# Comparison of Oxygen Liquefaction Methods for Use on the Martian Surface

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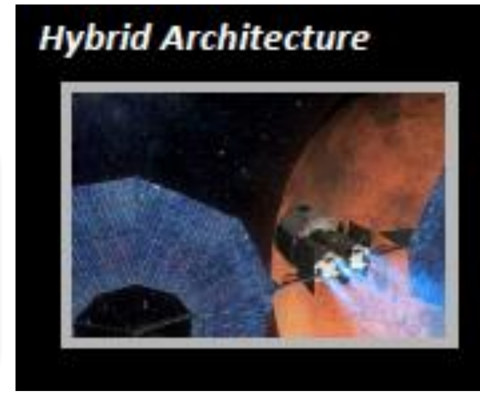
# Candidate Propulsion Options for Crewed Mars Exploration

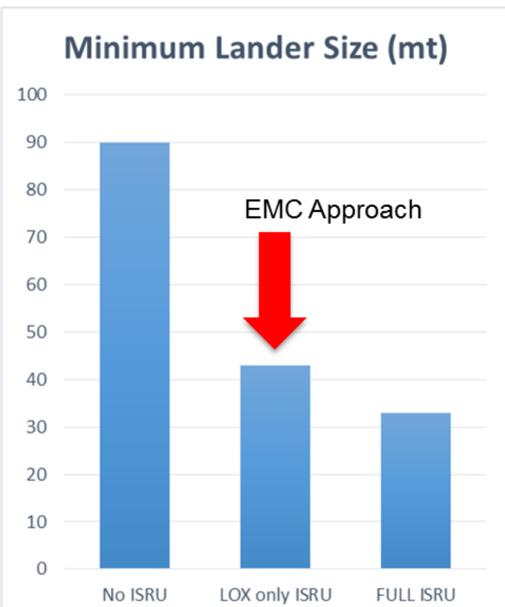

**Split Architecture**
Solar Electric Propulsion
• 190 kW Solar Arrays; 150 kW EP

LOX / Methane
• 25,000 lbf main engine; 100-1000 lbf integrated RCS
• Soft cryofluid management (90K)

**Hybrid Architecture**
Solar Electric Propulsion
• 440 kW Solar Arrays; 300 kW EP (2 x 150 kW)

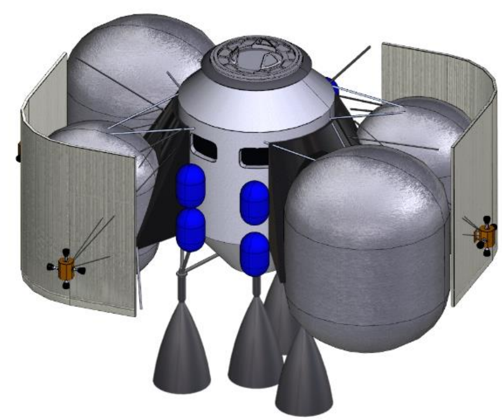
Storable chemical propulsion
• Space storable hypergolic biprop or Soft cryofluid management (90K)



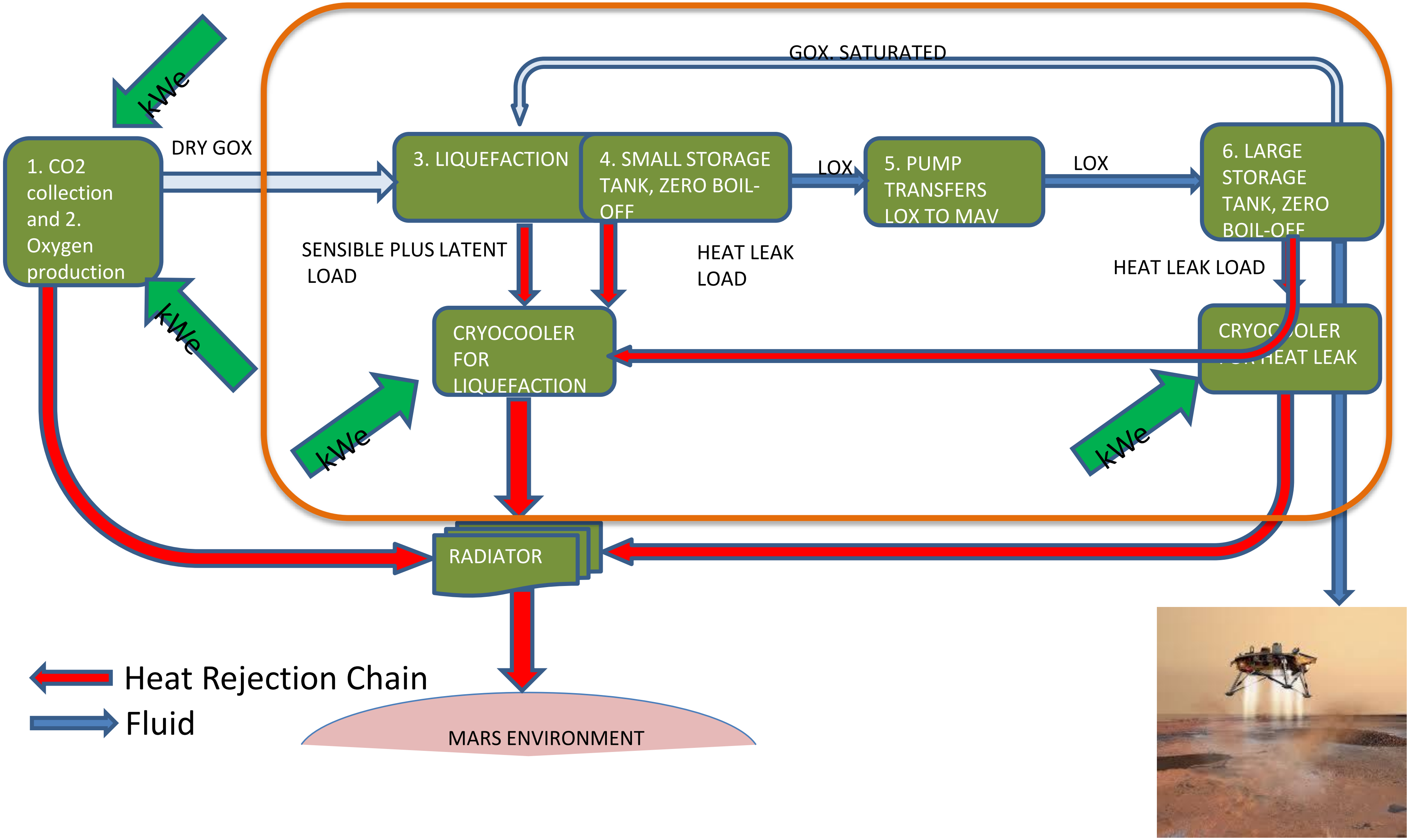

**NTP (fast transit option)**
• LEU fuels & reactor dev.
• Ground test & qualification
• 25,000 lbf main engine
• Hard cryofluid management (20K)

**Landers**
• Soft cryofluid management (90K)
• In Situ Resource Utilization
• Liquefaction and production



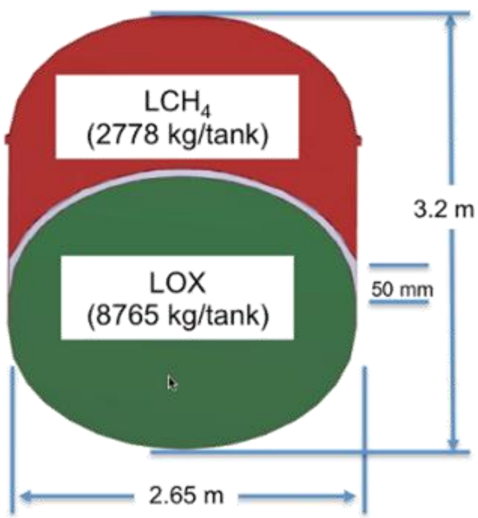
Mars Ascent Vehicle (MAV)

# Production – Liquefaction - Storage



# Ground Rules/Assumptions:

- ISRU flow system (oxygen only):
  - 273.15 K - Temperature
  - 1 ATM - Pressure
  - 2.2 kg/hr
- Environment
  - 260 K – heat rejection temperature
  - 273.15 K - insulation Warm Boundary Temperature (Tinf)
- Lander
  - Use current MAV first stage tank size
  - Steady State Heat Load: ~110 W/tank (includes 25% margin)
    - Includes ZBO maintenance of liquid methane
  - Heat transfer through nested bulkhead
    - Assumed negligible for now (i.e. props stored at similar temperatures)
- General
  - 50% margins on heat load
  - Gives ~ 132 W load (88 W base)



# Metrics for Trade

| IDENTIFIER | DEFINITION | SOME SELECT CONSIDERATIONS WHEN EVALUATING A PROPOSED SOLUTION |
|---|---|---|
| Mass | The total mass of the system being considered | Cryocooler system mass, component mass, not power generation, not radiator mass<br>Needs to include separate tank if needed or delta tank mass to MAV tank required<br>Any fluid transfer hardware needed, insulation for separate tanks and transfer lines |
| Input Power and Heat Rejection Power | The input power and the heat rejection power that a system requires | Amount of power required to run liquefaction system (includes cryocooler, pumps, valves, etc.)<br>Amount of heat rejection power needed to run liquefaction system (includes cryocooler, pumps, valves, etc.). Currently assumed to be 260 K.<br>Overall system efficiency |
| Cost | general ROM cost it may take to build this | - The ease with which included technologies/techniques can be matured to TRL 6 (development cost)<br>- Per unit flight cost |
| Manufacturability | How easy the system will be to manufacture and integrate onto spacecraft | - How many interfaces (and types) are there?<br>- How reasonable is the manufacturing of this system in the time frame given<br>- The ease of producing and integrating all aspects of the flight solution (e.g. - hardware & software)<br>- The extents of infrastructure alterations necessary to support the solution (both ground and flight) |
| Operability | The ease with which the system can be operated. | - The ease with which performance models can be developed and validated - low importance<br>- Concept of Operations flexibility (response to operational variations)<br>- Response to daily temperature cycles<br>- Response to seasonal temperature cycles<br>- Operable in wide range of landing locations<br>- Automation complexity (transfers, conditioning, batch processing, etc.) (i.e. number of steps and speed of steps)<br>- Ease of control |
| Scalability | How easily the system can scale up or down compared to baseline MAV cryocooler lift for fundamental architecture changes. | - the ease of scaling cryocooler cycles (both increase and decrease) lift to:<br>- change in flow rate<br>- change in insulation system performance |
| Reliability | Predicted events during life that may impede success of operations | - Failure modes<br>- Part count<br>- Risks associated with system<br>- Ability of the system to get humans off the surface with a nominal amount of warning |
| Volumility | Amount of relative volume the system tanks | The amount of volume used and where the volume is and how distributed/flexible packaging is |

# Relative Rating of Metrics

Three really important metrics:

- Mass
- Power
- Reliability

Two sort of important metrics:

- Operability
- Volumility

Three not so important metrics

- Cost
- Manufacturability
- Scalability

| Weighting | % |
|---|---|
| Mass | 22 |
| Input Pow er and Heat Rejection Pow er | 22 |
| Cost | 4 |
| Manufacturability | 1 |
| Operability | 13 |
| Scalability | 3 |
| Reliability | 25 |
| Volumility | 10 |

# OPTIONS

# Options Investigated

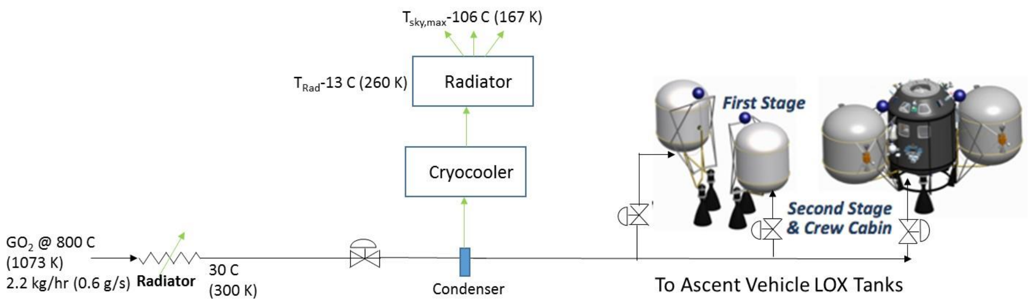
- In-line liquefaction
- Conduction liquefaction
- Tube-in-tank (Integrated Refrigeration and Storage)
- Linde Cycle (i.e. Joule-Thompson Expansion Cycle)
- Tube-on-tank (Broad Area Cooling)

# Liquefy Inline Before MAV Tank

- Liquefaction occurs inline before MAV Tank
- 15' long transfer line between liquefier and MAV tanks
  - Insulation composed of 1" aerogel (30 watt heat leak)
  - Transfer line length drives "parasitic" heat loads
- Gas Flow and Liquid Flow Driven by residual dP
- Cryocooler Sized for:
  - Liquefaction Load: 247 Watts
  - Transfer Line Heat Leak: 30 watts
  - Combined Load With 50% Margin: 415 watts

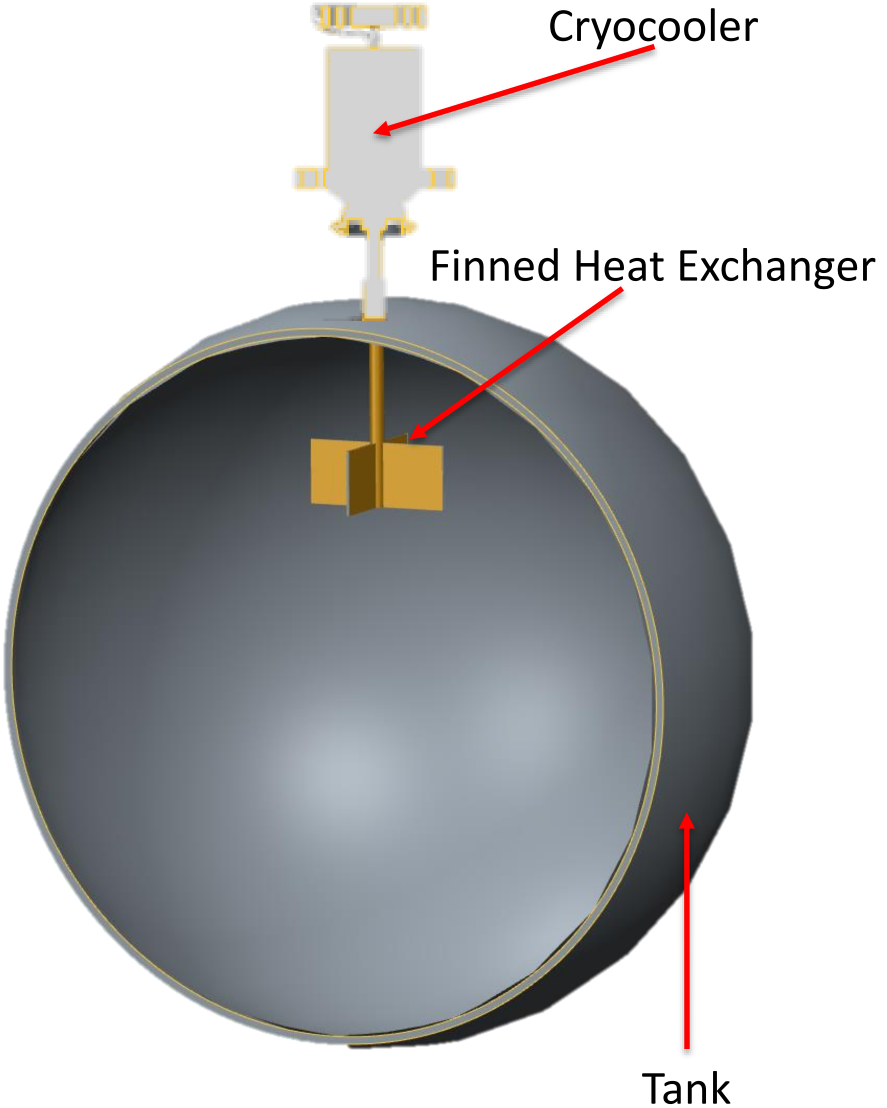
| | Mass, kg |
|---|---|
| Cryocooler | 93 |
| Plumbing (0.5" OD X 50') | 1 |
| Plumbing Insulation (1" Aerogel) | 4 |
| Pump | 2 |
| Valves(4x) | 4 |
| Condenser | 2.5 |
| **Total Mass, Kg** | **106.5** |

| | Power, watts |
|---|---|
| Cryocooler Input Power (RTB Cryocoolers) | 3,540 |
| Valves and Pump | 25 |
| **Total Input Power, watts** | 3,570 |



# Conduction Liquefaction Modeling

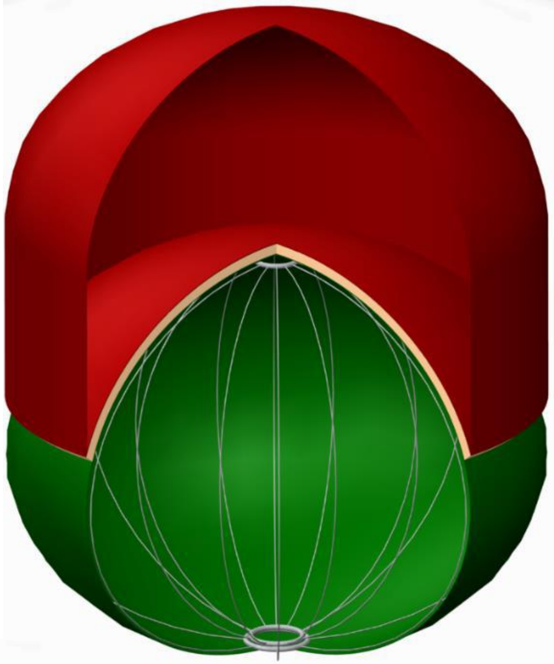
- Total System
  - Cryocooler Mass: 137 kg
  - Copper rod/fins: 26 kg
  - Structural supports: 10 kg
  - Total: **173** kg
- Power
  - Cryocooler: **4263** W
- Heat Rejection
  - Cryocooler: **4633.5** W



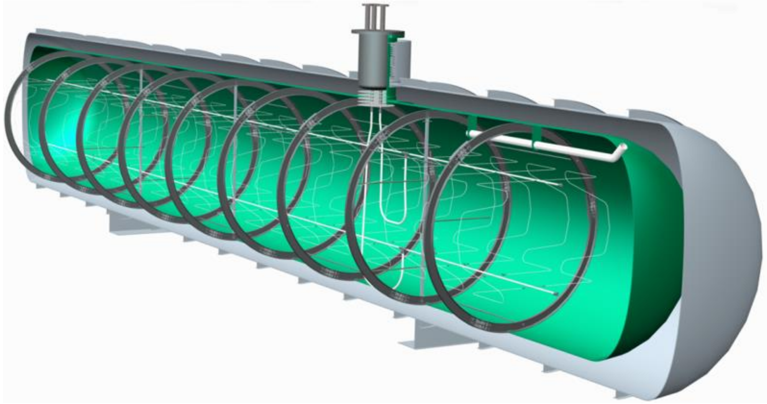
# Tube-in-Tank (Integrated Refrigeration and Storage)

## HX Details

- Roughly 50’ of 1/4” Al tubing
    - 9 lobes, ~ 10 ft each
- 1” manifolds (top, bottom entrance, bottom return)
- Needs structure to hold in place.



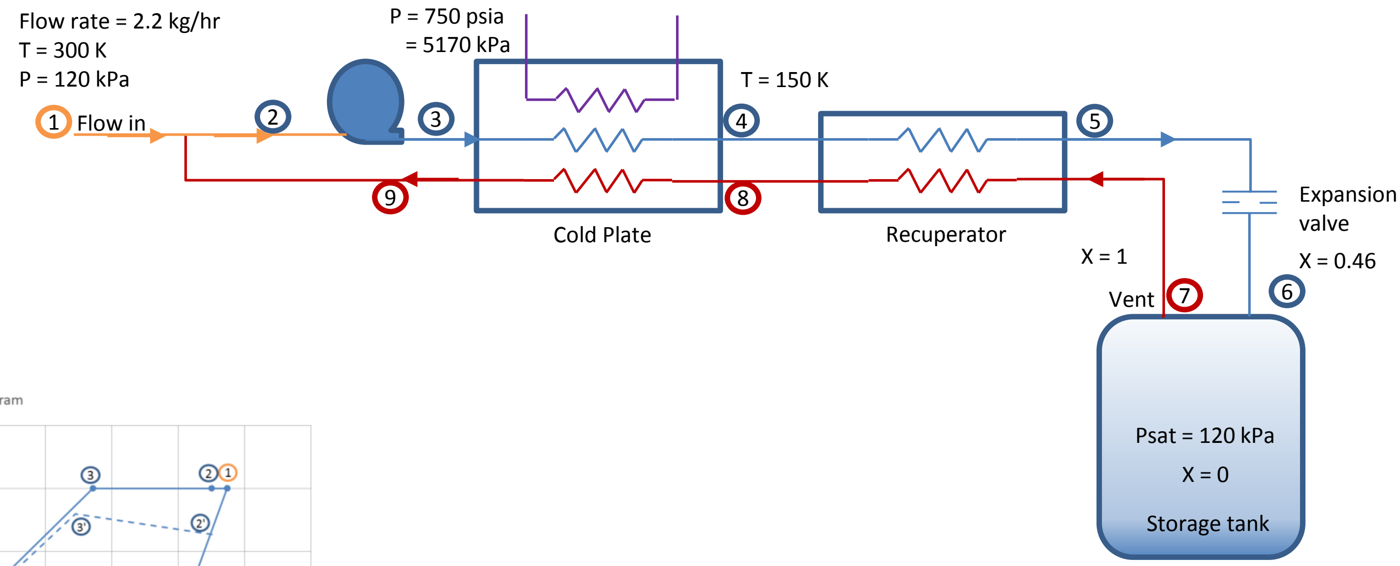
Tube in tank in notional MAV tank

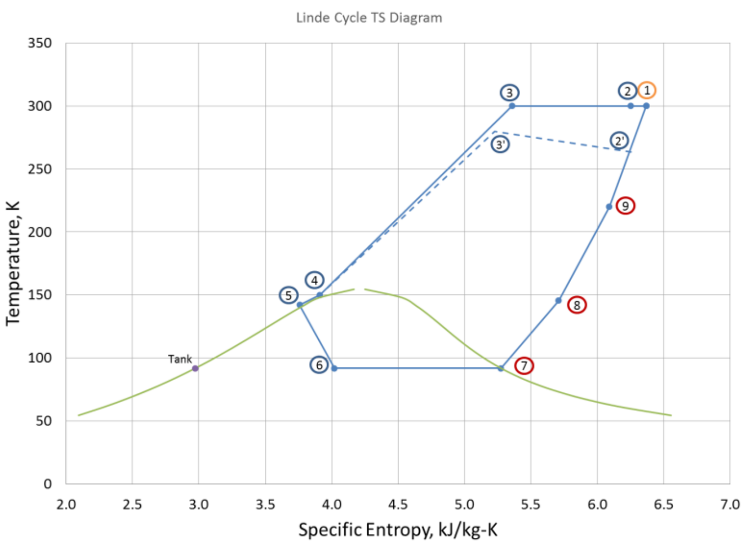


IRAS Tank cut-away view

IRAS tank internal image

# Linde Cycle




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Temperature, K | 273 | 273 | 273 | 150 | 143 | 91.8 | 91.8 | 138.4 | 220 |
| Pressure, kPa | 120 | 118.8 | 5167.5 | 5116 | 5065 | 120 | 120 | 118.8 | 117.6 |
| Mass flow, kg/s | 6.11E-04 | 1.15E-03 | 1.15E-03 | 1.15E-03 | 1.15E-03 | 1.15E-03 | 5.35E-04 | 5.35E-04 | 5.35E-04 |
| enthalpy, kJ/kg | 247.9 | 225.2 | 233.1 | -11.9 | -31.8 | -31.8 | 80.9 | 124.4 | 199.4 |
| quality | | 247.9 | | | | 0.47 | 1 | | |
| density | 1.7 | 1.7 | 76.3 | 721.6 | 816.0 | 11.1 | 5.2 | 3.3 | 2.1 |

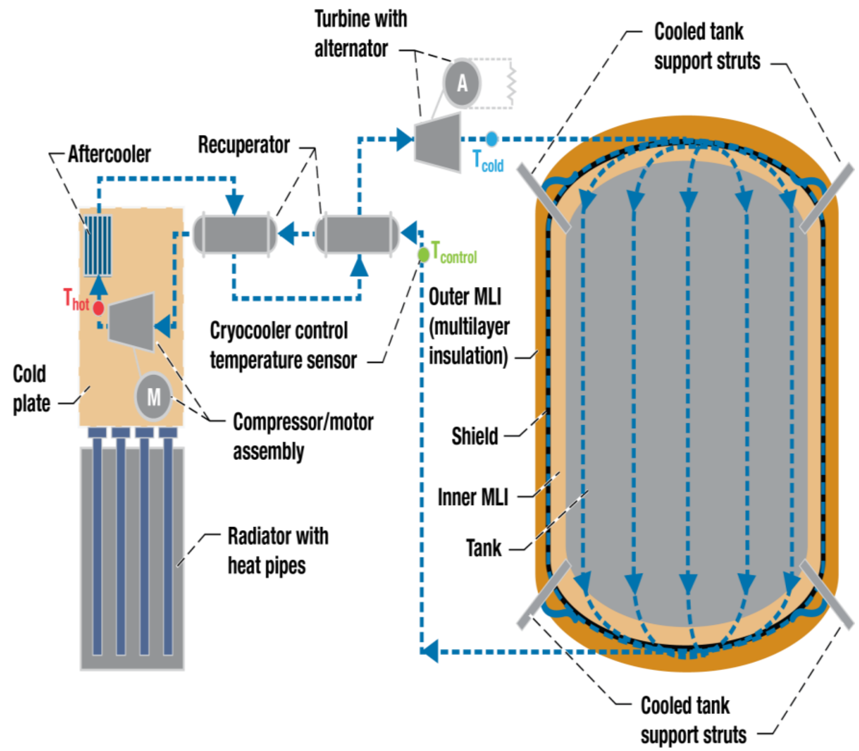
Due to quality at state 6 being 46%, the flow rate for states 2, 3, 4, & 5 are increased from 2.2 kg/hr to 4.1 kg/hr.

Blue and green cells set the state of each point.

Highly ideal cycle modeled.

# Tube on Tank (Broad Area Cooling - BAC)

- Point cooling is used on space telescopes, to cool the focal plane (very small)
- Distributed or broad area cooling is required to cool large surfaces
- Broad area cooling distributes this cooling via a tubing network over the whole surface of the tank
  - Cold gas is circulated via a tubing network around cryo tank to eliminate boil-off
  - Tubing is spot welded and epoxied to tank wall
- NASA has focused investments on reverse turbo-Brayton cycle, which features an integrated circulator
  - Neon (at LOX temps) gas is circulated at ~50 psi
  - More efficient than separate cooler/circulator that requires:
    - Counter-flow heat exchanger
    - Circulator to move fluid through tubing network



# Liquefaction Trade Summary

| | Tube-on-Tank | Linde Cycle | Inline Liquefaction | Conduction Cooling | Tube-in-Tank |
|---|---|---|---|---|---|
| Mass (kg) | 68 | 198 | 107 | 173 | 68* |
| Input Power (W) | 2873 | 2790 | 3570 | 4263 | 2873* |
| Radiator Power (W) | 3250 | 3335 | 4100 | 4634 | 3250* |

*For comparison purposes, the Tube-in-tank method was assumed to be similar to the Tube-on-tank method. Based on the implementation, this may or may not remain true.

| Relative Scoring Results | Mass | Input Power and Heat Rejection Power | Cost | Manufacturability | Operability | Scalability | Reliability | Volumility | % of total points scored |
|---|---|---|---|---|---|---|---|---|---|
| Conduction | 0.5% | 0.3% | 1.4% | 0.4% | 2.9% | 0.9% | 9.8% | 0.6% | 17 |
| Tube-on-Tank | 8.7% | 7.1% | 0.1% | 0.3% | 4.2% | 1.2% | 6.3% | 4.0% | 32 |
| Linde Cycle | 0.5% | 5.0% | 0.9% | 0.0% | 1.4% | 0.3% | 0.2% | 0.6% | 9 |
| Tube-in-Tank | 8.7% | 7.1% | 0.1% | 0.3% | 4.2% | 1.0% | 6.3% | 4.0% | 32 |
| In-line HX | 3.5% | 2.4% | 1.4% | 0.2% | 0.1% | 0.0% | 2.2% | 0.6% | 10 |

# Conclusions

- Five different options for liquefaction options were traded to understand the relative performance in the Mars architectures currently being developed by NASA
- Initial trades showed that tube-on-tank and tube-in-tank were very similar
- A final downselect was made to pursue tube-on-tank option
  - Programmatic personnel (project/program managers, chief engineers, etc) directed team to pursue tube on tank
  - Flight development teams preferred external heat exchanger for more access, preferred assembly timelines, and combined flight and ground implementation
  - Possible needs for system to work both on ground and on orbit also contributed (with previous development work on Tube-on-Tank)