well for more than 40 years.

However, over the past decade new concerns related to possible acts of terrorism in and around LNG terminals have led to studies considering possible major fire hazards resulting from such intentional acts. The most widely referenced such study was carried out by the United States Department of Energy (DOE) / Sandia National Laboratories. While the Sandia and other such studies have focused on the risk to the population in the vicinity of the terminal, the impact of such events on the vessel itself and the risk of possible cascading events have been recommended for further evaluation.

One particular concern which evolved from some of this discussion relates to the potential consequence of degradation of the insulation system, particularly on a moss type (spherical) LNG carrier containment system when exposed to the heat from an engulfing pool fire.

Introduction

In 2004 SIGTTO was approached by Professor J Havens of the University of Arkansas who expressed concern about the vulnerability of LNG carrier tanks that are insulated with low temperature materials such as polystyrenes or polyurethanes. The particular concern being possible overpressure and rupture of un-breached cargo tanks due to a level of heat flux into the cargo far greater than that envisaged in the relief valve sizing.

Following considerable dialogue between SIGTTO members, the LNG carrier containment system designers, the USCG and the major classification societies, at their April 2006 meeting the SIGTTO General Purposes Committee (GPC) sanctioned the formation of a working group to thoroughly investigate the subject and produce a detailed report on the possible effects and any mitigation measures that may be necessary. The Working Group was directed to investigate the response of LNG carrier cargo tanks exposed to a large enveloping pool fire that could possibly result from the spillage of LNG onto the sea and subsequent ignition.

The working group met six times between July 2006 and June 2008, under the chairmanship of Mark Hodgson of STASCo., with representatives of the following organisations participating in the work:- STASCo., University of Arkansas (UoA), University of New Brunswick, Bureau Veritas (BV), American Bureau of Shipping (ABS), GTT, Hoegh Fleet Services, BGT, Golar LNG, Germanischer Lloyd (GL), ExxonMobil, Lloyds Register (LR), Gaz de France, Suez LNG, Det Norske Veritas DNV), Moss Maritime and SIGTTO

At the first meeting of the WG the following terms of reference (TOR) were agreed;

1. Full consideration will be given to the question, making use of in house documentation, government or industry publications and the experience of the WG members.
2. A detailed determination should be made of the methods allowed and used to size Pressure Relief Valve (PRV) systems on liquefied natural gas carriers. This determination should include specific descriptions of current practices of allowing for insulation performance under severe thermal radiation (fire) exposure
3. An analysis should be performed of the increased boil-off of LNG that could occur if an un-breached LNG tank were subjected to an enveloping LNG pool fire burning on the water.
4. An estimation of the pressure development in the tank should be made to judge suitability of PRV sizing.

The activities discussed in this paper were carried out by working group members working in four sub groups each assigned specific tasks. The final SIGTTO report has been approved by the General Purposes Committee and Board of Directors and published in September 2009. It is available as a free download on the SIGTTO website. www.SIGTTO.org

1. Previous incidents

To date there has been no incident involving uncontrolled loss of containment on an LNG carrier so there is no experience to draw upon to estimate the effects of a release and subsequent ignition of a large quantity of LNG engulfing an LNG carrier.

There are however numerous well documented incidents involving conventional tankers and LPG carriers and these can give us an insight into the effects of an engulfing fire on the structure of a ship and also the characteristics of fires involving large quantities of refrigerated liquefied gases in insulated tanks. The following incidents were studied;

"Yuyo Maru", was of a design no longer permissible under the IGC Code whereby LPG was carried in the centre tanks and light naphtha in the wing tanks. In Nov. 1974 the vessel was involved in a collision with a bulk carrier resulting in a serious fire and the death of most of the crew of the bulk carrier and 5 members of the Yuyo Maru's crew. The vessel burned for 10 days after which time it was boarded and a survey carried out to ascertain if it could be towed.

It was estimated that approximately 25% of the naphtha and an unknown amount of propane and butane had been consumed in the fire. Most of the butterworth plates were missing on the wing tanks, but otherwise the deck was intact. The damage to the LPG tanks did not extend to any overpressure effects and was limited to the safety valves and part of the hatch covers where the float gauges were installed. The vessel was towed out to sea, and was eventually sunk.

"Gaz Fountain" was a fully refrigerated LPG carrier with a cargo-carrying capacity of 40,232 m3. Her three free-standing prismatic cargo tanks were insulated with loose fill perlite. On 12 October 1984, during the height of the Iran-Iraq war and whilst carrying 6,300 tonnes of propane and 12,140 tonnes of butane from Ras Tanura to Fujairah, the ship was attacked by an Iranian aircraft and suffered three hits from air-to-ground, armour-piercing missiles. The crew shut down the propulsion and cargo refrigeration systems and abandoned ship. The salvage team quenched the fires and salvaged the vessel and over 93 per cent of her cargo.

A ship-to-ship transfer was started a month after the missile attack and 17,200 tonnes of cargo were successfully transferred over. On 12 December the operation, including the lengthy gas-freeing of No 3 hold, was concluded and the vessel was handed back to her owners.

A single hull 25,000 dwt product carrier, owned and operated by a major oil company was involved in a collision in the Southern North Sea. The vessel was carrying a full cargo of gasoline which ignited and burned for over 24 hours before the fire was extinguished and the vessel boarded. Bronze butterworth plates and PV valves had melted in the intensity of the fire, and deck pipelines were badly buckled, but there was no serious buckling or distortion of the vessel's structure.

"Val Rosandra" Propylene Fire- On 28 April 1990 the 3,990 m^3 ethylene carrier *Val Rosandra*, laden with 2,250 tones of fully refrigerated propylene at –47degC, was discharging at Brindisi in Italy when a violent explosion occurred in the cargo compressor motor room.

The motor room was severely damaged and cargo pipe-work outside the room ruptured. In addition, the port and starboard domes of No 3 cargo tank also ruptured. As a result of the explosion, the escaping propylene ignited and the fire continued to be fed by cargo evaporating from the damaged domes.

The vessel was subsequently towed to the edge of the port limits where the fire was monitored from a safe distance. Eventually charges were detonated around the domes of the remaining four tanks to allow the propylene cargo to escape gradually and burn off.

Over three weeks after the initial explosion and with the fire still burning at No 3 tank, the vessel was towed out to sea. On 8 June 1990, 41 days after the initial explosion and fire, a large quantity of explosive was detonated on *Val Rosandra's* hull and on this occasion the ethylene carrier's demise was not long in coming.

2. Origins of the IGC criteria

A detailed determination was made of the methods allowed and used to size pressure relief valve systems on liquefied gas carriers. The criteria is provided in 8.5 of IGC Code. This included the following;

- A review of all working papers related to the requirements for cargo tank pressure relief valves generated between 1971 and 1974 at IMO Subcommittee on Design and Equipment.
- A review of the requirements for sizing of pressure relief valves contained in other standards and codes of practice in use today. This includes the CGA-S.1, API 521, API 2000 and NFPA 59-A as well as the requirements of the US Coast Guard.
- A detailed review of work carried out by the National Academy of Sciences (NAS) at the request of the USCG over a period of six(6) years as presented in the report " Pressure-Relieving Systems for Marine Cargo Bulk Liquid Containers" 1973 (ISBN 0-309-02122-7) /Ref-02/.

From the above it was determined that substantiating the criteria used for sizing pressure relief valves on vessels intended to carry liquefied gases in bulk calls into question three terms; the assumed heat flux q emanating from the fire, the area A of the tank to consider as subjected to the heat flux and finally the selection of an appropriate factor F which is intended to represent the effect of various factors in the design and arrangement that would tend to reduce the heat flux into the cargo. . These three terms should be considered separately as follows;

Heat flux q from the fire

There is considerable discussion in the NAS report regarding the proper heat flux to be used for sizing pressure relief vales for fire exposure. It is recognized in the NAS report that local heat fluxes from methane fire have been observed to be as high as 90,000 Btu/hr ft^2. However, it is recommended that 34,500Btu/hr ft^2 be used as a good approximation for the average, sustained heat flux over the entire wetted surface area exposed to fire. This exact same value is used in the CGA, API codes and NFPA codes as well as in the IGC-Code. It should be noted that 34,500 Btu / hr ft^2 is numerically equal to 108.78 Kw/m^2 but because of the 0.82 exponent on the area, when the conversion is made from US customary to SI units heat flux value becomes 70.93 Kw/m^2 This conversion factor has led to some confusion since the formulae in 8.5 of the IGC is in SI units.

Affected tank area A

In the criteria for sizing pressure relief valves the API and NFPA codes use the wetted surface of the tank. The CGA and the IGC-Code use the full surface area. Considering that LNG is almost always transported in fully loaded tanks the difference is negligible.

The NAS report proposed that in sizing pressure relief valves consideration should be given to effects of supporting structures or other specially introduced features that may serve to confine the fire such as bulkheads and weather shields

This precaution would serve to reduce substantially the effective safety device sizing requirements.

The NAS report proposed that a factor E be used which is defined as the ratio between the tank area under fire A_e exposure and the total tank area A ($E=A_e/A$. It is pointed out that for marine installations, by taking credit for protective structure afforded by the ships structure the effective area will in almost all cases be less that which would be determined by using the tank area A raised to a power of 0.82.

Notwithstanding the recommendations of the NAS report, the CGA, API, NFPA codes as well as the IGC Code use the more conservative approach raising the surface area of the tank to the power 0.82 and use this figure as the part of the tank subjected to the fire .

For a Moss tank, of approximately 36 m (125 ft) in diameter, using the IGC-Code criteria, the effective areas of the tank considered to be exposed to the heat of the fire is approximately 15 % of A. the total external surface area of the tank.

It should be noted that while the API and NFPA codes use the value of A to the 0.82 factor, areas of the tank more than 9 m above the ground are completely excluded from the total area used to size pressure relief valves. It is stated that tests have shown that the effective heat flux from a pool fire at such elevations is negligible.

The API and NFPA codes also exclude areas of the tank which are protected from direct fire impingement such as skirts and supporting structure on vertical tanks.

There is no reduction in effective area of the tank provided for in the IGC-Code which consequently means that the IGC-Code in inherently more conservative in this respect for sizing of pressure relief valves.

<u>Fire factor F</u>

In accordance with the NAS report, if the insulation covers more than, say 70% and the insulation system retains it's effectiveness at expected high temperatures a method to calculate the F factor as a direct function of the thermal conductivity of the insulation is provided. For tanks that are 100% insulated the F factors are below 0.05.

The above is consistent with the API codes and NFPA 59A. API 521 would allow a value of F between 0.026 and 0.3 based on a thermal conductivity of 0.58W/mK.

The insulation system on an LNG carrier has a typical thermal conductivity of 0.038W/mK. However, for LNG carriers the value of F for insulated tanks is not lower than 0.1 and that is only applicable to insulated tanks inside an inerted cargo hold where there is an extremely low probability of direct flame impingement.

It should also be noted, that the in the NAS report the maximum insulation thickness assumed is 1 inch (25.6 mm). The insulation thickness of an LNG tank on an LNG carrier is at least 300 mm.

Accordingly, it had been determined that the criteria for sizing pressure relief valves on cargo tanks provided in the IGC code is consistent with every other applicable recognized standard in the assumed heat flux value used and somewhat more conservative in the selection of effected surface area and fire factor.

3. Fire Scenarios

A research of available published reports identified the following works which were considered applicable to the task assigned to the WG. Each report was reviewed and the findings summarized.

Document №	Title	Organization	Date
1	Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water	Sandia Report	2004
2	Results of 40m3 LNG spills on water	Lawrence Livermore National Laboratory	(circa 1983)
3	Spill tests of LNG and Refrigerated Liquid propane on the sea, Maplin Sands, UK, 1980	Shell Research Ltd.	1980
4	Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers	ABS on behalf of FERC	May 13th 2004
5	Consequences of LNG Marine Incidents	DNV - CCPS Conference Orlando	June 29-July 1 2004
6	Consequence modeling of LNG Marine Incidents	DNV - Baik, Raghunathan, Witlox - American Society of Safety Engineers	March 18-22, 2005
7	Potential for BLEVE Associated with Marine LNG Vessel Fires	DNV - Dr. Robin Pitblado	August 2006
8	Model of Large Pool Fires	J.A. Fay - MIT	sept-05
9	Large Hydrocarbon fuel pool fires: Physical characteristics and thermal emission variations with height	Phani K. Raj - Technology & Management Systems	18th August 2006

Document №	Title	Organization	Date
10	Spread of Large LNG pools on the sea	J.A. Fay - MIT	October 2006
11	LNG Properties & Hazards - Understanding LNG Rapid Phase Transitions (RPT)	ioMosaic - G. Melhem,S. Saraf, H. Ozog	2006
12	Report on the Outline of Collision between Japanese tanker Yuyo Maru No. 10 & Liberia Freighter Pacific Ares	MSA - Japanese Govnmt.	March 1975
13	LNG Decisions Making Approaches Compared	Dr. R. Piblado, Dr. J. Baik, V. Raghunathan - DNV	2005
14	FDS LNG pool fire simulations : a preliminary study on the application of FDS to study potential marine tanker accidents	J E S Venart - University of New Brunswick	1st June 2006
15	Thermal Response of Gas Carriers to Hydrocarbon Fires	DNV For Shell International Marine Ltd.	26th November 1980
16	Public Safety Consequences of a terrorist attack on a tanker carrying LNG need clarification	US Government Accountability Office	February 2007
17	Department of Homeland security : LNG Tanker Security - Direct Testimony Dr. Phani K. Raj.	Dr. Phani K. Raj.- President - Technology & Management Systems, Inc.	
18	Maplin Sands experiments 1980 - Interpretations and modelling of Liquefied Gas Spills onto Sea	Shell Research B.V. & Shell Research Ltd.	1980 (Pub 1983)
19	Maplin Sands experiments 1980 - Dispersion results from continuous releases of refrigerated liquid propane & LNG	Shell Research B.V. & Shell Research Ltd.	1980 (Pub 1984)

Document №	Title	Organization	Date
20	Maplin Sands experiments 1980 - Dispersion & combustion behaviour of gas clouds resulting from large spillages of LNG & LPG on the sea	Shell Research B.V. & Shell Research Ltd.	1980 (Pub 1982)
21	Maplin Sands experiments 1980 - Dispersion results from continuous releases of refrigerated liquid propane	Shell Research B.V. & Shell Research Ltd.	1980 (Pub 1982)
22	Review of Published Experimental results	Lloyd's Register of Shipping	Last ref. 1992

Results of documentation review

The figures below should be considered as representative ballpark figures which were derived based on a summation of the overall review of available documentation.

There are undoubtedly contradictory values which appear in the work submitted for review, however those below were felt to provide a representation of the values proposed in the different works.

- Heat Flux
    - worst case direct flame impingement - 325 kW/m^2 (at source of flame hottest part)
    - This value is maximum at base of flame & reduces with height
    - Applies to Pool Fire (not cloud fire)

- Pool fire sizing v heat flux

	Diameter	kW/ m^2
Small Pool Fire	35m	220
⇩	⇩	⇩
Large Pool Fire	300m	90

- Fire Duration
  - release of 12,500m^3 = 8.1 minutes
  - For 330m (cloud fire) pool diameter ≈ 90 kW/m^2
- Fire Height
  - Not currently possible to define - not addressed by work to date
  - Pool size 35→300m diameter

<u>Summary</u>

The result of the document review was the realization that considerable uncertainty exists over the height of any LNG fire resulting from an accidental or deliberate release on water.

The height of the fire has a direct impact on the fire impingement and heat flux to which an LNG carrier would be subjected. The conclusion is that further definition of the flame height may only be achieved with appropriate modeling or alternatively from full scale tests of larger LNG pool fires on water from which the consequential heat fluxes could then be derived.

The latter full scale tests would also perhaps confirm the shift in opinions over Surface Emissive Power, where current expert opinion is now in favor of incomplete combustion in an LNG pool fire on water, reducing the heat flux as the size of any pool fire grows.

4. LNG Carrier Pressure Relief Systems

Included in the study was a review of the function, design and set points for pressure relief valves(PRVs) used on LNG carrier cargo tanks.

<u>Function</u>

Each cargo tank with a volume exceeding 20 m^3 should be fitted with at least two pressure relief valves of approximately equal capacity. The combined total capacity should be sufficient to ensure that the cargo tank vapour pressure does not increase more than 20% above the maximum allowable relief valve setting under fire conditions.

<u>Design</u>

It was established that pilot operated pressure relief valves are used for cargo tanks as well as for hold spaces on liquefied gas carriers. A pilot operated PRV consists of a main valve and a pilot. The basic principal is that the pilot controls the pressure on the top side of the unbalanced moving member .The design of the pilot for a pilot operated valve must be self actuated, that is, it must be actuated by the process pressure. It must also be fail-safe in the open mode. A seat is attached to the opposite side of the member.

- At pressures below set point, the pressure on the opposite sides of the moving member is equal.
- When set pressure is reached, the pilot opens, depressurizing the cavity on the top side and the unbalanced moving member strokes upward causing the main valve to relieve.
- When the process pressure decreases, the pilot closes, the cavity on the top is re-pressurised, and the main valve closes.

Set points

Typical pressure set points for a Moss type carriers PRVs would be:

High pressure alarm in tank:	220 mbarg
Opening of relief valve in tank:	250 mbarg
Low pressure alarm in tank:	10 mbarg
High pressure alarm in hold:	120 mbarg
Opening of relief valve in hold:	150 mbarg
Low pressure alarm in hold:	-20 mbarg
Opening of relief valve in hold:	-50 mbarg

5. Simplified Reapplication of the IGC for loss of insulation

As part of the study the working group reviewed the actual characteristics of a pressure relief system on a typical LNG carrier with Moss tanks. The investigation included a determination of the available capacity of the system at pressures well beyond the relief valve set point which was compared against the required capacity calculated using the IGC Code criteria for an un-insulated tank.

Actual data from a sample 140,000 m^3 Moss Rosenberg LNG Carrier has been used to assist with generating realistic outputs from the formulas within this document. That included specifications from the relief valve manufacture.

The design base is five spherical cargo tanks, externally insulated to restrict heat ingress, independently housed within sealed hold space containing inert gas. The maximum liquid loading capacity would be 98.5% of the total volume, thereafter reducing by 0.15% per day of cargo carriage.

Total Relieving Capacity Of Cargo Containment System

From Fig. 5.1 below, it can be seen that three over pressure relieving option are available and applicable on Moss Rosenberg type LNG Carriers.

Therefore the overall relieving capacity of a single tank is dictated by the maximum release capacity of the tank pressure control valve (orifice area 1) situated in the common vapor header and the combined capacity of the two pressure relieving valves (orifice area 2 and 3).

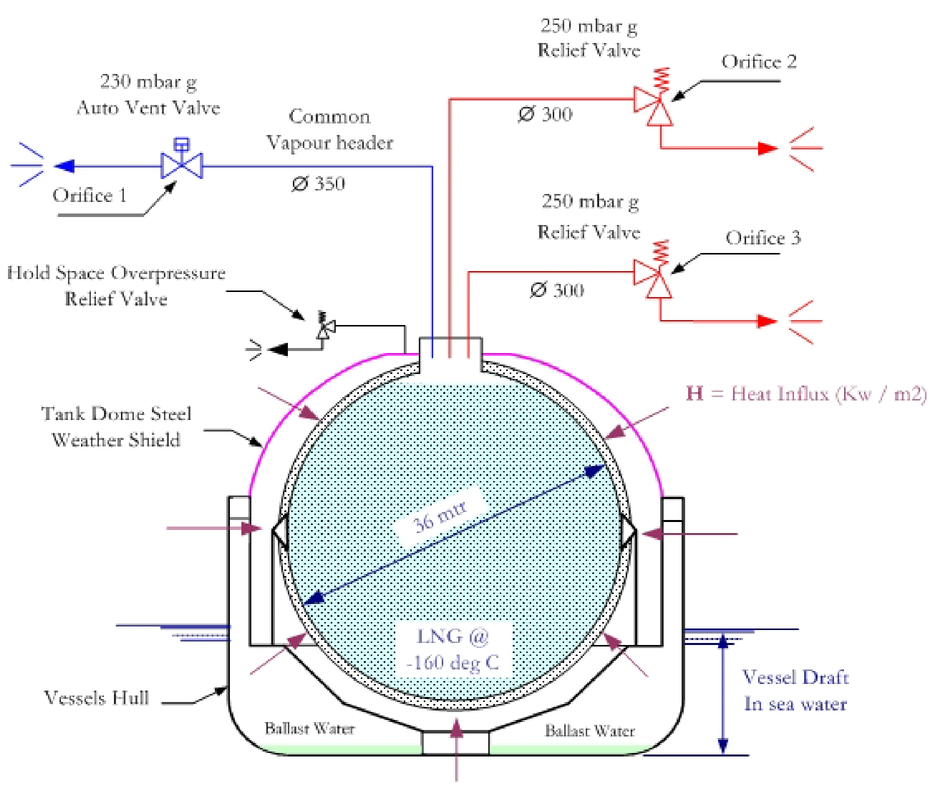

Fig 5.1 Cross section of relief system for a Moss tank

When considering a single 36 metre diameter Moss cargo tank layout, the relieving capacity available whilst remaining within the maximum pressure stipulated by the IGC Code; 300 mbar (includes 20 % permitted accumulation) , would equate to:

1) 47,500 + 47,500 = 95,000 kg/hr
2) 47,500 + 47,500 + 60,200 = 155,200 kg/hr

From paragraph 8.5 of The IGC Code, using F (fire factor) equal to 0.2 which is appropriate for an insulated tank in a hold , the calculated required capacity is 79,922 kg/hr.

From the above it is clear that this capacity is easily achieved by just the two PRV (case 1) and achieved by almost 200 % when including the vapor header (case 2)

Furthermore , when using a fire factor F equal to 0.5 , which would be applicable for an un-insulated tank in a hold, the required relieving capacity is 199,550 kg/hr. To achieve this capacity, the inlet pressure to the PRV valves needs to increase, which in turn gives a higher back pressure allowance and a greater relief capacity.

It has been determined that for the vessel considered in this study, if the tank were un-insulated, under the fire conditions assumed in the IGC, the pressure would rise from 0.3 bar to 1.15 bar if just the capacity of the relief valves was considered but only to 0.52bar if the total relieving capacity of the system was considered.

<u>Over Pressurization of Cargo Tank Due to Fire</u>

It was noted that Moss tanks are designed for emergency discharge of cargo with pressure in the event of loss of both submerged electric cargo pumps. The design for this scenario is based on the assumption that the vessel is at a berth or in a protected body of water and not underway in a heavy seaway, so there are no internal dynamic pressure loads on the tank. For a vessel engulfed in a pool fire, it would be reasonable to assume the vessel is moving very little.

Moss Maritime was able to provide guidance on the actual overpressure which the cargo tank could be subject to at design conditions.

Design allowable vapor pressure	2.0 barg
Overpressure before deformation	3.5 barg
Overpressure before yield point	5 – 6 barg
Overpressure before tensile failure	8 – 9 barg

It was confirmed that the above pressures would be applicable to any size of cargo tank as the scantlings of the shell plate are sized for the tank's actual diameter.

Results

For an existing LNG carrier, using just the relief valve, the system has an over capacity at the maximum design pressure of 2 bar g of 364%. At the deformation overpressure of 3.5 bar g the over capacity is 519%. Choke pressure occurred at a relieving pressure of 4.38 bar g.

It is important to note that the above figures are intended only to demonstrate the overcapacity of the relief valves using the IGC Code criteria and do not take any credit for the additional relieving capacity provided by the vapor header.

Under fire conditions the relief valves on the other tanks will also be able to operate up to the choke pressure of the flow through the common header tank outlet (normally 350 mm diameter). This also increases the flow.

6. Heat Transfer Analyses

The heat transfer evaluations conducted by members of the working group included two independent efforts.

A one dimensional (1 D) heat transfer analyses followed by a time dependant heat flow analyses was carried out by one sub-group (UoA).

A second sub-group (GL) carried out an independent 1 D analysis and time dependant heat flow analysis which included 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. An independent buckling analysis of the tank cover was carried out by ABS to calibrate their CFD model. All of the 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.

It was decided that the study consider a heat flux range of 88 kWm^{-2}up to 300 $kW\ m^{-2}$ as the heat fluxof an LNG pool fire. However, the fire itself was not modeled; instead simplified scenarios were used to model the heat flux into the ship structure above the waterline.

In the following the behavior of the tank under severe fire conditions is explained using;

The 1 D Model

The first phase of the investigations was carried out using simplified steady state 1-D models as shown below. The models consist of flat plates instead of spherical walls, which is a good approximation due to the large radius of the sphere. Fig. 6.1. Shows the model used in the GL study, as an example, but both were similar.

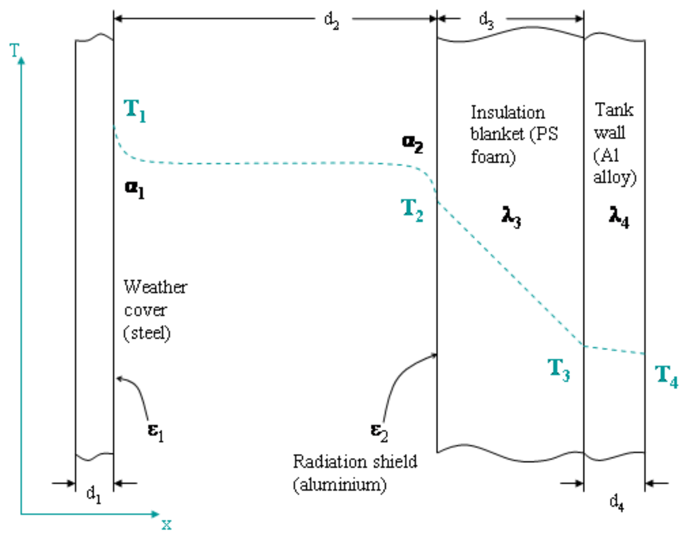

Fig. 6.1 Model of the spherical tank system,

The model consists of the steel weather cover (element 1), the air gap between weather cover and the polystyrene foam insulation which is covered by an aluminum vapor barrier (element 2) the insulation itself (element 3), and the aluminum inner tank wall (element 4).

Breaking down the problem

The easiest way to understand this complex heat transfer problem is to break it down into three phases;

- Phase 1 - Heating up the weather cover, from ambient temperature to the point where the insulation starts to melt.
- Phase 2 - Melting of the insulation to the point of complete deterioration
- Phase 3 – Heat flow direct into the tank after all the insulation had been destroyed

In good approximation the heat transfer from the fire to the weather cover can be regarded to be dominated by radiation. Therefore the heat flux from the fire into the cover decreases as the cover warms up. This is shown in Fig. 6.2 below for initial heat fluxes of 300 kW m^{-2} (the red curve) and 108 kW m^{-2} (the blue curve) respectively.

In addition the hypothetical heat flux into a completely un-insulated tank is illustrated in Fig. 6.2 by the green curve. The maximum possible heat flux into the tank wall, in steady state, for each initial heat flux assumed, can be found at the intersection of the green curve with the red and blue curves .

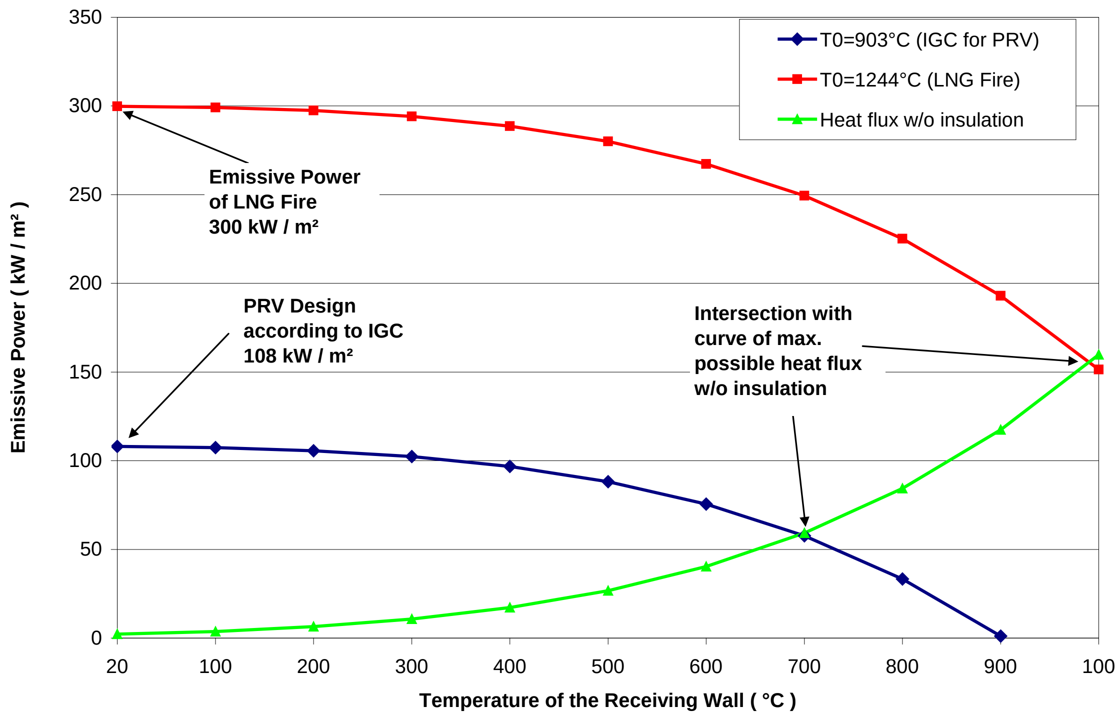

Fig. 6.2 Maximum heat flux (or emissive power) into the tank

From the 1D analysis it can be concluded that regardless of the initial heat flux assumed even with no insulation at all on the tank, due to the thermal shielding of the cover, the maximum heat flux into the cargo tank is about half of the initial emissive power of the fire as is illustrated in Fig 6.2.

Investigation of Film Boiling

If the heat flux into the tank were to reach a "critical heat flux", film boiling could occur. In this phenomena, a film of methane vapor would separate the tank wall from the cooling LNG. The heat flux into the fluid decreases significantly and the surface tank wall temperature increases. This can lead to what is called "burn out" of the submerged heated surface, which in this case is the tank wall. As a consequence the aluminum tank could collapse. Accordingly, it was imperative that the possibility of film boiling be fully considered in this study.

Fig. 6.3 shows the heat fluxes for nucleate and film boiling for methane as a function of the heat flux into the fluid and the temperature difference between the temperature of the wall (T_W) and the saturation temperature of the liquid (T_{Sat}). 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.

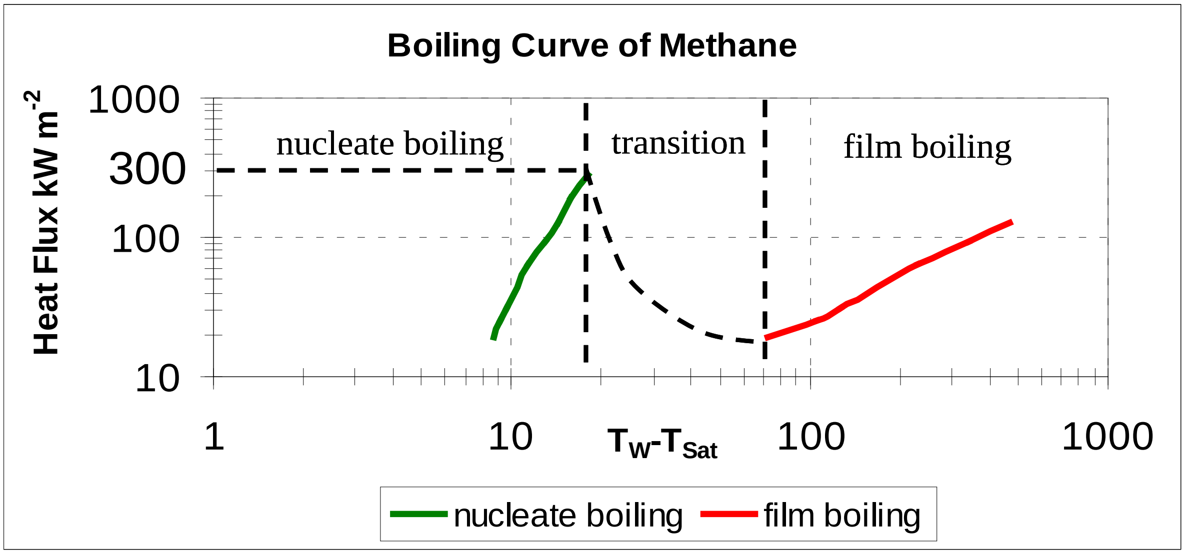

Fig. 6.3 Boiling curve of methane,

The critical heat flux is about 300 kW m^{-2} with a corresponding temperature difference of about 15 K.

Considering the conclusions resulting from Fig 6.2, even with an initial heat flux of 300 kW m^{-2} from the fire, the heat flux into the LNG will be not more than about 150 kW m^{-2} which is half the critical value for film boiling. Accordingly overheating of a filled LNG tank can be excluded even for the most severe fire conditions and a complete destroyed insulation.

The transient CFD Analysis

A computational fluid dynamics (CFD) method was used to perform a transient analysis of the response of the LNG containment system to fire exposure. Unlike the steady state calculations the transient heating up of the structure can be illustrated in such a study.

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. 6.4.

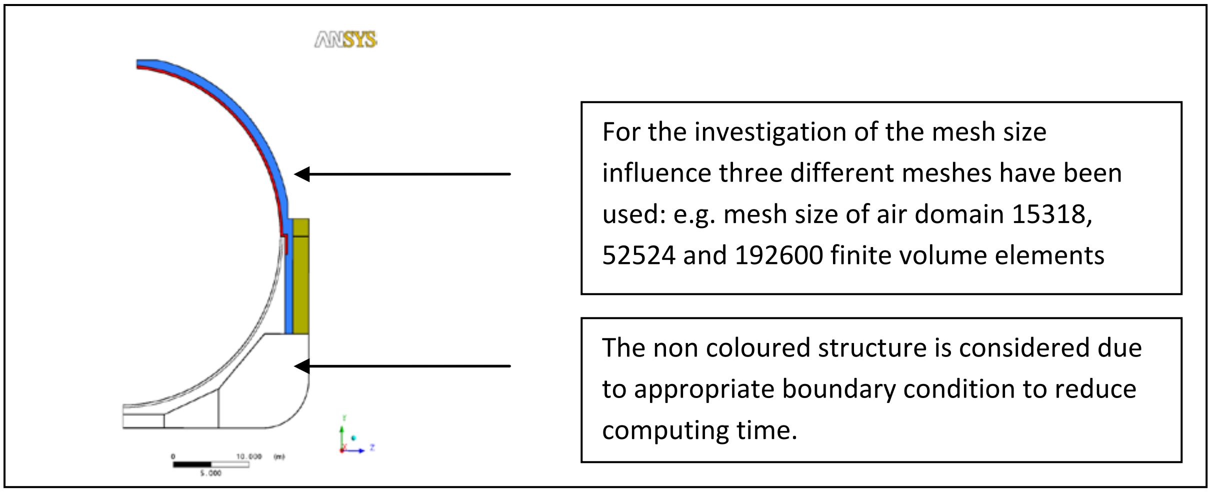

Fig. 6.4 Model of the solution domain, [10] modified

Buckling check of the weather cover

The importance of the weather cover in knocking down the heat flux from the fire had been demonstrated in the simplified analysis discussed above. So it was important that the survivability of the weather cover itself, at least to the extent that it provides effective thermal shielding, be established.

A fully coupled transient Finite Element (FEA) thermal stress analysis of a typical Moss type LNG tank weather cover was carried out. The cover was assumed to be subjected to three different constant heat flux levels from an external fire; 88, 108 and 200 KWm^{-2}. Very conservative boundary conditions were assumed just to predict the earliest possible point of buckling, as defined by a large local deformation. Such deformation would occur with an abrupt drop in the Young's modulus which for steel is at about 1023 K (1382 F).

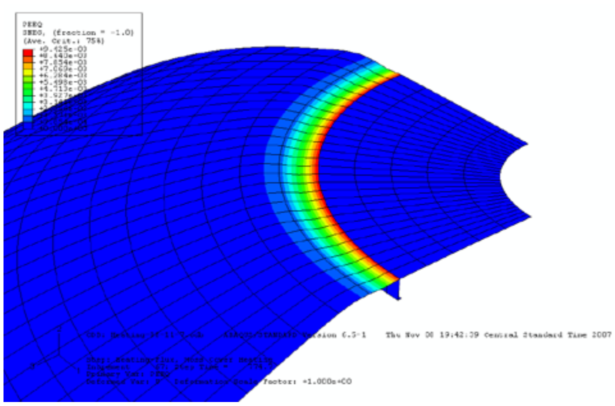

Fig. 6.5 Location of the thermal collapse (buckling),

Under the above conditions, failure of the cover was predicted around the connection of the cover sheet and top platform. Again for this study what is categorized as failure is the first sign of local deformation of sagging. It is not total collapse or melting of the steel weather cover. Furthermore, on a moss type LNG carrier this location is at least 40m above the surface of the water since no view factor was assumed the actual flames would have to be more than 70 m above the surface.

Checking the GL CFD model

The CFD model used in the GL analysis was checked by applying the same boundary conditions (steady state hate flux, adiabatic wall) used in the simplified ABS buckling analysis.

The results of ABS (curve1) and GL (curve 2) for a heat flux of 88 kW m^{-2} shows the good correlation in Fig. 6.6. The differences result from the assumption of adiabatic cover in the ABS calculation which leads to a faster heating of the cover compared to the GL calculation which considers the heating up of the air in the insulation space, the heat transfer into the insulation and the convection effects. It should be noted that the heat flux to the cover was kept constant for curve 1 and curve 2 which is not the case because the temperature difference between fire and cover is decreasing when the cover temperature increases.

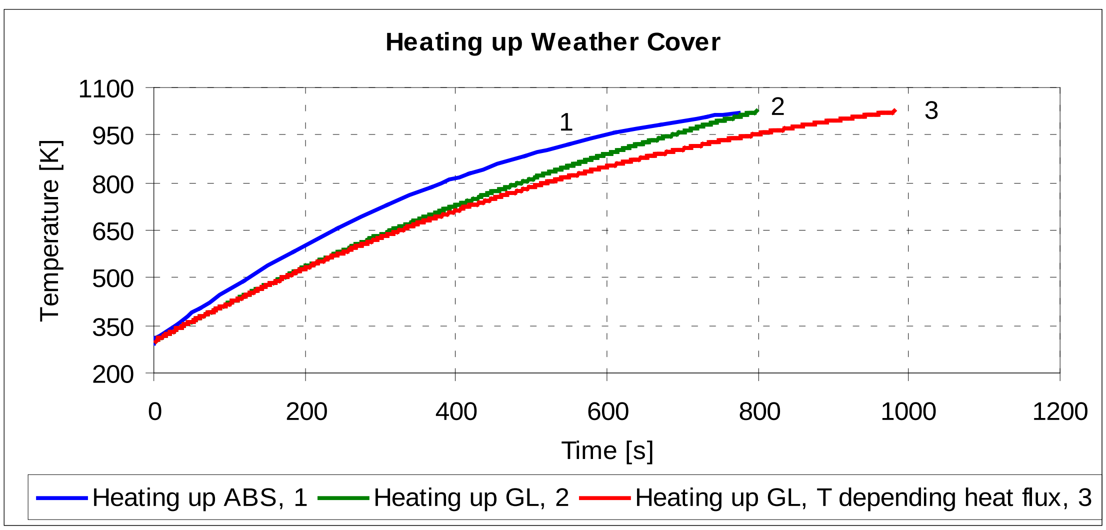

Fig. 6.6 Comparison heating up the weather cover ABS / GL

Curve 3 in Fig. 6.6 gives the heating up behavior of the cover considering the fact that the temperature increase of the cover is reducing the heat flux transferred by radiation from the fire to the cover. According to the more refined calculation given in curve 3, the cover takes 980 s to heat up to 1023°K, which extends the buckling of the structure by approximately 200 s compared to the values from curve 1 and 2.

Heating up Weather Cover / Insulation

The full CFD analysis includes transient simulations of complete heating up of the weather cover until buckling occurs. The transient calculations are related to the first two phases of the incident. The 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.

The heating up of the weather cover and insulation is shown inFig.6.7. with initial heat flux values of; 88 , 108 , 200 and 300 kW m^{-2} put in as boundary condition

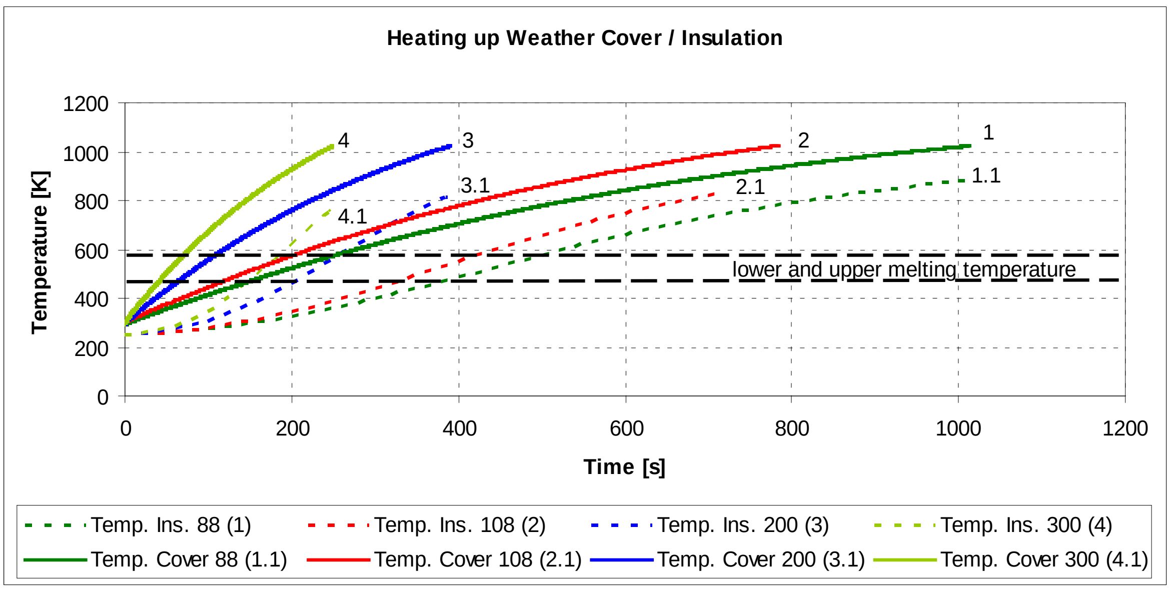

Fig.6.7 Heating up of the weather cover and insulation,

Fig. 6.7 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 of the cover with a time delay. To reach the melting temperature of 200 to 300° at the insulation surface about 450 s are needed for 88 kWm^{-2} initial heat flux and about 160 s are needed if 300 kWm^{-2} are assumed. The values for the weather cover to reach the temperature where buckling starts (1023 K) are 1015 s respectively 245 s.

Temperature of the insulation during incident

The detailed heat flow into the insulation has been calculated by means of the transient calculations. The calculated temperature distribution across the 300mm of insulation is shown in Fig. 6.8 for different levels of initial heat flux. The position x = 0 m corresponds with the position of the tank wall. The grey graph shows the temperature distribution under normal operation condition. The other colored graphs illustrate the temperature distribution in the cross section of the insulation at the beginning of melting on the surface.

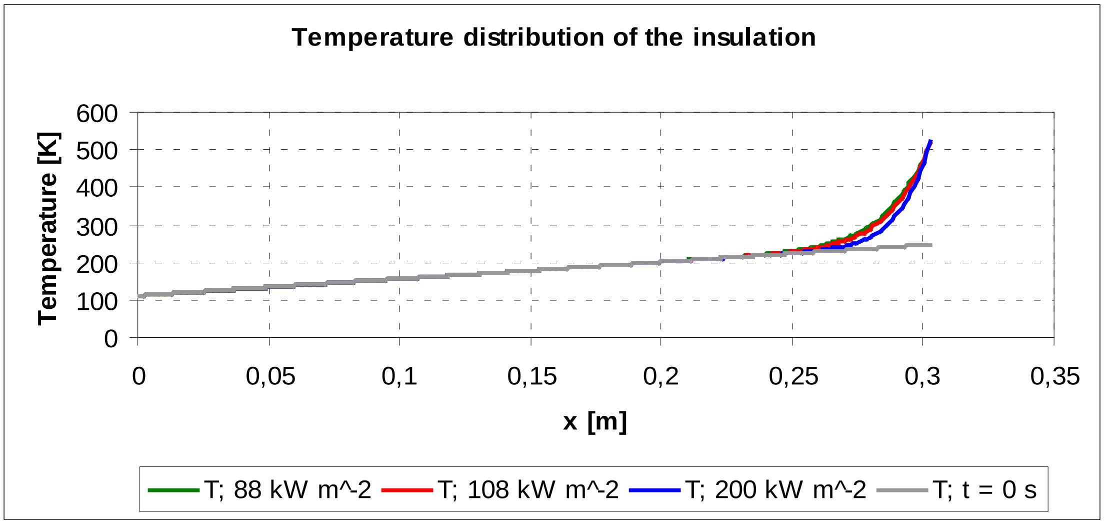

Fig. 6.8 Temperature distribution inside cross section of the insulation, [10] modified

What is most striking from Fig. 6.8 is that regardless of the magnitude of the initial heat flux only the outer 40 mm of the insulation thickness are affected at any given time span.

Consequently, what this confirms is that even a ship fully engulfed in a pool fire will see no significantly increased heat flow into the LNG containment system until the insulation system is almost completely destroyed. The only question then is will the insulation system survive long enough to outlast the fire. What also can be concluded fro Fig 6.8 is that the heating up of the insulation is following the melting process. This means that e.g. the insulation at x=0.15 m will start to heat up if the melting zone has reached about x=0.2 m and not before. It should be noted that only the calculation presented in section 6 of the report consider the energy needed to heat up the insulation to the melting temperature. The calculation presented in section 7 of the report only considers the energy needed to melt the insulation but not the energy needed to heat up the insulation which is two- to threefold the energy needed for melting.

Both studies conclude that the melting rate is about 3 cm/min. But only one took into consideration that another 2 min are needed to reach the melting temperature. Therefore the correct overall melting temperature can be assumed to be about 1 cm/min.

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

The results of the CFD analysis indicate that under the very extreme conditions assumed in the study, if the pool fire engulfing the vessel burns long enough there will be a degradation of the insulation system.

The study then looked to the findings in the previously referenced Sandia Study, as a source of information on range in size and duration of envisaged pool fires resulting from large-scale LNG spills over water.

The Sandia Report provides tables with probable pool diameters as a function on the breach size assumed in the vessel. For breaches sizes smaller than 3 m^2 the pool diameter is calculated to be less than 300 m which is about the length overall of a full size moss type LNG carrier. So the fully engulfing fire we have considered can only come from a breach size greater than 3m^2. The average burning duration for various breach sizes is indicated in tables 10 and 14 of the Sandia report, for accidents and intentional acts respectively.

The results of the Sandia report were used with the findings of this study and the following observations were made ;

- With an initial heat flux of 300 kW m^{-2} 4.16 min are needed to heat up the weather cover to the buckling temperature. Holes smaller than 10 m^2 would burn that long.
- A time of 6.51 min is needed to reach the buckling temperature 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 m^2.
- For hole sizes above 3 m^2 the weather cover can not reach the buckling temperature due to a fire with an initial heat flux of 108 kW m^{-2}
- For a heat fluxes lower than 108 kW m^{-2} caused by breach sizes less than 3 m^2 the weather cover can reach the melting temperature.

Similarly, Fig. 6.9 shows the minimum time related to the tank breach size until the deterioration of the insulation starts. The heat flux of 108 kW m^{-2} corresponds to the basis used in the IGC-Code

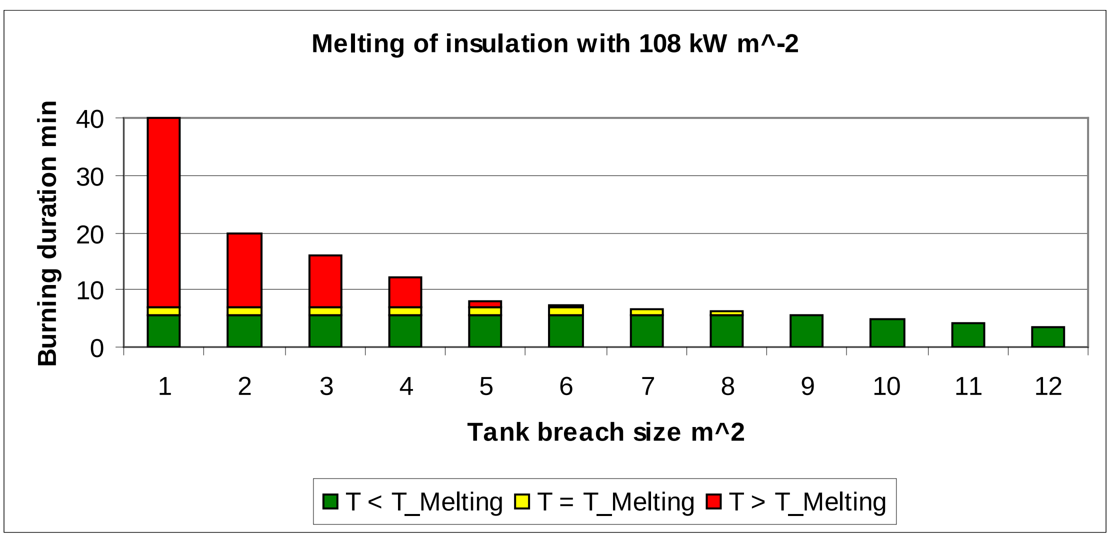

Fig. 6.9 Melting of insulation caused by a heat flux of 108 kW m^{-2},

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 breach sizes in the vessel with a red bar will create a fire which will last long enough to affect the insulation system. This means that fires from hole sizes above 5 m^2 will have expired before the insulation system is affected.

This study has determined that with an initial heat flux of 108 kW m^{-2} the complete deterioration of the insulation will not occur before at least 47.5 min into the fire. Even in the worse case scenario considered, with an initial heat flux of 300 kW m^{-2} the insulation system can be expect to last at least 29.5 min. As a consequence only leak sizes up to about 2 m^2 will create fires lasting long enough to destroy the insulation but the pools of these fires will not engulf the ship.

Conclusions of Heat Transfer Analysis

1. An engulfing fire as assumed is not able to destroy the complete polystyrene insulation of a Moss Tank.

2. With 300 kW m^2 initial heat flux:

    a. Only spills from holes below 2 m^2 burn long enough to destroy the insulation thickness. But the tank will not be engulfed by the fire in these cases.

    b. The minimum time period to destroy the insulation will be 29 minutes after the fire is started (not 10 min as assumed by other authors).

3. With the more realistic sizing heat flux of the PRVs (108 kW m^{-2}):

    a. for large engulfing fires with breach sizes of 5 m^2 or greater the fire duration is to short to heat up the weather cover to the buckling temperature (1023 K).

    b. only for leak sizes smaller than 3 m^2 the heat flux is able to heat up the weather cover above 1023 K.

    c. even with a small hole size of 1 m^2 the fire does not burn long enough to completely destroy the insulation system.

4. There is no increase in heat flow into the cargo tank until virtually all the insulation is destroyed.

5. Dangerous tank wall overheating of a LNG filled Moss tank can be excluded even if the insulation is destroyed completely

7. Conclusions of The Investigations

1. An engulfing fire as assumed is not able to destroy the complete polystyrene insulation of a Moss Tank.
2. There is no increase in heat flow into the cargo tank until virtually all the insulation is destroyed.
3. IGC Code formula and methodology for LNG carrier relief valve sizing compares favorably and is consistent with similar codes such as API, CGA, EN, ISO and NFPA.
4. For the Moss design tank with polystyrene based foam insulation, assuming the worst case scenario of losing the entire insulation effect, the tank pressure will rise to a level that can be accommodated by the tank structure without exceeding the IGC Code allowable stress levels for the tank material.
5. Due to the capability of the relief valves to accommodate greater gas flows with rising tank pressures even assuming the worst case of cargo tank cover damage and loss of heat shielding, the relief valve capacity is still sufficient to prevent overpressure failure of the tank.
6. In addition to conclusions 2 and 3 above, where even if the entire insulation was lost and the tank cover was completely lost, the capacity of the relief valves can accommodate a further estimated 30% rise in heat flux from a surrounding fire above that contained in the codes referred to in 1 above.
7. The limit of relief valve capability is the “choke point” at which no further increase of gas flow can be accommodated through the RV vent system. This is approximately at 4.3 barg.
8. The presence and use of the vapor header will provide further pressure relief via the assumed damaged (holed) cargo tank and the forward vent riser, however this has not been relied upon for the protection of the cargo tank against over pressure in the points above. The extent to which the vapor header contributes to pressure relief will be dependent upon the fire scenario.
9. The exact response of the insulation system to heat, with time, is unclear. One CFD/heat transfer calculations made by the working group indicate time periods of 10 minutes for a complete degradation to a depth of 30cm. However a more detailed study taking into account the time to heat up the insulation to the point at which melting first starts predicted a degradation time of up to 29 minutes. Additionally, reports from physical tests carried out in the 1970’s indicate time periods of greater than 2 hours, although in these tests, the conditions did not entirely accurately reflect actual LNG carrier dimensions or heat source temperatures.
10. From the behavior tests of polyurethane foam under heat in an N2 inerted atmosphere, insulation properties and strength are retained such that the concern for complete failure by degradation under fire conditions is likely to be substantially less for polyurethane based materials.
11. Based on experience from earlier fire incidents and studies included in the report, the tank cover is not likely to collapse under fire loads. The first point of local yielding is approximately 40 m above the sea level and the studies assumed radial heat flux into the cover. Furthermore, the effect of the water-spray system required under 11.3 of the IGC Code was not considered in any of the studies of the WG.