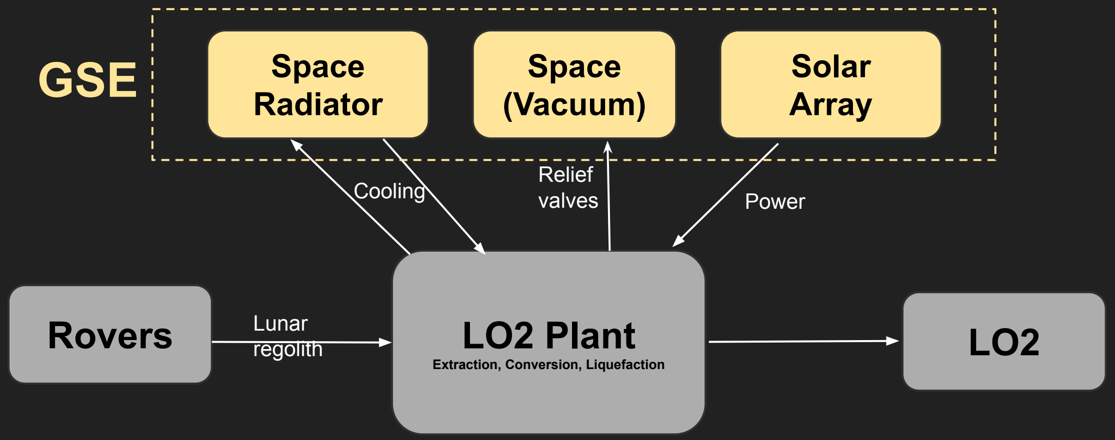
Project: Plant Ground Support Equipment - Scope & Goal

- Starpath's Plant… in Space
- Goal: Enable the Plant to be tested on Earth in an analogous Lunar environment



- Allocated Budget: $75k, Timeline: 3.5 mo.

Defining Requirements

- Cooling Requirements
  - To accommodate the 3 Plant Subsystems, as a stand-in for Space Radiator
    - Extraction: 5kW <50C
    - Conversion: 30kW <50C
    - Liquefaction: 3.3kW <0C
- Vacuum Requirements
  - Performance of valves proportional to pressure difference
  - 0.12 mol/s H2 leak rate = 5.7CFM
  - >leak rate + margin for quick pump down time
- Power Requirements
  - PEM Stack (electrolyzer, conversion): 60kW 200VDC
  - Other electronics: 10kW 120VDC
- Skid Requirements
  - Safely contain Cooling, Vacuum Subsystems
  - Transportable to Plant Test location
  - Aesthetically appealing for external stakeholder demo

Requirements

System	Plant 2
Subsystem	Ground Support Equipment
RE	Conor Zachar
Updated	11/7/2024

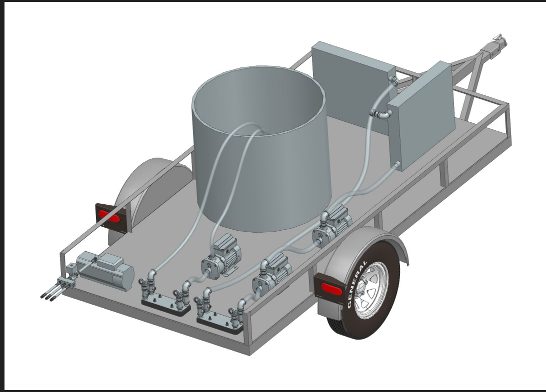
Requirements

# Number	Category	Statement	Source
0	systems	Subsystem shall supply 60kW @ 200VDC and 10kW @ 120VDC to Box 1	czachar
1	systems	Subsystem shall supply a minimum of 35kW of cooling power <50C and 3.3kW <0C	czachar
2	systems	Subsystem shall supply a near-vacuum of <0.01bar and pump at least 10CFM	czachar
3	build	Subsystem shall cost less than $75,000 in hardare/operational expenses	allocated, sys.12
4	environmental	Subsystem shall be transportable to/from test location	czachar
5	systems	Subsystem shall be of an appearance to inspire the public	flowed down, sys.10
6	systems	Subsystem shall not interfere with Rover or Tower installations	flowed down, sys.4
7	build	Subsystem shall complete testing on/before December 20, 2024	derived, sys.11

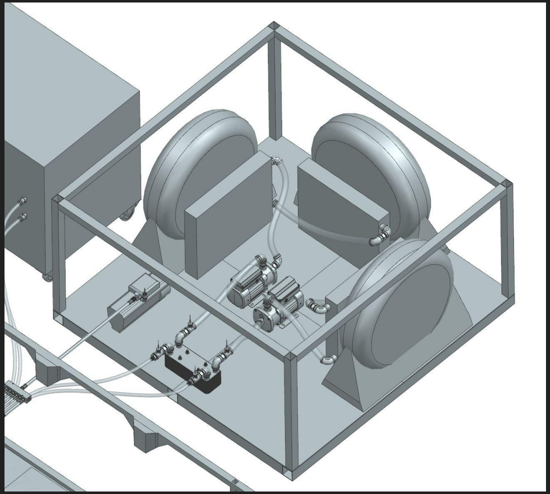
Skid - Concept Selection

- Size
  - Footprint driven by cooling loop size, 3-4 m^2
- Material
  - Criteria: cost, manufacturability, strength, safety, aesthetics
  - Chosen Material
    - Al 6061 (σy: 276 MPa (T6), 76 MPa (O), ρ: 2.70 g/cm3)
      - Advantages: cost, easy MIG weld, FEA indicates sufficient strength, nonflammable, good aesthetics
      - Drawbacks: warping while welding, see setup
  - Considered
    - Wood: (MOR: 40MPa, ρ: 0.6 g/cm3)
      - lowest cost, weight, but lacking in strength, flammable, aesthetic concerns
    - Low Carbon Steel (σy: 250MPa, ρ: 7.9 g/cm3)
      - higher strength but heavier, requires finishing (corrosion), challenges welding
- Concept
  - Chosen Concept
    - Welded skid & frame: in-house manufacturing saves cost, compact & customizable form factor
  - Considered
    - Trailer: enables on-road transportation* but adds cost, bulkier less efficient footprint

*Deleted requirement, unnecessary as complete build & test of the Plant to be done at Starpath HQ. Instead, pallet jack/forklift compatibility incorporated into design



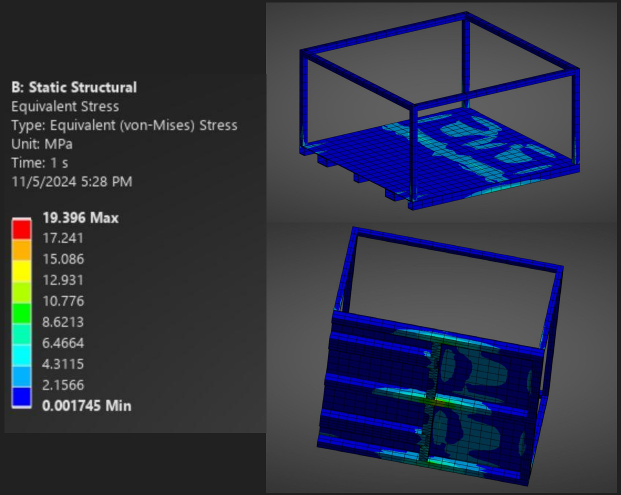
Trailer: evaluated concept

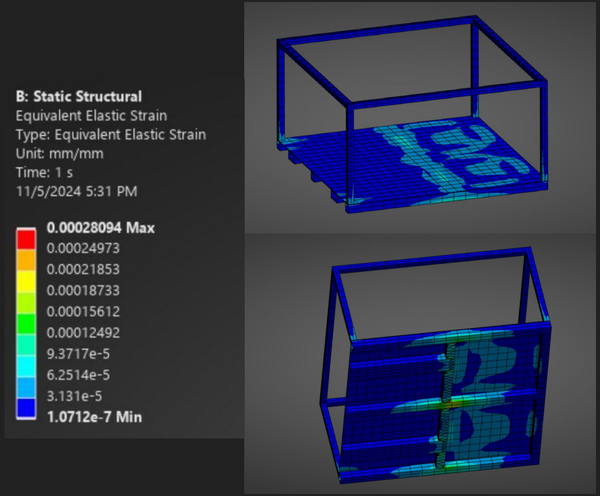


Skid: chosen concept

Skid - Detailed Design

- 6’ x 6’ to accommodate cooling loop, vacuum line
- Pallet jack compatible
- Aluminum 6061
- FEA: Fixed @ Forklift Mounts, 4000N downward force applied across platform





Material Properties	6061-T6	6061-O
Yield Strength (FOS)	276 MPa (14.2)	76MPa (3.9)
UTS (FOS)	310 MPa (16.0)	130 MPa (6.7)
Fracture strain (FOS)	0.08 (284.7)	0.20 (711.9)

Skid - Build

- Materials
  - Thickness selected for strength & ease of weld
  - 4x 36”x36”x1/4” plates
  - ⅛” rectangular tubing
- MIG Welded
- Aluminum perforated sheets + self-tapping screws

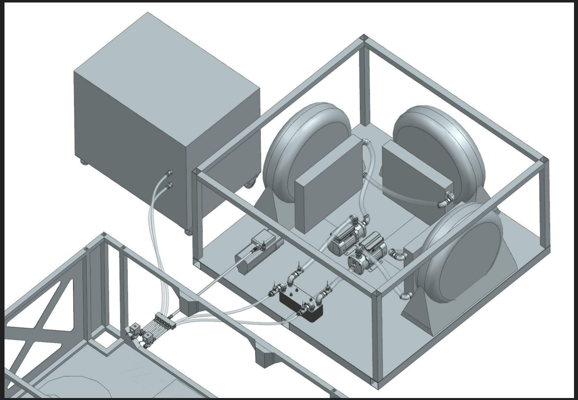
Full skid w/ perforated sheet enclosure

Welded frame

Weld setup: Bottom view

Cooling - Concept Selection

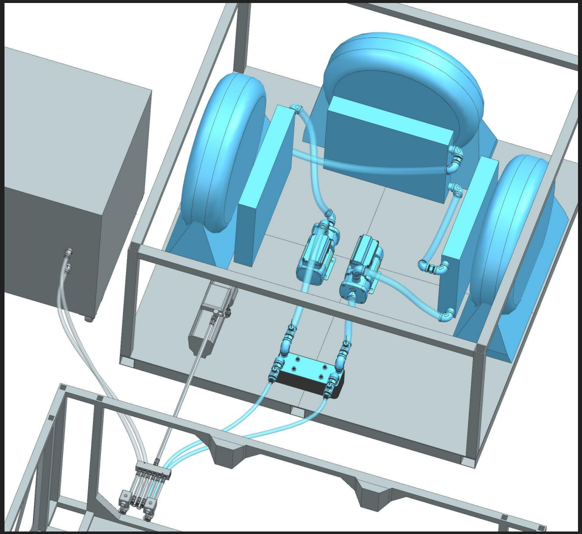
- Heat capacity & temperature requirements
  - Conversion + Extraction: 35kw <50C
  - Liquefaction: 3.3kW <0C
- Design decision: separate 2x cooling loops
  - Provide high heat capacity cooling at a higher temp for conversion & extraction
  - Lower heat capacity, lower temp for liquefaction cooling
- Conversion & Extraction Loop
  - Concept selected: Air-to-water heat exchangers
    - Use ambient air temp to cool below 50C
    - Low cost, low complexity, reliable
  - Considered: Heat Pump
    - Not selected due to higher cost & complexity
- Liquefaction Loop
  - Concept selected: Low Temp chiller
    - Found off-the-shelf within spec, reliable & customizable cooling
  - Evaluated: Immersion cooling
    - Copper pipes + ice bath
    - Not feasible due to test length requirements



Ambient Temp Cooling - Design Details

Requirement: 35kW cooling, ~100C -> <50C

- Air-To-Liquid HEX in Series
  - Specced for heat capacity, dT, see subscale test
  - Coolant pumps in series to offset head loss
- Plate HEX
  - Compact, efficient
- Sensing: calculate Q*=m*cΔT
  - K Type Thermocouples, breakout boards
    - Optimal within 0-100C range
  - 10V Flowmeter
    - Voltage compatible w/ Arduino (for test) & Plant brain



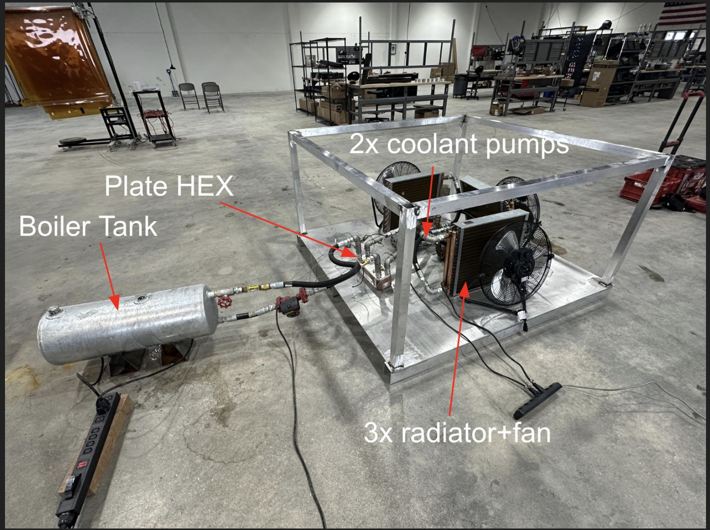
Max Cooling needed		
Water Thot (plant)	373	K
Water Tcool (plant)	323	K
cp water	4.186	kJ/kgK
mass flow rate	0.15	kg/s
Required Qlost, plant	31.395	kW
Temp change of working fluid		
cp working fluid (water)	4.186	kJ/kgK
V* working fluid	3	gal/min
V* working fluid	11.34	l/min
m* working fluid	0.189	kg/s
Plate HEX efficiency	0.90	
dT required, working fluid	44.09	K

3x 20"x20" HEX		
V*	3	GPM
V*	0.000189270589	m3/s
d_pipes	0.00953	m
A_pipes	0.000071	m2
v_h20	2.65622	m/s
# pipes/row	3	
rows	20	
# HEX	3	
l_row	0.5588	m
l_pipes	100.584	m
friction factor	0.0200	
ρ_h20	1000.00	kg/m3
ΔP	745.0599518	kPa
ΔP	249.3	ft head

Ambient Temp Cooling - Build

Requirement: 35kW cooling, ~100C -> <50C

- Subscale test
  - Boiler tank
    - 15gal Tank + 2x 5kW heating elements
      - Heating could not be scaled further due to power constraints at the time, safety considerations (arcing @ high current, gap between conductors)
  - Setup with 1x HEX
  - Indicated HEX cools @ approx 50% of nominal capacity, 95C-> 50-60C
  - Decision for 3x in series: anticipating decrease in efficiency but increase in dT
- Build
  - 3x 40kW HEX in series
  - NPT fittings & liquid hydraulic thread sealant to prevent leaks



Full test setup

Subscale test setup

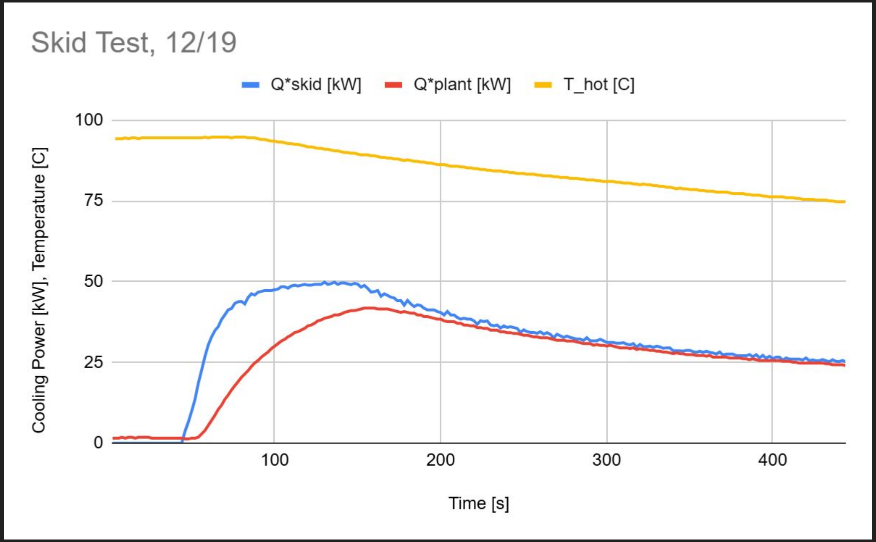
Max Sustainable Q*		
V_boilertank	15	gal
V_boilertank	56.781	L
Tmax	100	C
Tfinal	30	C
c_H20	4.187	kj/kgC
Qmax	16641.99	kJ
t_test	0.2	hr
Q*_heaters	10	kW
Q*max sustained	33.11	kW

Test limitations

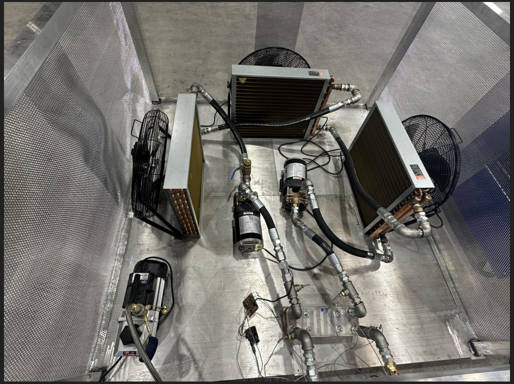
Ambient Temp Cooling - Test

Requirement: 35kW cooling, ~100C -> <50C

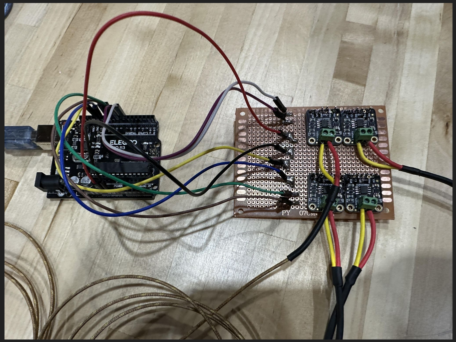
- 40 kW peak
- Performs best at higher dT
  - Planned plant input of 100C is ideal
  - Test limitation: setup can only heat at 10kW, max
- Tcool Maintained <40C



Cooling capacity of cooling loop



Cooling loop



Arduino & perfboard for data collection

Low Temp Cooling - Initial Design

Requirement: 3.3kW cooling, <0C

- Initial Design: Immersion Chilling
  - 30m copper tubing
  - Saltwater ice bath
- System wide requirements changed: 3hr test to 15hr
  - Deemed infeasible due to volume of ice required
  - Hand calcs: Lf ice not suitable for 45kWh
    - LN2- lower temps easily achievable, but mass not feasible

Variable	value	unit
Copper Tubes		
HEX_e	0.8	
V*	3	GPM
m*	0.1892705	kg/s
Q*	3.75	kW
c_h20	4.184	kJ/KgK
dT_h20	4.73539992	K
Tcold_pipes	270	K
Thot_pipes	274.7353999	K
Tbath	270	K
dT_m	2.36769996	K
U_copper	2	kW/m2K
A_req	0.791907772	m2
d_pipe	0.0127	m
l_req	19.84821147	m

Length tubes required

Q=UAdT

Immersion cooling setup

Ice Required		
Q*	3.3	kw
t	15	h
Q*	49.5	kWh
Lf_ice	334	kj/kg
Lf_ice	0.093	kWh/kg
m_ice_req	532.26	kg
minV_cubedice_req	1064.516129	L
minV_cubedice_req	281.2153548	gal
% loss, to ambient	50	%
V_cubedice_req	562.4307097	gal

LN2 Required		
Q*	3.3	kw
t	15	h
Q*	49.5	kWh
Lf_LN2	199	kJ/kg
Lf_LN2	0.0552	kWh/kg
m_LN2	896.74	kg

Immersion fluid required

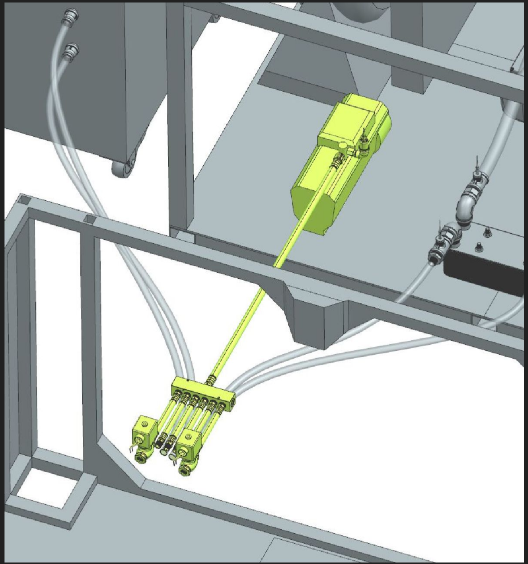
Low Temp Cooling - Design Details

Requirement: 3.3kW cooling, <0C

- Cooling capacity
  - 5.07 kW @ -2.5C
  - 3.58kW @ -12.2C
- Fluid
  - 50% ethylene glycol (antifreeze)
- Operation
  - ¾ NPT Inlet/Outlet
  - 208-240VAC input, 37A max current draw
    - Use 240V welding plug

Vacuum - Concept Selection & Design

- Vacuum requirements
  - Near-perfect vacuum applied to valves, <0.01bar
- Concept Selected: Vacuum line: roughing pump, hoses, manifold, solenoids
  - Enables high CFM (offset H2 leak rate), minimize leaks from vacuum pump
- Considered: vacuum chamber
  - No added utility: relief valves the only vac-rated hardware
  - Adds pump down time, valves spaced around wide area, seals interfere with Plant functions
- Hardware
  - 12 CFM roughing pump, 4E-5 bar minimum Pvac
  - Flow control: on/off via solenoid valves
    - Ball valves considered, but remote operation desired for safety
  - Manifold, fittings, hoses
    - NPT, pneumatic-rated liquid thread sealant (Loctite 545)
  - Sensing
    - Vacuum gauge



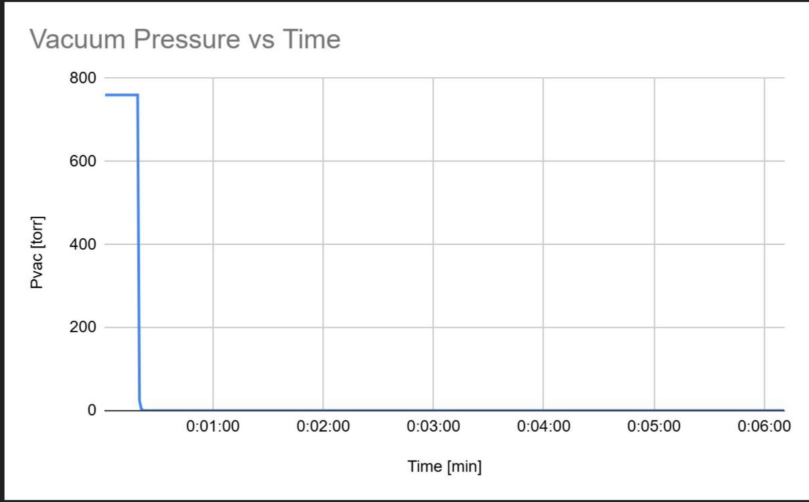
$$T = V/S * \ln(P1/P2)$$

Pump dow time - hoses		
Length of piping	10	m
Diameter of piping	0.0127	m
Volume of piping	0.00127	m^3
Initial pressure	1	atm
Final pressure	1.00E-04	atm
Pump speed	12	CFM
Pump speed - leak rate	6	CFM
Pump Speed	0.0028	m3/s
Pump down time	4.120	s

Pump down time - chamber		
Volume of piping	1.00000	m^3
Initial pressure	1	atm
Final pressure	1.00E-04	atm
Pump speed	12	CFM
Pump speed - leak rate	6	CFM
Pump Speed	0.0028	m3/s
Pump down time	3252.606	s

Vacuum - Build & Test

- Min vacuum pressure: 0.075 torr = 1E-4bar
- On/off via solenoids



Test results

Vacuum line

Subsystem - Power

Requirement: 60kW @ 200VDC, 10kW @ 120VDC

Starpath HQ Breaker

5x
480VAC 3phase 25A

DC Power Supplies

4x 18kW 200VDC
1x 18kW 120VDC

Plant

72kW @ 200VDC
18kW @ 120VDC

**notes:*

- *90kW total power*
- *Each 18kW supply can be fine-tuned between 0-600VDC*
- *Rental Jan 1 - Feb 28 for budget considerations*