Ice Growth Model and Lunar Tanker for Polar Water Extraction

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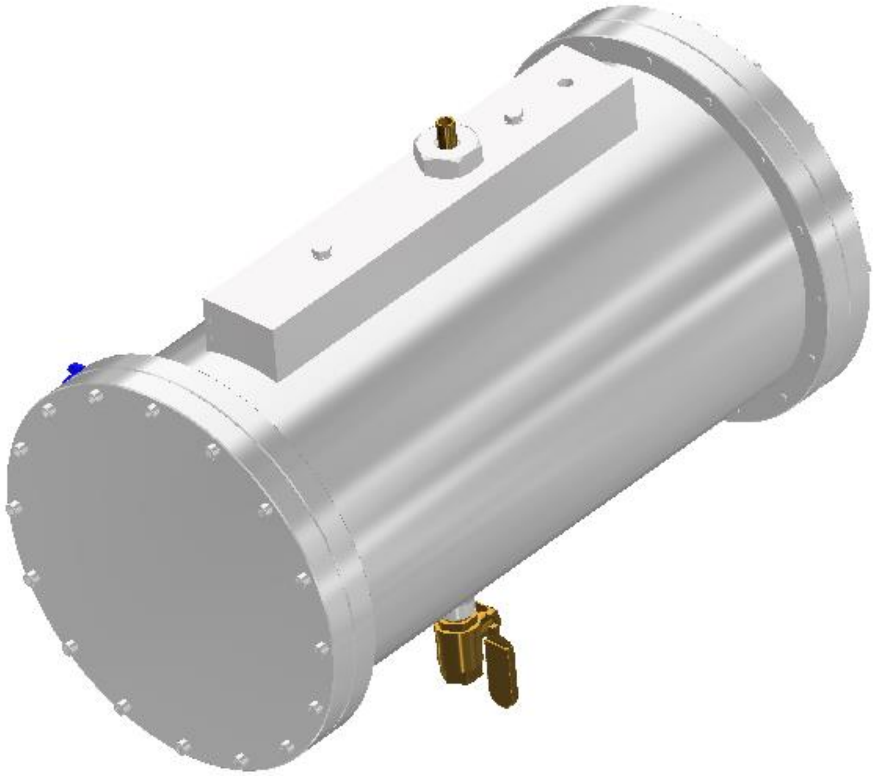
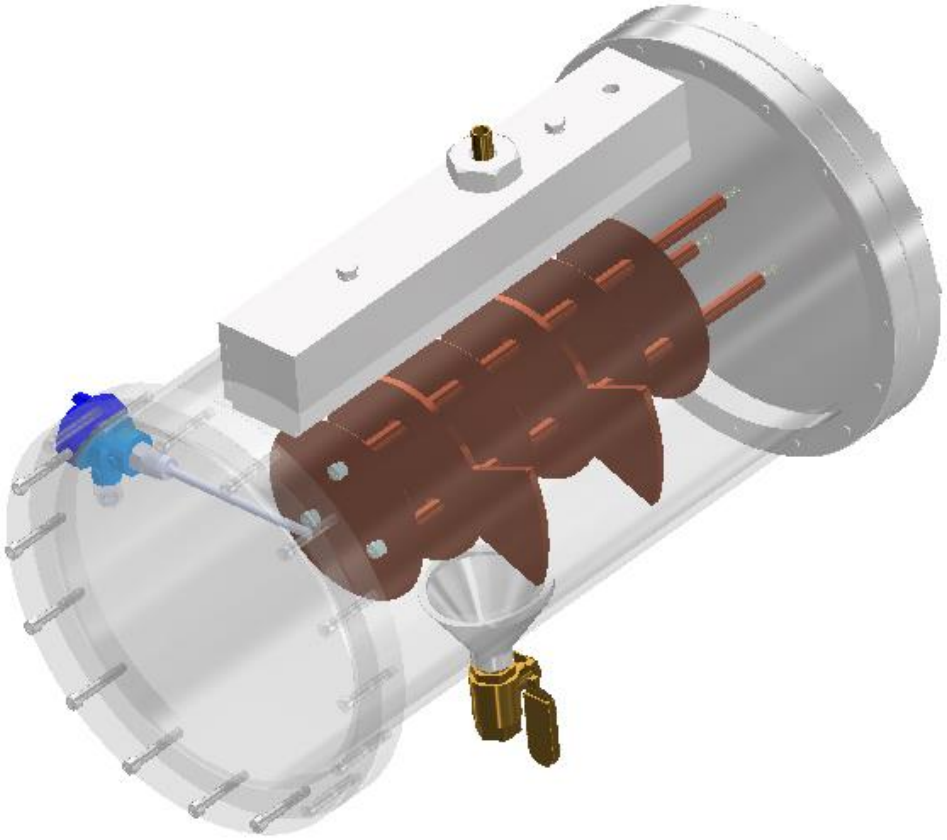
Beau M. Compton/NASA GRC
Diane L. Linne/NASA GRC
Landon E. Moore/TTU
Alexis M. Palomarez/TTU
Songoli E. Egwuatu/TTU

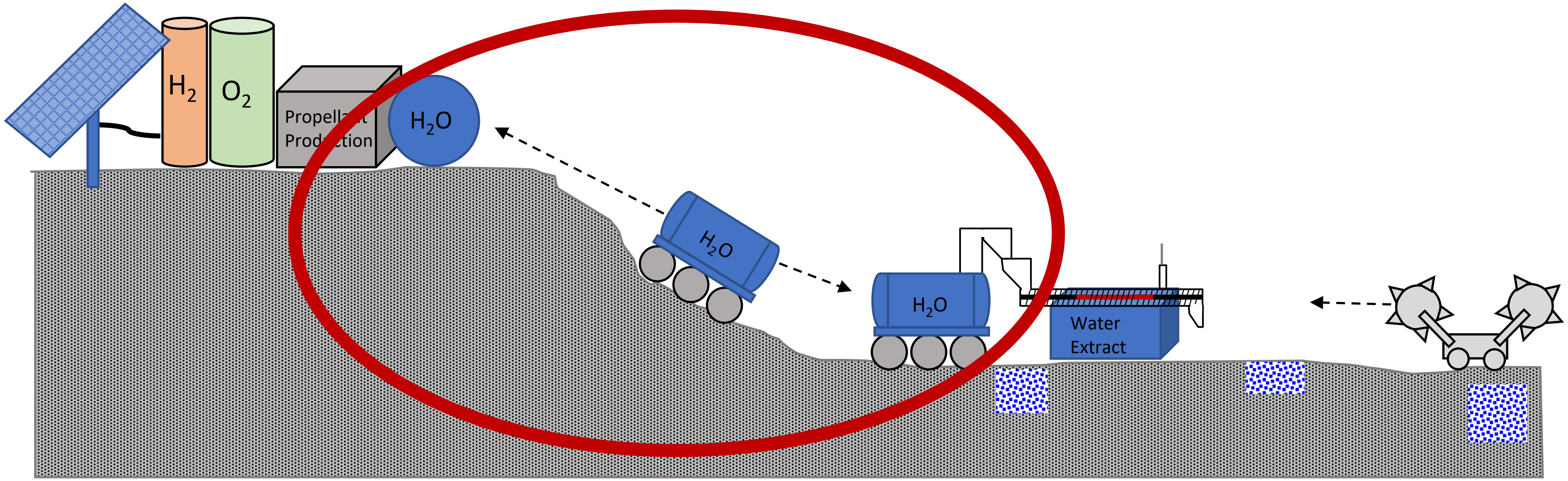
Background





Polar Water Pilot Plant Background

- NASA GRC-led Compass study to develop a conceptual design for an ISRU system that extracts water from the permanently shadowed regions (PSR) and processes it on the sunlit ridge
  - Goal is 1000 kg of oxygen in one year
- Power in PSR provided by previously landed nuclear power supply
- Power on ridge provided by solar arrays
  - Assume operation only during 225 days of continuous sunlight
- Regolith in PSR assumed to contain 5% water by mass
- The concept of operations was to harvest lunar regolith, bake it to get water vapor, and electrolyze the water to get H_2 and O_2 propellants



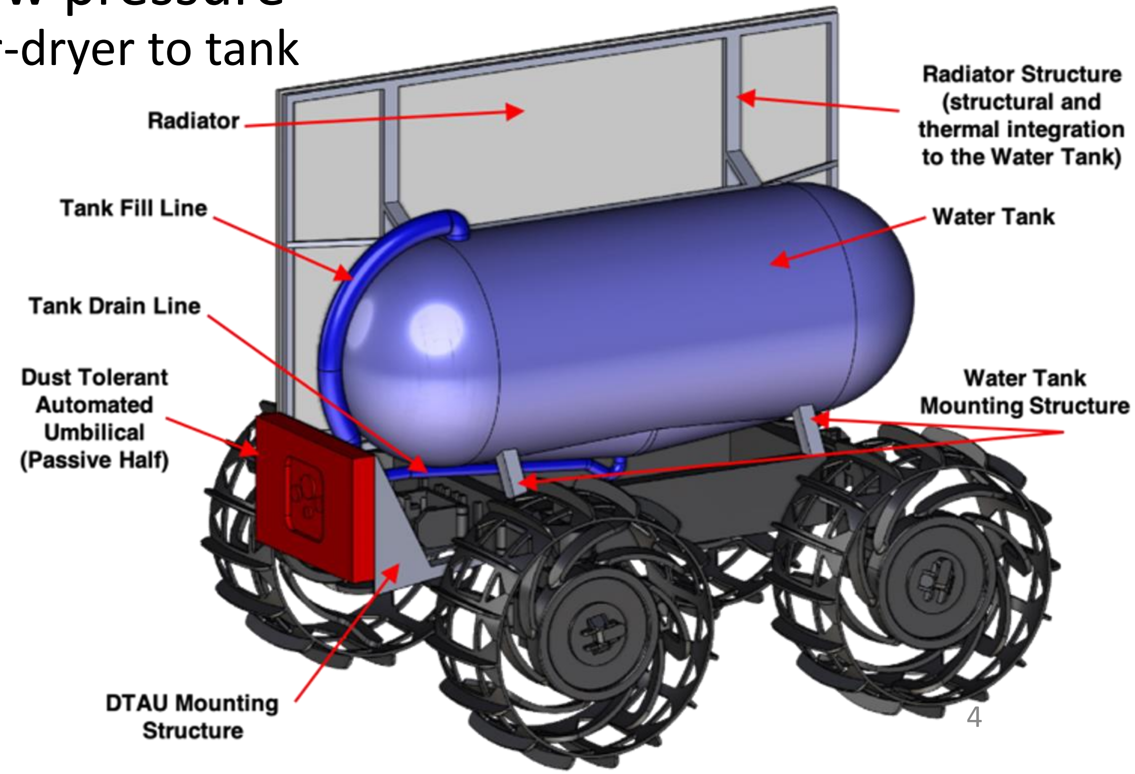
ConOps schematic for lunar water extraction, electrolysis, liquefaction, and storage

Ref: *Linne, D.L., Kleinhenz, J.E., and Paz, A., "Lunar Polar Water Pilot Plant Conceptual Design," AIAA 2020-4236, November 2020*

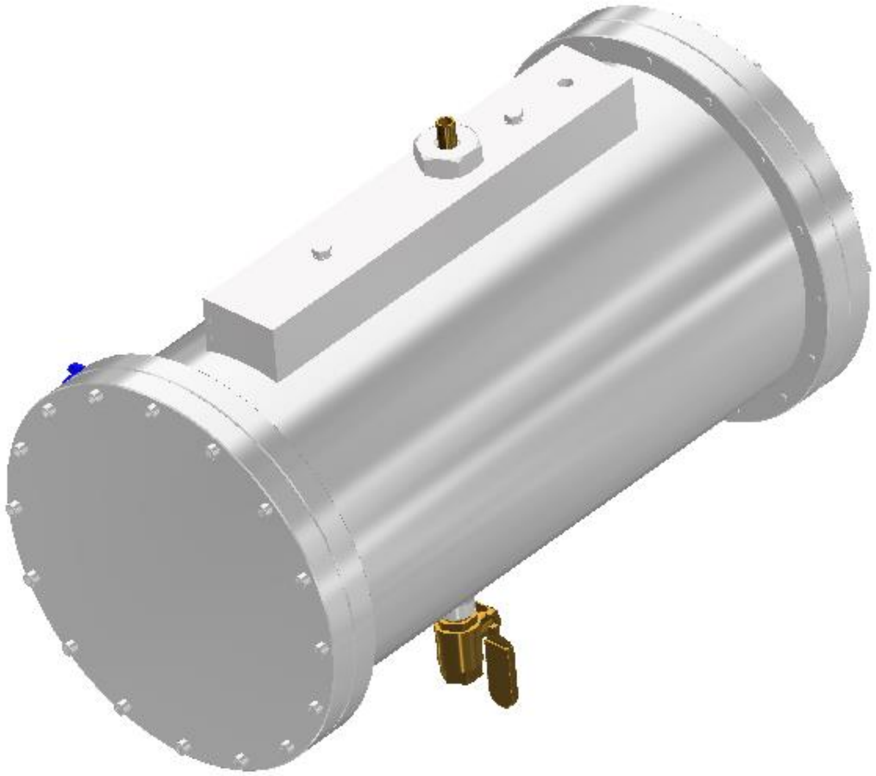
Lunar Tanker Background

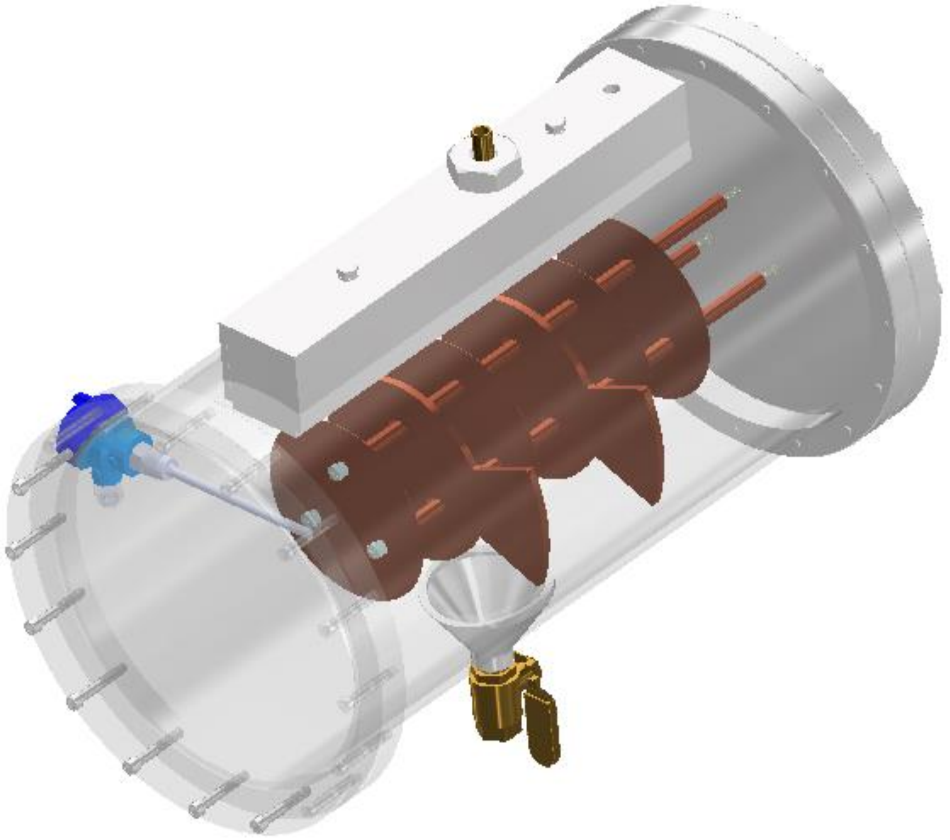
- Initially designed as liquid water tanker
  - Required significant energy and insulation to maintain water as liquid in PSR and during transport
  - Either triple mass of mobile platform battery for same number of trips, or triple number of trips out of PSR
- Ice tanker takes advantage of surrounding environment
  - Radiator sized to freeze water at the extraction rate
  - Each tanker carries 54 kg of ice per trip (1 trip every 11 days)
  - Radiator turned towards sun on ridge to melt ice before transfer to Ridge plant
- Freezing water also maintains ice tanker at very low pressure
  - Acts as cryopump to maintain flow of water from auger-dryer to tank

Ice Tanker was sized based on total ice volume (with some margin). No thermal analysis was performed to determine feasibility of freezing all the water on the interior tank walls



Diffusion-Limited Aggregation (DLA) Frost Model

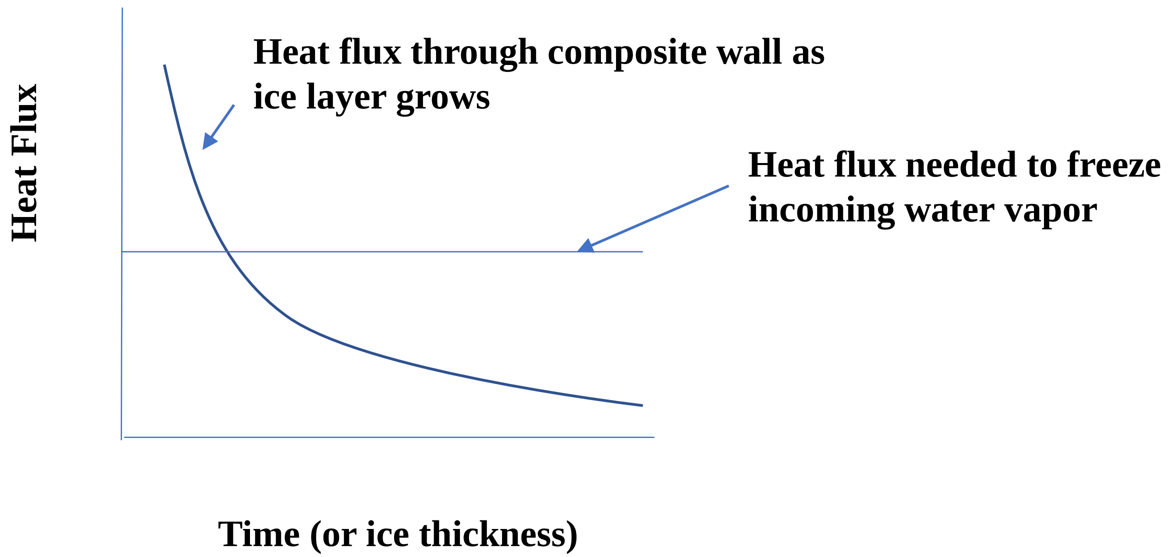


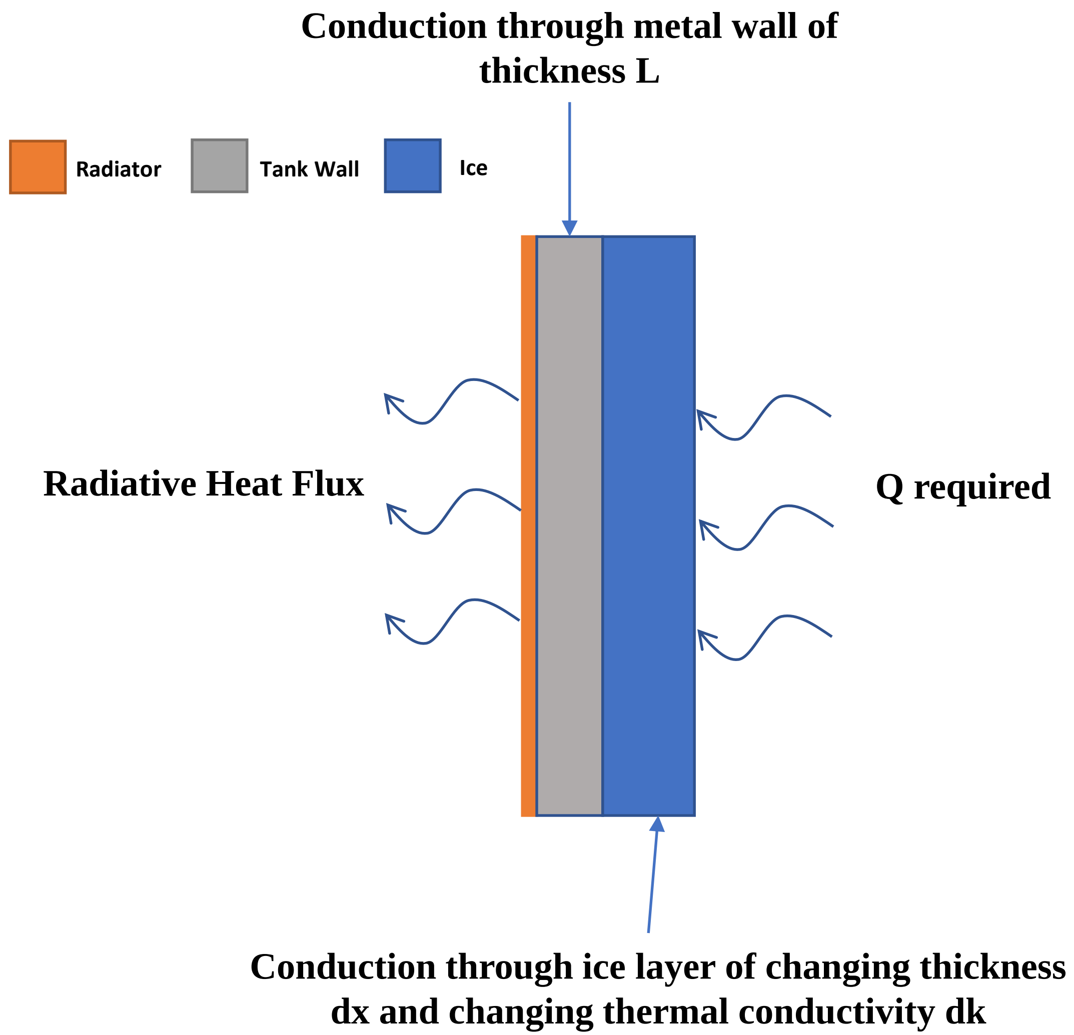


DLA Frost Model

Current Problem

- As the ice layer builds, the thermal conductivity will drastically decrease as ice has a much lower thermal conductivity than the tank wall and radiator
- The rate at which the thermal conductivity decreases with ice layer growth needs to be determined
- Using this flat plate model for a composite wall, we need to determine if the heat flux will remain above the minimum value required to continue to freeze the incoming vapor





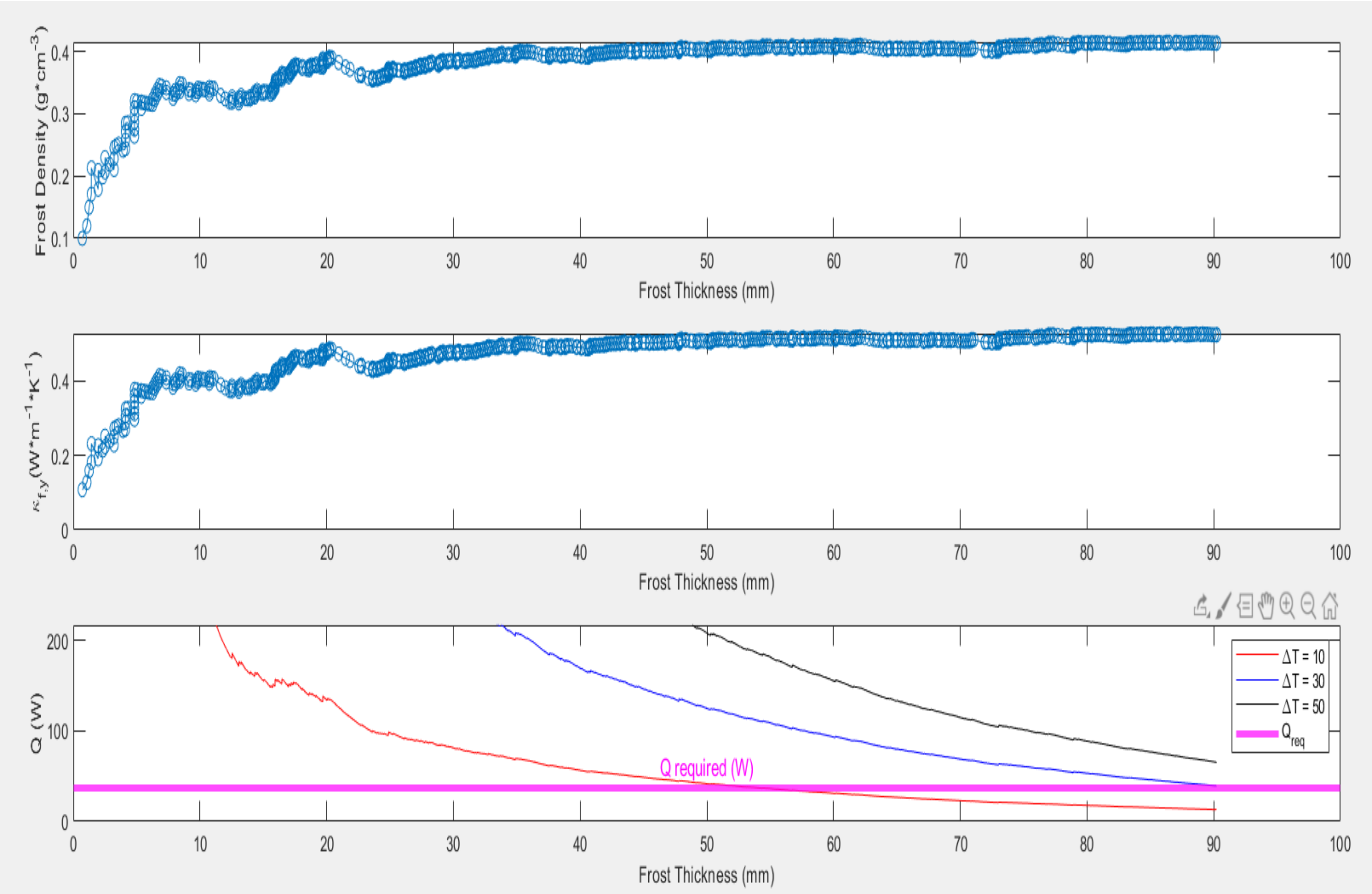
DLA Frost Model

Ice Growth Modeling

- DLA model was used to model the buildup of frost layer over time with density measurements taken for a given timestep
- Effective thermal conductivity measurements are calculated using a popular correlation by Yonko & Sepsy:

$$\kappa_f = 0.0140 + 0.00668\rho_f + 0.000175\rho_f^2$$

    - This correlation is generally applicable in the range of 243 – 263 K

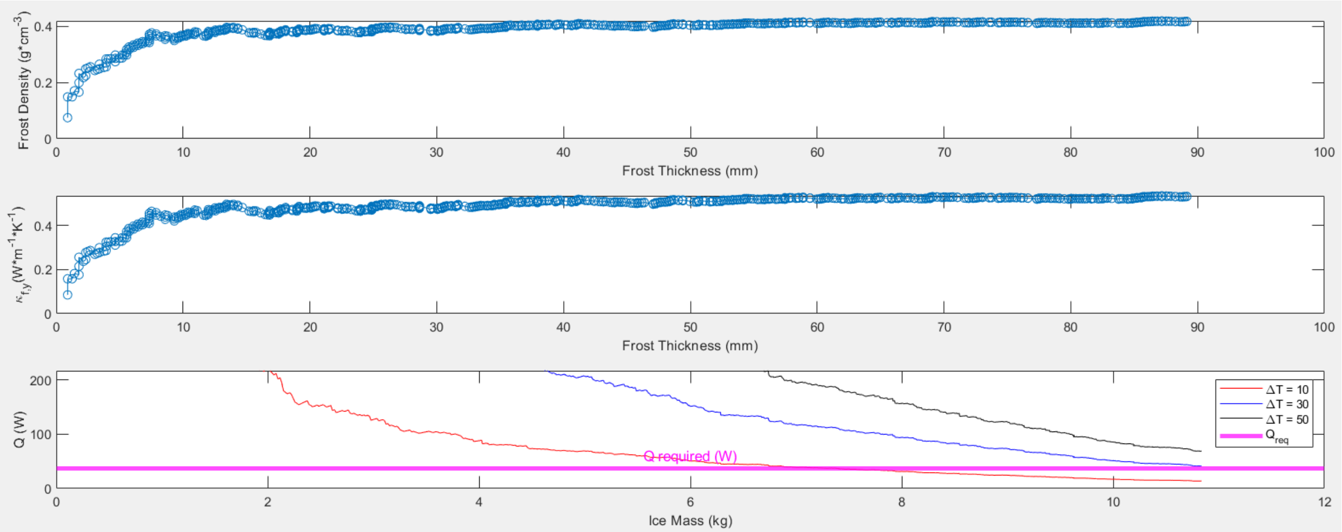


Predicted critical frost layer thickness for polar water pilot plant conditions. (Top) density from DLA model; (middle) thermal conductivity using Yonko & Sepsy correlation; (bottom) critical ice layer thickness for different temperature differentials.

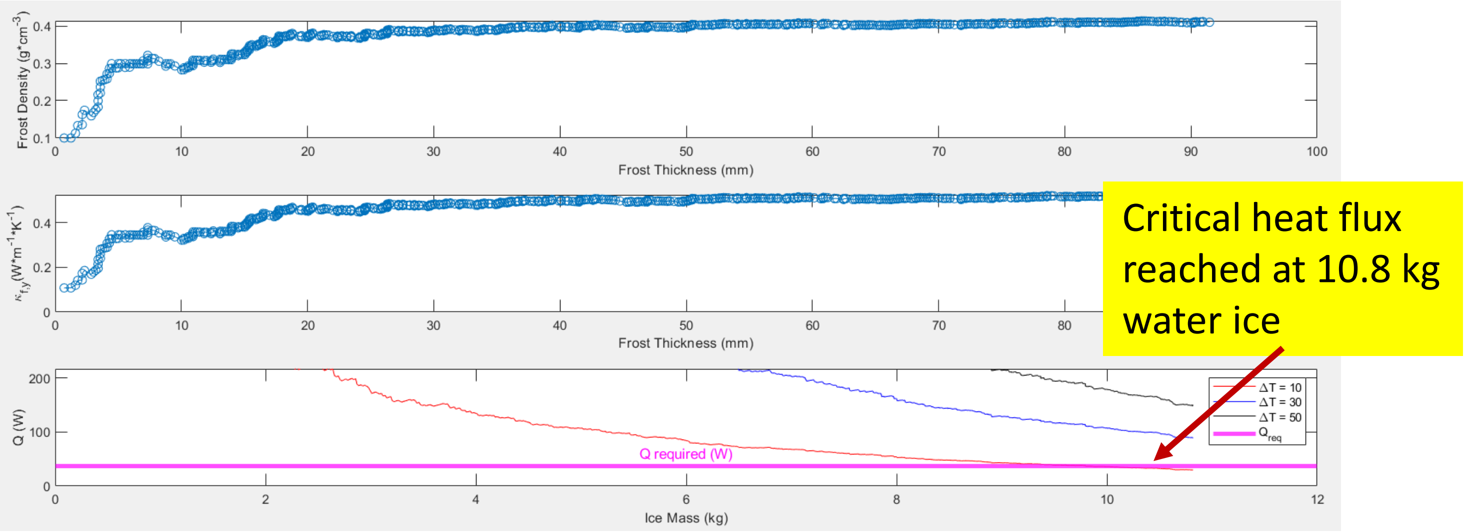
DLA Frost Model

Predictions made by model

- According to the model, approximately 3000 cm² (465 in²) of added surface would be sufficient to allow all water vapor to freeze for the 1/5 scale model (10.8 kg of water)
- This is integrated into the final test article build

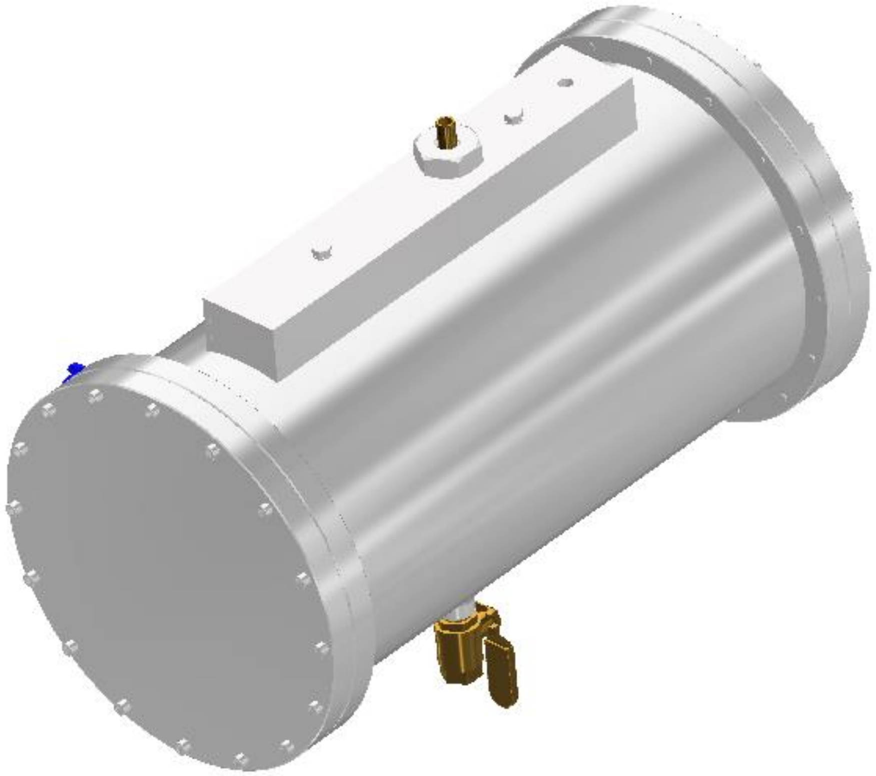


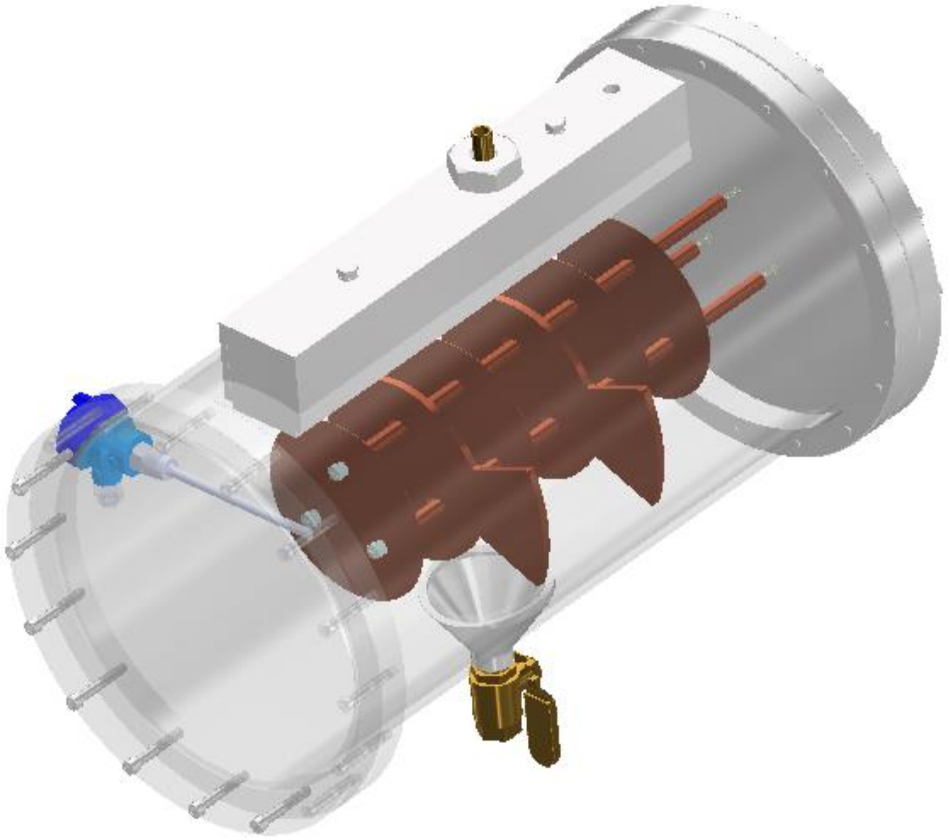
Simulation with no added surface area



Simulation with 3000 cm² of added surface area

Lunar Tanker Test Article





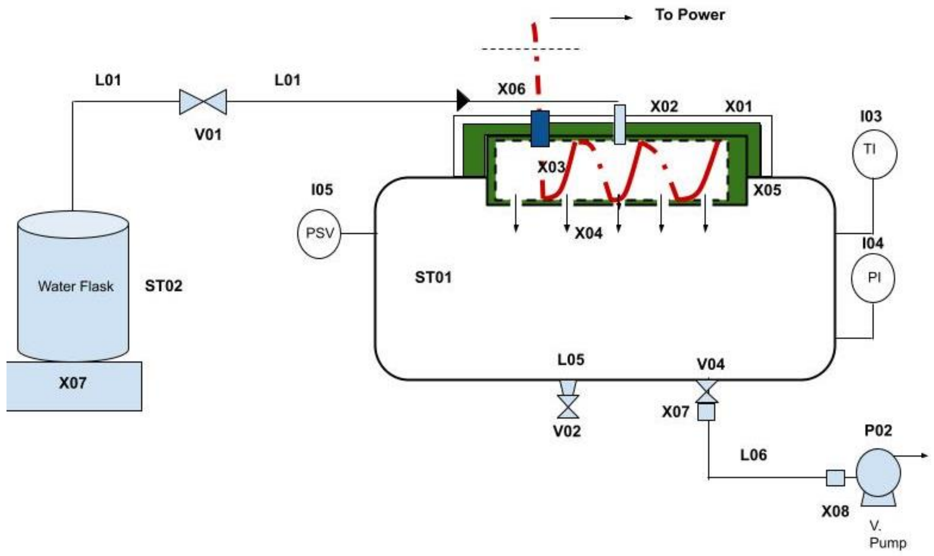
Lunar Tanker Test Article

- Objective: build a sub-scale ice tank test article to demonstrate ability to distribute water vapor and freeze on multiple surfaces.
- Pressure
  - Absolute pressure of 500 Pa
- Temperature
  - Dry Ice (194.7 K – Used for initial checkout testing)
  - Liquid nitrogen (77 K – Heat sink temperature used to simulate radiator)
- Volume
  - The vacuum chamber has a 0.61 m (24 in) diameter which set the scale of the test article
  - 1/5 volume of original test article (0.041 m^3) excluding thermal system and other components
  - Designed to hold 10.8 kg of ice

Lunar Tanker Test Article

Flow Processes

- Water enters the system via steam
- It enters the distribution system where square nozzles distribute it evenly across the tank
- The vapor is immediately frozen as it deposits on the inner tank surfaces
- Once the test is finished, the tank is repressurized and the ice melts and is rejected through the bottom of the tank



Flow Diagram of Essential Processes

Lunar Tanker Test Article

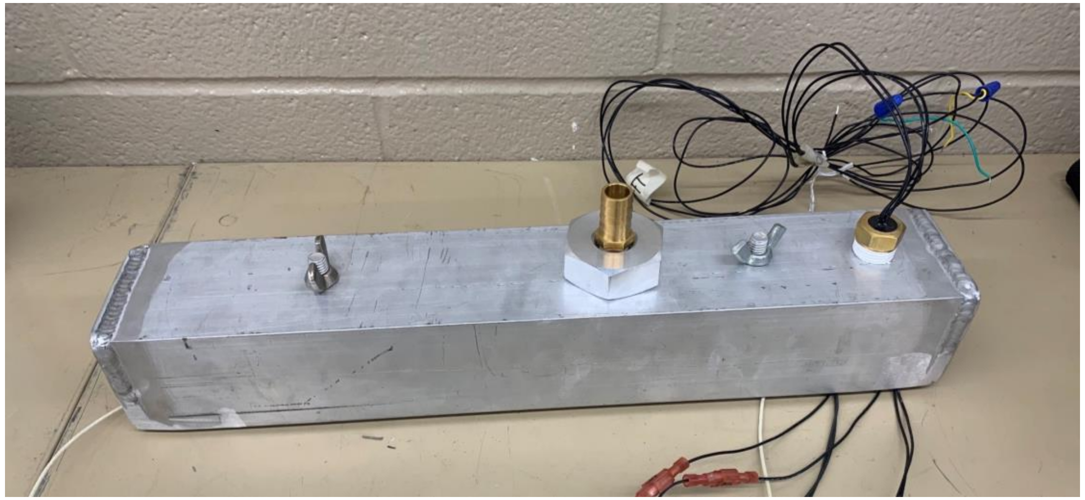
Thermal System

- Copper fins are added for surface area (3000 cm^2)
- Connected by copper piping to facilitate heat flow path
- Two plates have fins that extend to inner wall for additional heat flow path to tank wall and radiator
  - Micronized silver thermal paste used to ensure good thermal connection

Lunar Tanker Test Article

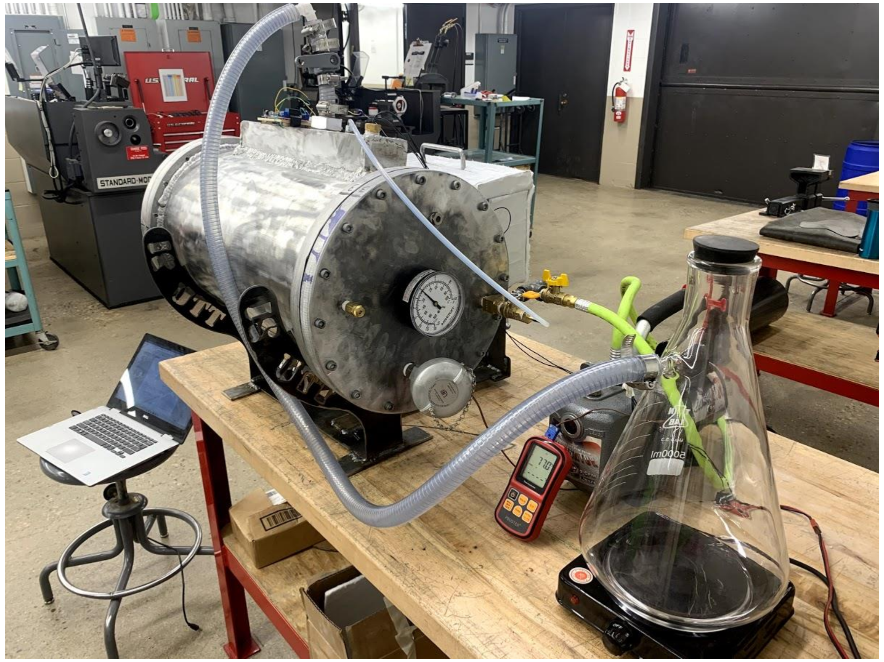
Distribution System

- Five nozzles that distribute evenly across the tank
- Distribution pipe is wrapped in heat rope and insulation to prevent vapor from freezing before distribution
- Feedthroughs allow electrical connection



Lunar Tanker Test Article

Final Assembly



Summary

- Analysis suggests freezing extracted water for trip out of PSR is more energy efficient than transporting as liquid water
- Need to understand how thick an ice layer will grow on internal tank surfaces
- Developed a multifaceted model that evaluates heat transfer through a frost layer
  - Need to increase internal surface area by ~43%
- Designed, fabricated, and assembled a test article that fits in a vacuum chamber and can be used to confirm the frost growth model