National Aeronautics and Space Administration

Concepts for the Liquefaction of Hydrogen for In-Situ Operations on the Lunar or Martian Surface

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Introductions

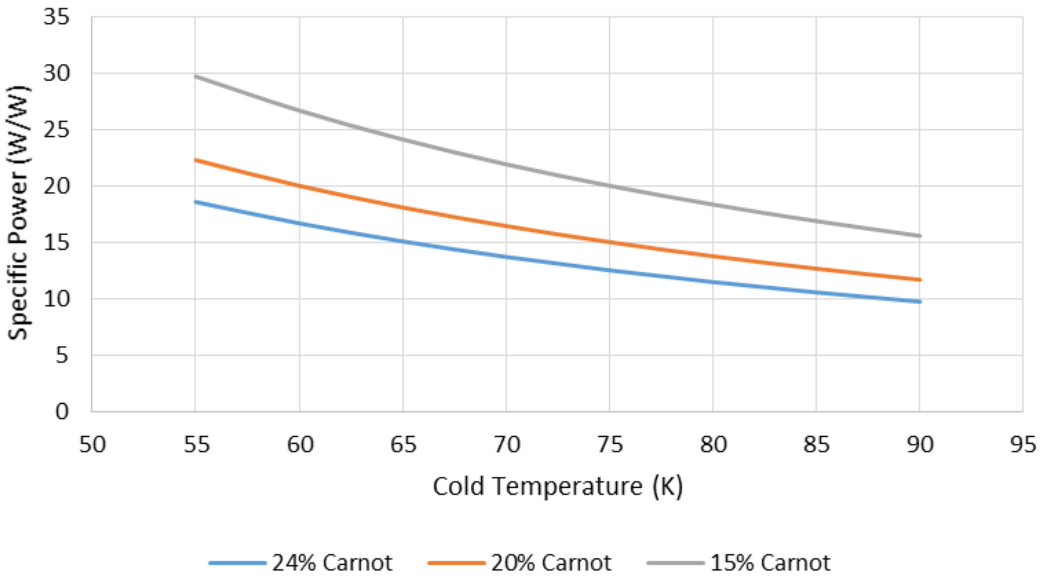
- NASA has been studying Lunar and Martian surface propellant production for approximately 30 years.
- The last step of propellant production is the liquefaction process.
  - Initially done within lander tanks, simply refueling them.
- NASA focused on oxygen liquefaction first:
  - Greater than 55% of any Lunar or Martian return vehicle is oxygen by mass.
    - Production on the surface decreases lander mass which decreases launch vehicle mass.
  - Oxygen production on Mars was demonstrated by Mars Oxygen ISRU Experiment (MOXIE) as a part of the Perseverance rover at rates between 1.5 and 11.2 mg/s.
    - Production was done on stationairy portion of the rover using carbon dioxide gas from the atmosphere.
    - Lunar production is done either through mining water ice or reforming oxides within regolith.
  - Completed CryoFILL oxygen liquefaction Demonstrations
    - (10/25) EXP-14: Cryogenic Fluid In-Situ Liquefaction for Landers: Prototype Demonstration
- NASA internally started doing analysis on hydrogen liquefaction several years ago.
  - Pulling together results from analysis completed over several years
  - Supporting multiple ISRU system level analysis campaigns

Hydrogen Specific Challenges

- Orthohydrogen to Parahydrogen conversion:
  - Hydrogen has at least two magnetic forms based on proton spin direction in the nucleus (para-hydrogen and ortho-hydrogen).
  - The equilibrium distribution of hydrogen between the two is a function of temperature.
  - The two magnetic forms have different energy states (ortho to para conversion is exothermic).
  - This increases in cooling power due to rejecting the energy of conversion.
- Enthalpy Change: Sensible Heat vs Latent Heat (assumption gas input at 300 K)
  - Hydrogen has a ~10x amount of enthalpy change due to gas changing temperature (sensible) compared to phase change (gas to liquid, latent).
  - Allows for much more impact to be seen by pre-cooling incoming gas.
  - Oxygen enthalpy changes for sensible and latent heat are similar to each other.
  - Methane has more enthalpy in latent heat than sensible heat.
- Specific Power of 20 K Cryocoolers.
  - Even with the same performance relative to ideal (Carnot) efficiencies, 20 K class cryocoolers require significantly more input power than 90 K class.
    - 20 K cryocooler development threshold: 80 $W_{elec}/W_{cryo\ heat\ removal}$.
    - 90 K cryocooler development threshold: 15 $W_{elec}/W_{cryo\ heat\ removal}$.
- Based on the greatly increased specific power and increase in sensible heat, significantly more electrical power is required for hydrogen liquefaction than oxygen or methane liquefaction.

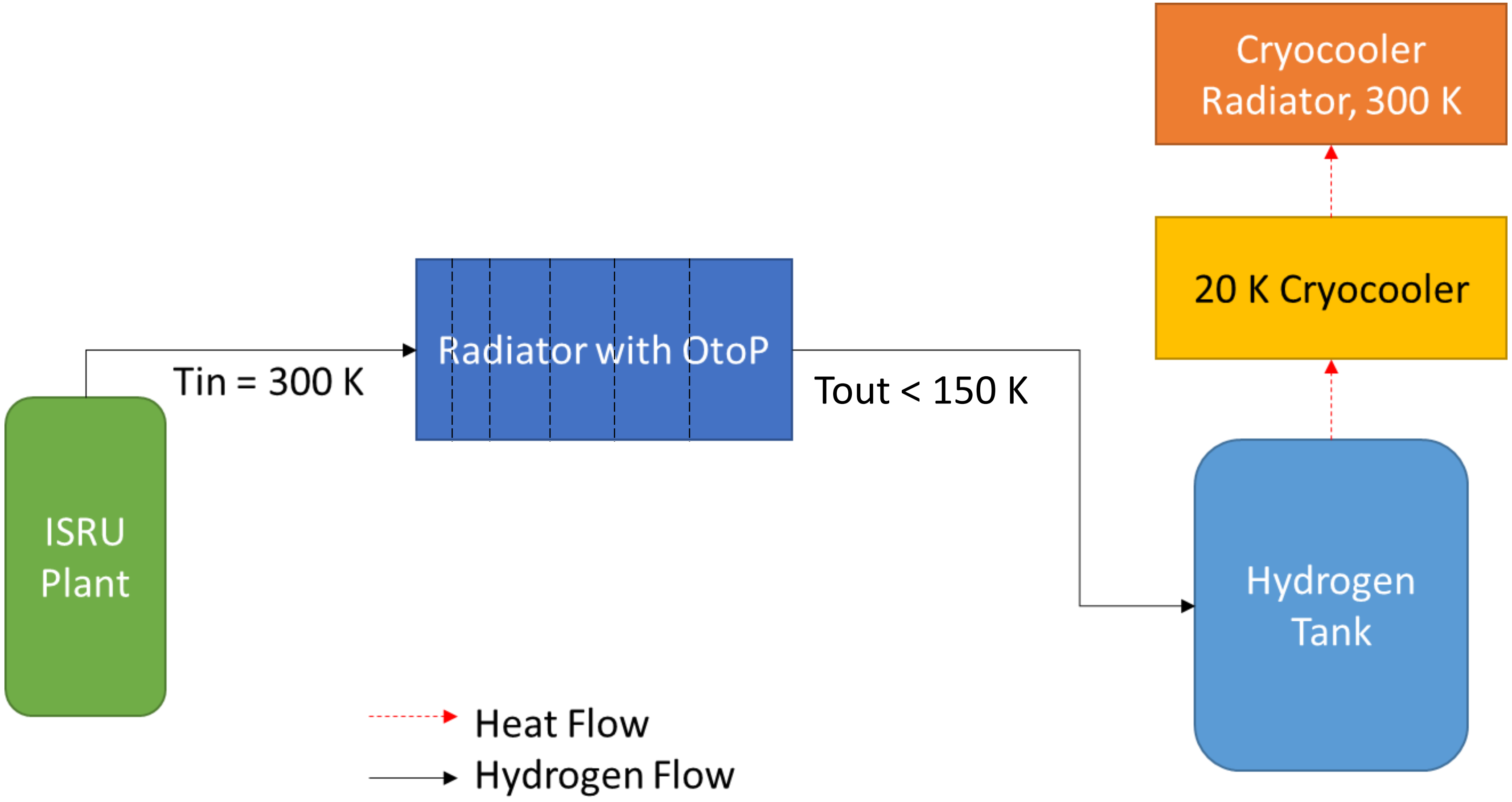
Baseline Assumptions

- Liquefaction rate of 0.3 kg/hr of hydrogen (~10 ton/yr total prop, ~1.6 ton/yr LH2) with production margin
- Inlet temperature: 300 K
- Includes ortho to para hydrogen conversion energy
- Investigate 3 different architectures
  - Single intermediate cryocooler
  - Single intermediate radiator (e = 0.7)
  - Both intermediate radiator (150 K) and cryocooler
- Trade Intermediate Cooler Eff
- Trade Intermediate Cooler Temp
  - Cryocooler efficiency as a function of temperature is shown in plot.

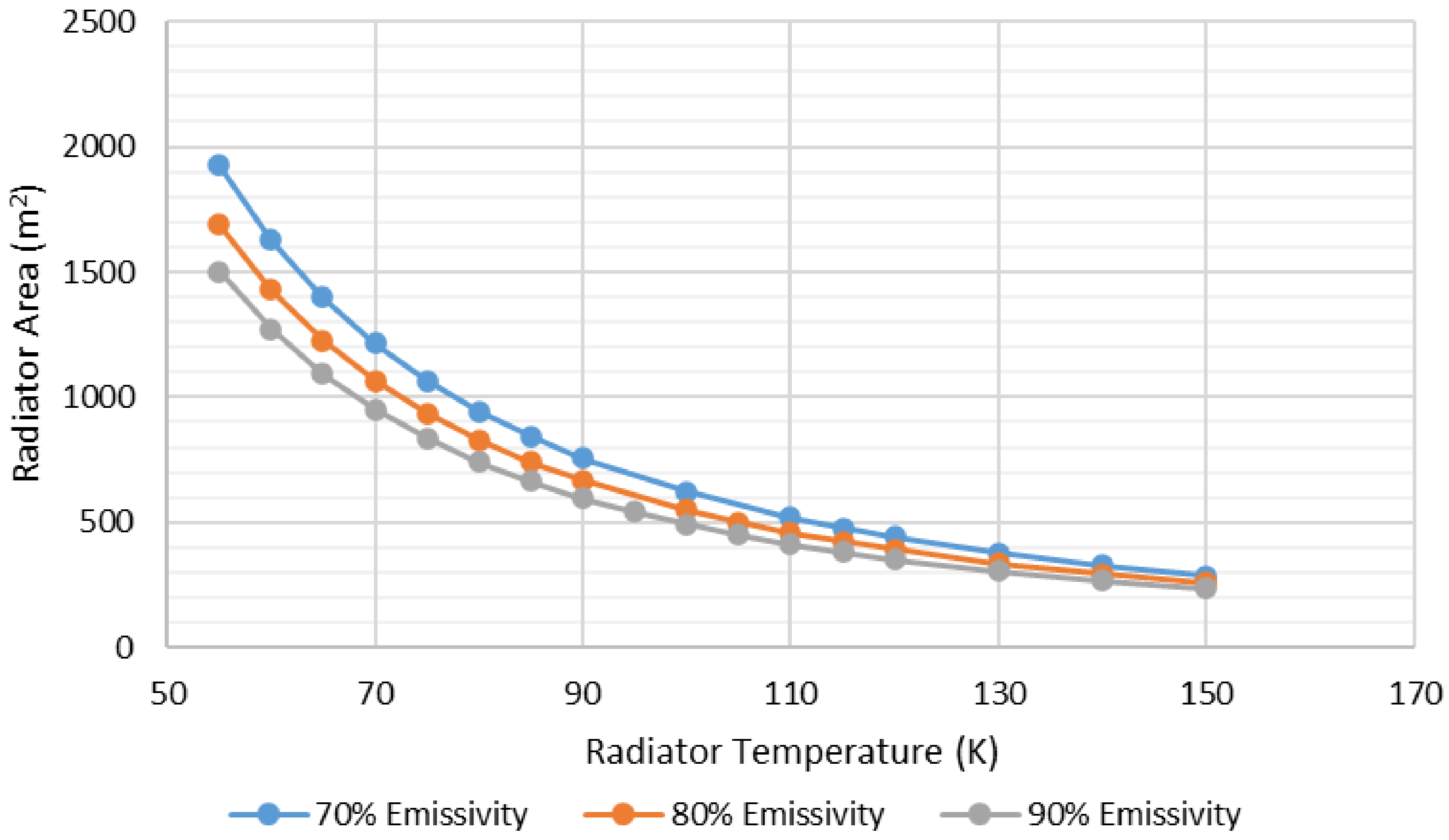


- 300 K radiator for cryocoolers (e = 0.8)
- For comparison: Single 20 K cryocooler requires 35 kW input power and 85 m^2 radiator
  - 6612 kg mass
  - No intermediate cryocooler for comparisons sake for other investigations.
- System oxygen liquefaction system would require < 2 kW

Radiative Pre-cooled Option



Radiator Only Option



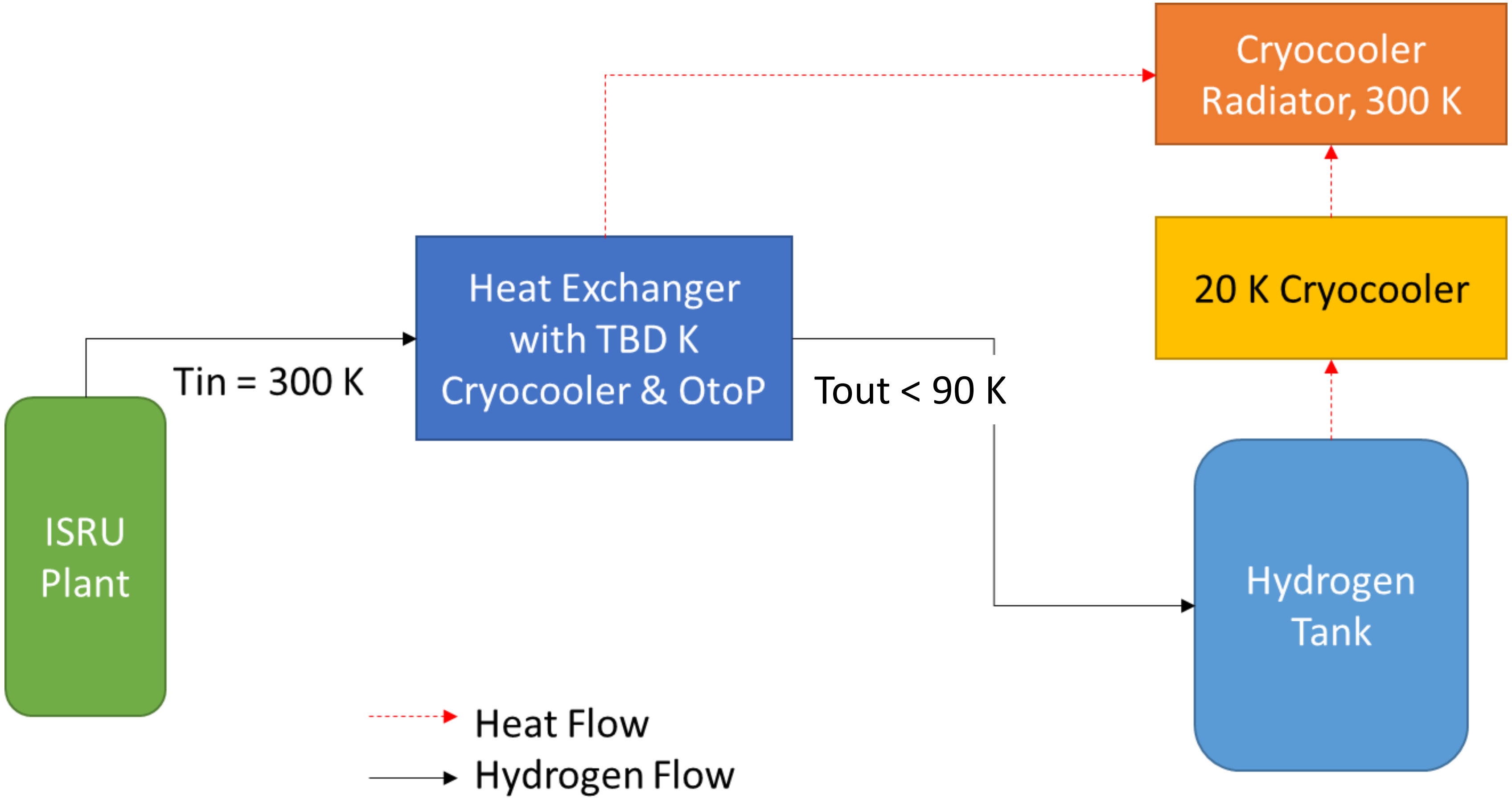
Areas for Radiators below ~ 120 K exit temperatures.

Areas get down to around 200 m^2 for 150 K option.

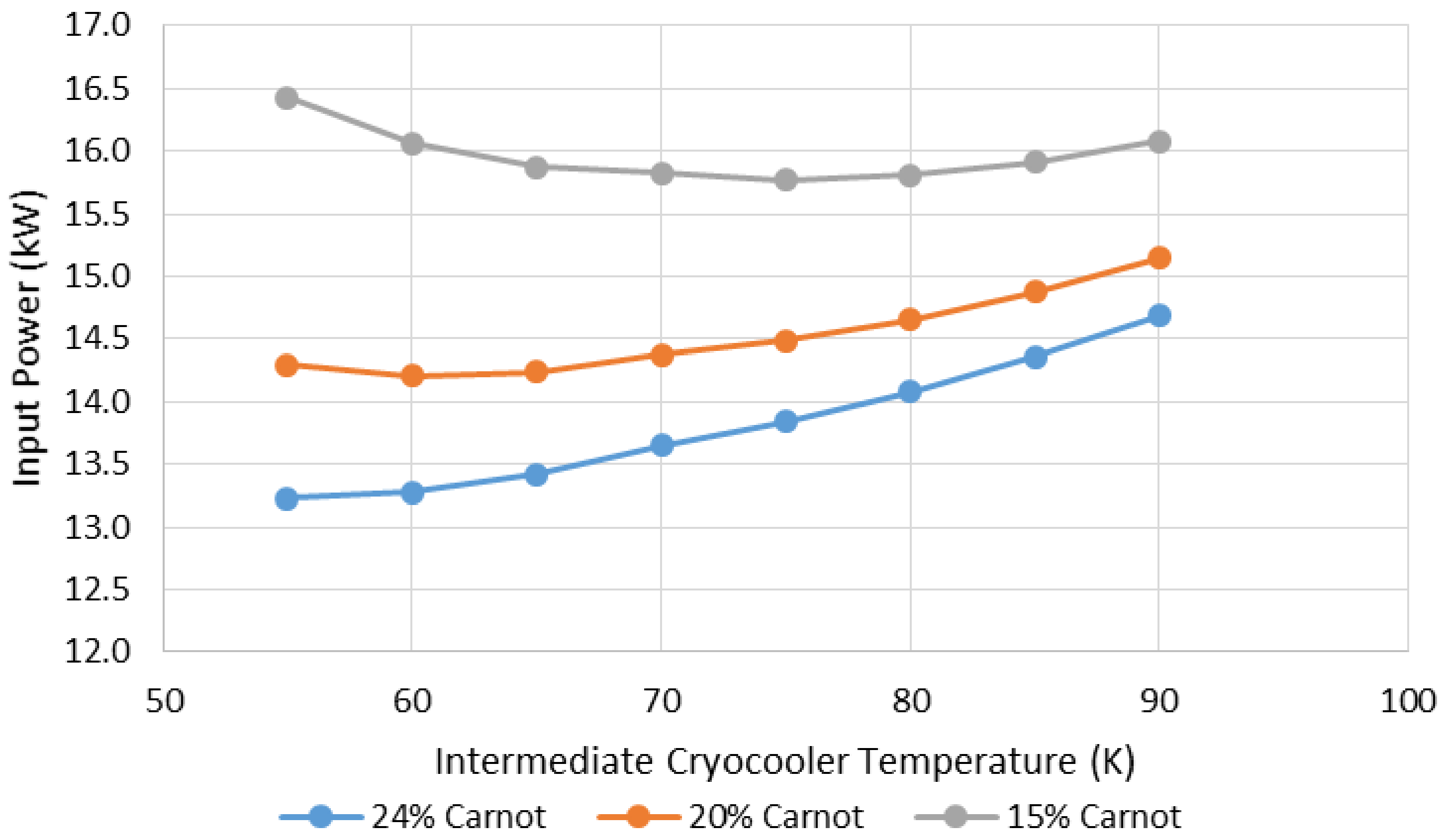
Input power reduced from 34 kW to 19 kW at 150 K radiator temperature.

- Change proportional to temperature.

Cryocooler Pre-cooling Option



Cryocooler Only Option

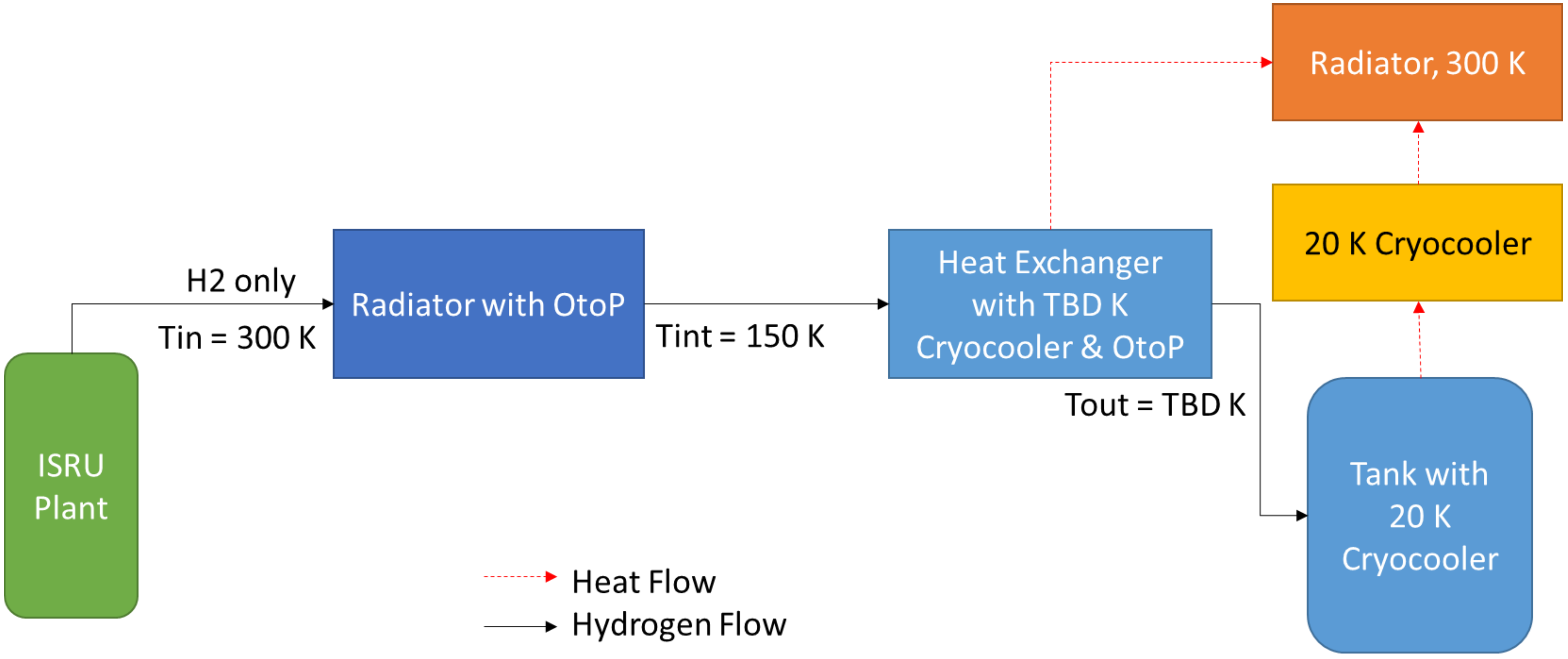


Depending on cryocooler efficiency, Intermediate temperature appears to minimize between 60 K and 75 K.

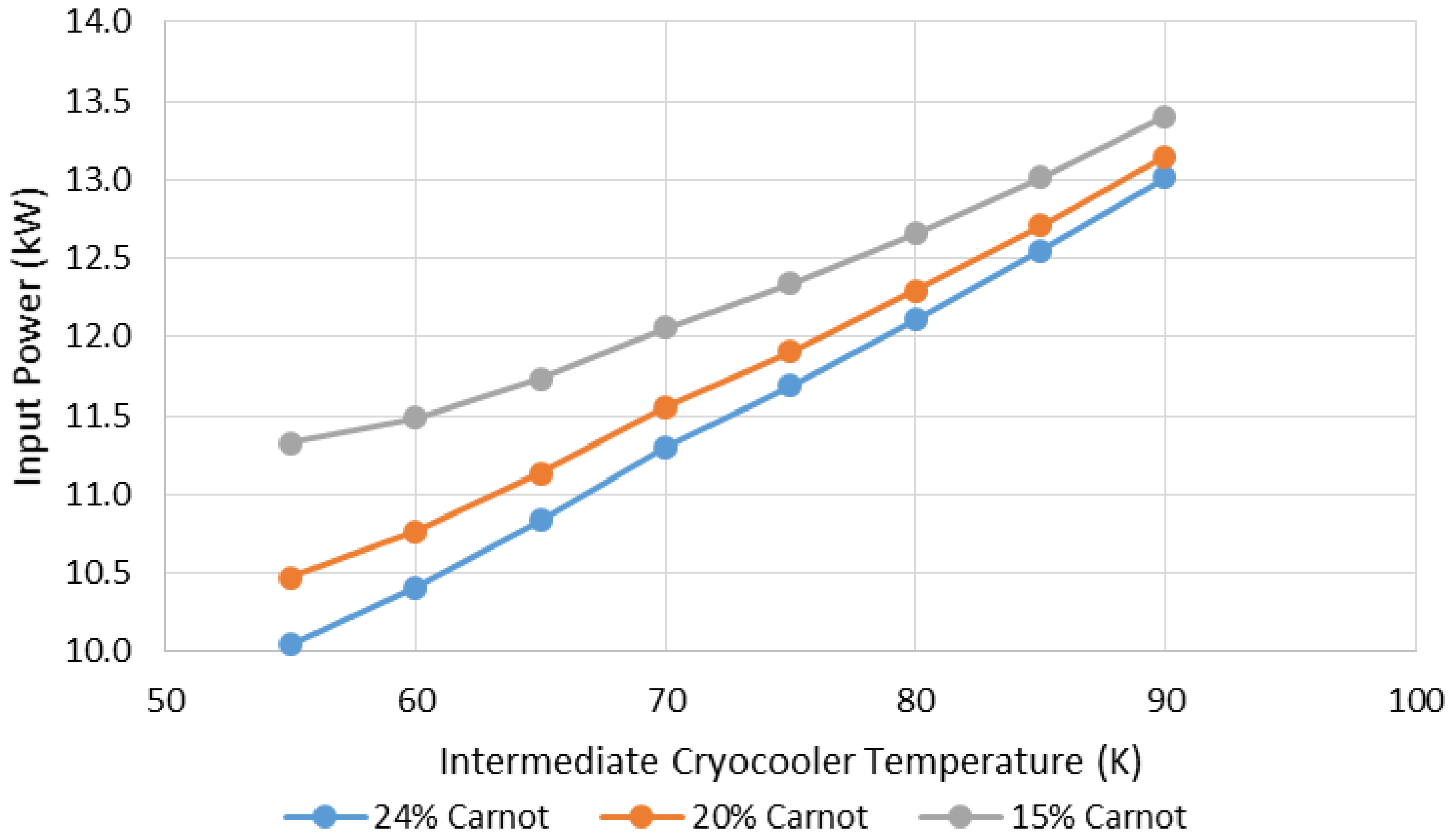
Reduces power input by 50% or more.

All radiator areas below 50 m^2.

Combined Pre-cooling Option



Radiator and Cryocooler Pre-coolers



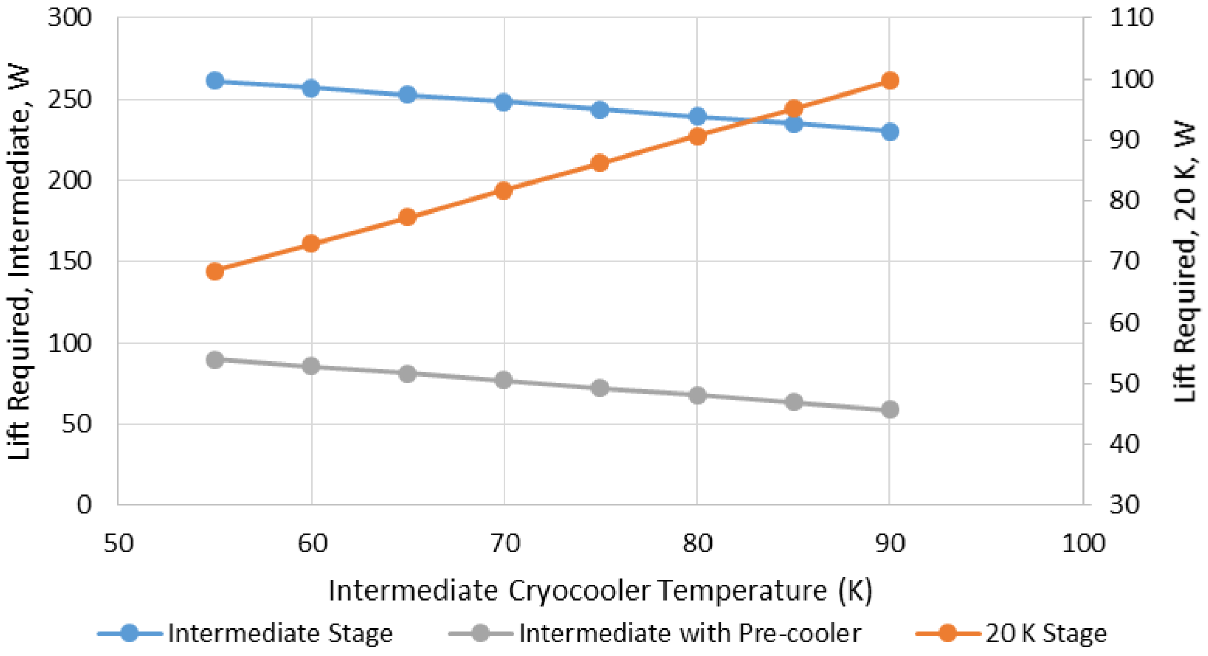
150 K Radiator skews intermediate cryocooler temperature towards 50 K.

Even with 15% Carnot intermediate cryocooler, cut input power by 70%.

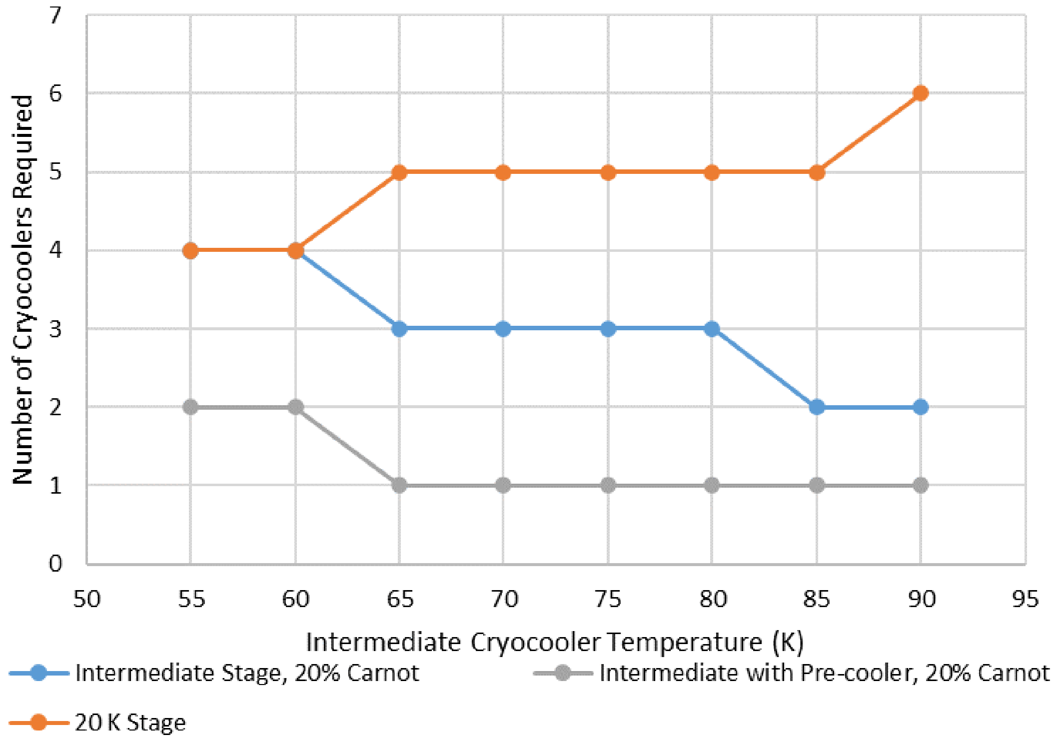
Radiator areas between 40 m^2 and 50 m^2.

Similar radiator area as Cryocooler Only pre-cooler with lower input power.

Cryocooler Lift Requirements



Requires on the order of 4-6 of currently in development High Capacity 20 K cryocoolers (approximately 20 W each).



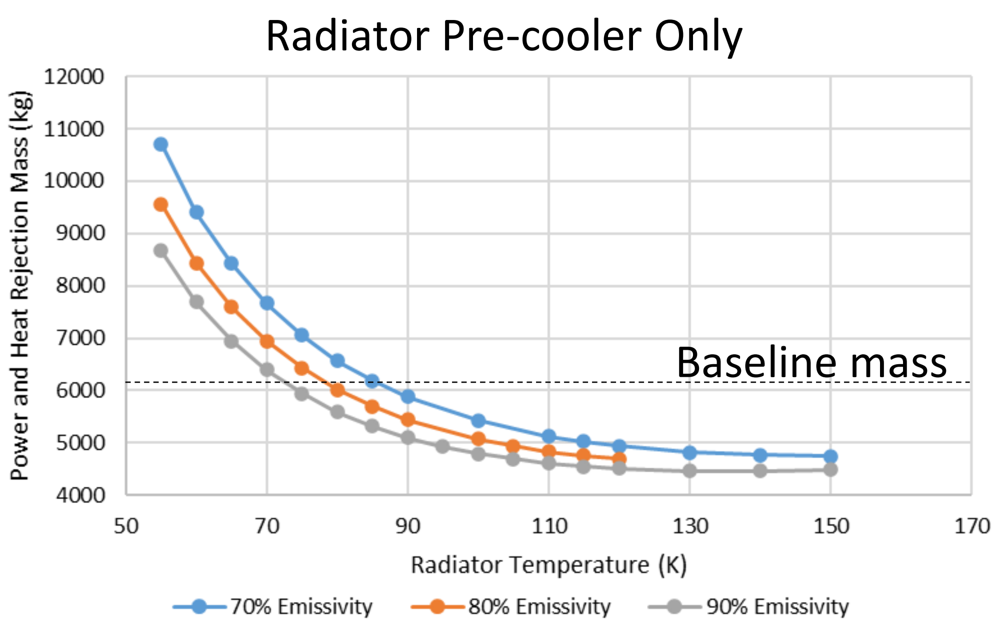
Requires 1-2 of currently in development High Capacity 90 K class cryocoolers (approximately 150 W each at 90 K).

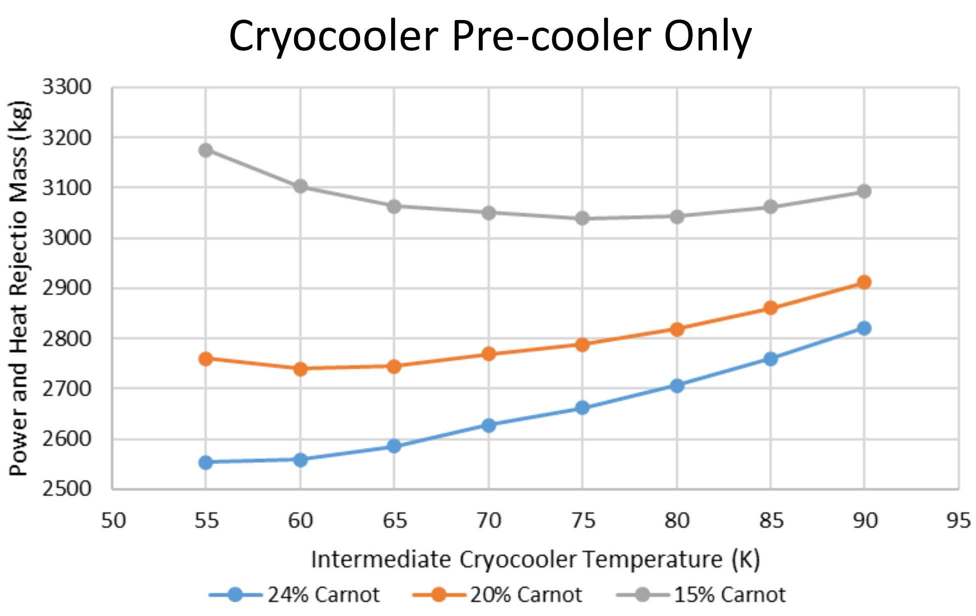
- 90 K class cryocoolers should be able to extend down to 50 K.
- Count may change with cryocooler efficiency.

Mass Assumptions

- Power mass
  - Based on trades for Lunar South Pole using methodology developed by Lee Mason, NASA Senior Technologist for Power.
  - Fission Surface Power – 378 kg/kW user power
  - Generally flat over the range (10 kW – 34 kW) of interest
- Radiator mass
  - Based on system level analysis studies by GRC Compass Team.
  - Double-sided vertical radiator – 3.9 kg/kW heat rejection
  - Extrapolated this for all temperatures (nominally for 300 K type temperatures)
- Ignore cryocooler mass
  - On the order of a few hundred kgs
  - A second order effect compared to the radiator and power mass
- Could also do optimizations on compressor operating temperature.

Individual Pre-coolers



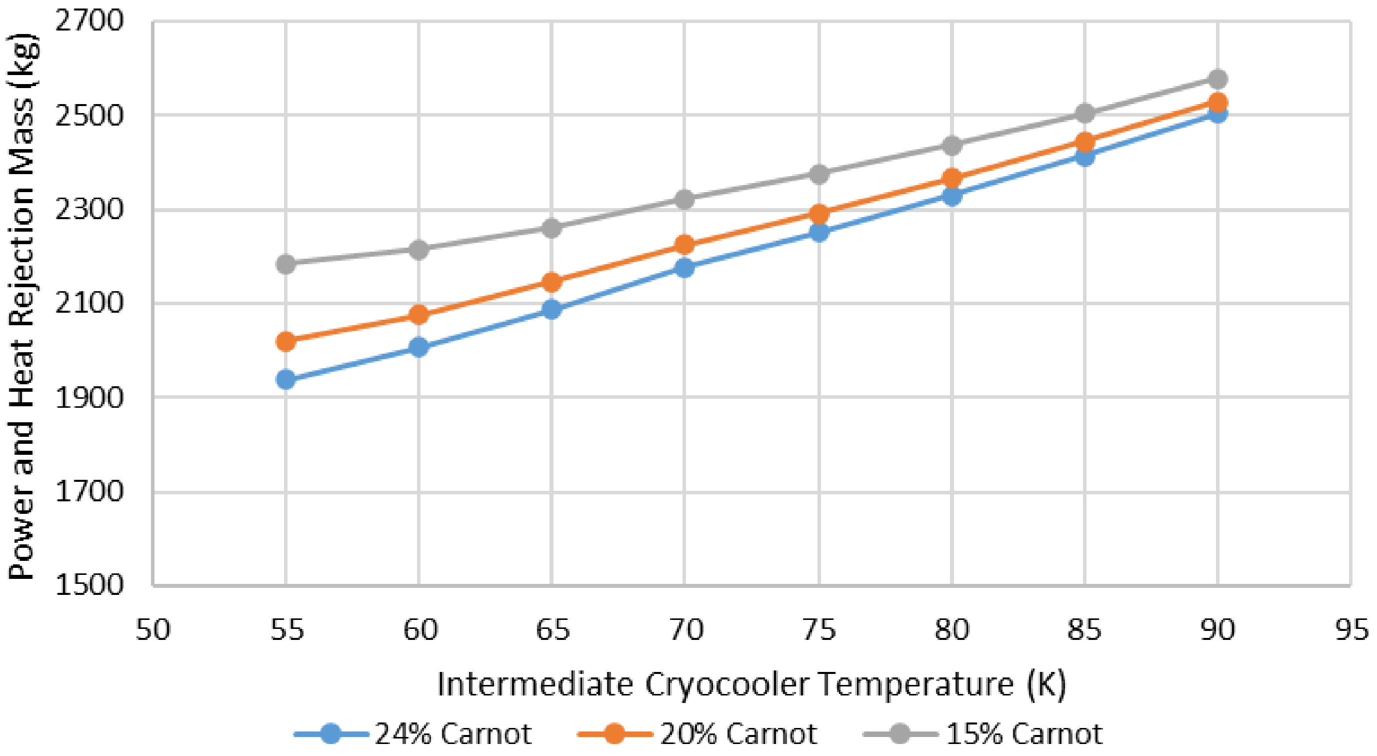


Radiator only beats baseline mass at Temperatures below 90 K

Intermediate cryocooler masses optimize similar to input power, between 60 K and 75 K depending on cryocooler efficiency.

Beats Baseline mass in all scenarios modeled.

Combined Pre-cooling Mass



Significantly reduced mass compared to baseline (6612 kg) and other cases (~20% reduction).

Combined precooling system mass follows input power trends for minimizing total mass.

Conclusions

- Hydrogen liquefaction in any environment is a power intensive activity.
- Currently in development 90 K class cryocooler of appropriate size for these systems.
- Would need to trade 20 K cryocooler size vs redundancy approach to determine if 20 W system is of appropriate size.
- Requires use of 20 K cryocoolers for significant energy removal, both on sensible and latent heat
  - Use of pre-cooling systems can help to minimize the input power for the 20 K cryocoolers.
  - Use of either radiative pre-coolers or intermediate temperature cryocoolers significantly reduce the input power and radiator mass required.
  - Use of both radiative pre-coolers and intermediate temperature cryocoolers reduces the input power by up to a factor of 3 and reduces system mass by similar factor.
- Development of radiator technology that allows efficient pre-cooling (segmented or low conductivity heat rejection surface) is a technology gap that should be considered for development.
- Paper includes details on modeling approach and sensitivity trades on radiator temperature at 250 K (Mars applications) and 20 K cryocooler efficiency.

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Questions?

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