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Comparison of Oxygen Liquefaction Methods for Use on the Martian Surface

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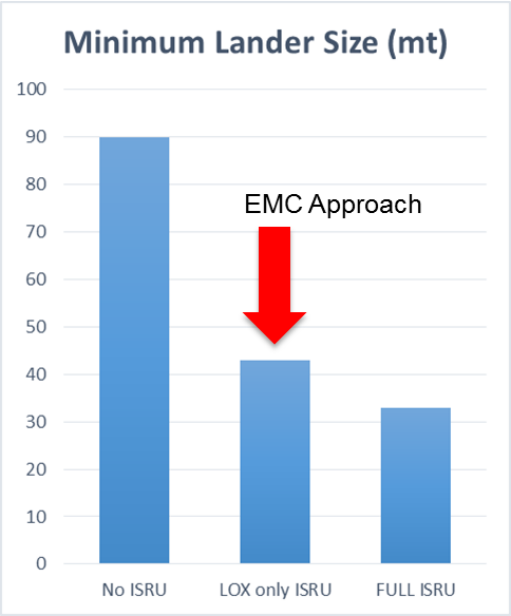
Candidate Propulsion Options for Crewed Mars Exploration

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)

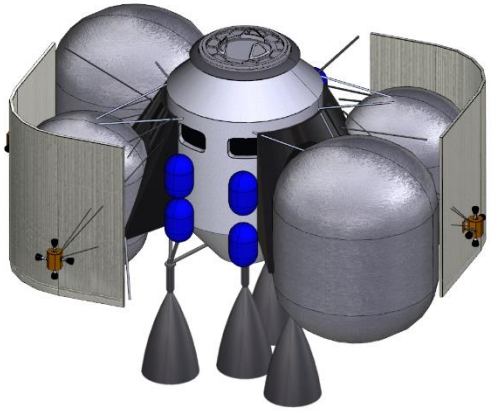
Hybrid Architecture
Solar Electric Propulsion
- 440 kW Solar Arrays; 300 kW EP (2 x 150 kW)

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



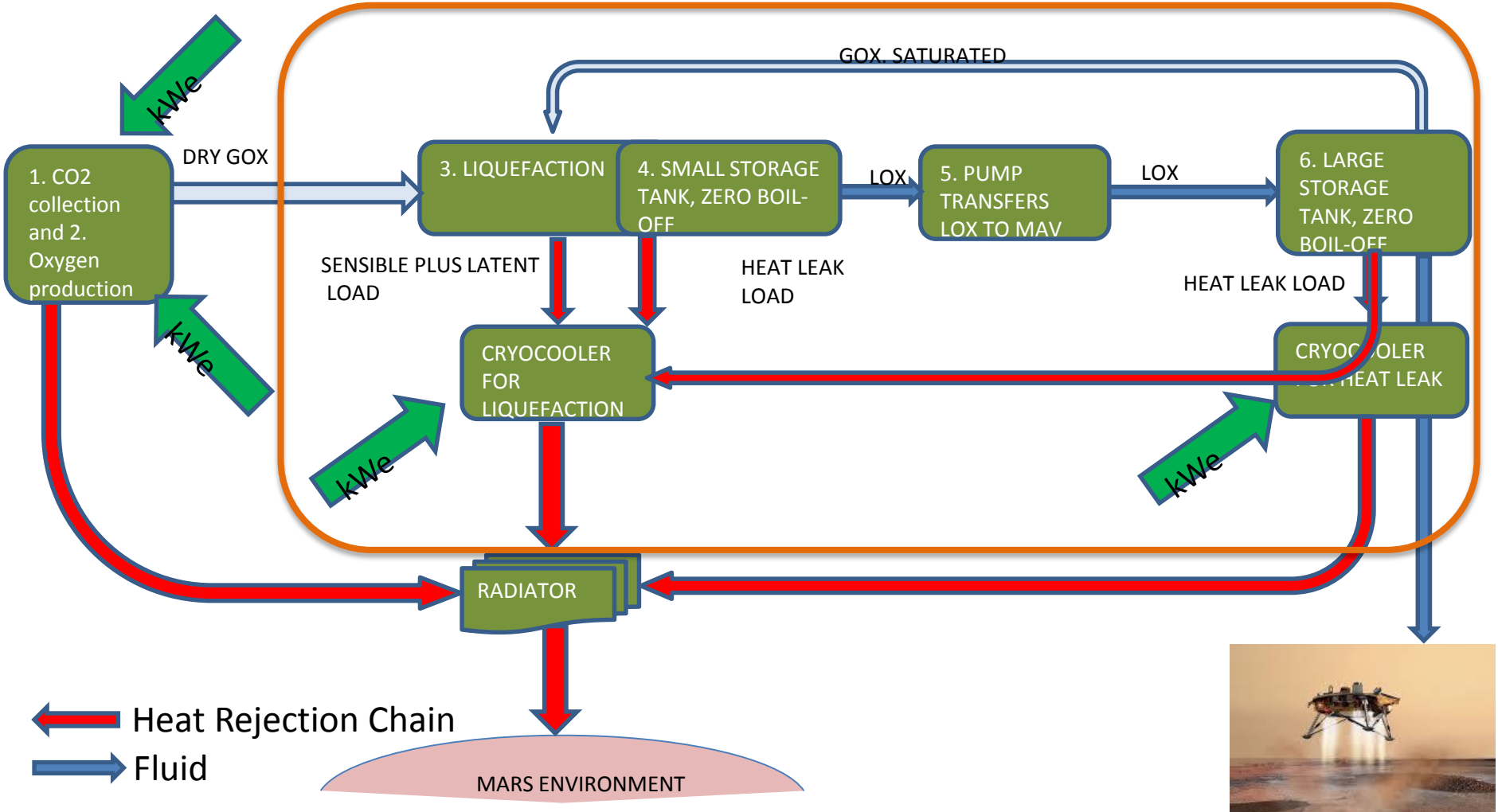
NTP (fast transit option)
- LEU fuels & reactor dev.
- Ground test & qualification
- 25,000 lbf main engine
- Hard cryofluid management (20K)

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



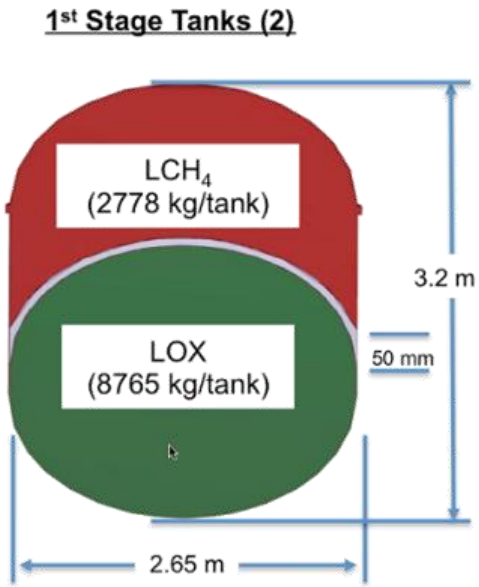
Mars Ascent Vehicle (MAV)

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 Needs to include separate tank if needed or delta tank mass to MAV tank required 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.) Amount of heat rejection power needed to run liquefaction system (includes cryocooler, pumps, valves, etc.). Currently assumed to be 260 K. 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) - Per unit flight cost
Manufacturability	How easy the system will be to manufacture and integrate onto spacecraft	- How many interfaces (and types) are there? - How reasonable is the manufacturing of this system in the time frame given - The ease of producing and integrating all aspects of the flight solution (e.g. - hardware & software) - 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 - Concept of Operations flexibility (response to operational variations) - Response to daily temperature cycles - Response to seasonal temperature cycles - Operable in wide range of landing locations - Automation complexity (transfers, conditioning, batch processing, etc.) (i.e. number of steps and speed of steps) - 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: - change in flow rate - change in insulation system performance
Reliability	Predicted events during life that may impede success of operations	- Failure modes - Part count - Risks associated with system - 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
Manuf acturability	1
Operability	13
Scalability	3
Reliability	25
Volumility	10

OPTIONS

Options Investigated

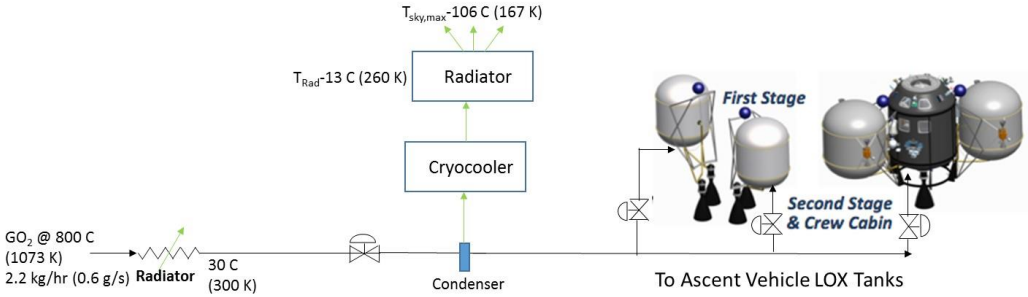
- In-line liquefaction
- Conduction liquefaction
- Tube-in-tank (Integrated Refrigeration and Storage)
- Linde Cycle (i.e. Joule-Thompson Expansion Cycle)
- Tube-on-tank (Broad Area Cooling)

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

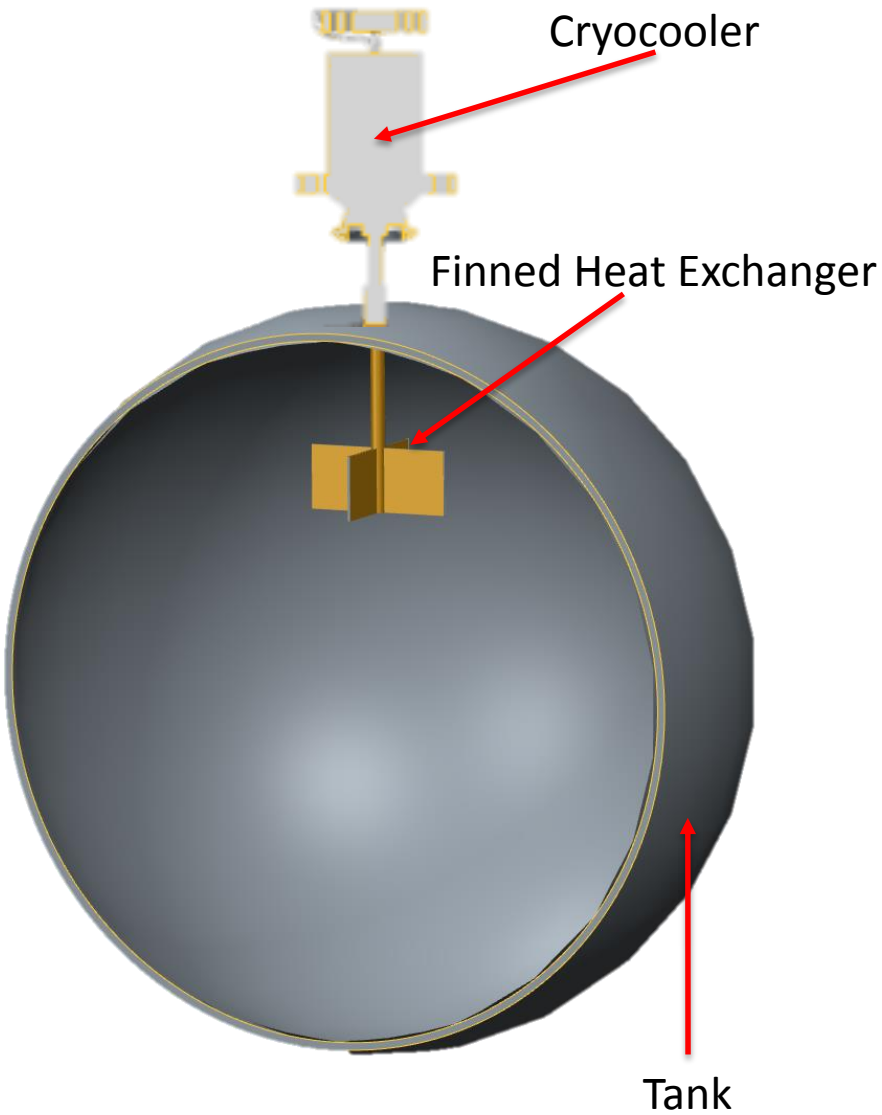
	Mass, kg
Cryocooler	93
Plumbing (0.5” OD X 50’)	1
Plumbing Insulation (1” Aerogel)	4
Pump	2
Valves(4x)	4
Condenser	2.5
Total Mass, Kg	**106.5**

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



Conduction Liquefaction Modeling

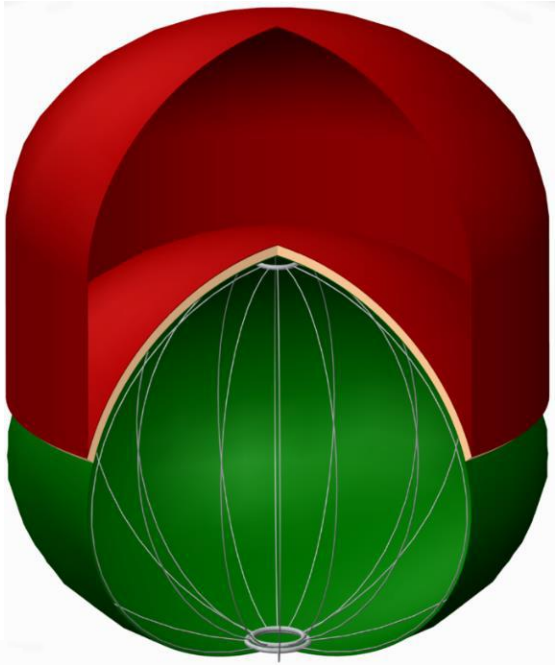
- Total System
  - Cryocooler Mass: 137 kg
  - Copper rod/fins: 26 kg
  - Structural supports: 10 kg
  - Total: **173** kg
- Power
  - Cryocooler: **4263** W
- Heat Rejection
  - Cryocooler: **4633.5** W



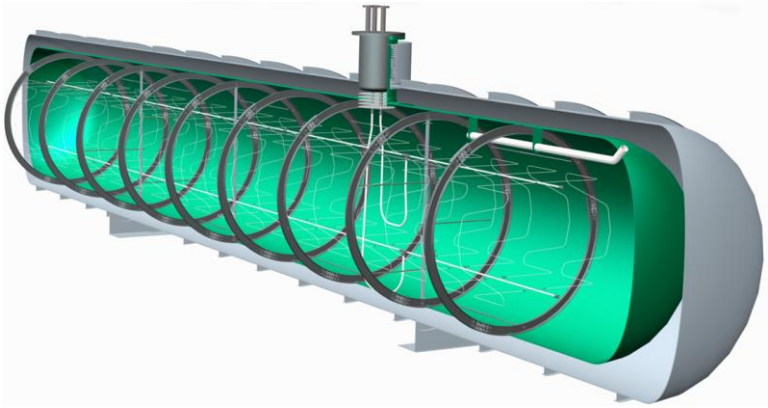
Tube-in-Tank (Integrated Refrigeration and Storage)

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.



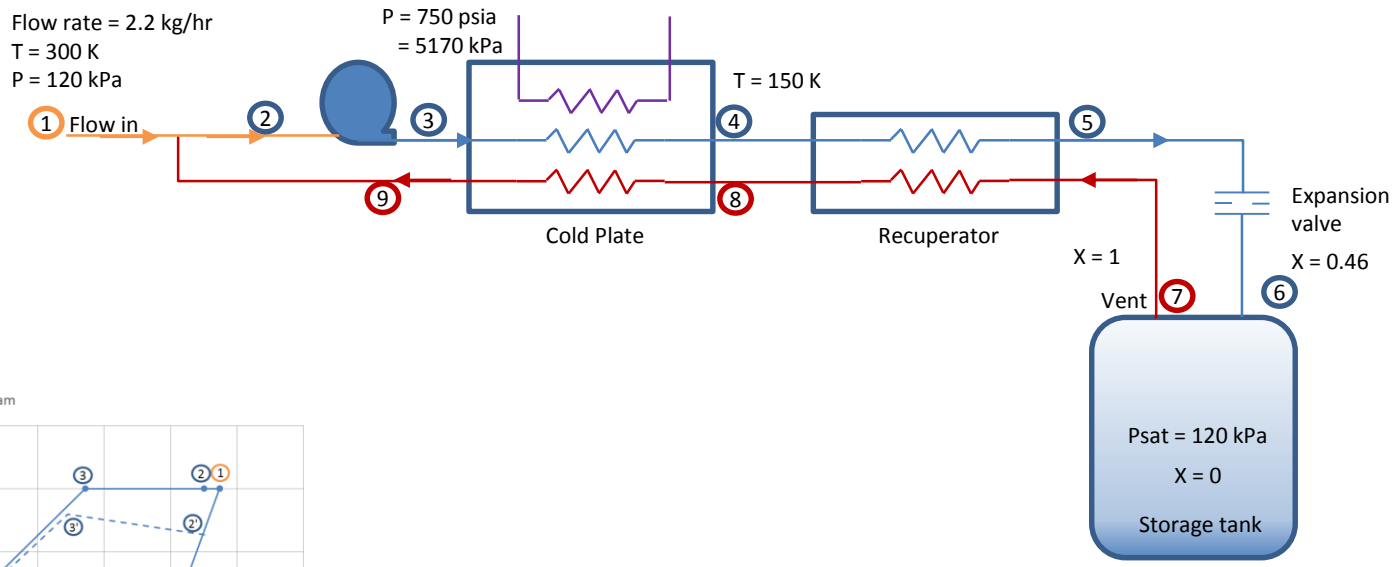
Tube in tank in notional MAV tank

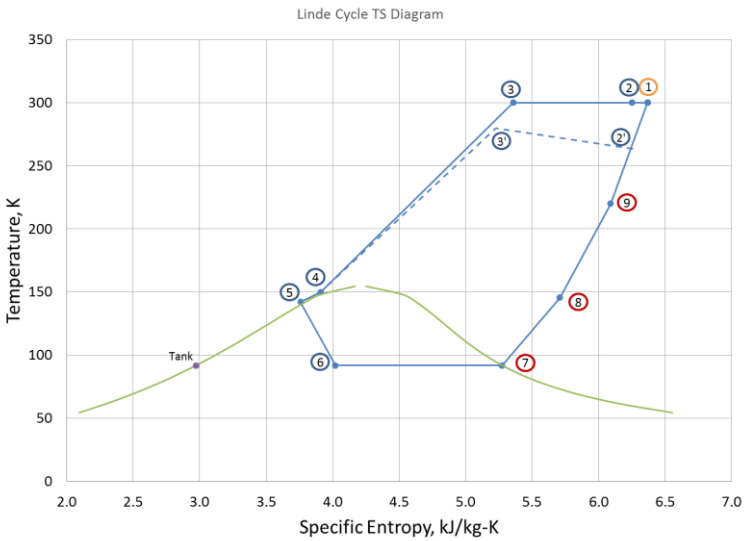


IRAS Tank cut-away view

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

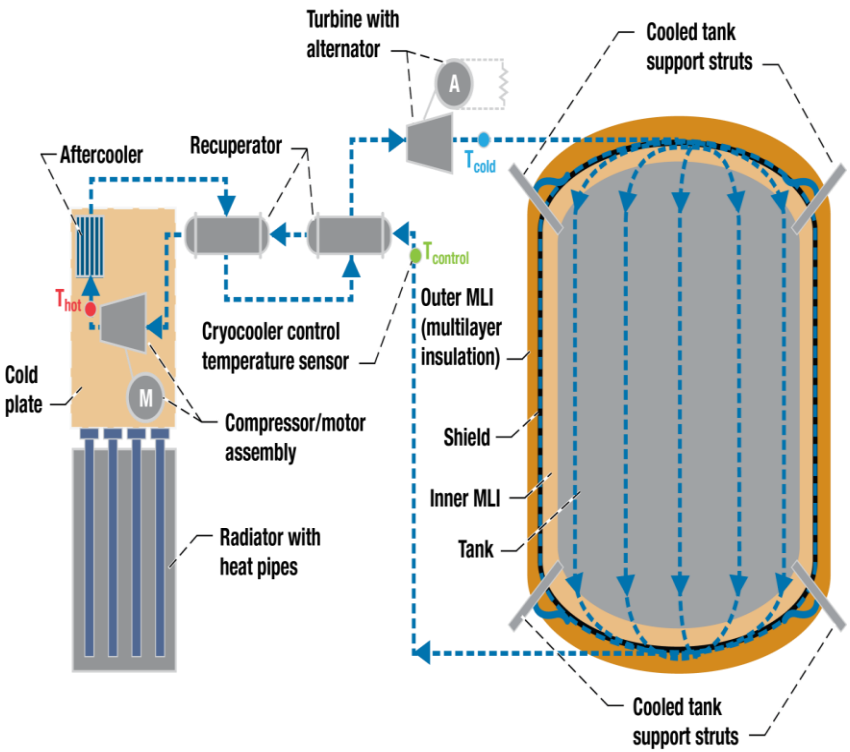
Due to quality at state 6 being 46%, the flow rate for states 2, 3, 4, & 5 are increased from 2.2 kg/hr to 4.1 kg/hr.

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

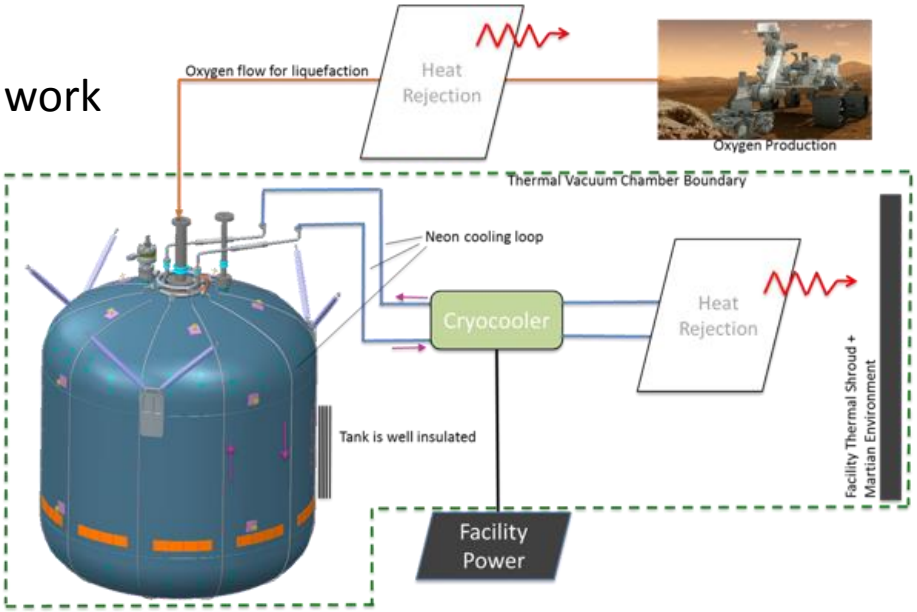


Liquefaction Trade Summary

	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)