Assessment of Insulation Systems for Aircraft Liquid Hydrogen Tanks

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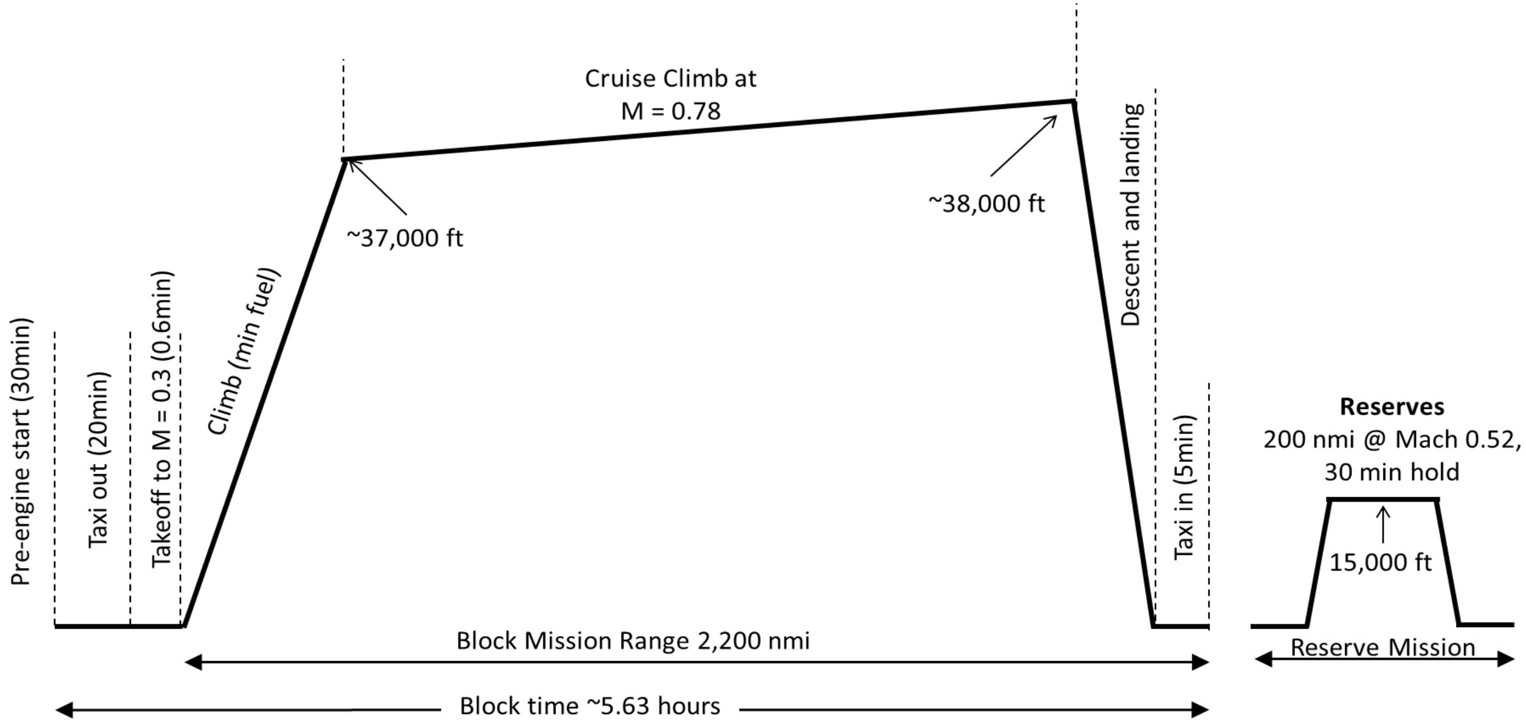
Objective of the Analysis

- Evaluate the effective heat loads and insulation masses/thicknesses for aircraft tanks
- Consider several insulation options:
  - Vacuum Jacketed with Multilayered Insulation (MLI)
  - Vacuum Jacketed with Glass Bubbles
  - Polyurethane Foam
  - Aerogel Blankets
- Provide final results that can guide selection of the most appropriate insulation options for further study
- Analysis was completed using the Thermal Insulation System (TIS) – Tool developed by NASA along with test data from calorimeters at Kennedy Space Center

Aircraft Description and Mission

- Single aisle (A320/B737 type), entry into service 2030
  - 150 passengers
  - 2200 nmi range
  - Two hydrogen burning geared turbofan engines



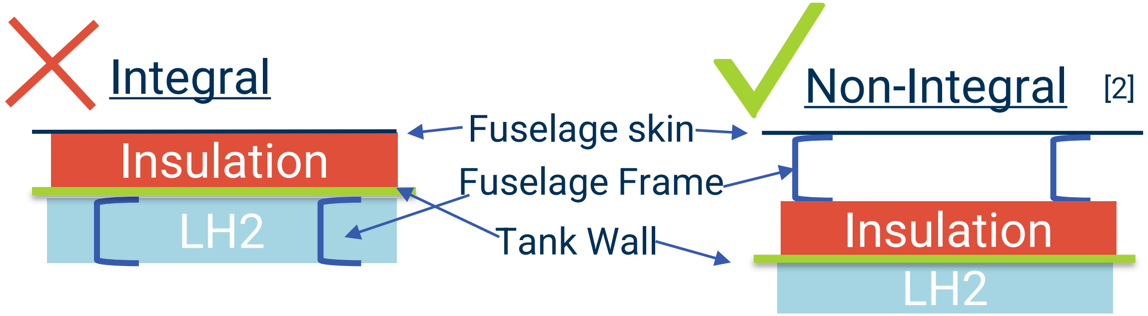
LH2 Tank Architecture

Tank Location:

- Aft tanks similar to Airbus concept
- Fuselage extended to fit tanks rather than removing passengers
- Range reduced to control CG movement

Integral vs Non-integral:

- Non-integral = designed only for fuel containment loads
- Integral = tank structure is part of fuselage structure



Swappable vs Non-swappable:

- Non-swappable = only removed for maintenance
- Swappable = empty tanks are swapped with full tanks between each flight

Non-swappable

Swappable [3]

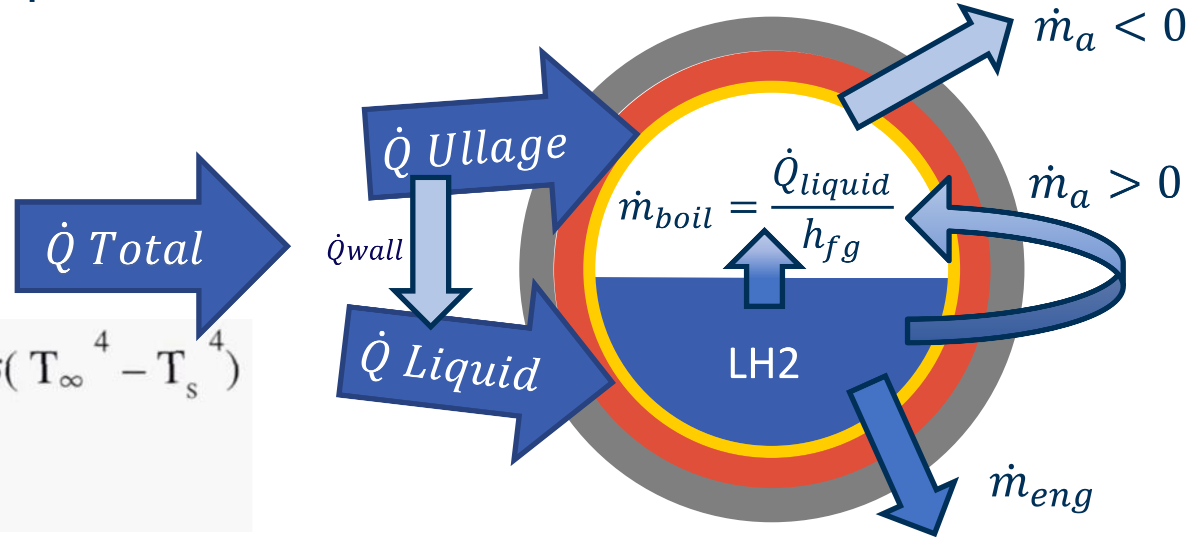
1. "How to store liquid hydrogen for zero-emission flight," *Airbus* Available: https://www.airbus.com/en/newsroom/news/2021-12-how-to-store-liquid-hydrogen-for-zero-emission-flight. https://hydrogen.aero/product/
2. Brewer, G. D., Morris, R. E., Lange, R. H., & Moore, J. W. (1975). *Study of the application of hydrogen fuel to long-range subsonic transport aircraft Volume 2*. *2*, 1–386.
3. "Product," *Universal Hydrogen* Available: https://hydrogen.aero/product/.

Thermal Analysis

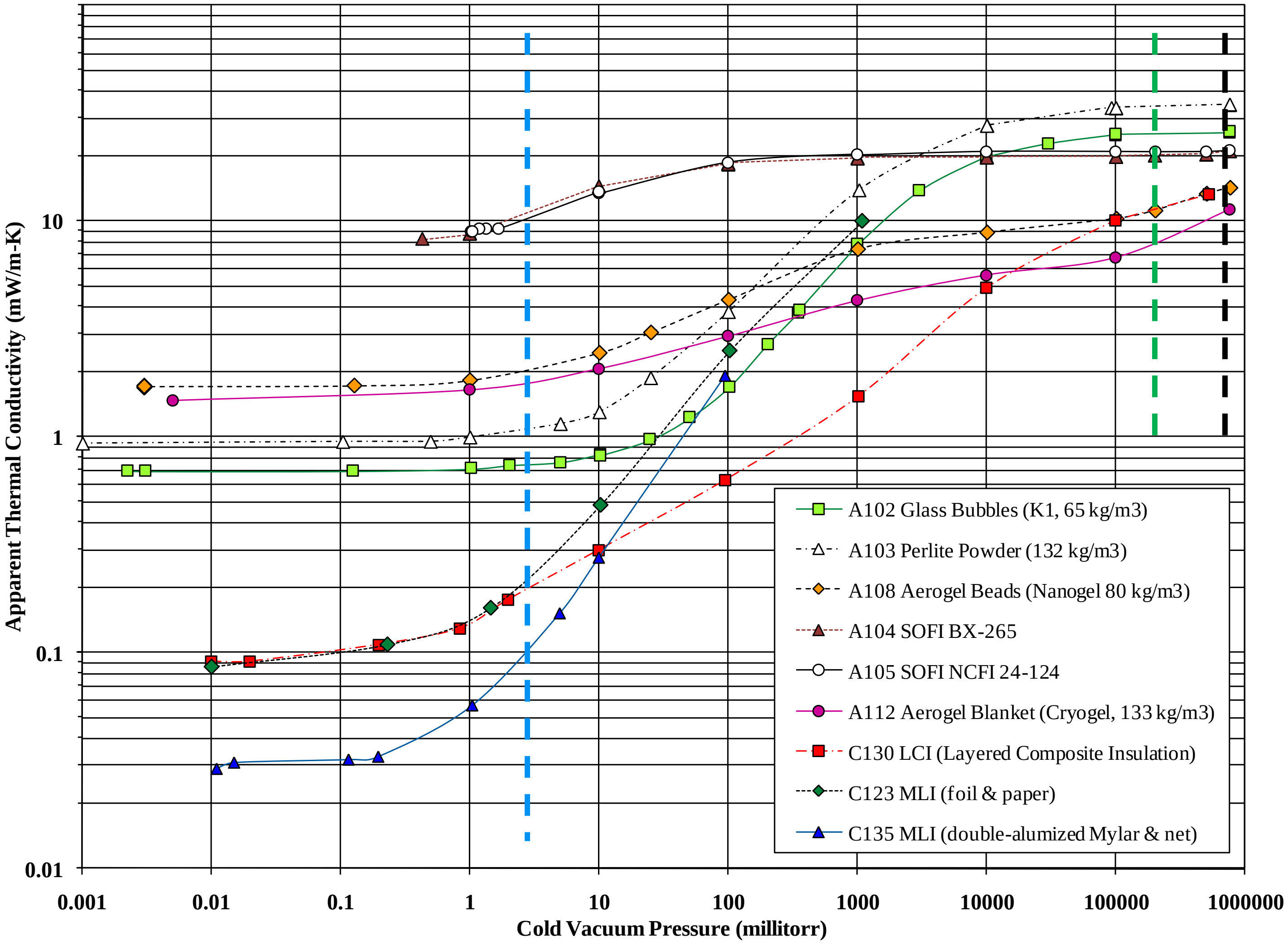
- Solves a quasi-steady heat transfer model for every time step
  - Tank assumed isolated with no active blowing
  - Ideal gas
  - Heat out: Radiation + Natural Convection
  - Heat in: conduction
- Splits total heat between liquid and ullage as a function of fill level
- Assume saturated LH2 such that all heat entering liquid causes it to boil
- Calculates rate of change in tank pressure due to boiloff rate and fuel flow to engines
  - If pressure is rising: vent
  - If pressure is falling: boil additional fuel

$$Q_{in} = Q_{convection} + Q_{radiation} = h(T_\infty - T_s) + \varepsilon\sigma(T_\infty{}^4 - T_s{}^4)$$

$$Q_{out} = Q_{conduction} = K\,(T_s - T_{LH2})\,/L$$



Insulation Performance Curves



Aircraft typically operate between 760 Torr at sea level and 200 Torr during cruise.

Insulation systems work the best at < 10 milliTorr

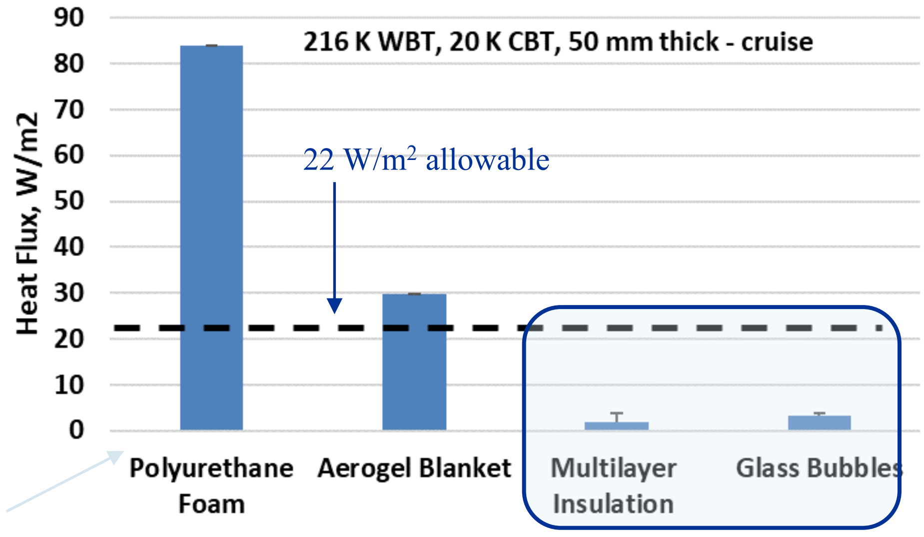
Allowable Heat Fluxes

Mission Segment	Flow Rate per Tank* (kg/s)	Allowable Heat Load (kW)**	Allowable Heat Flux (W/m2)***
Cruise	0.16	1.4	22
Ground – Take off	0.45	3.8	61
Ground - Idle	0.045	0.38	6.1

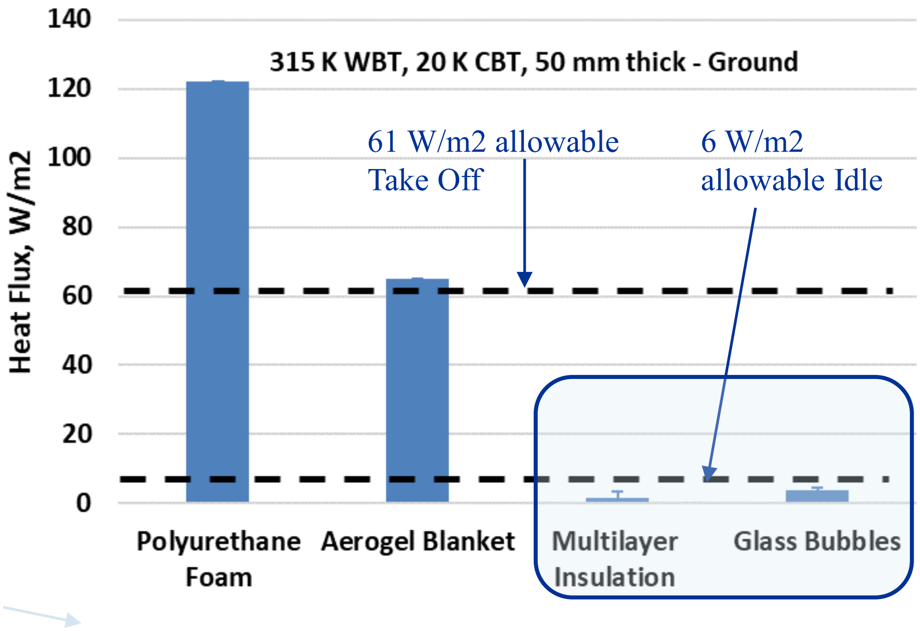
*Assumed that two tanks were feeding engines per 14 CFR § 23.2430
**Ratio of vapor to liquid density: 0.019; Heat of vaporization: 448 kJ/kg
***Tank area of 63.1 m^2

Results

Cruise

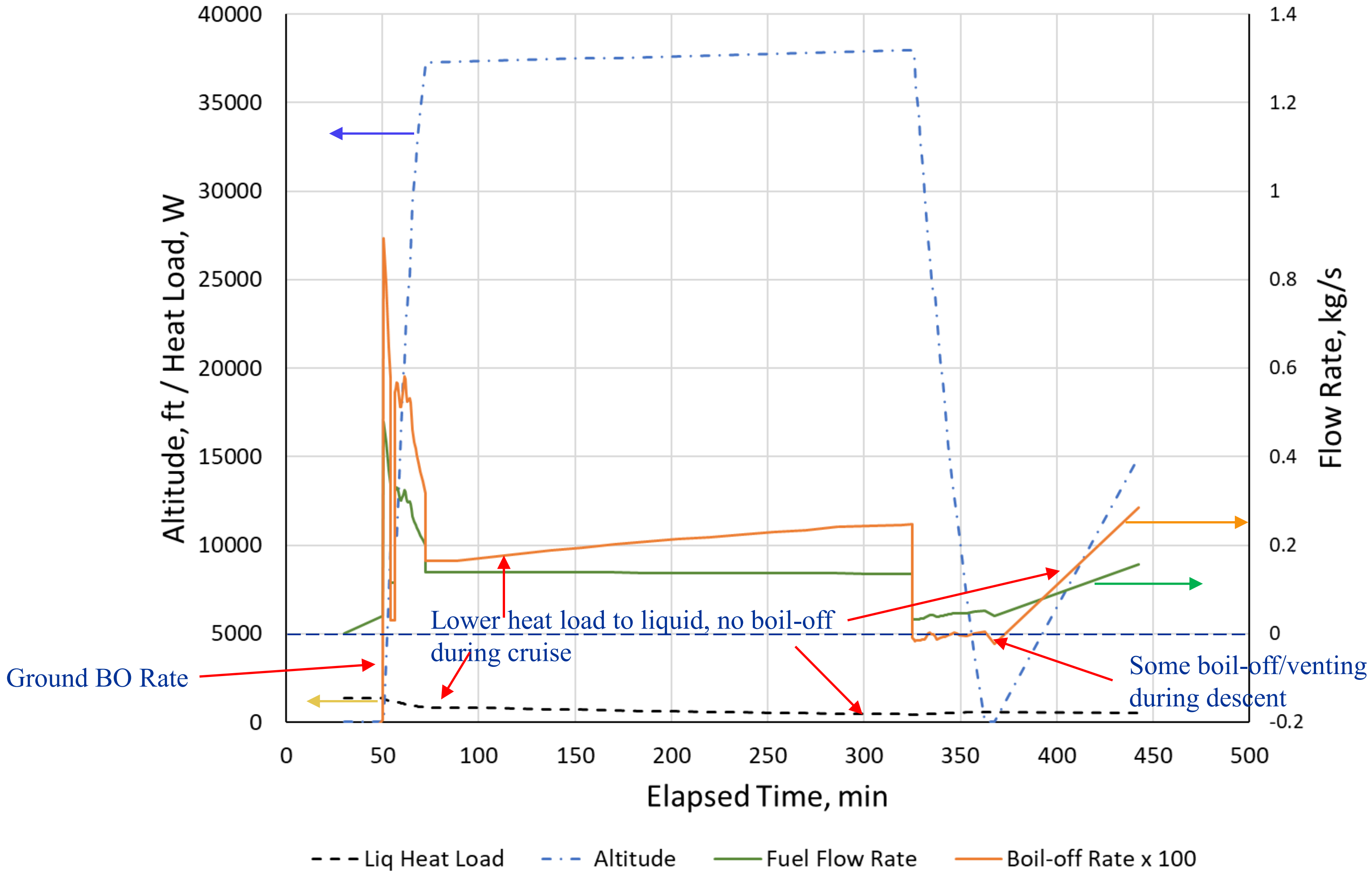


Ground



- Only vacuum jacketed insulations can meet all heat load requirements to prevent venting at 50 mm thickness.
- Aerogel blankets could meet requirements at slightly higher thicknesses for all except idle engine states.

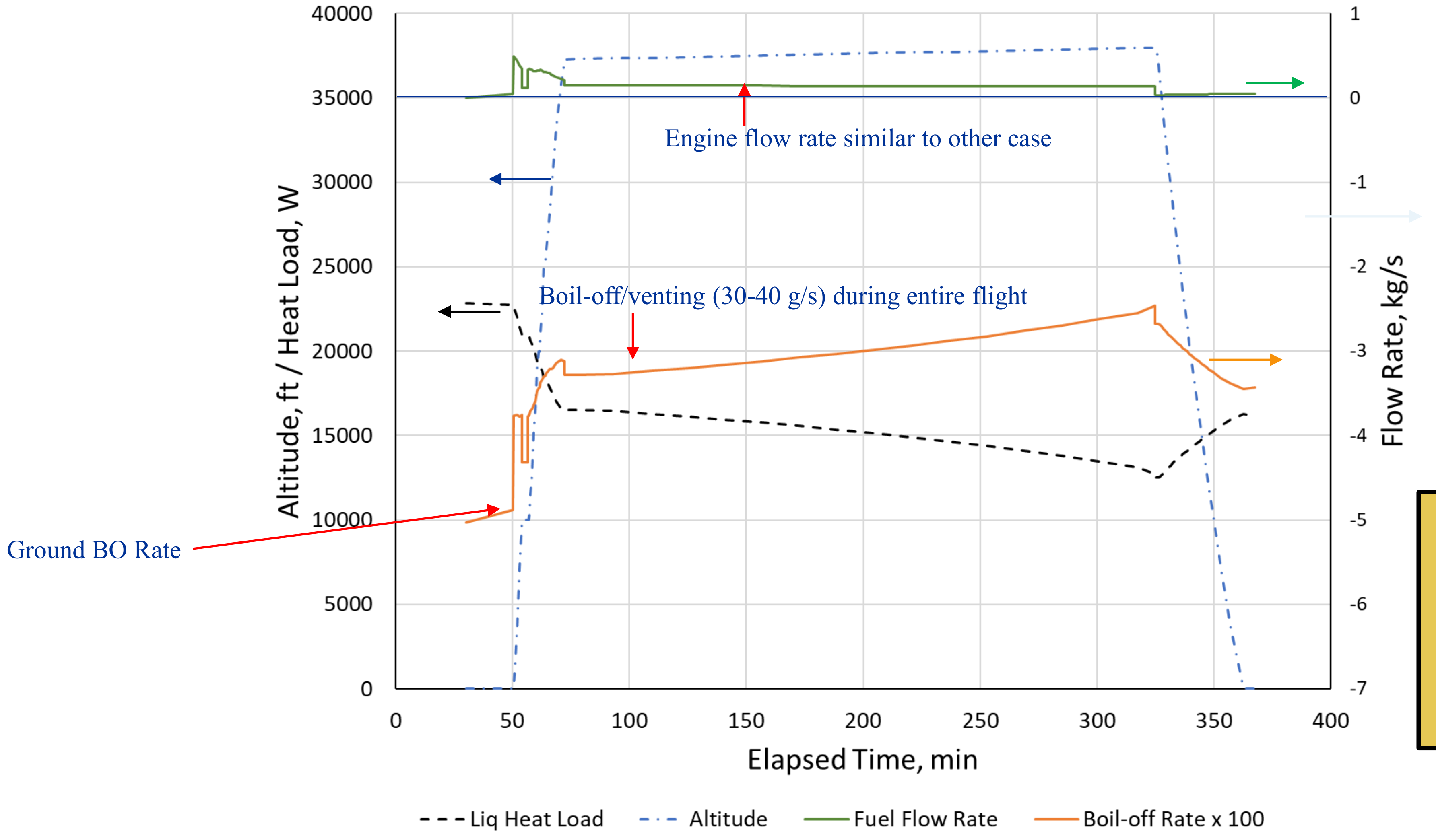
Glass Microspheres Flight Simulation



- Positive Boil-off rate is heat added to system, negative is mass lost.
- Only 7.9 kg vented during flight duration. Of which > 5 kg is during ground portion.

Glass Microsphere only vents pre-takeoff and minimally during descent

Polyurethane Foam Flight Simulation



- Positive Boil-off rate is heat added to system, negative is mass lost.
- Significant hydrogen vented due to boil-off.

Hydrogen being vented throughout duration of flight.

LH2 Tank Weight Breakdown

Insulation weight = (Insulation Volume)*65 $\frac{kg}{m^3}$ + (Insulation Surface Area)*1.1 $\frac{kg}{m^2}$

+ Tank weight = (Tank Volume)*2660 $\frac{kg}{m^3}$

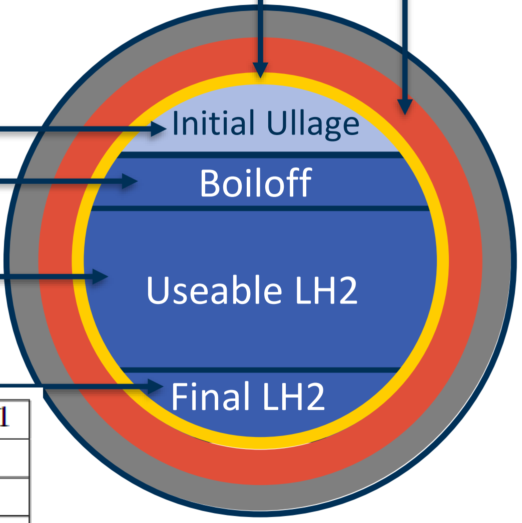
+ Additional Fuel System Component = 1.5(Tank weight + Insulation Weight)

Fuel system empty weight

+ Unusable Fuel = Initial Ullage + Boiloff + Final LH2

+ Useable Fuel = Mission Fuel

Total Fuel system weight

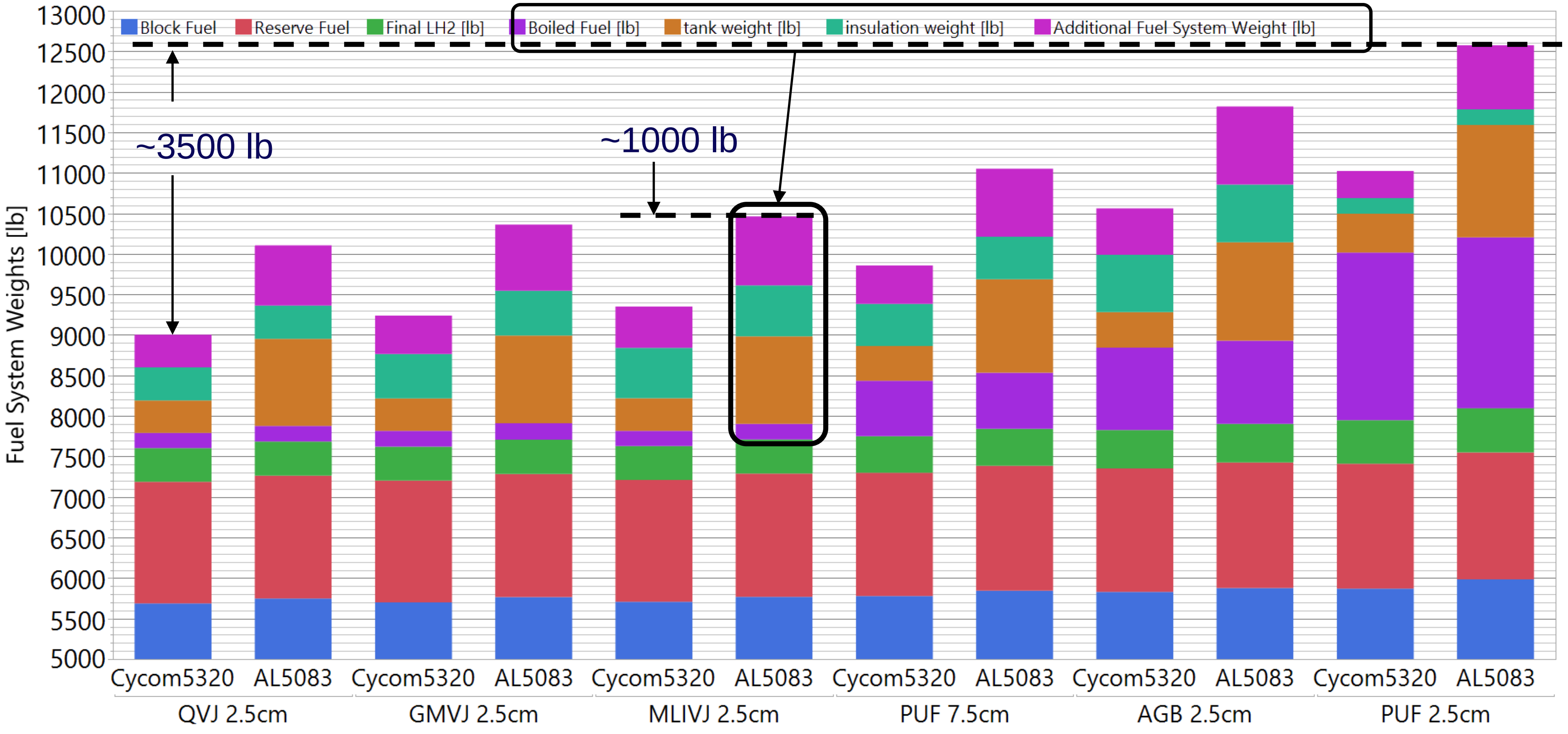


Insulation	Density $[kg/m^3]$	Surface Area Density $[kg/m^2]$	Thermal conductivity $[W/(mK)]$
Polyurethane Foam (PUF)	32.0	0.0	2.2E-2
Aerogel Blanket (AGB)	130.0	0.0	1.13E-2
Glass microsphere vacuum jacket (GMVJ)	65.0	1.1	8.25E-4
Multi-layer insulation vacuum jacket (MLIVJ)	80.0	1.1	2.2E-4
Quest Vacuum Jacket (QVJ)	0.0	2.0	2.1E-4

Properties	AL5083	Cycom5320-1
Yield Stress $[psi]$	33,000	190,000
Density $[kg/m^3]$	2,660	1,310
Thermal conductivity $[W/(mK)]$	17.2	0.167

Tank weight buildup is important to assess impacts of weight on aircraft fuel burn

Comparison of Different Insulation Systems



Tank Wall Materials

- Aluminum: AL5083
- Composite: Cycom5320

Insulation Materials (2.5 cm):

- Polyurethane Foam (PUF)
- Aerogel Blanket (AGB)
- Glass microsphere vacuum jacket (GMVJ)
- Multi-layer insulation vacuum jacket (MLIVJ)
- Quest Lightweight vacuum jacket (QVJ)

Polyurethane foam is light (lower fuel system mass), but the higher boiloff requires additional fuel to be carried. Which results in larger tanks, increased aircraft structural weight, and worse fuel burn

Conclusions

- Insulation choice critical to avoiding venting during key phases of flight.
  - Use of higher performance vacuum insulation required to avoid venting on the aircraft analyzed.
  - May require development to decrease weight and increase reliability
- Holding tank pressure constant during operation allows for simpler analysis and may be practical implementation.
- Composite tank decreases fuel system mass by roughly several hundred kg over AL5083 tank.
- Vacuum jacketed insulations decrease fuel consumption by at least 10% from foams or aerogel blankets.
  - Due to savings in vented fuel during mission.
  - Does not include impacts of maintenance on either.

Questions

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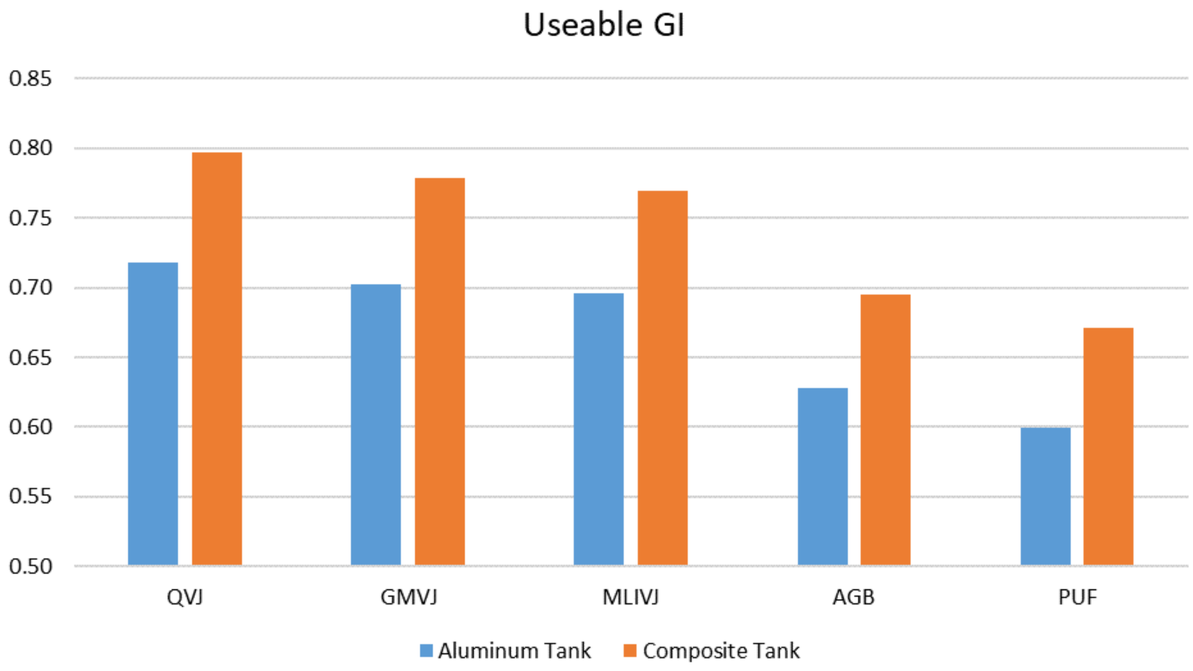
Gravimetric Index

$$Gi_{usable} = \frac{Block\ Fuel + Reserve\ Fuel}{Initial\ Liquid\ Mass + Initial\ ullage\ mass + Fuel\ System\ mass}$$

Fuel System Mass = (Empty tank mass + insulation mass)*1.5

Note: fuel distribution system assumed to be 50% of empty tank + insulation mass



Tool Inputs

- Tank Shape:
  - Inner Radius: 3.66 m
  - Length: 3.33 m
  - Inner Surface Area: 166.7 m2
  - Tank Wall: Aluminum 6061/NIST
- Environment:
  - Cruise Temp: 216 K
  - Ground Temp: 315 K
  - Sweeps between
  - Cruise pressure: 200 torr
  - Vacuum pressure: 0.01 torr
  - Ambient pressure: 760 torr
- Insulation Thickness:
  - Nominal 50 mm
  - Increasing thickness up to 175 mm
- Insulation Materials:
  - 19700 – Aluminum 6061 (Tank wall)
  - 10102 – Glass Bubbles (A102)
  - 10104 – SOFI/BX-265 (A104)
  - 10125 – Multilayer Insulation (A125)
  - 10112 – Blanket Cryogel/Aerogel (A112)