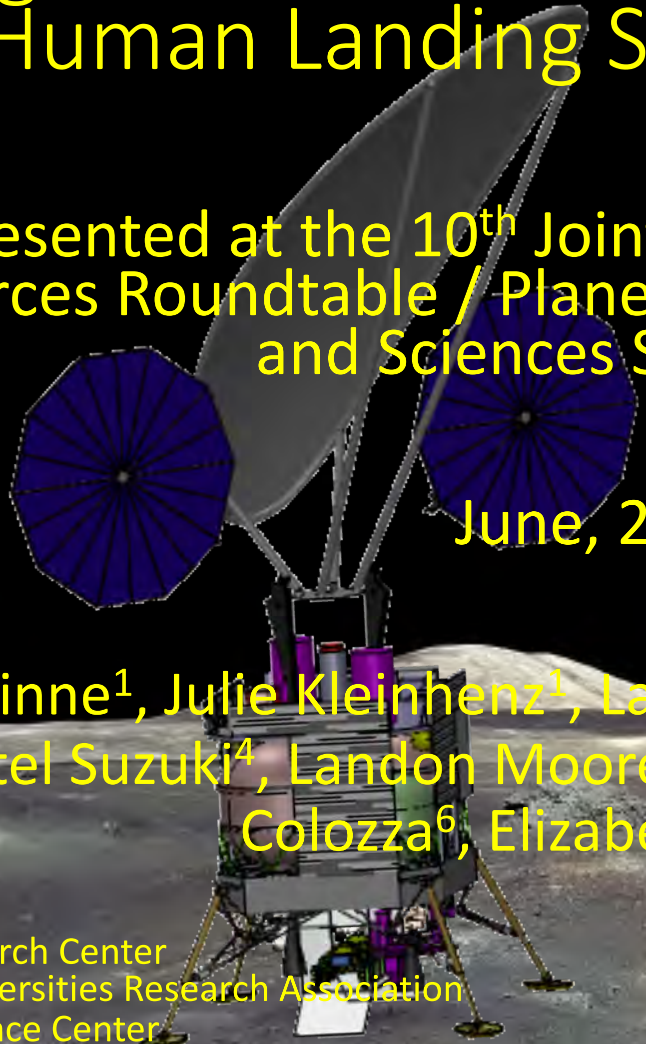
Oxygen Production System for Refueling Human Landing System Elements



Presented at the 10th Joint Meeting of the Space Resources Roundtable / Planetary and Terrestrial Mining and Sciences Symposium

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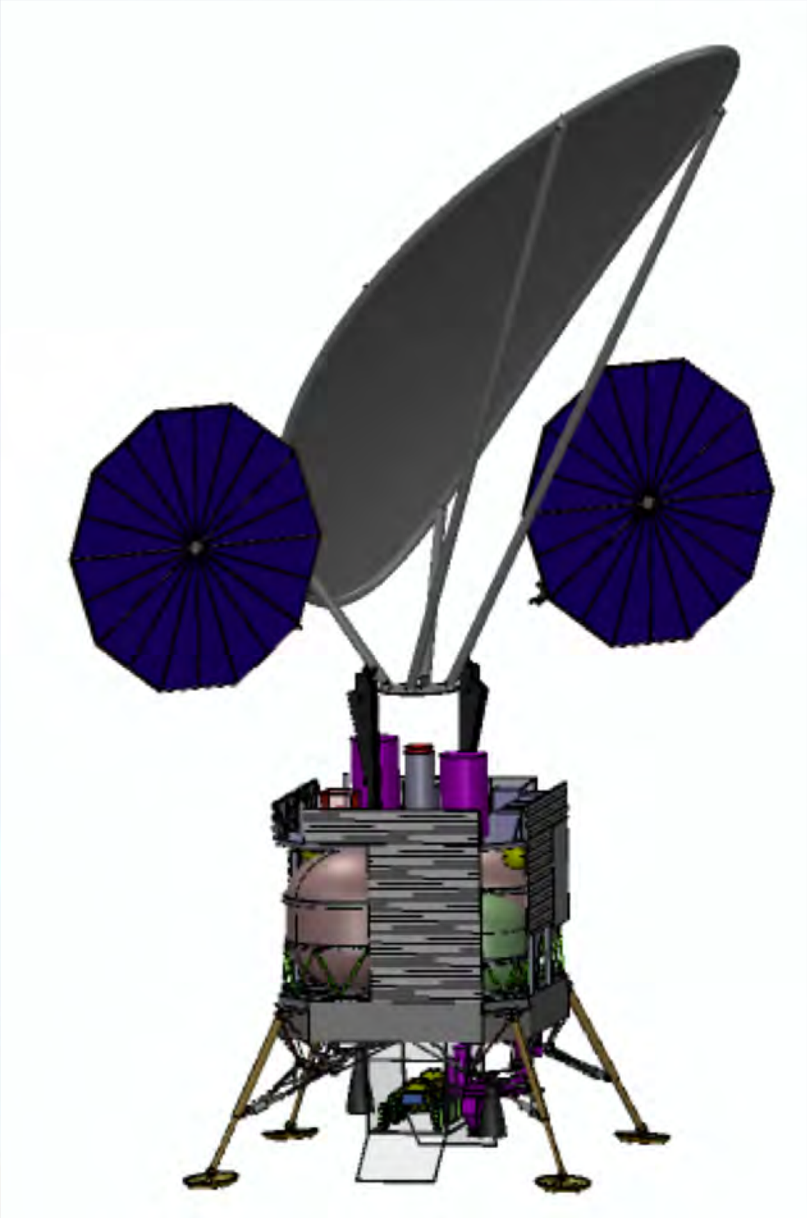
[4]NASA Headquarters
[5]NASA Johnson Space Center
[6]Vantage Partners

Study Overview

- Purpose: Develop a conceptual design for an ISRU system, delivered on a single lander, that produces and stores 10 tons of oxygen per year at the south pole of the moon for users landing 150 m away.
- Figures of Merit: ISRU yearly production, mass of system, power required
- ISRU basic assumptions
  - The customer of the produced oxygen is a refuelable lander that will land 150 m away from the ISRU operation.
  - ISRU plant will use the carbothermal reaction as the primary reactor to extract oxygen from the lunar soil.
  - Thermal power will be provided by solar concentrator and electric power will be provided by solar arrays
  - O_2 production will occur during season of near-continual sunlight, and go dormant during season of multiple dark/light cycles
  - The LOX delivery system will be designed in later studies
  - ISRU plant will consist of multiple self-contained modules, each sized to produce 3.5 t of O_2 per year
- Compass team design responsibilities
  - ISRU plant integrated into the lander
    - LOX cooling/storage
  - Power system for the ISRU
  - Determination of days/hours of direct sunlight available at landing site
  - Packaging of ISRU plant components on the lander
    - Launched in 7-m shroud, capable of landing 3.6 t payload near the lunar south pole

Team Roster

- Customer: ACSC, Nantel Suzuki, Diane Linne, Jerry Sanders, Laurent Sibille, Jason Schuler, Landon Moore, Julie Kleinhenz
- Lead - Steve Oleson
- System Integration, MEL- Betsy Turnbull
- Structures - John Gyekenyesi
- Environmental - Tony Colozza, Geoff Landis
- Power - James Fincannon, Brandon Klefman, Paul Schmitz
- Propellant Handling/Mobility: James Fittje
- C&DH/Software – Nicholas Lantz
- Communications – Robert Jones
- Configuration - Tom Packard
- Cost –Betsy Turnbull



Ref for Lander: Alexander, R., Chavers, G., and Percy, T., “Robotic Lunar Lander Concept,” presented at the International Space Development Conference, May, 2018.

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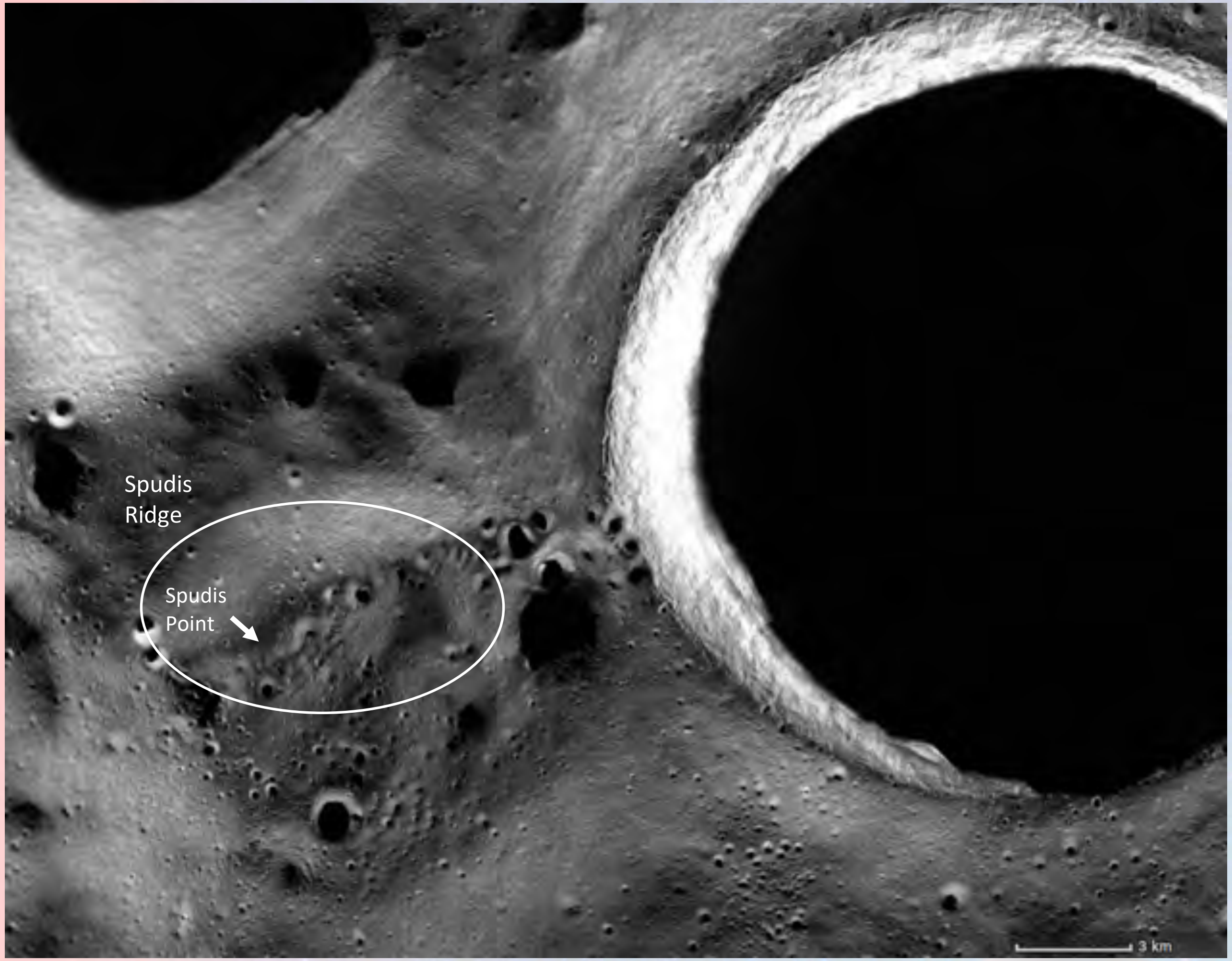
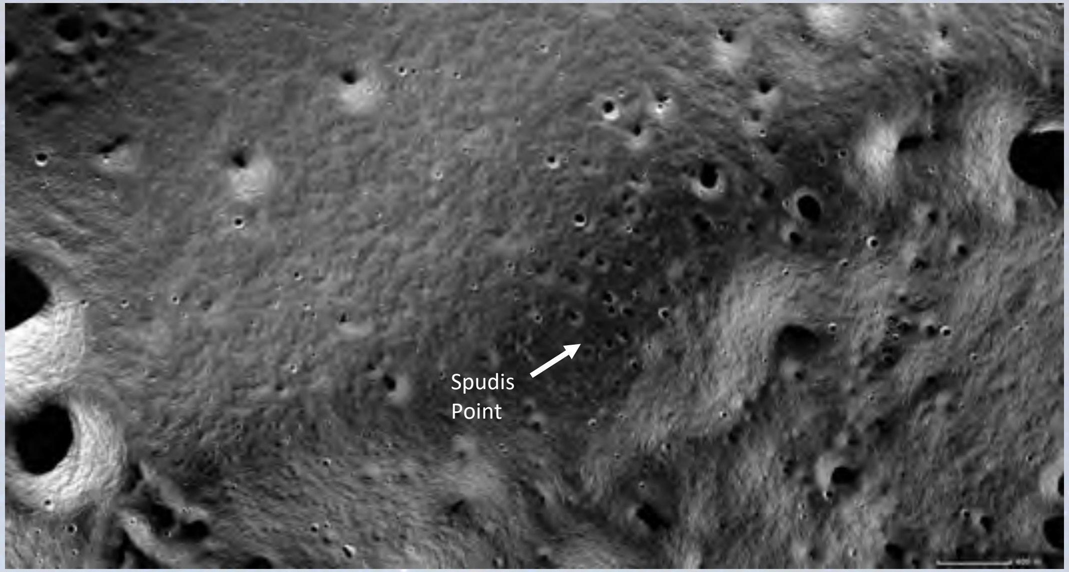
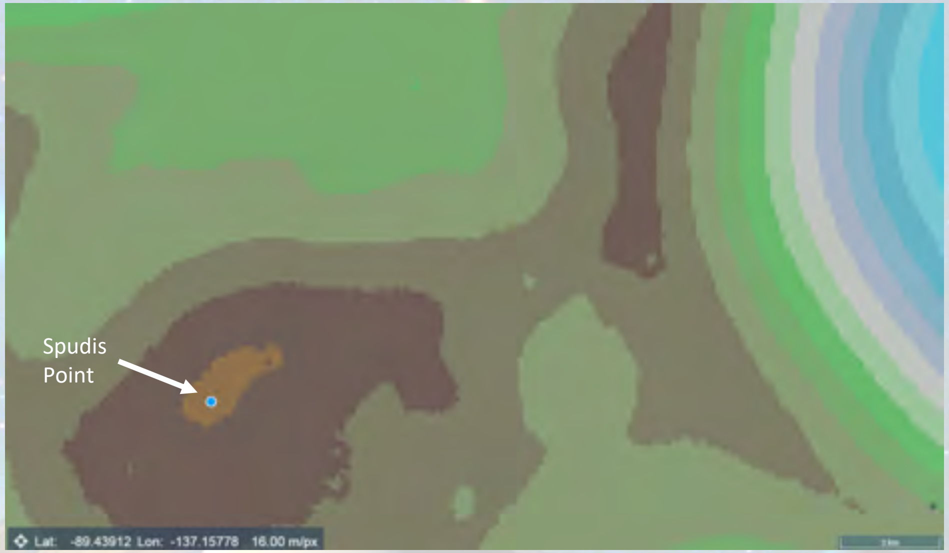
Landing site on ridge between Shackleton and de Gerlache (~89.439° S, -137.145° W)
Best illuminated site: aka “Spudis Ridge” Area, “Spudis Point” (not official)

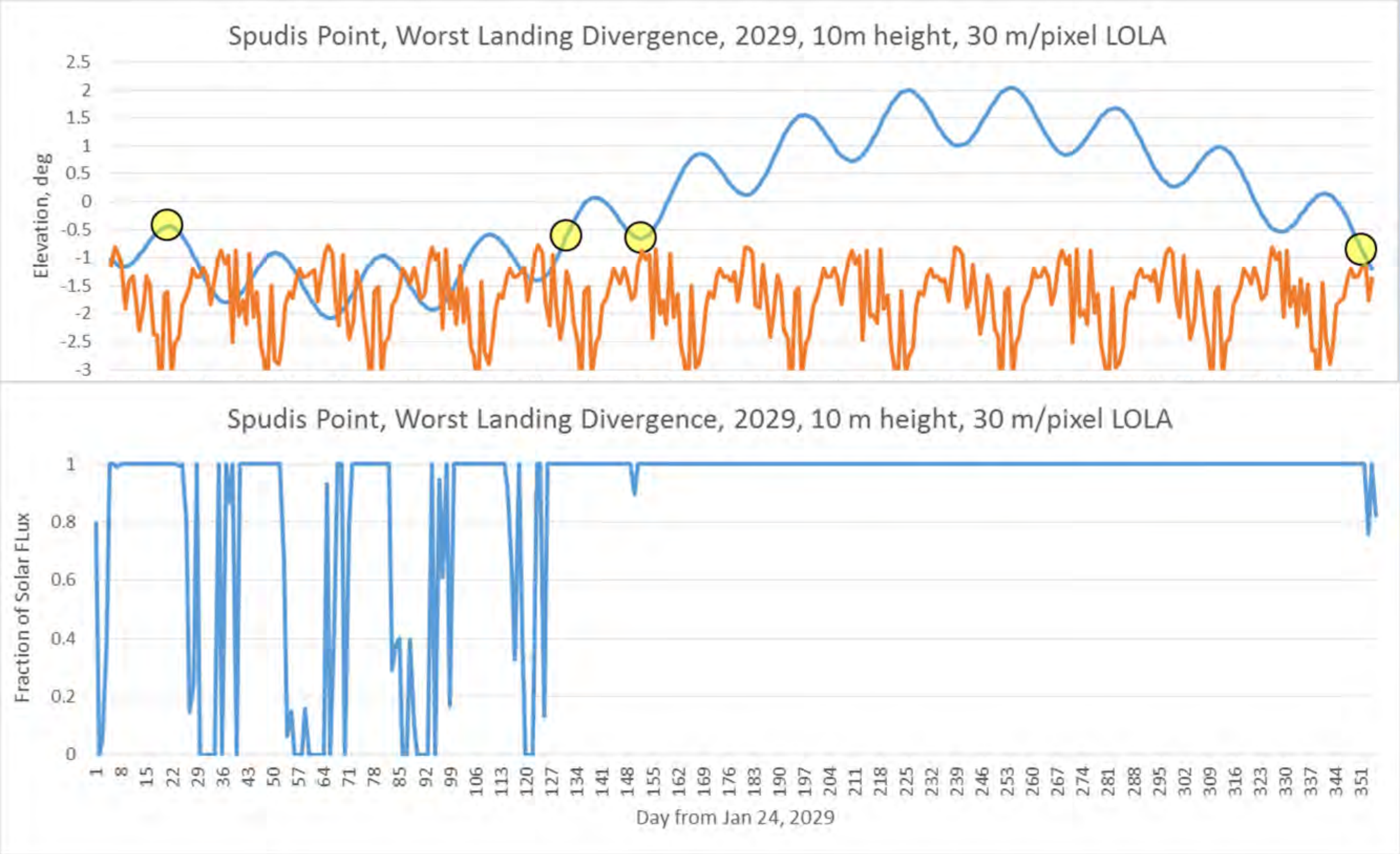






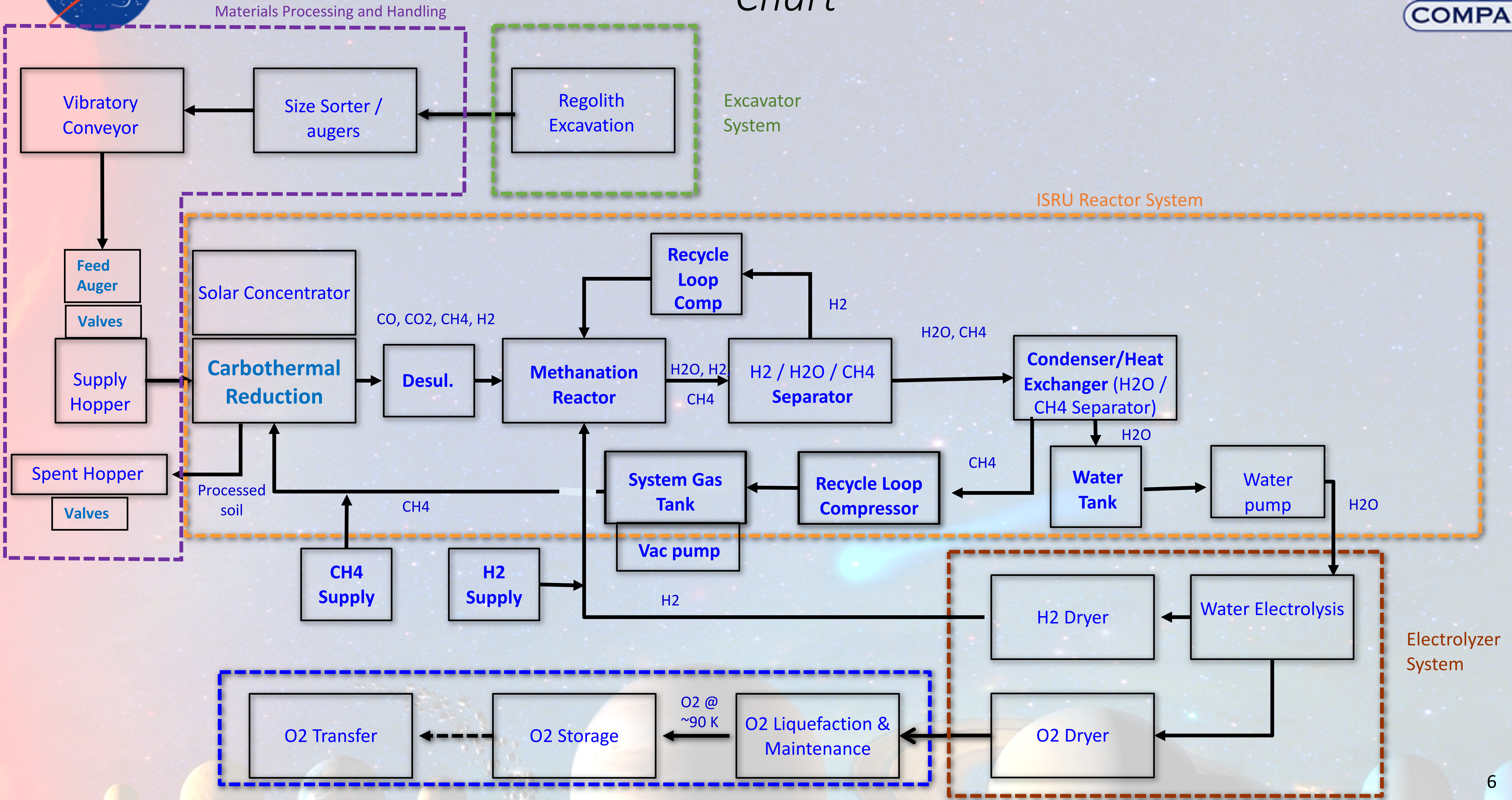
Above/upper right: LRO Image Mosaic, Lower right: DEM

Site Illumination Elevated 10 m



- Annual Average Illumination=87.8%
- Continuous 100% illumination period= 6.8 months
- Continuous >75% illumination period=7.8 months
- Continuous solar input 0% = 5 days
- Continuous solar input <15% = 9 days
- RFC must have enough fuel to handle ~22 days of low solar input during winter

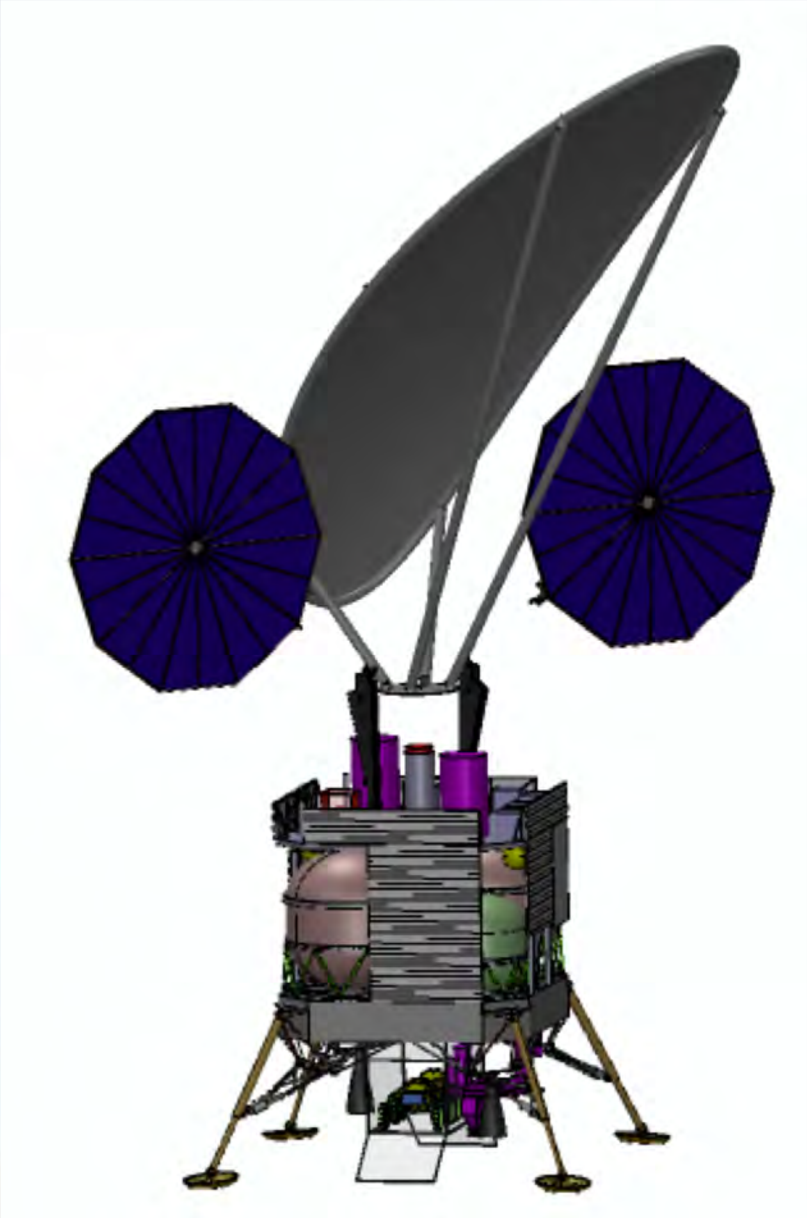
Carbothermal Reduction End-to-End Integrated System Flow Chart



Oxygen from Regolith

(Carbothermal option w/solar concentrator)

Conops



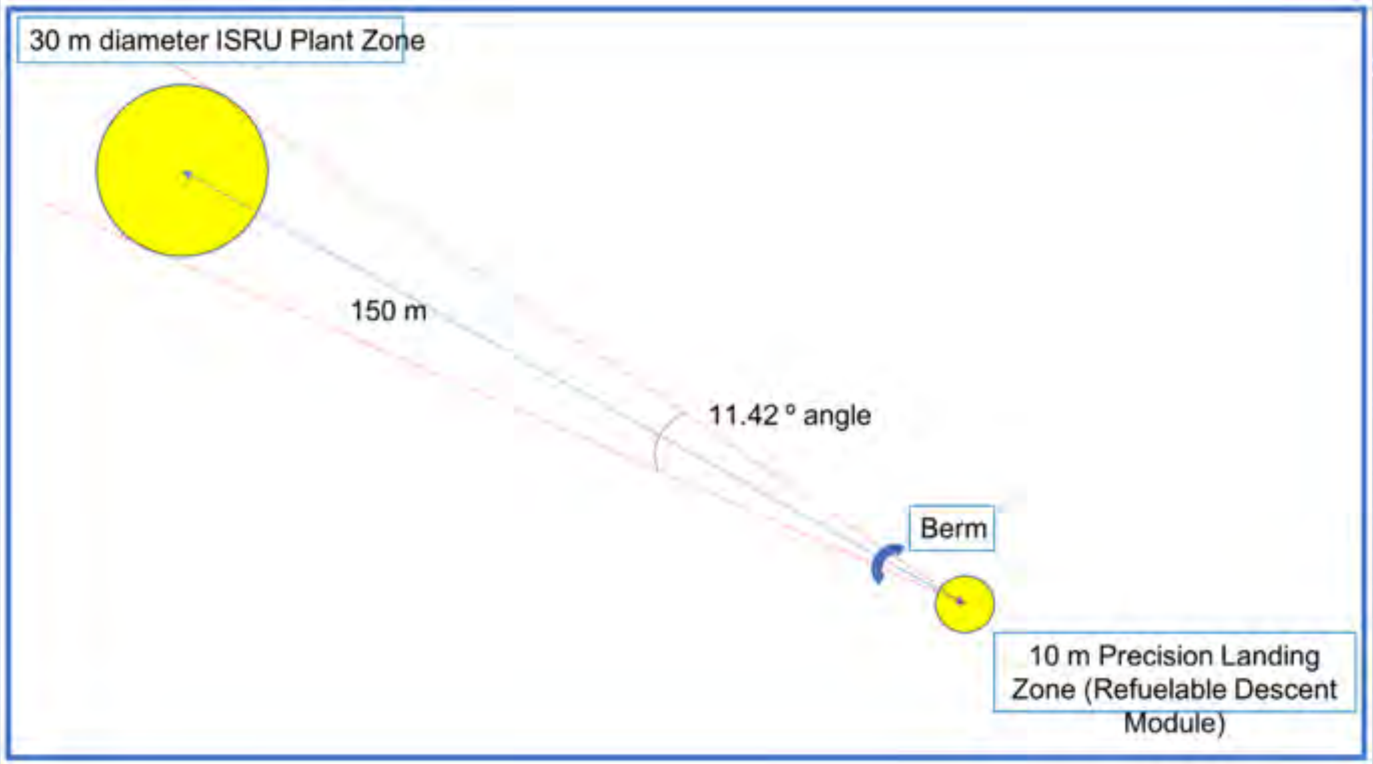
Conops: Resource Gathering

(7.4 continuous months per year)

- ISRU plant, excavation zone, and dump zone form triangle with 100 m each leg
- Each excavator provides 4 deliveries of 35 kg per day to ISRU plant (20 mins total per delivery)
  - 3 mins to gather regolith
  - 6 mins to drive to ISRU plant
  - 5 mins to drive into payload box and deliver regolith into size sorter dump trough
  - 6 mins to drive back to excavation zone
- Each excavator provides 3 disposal runs of 40 kg per day to clear out the two ISRU modules (17 mins total per disposal run)
  - 5 mins to position and receive slag
  - 6 mins to drive to disposal zone and deposit slag
  - 6 mins to drive back to ISRU plant or excavation zone
- Assume charging each excavator every 4.5 days
  - 1 kWhr battery discharged maximum 80% (50 charge cycles per 'year')
  - Charge with 100 W for 10 hours using inductive charge plate housed on floor of lander box
- Excavators comm link through lander to Gateway

Conops: Berm Building

- Without berms or a consolidated landing pad the second landing zone would need to be 2 km away from ISRU plant to avoid damaging ISRU plant with ejecta.
- The 3° ejecta angle value is the minimum recommended based on simulations and small-scale tests
- 5° and 6° angles would block larger particles
- The excavator design baselined in this study has a dump bin narrower than its wheel base, requiring extra width in the berm base to allow the excavator to climb higher with subsequent loads



Berm Distance from Landing (m)	Berm Height (m)			Berm Volume (m3)	Berm Regolith Mass (kg)	Time Required to Build* (hr)
	Ejecta Angle (°)			(for ejecta angle = 6°)		
	3	5	6			
25	1.3	2.2	2.6	48	72,200	690
40	2.1	3.5	4.2	220	330,000	3100
50	2.6	4.4	5.3	399	598,000	5700

*Time calculations assume same profile as excavation delivery to plant: 35 kg delivered from 100 m distance every 20 minutes. Time does not include down time for recharging.

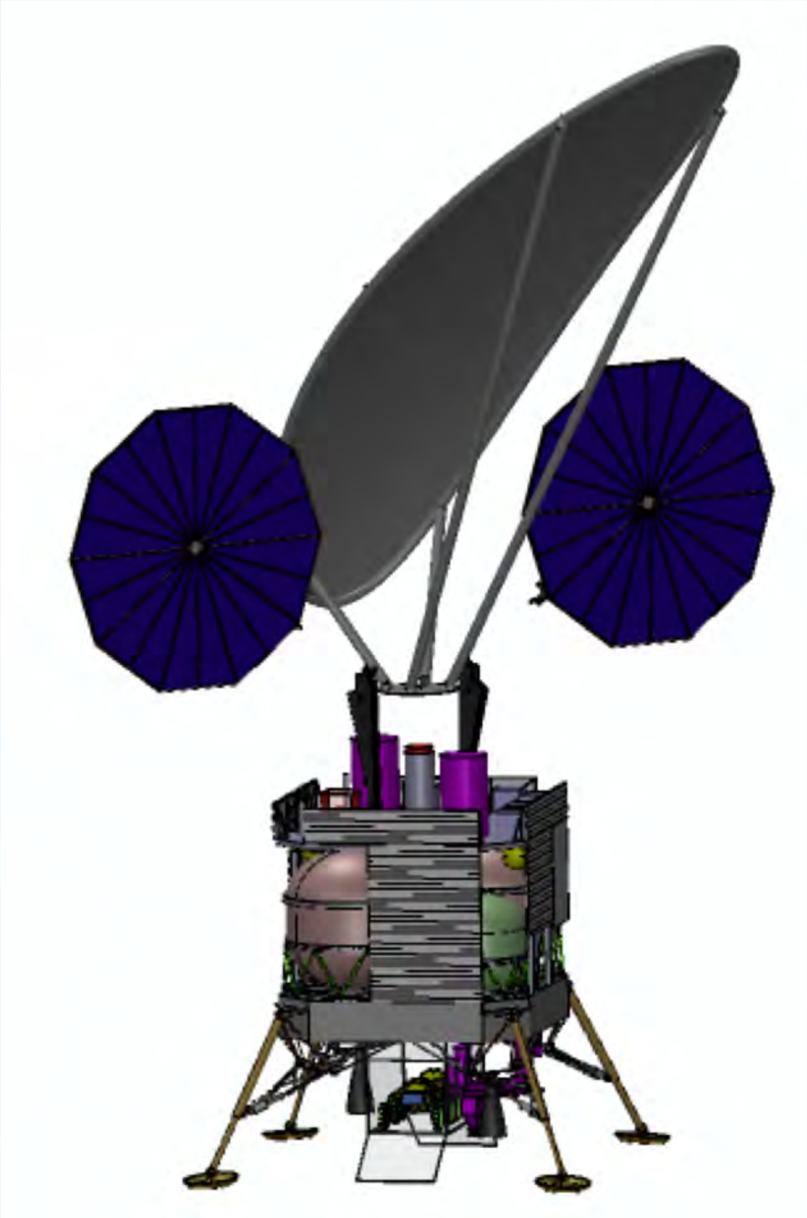
ConOps: LOX Production

(7.4 months continuous per year)

- **Each ISRU module (there are two)** produces 15.6 kg of O_2 per day (3500 t O_2 per year per module)
- Excavators deliver fresh regolith to the 'size sorter dump trough'
  - Screen on top prevents particles > 2 cm from entering trough
  - Two augers in trough move regolith to either side
- A vibratory conveyor lifts the regolith up to the top of the supply hopper
  - A small auger transfers regolith into the supply hopper
  - Supply hopper sized to hold 1 day's of regolith so excavator operation is decoupled from reactor batch timing
- The carbothermal reactor combines carbon (from cracked CH_4) into molten regolith zones and produces predominantly CO and H_2
  - 9.3 kg of regolith processed every 100 mins (14 batches per day)
- The methanation reactor processes the CO and H_2 into H_2O and CH_4
  - CH_4 recycled back to carbothermal reactor
- The water produced/gathered as vapor is transferred to cleanup steps, then to condenser
  - 0.73 kg of H_2O produced per hour
- Electrolysis subsystem converts H_2O into O_2 and H_2
  - 0.65 kg/hr of O_2
  - H_2 recycled back to methanation reactor
- Oxygen is liquefied and stored in the descent stage LOX tank (single system tied into all ISRU modules)
  - 1.3 kg/hr of O_2 (total from two ISRU modules) liquefied and placed in lander tanks

Lunar ISRU Plant: Carbothermal
(aka: Case 2)

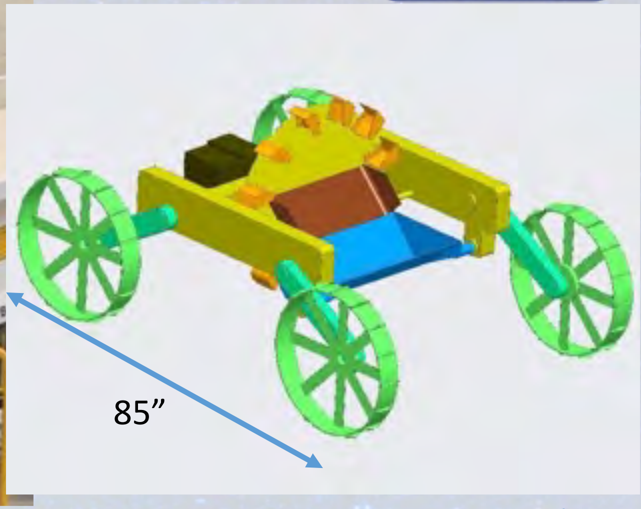
Excavation Subsystem



Excavator Overview

- Excavator design based on Astrobotic Polaris design
  - Transverse bucket wheel delivers regolith into central holding tray
  - 200 kg excavator tested in gravity-offloading tests
  - Digging rate: 0.5 kg/sec
  - Baseline driving velocity: 28 cm/s
  - Demonstrated payload ratio: 25 – 50 %
- Scale down to ½ the mass
  - Assume same payload *ratio* and driving velocity
  - Assume digging rate cut in half
- Each ISRU module requires 130 kg of fresh regolith each day
  - Four deliveries per day (per module) at 35 kg / load for payload ratio of 35%
- Excavators also need to receive processed regolith (aka, slag) and dispose of in dump zone
  - Slag removed from reactor in form of solid half-spheres ~10 cm diameter
  - Multiple batches of slag nodules held in dump hopper until ready to be removed
  - 115 kg/day of slag (per module) (130 kg of fresh regolith less 12 % oxygen extracted)
  - Three disposal trips per day (per module) at 40 kg / load for payload ratio of 40%

Prototype Astrobotic Polaris excavator in NASA GRC SLOPE Lab

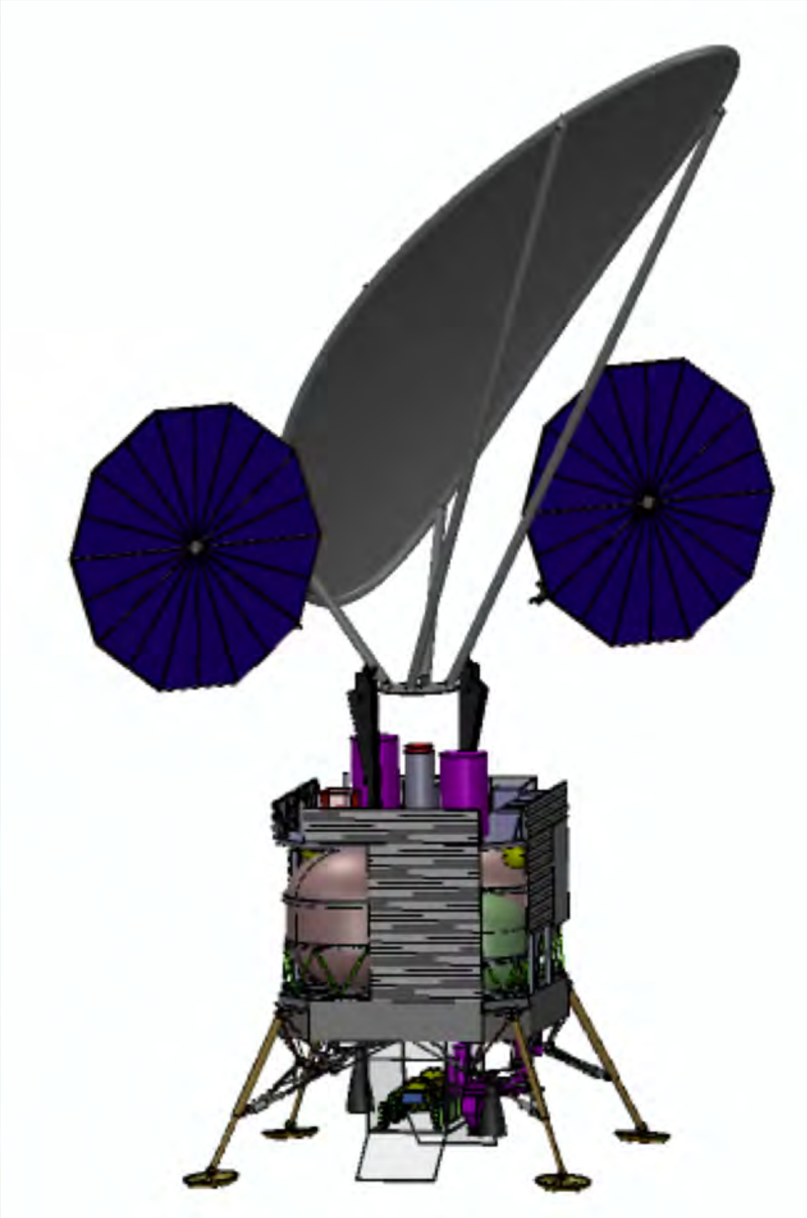


CAD rendering of scaled version (1/2 scale by mass)

Ref 1: Skonieczny, K., “Lightweight Robotic Excavation,” Doctoral Thesis, CMU-RI-TR-13-09, May, 2013.
Ref 2: Thornton, J., “Lightweight Robotic Excavation, Phase 2 Summary Report,” Contract NNX11CB55C, May, 2013

Lunar ISRU Plant: Carbothermal
(aka: Case 2)

Carbothermal Subsystem



Carbothermal Reduction

- Terrestrial technology for producing high-purity silicon from silica (SiO_2)
- Three-step process (temperature >1625 °C)
  - Reduction of metallic oxides with a carbonaceous source (e.g., methane)
  - Reduction of carbon monoxide with hydrogen to form methane and water
  - Electrolysis of water to form oxygen and hydrogen

$$MO_x + x\,CH_4 \rightarrow M + x\,CO + 2x\,H_2 \qquad (1)$$

$$x\,CO + 3x\,H_2 \rightarrow xCH_4 + x\,H_2O \qquad (2)$$

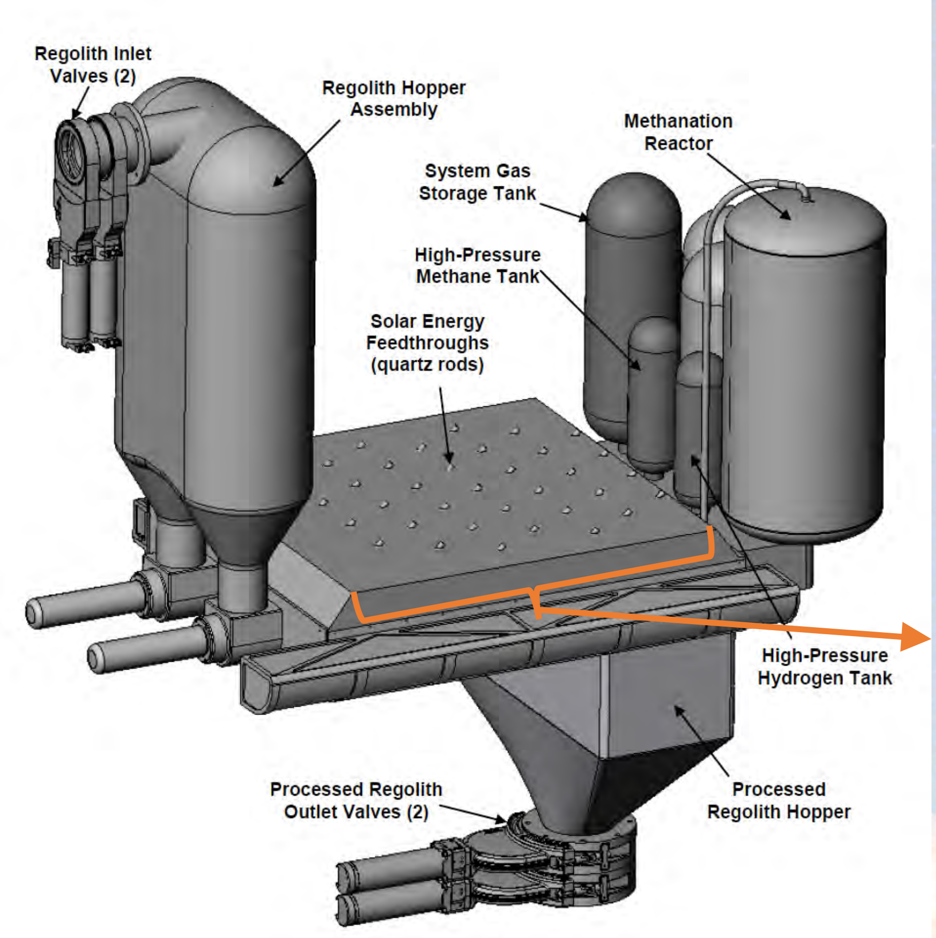
$$x\,H_2O \rightarrow x\,H_2 + 0.5x\,O_2 \qquad (3)$$

$$MO_x \rightarrow M + 0.5xO_2$$

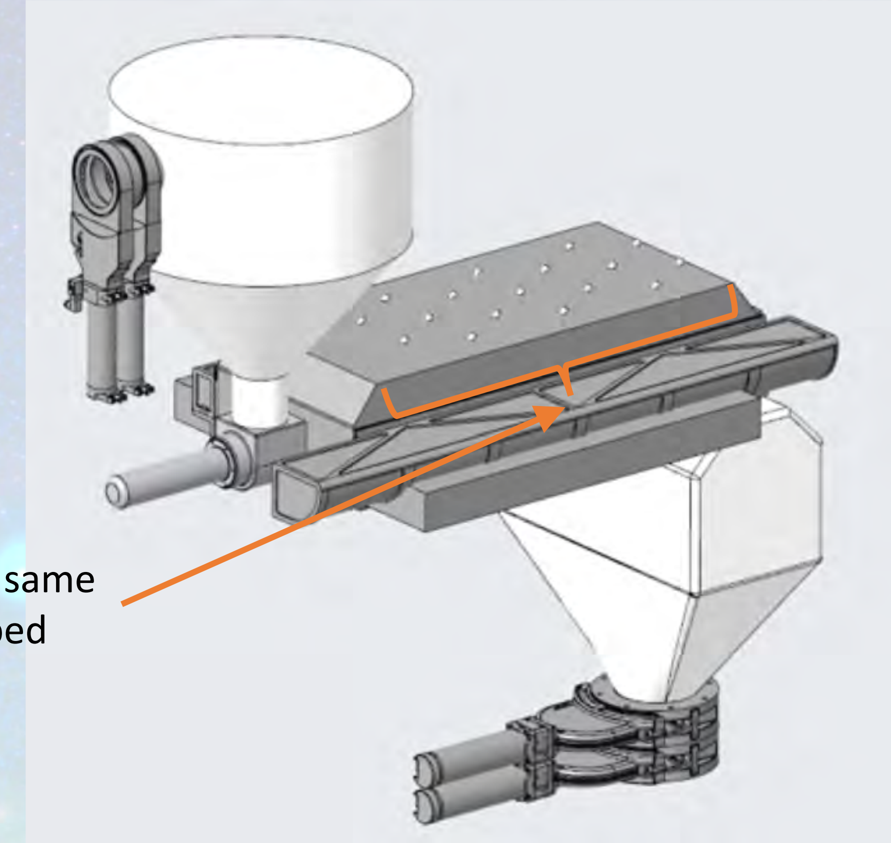
- Hydrogen produced in equations 1 and 3 is recycled to equation 2
- Methane formed in equation 2 is recycled to equation 1

Carbothermal Reactor

- Carbothermal reactor based on design by Orbital Technologies Corporation (Orbitec), now part of Sierra Nevada Corp.
- Orbitec 8 t O_2 / year design scaled down to 3.5 t O_2 / year



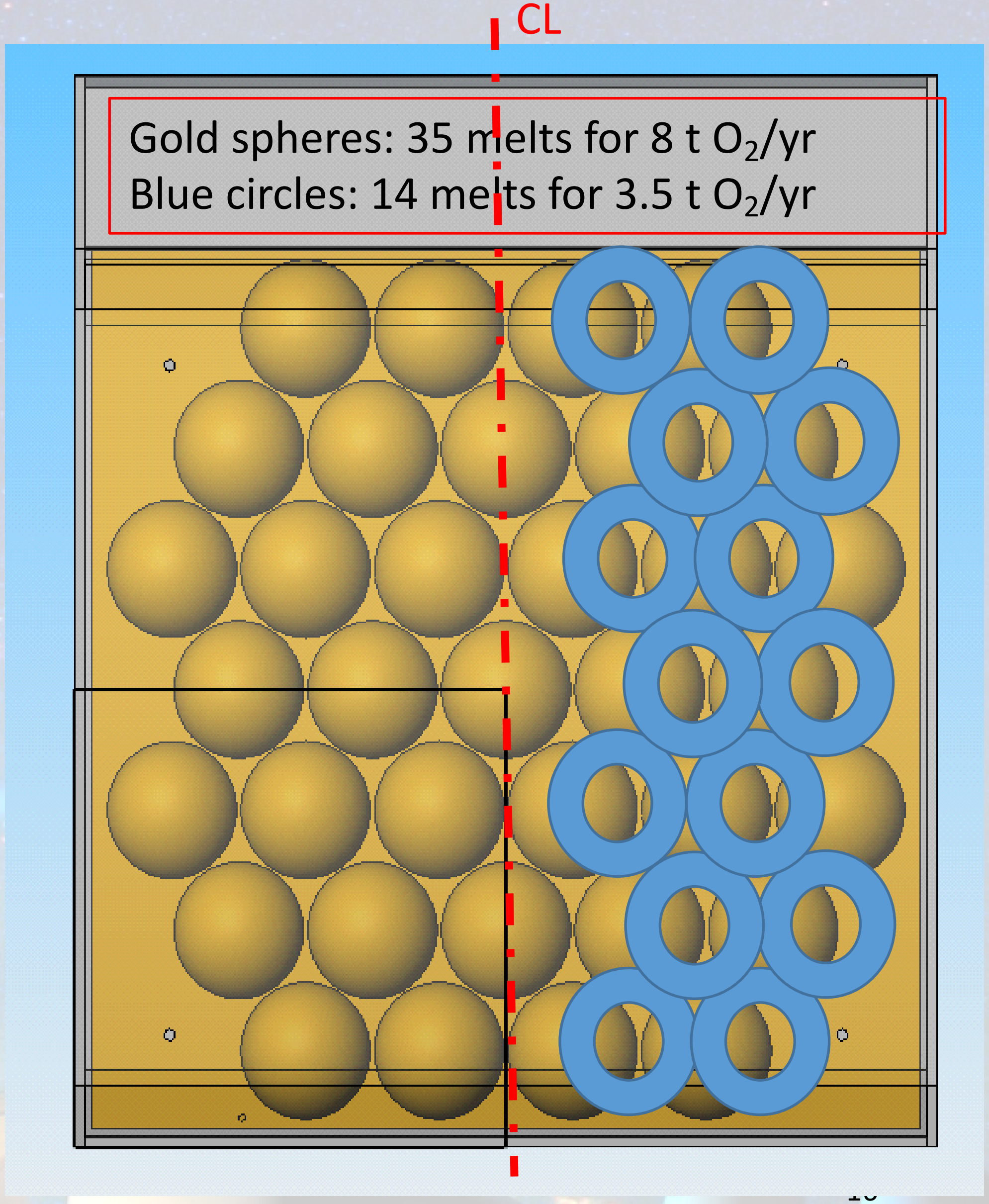
Scaled version has same length reactor bed



Ref: Gustafson, R., “Carbothermal Reduction of Lunar Regolith, Phase I Final Report”, Contract NNJ05HB57C, September, 2006.

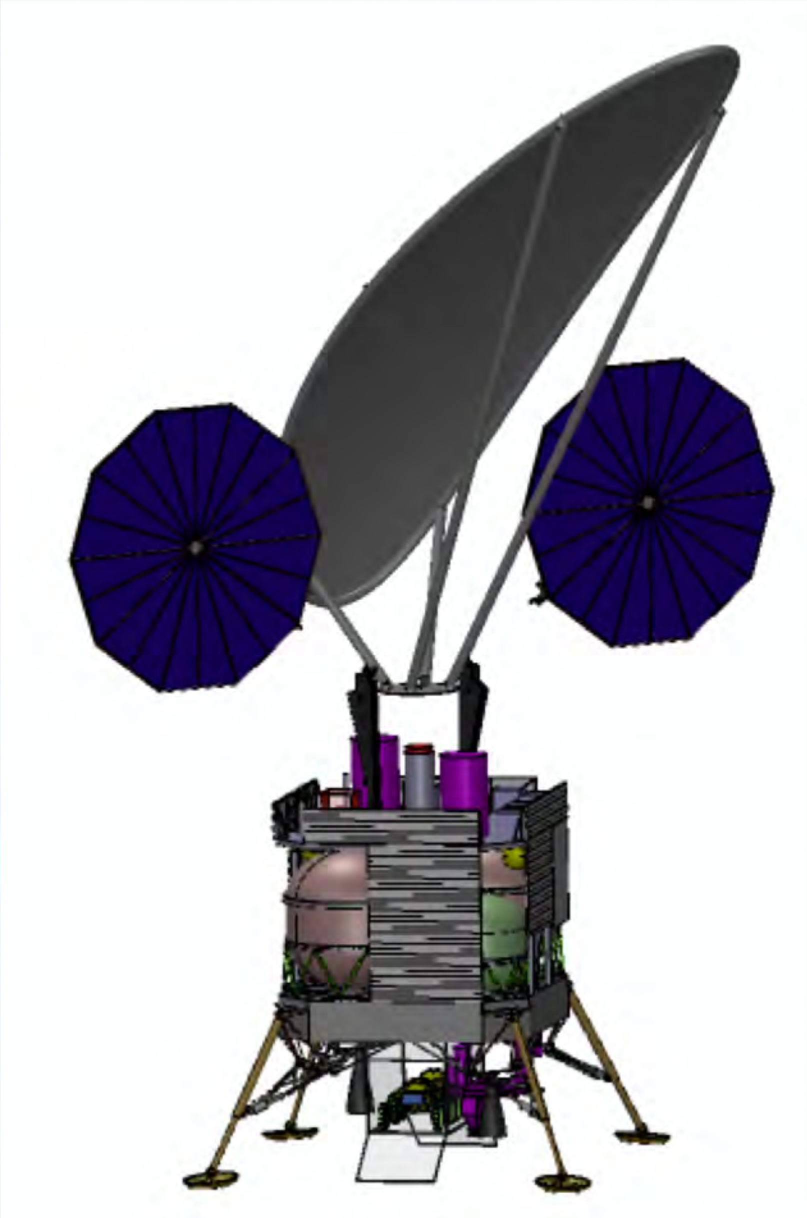
Carbothermal Reactor Resizing and Operating Conditions

- Original design utilized 35 reaction ‘melt’ zones to produce 8 t O_2 / year
- Reactor bed was re-sized for 14 melt zones to produce 3.5 t O_2 / year
  - Half-width reactor bed can accommodate the 14 melt zones
  - Each reactor requires 11 kWth delivered to melt 14 processing zones
  - Assumed 12.1% yield at 1800 °C melt temperature
- Regolith hopper assembly and processed regolith hoppers also reduced in width
- Remaining components for downstream processing resized, based on new volume required, using COMPASS team tank sizing routines



Lunar ISRU Plant: Carbothermal
(aka: Case 2)

Regolith Feed Subsystem



Regolith Feed System

- Uses a common trough/size sorter placed across the excavator box with a double auger that delivers alternately to the reactors on either side of the box The trough size sorts the regolith per the requirements of the auger in the trough
- The trough delivers to conveyors on each side of the box that each feed 1 reactor
- The total feed system serving 2 reactors thus includes:
  - 1 trough in the excavator box that receives regolith from the 2 excavators
  - 2 conveyors
  - 1 manifold
- NOTE: placing the trough/size sorter inside the box incurs the risk of accumulating dust inside the box with no means to remove it
- Two options were considered for conveying the regolith from a dump trough at or near surface level to the top of the feed hopper of the carbothermal reactor
  - Option 1: upward screw conveyor
  - Option 2: spiral vibratory conveyor

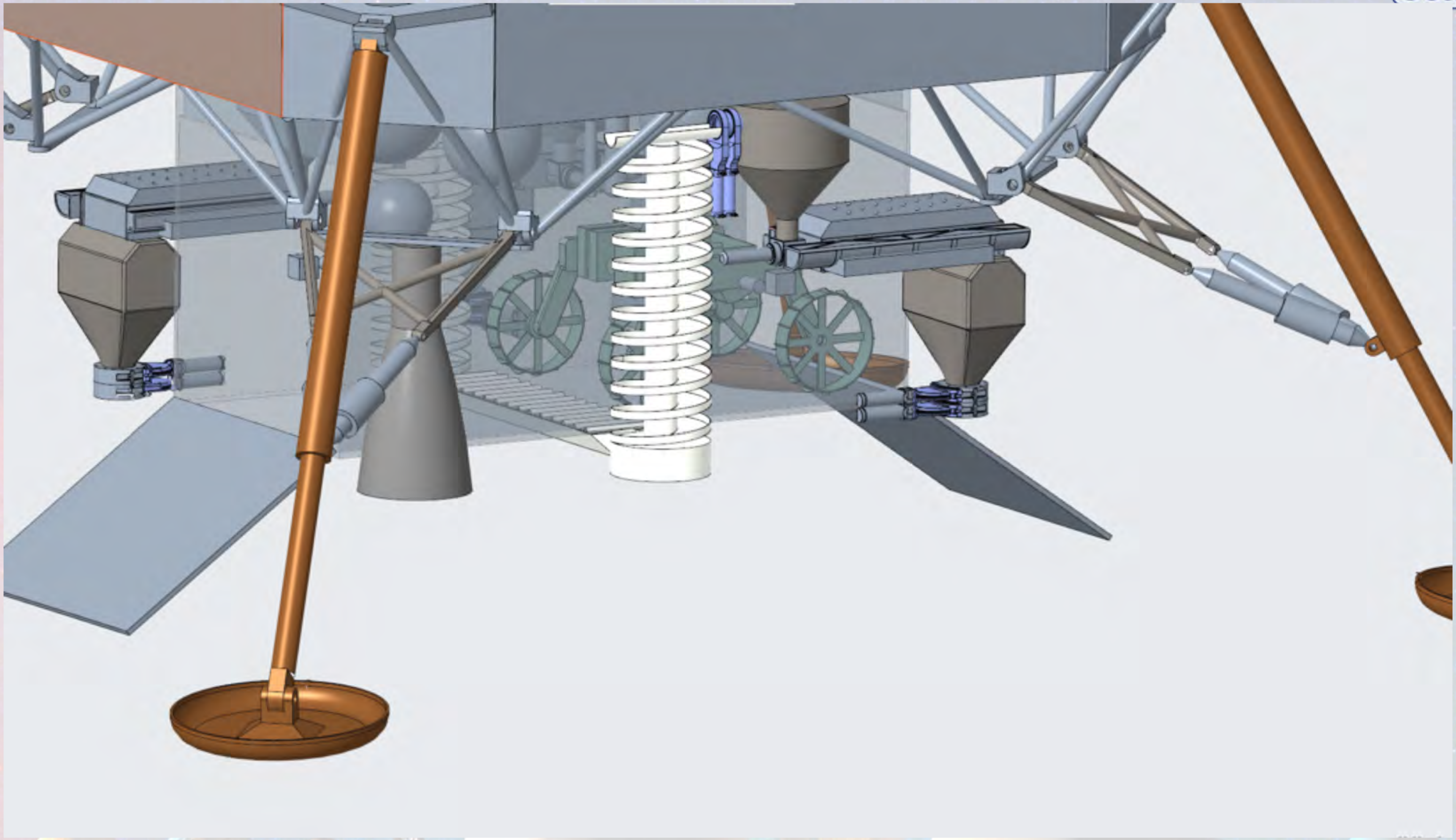
Spiral Vibratory Conveyor

- Characteristics (under 1 G)
  - Dry, rigid particles can be conveyed upward on 15º slope angles
  - Particles with a flat side and non-spherical in shape may achieve climb of 45º
  - Material volumes: thickness of transported mass (material's mat depth) can be 10 times the particle thickness
  - Conveying velocity: 30 cm/s typical for dry rigid particles
  - Frequencies vary from 5 to 57 Hz for dry rigid particles (low values for thick mat depth)
  - Conveyor can be suspended by steel cables if needed. Dampening system
  - Note: Frozen granular material is conveyed in same manner as dry rigid particles.
- Advantages
  - Experiments to transfer regolith upward have been conducted at KSC, GRC
  - Industrial, highly matured technology for granular conveying
  - Low maintenance frequency because system does not exert force on abrasive regolith. Rotating mechanisms not in contact with regolith reduces risk of failure
  - Can handle all particle sizes (small particles driven upward faster than large ones that can be discarded if desired)
  - Lower power than screw conveyors
  - Well suited for vacuum operations
  - Open system makes observation / monitoring easy
- Disadvantages
  - No full scale unit has bee tested for regolith simulant

Industrial spiral vibratory conveyor

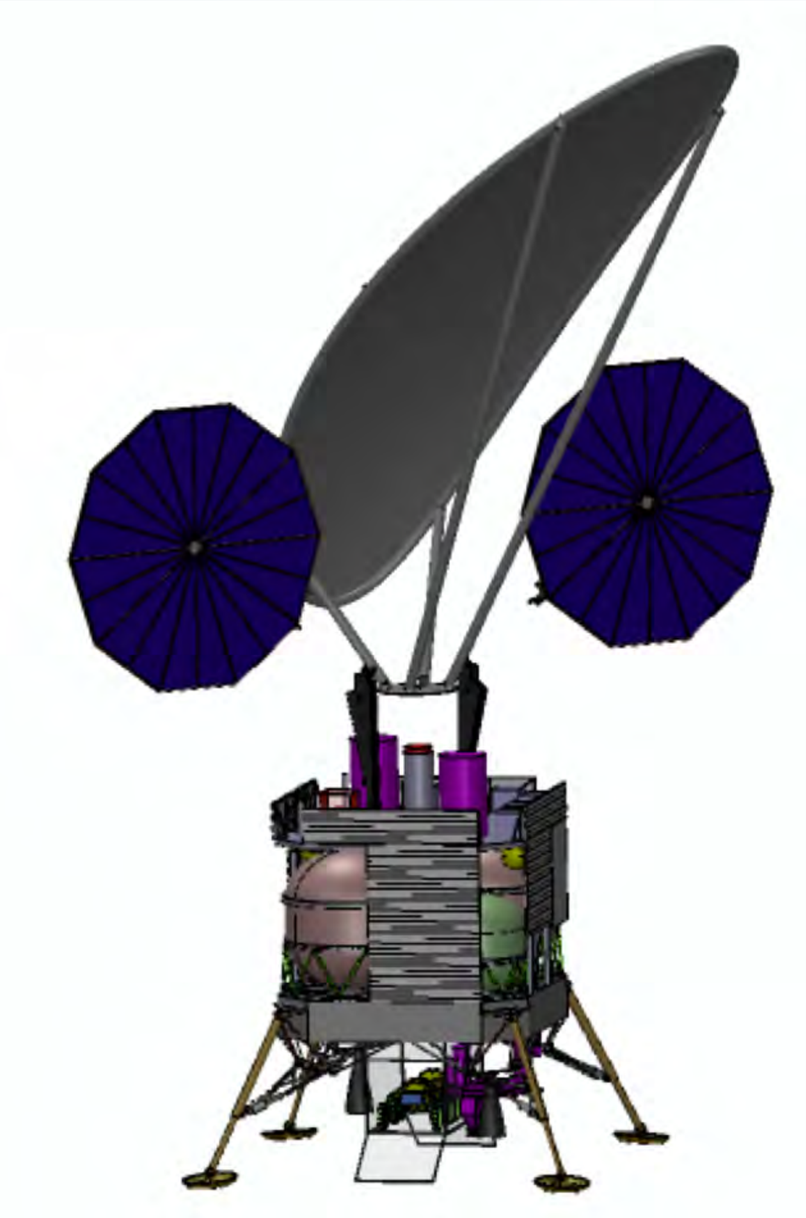
Ref: Kinergy Corp., "Kinergy Driven Vibrating Conveyors", Bulletin No. KDC-1, 10/97

Central trough/size sorter with spiral vibratory conveyor



Lunar ISRU Plant: Carbothermal
(aka: Case 2)

Power and Thermal Management



Concentrator Trades

- Final Requirement: 11.1 kWth energy delivered to each of two ISRU reactors via a 10 m fiber optic run to produce 14 molten zones in each reactor at 1800 °C
- Fiber optic transmission efficiency dependent on distance between focal point and reactors
  - 10 m length: 75% efficiency (requires 46.8 m^2 total area, 7.7 m diameter)
  - 5 m length: 84% efficiency (requires 33.3 m^2 total area, 6.5 m diameter)
- Shape
  - Cassegrain:
    - 8000:1 max concentration ratio (rigid)
    - 2400:1 max concentration ratio (inflatable)
  - Offset Parabola:
    - 4000:1 max concentration ratio (rigid)
    - 2400:1 max concentration ratio (inflatable)
- Rigid: heavy (10 kg/m^2), expensive
- Spline mirror: lighter (2 kg/m^2)
- Inflatable: lightest (0.2 kg/m^2), but less accurate – requires secondary concentrator to achieve comparable concentration ratios
- Secondary Concentrators

Power

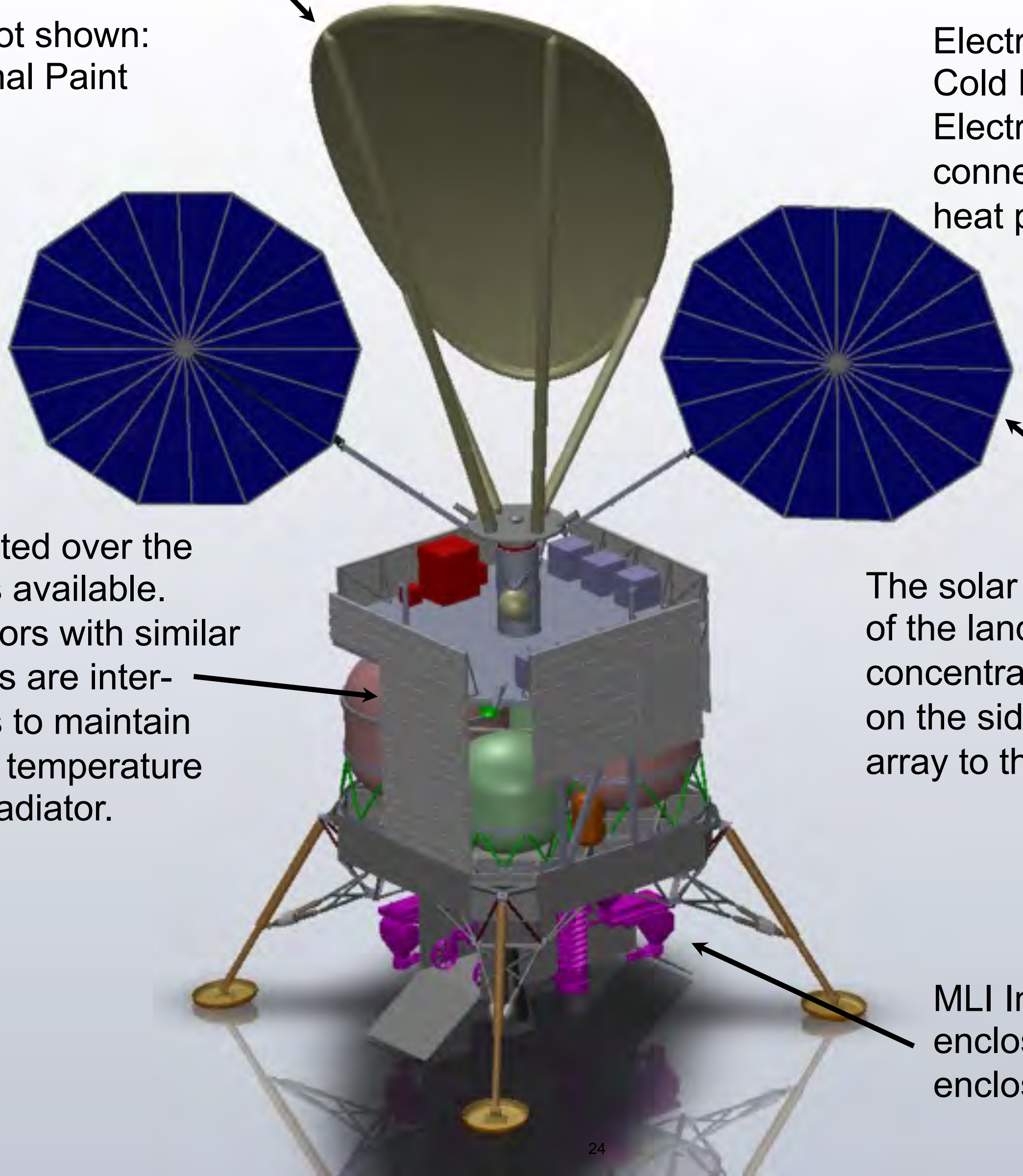
- Thermal Power: 7.7 m offset parabola (46.3 m^2)
  - Need 22.2 kWth required at reactors, 32.3 kWth from concentrator with 4000:1 concentration ratio
    - 1000:1 primary, 4:1 secondary
  - Spline parabola based on Comsat large antennas
    - Notional packaging and deployment
- Electrical Power: 15 kWe (entire system, with 30% growth)
  - Two ultraflex arrays at 5.4 m diameter
  - Assume single gimbal with hole for the fiber optic bundle
  - ISRU standby mode (4.6 'winter' months)
    - 807 W (incl 30% growth) from fuel cell required during 1-9 day eclipse periods (<15% solar input)
    - 3481 W (incl 30% growth) by solar arrays during 1-20 day Sun periods for maintenance and to recharge fuel cells

Thermal Control System Components

Solar Concentrator: The concentrator is located above the reactor.

Additional Items not shown:
- Spacecraft Thermal Paint
- Thermal Sensors
- Heat Pipes
- Cold Plates

Electronics Cold Plates: Located Beneath Each Electronics Package these are connected to the radiator through heat pipes.



Radiators are distributed over the surface where area is available. Certain system radiators with similar rejection temperatures are inter-linked with heat pipes to maintain the desired operating temperature and function as one radiator.

The solar array is positioned on the top of the lander to the sides of the concentrator. With the radiators located on the sides there is a small view of the array to the radiators.

MLI Insulation: Electronics enclosure surfaces and rover enclosure are wrapped with MLI

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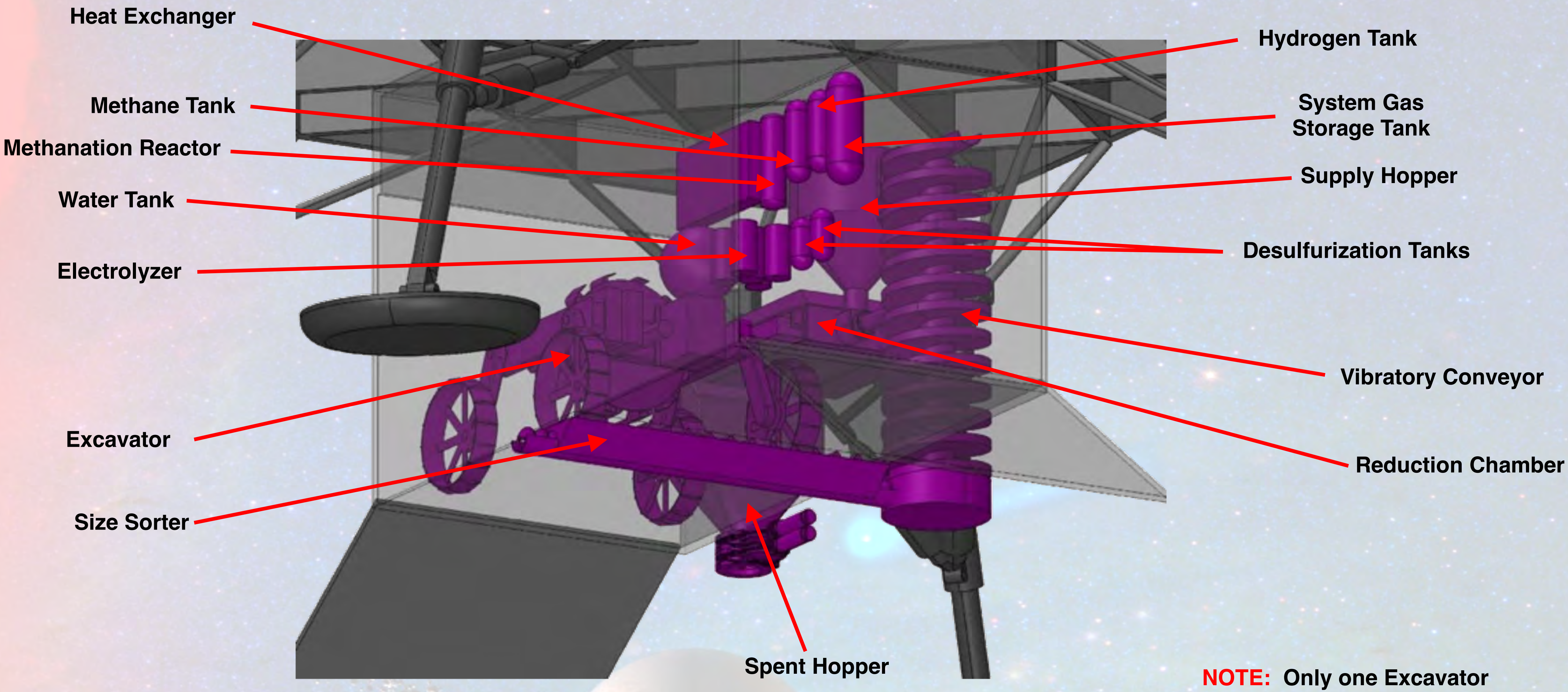
Energy Storage System Design

- Regenerative Fuel Cell
  - Fuel cell sized for average 374 W (i.e. PEL value minus fuel cell efficiency losses) for ~22 days of low solar input
  - Electrolyzer sized for 5.4 kW
  - Voltage: 120 V
  - Sized using a detailed model based on test data from fuel cells and electrolyzers and thermal and fluid modelling.
  - RFC system includes all ancillary equipment (harness, tubes, valves, etc) except as specified for the O_2 and helium tank adaptations.
  - Uses a common thermal enclosure to house water tank/water, electrolyzer, and fuel cell and some PMAD electronics.
  - Radiator provided by thermal subsystem
  - 88 kg of water for fuel and 20 kg water tank (sized to handle structural landing loads)
    - **If we had assumed the non-ISRU operation time of the year (12-7.4=4.6 months) was dark, H_2O mass=221 kg**
    - **If we used the average illumination (100%-87.8%=12.2%) to get the dark period, H_2O mass=173 kg**
    - **But because we have the time varying illumination profile, we got it to 88 kg!**
    - **Phasing of charge and recharge in smaller chunks enabled this. <u>Without this data</u> we need lots of H_2O! Affects tank size too!**
  - Total mass: 252 kg (fuel cell+electrolyzer+ thermal enclosure+water+water tank+ancillaries)
  - <u>Why not a battery? To provide 374 W for 22 days would take ~1000 kg worth of batteries!</u>

Lunar ISRU Lower Payload Components



NOTE: Only one Excavator and ISRU System is shown

Master Equipment List

Description Case 2 ISRU CD-2018-162	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
ISRU	2743	18%	505	3248
Bus	1510	19%	282	1792
Command & Data Handling	6.5	30%	2.0	8.5
Communications and Tracking	42.0	11%	4.4	46.4
Electrical Power Subsystem	347.3	23%	81.5	428.8
Thermal Control (Non-Propellant)	340.0	16%	55.8	395.7
Structures and Mechanisms	774.2	18%	138.2	912.4
ISRU System	1021	18%	179	1200
O2 Production	519.7	17%	86.9	606.6
Command & Data Handling	18.1	30%	5.4	23.5
Thermal Control (Non-Propellant)	368.2	18%	66.3	434.5
O2 Storage and Transfer	115.1	18%	20.7	135.8
Excavator System	212	21%	44	256
Excavator	200.0	20%	40.0	240.0
Electrical Power Subsystem	12.0	30%	3.6	15.6

Systems Rollup

MEL Summary: Case 2 ISRU CD-2018-162	Bus	ISRU System	Excavator System	TOTAL
Main Subsystems	**Basic Mass (kg)**	**Basic Mass (kg)**	**Basic Mass (kg)**	**Total Basic Mass(kg)**
Science	0.0	519.7	200.0	719.7
Attitude Determination and Control	0.0	0.0	0.0	0.0
Command & Data Handling	6.5	18.1	0.0	24.6
Communications and Tracking	42.0	0.0	0.0	42.0
Electrical Power Subsystem	347.3	0.0	12.0	359.3
Thermal Control (Non-Propellant)	340.0	368.2	0.0	708.2
Propulsion (Chemical Hardware)	0.0	115.1	0.0	115.1
Propellant (Chemical)	0.0	0.0	0.0	0.0
Propulsion (EP Hardware)	0.0	0.0	0.0	0.0
Propellant (EP)	0.0	0.0	0.0	0.0
Structures and Mechanisms	774.2	0.0	0.0	774.2
Element Total	***1509.9***	***1021.1***	***212.0***	***2743.0***
Element Dry Mass (no prop,consum)	1509.9	1021.1	212.0	2743.0
Element Propellant	0.0	0.0	0.0	0.0
Element Mass Growth Allowance (Aggregate)	281.9	179.4	43.6	504.8
Additional System Level Growth (For 30% tot)	171.1	127.0	20.0	318.1
Total Wet Mass with 30% Growth	**1962.9**	**1327.4**	**275.6**	**3565.9**

Total payload < 3600 kg lander capability

Powered Equipment List (values are before 30% growth)

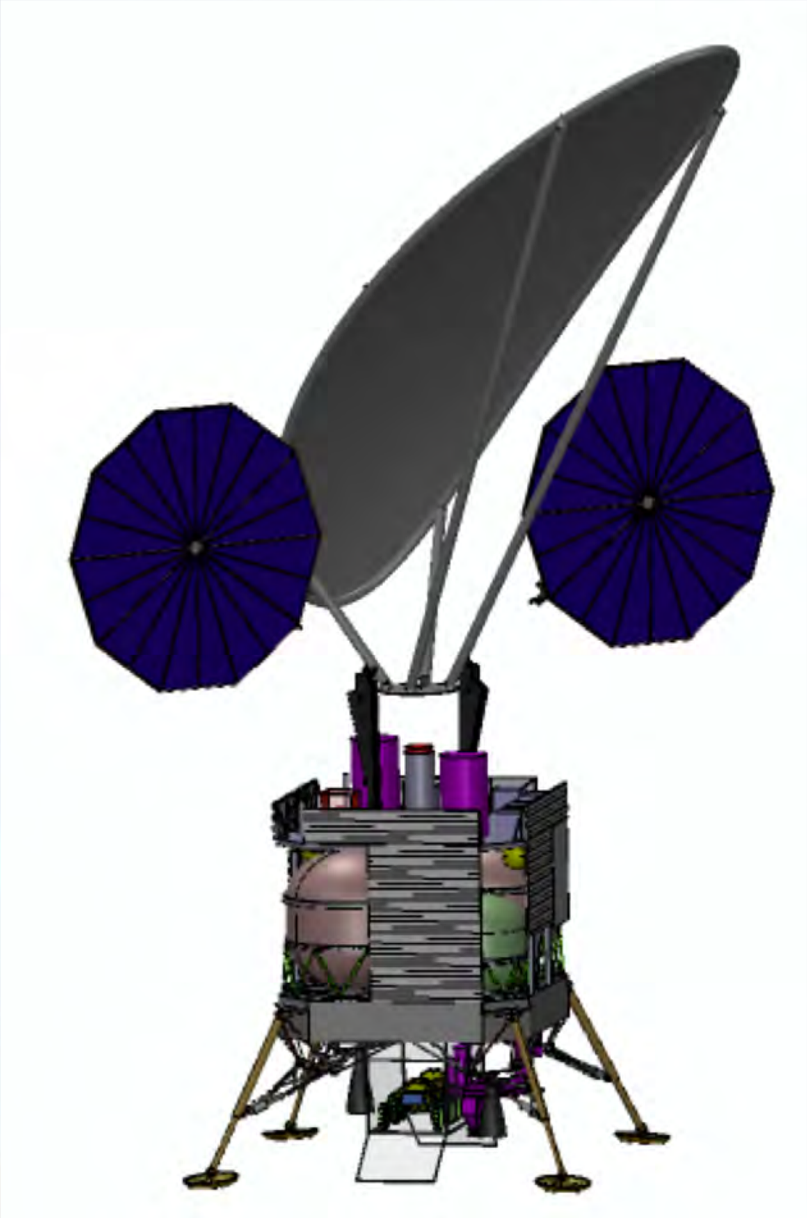
Description	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7
Case 2 ISRU CD-2018-162	Launch/ Transit and Landing	Commissioning	Sunlit LOX Production	Sunlit Standby	Night Standby	LOX Transfer	Excavator Recharging
	4 Days	2 Days	7.4 Months	1 - 20 Days	1 - 9 Days	30 Minutes	10 Hours
	(W)	(W)	(W)	(W)	(W)	(W)	(W)
ISRU	**32**	**62**	**11544**	**2678**	**621**	**2021**	**298**
Bus	**11**	**11**	**817**	**1007**	**438**	**96**	**51**
Command & Data Handling	10.8	10.8	10.8	10.8	10.8	10.8	10.8
Communications and Tracking	0.0	0.0	85.0	85.0	85.0	85.0	0.0
Electrical Power Subsystem	0.0	0.0	721.0	911.0	342.0	0.0	40.0
Thermal Control (Non-Propellant)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ISRU System	**22**	**52**	**10727**	**1672**	**123**	**1926**	**48**
O2 Production	0.0	0.0	8080.0	0.0	0.0	0.0	0.0
Command & Data Handling	21.6	47.6	77.6	47.6	47.6	51.6	47.6
Thermal Control (Non-Propellant)	0.0	0.0	2565.2	1620.0	71.9	1620.0	0.0
O2 Storage and Transfer	0.0	4.0	4.0	4.0	4.0	254.0	0.0
Excavator System	**0**	**0**	**0**	**0**	**60**	**0**	**200**
Excavator	0.0	0.0	0.0	0.0	60.0	0.0	160.0
Electrical Power Subsystem	0.0	0.0	0.0	0.0	0.0	0.0	40.0

Summary

- Assuming a 15 t class commercial launcher and a LOX/LH2 FLEX-2 lander a **LOX ISRU plant can gather, produce and store 7 t of LOX during a 7.4 month continuous sunlit period** at the lunar south pole
  - The other 4.6 months of the year the sunlight is not continuous so production is halted
  - Transfer of LOX product from storage tanks to customer's reusable lander provided by separately landed assets
- An ISRU plant has many processes (gathering, sorting, heating/reacting, electrolysis, O_2 liquefaction and storage) that compete for mass, power, and volume on a lunar lander
  - The Compass design is NOT optimized but closes – further work should be done to investigate how all these processes could better work together
- Significant savings in volume and mass were made by reusing the lander's cryogenic oxygen storage and zero boiloff (ZBO) systems
  - This will require redesigning/requalifying these systems for lunar landing, surface and night-time operations for multiple years
  - The ZBO cryocoolers were assumed capable of cold soak to ~50 K for up to 8 days
- A solar concentrator is perhaps the only efficient way to generate the high temperatures for carbothermic processing (~1800°C)
  - Any direct-contact electric heaters would be destroyed when the molten regolith solidifies before removal
- A polar mission site has unique resources and power and thermal requirements
  - An ISRU plant at the equator would probably look much different (i.e. a polar ISRU system and equatorial ISRU system optimize to much different designs)

Lunar ISRU Plant: Carbothermal
(aka: Case 2)

Back-up Charts



Conops: Berm Building

Half scale Polaris numbers using stair stepped method
(excavating 100 m from berm)

		3°			5°			6°		
Berm Distance from landing (m)	BERM Length (ramps not included) (m)	Berm Volume (m^3)	Berm Regolith Mass (kg)	Time Required to Build (hr) (includes battery charging time)	Berm Volume (m^3)	Berm Regolith Mass (kg)	Time Required to Build (hr) (includes battery charging time)	Berm Volume (m^3)	Berm Regolith Mass (kg)	Time Required to Build (hr) (includes battery charging time)
25	5	14	20,800	228	38	56,500	618	48	72,200	790
40	8	46	68,300	748	139	209,000	2289	220	330,000	3614
50	10	96	144,000	1580	275	413,000	4517	399	598,000	6549

$$H_{berm} := 5.25\ m$$

$$L_{berm} := 10\ m$$

$$N_{lifts} := \frac{H_{berm}}{30\ cm} = 17.5$$

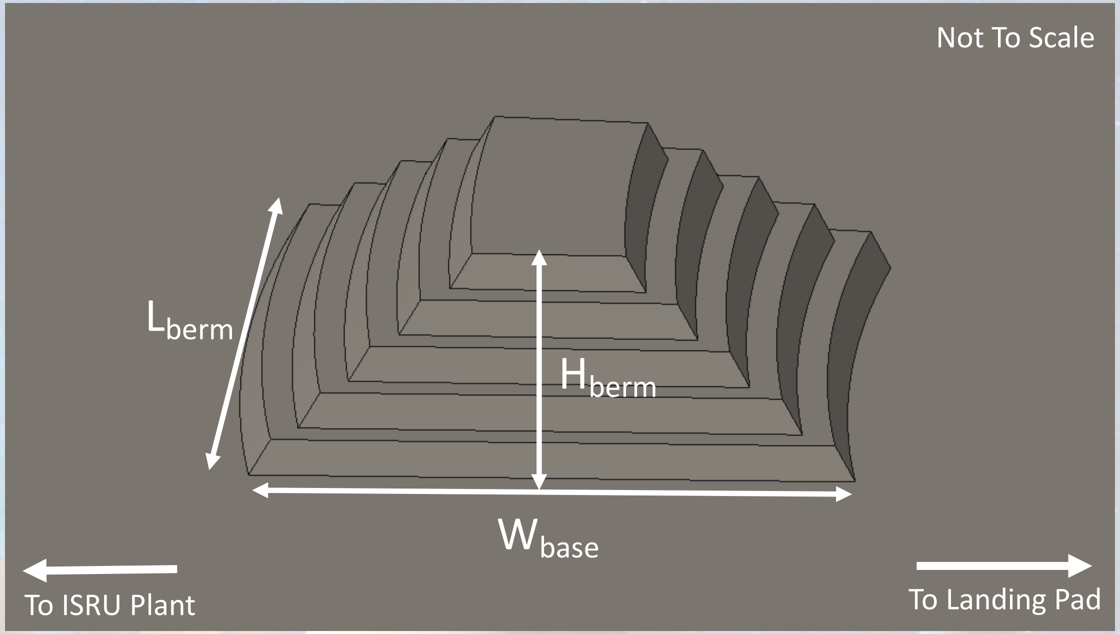
$$i := 1$$

$$f(n) := 70\ cm + (17.32\ cm \cdot 2 \cdot n) + 50\ cm\ (n-1)$$

$$W_{all\_lifts} := \sum_{n=i}^{N_{lifts}} f(n) = 132.899\ m$$

$$V := L_{berm} \cdot 30\ cm \cdot W_{all\_lifts} = 398.698\ m^3$$

Width of Polaris bucket = 70cm
60 degree angle of repose contribution to width = 17.32cm
Width from outside of polaris wheel to bucket = 50cm
Maximum lift height = 30cm



Notional berm

Lunar ISRU Case 2 - Excavation Subsystem

Description Case 2 ISRU CD-2018-162	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Excavator System			**212**	**21%**	**44**	**256**
Excavator			**200.0**	**20%**	**40.0**	**240.0**
Excavation and Processing			**200.0**	**20%**	**40.0**	**240.0**
Mobile Excavator with transverse bucket wheel	2	100.0	200.0	20%	40.0	240.0
Electrical Power Subsystem			**12.0**	**30%**	**3.6**	**15.6**
Power Management & Distribution			**12.0**	**30%**	**3.6**	**15.6**
DC to AC rover recharge	2	4.5	9.0	30%	2.7	11.7
Rover recharge coupling	2	1.5	3.0	30%	0.9	3.9

Lunar ISRU Case 2 - ISRU O_2 Production System

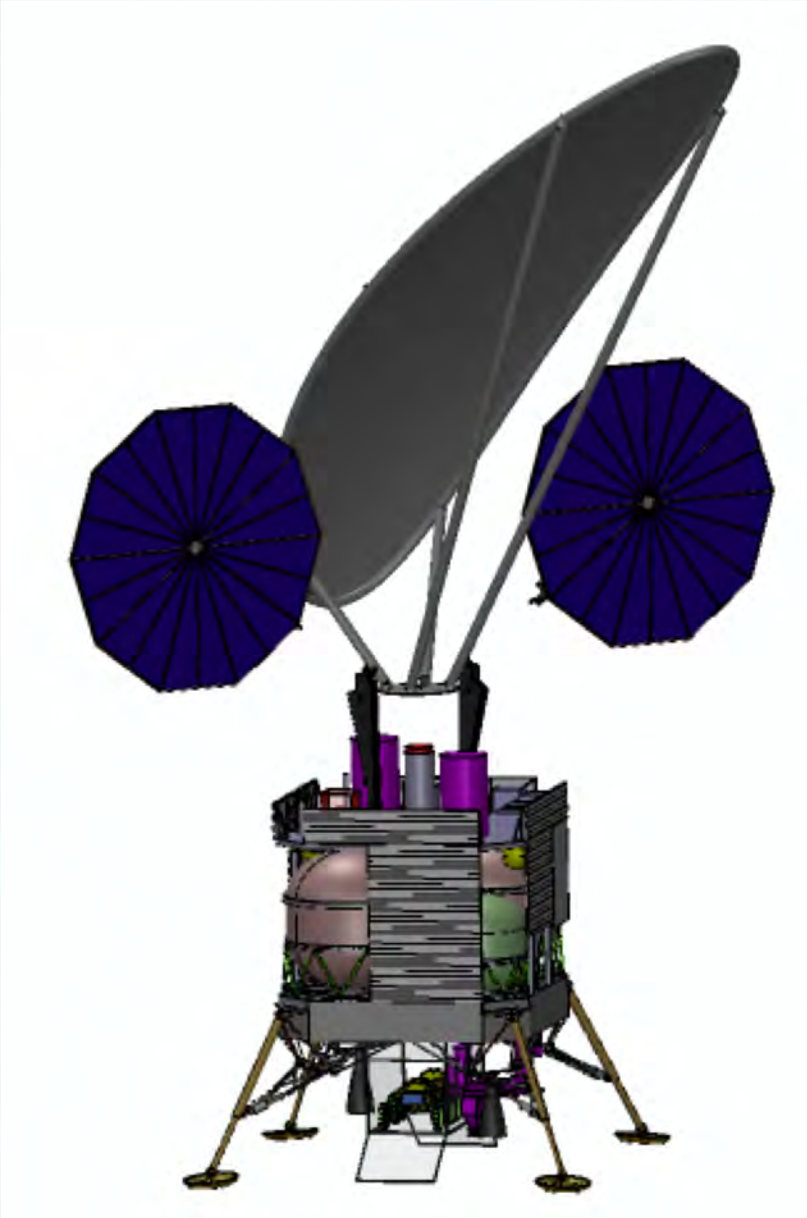
Description Case 2 ISRU CD-2018-162	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
O2 Production			519.7	17%	86.9	606.6
ISRU Reactor System			193.0	19%	37.6	230.6
Methanation Reactor and Separator	2	10.7	21.4	20%	4.3	25.7
Desulfurization Subsystem	4	10.0	40.0	20%	8.0	48.0
Carbothermal Reduction Chamber	2	45.3	90.6	20%	18.1	108.7
Recycle Loop Compressors	2	0.4	0.8	20%	0.2	1.0
Condenser Heat Exchanger	2	4.3	8.6	20%	1.7	10.3
Hydrogen Tank	2	2.1	4.2	8%	0.3	4.5
Methane Tank	2	2.1	4.2	8%	0.3	4.5
Condenser/Electrolyzer Water Tank	2	7.1	14.2	20%	2.8	17.0
System Gas Tank, with Compressor	2	4.5	9.0	20%	1.8	10.8
Materials Processing and Handling			224.6	13%	28.9	253.5
Supply Hopper	2	9.5	19.0	20%	3.8	22.8
Spent Hopper w/ Valve	2	22.0	44.0	20%	8.8	52.8
Feed Auger w/ Valve	2	22.8	45.6	20%	9.1	54.7
Size Sorter Dump Trough w/ 2 Augers	1	36.0	36.0	20%	7.2	43.2
Vibratory Conveyor	2	40.0	80.0	0%	0.0	80.0
Electrolyzer			102.1	20%	20.4	122.5
Pump	2	1.5	3.0	20%	0.6	3.6
Electrolyzer Subsystem	2	38.9	77.8	20%	15.6	93.4
Dryer Subsystem	2	0.9	1.8	20%	0.4	2.2
Valves and Lines	2	9.7	19.4	20%	3.9	23.3

Lunar Night ConOps

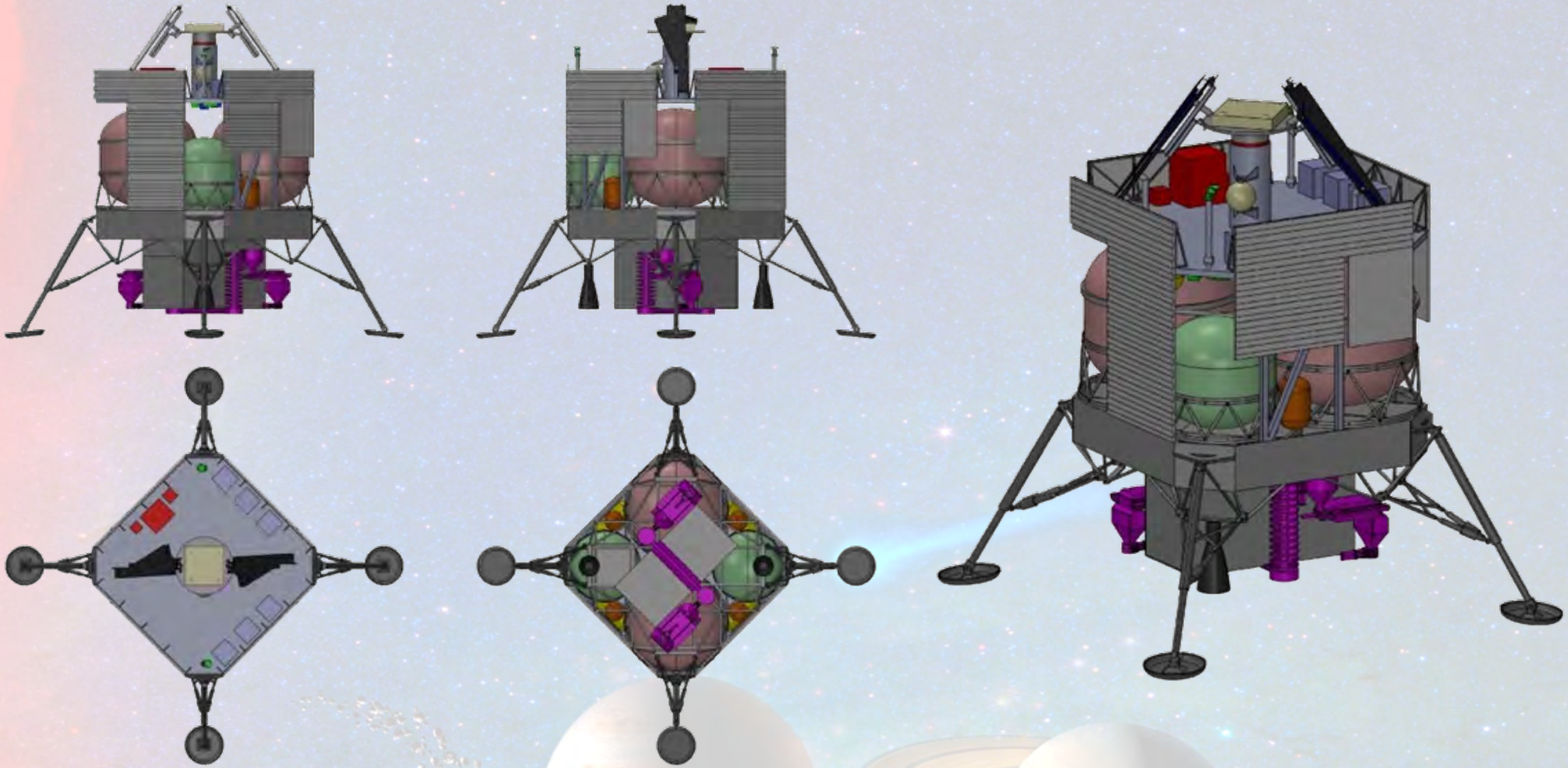
- For 4.6 months, sun only periodically in view (winter)
  - ISRU system dormant during this time; no excavation or production
  - Cryocoolers will be cycled as needed to maintain product
- Longest period with < 15% solar input is 9 Earth days
- ISRU systems thermal management during 'night'
  - Excavators stored in cargo box on inductive charging pads (20 W heaters for each)
    - Keeping off the lunar surface reduces power needs
    - Doors reclosed to further minimize heat loss
  - ISRU reactors allowed to go ambient (50 K)
  - Maintain water lines, electrolyzer stacks, and water tanks > 0 °C (72 W)
  - Maintain avionics at -40 °C
    - Main Bus electronics: 156 W
    - ISRU command and control electronics: 48 W
- Fuel Cell system sized for keep-warm power and keep-warm duration
  - 1 – 9 days <15% solar input sets peak power
  - 22 day period with insufficient sunlight times to recharge sets total reactant (water) needed
  - Assumed 50% efficient – (waste heat keeps itself warm)

Lunar ISRU Plant: Carbothermal
(aka: Case 2)

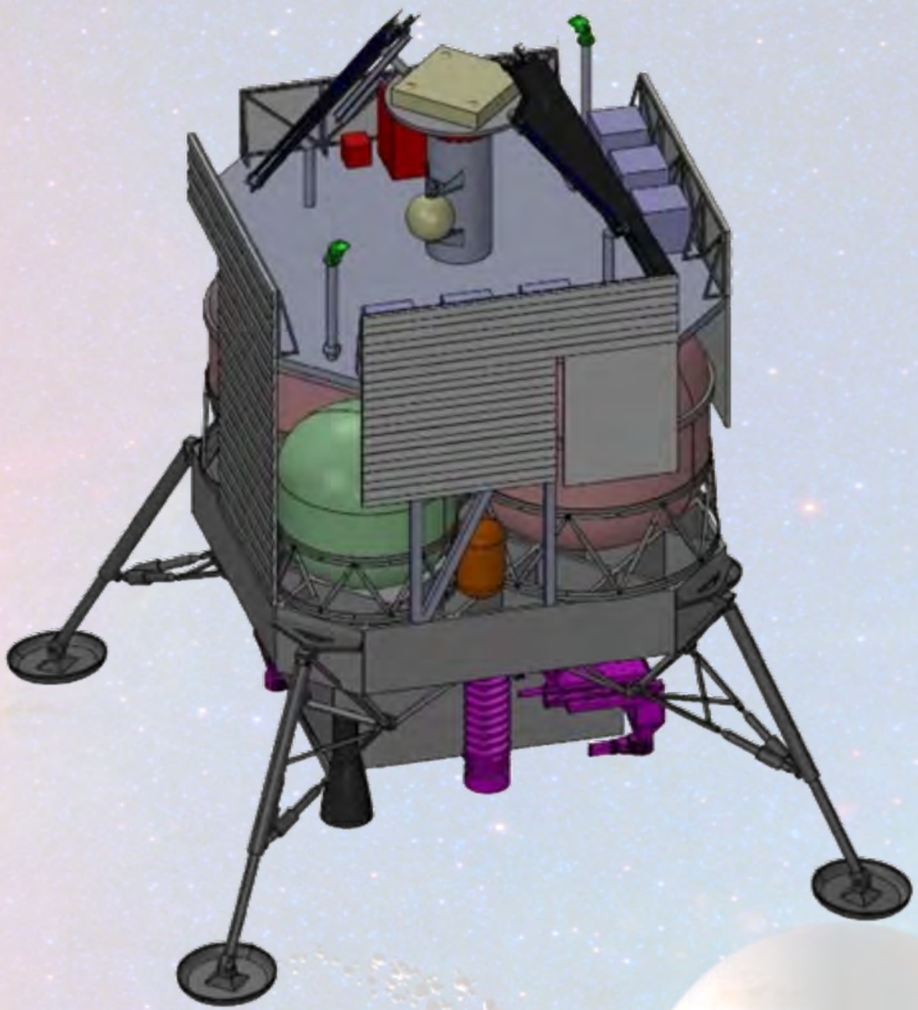
Configuration

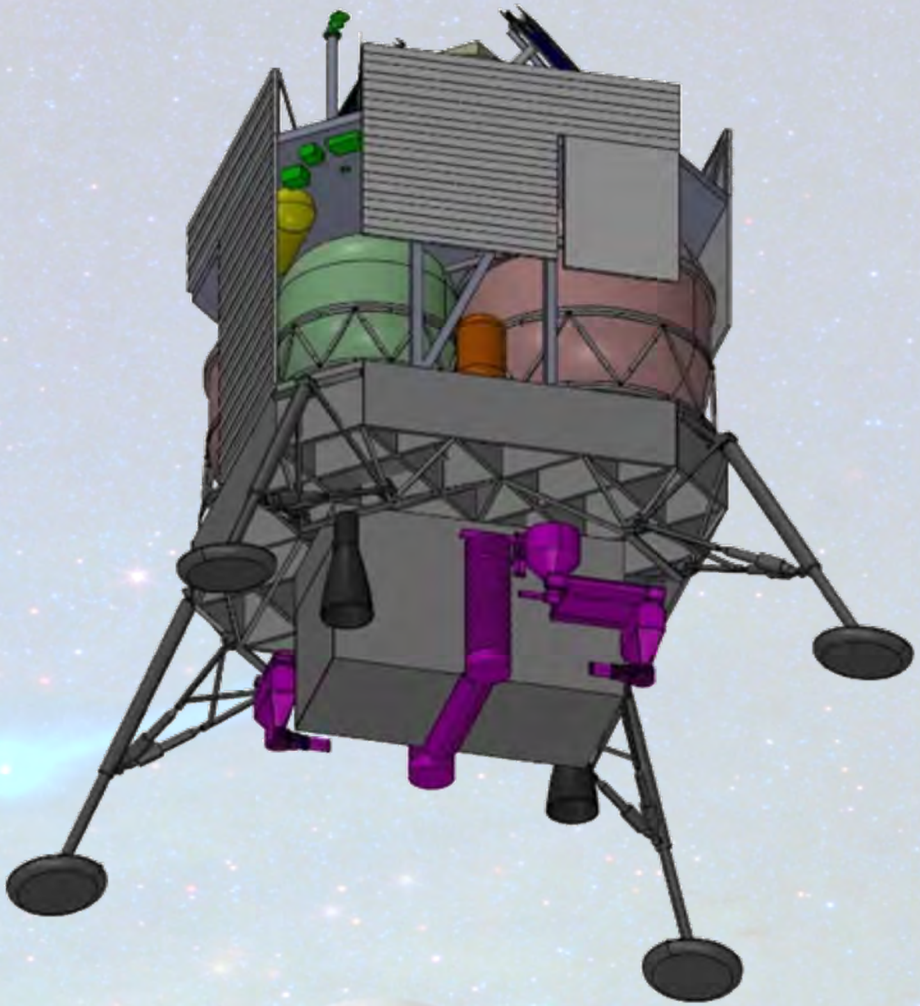


Lunar ISRU Case 2 Stowed Configuration

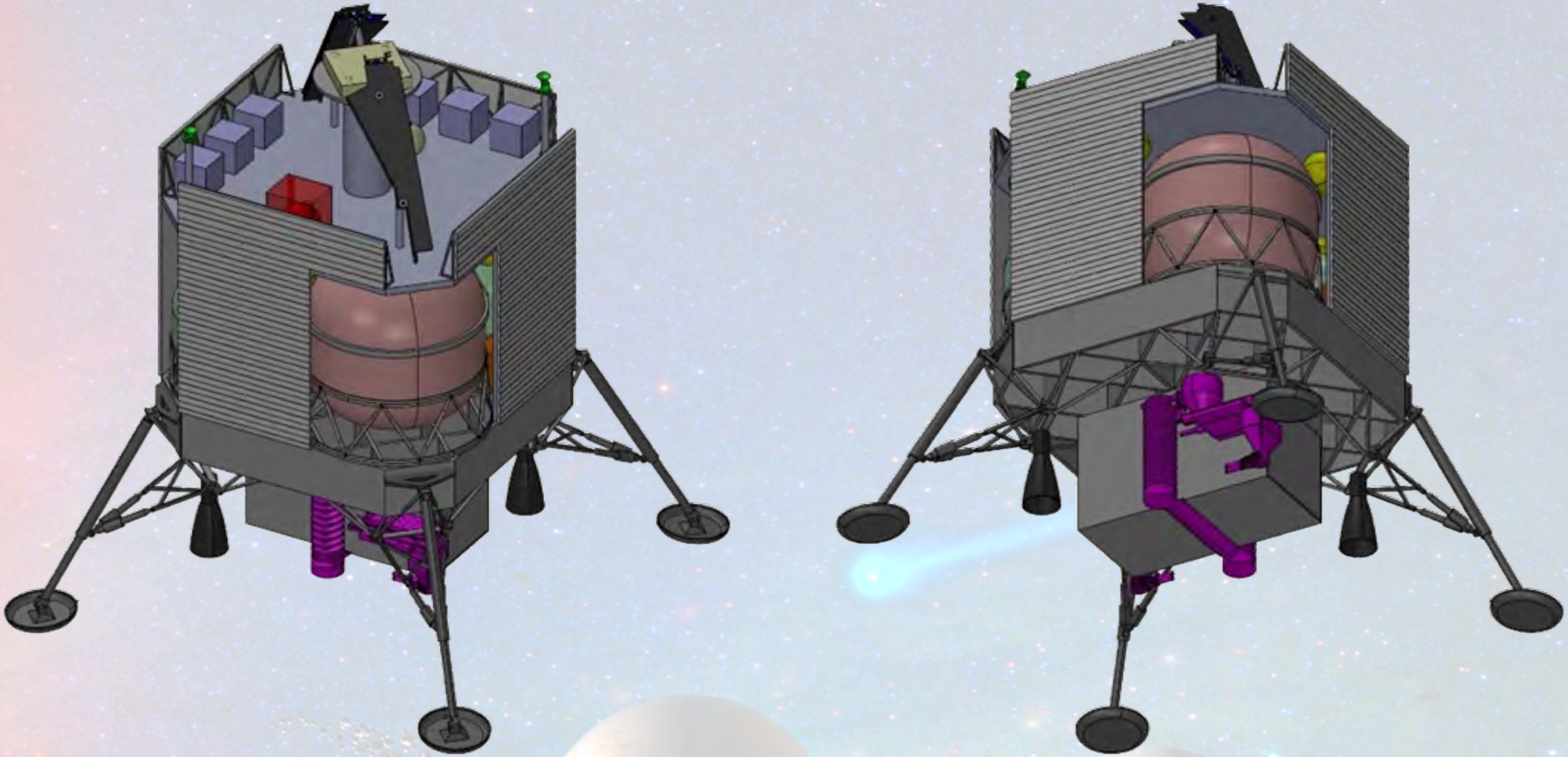


Lunar ISRU Case 2 Stowed Isometric Views (1 of 2)

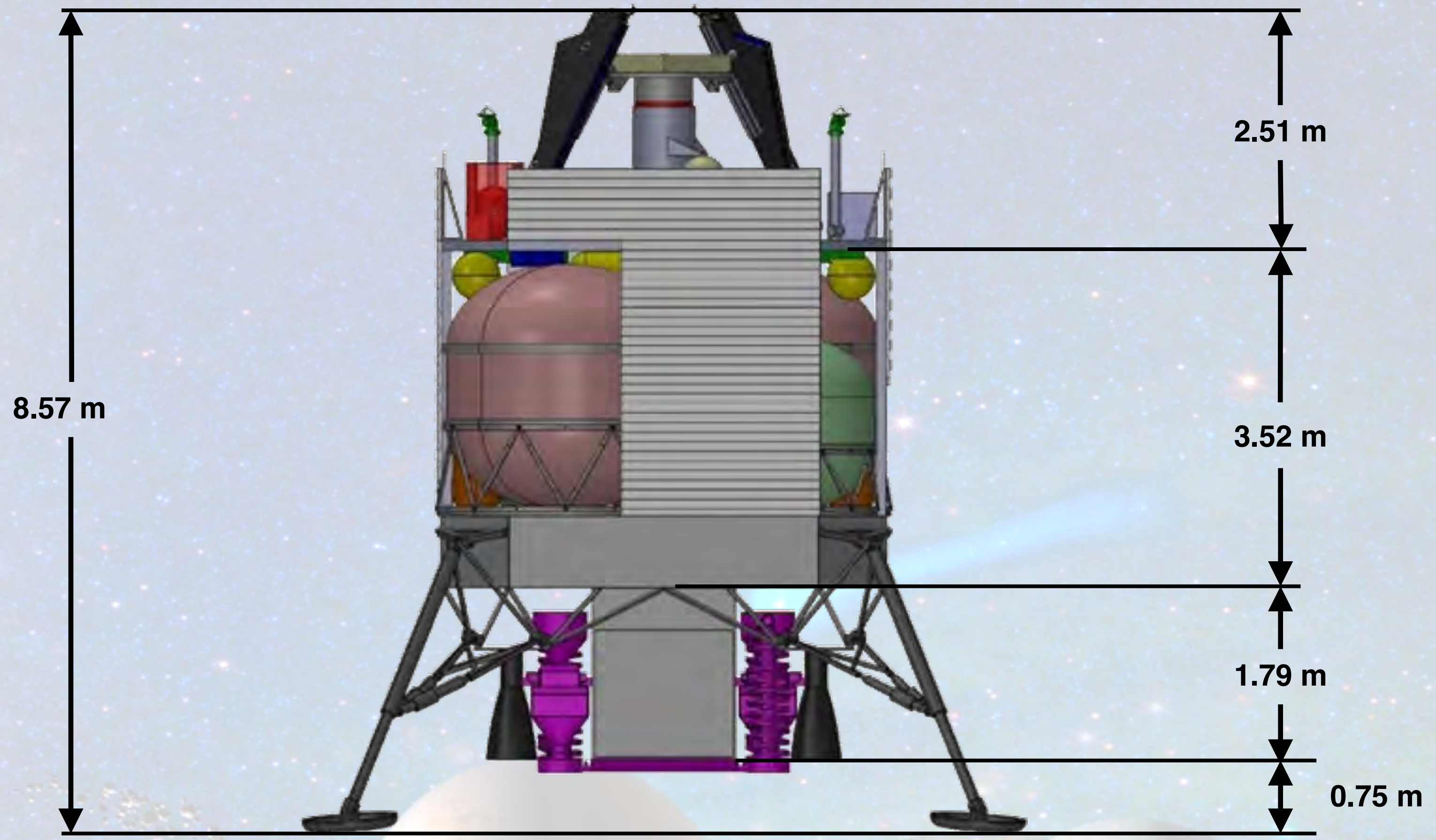




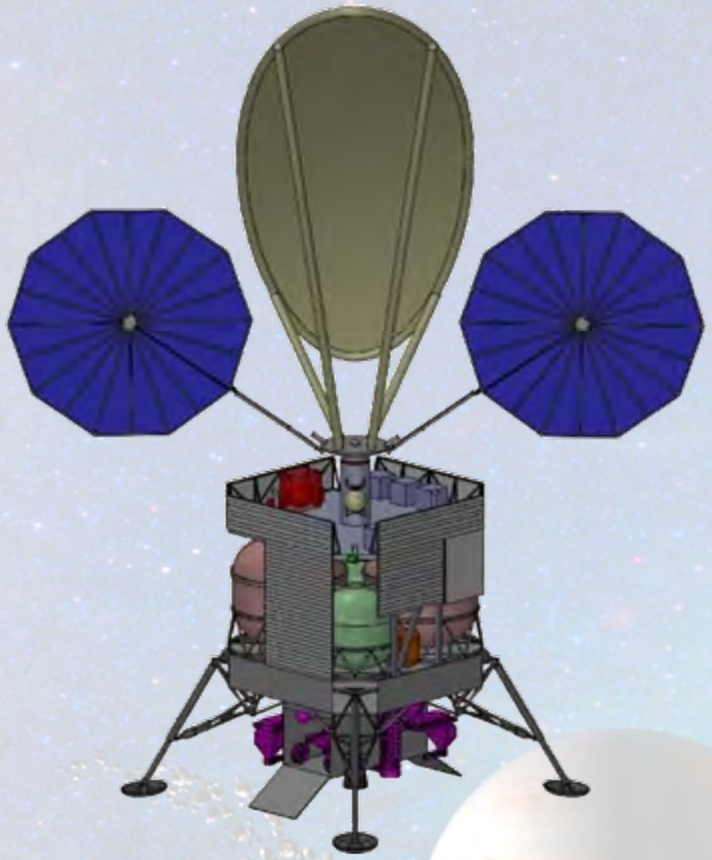
Lunar ISRU Case 2 Stowed Isometric Views (2 of 2)

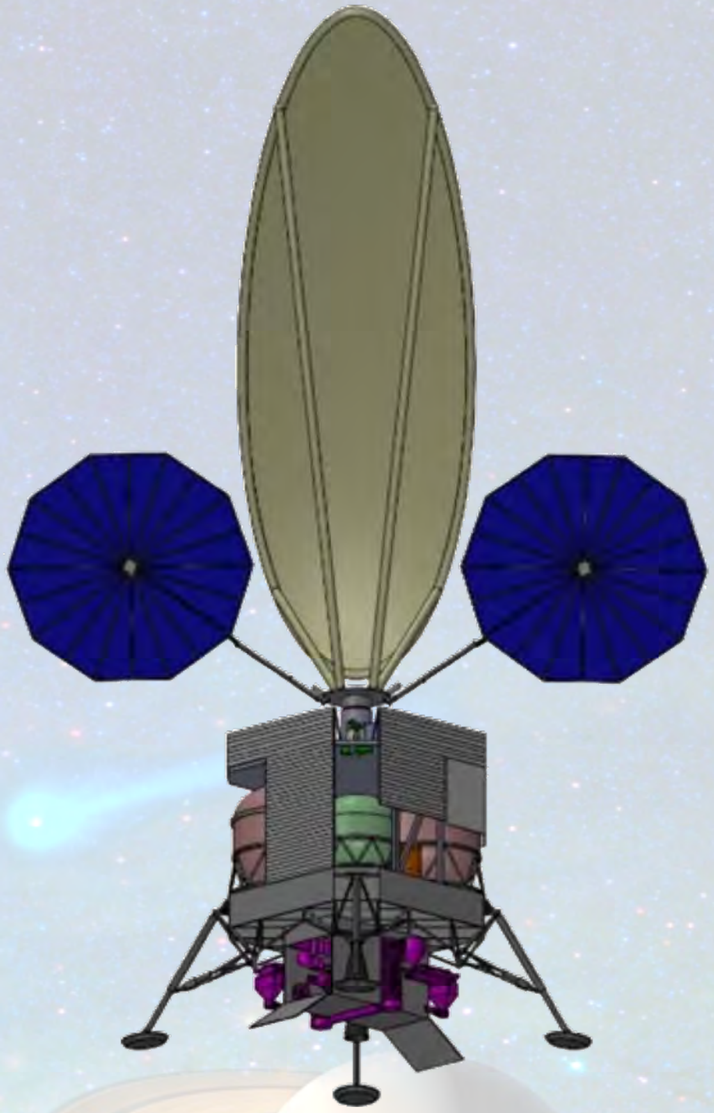


Lunar ISRU Case 2 Stowed Dimensions

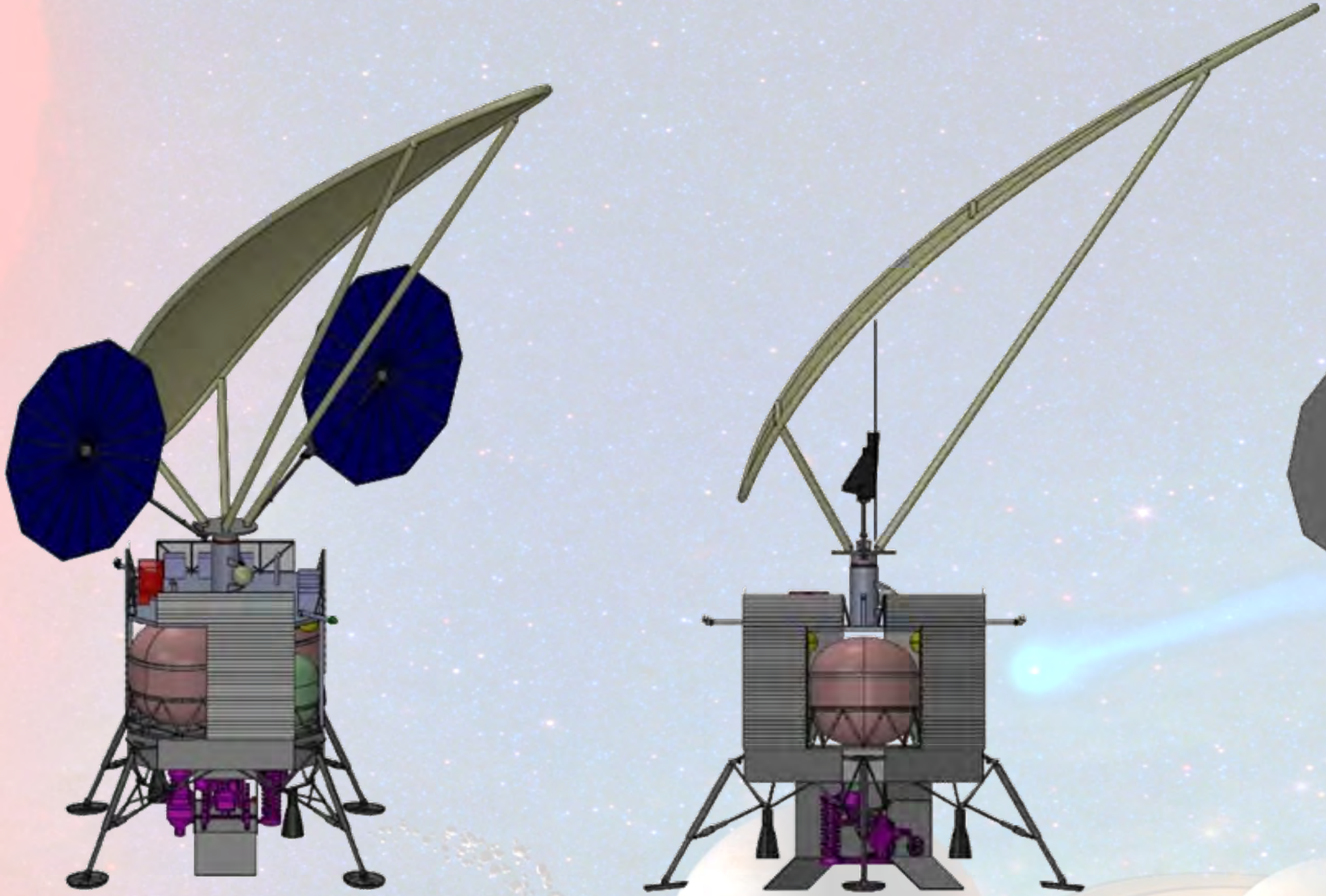


Lunar ISRU Case 2 Deployed Configuration (1 of 2)

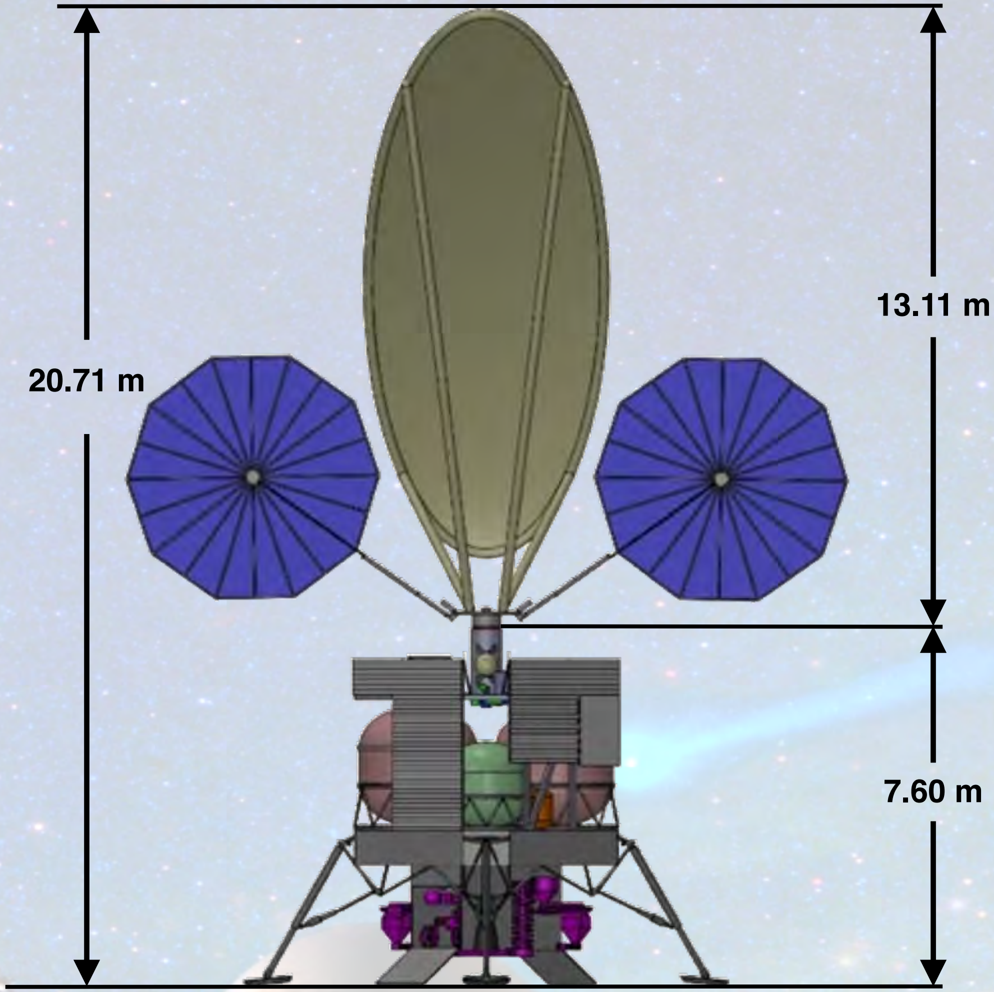




Lunar ISRU Case 2 Deployed Configuration (2 of 2)



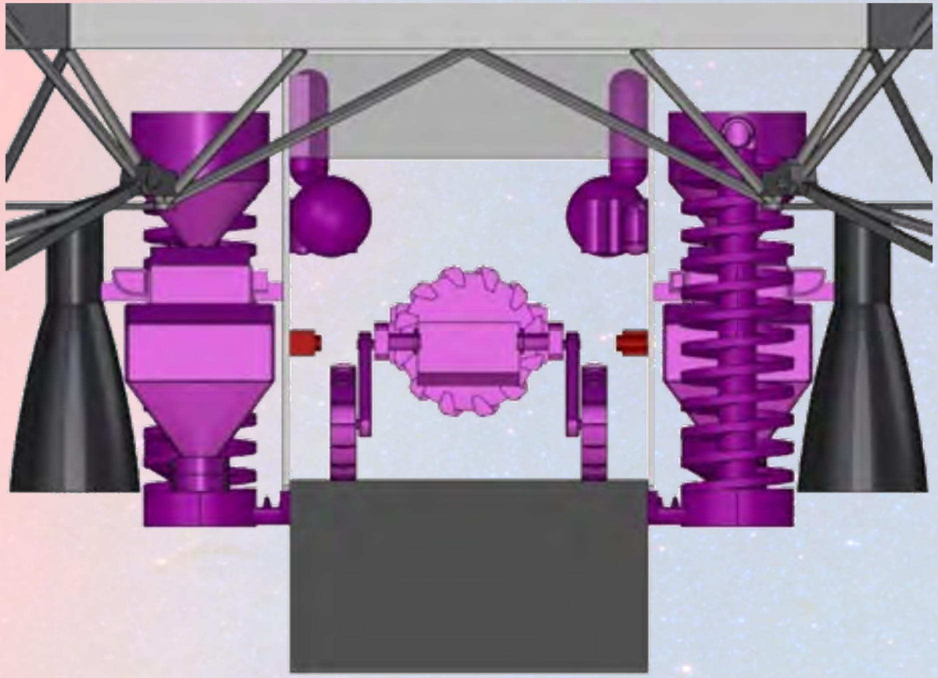
Lunar ISRU Case 2 Deployed Dimensions

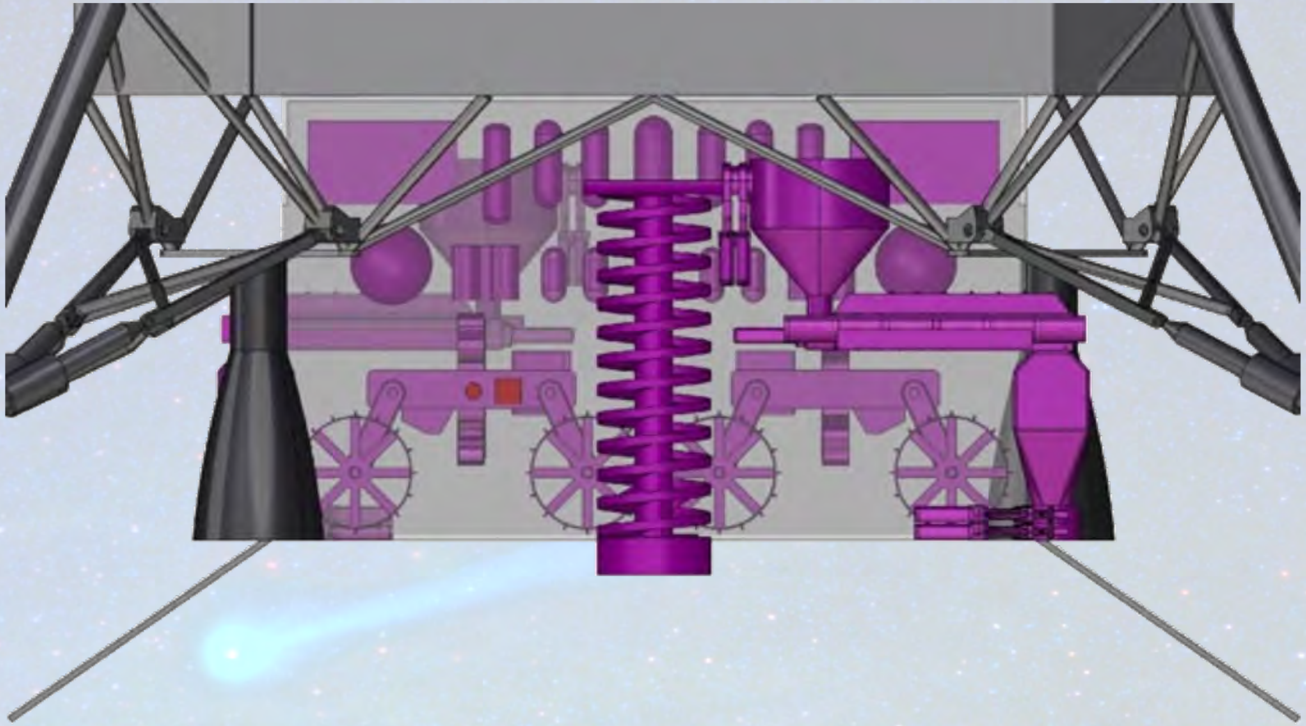


NOTE: Both solar arrays create a width of 15.34 m

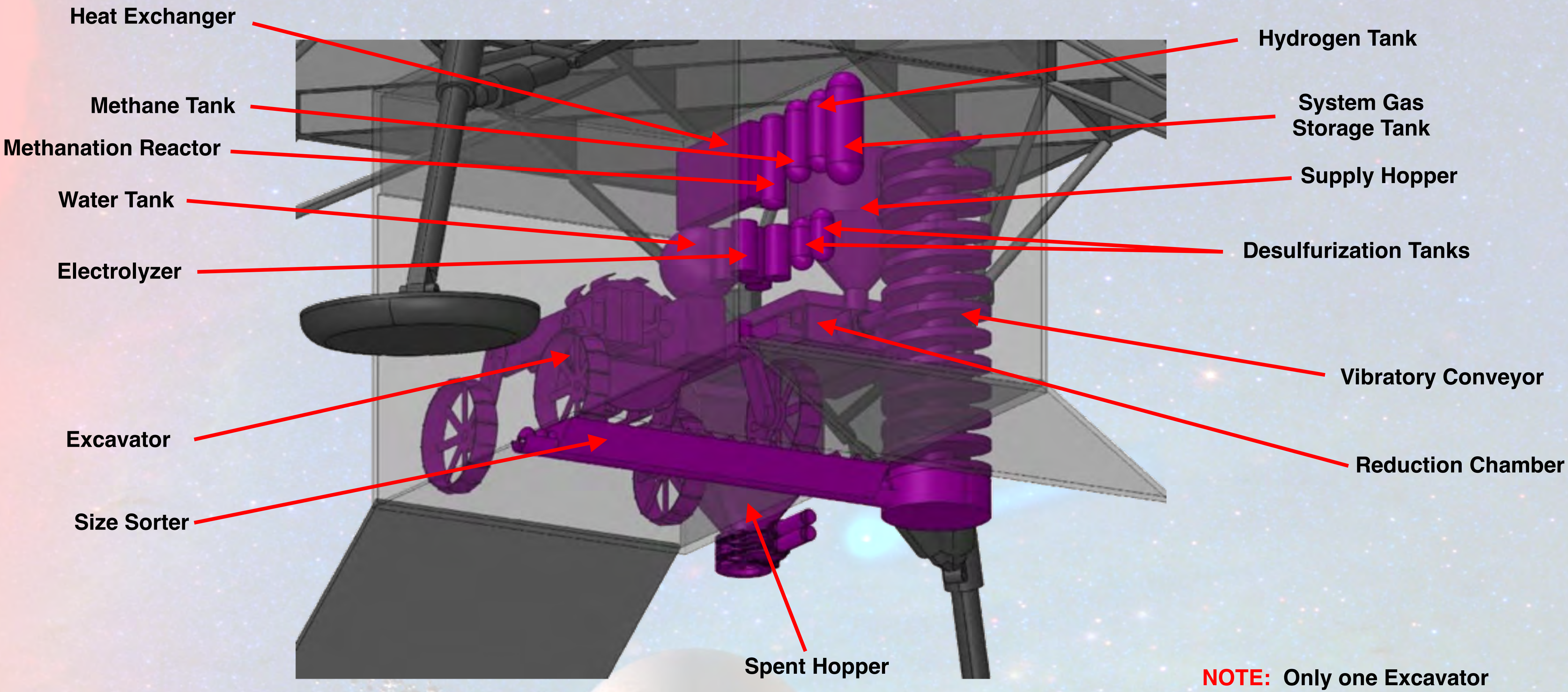
NOTE: Overall Concentrator height is 11.65 m with a width of 5.24 m

Lunar ISRU Case 2 ISRU Payload



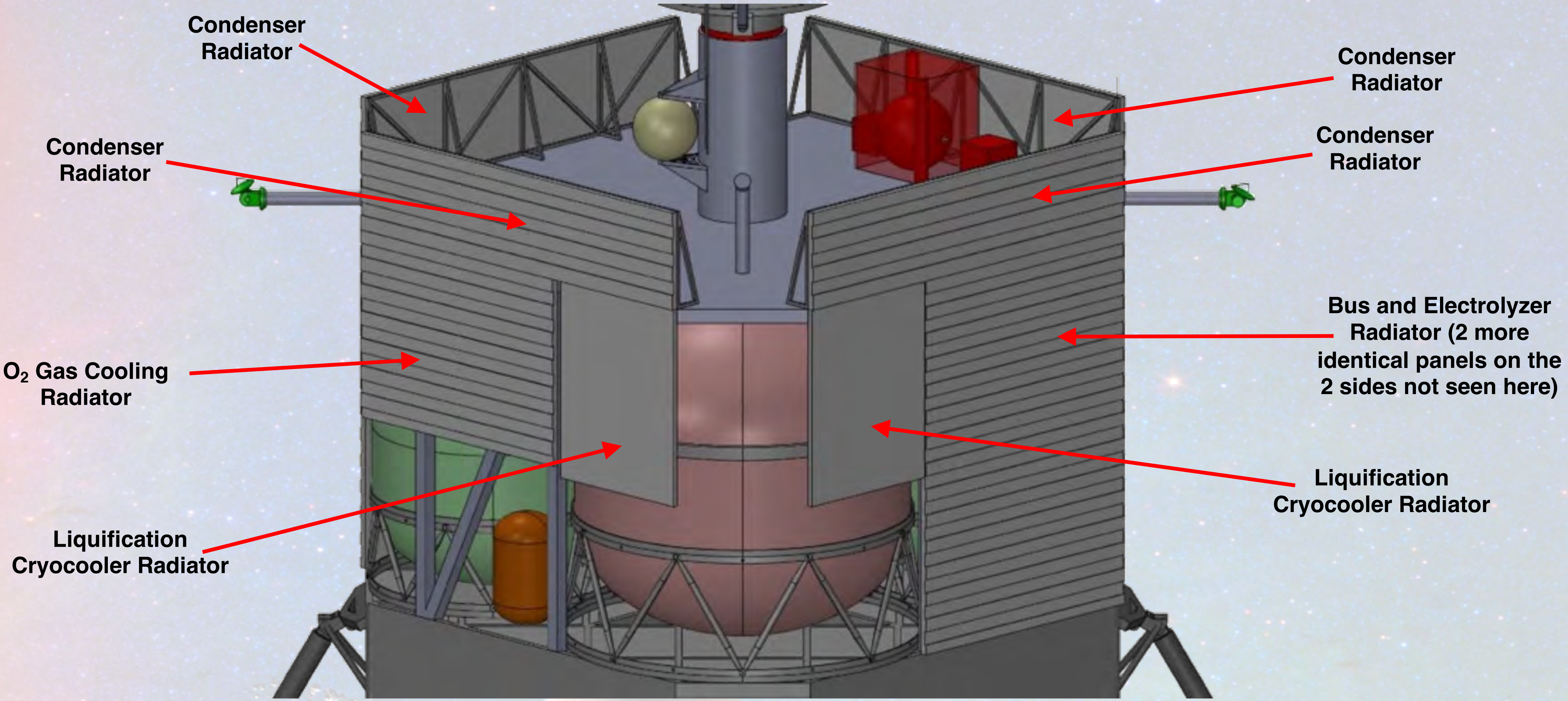


Lunar ISRU Case 2 Lower Payload Components

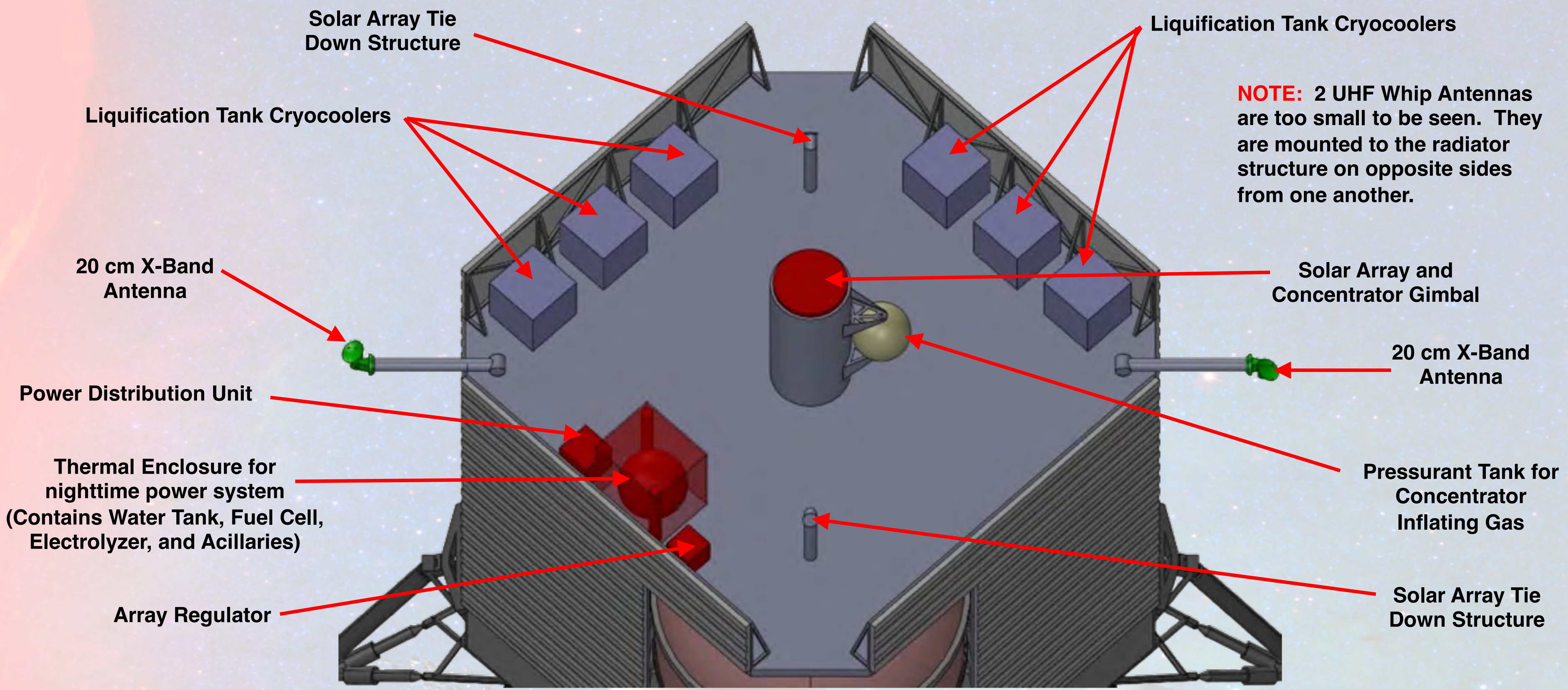


NOTE: Only one Excavator and ISRU System is shown

Lunar ISRU Case 2 Radiators

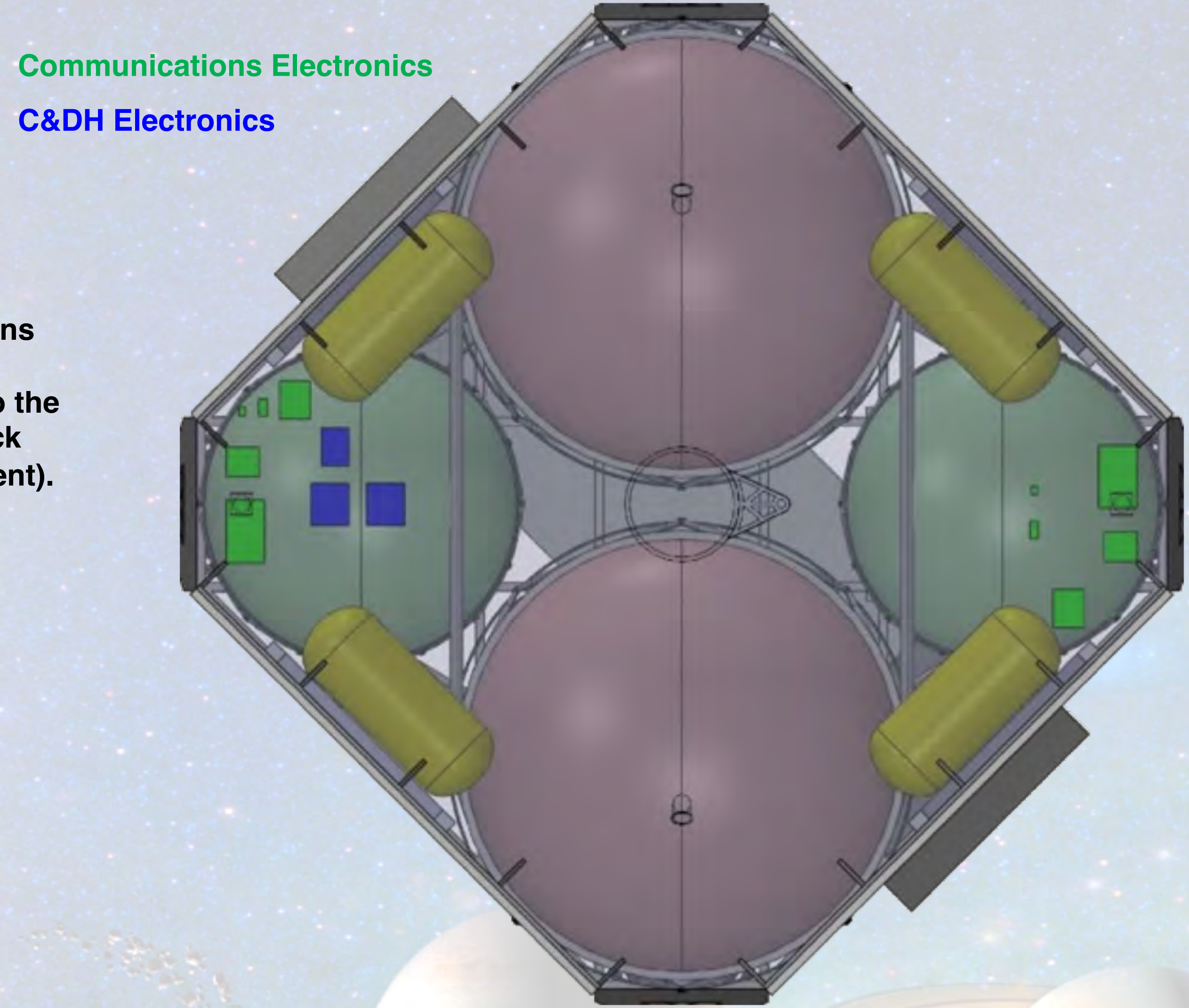


Lunar ISRU Case 2 Upper Payload Elements



Note: Fiber optic lines are assumed to go through the center of the lander and then distribute to the reactors

Lunar ISRU Case 2 Communications and C&DH Electronics

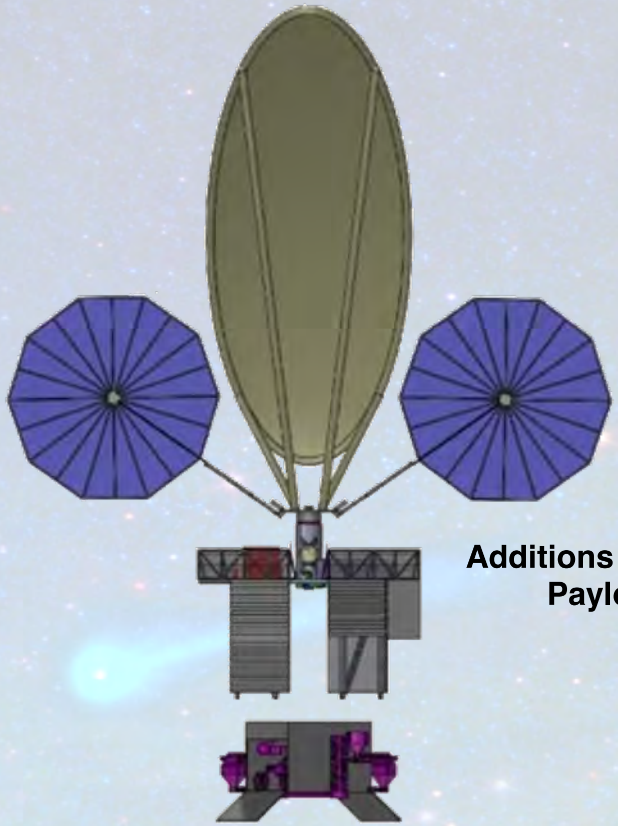


NOTE: The Communications Electronics and the C&DH Electronics are mounted to the underside of the upper deck structure (shown transparent).

NOTE: The Yellow Tanks are the pressurant tanks for the Lander. They were moved from below the Lander deck to below the upper deck to allow room below the Lander deck for the Excavators and ISRU Reactor System

Lunar ISRU Case 2 Additions to Lander (1 of 2)

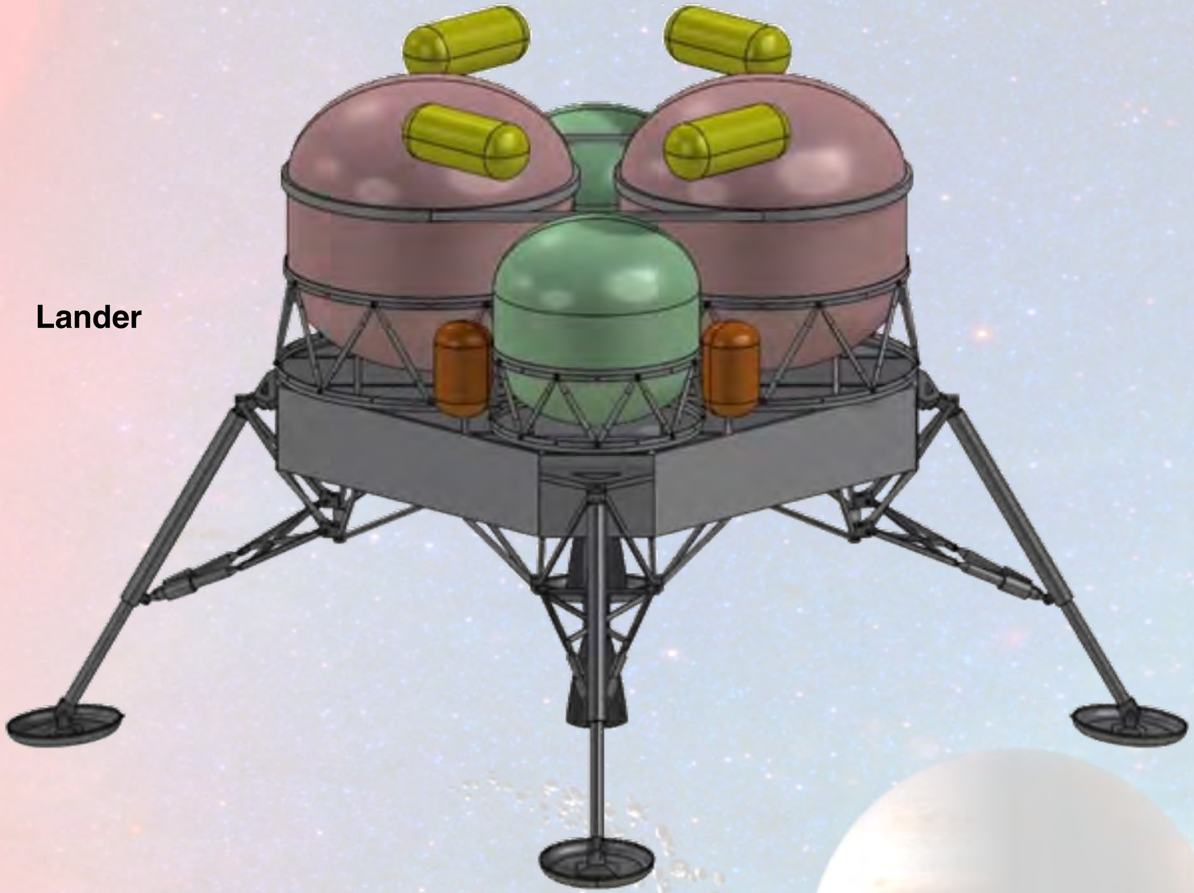
Lander

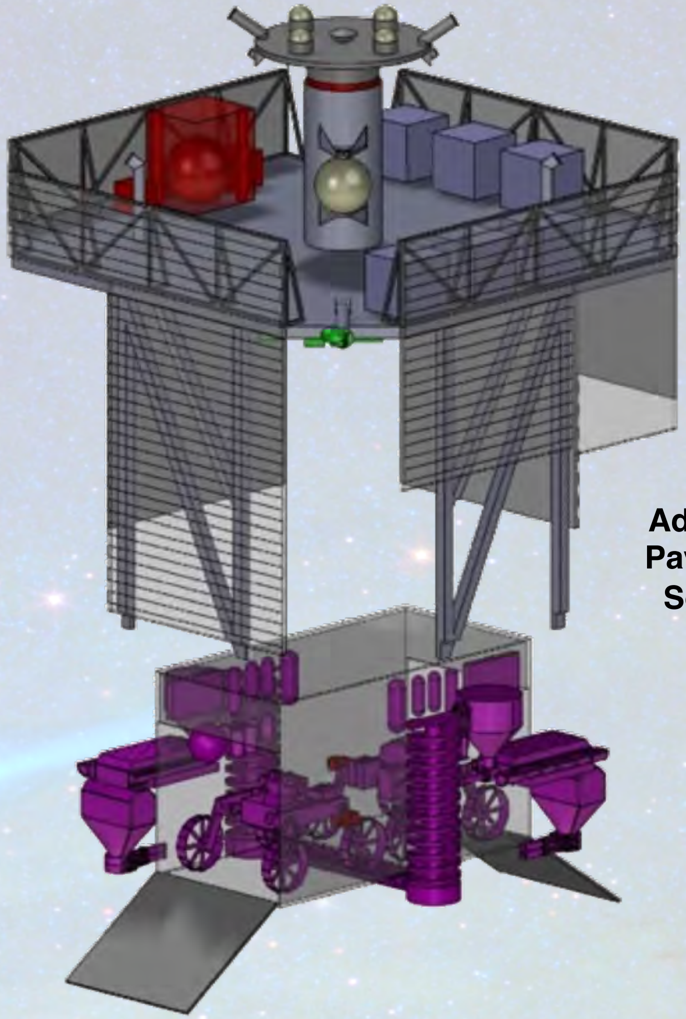


Additions for ISRU Payload

Lunar ISRU Case 2 Additions to Lander (2 of 2)

Lander





Additions for ISRU Payload (Minus the Solar Arrays and Concentrator)