C2PoB-07

Pressure and Boil-Off Gas Management of Liquid Hydrogen Storage Onboard Maritime Carriers for Export

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Background

One of the main barriers to large scale liquid hydrogen (LH2) export is the high cost of pressurized, double-wall insulated tanks onboard ships. Pressure rise in the tank forces venting or consumption of boil-off gas (BOG), reducing net cargo delivered. On the return (ballast) voyage, net heat ingress into the tank may incur an additional costs in tank childown. In this study, a 160,000cbm capacity "Type-B" LH2 carrier is considered with double walled perlite insulation. The parametric effects of tank maximum allowable pressure, initial temperature conditions, fill level and voyage duration are investigated.

Key Objectives

- Develop efficient model to predict pressure and energy flows in large LH2 tanks.
- Investigate the effect of tank maximum allowable working pressure (MAWP) and journey duration on BOG losses.
- Investigate heat gain within tank during ballast (or return) voyage, at low fill levels.
- Understand the impact of BOG consumption on pressure rise

Methodology

Semi-Analytical Model

An analytical model was developed in MATLAB as a quick tool to predict mass and energy flows. The model is linked to REFPROP for parahydrogen properties. Insulation temperature profile is assumed to be axisymmetric, modelled in 2D (see Fig. 1).

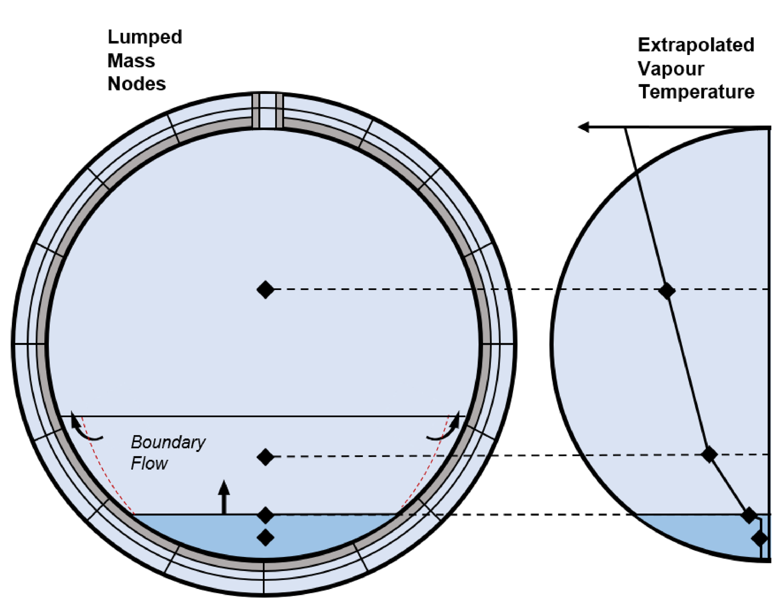


Fig 1: Analytical model for spherical tank (left) and solver overview (right).

Key Assumptions

- Hydrogen assumed to be 100% parahydrogen (P-O conversion neglected.
- Sloshing modelled as liquid-vapour heat transfer enhancements, based on semi-empirical correlations (Ludwig, 2013) [1]
- **Liquid surface** remains in equilibrium with vapour pressure.
- **Boundary Layer Flow** modelled as proportional to flow over a semi-infinite, isothermal vertical plate (Eckert, 1950)
- **Wall-fluid Heat Transfer** modelled using natural convection correlation for spherical enclosure (Schmidt, 1956):
  $$Nu = 0.98Ra^{0.321}$$
- **Vapour-Surface Heat Transfer** modelled using natural convection correlation for the upper surface of a cold plate (Churchill & Chu):
  $$Nu = 0.56Ra^{0.2}$$
- **Surface-Liquid Heat Transfer** assumed to occur via conduction
- Perlite thermal conductivity is shown in Figure 3, and expressed as [2]:
  $$k = k_{sc} + k_r + k_{gc} = \frac{2.52T}{10^6} + 7.89\frac{T^3}{10^{11}} + \frac{1.2437T^{0.587}P}{10^3(0.895T + P)}$$
- **Perlite Specific Heat Capacity,** shown in Figure 3, is calculated based on its constituent components of SiO2 and Al2O3.

Model Validation

Self-pressurisation & Vapour Stratification

Self-pressurisation data of 4.9m³ spheroidal LH2 tank (Hasan, 1991) [3]. Heat flux is assumed to be uniform. Experimental data of (Krikkis, 2018) [4] of 45,000m³ prismatic LNG NO96 tank with ballast (6% liquid fill) and vapour-only. LNG is assumed to be 100% methane.

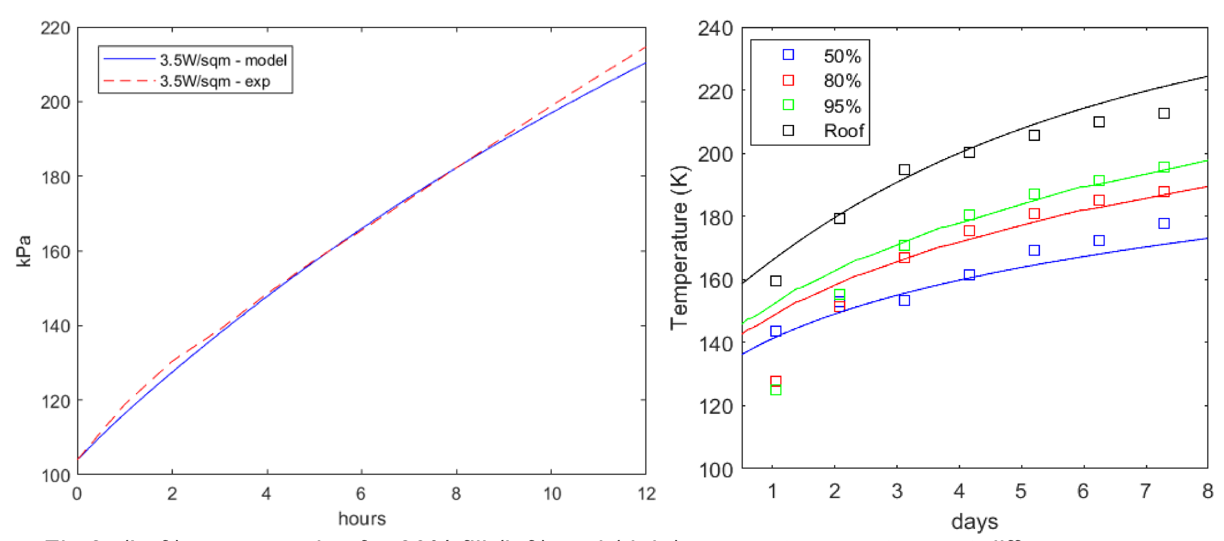


Fig 2: (Left) pressure rise for 29% fill (left) and (right) vapour temperatures at different heights for 6% heel LNG voyage.

Perlite Properties

Perlite insulation model validated against boil-off data of 3,400m³ spherical dewar chilldown (Krenn, 2019) [5] .

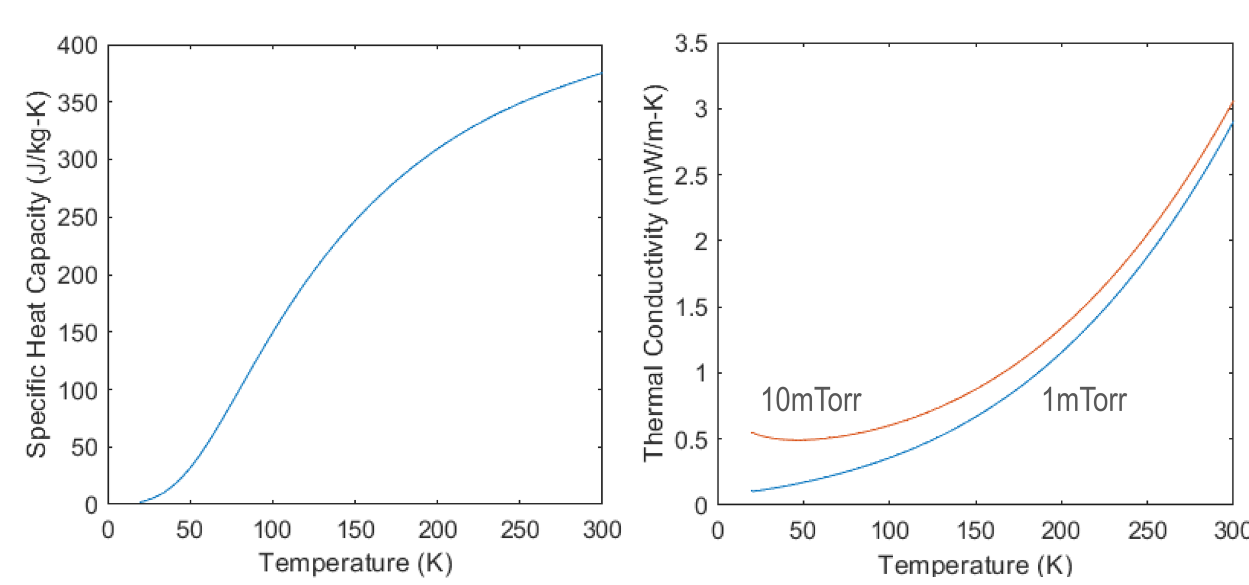
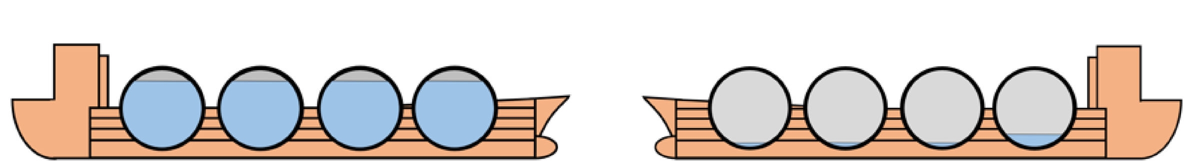


Fig 3: Estimations for specific heat capacity (left) thermal conductivity (right) of perlite



Model Parameters

A one-way voyage duration of up to 21 days (42 day round-trip) was considered. Onboard fuel cell for ship auxiliary power was assumed to consume up to 1.89 tonnes GH2 per day.

Tank Volume	40,000m³
Annulus thickness	0.75m Expanded perlite @ 10-100mTorr
Inner wall thickness	0.063m 304 SS
Steady State BOR	0.05% per day
Auxiliary Power	1.5MW (0.0165% per day)

Laden Voyage Fill	90 – 95%
Ballast Voyage Fill	1 – 10%
Initial Pressure	101kPa (absolute)
MAWP	125 – 200 kPa (absolute)

Pressure Rise and a General Correlation

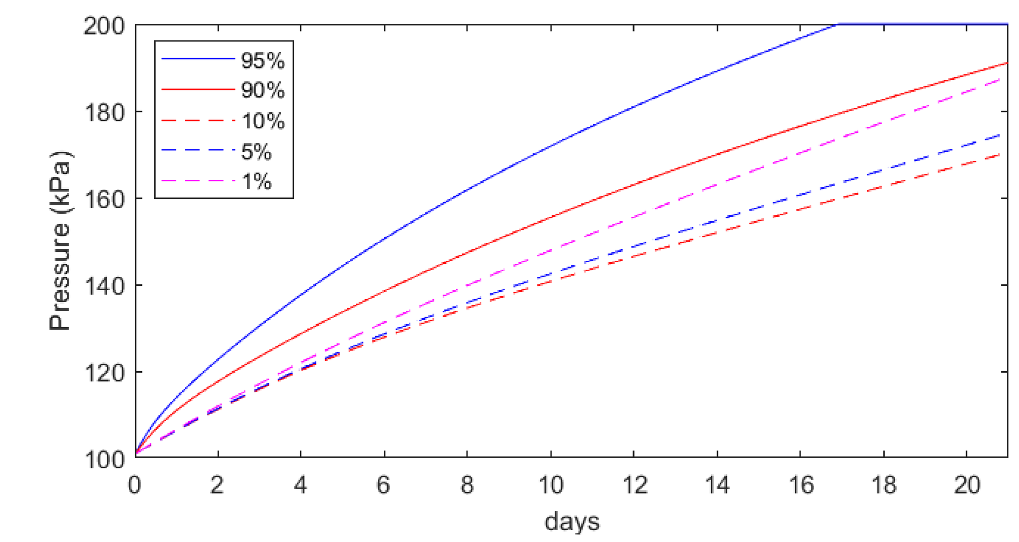


Fig 4. Review of existing experimental data & present analytical model estimates.

A review of existing experimental data for self-pressurisation reveals a general relationship between modified Rayleigh number (Ra*), fill level and dimensionless pressure rise, defined as:

$$(\varphi) = \frac{\Delta P_{observed}}{\Delta P_{isothermal}}$$

Fitting a simple linear model to 28 data points, a general correlation can be established for quick estimations.

$$\ln(\varphi) = 0.048 + 0.0122\ln(Ra) + 1.471\left(\frac{Fill}{100}\right)^2$$

This returns an adjusted R^2 of 0.775, with greater error for higher fill levels.

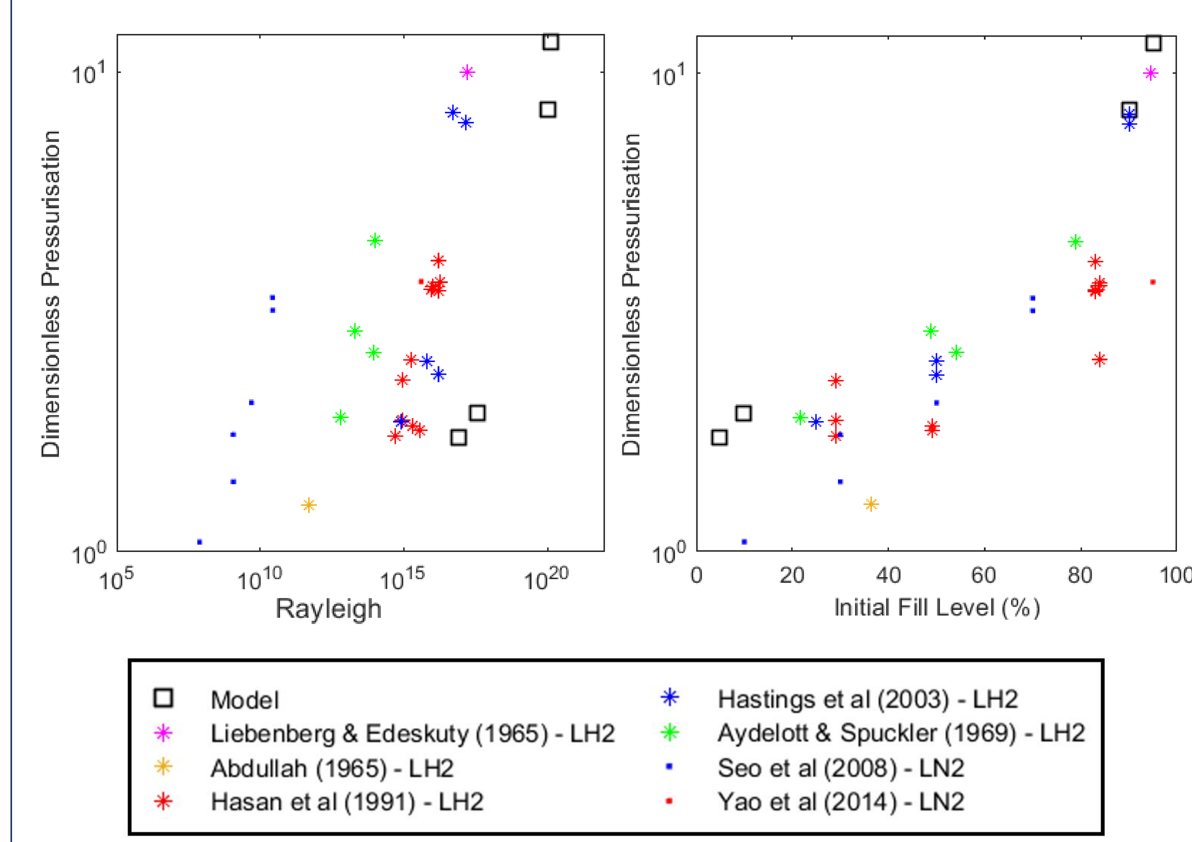


Fig 5. Review of existing experimental data. Present analytical model estimates are shown

BOG Consumption

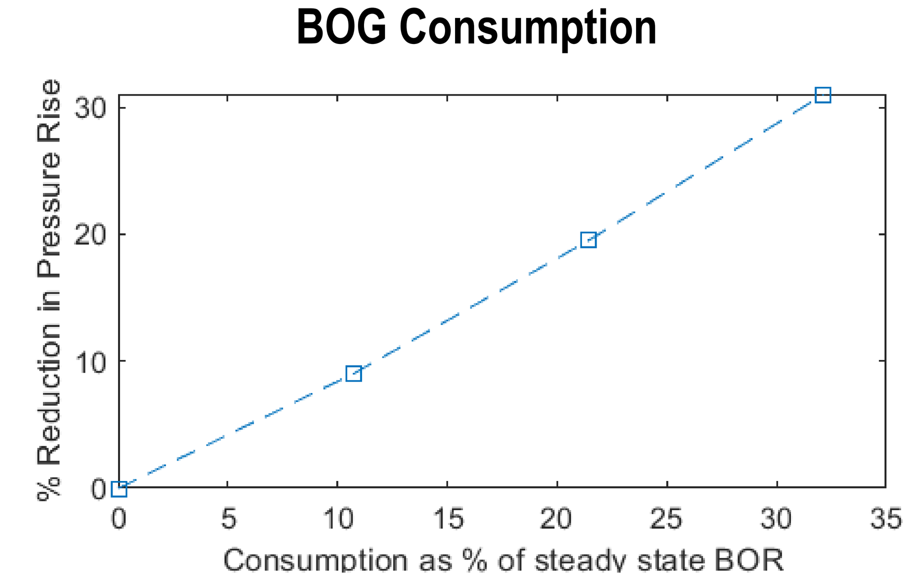


Fig 6. Effect of consumption on pressure rise

Consumption is assumed to ramp from zero to full power over 24 hours, based on LNG carrier power profiles. Consumption as a function of steady state boil-off rate generally has a proportionate effect on pressure rise during self-pressurisation.

Boil-Off Gas (BOG) Losses

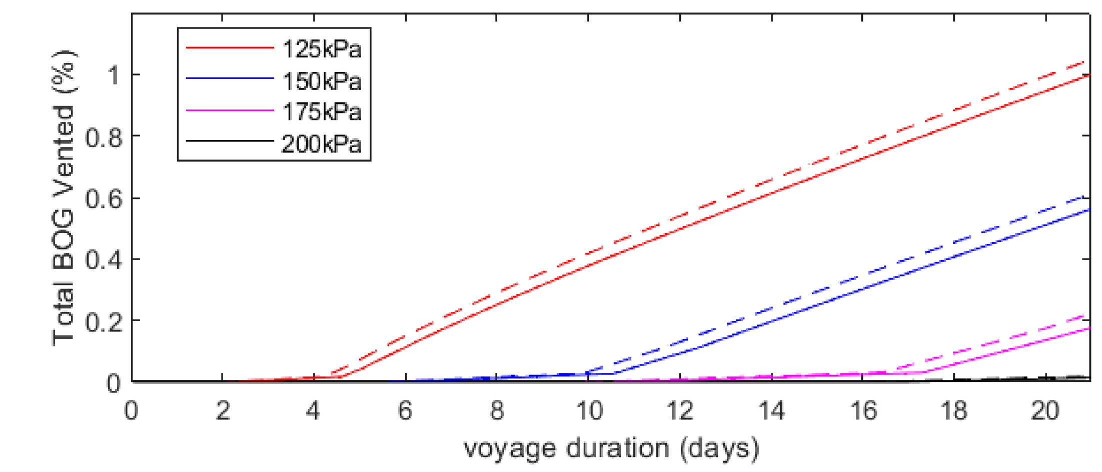


Fig 7. Round-trip BOG losses for 95% heel, 5% ballast voyage.

Round trip (laden and ballast) losses are shown. Majority of venting losses occur during ballast voyage, due to decreased subcooling in the liquid and higher BOG generation. Average daily BOR over 21 days was predicted to be 0.023% and 0.013% for MAWP of 125 and 150kPa respectively. Subcooling in the liquid leads to a "transient" period after venting, where bulk boiling does not occur. For all pressures considered during the laden voyage, bulk boiling is not predicted to occur.

Tank Heat Gain

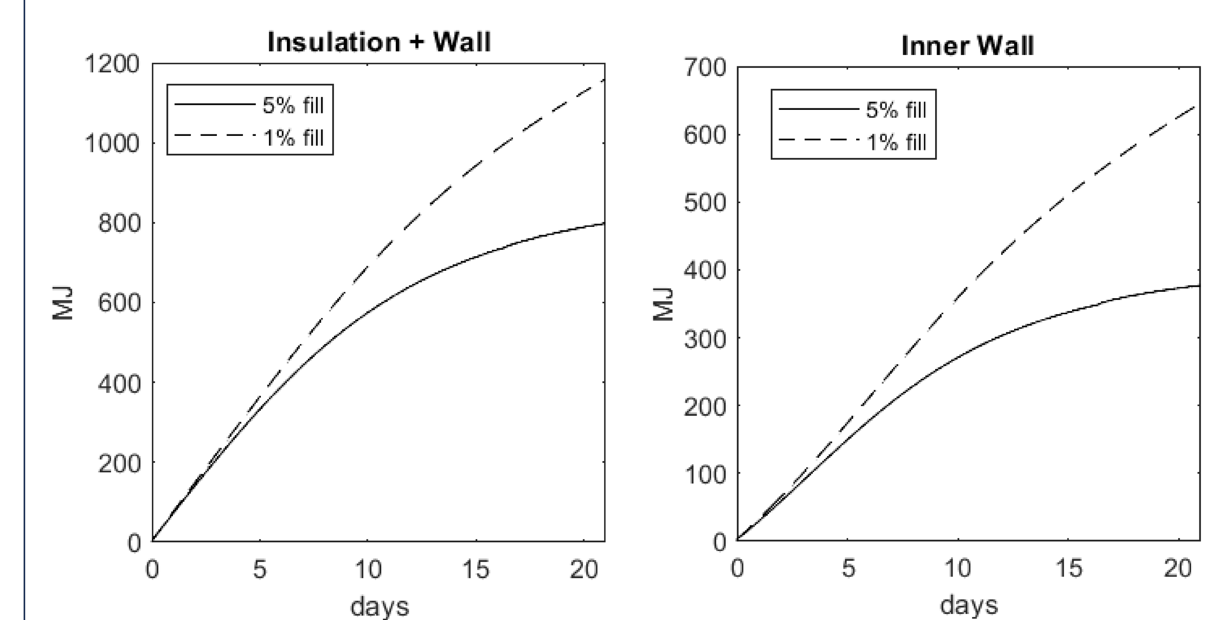


Fig 8. Net heat gain in insulation & metal wall (left) and vapour temperature (right)

Over 21 days, the heat gain in all 4 tanks is predicted to be 4,275 MJ, equating to a cooling load of <135m³ (0.34% fill) LH2 (based solely on enthalpy of vapourisation). This is significantly lower than typical heel requirements for LNG carriers, suggesting requirements for ballast heel will be mainly driven mainly by the need to service ship hydrogen consumption. This is partially attributed to the low predicted heat capacity of stainless steel and perlite at low temperatures.

Conclusions

- Allowing the tank to self-pressurise along the voyage can enable average daily BOR significantly lower than steady state BOR.
- A general correlation for dimensionless pressure rise has been developed, based on available experimental data.
- Heel required on ballast voyage significantly lower than that for a typical LNG carrier, and points to the potential of operating the tank near-empty to maximise net delivered cargo.
- Economics of utilising PEMFC as auxiliary power load are favourable compared to marine diesel engine, irrespective of carbon price. Utilising onboard vapour for ship propulsion is favourable for a carbon price of ~$80/kg e-CO2, assuming $10/kg H2.

Acknowledgements

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Selected References

[1] Ludwig, C., M.E. Dreyer, and E.J. Hopfinger, *Pressure variations in a cryogenic liquid storage tank subjected to periodic excitations.* International Journal of Heat and Mass Transfer, 2013. **66**: p. 223-234.

[2] Ratnakar, R.R., Z. Sun, and V. Balakotaiah, *Effective thermal conductivity of insulation materials for cryogenic LH2 storage tanks: A review.* International Journal of Hydrogen

[3] Hasan, M., C. Lin, and N. Vandresar, *Self-pressurization of a flightweight liquid hydrogen storage tank subjected to low heat flux.* 1991

[4] Krikkis, R.N., *A thermodynamic and heat transfer model for LNG ageing during ship transportation. Towards an efficient boil-off gas management.* Cryogenics, 2018. **92**: p. 76-83

[5] Krenn, A. and D. Desenberg, *Return to service of a liquid hydrogen storage sphere.* IOP Conference Series: Materials Science and Engineering, 2020. **755**(1): p. 012023.