HEAT AND MASS TRANSFER MODELING OF VACUUM INSULATED VESSEL STORING CRYOGENIC LIQUID IN LOSS OF VACUUM ACCIDENT

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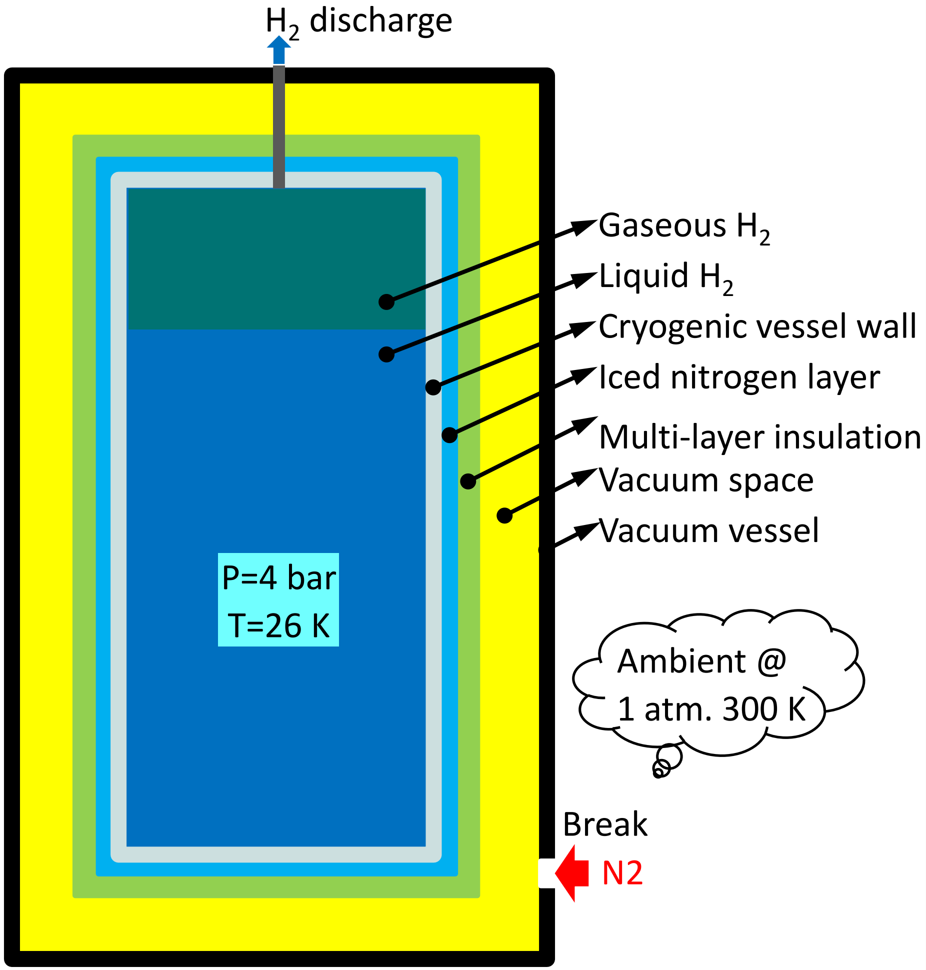
Background

- Cryogenics technology (T<120 K) in applications of superconductor, aerospace, hydrogen technology etc.
- Application examples,
  - LHe of LHC of CERN
  - massive cryogenic storage system of NASA
  - shaft seal cooling system of large-scale device
  - liquid hydrogen application
- Standing and mobile hydrogen systems
  - LH2 storage system
  - H2 refueling station
  - LH2 powered LKWs, agriculture machinery, ships, airplanes etc.

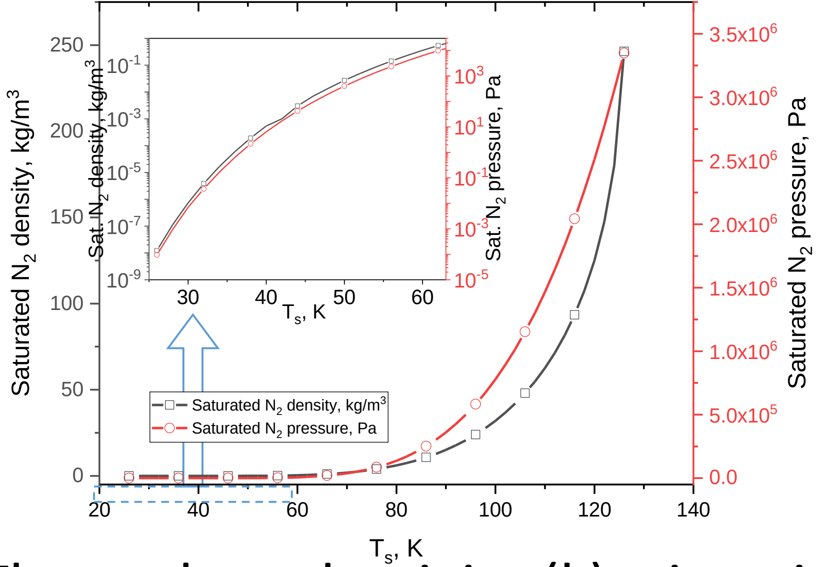
Basic assumptions of vacuum insulated vessel in LOVA

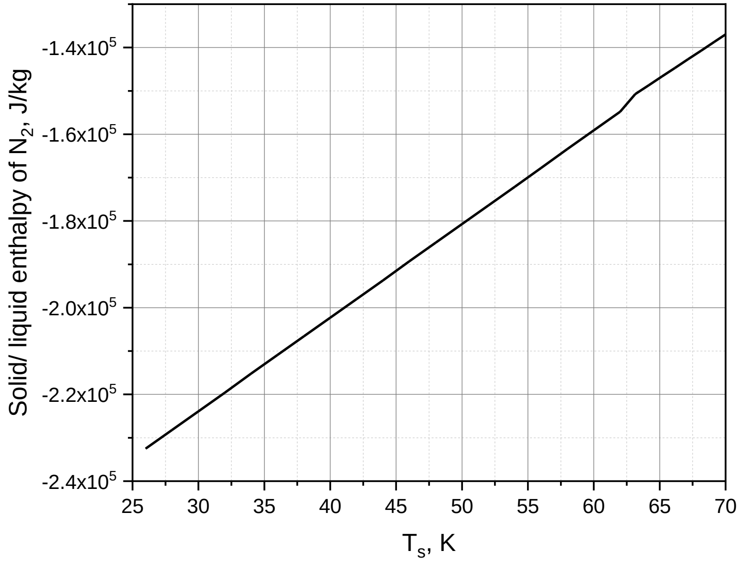
- ☐ What is LOVA: **l**oss **o**f **v**acuum **a**ccident
- ☐ LOVA scenario: 10^{-5} mbar to 1 atm.
- ☐ Venting gas deposition occurs at the cryogenic temperature of outer wall surface of cryogenic vessel
- ☐ Iced layer can be on cryogenic vessel wall, or, in inner layers of MLI
- ☐ Venting gas is N_2 at 300 K and 1 amt.
- ☐ Safety discharge of H2 activated at 4 bar
- ☐ Temperature of saturated two phase H_2 stays at 26 K uniformly



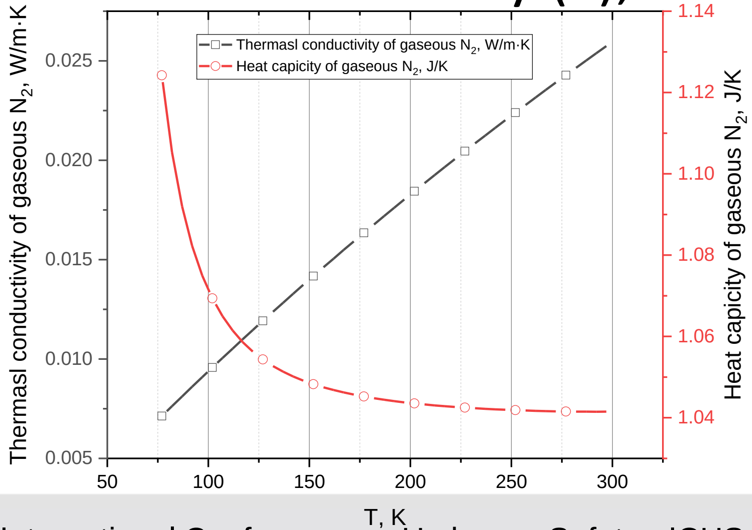
Material properties – gaseous N2

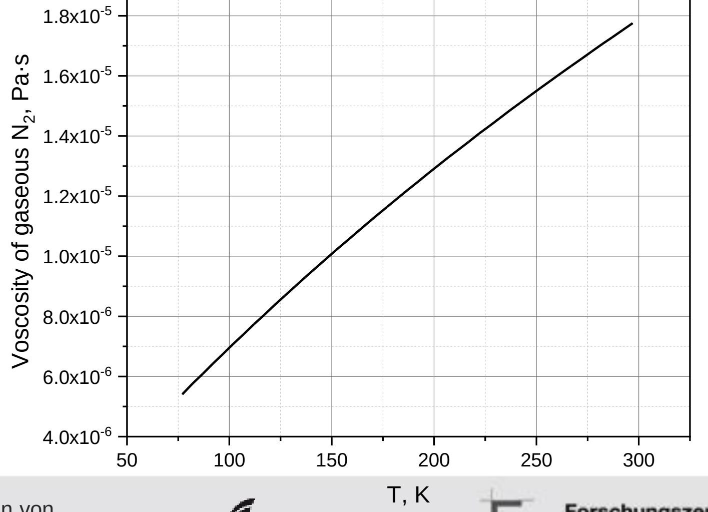
- Saturated N2 gas density, enthalpy of iced N2 or condensate, on REFPROP





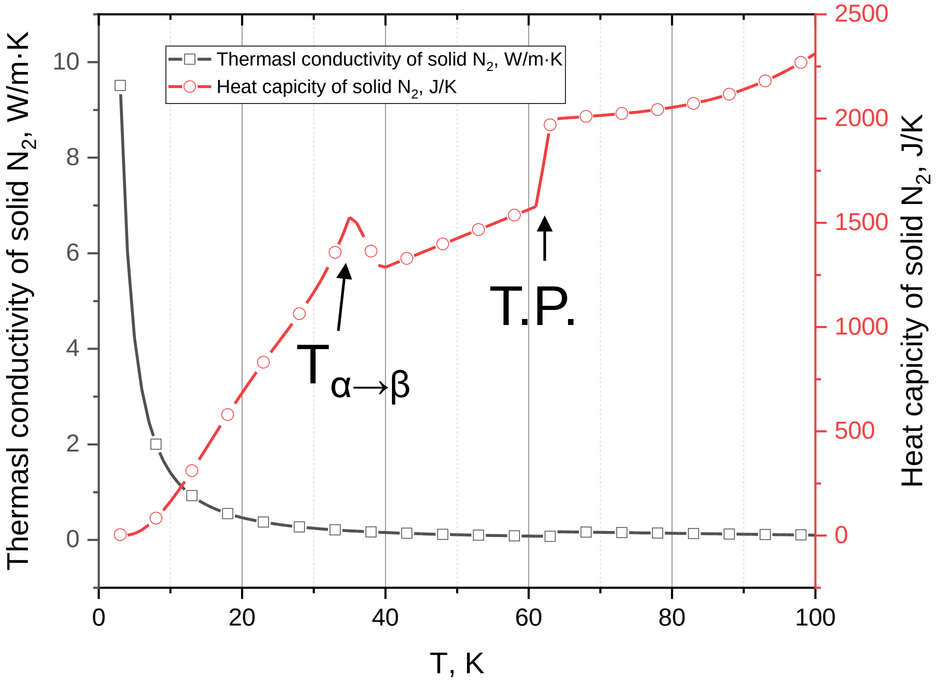
- Thermal conductivity (k), viscosity (μ) and heat capacity (Cp) on REFPROP

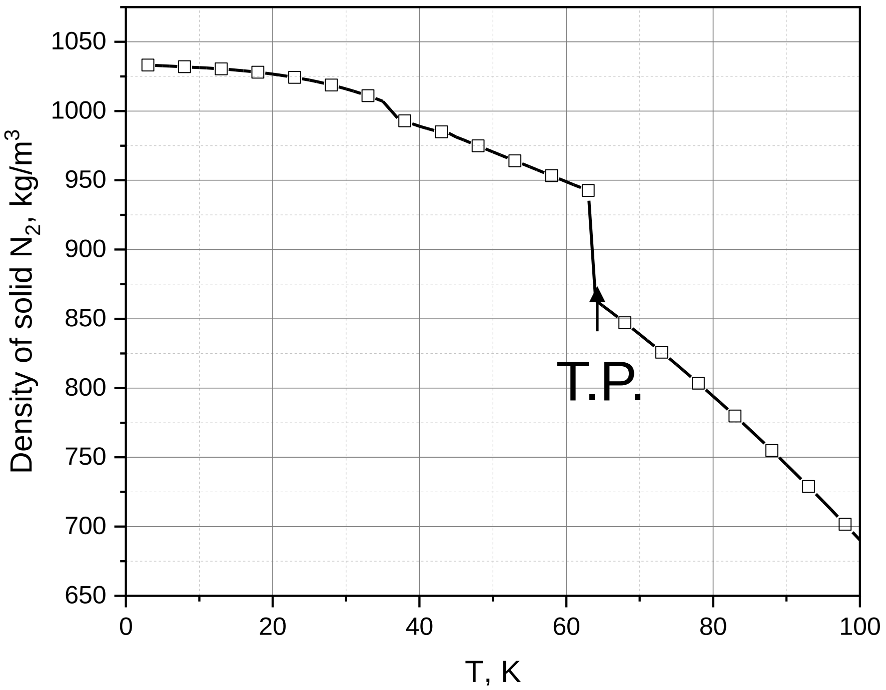




Material properties – solid N2

☐ Temperature dependent thermal conductivity k_sn, heat capacity Cp_sn and density ρsn – piecewise fitted



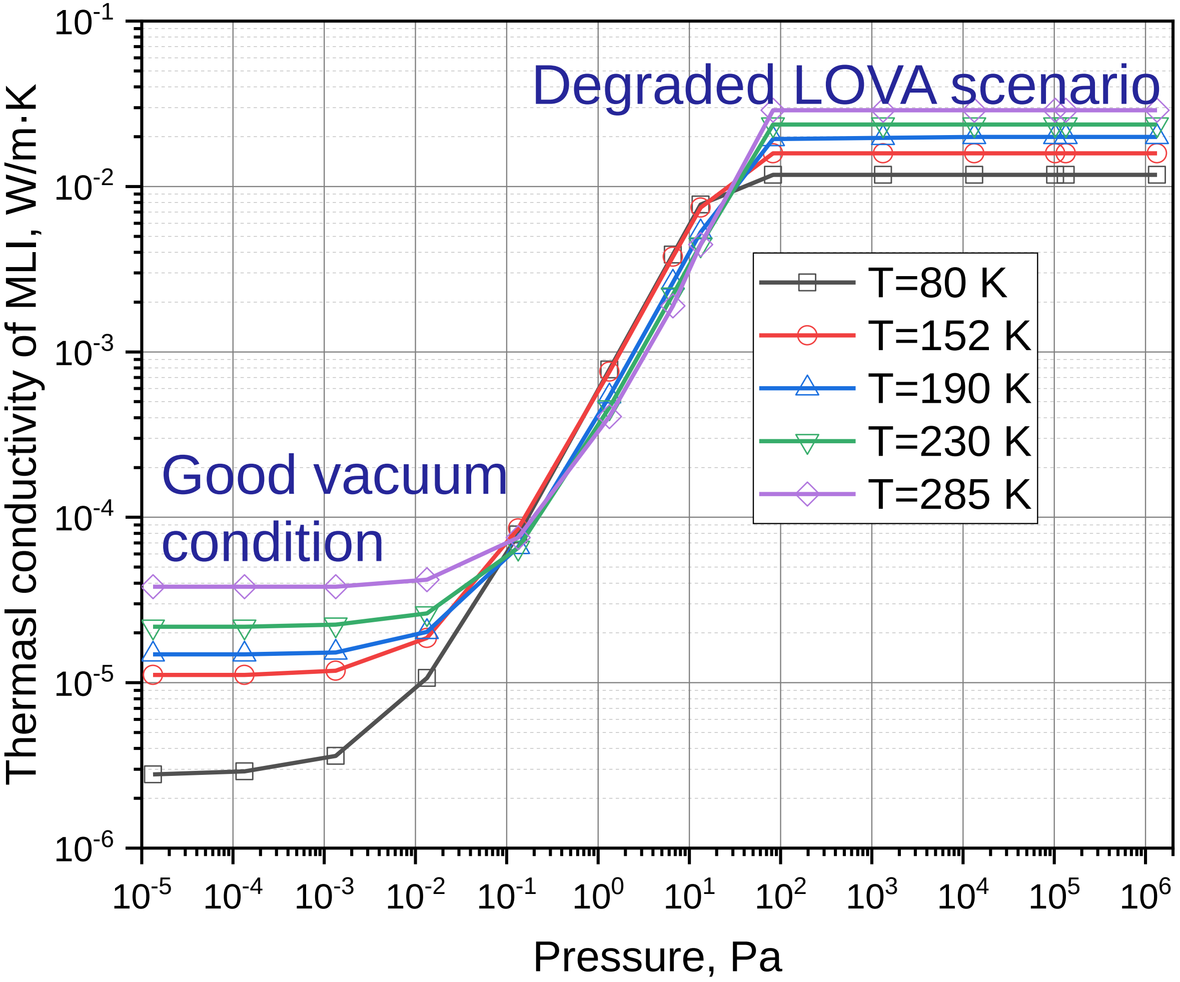


- ***Solid and liquid nitrogen, T.A. Scott, Physics Reports 27, 89 – 157 (1976), ISSN 0370-1573***
- ***NIST REFPROP***

Material properties –MLI

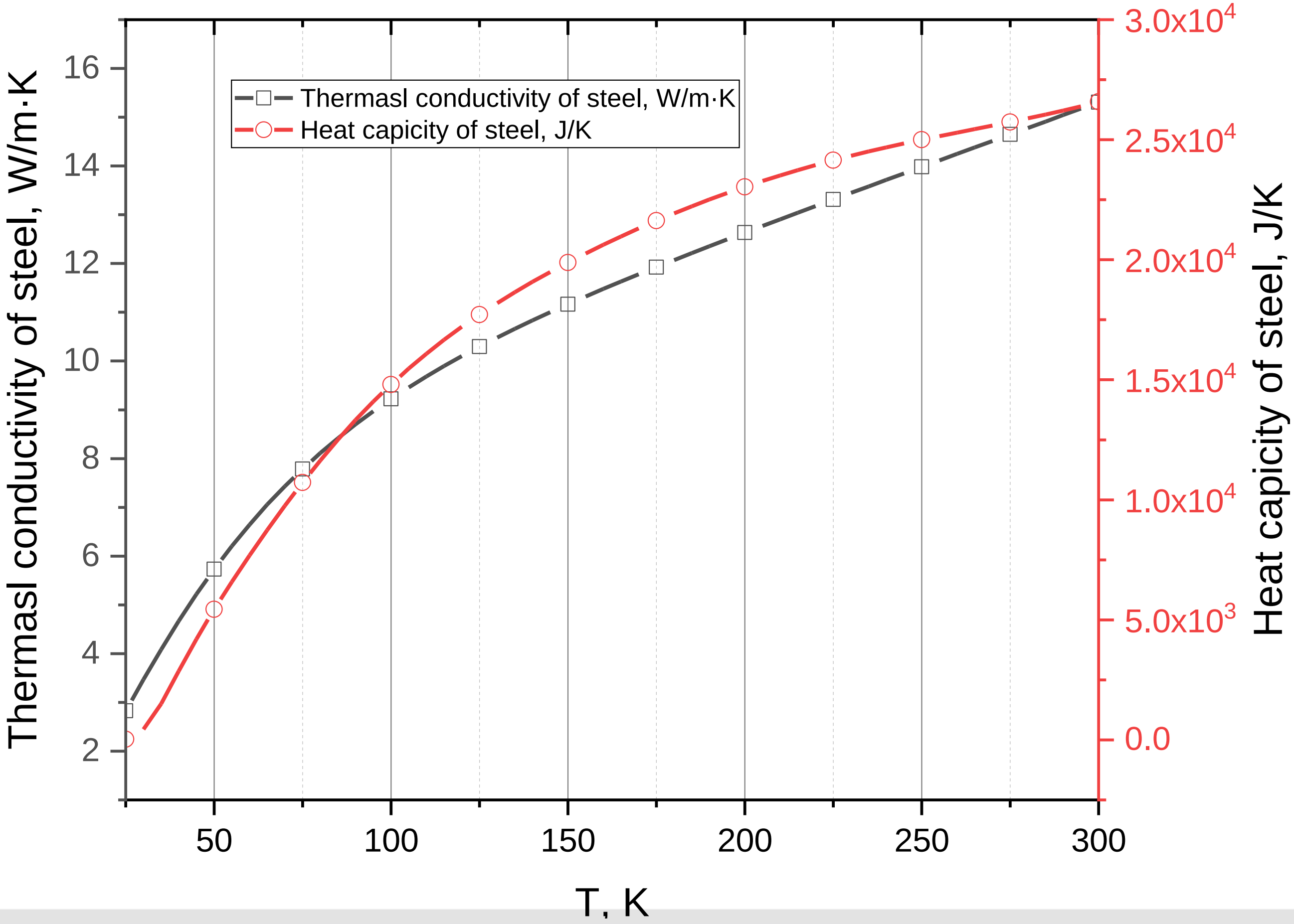
- ☐ What is MLI: **m**ulti-**l**ayer **i**nsulator
- ☐ Effective conductivity of MLI:

  k_ins = k(P,T)
- ☐ Cp_ins = 10 J/(kg·K)
- ☐ Thickness th_ins = 0.01 m
- ☐ Total mass M_ins = 0.5 kg



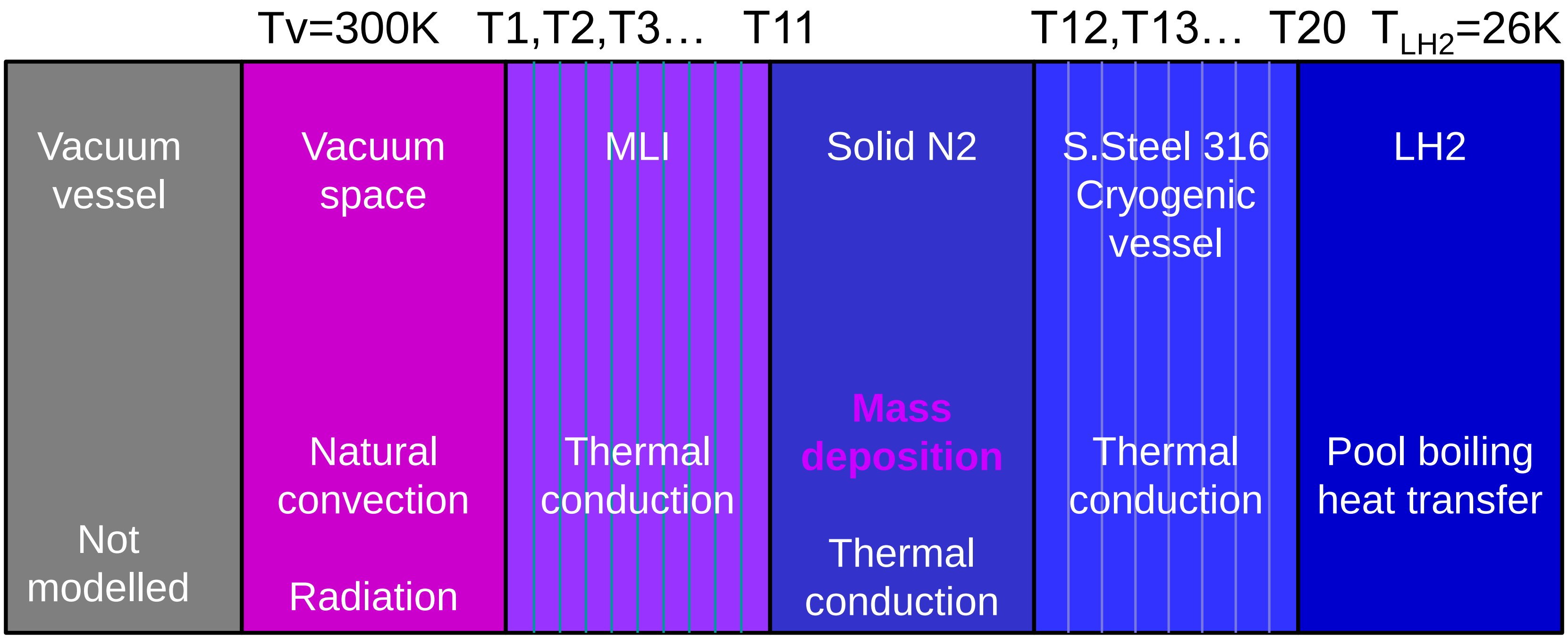
Material properties – S.Steel 316

- ☐ Thermal conductivity (k) and heat capacity (Cp) in 4K-300K from NIST
- ☐ Polynomial fitted



Lumped parameter model

- ☐ Lumped parameter model for heat and mass transfer calculation



Tv=300K T1,T2,T3… T11 T12,T13… T20 T_{LH2}=26K

Vacuum vessel	Vacuum space	MLI	Solid N2	S.Steel 316 Cryogenic vessel	LH2
Not modelled	Natural convection Radiation	Thermal conduction	**Mass deposition** Thermal conduction	Thermal conduction	Pool boiling heat transfer

Dynamic venting flow at break

- ❑ Venting gas flow model: sonic or subsonic flow at vacuum break

$$mIn(P_v) = \begin{cases} A_v(2P_a\rho_a)^{0.5}\left(\frac{2}{\kappa_a+1}\right)^{\frac{1}{\kappa_a-1}}\left(\frac{\kappa_a}{\kappa_a+1}\right)^{0.5} & , if\ P_v < P_{vc} \\ A_v(2P_a\rho_a)^{0.5}\left\{\frac{\kappa_a}{\kappa_a-1}\left[\left(\frac{P_v}{P_a}\right)^{\frac{2}{\kappa_a}} - \left(\frac{P_v}{P_a}\right)^{\frac{\kappa_a+1}{\kappa_a}}\right]\right\}^{0.5} & , if\ P_v \geq P_{vc} \end{cases}$$

$$P_{vc} = P_a\left(\frac{2}{\kappa_a+1}\right)^{\frac{\kappa_a}{\kappa_a-1}}$$

- ❑ Loss of vacuum

$$\frac{dP_v}{dt} = \frac{T_vR_a}{V_v}\left[mIn(P_v) - A_{cr}m_{dep}(P_v, T_v, T_{cr})\right]$$

Mass transfer model

❑ Mass deposition

$$m_{dep}(P_v, T_v, T_{cr}) = k_{dep}[\rho_v(P_v, T_v) - \rho_{sat}(T_{cr})]$$

$$k_{dep} = 0.075 \text{ m/s}$$

$$q_{dep}(P_v, T_v, T_{cr}) = m_{dep}(P_v, T_v, T_{cr})[h_v(T_v) - h_{cr}(T_{cr})]$$

$$\frac{dM_{sn}}{dt} = m_{dep}A_{sn}$$

Convection model

- ☐ Natural convection in vacuum vessel
  - ☐ Based on natural convection between two vertical parallel plates

$$Nu = \begin{cases} 0.197Ra^{0.25}\left(\frac{L}{\mathrm{H}}\right)^{\frac{1}{9}}, if \ \mathrm{Ra} < 2\cdot 10^5 \\ 0.073Ra^{\frac{1}{3}}\left(\frac{L}{\mathrm{H}}\right)^{\frac{1}{9}}, if \ \mathrm{Ra} \geq 2\cdot 10^5 \end{cases}$$

$$\alpha = \frac{Nu \cdot k_{N2}}{L}$$

$$q_{conv} = \alpha(T_v - T_1)$$

- ***G.F. Xie, et.al. Study on the heat transfer of high-vacuum-multilayer-insulation tank after sudden, catastrophic loss of insulating vacuum, Cryogenics 50 (2010) 682–687***

Radiation model

- ☐ Thermal radiation in vacuum vessel
  - ☐ Based on radiation model between two concentric cylinders

$$q_{rad} = \frac{\sigma(T_v^4 - T_1^4)}{\frac{1}{\epsilon_{ss}} + \frac{A_{ss}}{A_{al}}\left(\frac{1}{\epsilon_{al}} - 1\right)}$$

$\varepsilon\_ss := 0.8$

$\varepsilon\_alu := 0.15$

- ***Weber C, Henriques A and Grohmann S, Study on the heat transfer of helium cryostats following loss of insulating vacuum, IOP Conf. Series: Materials Science and Engineering 502 (2019) 012170, doi:10.1088/1757-899X/502/1/012170***

Pool boiling heat transfer model

- ☐ Pool boiling heat transfer
  - ☐ Regime of nucleate pool boiling, due to heat flux ~1-2 W/cm^2 at cryogenic condition
  - ☐ Kutateladze (1952) correlation, (improved by Rohsenow, 1952)

$$q_{boil}(T_w) = \mu_f H_{fg}\left[\frac{g(\rho_f - \rho_g)}{\sigma_f}\right]^{0.5}\left[\frac{Kp^{0.7}Cp_f(T_w - T_s)}{881Pr_f^{0.65}H_{fg}}\right]^{\frac{10}{3}}$$

$$Kp = \frac{\rho_f P_s}{\rho_g\left[g\sigma_f(\rho_f - \rho_g)\right]^{0.5}}$$

“The pool boiling correlation of Kutateladze (Kutateladze 1952; Brentari and Smith 1965) has been verified for cryogenic fluids including N2, O2, H2, and He”, cited from

- ***Cryogenic Heat Transfer, Second Edition, by R F Barron***

Conduction models

❑ Thermal conduction through MLI

$$R_{ins}(P_v, T_{ins}) = \frac{th_{ins}}{k_{ins}(P_v, T_{ins})}$$

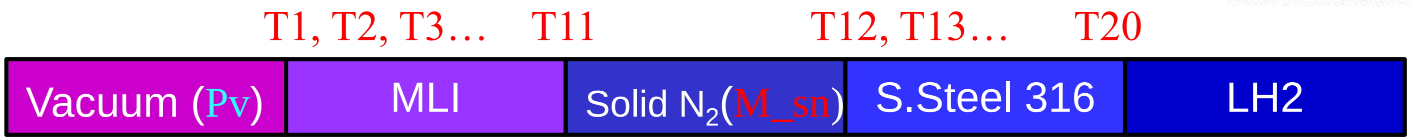
❑ Thermal conduction through iced layer

$$R_{sn}(M_{sn}, T_{sn}) = \frac{th_{sn}(M_{sn}, T_{sn})}{k_{sn}(T_{sn})} \qquad th_{sn}(M_{sn}, T_{sn}) = \frac{M_{sn}}{\rho_{sn}(T_{sn})A_{sn}}$$

❑ Thermal conduction through vessel wall (S.S.316)

$$R_{ss}(T_{ss}) = \frac{th_{ss}}{k_{ss}(T_{ss})}$$

Governing equation group (ODEs)



22 independent variables
22 ODEs

$$\frac{d}{dt}Pv = \frac{Tv \cdot Ra}{Vvacuum}\cdot\left(mIn(Pv) - Acr\cdot mdep(Pv, T11)\right)$$

State equation of gas in vacuum closure

$$\frac{d}{dt}M\_sn = A\_sn\left(M\_sn, \frac{T11+T12}{2}\right)\cdot mdep(Pv, T11)$$

Mass deposition rate equation

Fourier law based heat transfer equations

$$\frac{d}{dt}\left(\frac{T_i+T_{i+1}}{2}\right) = \frac{A_i}{M_i \cdot Cp_i}\left[q_{src} + \frac{T_{i-1}-T_i}{R_{i-1}\left(\frac{T_{i-1}+T_i}{2}\right)} - \frac{T_i-T_{i+2}}{R_i\left(\frac{T_i+T_{i+1}}{2}\right)+R_{i+1}\left(\frac{T_{i+1}+T_{i+2}}{2}\right)}\right] \quad (i = 1,2 \ldots 19)$$

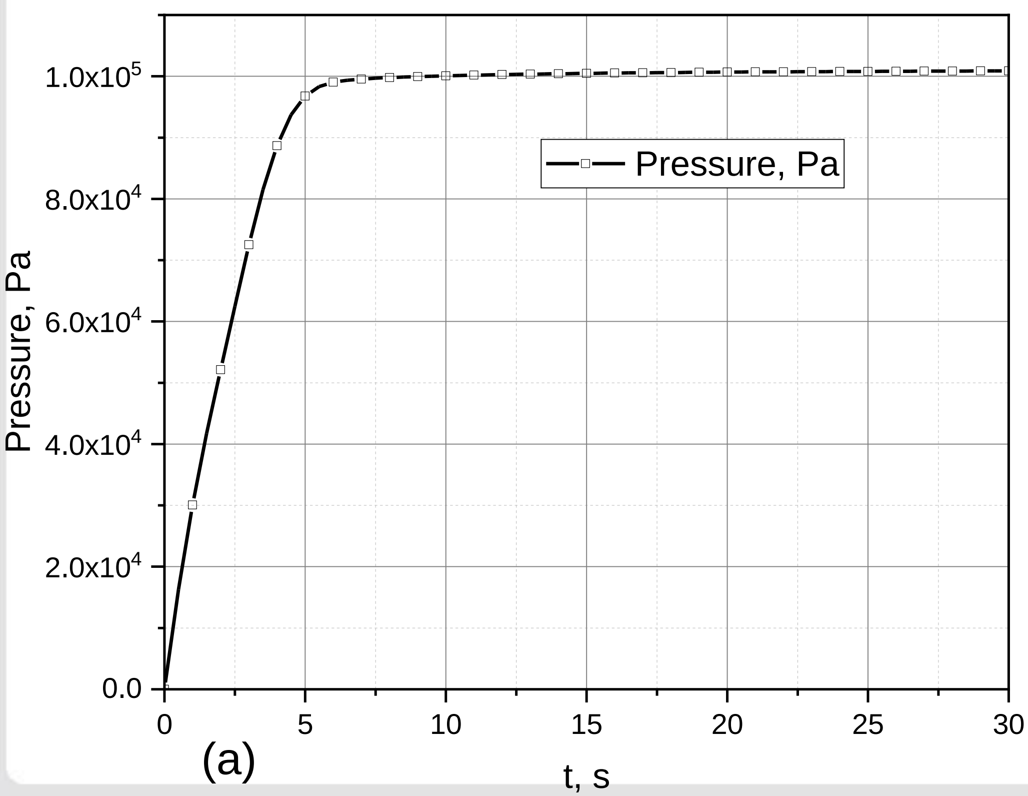
Boiling heat transfer on cryogenic vessel wall

$$\frac{dT_i}{dt} = \frac{A_i}{M_i \cdot Cp_i}\left[\frac{T_{i-1}-T_i}{R_{i-1}\left(\frac{T_{i-1}+T_i}{2}\right)} - q_{boil}\right] \quad (i = 20)$$

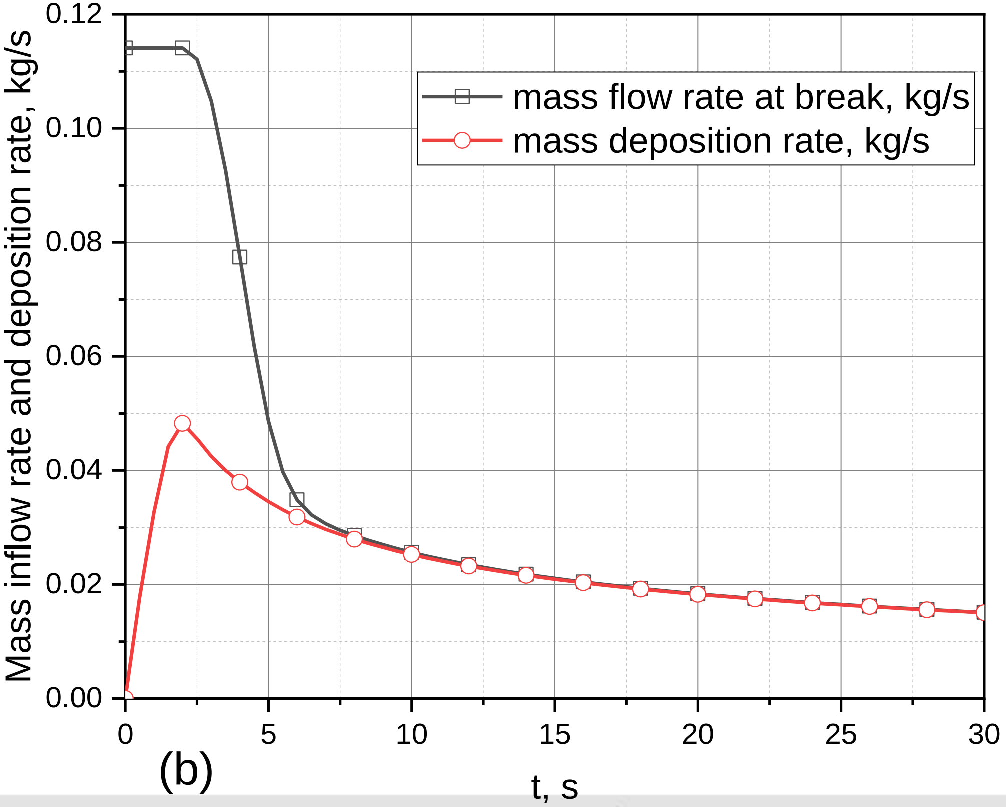
Calculation results

☐ Initial conditions   Pa = 1 atm. Ta = 300 K   D = 0.025 m

☐ Pressure in vacuum closure

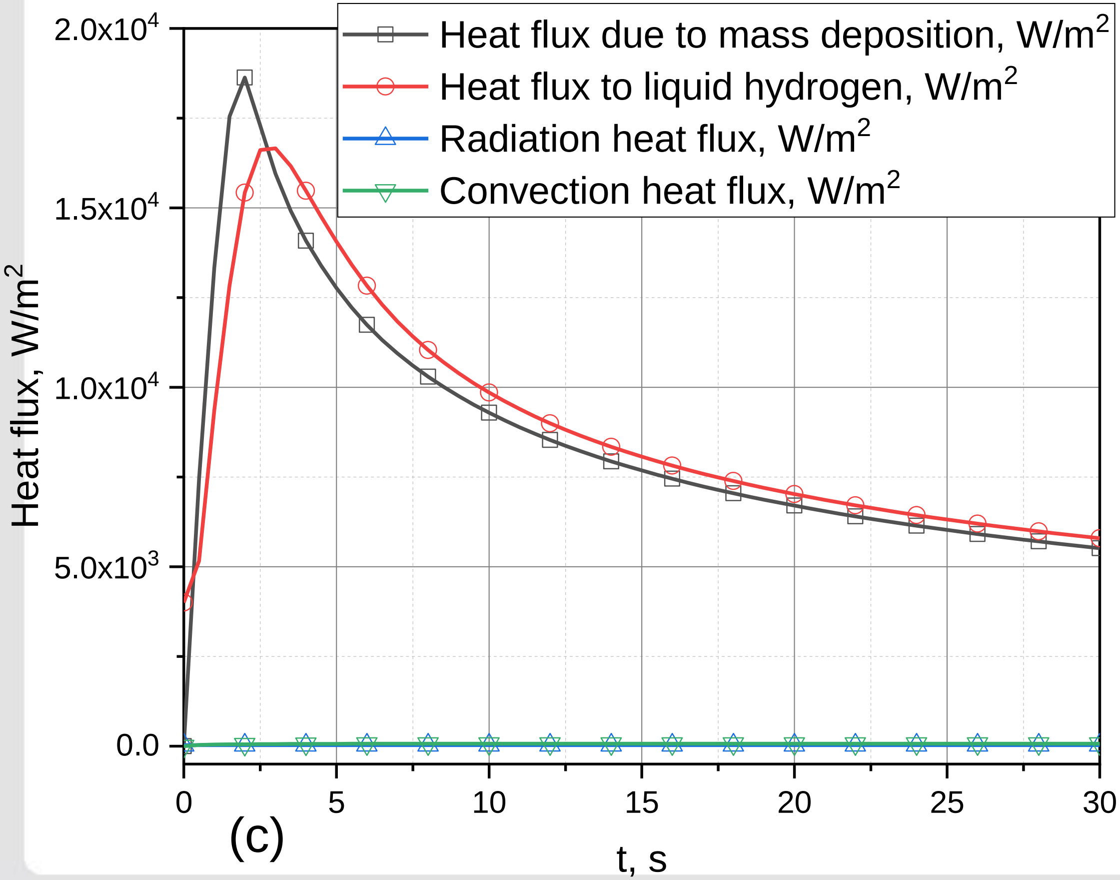


☐ Venting gas mass flow rate and deposition rate

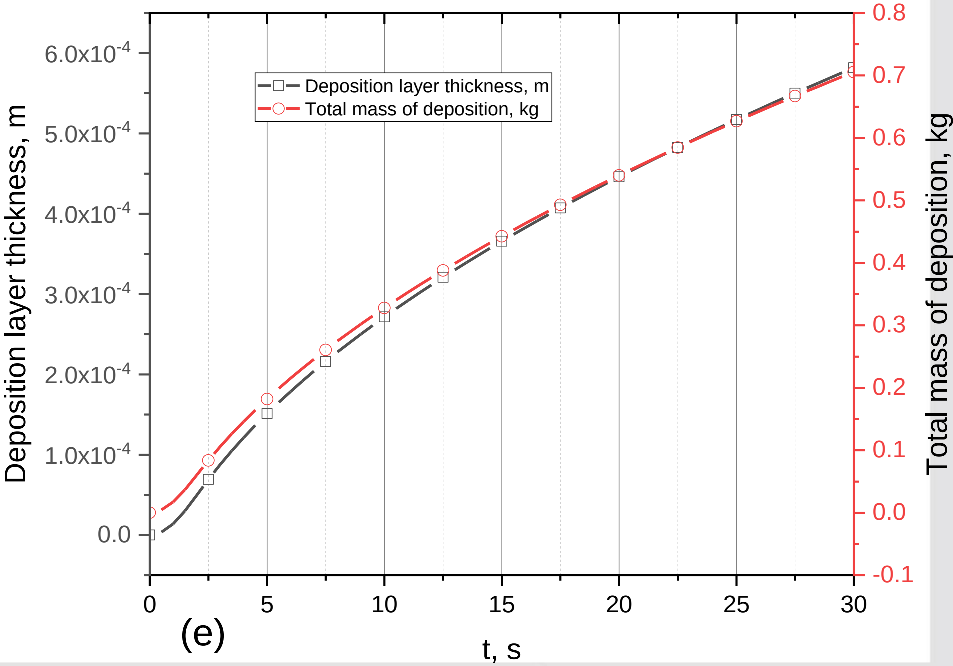


Calculation results

- ❑ Heat fluxes due to mass deposition
  - ❑ Max. heat flux: **1.87 W/cm²**
  - ❑ Max. heat flux to LH2: **1.67W/cm²**



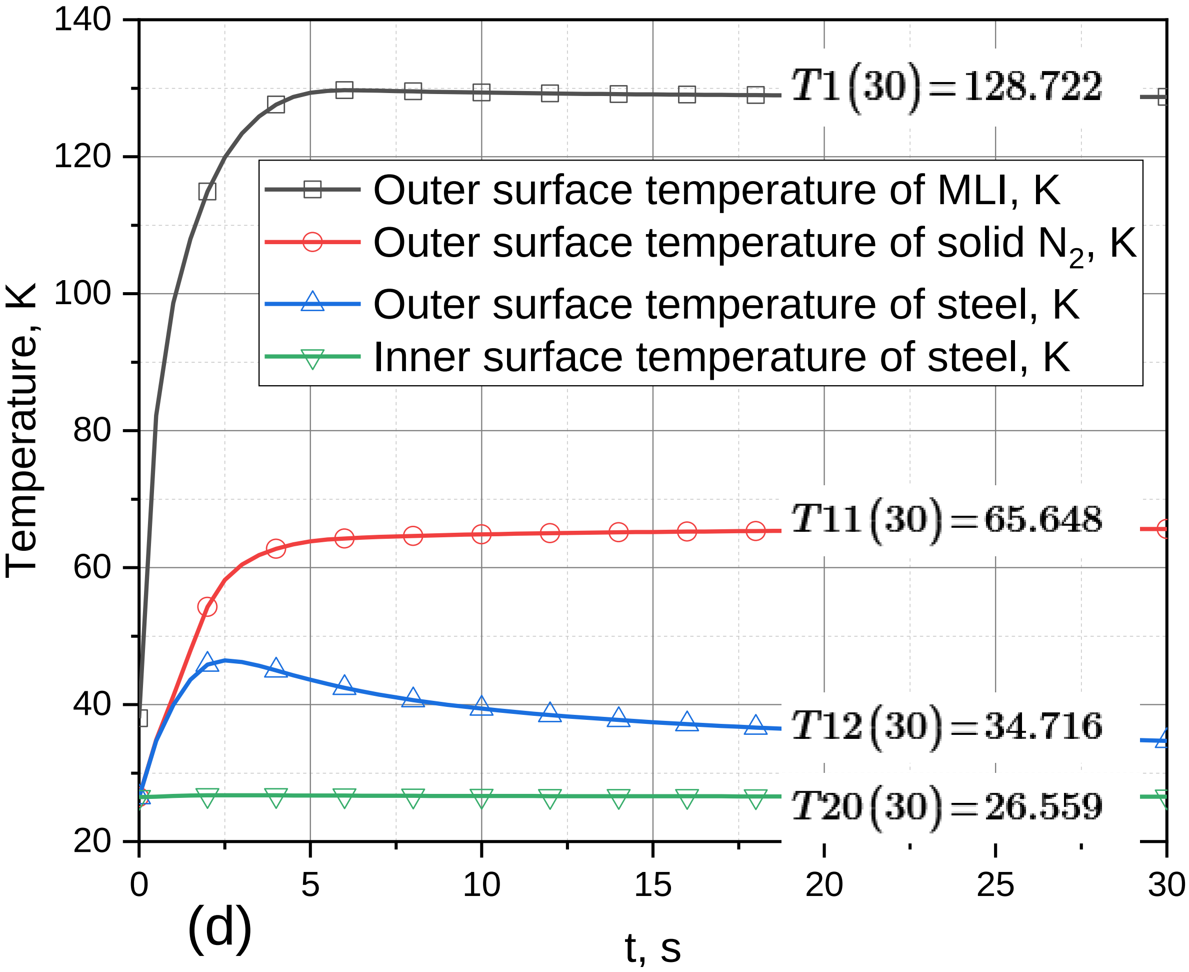
- ❑ Iced N2 layer thickness and mass



Calculation results

- ❑ Temperatures at surfaces of MLI (T1), iced layer (T11), outer surface of steel (T12) and inner surface of steel (T20)

- ❑ ΔT_MLI = 63 K
- ❑ ΔT_solid N_2 = 31 K
- ❑ ΔT_steel = 8 K
- ❑ ΔT_boiling = 0.6 K



Conclusions

- ☐ Material properties are precise as possible, including gaseous, liquid and solid nitrogen, gaseous and liquid hydrogen, and stainless steel 316 at cryogenic condition
- ☐ Lump parameter models of heat and mass transfer are developed to find heat load to LH2 in LOVA scenario, by modeling MLI, iced layer, convection on venting side and pool boiling heat transfer on LH2 side
- ☐ Mass deposition of venting gas dominates heat load to LH2, thermal radiation and convection play significantly less roles
- ☐ Venting mass does not deposit on outer surface of MLI, but in region between MLI and cryogenic wall if temperature is low enough
- ☐ In case of Φ2.5 cm break, maximal heat load to LH2 is ~1.67 W/cm^2, iced layer thickness ~ ½ mm in the first 30 s in LOVA
- ☐ Thermal resistance of ½ mm thick iced layer is not ignorable, due to its low conductivity at cryogenic temperature. The resulted temperature decrease (31K) is about half of that of MLI (63K)
- ☐ Verification against experimental data is expected next step