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Fire performance of LNG carriers insulated with polystyrene foam

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Abstract

Analysis of the response of a liquid-full Moss Sphere LNG tank insulated with polystyrene foam to an engulfing LNG fire indicates that current regulatory requirements for pressure relief capacity sufficient to prevent tank rupture are inadequate. The inadequacy of the current requirements stems primarily from two factors. Firstly, the area of the Moss Sphere protruding above what would be the nominal deck on a conventional carrier, which is protected only by a steel weather cover from exposure to heat from a tank-engulfing fire, is being underestimated. Secondly, aluminum foil-covered polystyrene foam insulation applied to the exterior of the LNG tank is protected above the deck only by the steel weather cover under which the insulation could begin to melt in as little as 1–3 min, and could completely liquefy in as few as 10 min. U.S. and International Regulations require that the insulations on the above-deck portion of tanks have approved fire proofing and stability under fire exposure. Polystyrene foam, as currently installed on LNG carriers, does not appear to meet these criteria. As a result of these findings, but giving no consideration to the significant potential for further damage if the polystyrene should burn, the boil-off rate is predicted to be an order-of-magnitude higher than provided for by current PRV sizing requirements.

Keywords: LNG; Polystyrene foam insulation; Pool fire radiation; Pressure relief valve sizing

1. Introduction

A recent report by the Government Accountability Office [1] states that both the cold temperature of spilled LNG and the hot temperature of an LNG fire have the potential to significantly damage LNG ship tanks, possibly causing multiple tanks on the ship to fail in sequence. A recent report by Sandia [2] proclaims the credibility of a spill and fire on the sea following a terrorist attack that would have the potential to engulf one or more adjacent tanks on an LNG ship, potentially leading to cascading (successive) failures. As such failures could increase the severity of a catastrophic incident, the report cites as the leading unaddressed research need the determination of the potential for cascading failures of cargo tanks on LNG carriers. This paper first considers the adequacy of present regulatory requirements for pressure relieving systems to prevent overpressure failure of a current-design, polystyrene foam insulated, liquid-full Moss Sphere exposed to an LNG fire. Then, as the philosophy of fire protection for such hazardous cargo containment systems is based on provision of protection from fire adequate to prevent failure for a prescribed period of time, the paper describes a one-dimensional transient analysis of the expected response to heat absorption from an LNG fire contacting a single liquid-full, ~36 m diameter (25,000 m^3 volume) Moss Sphere on an LNG carrier.

2. Adequacy of regulatory requirements for pressure relief systems on LNG ships

The International Maritime Organization [3] and the U.S. Coast Guard [4] specify similar requirements for pressure relief valve sizing on liquefied gas carriers. The following, quoted from the Coast Guard Regulation, is in all practical respects identical to the requirements of the IGC Code.

"The relief valve discharge for heat input of fire must meet the following formula:

$$Q = F\,G\,A^{0.82} \tag{1}$$

where Q = minimum required rate of discharge in cubic meters per minute of air at standard conditions 0 °C and 1.03 kPa;

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F = fire exposure factor for the following tank types—$F = 1.0$ for tanks without insulation located on the open deck, $F = 0.5$ for tanks on the open deck having insulation that has approved fire proofing, thermal conductance, and stability under fire exposure, $F = 0.5$ for uninsulated independent tanks installed in holds, $F = 0.2$ for insulated independent tanks installed in holds, $F = 0.1$ for insulated independent tanks in inerted holds or for uninsulated independent tanks in inerted, insulated holds, $F = 0.1$ for membrane and semi-membrane tanks, and

$$G = \text{Gas Factor} = \frac{177}{(L\,C)}\left(\frac{Z\,T}{M}\right)^{1/2}$$

where L = latent heat of the material being vaporized at relieving conditions, kcal/kg, C = constant based on relation of specific heats (K), Table 54.15–25(c), Z = compressibility factor of the gas at relieving conditions (if not known $Z = 1$); T = temperature in K at the relieving conditions, (120% of the pressure at which the pressure relief valve is set), M = molecular weight of the product, and A = external surface area in m^2(for a tank with a body of revolution shape)."

According to the IMO-IGC, for a Moss Sphere (insulated independent) tank installed in a hold, the fire exposure factor is designated to be 0.2. In contrast, Paragraph c-1 of 46 CFR 54.15-25 further states that "For an independent tank that has a portion of the tank protruding above the open deck, the fire exposure factor must be calculated for the surface area above the deck and the surface area below the deck, and this calculation must be specially approved by the Commandant (GMSE)". This added provision of the USCG regulation is important because it indicates the need for careful consideration of the surface area of the tank that could be most severely exposed to heat from a fire, as will be shown below. However, as this provision only affects the value of the fire exposure factor F, and noting that the Gas factor G in Eq. (1) can be represented by the product of a heat flux to the cargo multiplied by an appropriate constant K representing the thermodynamic properties of the cargo, Eq. (1) becomes:

$$Q = F\,K\,q\,A^{0.82} \tag{2}$$

The development of Eq. (2) is described in considerable detail by Heller [5]. This empirical equation is based on fire tests conducted more than fifty years ago; long before the practice of carrying LNG in shipping containers of the size and type considered here. Importantly, the equation precedes current widespread concerns for terrorist attacks on ships that could result in very large LNG fires engulfing the tank. The largest tests for which data were available for the development of Eq. (2) involved tank surface areas of 568 ft^2 (53 m^2), nearly 80 times smaller in area and over 600 times smaller in volume than the single LNG Moss Sphere under consideration. Furthermore, Eq. (2) is based on tests in which the liquid wetted area, the total surface area, and the area exposed to fire were all varied, the latter in particular resulting in the $A^{0.82}$ term. It appears that Heller considered, as we do, that the use of the area ($A^{0.82}$) term in Eq. (2) is inappropriate for application to a catastrophic engulfing pool fire.

In consideration of the much larger fire sizes as well as containment (tank) sizes in use today, it is appropriate to briefly review the current state of knowledge of LNG fire-on-water sizes and durations that might result from an intentional attack on an LNG carrier. The Sandia Report cited earlier [2] analyzed the fire scenario that could follow spillage onto the water of the contents of a single 1/2 tank (12,500 m^3) of LNG, providing analyses for hole size (areas) ranging from 1 to 10 m^2. The pool size diameter for the nominal hole size of 5 m^2 was 330 m with a burn time of 8.1 min. Since the fire diameter would be similar to the pool size, the Sandia Report suggests that with the nominal hole size, the size of the fire (diameter) could be larger than the length of the ship. And while the predicted burn time for the 5 m^2 hole is only 8.1 min, the 2 m^2 hole size spill is predicted to result in a pool size of 209 m diameter with a burn time of 20 min, and the 1 m^2 hole size spill is predicted to give a fire with 148 m diameter lasting for 40 min. Thus the smallest hole size spill could have a diameter of almost 500 ft, or more than half the length of the ship, and might burn for 40 min. Finally, assuming the smallest hole size spill and a conservative flame height to flame diameter ratio of 1/2, the flame height could, even for the smallest hole size, considerably exceed the maximum height of the ship above the water line. Given the uncertainties that would attend the actual spreading that would occur as the LNG reaches the water, including wind effects, momentum of the ship, and the presence of objects (including the ship) that could channel the LNG flow, the possibility of complete engulfment of the entire above-deck portion of at least one tank adjacent to the tank ruptured in the attack must be anticipated.

With this background, and to consider the propriety of the current regulatory requirement (based on Eq. (2)) for determination of PRV sizing on LNG carriers in service currently, we reviewed an analysis of PRV system design methods performed for the U.S. Coast Guard by the National Academy of Sciences in 1973 [6].

2.1. The National Academy of Sciences Report

The analysis provided in this paper was presented almost four decades ago to the U.S. Coast Guard, at its request, by the U.S. National Academy of Sciences. However, as far as we can tell, there has been no follow-up to the conclusions of the NAS report, despite its suggestion of an urgent need to update the regulatory requirements for pressure relief systems design to accommodate changing practices in the LNG industry. Such a recommendation was particularly apt for the LNG industry in the seventies, as today, as the report was prepared when the LNG industry was just beginning the expansion which has been so much increased recently.

We support the NAS report's statement (applied here to LNG carriers) that the determination of the heat absorbed by an LNG-full Moss Sphere exposed to an engulfing fire can be expressed properly as:

$$Q_{\mathrm{H}} = F_{\mathrm{I}}\,q\,E\,A \tag{3}$$

where Q_{H} = total heat absorbed by the cargo, F_{I} = environmental factor, including insulation and radiation shielding, q = heat flux

Table 1
Comparison of PRV requirements using Eqs. (2) and (4)

	Area (m^2)					
	1	10	53	100	1000	4072
Ratio (Eq. (4)/Eq. (2))—IGC Code	$2\ F_{\mathrm{I}}$	$3\ F(_{\mathrm{I}}$	$4.1\ F_{\mathrm{I}}$	$4.6\ F_{\mathrm{I}}$	$6.9\ F_{\mathrm{I}}$	$8.9\ F_{\mathrm{I}}$
Ratio (Eq. (4)/Eq. (2))—45 CFR 54	$1.3\ F_{\mathrm{I}}$	$1.9\ F_{\mathrm{I}}$	$2.6\ F_{\mathrm{I}}$	$2.9\ F_{\mathrm{I}}$	$4.3\ F_{\mathrm{I}}$	$5.6\ F_{\mathrm{I}}$

to the outside of the container, E = exposure factor, the fraction of the total tank area (A) exposed to fire, and A = tank surface area (for full tanks, equal to the wetted area).

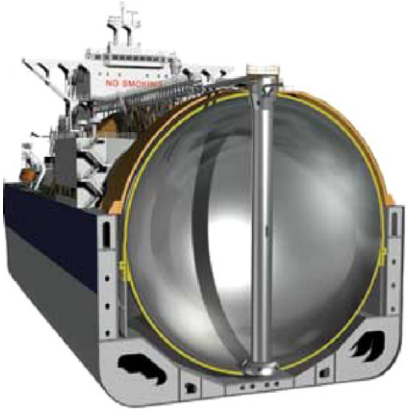
The heat absorbed by the cargo, Q_{H}, multiplied by the part of the gas constant G that accounts for the thermodynamic properties of the cargo (K in Eq. (2)), gives the relieving capacity:

$$Q = K\,q\,F_{\mathrm{I}}\,E\,A \tag{4}$$

where the product (EA) represents the area of the outside of the container exposed to fire.

2.2. *Comparison of Eqs. (2) and (4)*

We assumed that 40% of the Moss Sphere protrudes above what would be the nominal deck on a conventional carrier. This area is protected from the heat of an engulfing fire only by the insulation and by the steel weather cover (see illustrations following). With E = 0.4, and a tank-engulfing fire, Table 1 shows the ratio of Eq. (4) to Eq. (2) determined for values of the tank surface area ranging from 1 to 4072 m^2 (the area of a 36 m diameter Moss Sphere), along with the largest value (53 m^2) from the data base from which the $A^{0.82}$ term in Eq. (2) was developed, using the requirements for designating the insulation factor F from the IGC Code and 46 CFR 54 respectively.



Following paragraph (c-1) of the Coast Guard Regulation, the value of F was determined for the surface area above the deck and the surface area below the deck, assuming the fraction of the tank area above the deck as 0.4, as (0.4)(0.5) + (0.6)(0.2) = 0.32. We note that this method of determination of the value of the fire exposure factor F increases the required PRV size by 60%, illustrating the importance of careful handling of the determination of the area of the tank effectively exposed to a fire.

In either case, the extrapolation over tank surface area of the correlation assumed in Eq. (2) (the $A^{0.82}$ term) by two orders of magnitude is clearly not applicable to the Moss Sphere tank configurations in use today, particularly in view of the severity of fire exposure that could result from terrorist attack. The highest value of this ratio (using the IGC Code) for a typical Moss Sphere (8.9 F_{I}) means that the value of the factor F_{I} accounting for insulation (and shielding by the steel weather cover) in Eq. (4) must not be greater than 0.11 in order that the required relief capacity be as small as indicated by Eq. (1). Conversely, total loss of insulation and weather cover (radiation) shielding on the part of the tank exposed to fire, i.e., above the deck, would result in under-prediction of the required relieving capacity by a factor of 9.

Furthermore, we believe that the heat flux implicit in the current regulation may not be appropriate for describing engulfing LNG fire exposure. We note that increasing the heat flux from the currently used value (71–108 kW/m^2), which is based upon test data for gasoline or kerosene fires only (see Heller [5]), will increase the required vapor relieving capacity by an additional factor proportionally. Whereas local surface emissive heat fluxes have been measured in test LNG fires as high as ∼300 kW/m^2, there is considerable debate regarding the appropriate value for the heat flux applicable to a large engulfing LNG fire. This question is currently being investigated, with large-scale LNG fire tests planned in the United States for completion in 2008. While it appears clear that with the presently prescribed heat fluxes the relief systems on LNG carriers could be undersized by an order of magnitude; it follows that exposure to an engulfing LNG fire with greater heat fluxes could worsen the under-estimation of the relieving capacity.

As it appears clear then that a Moss Sphere with a pressure relief system designed according to Eq. (1), and for which the PRV system fitted to a specific tank exposed to the fire is required to provide the only pressure relief [7], could be subject to bursting overpressure if the insulation should fail, it is necessary to determine whether the insulation could withstand

Table 2
Specifications and thermodynamic properties of system components

Zone	Thickness (m)	Density (kg/m^3)	Heat capacity (J/kg K)	Thermal conductivity (W/mK)	Emissivity	Failure temperature (K)
R2	0.015	7850	475	44.5	0.85	810[a]
R3	1.0	COMSOL	COMSOL	COMSOL	NA	NA
R4	0.0003	2700	900	70	0.1,0.5	873[b]
R5	0.30	26.5	1045	0.038	NA	510[c]
R6	0.02	2700	904	70	NA	873[b]

[a] Limit temperature for fire exposure, mild carbon steel [8].

[b] Solidus temperature [9].

[c] Melting temperature [10].

such a fire for its duration or until remedial action could be taken.

3. One-dimensional transient heat transfer analysis of a Moss Sphere tank section

We utilized COMSOL Multiphysics® (formerly MATLAB) to perform a one-dimensional analysis of the thermal response of a unit area section of a Moss Sphere (assumed flat) in which fire (R1) is contacting the steel weather cover (R2), followed by serial resistances representing the air gap (R3) between the cover and the aluminum foil covering the insulation, the aluminum foil (R4) covering the insulation, the insulation (R5), and the inner aluminum tank wall (R6), which is in contact with LNG (R7).

Table 2 specifies the properties of the resistances R2–R6 assumed for the analysis.

The following sections describe the initial conditions assumed for the analysis and the boundary conditions interconnecting the resistances specified in Table 2 as well as the boundary conditions connecting the fire (R1) to the steel cover (R2) and the aluminum tank wall (R6) to the LNG (R7).

3.1. Initial conditions

The initial condition temperature profile for the one-dimensional system was calculated with a steady-state COMSOL analysis assuming an ambient air temperature of 305 K. Fig. 1 shows the temperature profile through the system with aluminum emissivity specified as a parameter, illustrating the sensitivity of the heat transfer calculations to the emissivity of the aluminum foil covering the insulation. Fig. 2 shows the heat flux into the cargo with the foil emissivity as a parameter. For an emissivity of 0.1 (assumed appropriate for a new, clean system) the heat flux into the cargo is approximately 20 W/m^2. For a 36 m diameter Moss Sphere, this heat flux to the cargo at ambient conditions (305 K) would result in a boil-off rate of ~0.12% of the cargo per day. This result, which is in good agreement with typical specifications for operating Moss-design carriers, provides a useful check on the propriety of the heat transfer calculation methods utilized in the analysis.

3.2. Boundary conditions

We accounted for radiative heat transfer (assuming grey body properties) and convective heat transfer ($h = 28$ W/m^2 K [11]) from the flame to the weather cover. Radiative heat transfer and conductive heat transfer were accounted for in the air space under the weather cover; convective heat transfer in that space was neglected. The temperature profiles at the interfaces R4/R5, R5/R6, and R6/R7 assumed continuity (infinite heat transfer coefficient assumed from the tank wall to the LNG). Calculations were made for flame temperatures of 1300, 1400, and 1500 K—corresponding to calculated initial (maximum) total (black-body radiative and convection) heat fluxes from flame to

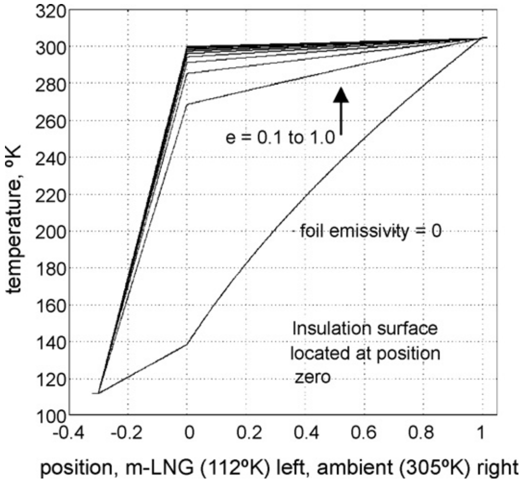


Fig. 1. Initial temperature profile.

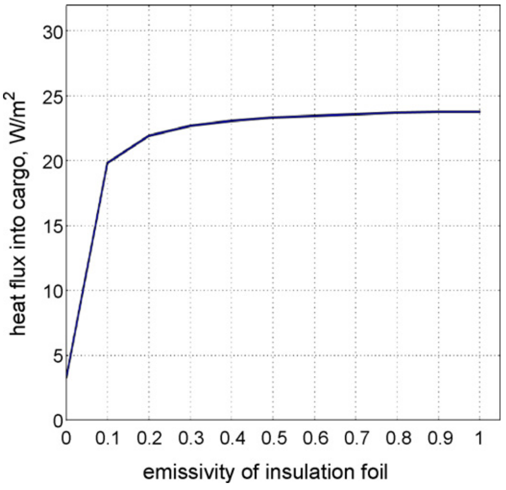


Fig. 2. Operating heat flux into cargo.

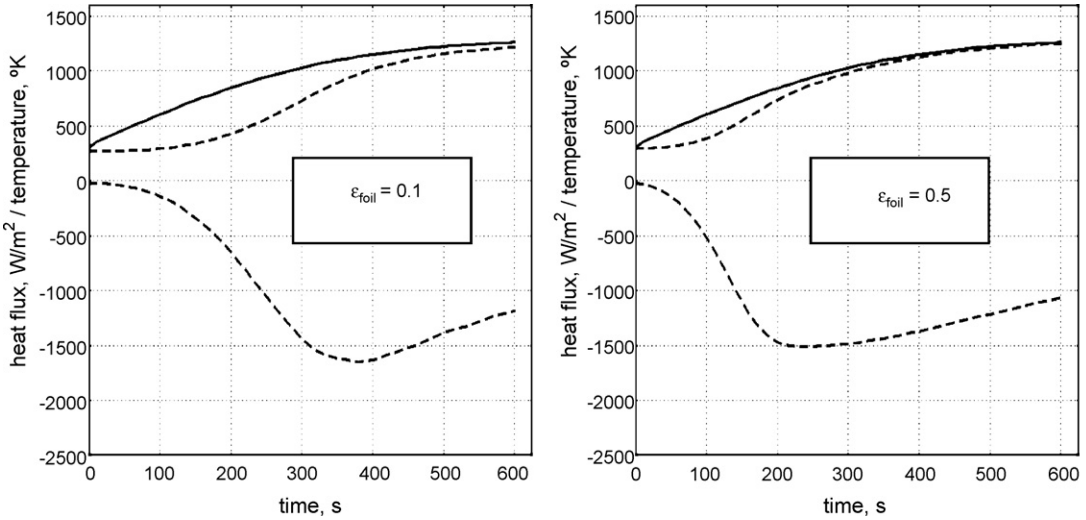


Fig. 3. Temperature and heat flux—wc solid, ins dashed—$T_{\text{fire}} = 1300$ K.

the steel weather cover (with emissivity = 1.0) of 188, 245, and 315 kW/m^2 respectively.

3.3. Results and conclusions

We calculated the time-varying temperatures and heat fluxes throughout the system with properties as specified in Table 2, with flame temperatures of 1300, 1400, and 1500 K, and aluminum foil emissivities of 0.1 and 0.5, the latter representing the range of emissivities that might be expected for new, clean, aluminum foil and dirty, aged aluminum foil respectively. All of our calculations assume that all of the materials (including the insulation) remained in place and functioning with the properties specified above. The purpose of these calculations was to estimate the times at which the components of the tank system would reach temperatures sufficient to cause failure, and further therefrom (using the heat flux at the time of incipient failure) to estimate the time period expected for complete failure of the insulation—the calculation results are not considered applicable for greater times.

We assumed for purposes of this analysis that failure of the steel and aluminum components of the system would begin upon reaching the designated failure temperature, and we assumed that the minimum rate at which the polystyrene insulation would fail would be determined by its melting rate, which would in turn be determined by the heat flux into the foam at the time at which the foam reached its melting temperature.

Figs. 3–5 show, as a function of time for 600 s of fire exposure, temperatures of the steel weather cover (wc) surface (contacting flame with $\varepsilon = 0.85$) and the (hot-side) insulation (ins) surface, as well as the heat flux into the insulation surface, for aluminum foil emissivities of 0.1 and 0.5, for flame temperatures of 1300, 1400, and 1500 K.

3.4. Predicted component failure commencement times

Table 3 shows the estimated times from the plots in Figs. 3–5 for the (outer) steel weather cover surface, the aluminum foil, and the polystyrene foam insulation (hot-side) surface to reach the failure temperatures designated in Table 2. Because of the

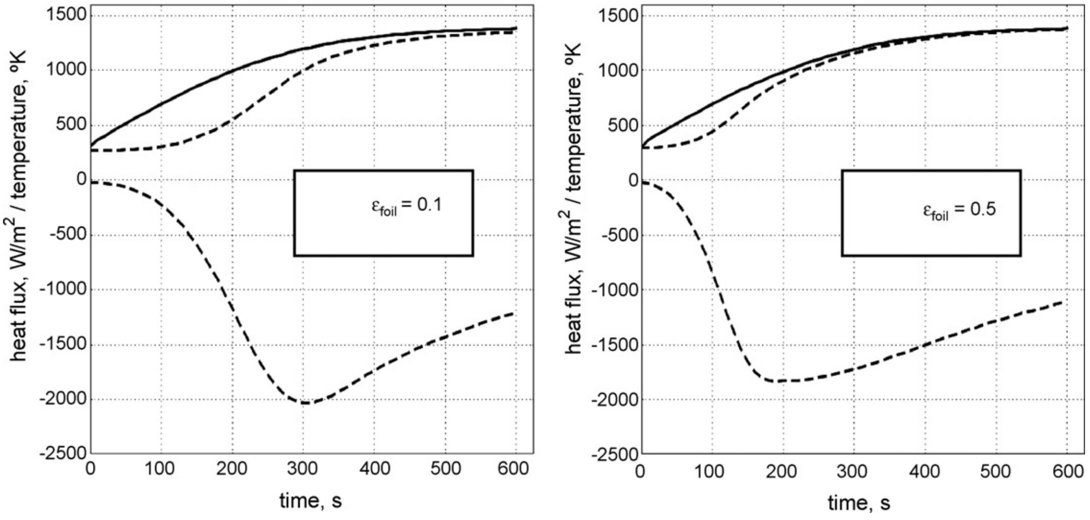


Fig. 4. Temperature and heat flux—wc solid, ins dashed—$T_{\text{fire}} = 1400$ K.

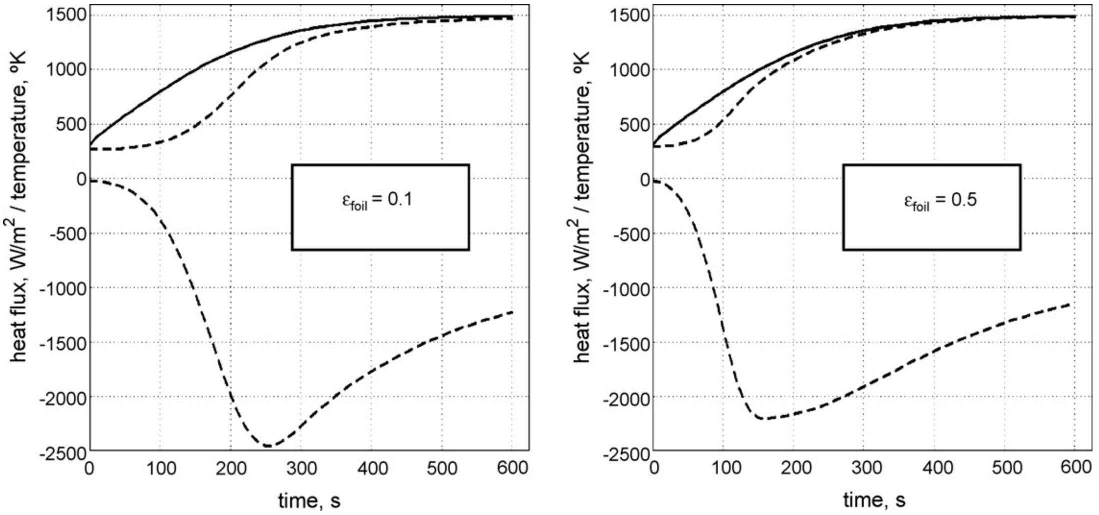


Fig. 5. Temperature and heat flux—wc solid, ins dashed—$T_{\mathrm{fire}} = 1500$ K.

small thickness of the aluminum foil (0.3 mm), the temperatures of the foil and the insulation (hot-side) surface were assumed identical for this analysis.

3.4.1. *Metal failure*

The temperature of the steel outer surface reaches 810 K, indicating approach to failure, in the range 100–180 s. The time when the aluminum foil reaches its melting temperature (873 K) ranges from 150 to 330 s. To calculate more accurately the actual response of the system is difficult, requiring assumptions as to the specific behavior of the system components as they fail (and beyond). Nevertheless, inclusion of such information for specific failure modes can do nothing, it appears, but increase the rapidity with which the system components would fail.

3.4.2. *Insulation failure*

The polystyrene surface temperature reaches its melting point of 510 K in the range 95–225 s. Following the time at which the polystyrene foam reaches its melting temperature, the heat flux into the foam insulation maintains an average value ranging from about 1 to about 1.5 kW/m^2 for the balance of the 10 min period shown. With a continuous heat flux of 1.5 kW/m^2 into the foam surface, the foam would melt at a rate (approximately) given by 1.5 kW/m^2 divided by the product of the foam density and its latent heat of fusion. The latent heat of fusion for styrene monomer is 105 kJ/kg and the density of polystyrene foam is 26.5 kg/m^3, indicating a melting rate of about 3 cm/min. However, this appears to be a lower limit on the melting rate because the latent heat of polystyrene (mass basis) could be (much) smaller, depending on the molecular weight of the polymerized styrene. Nonetheless, this analysis indicates that total melting of a polystyrene insulation layer 0.3 m thick could occur in less than 10 min after it reaches its melting temperature if the foam were subjected to the heat exposure considered here.

Table 3
Predicted component failure times (s)

Component	$T_{\mathrm{fire}} = 1300$ K		$T_{\mathrm{fire}} = 1400$ K		$T_{\mathrm{fire}} = 1500$ K	
	$\varepsilon = 0.1$	$\varepsilon = 0.5$	$\varepsilon = 0.1$	$\varepsilon = 0.5$	$\varepsilon = 0.1$	$\varepsilon = 0.5$
Weather cover	170	180	125	125	100	100
Aluminum foil	330	260	265	180	215	150
Foam insulation	225	140	190	120	160	95

3.4.3. *Insulation combustion*

This analysis has not considered the potential for combustion of (poly)styrene vapors mixed with air in the space between the weather cover and the insulation surface. Both the IGC and 46 CFR 54 require, in order to take credit for the insulation in PRV sizing, that the insulation on the above-deck portion of tanks have approved fire proofing and stability under fire exposure. Polystyrene foam, as currently installed on LNG carriers, does not appear to meet these criteria. Even if the exterior fire were isolated from the foam (by an intact weather cover), ignition of these flammable vapors appears highly likely, given the relatively low autoignition temperature of styrene (∼760 K), and the fact that only about 1 mm thickness of the insulation would have to vaporize to raise the average vapor concentration in the air space under the weather shield above the lower flammable limit. Given the flue-like configuration formed by the space between the cover and the insulation, the volume of air in that space, and the potential for failure of the steel weather cover that would admit additional air, there is a potential for rapid burning of the insulation material [12], even if the ignition of the vapors prior to the steel weather cover failing did not result in an overpressure that failed the cover instantly.

We estimated, assuming that all of the foam melts and either burns or runs off, thereby exposing the tank wall to radiation heat transfer from an intact weather cover, that the steady-state heat flux into the cargo (all surface emissivities assigned a value of 1.0 except the steel weather cover, assigned $\varepsilon = 0.85$) would range from 80 to 135 kW/m^2 for a flame temperature range of 1300–1500 K. An accurate determination of the potential for failure, and the probable mode, whether overheating of the tank wall in the vapor space or general failure due to overpressure, is beyond the scope of this paper. Nevertheless, even if potential for failure of the metal components of the system is neglected and no consideration is given to the potential for combustion of the insulation, it appears that a Moss Sphere insulated with non-fire resistant polystyrene foam, protected only from the heat of an engulfing fire by the steel weather shield, could rupture as a result of overpressure if the weather cover were subjected to an engulfing LNG flame for a time period of order 10 min.

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[7] We are informed that all current LNG carriers utilize piping interconnecting all of the LNG tanks on the vessel in order to collect LNG boil-off gas for propulsion and that all valves in said interconnected piping connecting the cargo tanks to additional relief valves are required to be locked open when the ship is in service. As a result, actual relieving capacity may exceed that prescribed by Eq. (1). While this may be true, we believe that the current regulatory practice deserves careful review, since it is not clear whether relief valve capacity placed on external piping (as opposed to the tank itself) is authorized, or whether any such additional piping is designed to allow the boil-off gas flow rates that could occur if the vessel were exposed to severe, even multiple-tank, fire engulfment.

[8] At 538 °C the maximum permissible design strength (60% of yield) would equal its strength at temperature, SFPE Handbook of Fire Protection Engineering, 1988.

[9] The range of solidus temperatures, or commencement of melting, for Aluminum alloys is ∼510–640 °C.

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