# FIRE RESPONSE OF POLYSTYRENE FOAM LNG SHIP INSULATION: UNRESOLVED ISSUES

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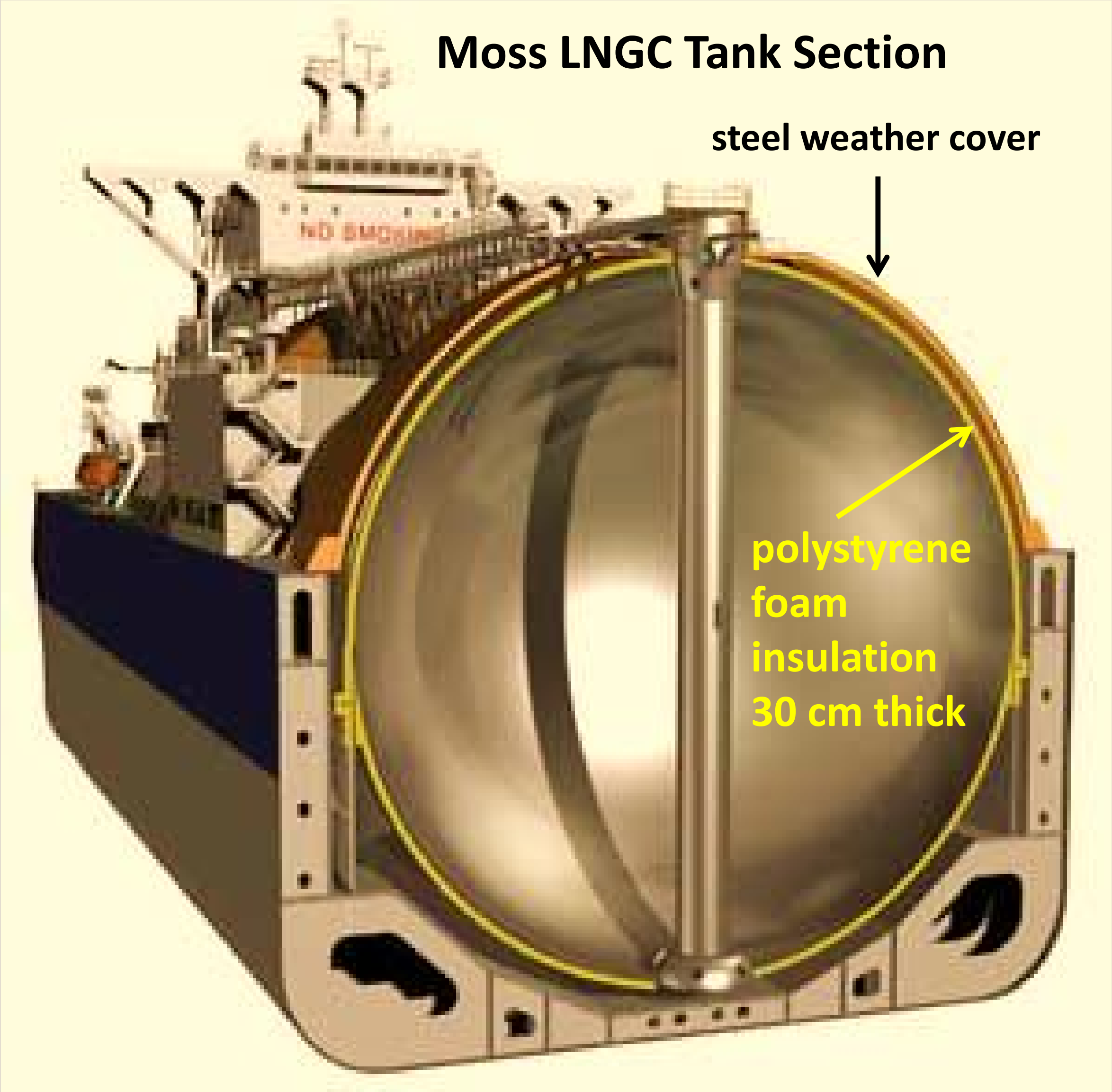



2006 - Havens notified SIGTTO of concerns about the potential for external fire-heating damage to foamed plastic insulation on LNG Carriers. A SIGTTO Working Group was formed.

2007 - The United States Government Accountability Office (GAO) issued a report ***Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*** stating that "The leading unaddressed priority ... was the potential for cascading failure of LNG (Carrier) tanks".

2009 – The SIGTTO Working Group issued its Working Group's Findings - ***Report on the Effects of Fire on LNG Carrier Containment Systems***.

# 2009 SIGTTO REPORT <u>CONCLUSIONS</u>

1. 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 … without failure …
2. Further … due to the capability of the relief valves to accommodate greater gas flows, with rising tank pressures and assuming the worst case of cargo tank cover damage and loss of heat shielding due to the possibility of combustion of the insulation and degradation products causing overpressures sufficient to fail the tank cover, the relief valve capacity is still sufficient to prevent overpressure failure of the tank.
3. In addition to the two preceding conclusions, 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 applicable codes.
4. <u>The response of the insulation system to heat, with time, is unclear; a detailed understanding of rates of insulation degradation and recession was not available for the structural arrangement of an LNG carrier.</u>

# 2009 SIGTTO REPORT RECOMMENDATIONS

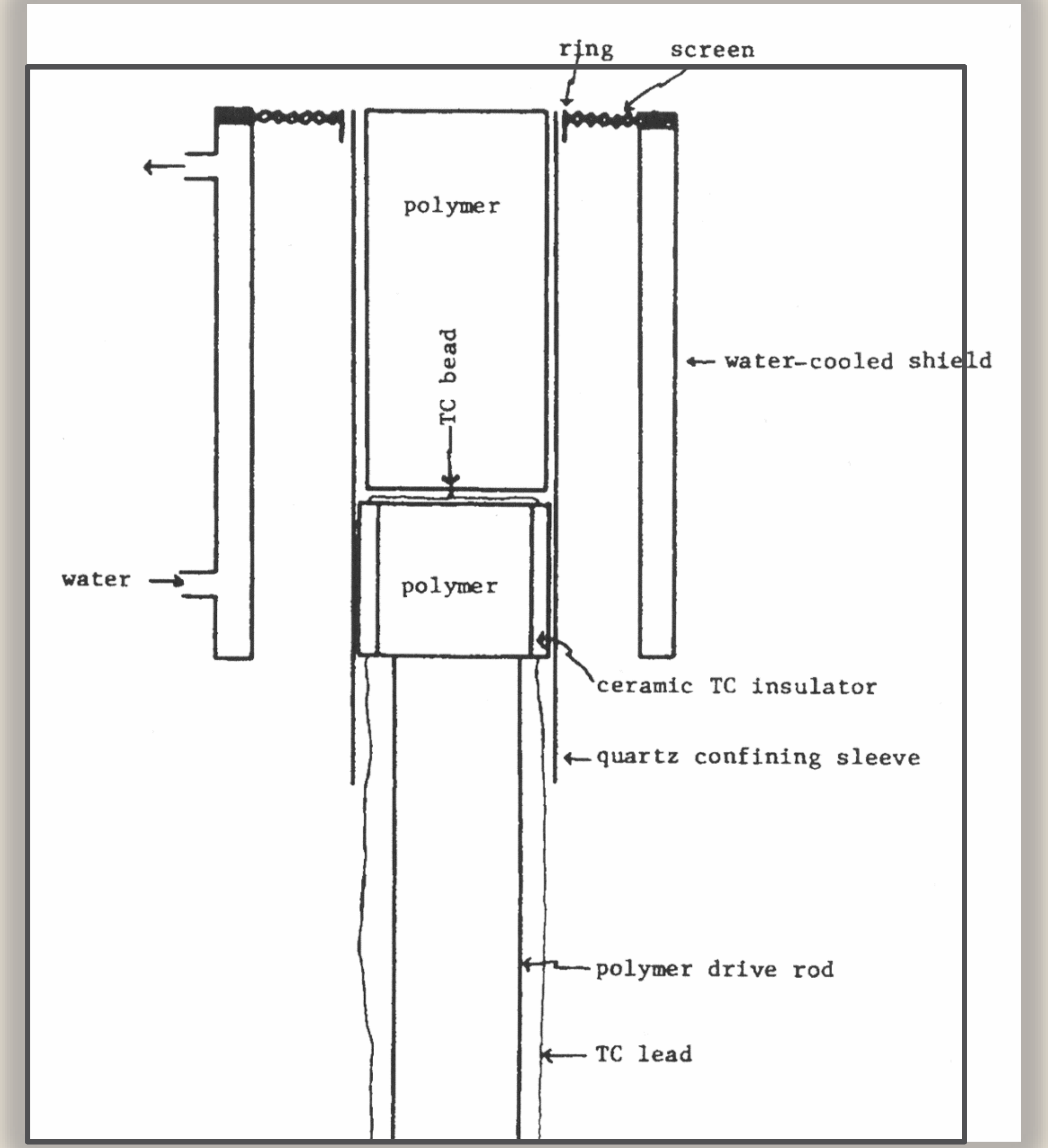
1. **If large scale LNG fire tests are carried out by Sandia, or others, that show significant conflict with existing values of heat flux used in the IGC code and other industry codes and standards, the question of the current equations for determining fire-case pressure relief loads merit reexamination by the whole LNG industry and not just the shipping element.**
2. **Although the WG has determined that current polystyrene foam insulated Moss sphere LNG carriers are equipped with pressure relief valves that provide additional capacity to prevent failure by overpressure …, better understanding of foam plastic insulation vulnerability to heating is required to adequately assess the hazards that could result from loss of insulation effectiveness… . Given the comparatively short duration of LNG fires …, a much better understanding of the temporal response of foam plastic insulation materials is necessary to determine the worst case circumstances referred to in the conclusions above. Further research, which should include physical insulation testing as well as a determination of the potential for additional damage due to combustion of the foam degradation products, is recommended"**

# FURTHER STUDIES COMPLETED 2010 - 2015

1. **University of Arkansas – Laboratory experimental measurement of recession (failure) rates of solid and foam-plastic polystyrene samples as a function of applied radiant heat flux.**
2. **University of Arkansas – Differential Scanning Calorimetric (DSC) Analysis and Thermal Gravimetric Analysis (TGA) of solid and foam plastic polystyrene samples to provide thermodynamic data (specific heat, heat of melting and heat of decomposition) data required for CFD simulation of failure rates of bulk specimens of solid and foam polystyrene as a function of applied heat flux.**
3. **Sandia National Laboratory – Large Scale LNG Fires on Water to Determine Maximum Fire-Surface Radiant Heat Fluxes.**
4. **Sandia National Laboratory - Pilot scale tests of (nominal) one meter square sections of as-installed polystyrene foam plastic LNGC insulation panels exposed to the maximum heat fluxes determined in the large scale fire tests.**
5. **University of Arkansas – Development and Verification of a One-Dimensional CFD model (using the commercially available model COMSOL) suitable for simulating the ship-insulation-panel tests for verification and subsequent application to the LNGC hazard in question.**

# University of Arkansas Experimental Measurements

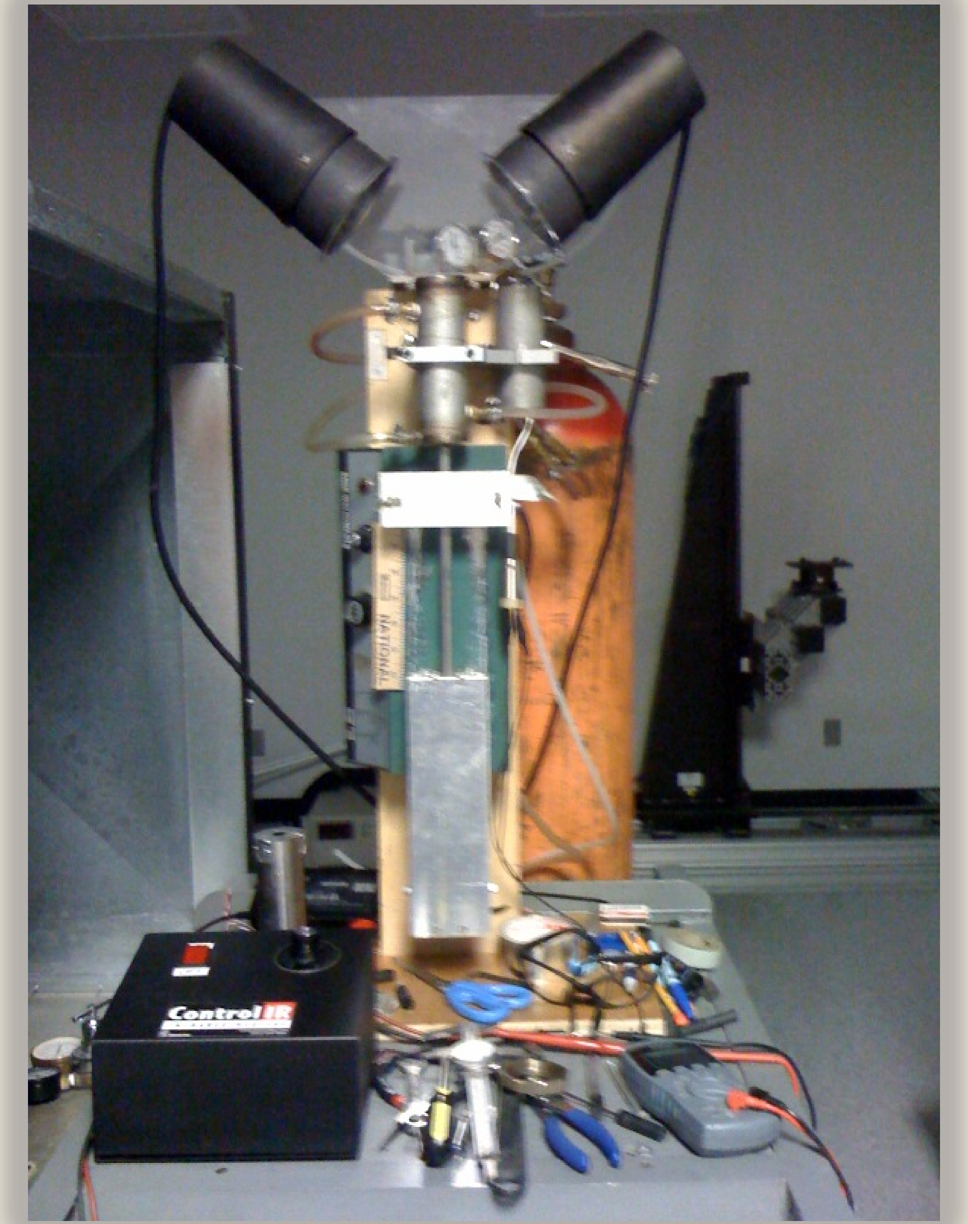
**Brauman, Chen, and Matzinger (BCM) (see References Cited) reported steady-state linear regression rates of vertical mounted polystyrene (PS) rods degrading under radiant heat exposure at the top end of the rod. Figure 1 shows a schematic drawing (after BCM) of a polymer rod mounted in a quartz confining sleeve with radiant heat exposure at the top. The regressing polymer surface was maintained level with the sleeve top end by a mechanical syringe pump. Radiant heat flux was generated by halogen lamp spot heaters and calibrated by substituting a calorimeter for the rod at the location of the rod top surface.**



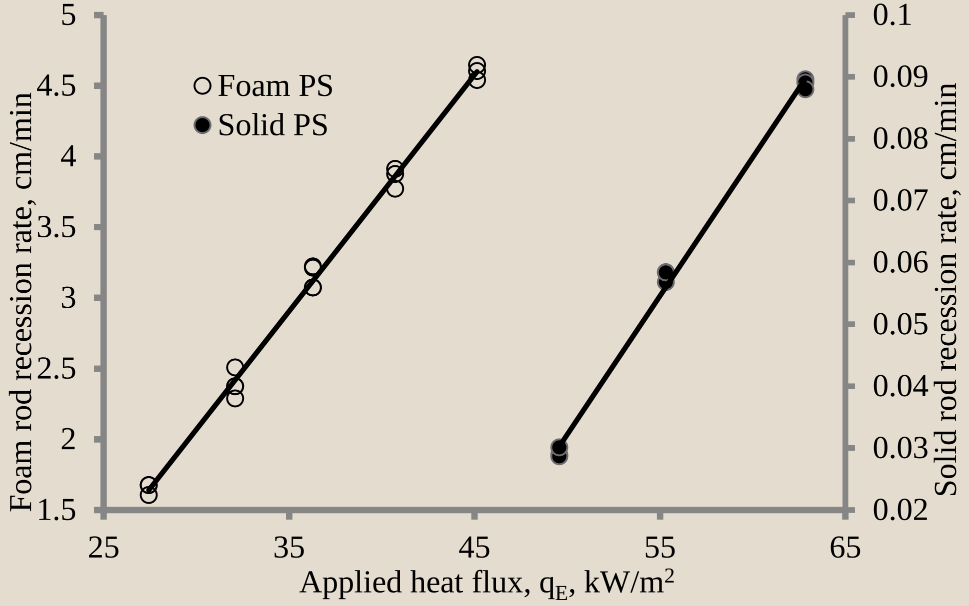
# University of Arkansas Experimental Measurements

We replicated the BCM apparatus to test polystyrene solid rods for direct comparison with polystyrene foam insulation rods. We tested custom-molded solid 1.2 cm ID PS rods for a range of applied fluxes of approximately 45 kW/m$^2$ to 65 kW/m$^2$ as reported by BCM. We verified their measured sample recession results with less than 5% differences.

We then tested foam PS rods of 1.2 cm ID, 15.24 cm length, cut from Dow Styrofoam® for an applied heat flux range of approximately 25 kW/m$^2$ to 45 kW/m$^2$ - **the reduction in magnitude of the input fluxes was necessitated due to the much faster rates of linear regression of the foam polystyrene compared to the solid rods (factor ~40 for the same applied heat flux).**



# University of Arkansas Experimental Measurements Verifying BCM Measurements for Solid/Foam Comparison




$\dot{m} = (q_E - q_L)/L_{PC}$

where $\dot{m}$ = mass flux, g/cm$^2$ s,

$q_E$ = external heat flux, J/cm$^2$ s,

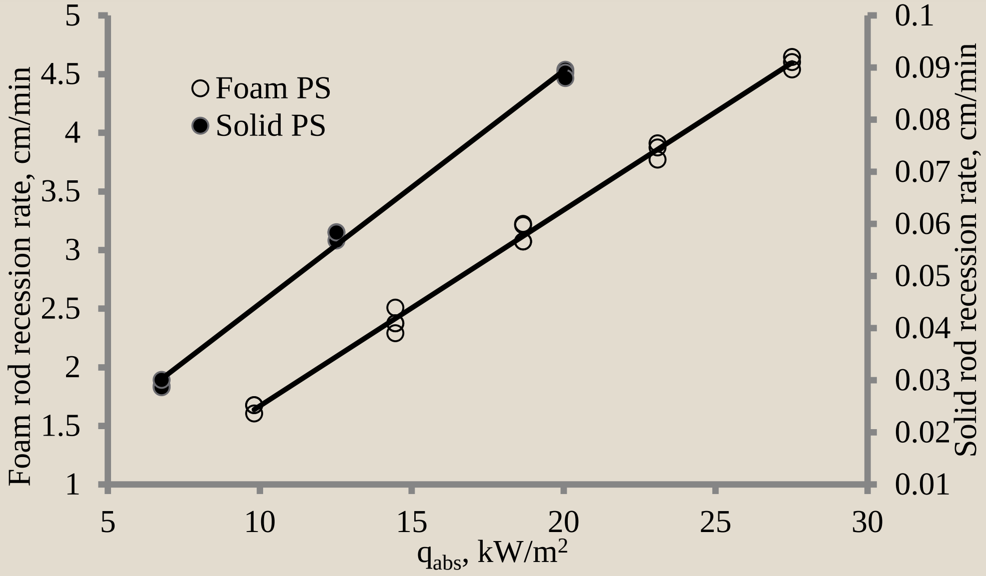
$q_L$ = heat flux lost, J/cm$^2$ s,

$L_{PC}$ = heat of phase change, J/g

Data indicates:

PS solid: $L_{PC}$ = 1282 J/g, $q_L$ = 42.7 kW/m$^2$

PS foam: $L_{PC}$ = 1352 J/g, $q_L$ = 17.6 kW/m$^2$




Data indicates recession rates in cm/min:

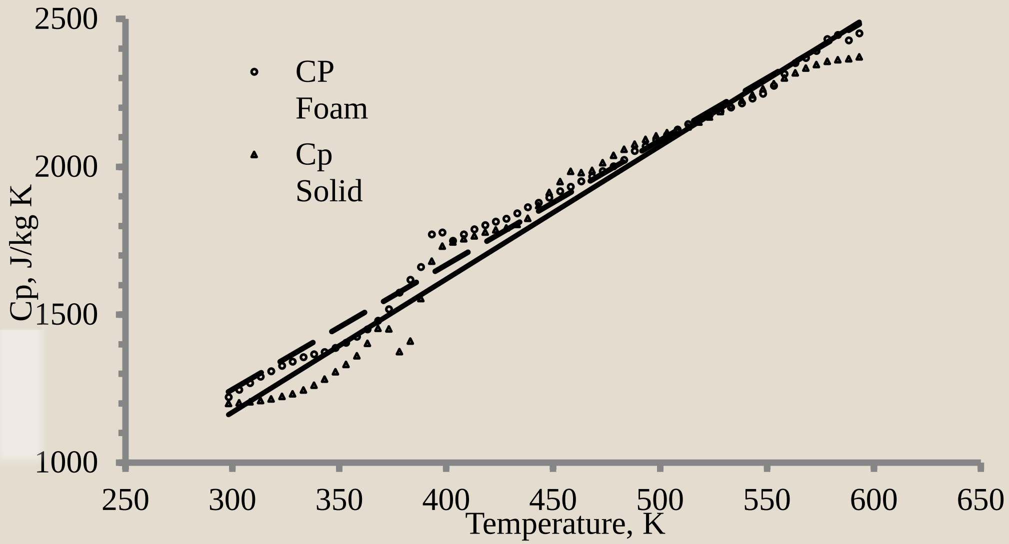
PS solid: 0.0045 $q_{abs}$

PS foam: 0.1672 $q_{abs}$

Ratio of the recession rates (per unit absorbed heat flux), ~37, is very close to our measured ratio of the densities of the materials (~40) – indicating that the failure rate largely reflects the melt/collapse of the foam structure.

# University of Arkansas Experimental Measurements

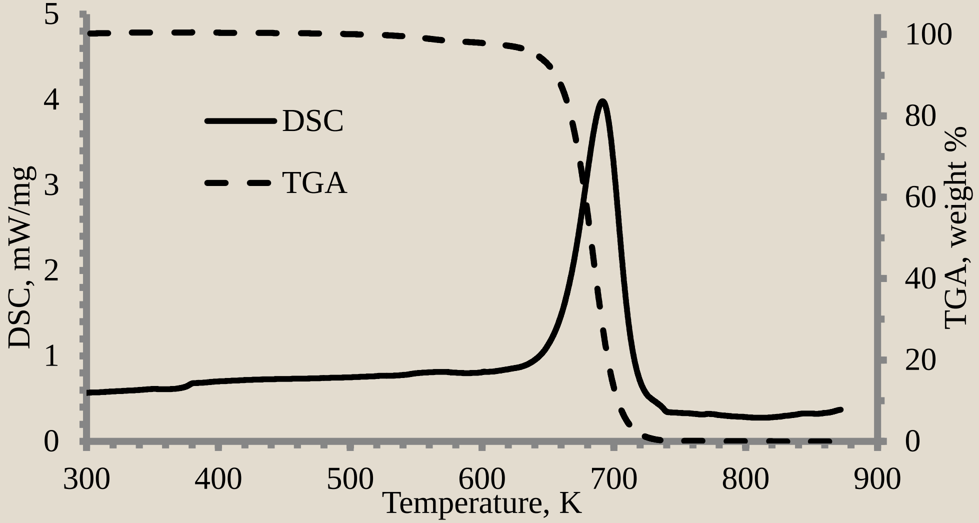
## Differential Scanning Calorimetric and Thermal Gravimetric Data for CFD Simulation




Specific heat capacities:

PS solid: $C_p = 4.50\ T - 180$, J/kg K
PS foam: $C_p = 4.22\ T - 18$, J/kg K

Similarity indicates factor ~ 40 in volumetric heat capacity is due largely to density difference

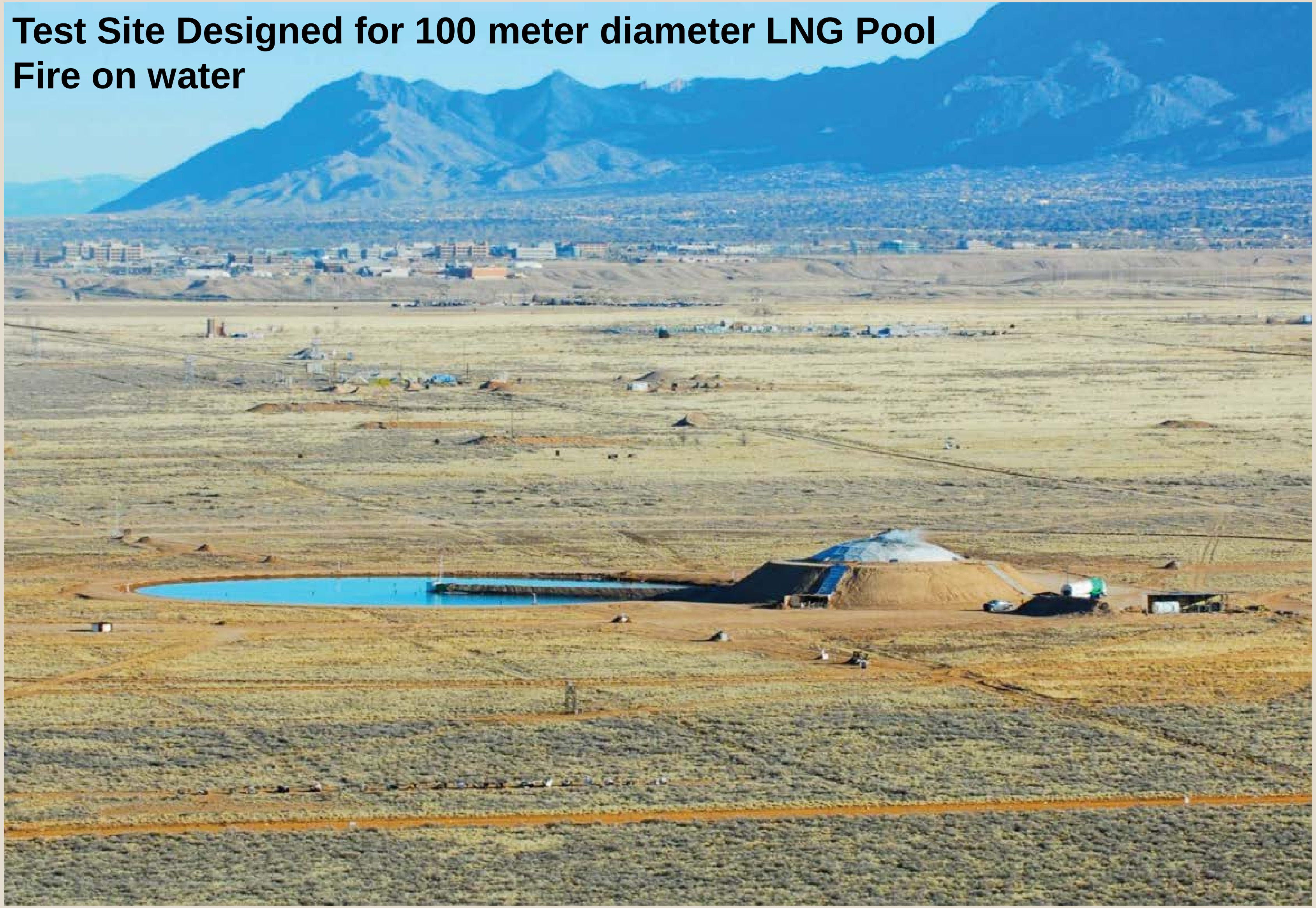



DSC measured Heats of Gasification, $L_{PC}$ (includes energy input necessary to heat material from 298 K to 720 K):

PS solid: $L_{PC} = 1399$ J/g
PS foam: $L_{PC} = 1561$ J/g

Reasonable agreement with Butler's data (10 – 15% higher)

# Sandia National Laboratory Fire Tests
# to determine large LNG fire (on water) surface emmisive power (SEP)



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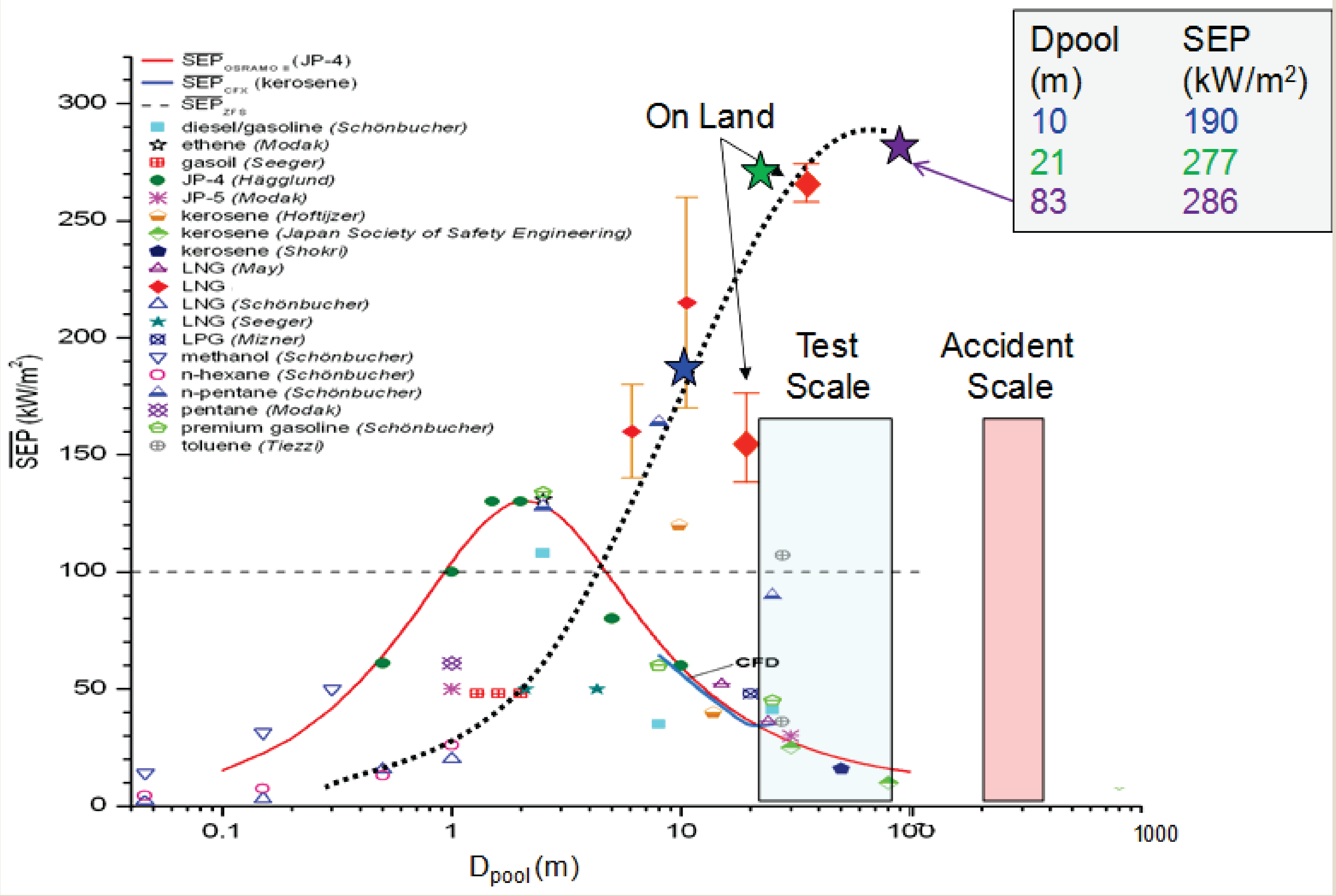

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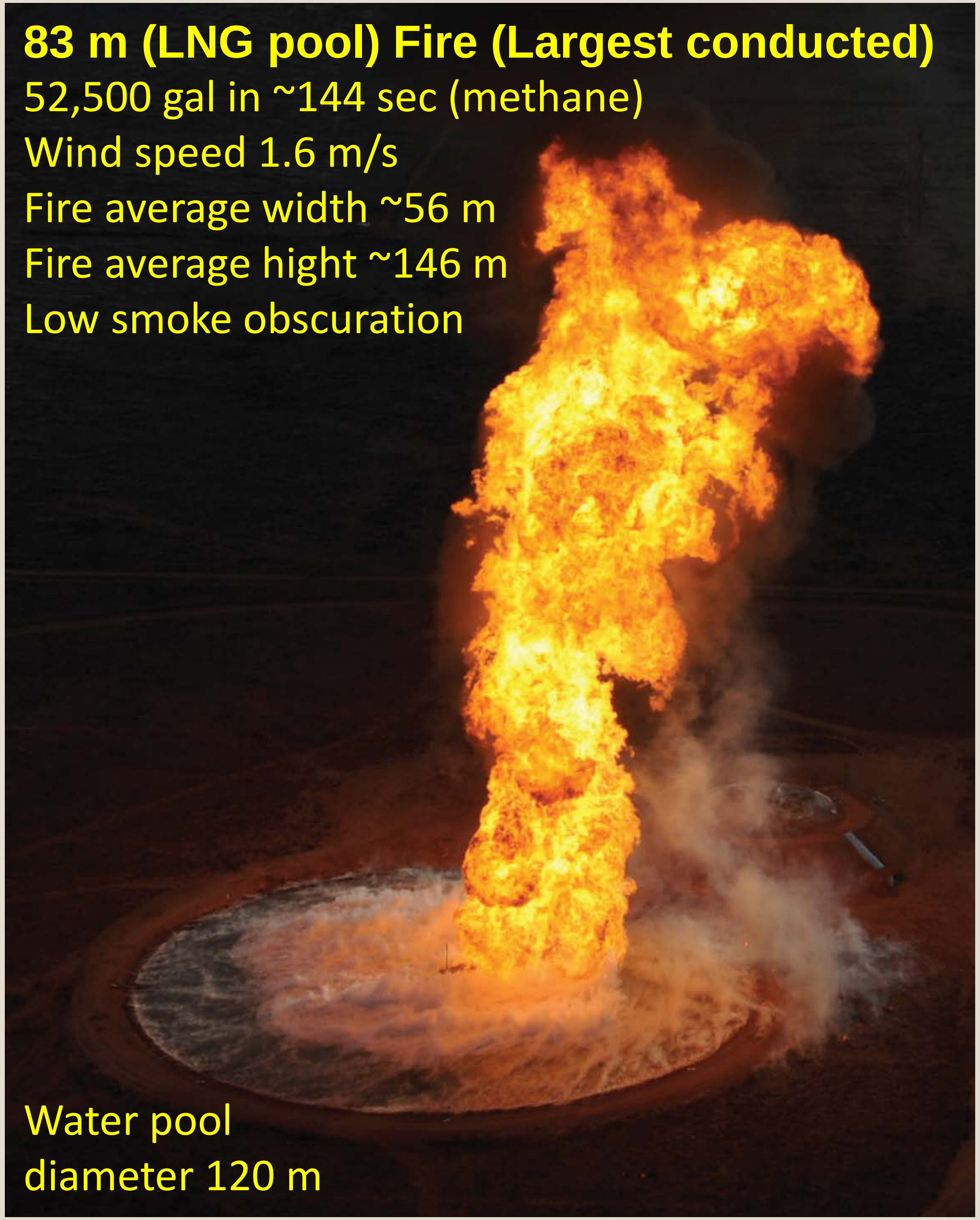



**Principal Observations Relevant to LNGC Insulation Experiments**

- **Fire diameter < Pool diameter**
- **Low smoke obscuration**
- **Data from these tests justifies use of an overall flame average SEP of 286+20 (2$\sigma$) kW/m$^2$**

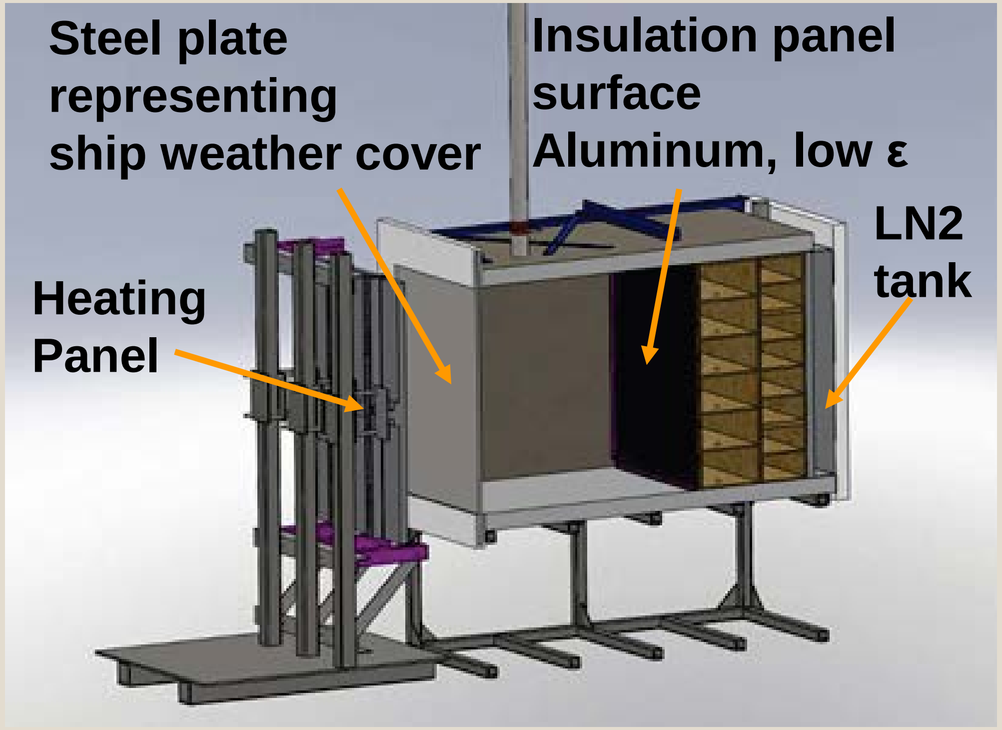
**Based on these observations, the insulation testing phase were designed to expose the "weather cover" surface covering the Moss insulation system to a radiative heat flux of 270 kW/m$^2$ for a period of 40 minutes, after which the heating lamps were turned off.**

**We now consider the Moss insulation system tests.**

# Sandia National Laboratory Insulation Test of Moss polystyrene insulation system

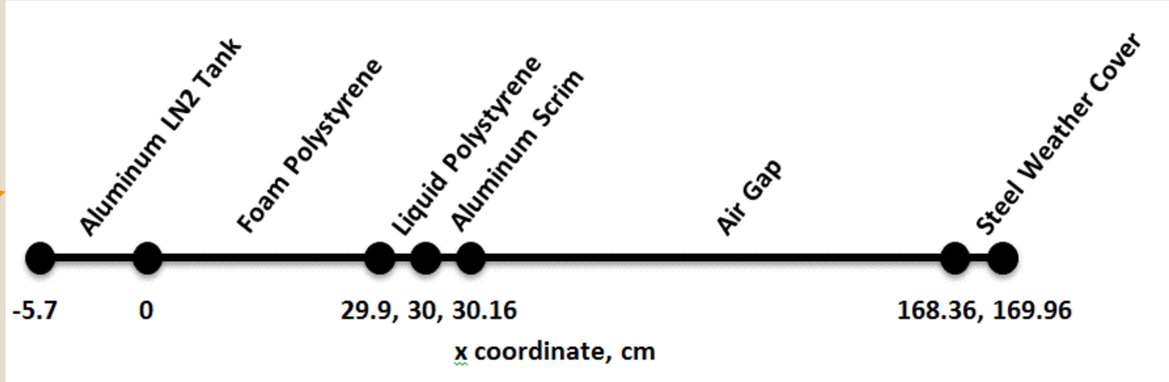
Heat lamps

Electrically-powered tungsten heat lamp panel – heating surface Is bare heat lamps - approx 1.4 $m^2$

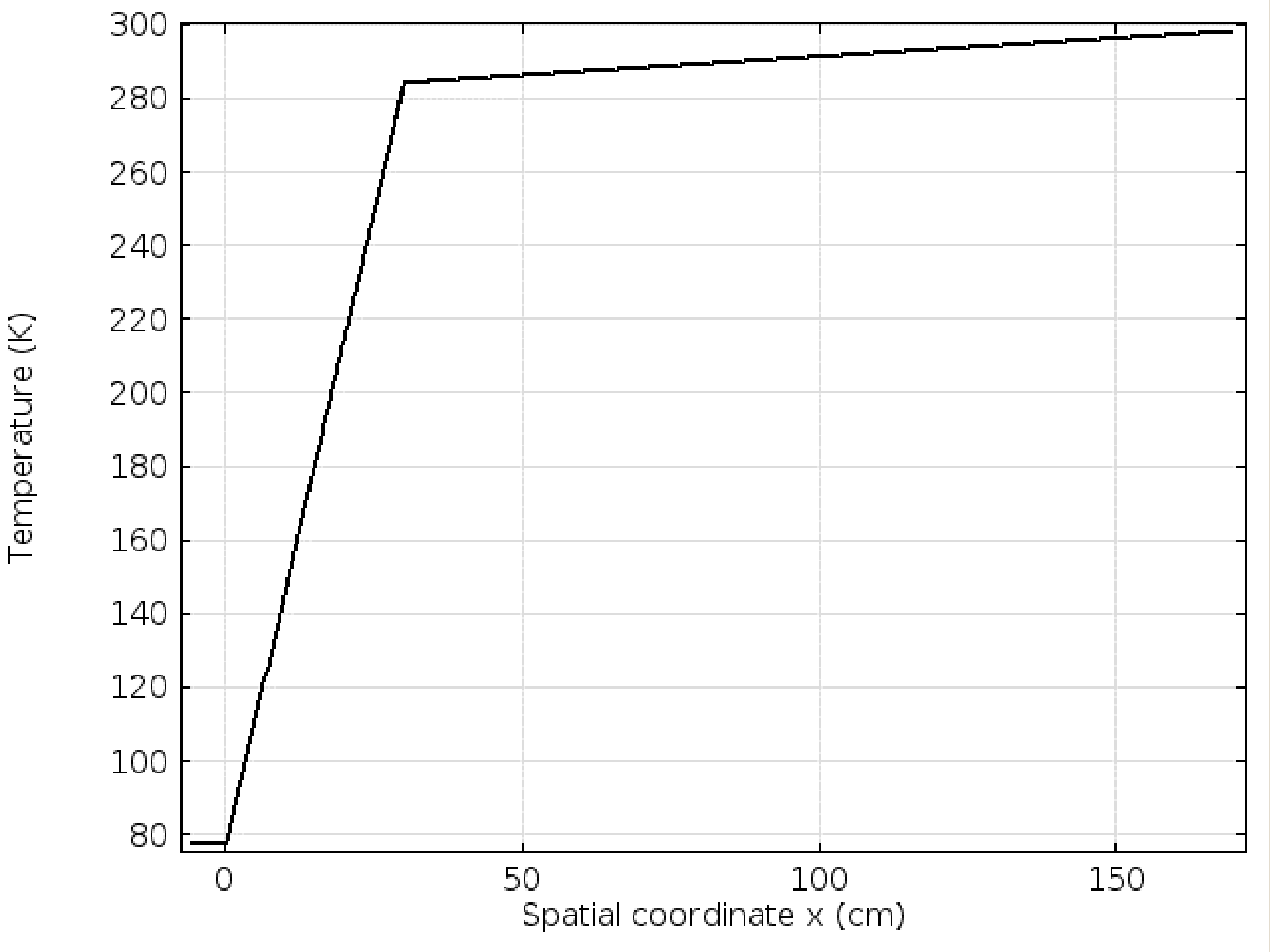



Cutaway view of heater/insulation assembly
Heat Flux applied to weather cover : 270 $kW/m^2$

Test assembly 1-D Model

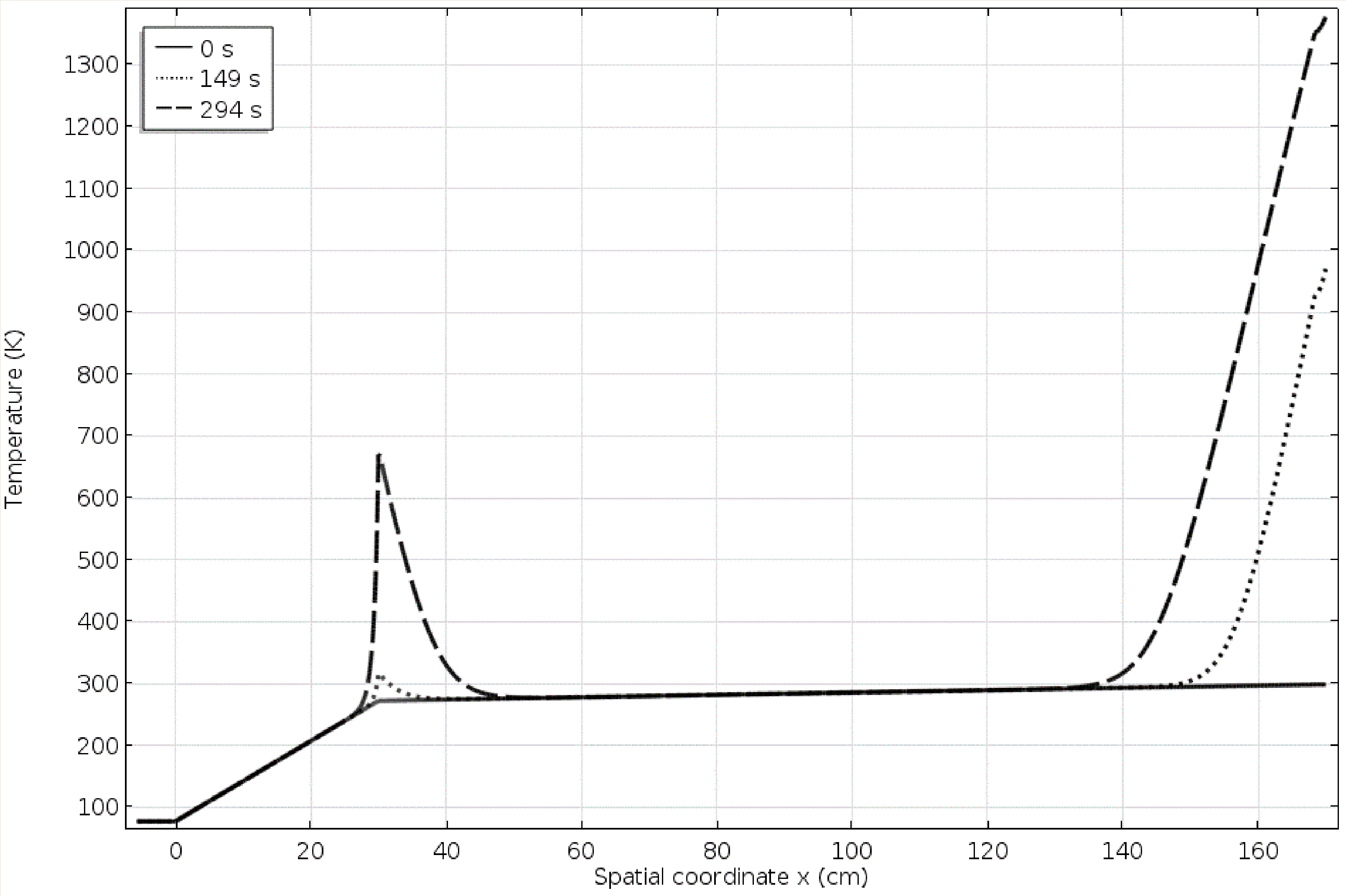


# COMSOL Model Predictions for Sandia Moss Insulation System Test



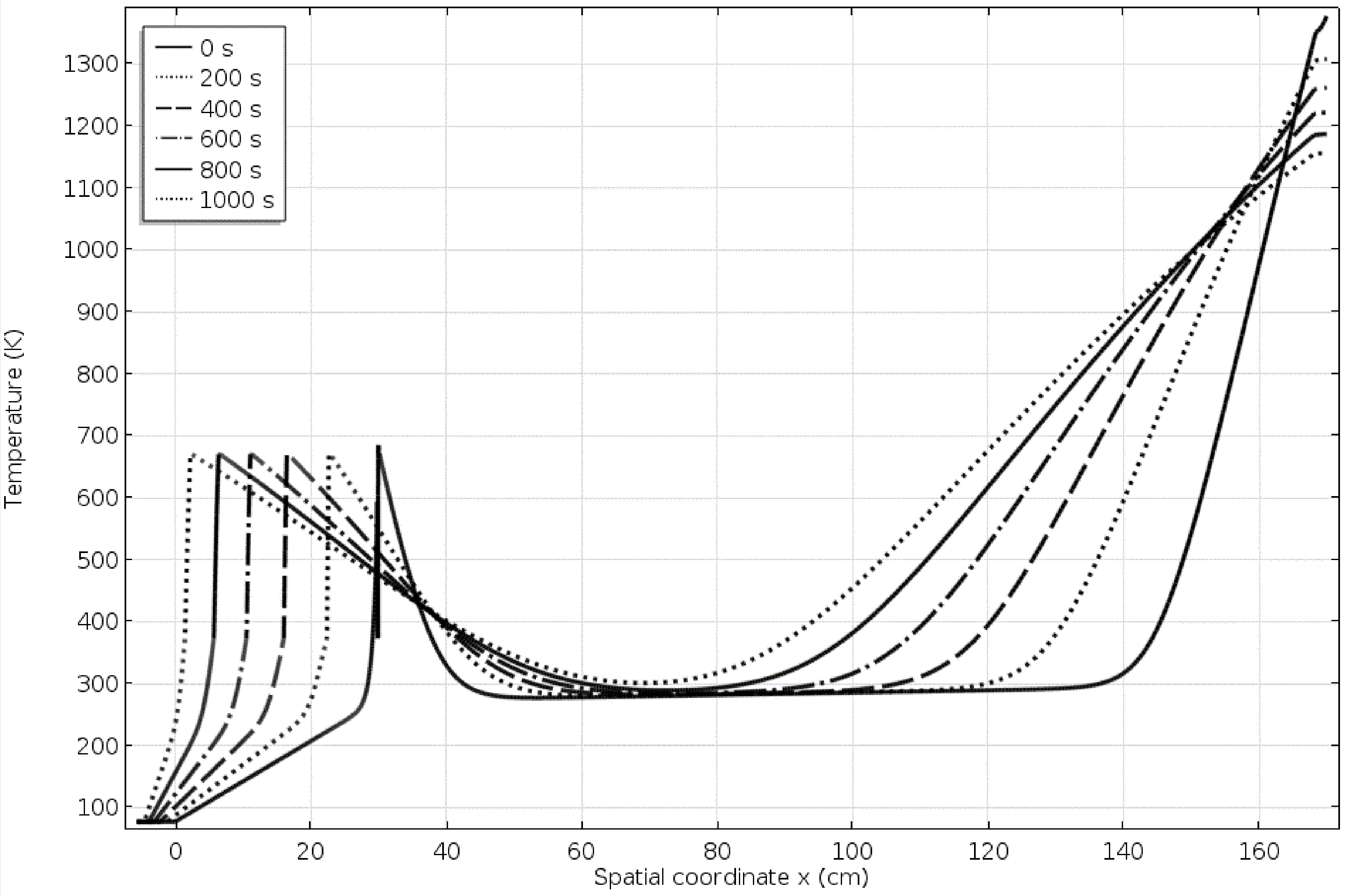

**Temperature Profile Before Radiant Heat Application**

# COMSOL Model Predictions for Sandia Moss Insulation System Test




**Temperature Profile beginning with Heat Application to beginning of Insulation Recession**

# COMSOL Model Predictions for Sandia Moss Insulation System Test



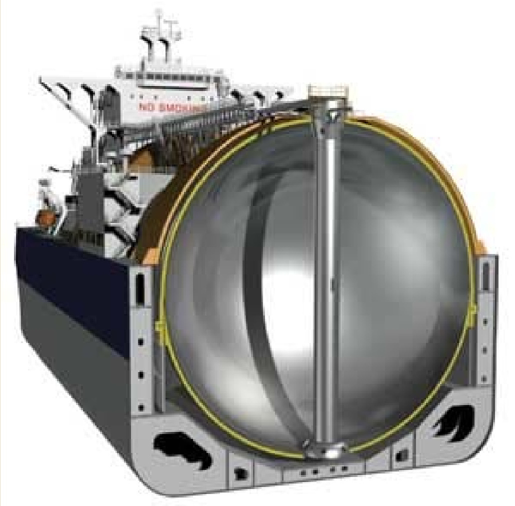

**Temperature profile during Period of Insulation Regression**

# Conclusions from Reported Sandia MossTest Results and Comparison with COMSOL Simulation

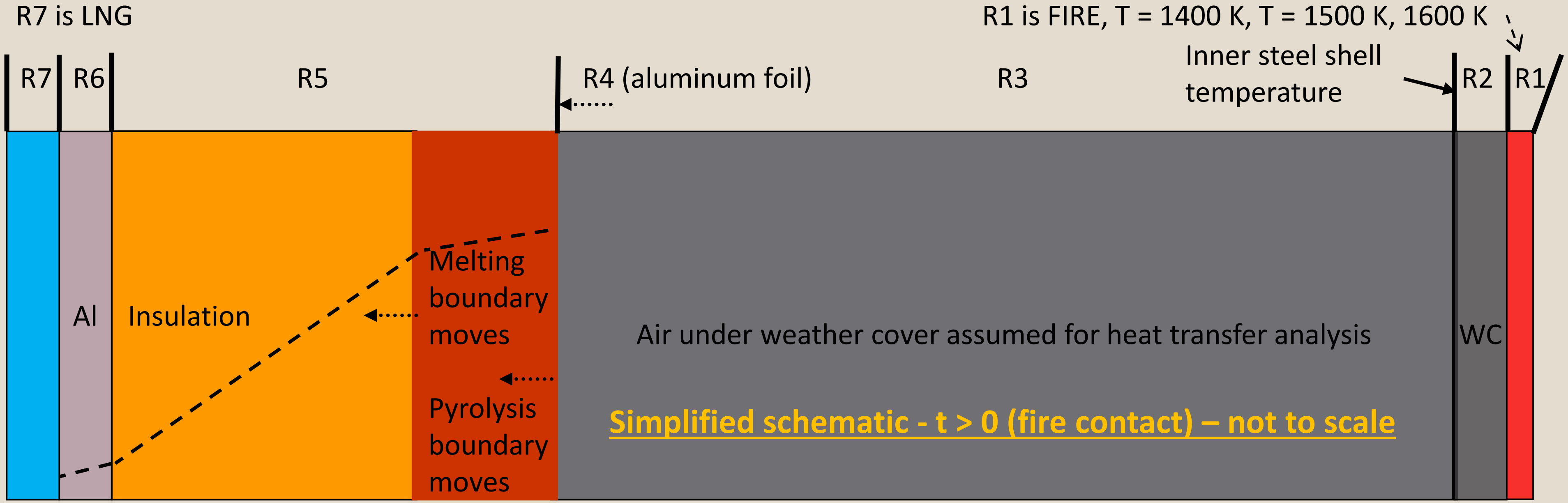
1. Sandia applied radiative flux of 270 $kW/m^2$ to the Moss panel surface for a period of forty minutes, after which the heat lamps were turned off and the assembly allowed to cool.
2. Sandia reported that the Moss panel tested completely failed (melted/decomposed) throughout its 30 cm thickness within the 40 minute period before the lamps were turned off. The exact time of the completed failure was not reported but other data summarized suggested it was nearly 40 minutes.
3. Sandia did not specify the emissivity of the aluminum covering of the Moss System. The University of Arkansas requested that information for use in our simulations of the test, but Sandia stated the information was proprietary.
4. All other information required for our simulations (excepting the aluminum emmisivity) was available to us, so we used a value of emissivity of 0.02 from the literature represented to be the lowest aluminum foil emissivity commercially available. We obtained values of the times to failure using emissivities of 0.02 (best commercially available), 0.1, and 0.2 (values representing surfaces with normal contamination due to age and usage (contaminant accumulation). If the aluminum surface fails structurally for any reason, soot contamination of the surface, or absence (by melting) is likely to raise the emissivity of the surface of the insulation panel to much higher values. The following failure times were computed:

   Emmissivity/Failure Time — 0.02 / ~52 min — 0.1 / ~22.5 min — 0.2 / ~20 min
5. While our predictions of the failure time with different emmisivities are consistent with our expectations, we cannot further verify the model without specification of the emissivity.
6. The low emissivity of the as-installed system is the primary determinant of the time to failure. If the highly reflective foil, which is very thin, with very little structural strength, is damaged so as to lose its high reflectivity, the failure rate of the foam will dramatically increase.

# Modeling Heat Transfer and Insulation Failure Rate
# 1-D section of Moss Sphere Above Deck




| Zone | Thickness (m) | Density (kg/m³) | Heat Capacity (J/kg K) | Thermal Conductivity (W/m K) | Emissivity |
|---|---|---|---|---|---|
| R2 | 0.015 | 7850 | 475 | 44.5 | 1.0 |
| R3 | 1.0 | COMSOL | COMSOL | COMSOL | NA |
| R4 | 0.0003 | 2700 | 900 | 70 | 0.1, 0.2 |
| R5 | 0.30 | 26.5 | (Figure 4) | 0.038 | NA |
| R6 | 0.02 | 2700 | 904 | 70 | NA |



# Modeling Heat Transfer and Insulation Failure Rate
# 1-D section of Moss Sphere Above Deck

| Temperature (K) | Emissivity (dimensionless) | Heatup Time (seconds) | Failure Time (seconds) | Total Failure Time (minutes) |
|---|---|---|---|---|
| 1400 | 0.1 | 234 | 785 | 17 |
| 1400 | 0.2 | 190 | 492 | 11.4 |
| 1500 | 0.1 | 187 | 595 | 13 |
| 1500 | 0.2 | 153 | 380 | 8.9 |
| 1600 | 0.1 | 153 | 465 | 10.3 |
| 1600 | 0.2 | 125 | 300 | 7.1 |

**The fire temperatures assumed run from lower-than to higher-than those that would exhibit surface emissive powers of 270 kW/m$^2$ observed in the Sandia tests (assuming optically thick flames with emissivity of 1.0). The 270 kW/m$^2$ value would correspond roughly with the 1500 K temperature. The message here is that the low emissivity of the thin aluminum covering of the foam provides the only protection from early <u>complete</u> failure of the insulation. Even with operative emissivity of 0.1, PS foam insulation will completely fail to insulate the cargo in time periods less than 17 minutes.**

**<u>Such time periods are well within the fire-on-water durations cited by Sandia for rapid ½ tank spills on water.</u>**

# Conclusions

The order 10-minute times for complete insulation failure are well within the fire duration times suggested in the Sandia 2004 and subsequent reports.

The temperatures indicated to result in the cargo system signal additional concerns for cascading damage to a Moss-Sphere tank system:

- Structural instability of the weather cover and tank supports.
- Vulnerability of the aluminum foil - loss of support or attachment and potential pressurization below by gasification of the insulation - suggests it is unlikely that the foil could maintain the relatively low effective values of emissivity typically assumed.
- The potential for explosion in the space under the weather cover should not be neglected; our measurements and predictions indicate that significant vaporization of the polystyrene could occur, resulting in flammable gas concentrations under the weather cover if the inerting protection was compromised. The temperature of the air (or inert-gas) nearest the weather cover exceeds the autoignition temperature of styrene monomer (~760 K), as does the inside surface of the weather cover. The flammability limits of styrene monomer (1.2 – 7.1%) suggest that even minimal pyrolysis of the foam (~ 1%) could pose an explosion hazard if the inerting system is not operational.

# Conclusions (continued)

While Sandia stated that the fluxes to the LN2 rose to maximum values that would not endanger the tanks by overpressure, it is our understanding that the heat lamps were turned off at 40 minutes. The report stated that the 40 minute duration was based on the latest information on large scale spills and fires as determined by Sandia. The important point raised is that if the actual melting time is demonstrated to be significantly less than 40 minutes, the question regarding the pressures that could be achieved by continued heating by the fire remains… Havens and Venart estimated heat fluxes into the cargo, assuming total loss of insulation, could reach ~135 $kW/m^2$ with a fire temperature of 1500 K. While accurate estimation of the heat absorption by the cargo following insulation failure is beyond the scope of this paper, we continue to believe that such conditions have the potential to exceed the capability of the pressure-relief systems provided.

As indicated in Havens and Venart, 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 that criterion.

The Sandia Test Results indicate that LNG fire SEP values importantly exceed those resulting from previous hydrocarbon based fire tests. The SIGTTO recommendation that if LNG fire tests show significant conflict with existing values of heat flux used in the IGC code and other industry codes and standards, the question of the current equations for determining fire-case pressure relief loads merit reexamination by the whole LNG industry and not just the shipping element. We agree.

# Acknowledgements and References Cited

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**SIGTTO Report, http://www.sigtto.org/media/7203/report-on-the-effects-of-fire-lng-containment-systems.pdf**

**Questions ?**