ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

BAM Bundesanstalt für Materialforschung und -prüfung

Sicherheit in Technik und Chemie

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CRYOGENIC LIQUID HYDROGEN TANKS WITH MULTILAYER INSULATION EXPOSED TO FIRE

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Cryogenic fluids

- Cryogenic Fuels as LH2 or LNG are important on the way to the energy transition
- The behavior of cryo vessesls in accidents and the consequences are less understood because of few accidents and experiments

[Kaw22]

[NAS22]

[Ive17]]

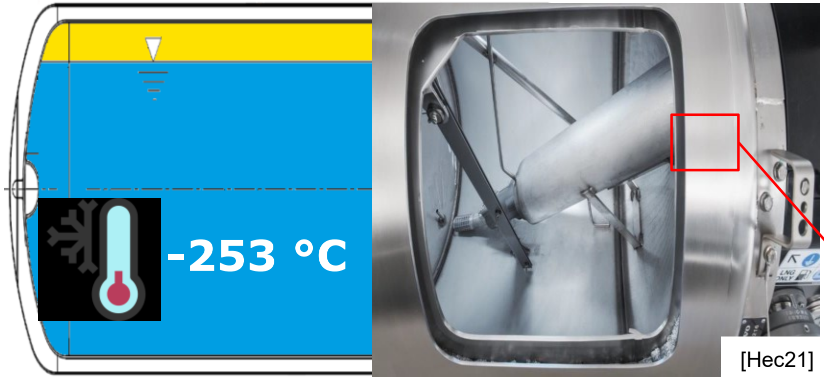
The Zarzalico accident
Spain 2011

[Pla15]

[Air23]

Super insulation systems for LH_2 tanks

Heat transper reduction by { conduction, convection, Radiation } → Vacuum + Radiation barrier



[Hec21]

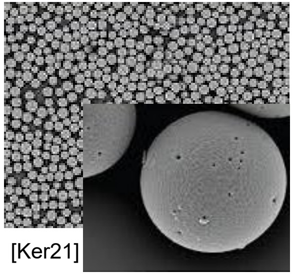
Perlite


[Kra16]

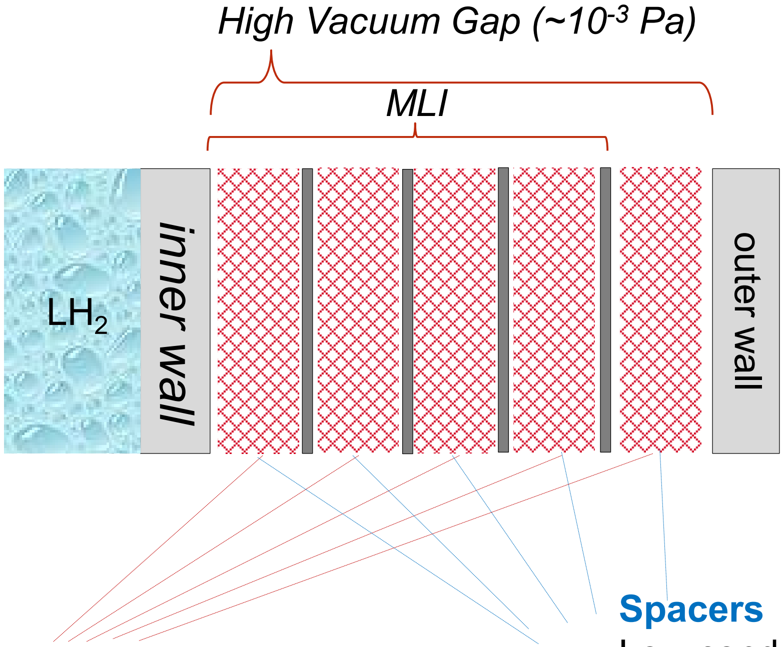
Multi-Layer Insulation (MLI)


[Cos22]

Microspheres


[Ker21]

Multi-Layer Insulation (MLI) systems
Attractive for tanks in which space and weight are limited



Radiative layers
Low emissivity material
(aluminium or aluminium-coated polyester)

Spacers
Low conductivity material with high void fraction made from non-woven polyester or glass fibers

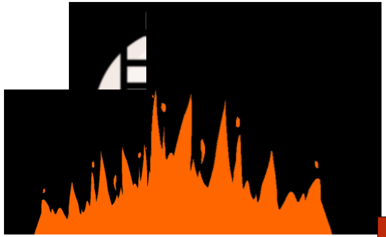
MLI systems ensure:
- High insulation (heat leak ~1 W/m^2)
- Small space requirements (~1÷4 cm)
- Lightness (~1 kg/m^2)

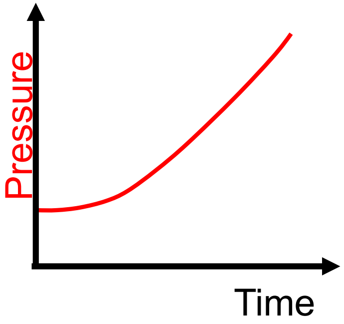
Applications:
- Laboratory tanks (< 1 m^3),
- Truck tanks (< 1 m^3)
- Road tanker (< 70 m^3)
- Ships (< 1250 m^3)

[Cos22]

Cryogenic tanks equipped with MLI exposed to fire may FAIL under FIRE exposure

Fire exposure





Tank failure

SH_2IFT EU Project [Win22]

BLEVE

Fireball

Fragments

Why does the tank fail if it is insulated?

The characterization of this kind of scenarios is paramount to ensure LH_2 safety

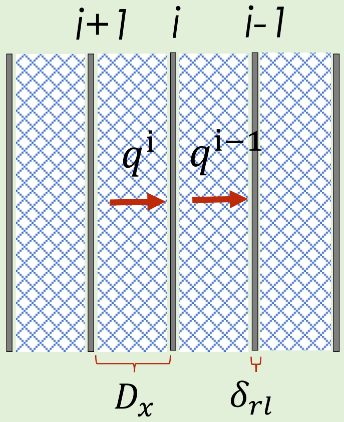
Methodological approach

Testing MLI behaviour in fire-like conditions

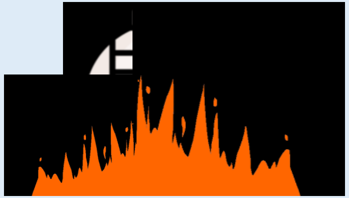
Data on degradation

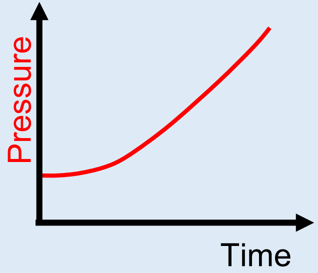
Validation

Developing of heat transfer / thermal degradation models

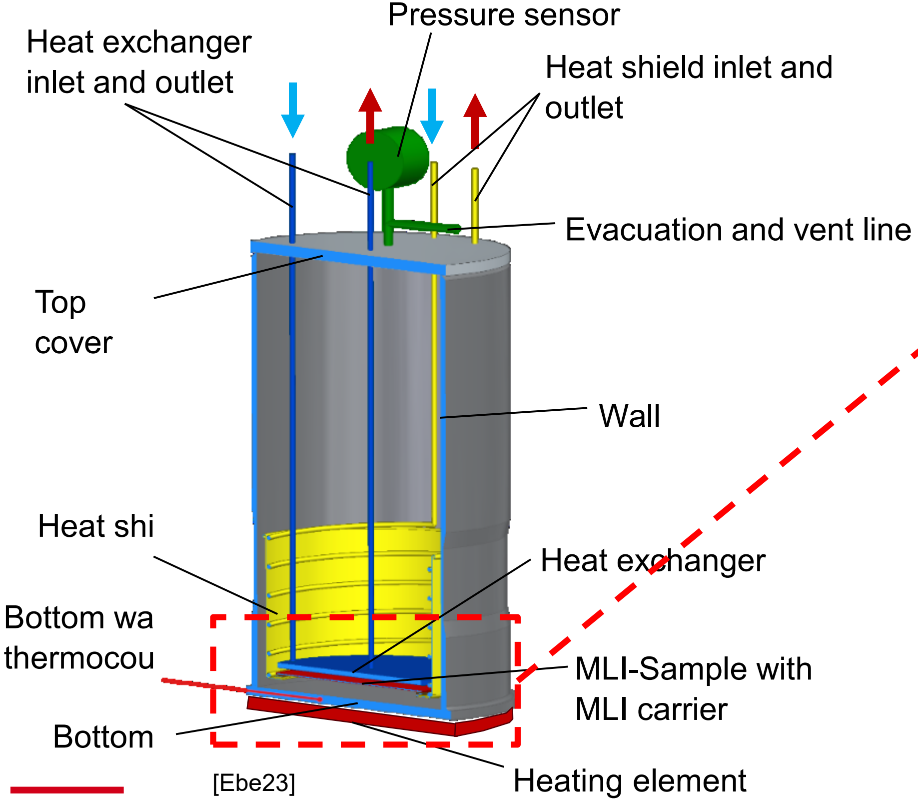


Developing a model for tank behaviour under fire attack



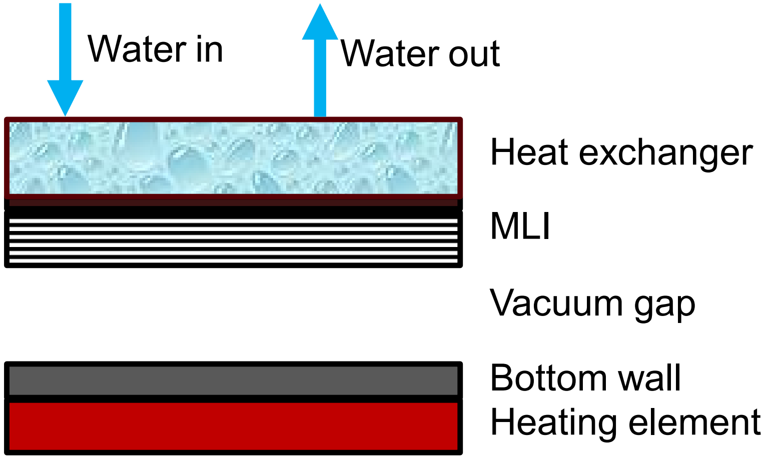


Testing MLI behaviour at high temperature

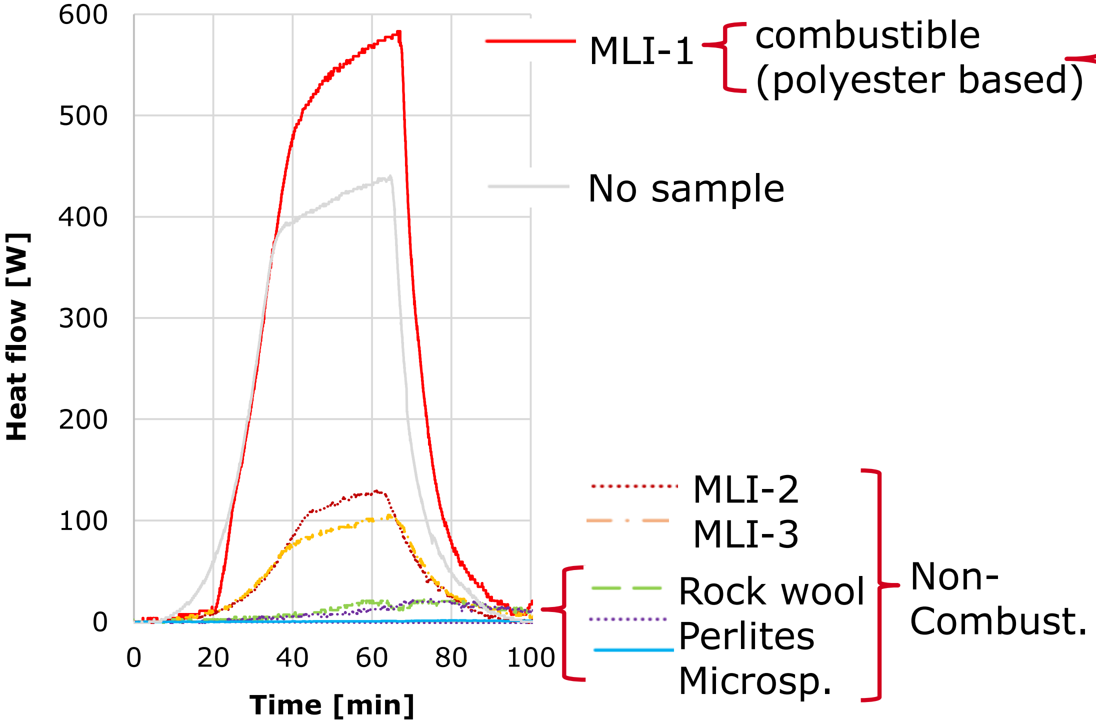


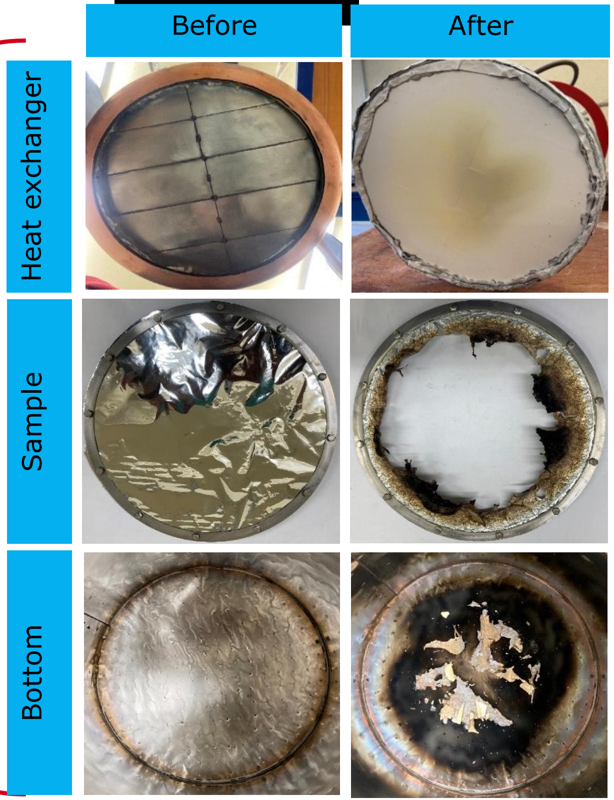
[Ebe23]

- vacuum conditions up to 10 Pa
- maximum wall temperature of 850 °C

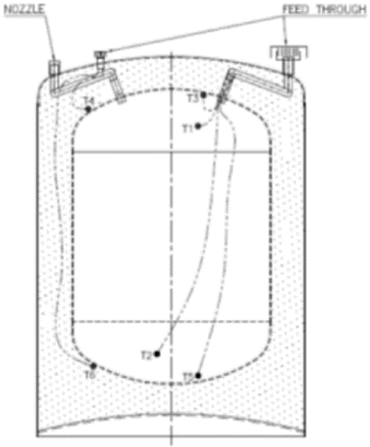


Experimental Results

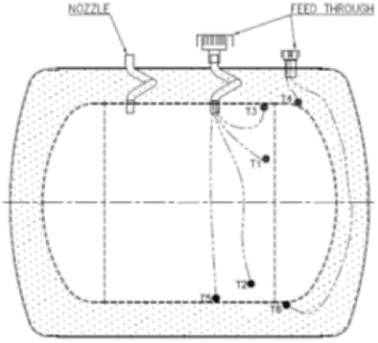




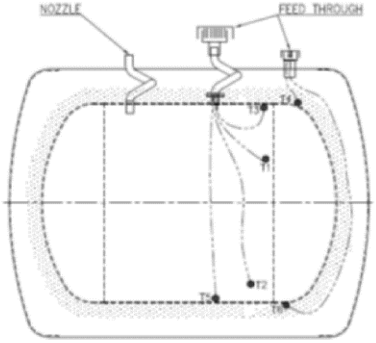
Fire tests with tanks for LH_2 within the SH_2IFT pro



Perlite + vacuum (vertical)



Perlite + vacuum (horizontal)



MLI + vacuum (horizontal)

[Win22]

Heat transfer modelling

The heat transfer model is based on the “**Layer by layer**” approach proposed by McIntosh in 1994 [McI1994]

1-D heat balance to the i-th radiative layer

$$\rho_{rl}\delta_{rl}c_{p,rl}\frac{dT_i}{dt} = q_i - q_{i-1}$$

3 heat transfer mechanisms considered

$$q^i = q^i_{rad} + q^i_{s,cond} + q^i_{g,cond}$$

Layer to layer radiation

$$q^i_{rad} = \frac{\sigma}{\left(\frac{2}{\varepsilon_i} - 1\right)}\left(T^4_{i+1} - T^4_i\right)$$

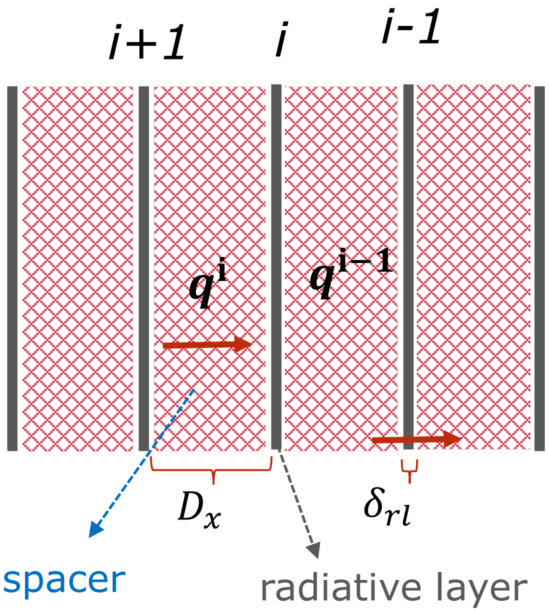
Spacer conduction

$$q^i_{s,cond} = \frac{C_2 f k_s}{D_x}\left(T_{i+1} - T_i\right)$$

Gas conduction

$$q^i_{g,cond} = C_1 P\theta\left(T_{i+1} - T_i\right)$$

MLI system



Thermal degradation model for polyester based MLI

BAM

Based on apparent kinetics of degradation

$$\frac{dY_{s,i}}{dt} = -A\,exp\left(-\frac{E_a}{RT_i}\right)\left(Y_{s,i}\right)^n$$

A, E_a, n obtained by TG analysis

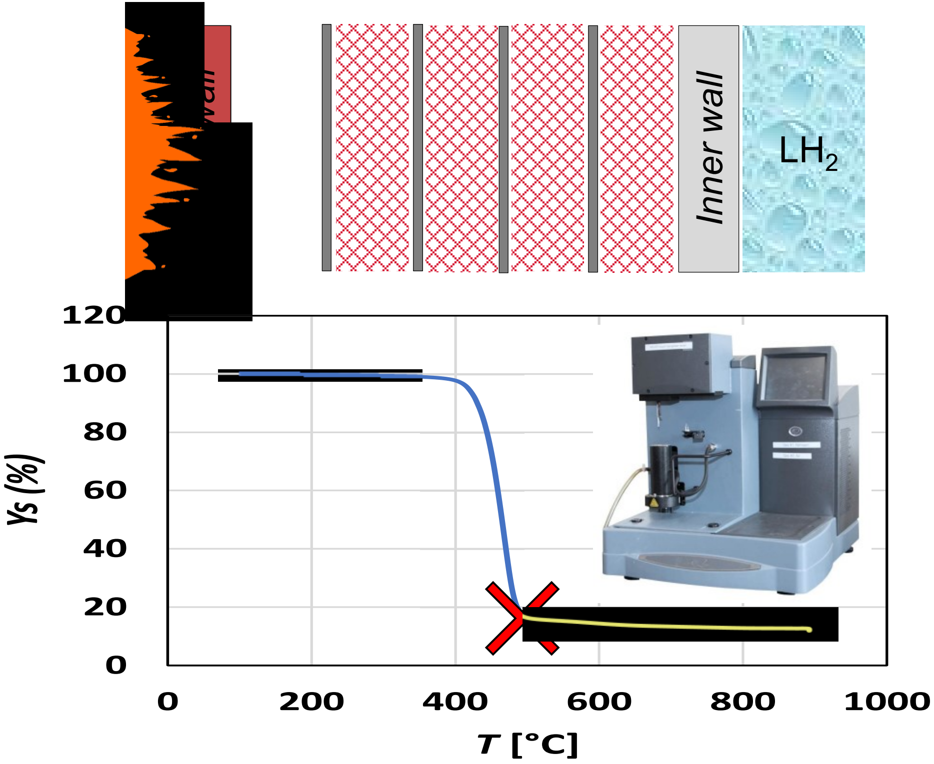
$$Y_{s,i} = \frac{m_i}{m_0}$$

$$Y_{s,i}(0) = 1$$

$\delta_{rl,i}(Y_{s,i}) = \delta_{rl,0} \cdot Y_{s,i}$ **Layer thickness**

$f_i(Y_{s,i}) = f_0 \cdot Y_{s,i}$ **Spacer solid density**

When $Y_{s,i} = Y_{s,T}$ → the i-th layer is removed



Thermal degradation model for aluminum based MLI

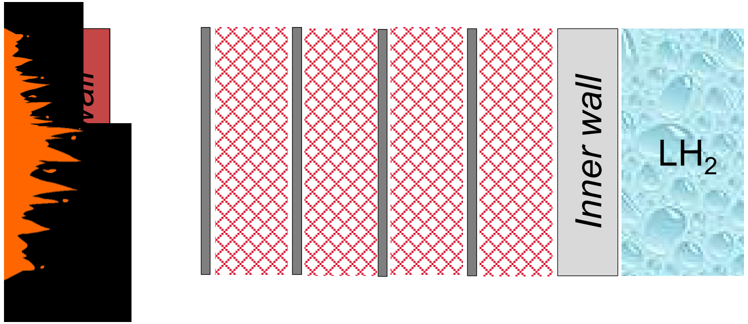
Based on the melting point of aluminium layers

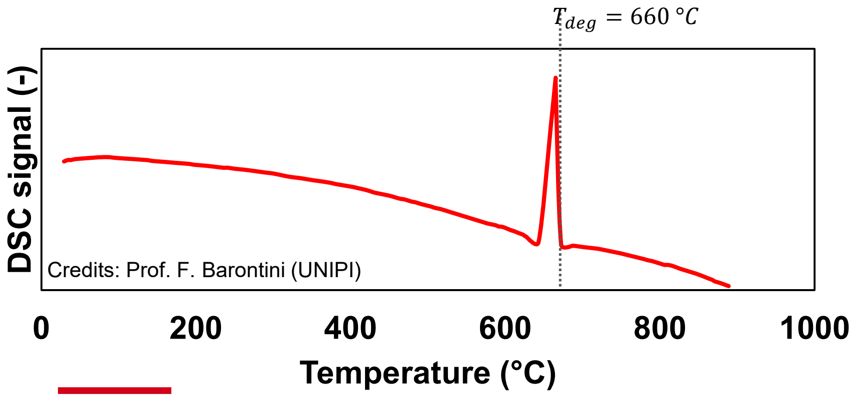
$$\rho_{rl}\delta_{rl}c_{p,rl}\frac{dT_i}{dt} = q_i - q_{i-1}$$

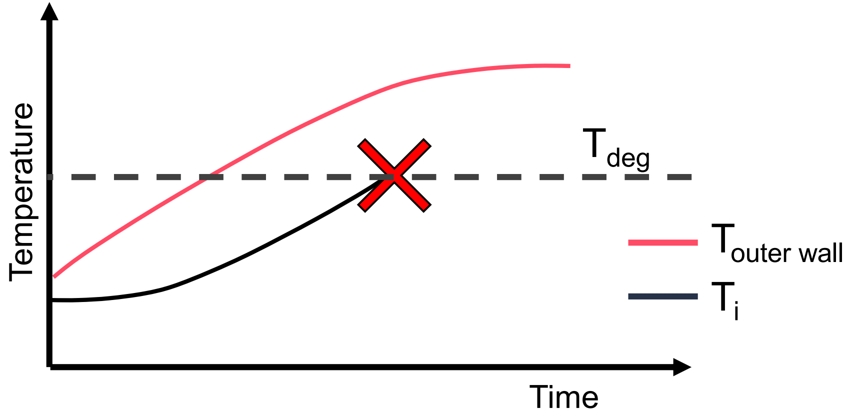
When $T_i = T_{deg}$ → the i-th layer is removed

$$T_{deg} = 660°C$$

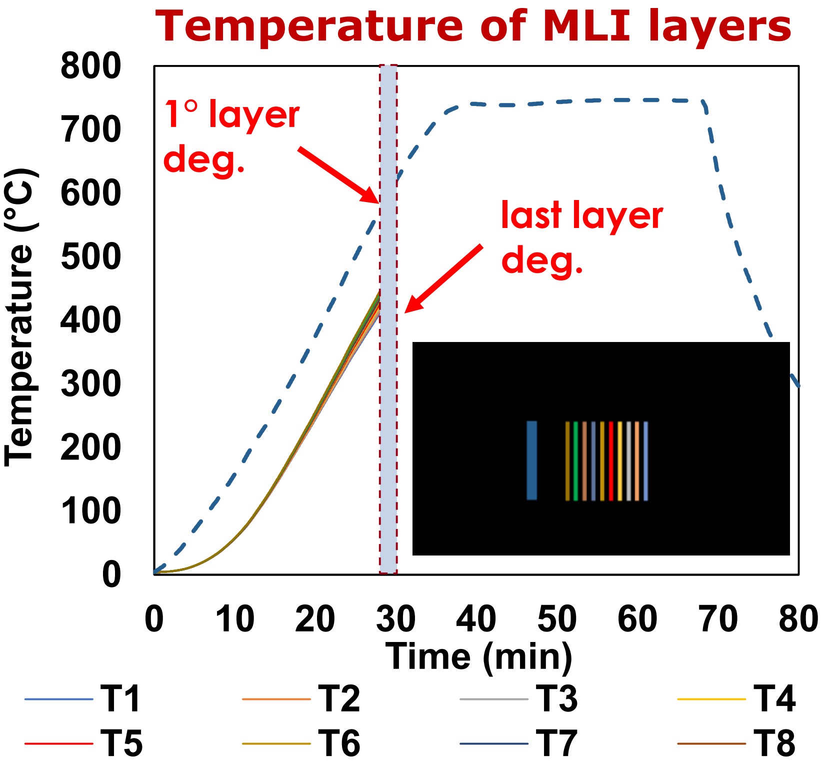
(melting point of aluminum layers from DSC analysis)

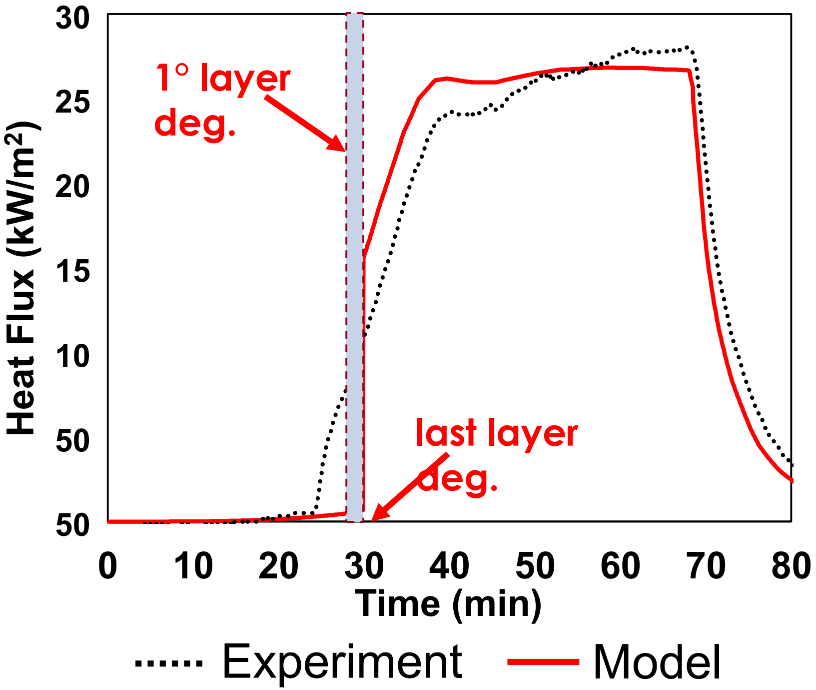




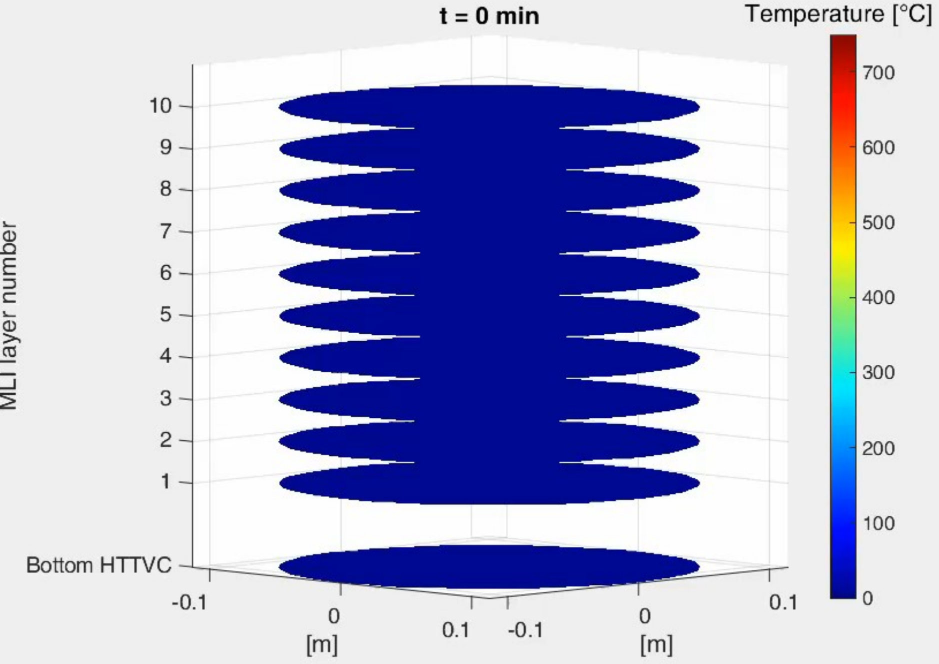


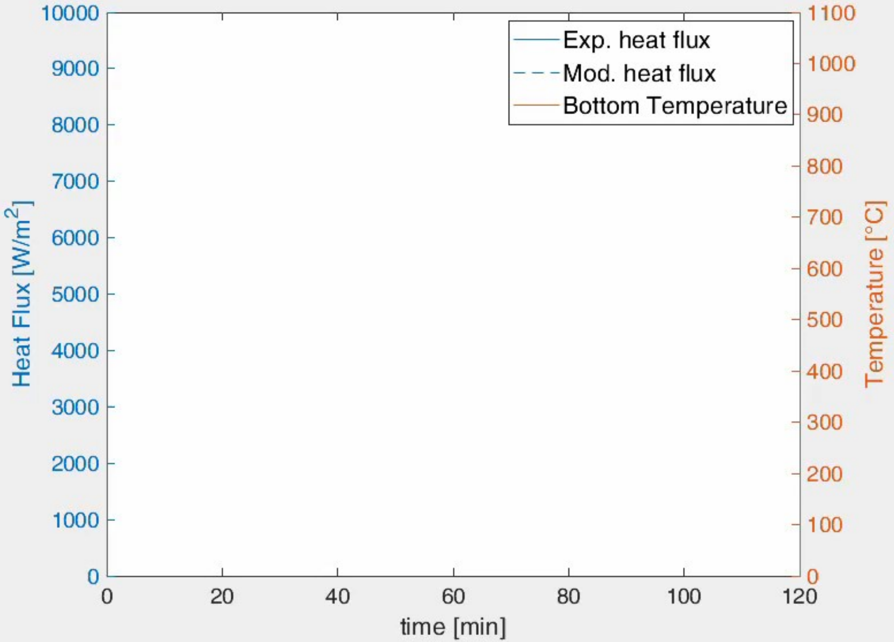
Model validation for polyester based MLI





Model validation for aluminum based MLI

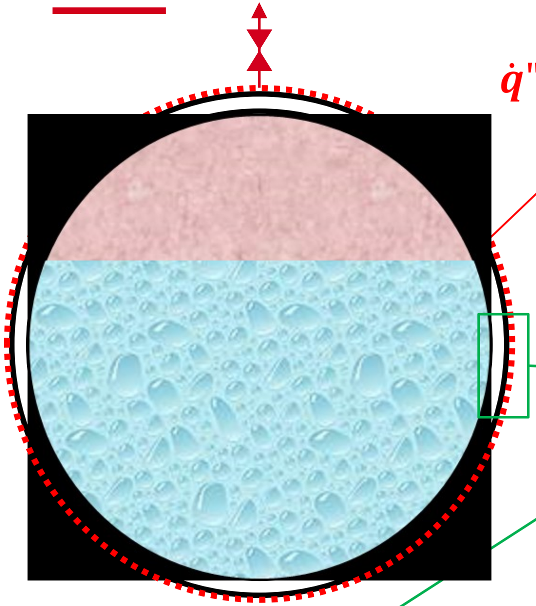




Note: results refer to a 2D simulation

Lumped model for the simulation of tank behaviour under fire attack model

$$\dot{q}'' = \sigma\varepsilon_w\left(T_F^4 - T_{w,out}^4\right) + h\left(T_F - T_{wout}\right)$$

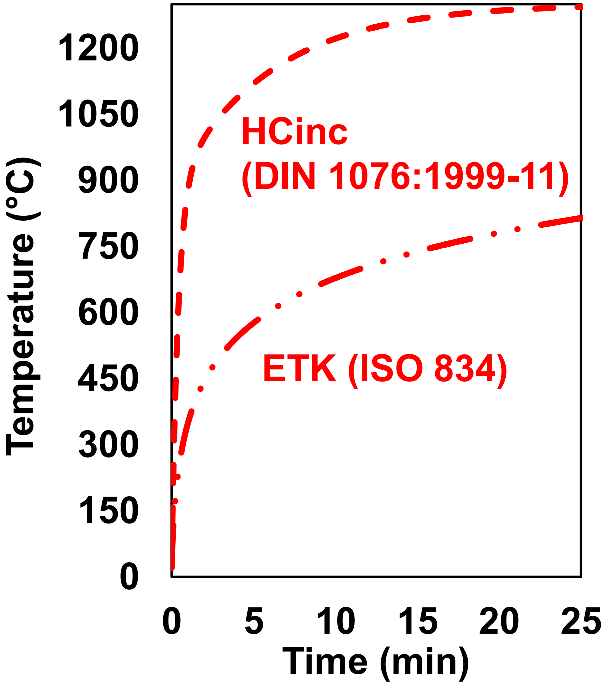


MLI degradation model

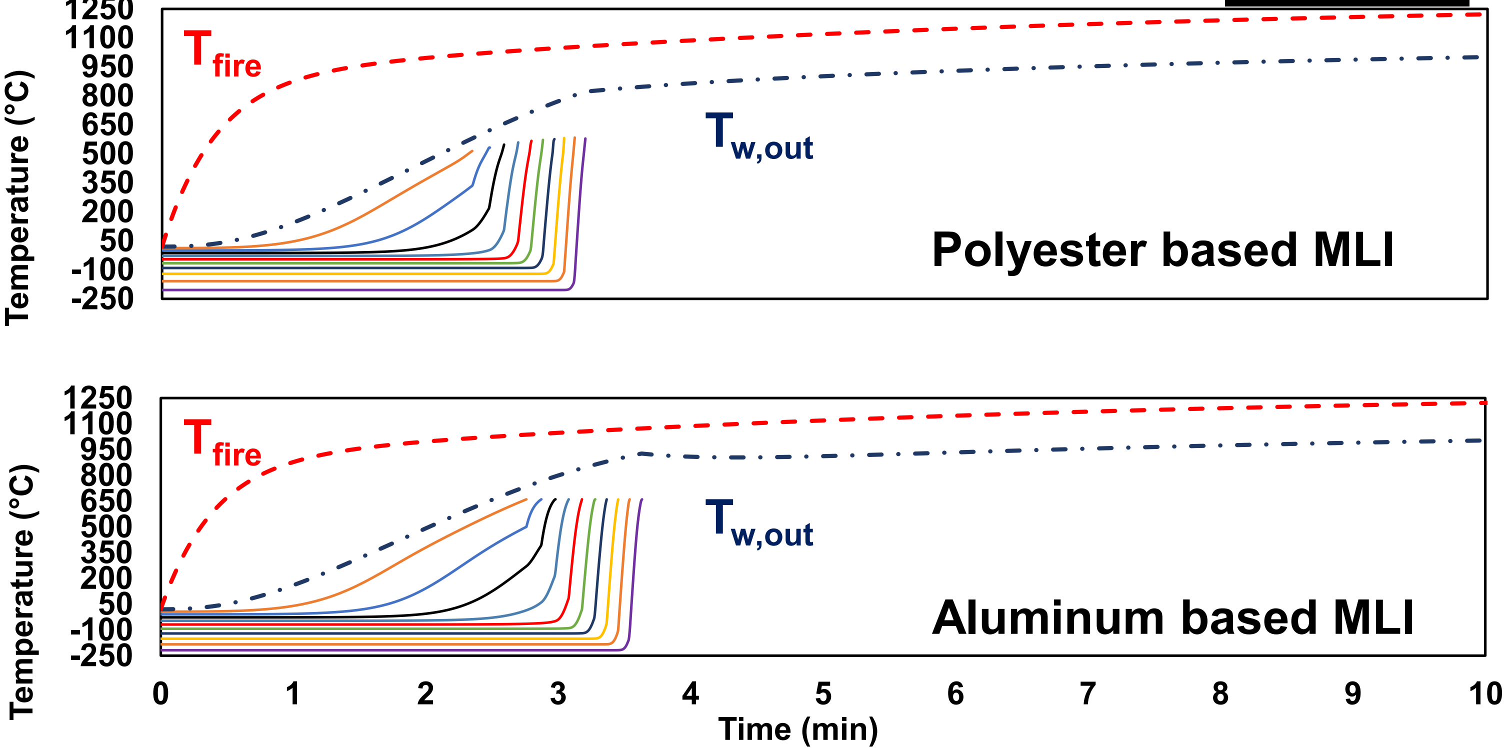
$$\frac{dU}{dt} = Ah\left(T_{w,in} - T\right) - \phi \dot{m}_{PRV}\widehat{H}_{PRV}$$

Tank parameters	
Diameter	0.6 m
Length	1.2 m
Volume	0.31 m^3
Filling	80 %

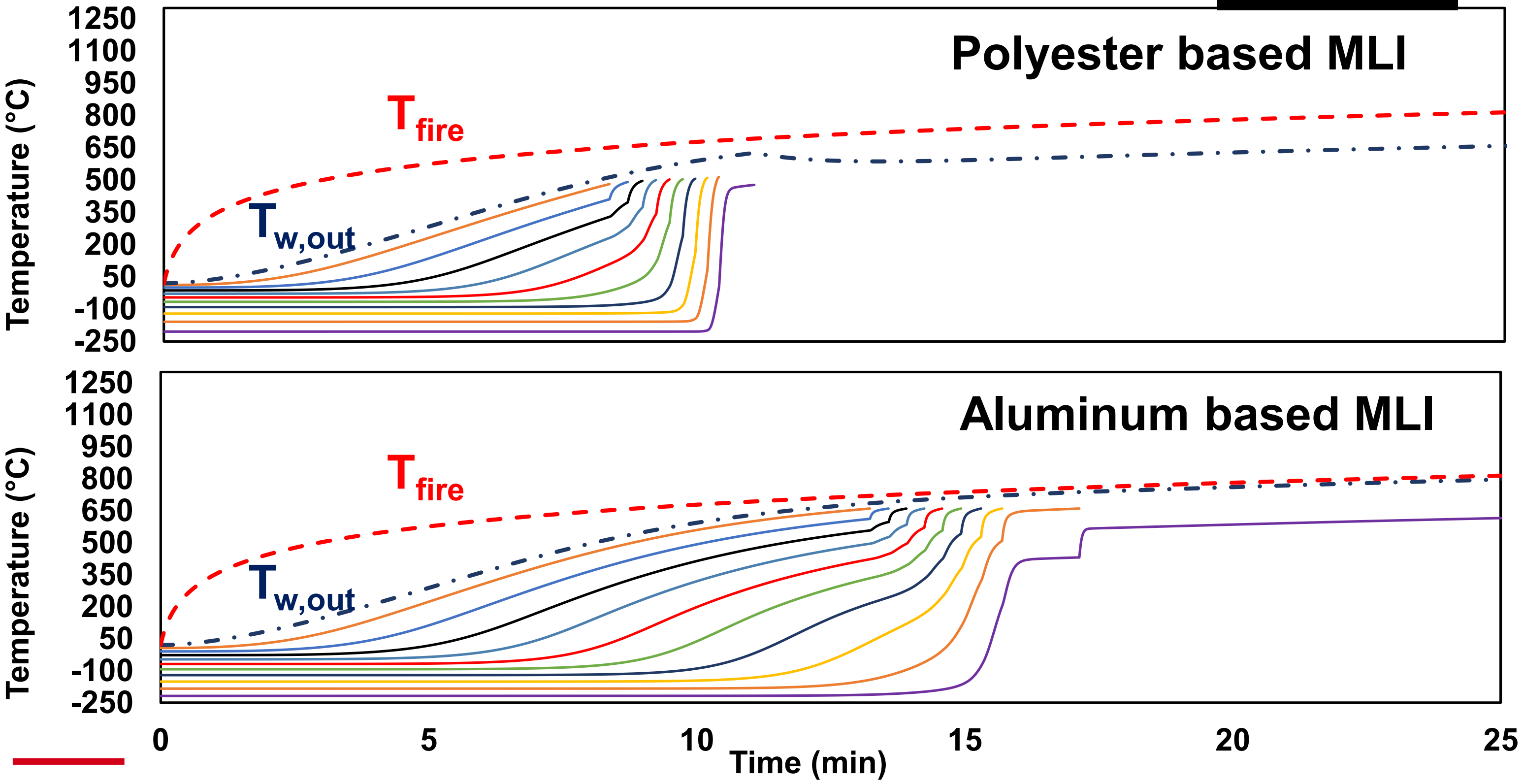
Standard fire curves



Results of case studies: HCinc fire curve

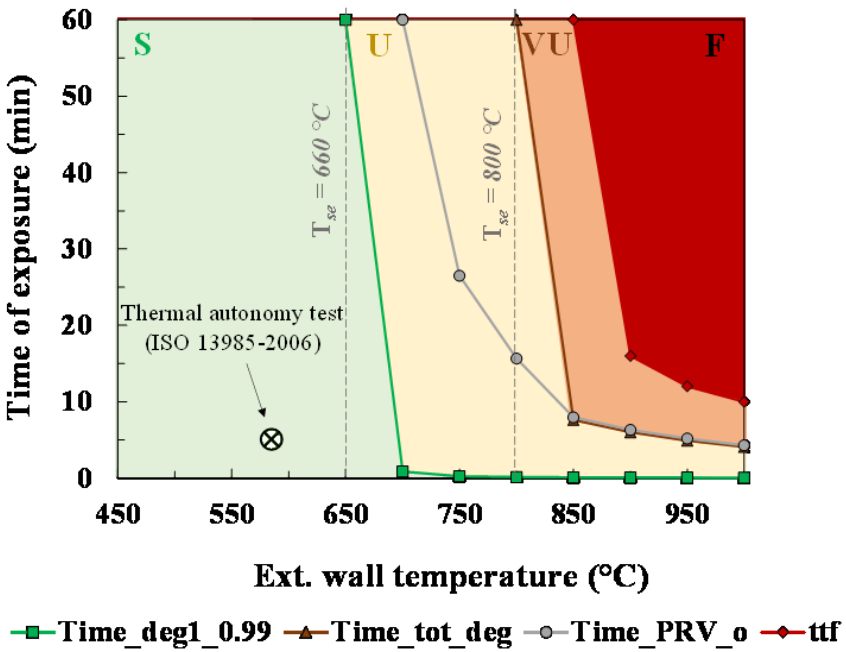


Results of case studies: ETK fire curve

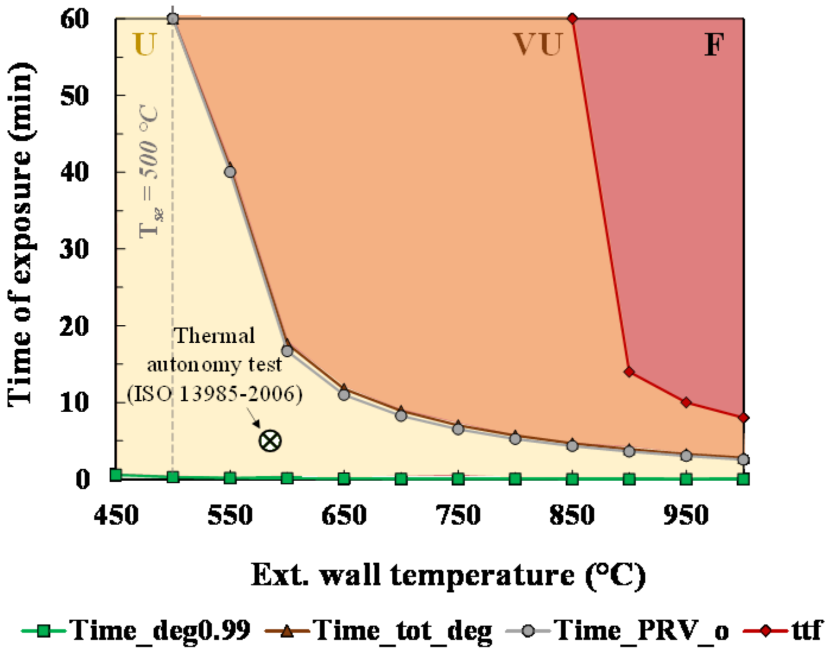


Parametric assessment of wall temperature effec

Aluminium-based MLI, 80 layers

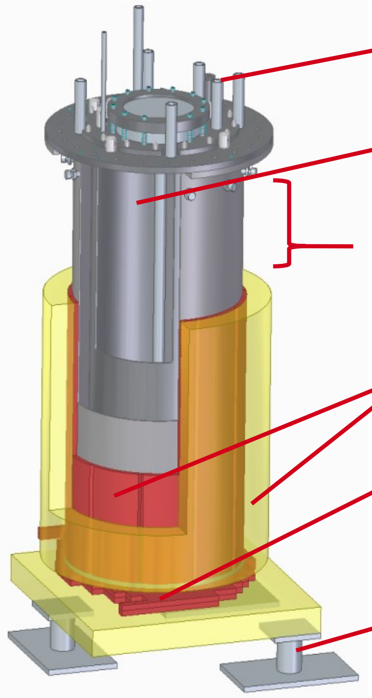


Polyester-based MLI, 80 layers



⊗ Thermal autonomy test (ISO 139985-2006): T_{fire}=590 °C, exposure time = 5 min

Outlook
Fire testing at cryogenic conditions



Periphery of the CHTTVC
Openable double wall

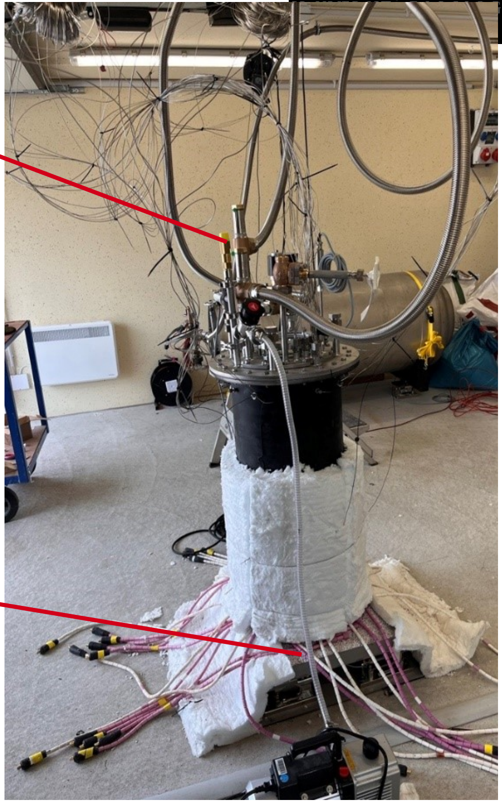
Inner tank that enables storage
of liquefied nitrogen (LN2)

Transition zone from the heated
to the cold part

Heating mats and its thermal
insulation at the circumstance

Heating mats at the bottom
with thermally insulation

Load cells



Outlook
Research fires for the approval of tanks

A calorimeter simulates a tank in a fire


Poolfires


Tire-fires


Carbine-fires

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