Lunar Water Pilot Plant Conceptual Design

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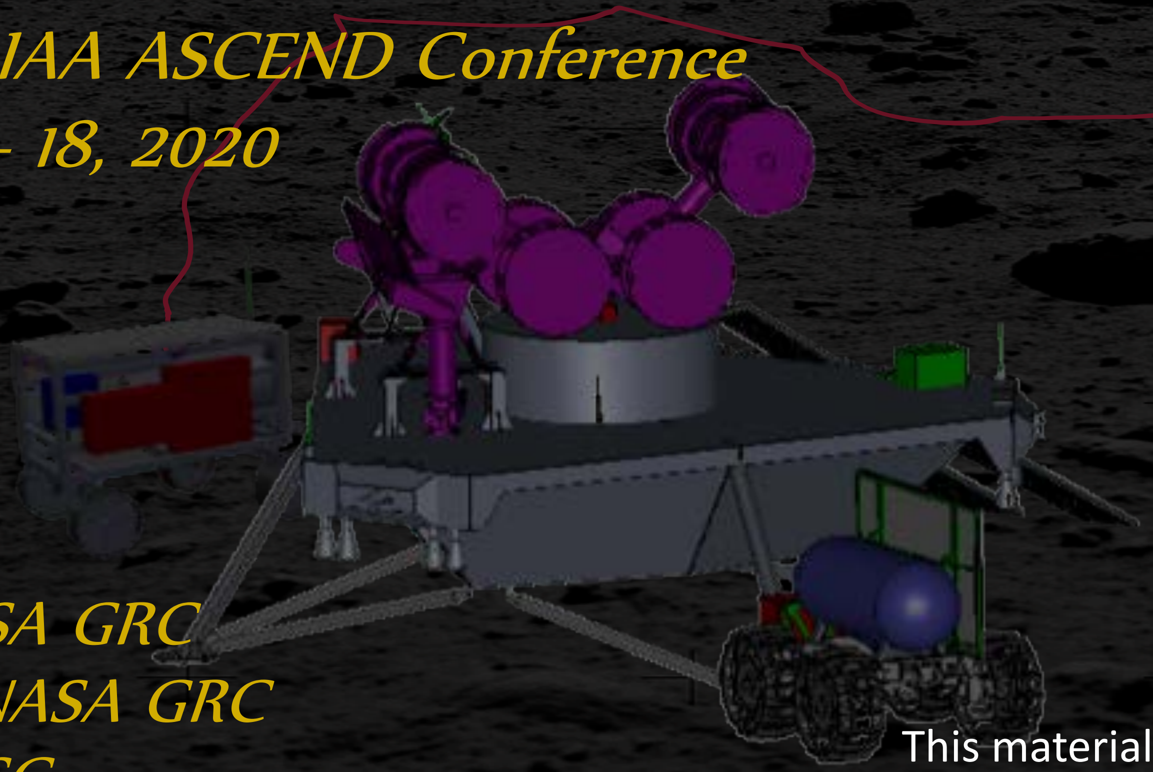
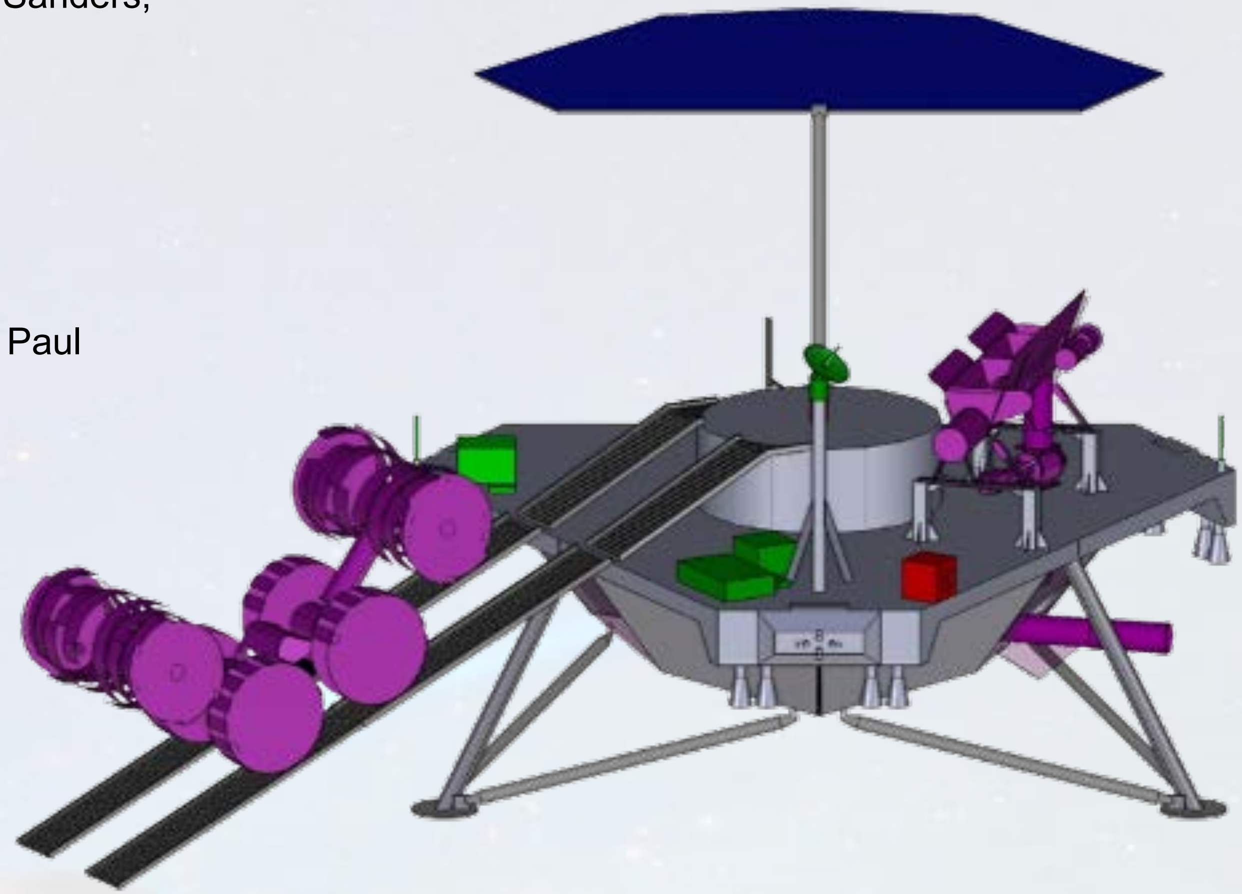


Diane L. Linne/NASA GRC
Julie E. Kleinhenz/NASA GRC
Aaron Paz/NASA JSC

GRC Compass Team Participants

- Customer: STMD LSII, David Reeves, Diane Linne, Jerry Sanders, Julie Kleinhenz, Aaron Paz
- Lead - Steve Oleson
- System Integration, MEL- Betsy Turnbull
- Structures - John Gyekenyesi
- Environmental - Tony Colozza
- Power - Brandon Klefman, Lucia Tian, Nicholas Uguccini, Paul Schmitz
- Propellant Handling/Mobility: James Fittje
- C&DH/Software – Peter Simon, Christopher Heldman
- Communications – Bushara Dosa
- Configuration - Tom Packard



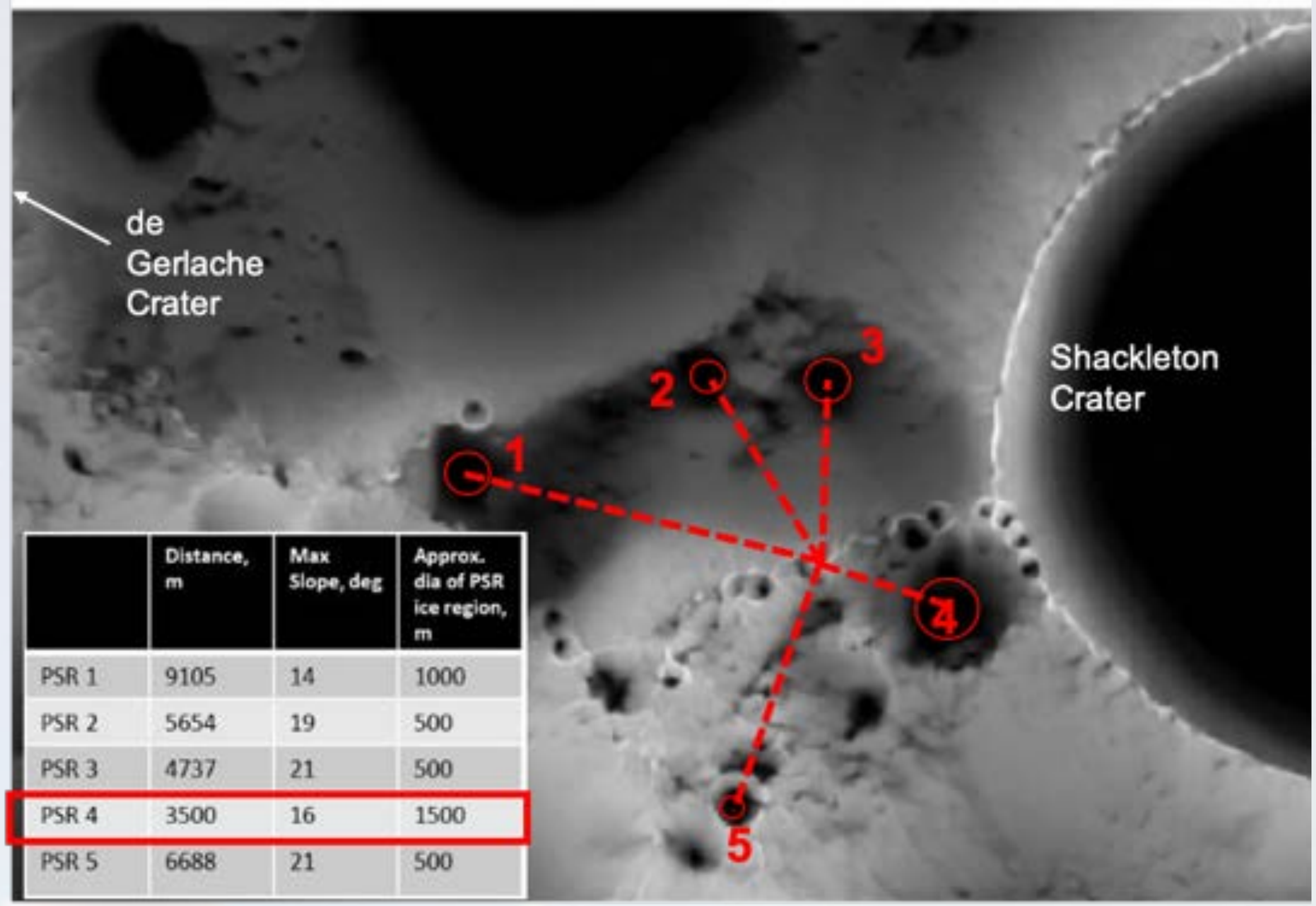
- All sessions ‘remote’ due to Covid-19
- 6 sessions over two weeks

Study Overview

- Purpose: Develop a conceptual design for an ISRU system that extracts water from the icy dirt in the permanently shadowed regions (PSR) and processes it into liquid oxygen and hydrogen
  - Goal is 1000 kg of oxygen in one year
- Power Assumptions
  - Power in PSR provided by previously landed nuclear power demonstrator
  - Power on ridge provided by solar arrays
    - Assume operation only during 225 days of continuous sunlight
- Water Assumption
  - Regolith in PSR contains 5% water by mass
  - Icy regolith underneath 20-cm desiccated layer

Site Selection

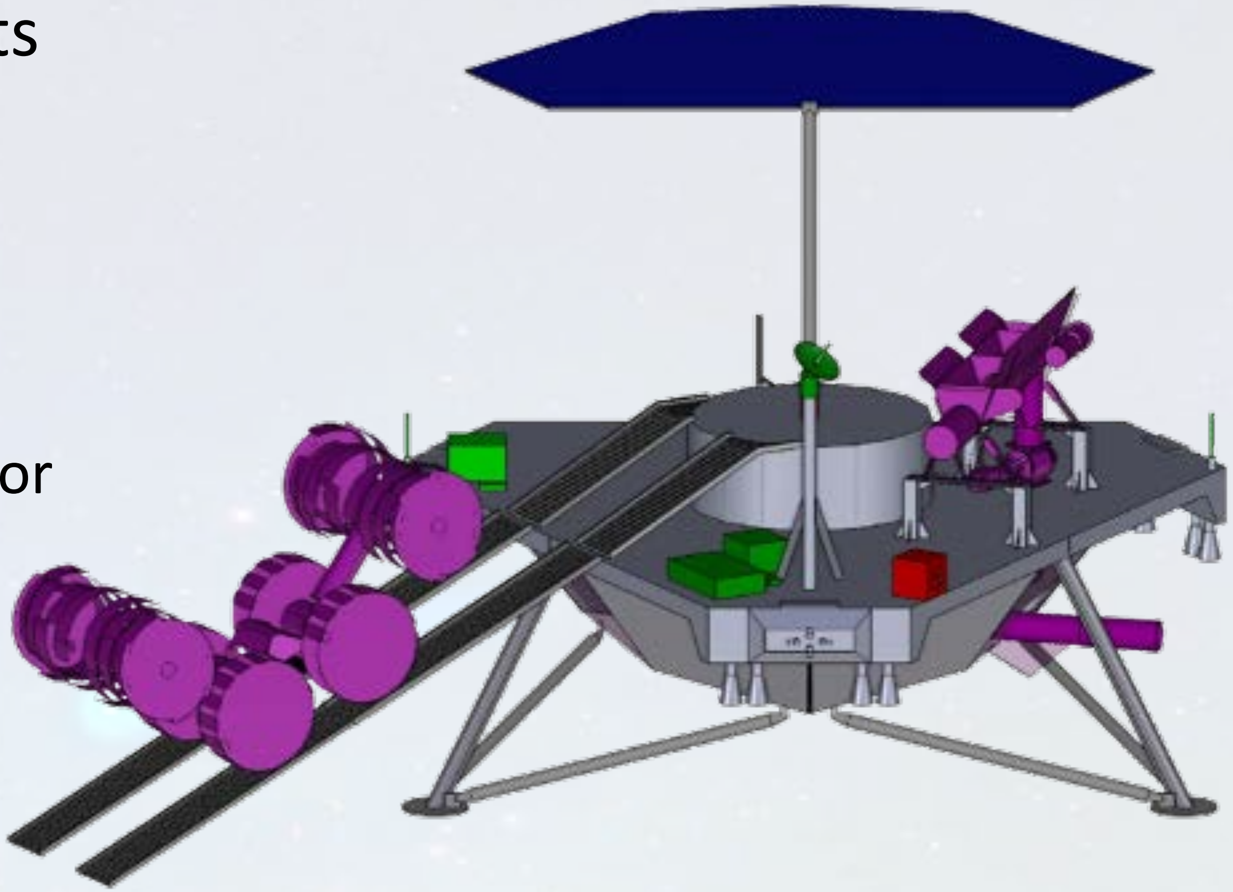
- Wanted a reasonably-sized permanently shadowed region (PSR) accessible from locations along the ridge between de Gerlache and Shackleton craters
  - Favored location for human missions due to high illumination periods
- Five craters assessed for suitability for mining
  - Distance
  - Maximum slope



	Distance, m	Max Slope, deg	Approx. dia of PSR ice region, m
PSR 1	9105	14	1000
PSR 2	5654	19	500
PSR 3	4737	21	500
PSR 4	3500	16	1500
PSR 5	6688	21	500

PSR Lander

- A primary objective was to demonstrate packaging of the ISRU PSR components on a small lander
- Lockheed Martin McCandless lander concept used based on:
  - Ample open-deck payload space
  - Reasonable access to ground for excavator
  - 350 kg payload capability



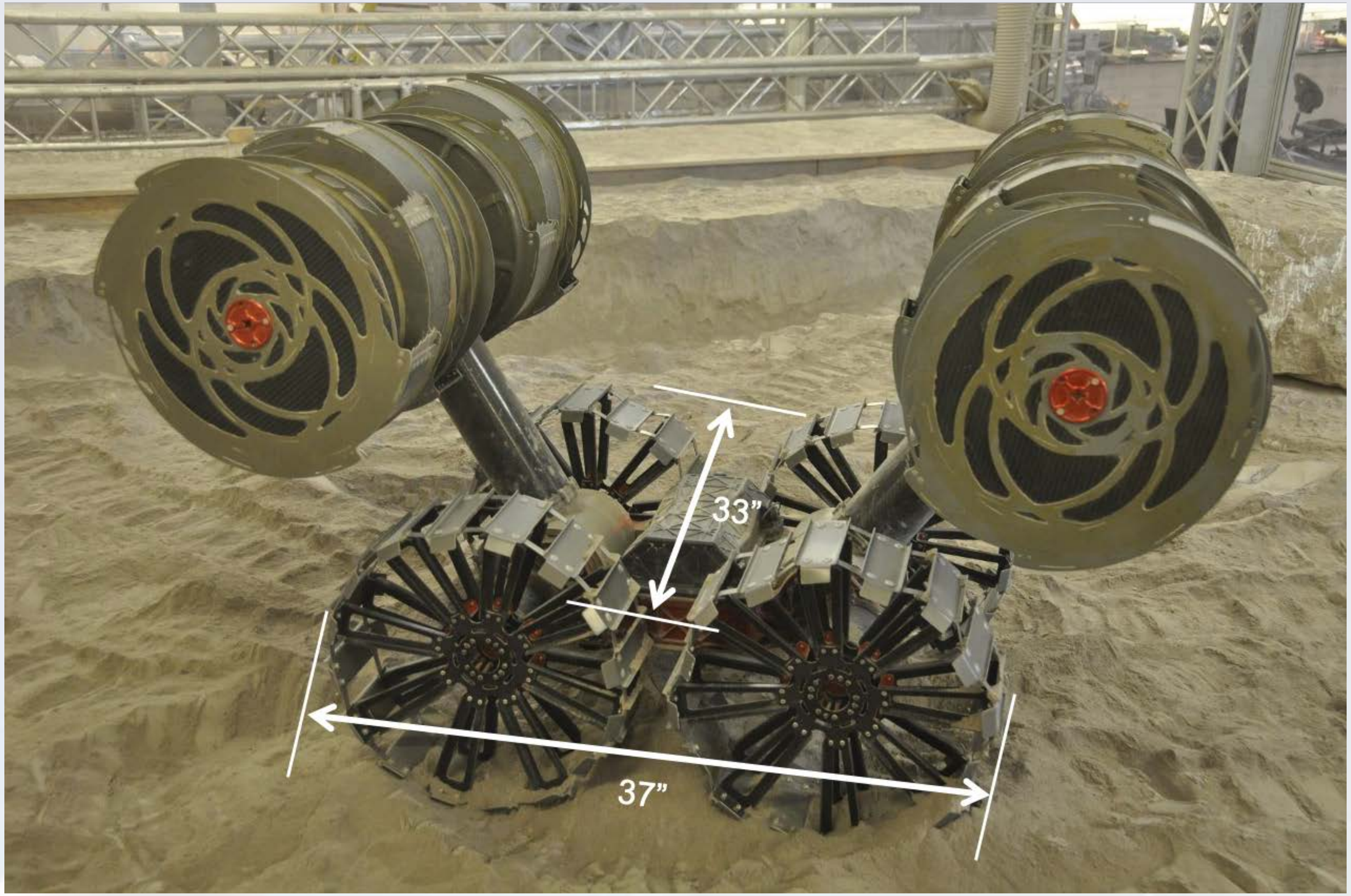
Concept of Operations

- Within 24 hours of landing, power cart connects nuclear power to PSR plant
- Ramps are deployed and excavator travels to pre-selected mining site
- Excavator removes dry overburden from the required surface area (~ 4 days)
  - PSR and Ridge plants are dormant
- Tanker 1 travels from ridge down into PSR and connects to PSR plant
- Excavator delivers first load of icy regolith and water extraction begins
- When Tanker 1 is nearing full, Tanker 2 travels down into the PSR and swaps with Tanker 1
  - Water extraction is temporarily halted during tank swap
- Tanker 1 travels up to Ridge plant and transfers water for further processing

ISRU PSR Plant – Water Extraction

Excavator

- Excavator concept being developed at NASA KSC
  - Two sets of bucket drums provide counter-force while digging
- Gathers 40 kg icy regolith in each set of drums
- After delivering complete load, excavator drives down to discard location and gathers up pile of processed regolith



Excavator Performance

- Used measured excavator energy in terrestrial tests and adjusted for lunar operations

Activity	Power		Digging		Disposal	
	Terrestrial[a] (W)	Lunar[b] (W)	Time (min)	Energy (W-hr)	Time (min)	Energy (W-hr)
Digging/Receive Slag	215	215	2.5	9.0	2	7.2
Drive Empty	200	65			8.5	9.2
Drive Full	210	66	8.5	9.4	8.5	9.4
Dump	155	155	5[c]	2.6	< 1	2.6
Totals			**16**	**21.0**	**20**	**28.4**

[a]Tests run at 0.44 m/s; hotel load = 53 W

[b]Assume velocity = 0.2 m/s; hotel load = 53 W

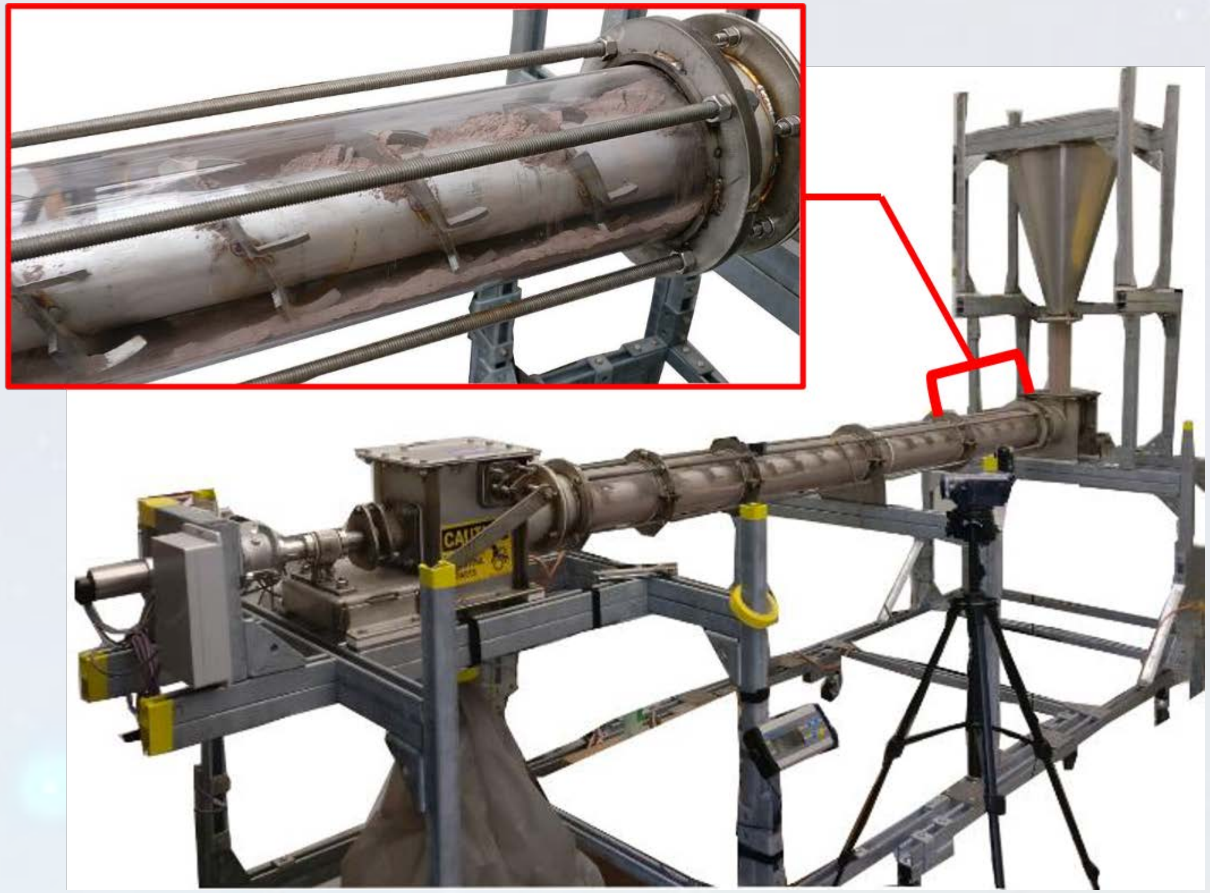
[c]1.0 minute for depositing in hopper; remaining time is low energy positioning

Regolith Hopper

- Hopper on top payload deck allows easy access for excavator
- Hopper horizontal auger transport regolith to one end
  - Vertical tube through valves connects to water extraction reactor
- Hopper can only hold 40 kg of regolith
  - Excavator deposits 1 drum-load into hopper and waits for PSR plant to process 1st load
  - Excavator then spins around and deposits 2nd drum-load into hopper

Water Extraction Reactor

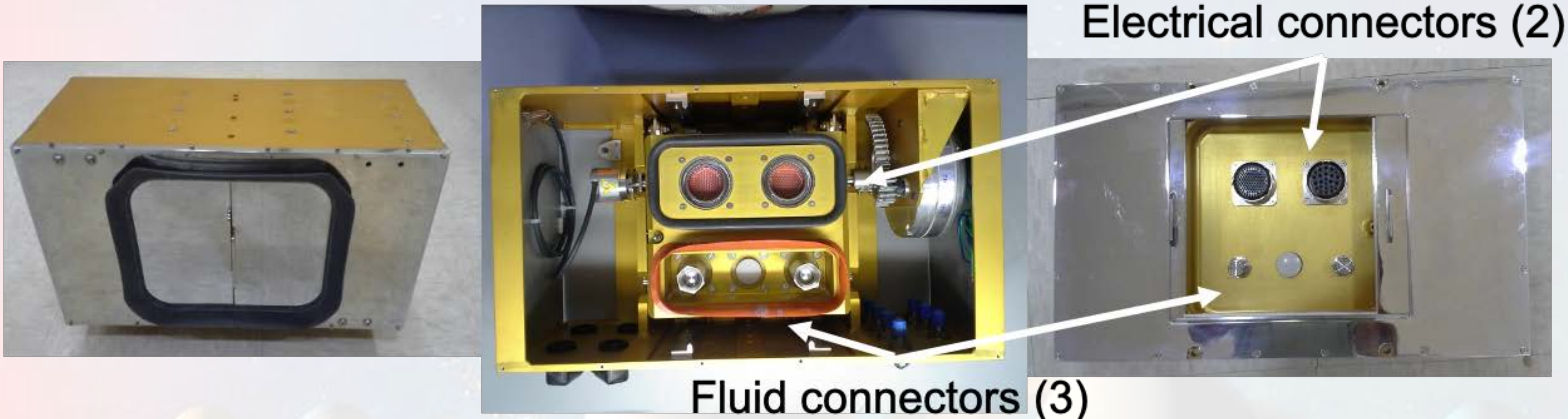
- Auger-dryer based on terrestrial soil dryers
  - Terrestrial goal is dry soil whereas lunar goal is extracted water
- Heaters wrapped around outer metal casing heat regolith to ~100 °C as auger moves it from one end to the other
- Extracted water sent through insulated & heated line to tanker
  - Assume 75% water extraction/capture efficiency
- Processed regolith empties into sloped dump chute to deposit spent regolith away from lander structure



Full-scale auger-dryer with clear outer casing being tested at NASA JSC to study regolith flow behavior

Fluid and Electrical Umbilical

- Dust tolerant automated umbilical mounted provides fluid and electrical connections
  - Active half on PSR lander leg and Ridge plant
  - Passive half on tankers
- Developed at NASA KSC and successfully field tested on NASA-built rover



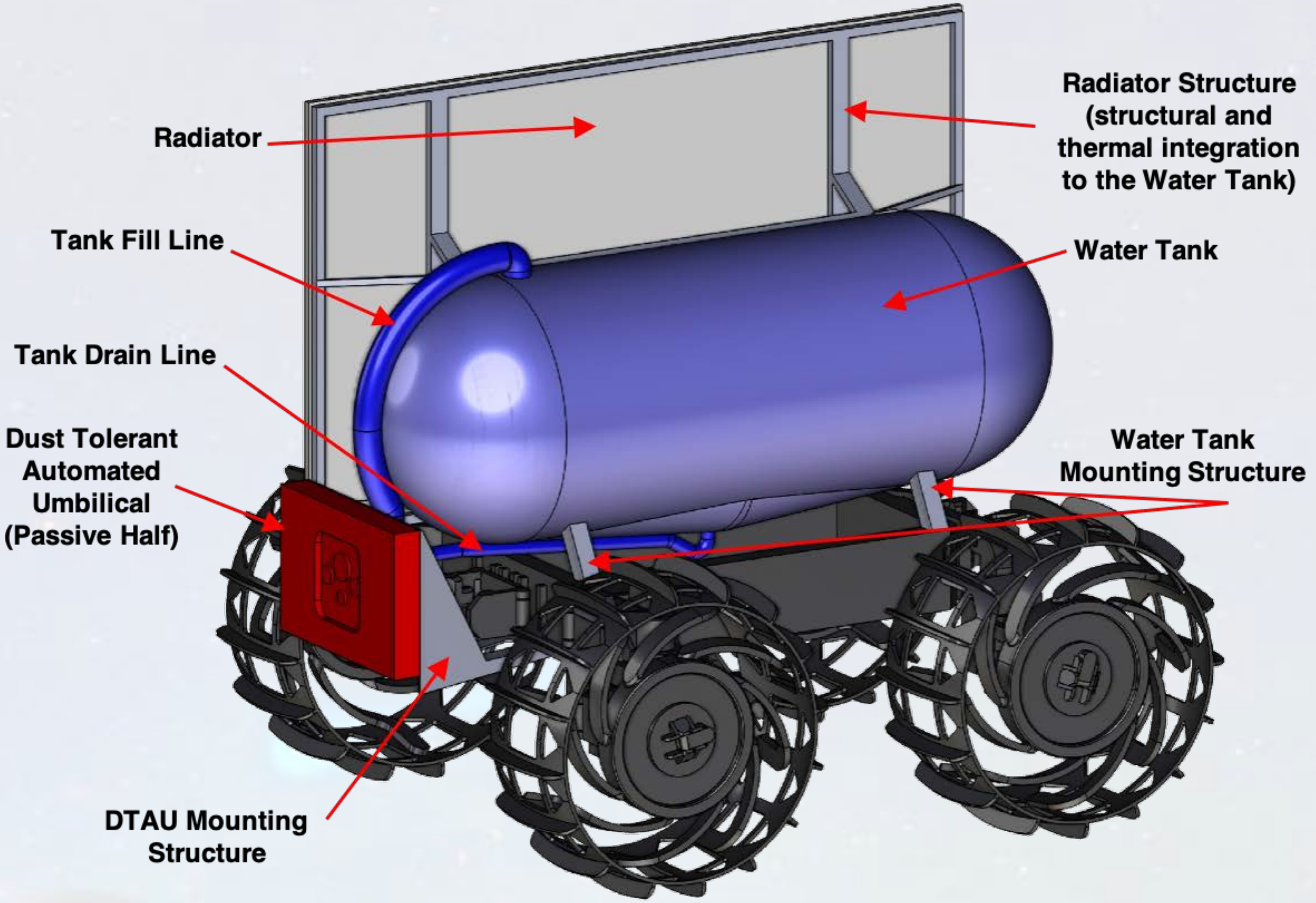
Ice Tanker

- Initially designed as liquid water tanker
  - Required significant energy and insulation to maintain water as liquid in PSR and during transport
  - Either triple mass of mobile platform battery for same number of trips, or triple number of trips out of PSR
- Ice tanker takes advantage of surrounding environment
  - Radiator sized to freeze water at the extraction rate
  - Radiator turned towards sun on ridge takes ~ 15 hours to melt ice before transfer to Ridge plant
- Freezing water also maintains ice tanker at very low pressure
  - Acts as cryopump to maintain flow of water from auger-dryer to tank
- Mobility platform assumed capable of payload ratio of 1.5

Ice Tanker

- Each tanker carries 54 kg of ice per trip
- Two tankers make total of 21 trips

Item	Mass (kg)
Water Ice	54.2
Tank empty	11.8
Battery	6.3
DTAU (passive half)	4.5
Mobile platform	48.2
Radiator	5.1
Total dry mass	75.9
Total wet mass	130.1



ISRU Ridge Plant – Water Processing and Storage

Water Electrolysis Subsystem

- Liquid cathode feed PEM electrolyzer
  - Performance based on recent NASA-funded contracts
- Pump on Ridge plant transfers water from tanker into water electrolyzer storage tank
  - Wait 15 hours after receiving first load before starting electrolyzer to ensure system never ‘runs dry’

O_2 and H_2 Liquefaction and Storage

- Cryocoolers used to bring O_2 and H_2 gas temperature down to saturation and to liquefy
  - Required change in enthalpy to cool hydrogen much greater than for oxygen, but total energy change similar due to 8:1 O_2/H_2 ratio
- Hydrogen uses one cryocooler to cool gas down to 70 K, then second cryocooler to cool to 20 K and liquefy
  - Electrical efficiency of cryocooler with 70K cold-head much greater than one with 20K cold-head
  - Use of pre-cooler reduces total H_2 liquefaction power by 60%

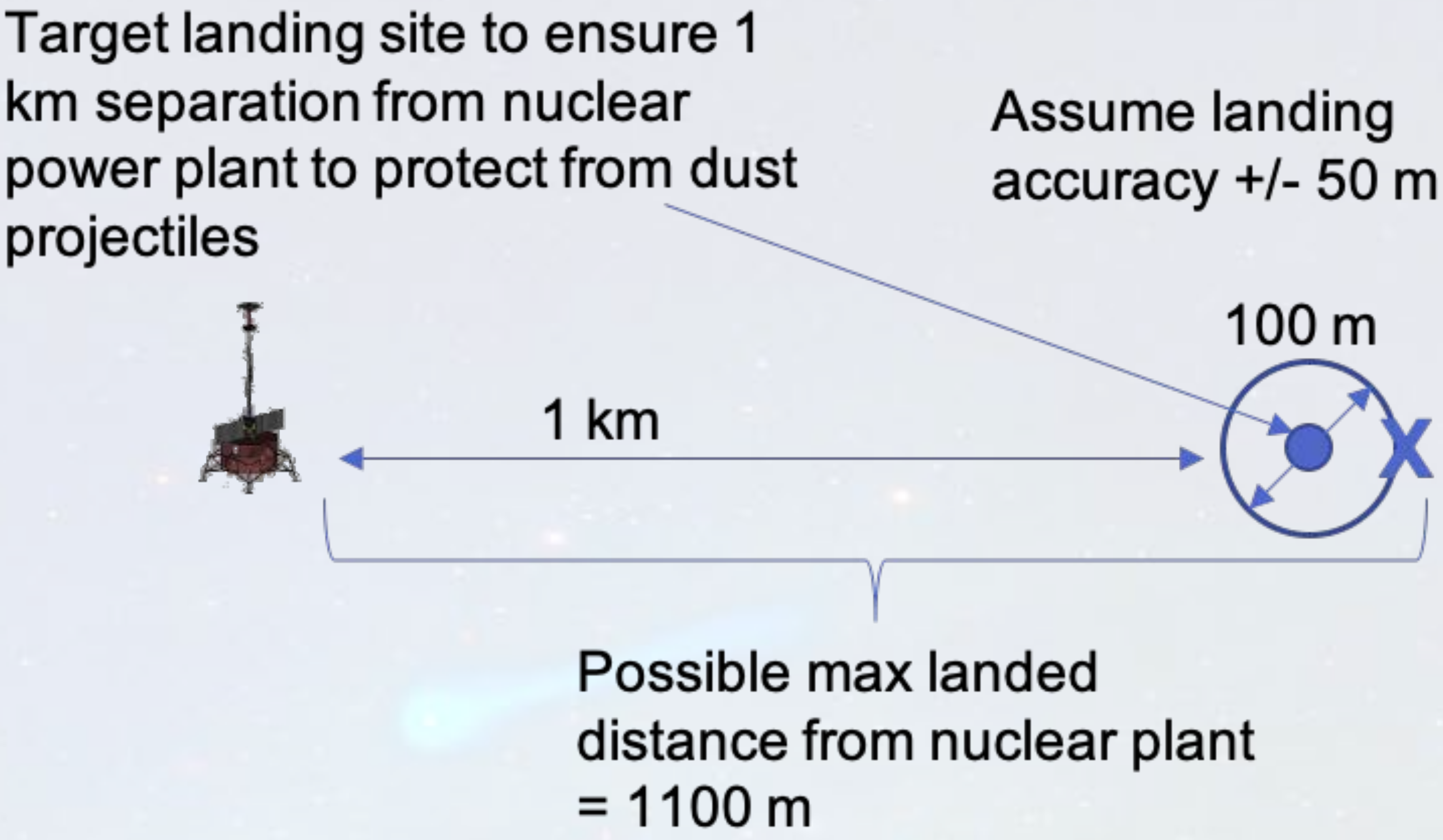
Power in PSR

Nuclear Power Trade

- Evaluated bringing reactor on same lander as ISRU hardware
- Shielding options:
  - – Leave reactor on lander with sufficient shielding to protect ISRU electronics
    - Significant mass required
  - – Use excavator to dig hole and bury reactor
    - Due to trenching nature of excavator, wall stability angles, etc., would take ~40 days to dig sufficient size hole
    - Excavator would require recharging while digging, before reactor is turned on
    - Would also require crane or other device to lift reactor off lander and place in hole

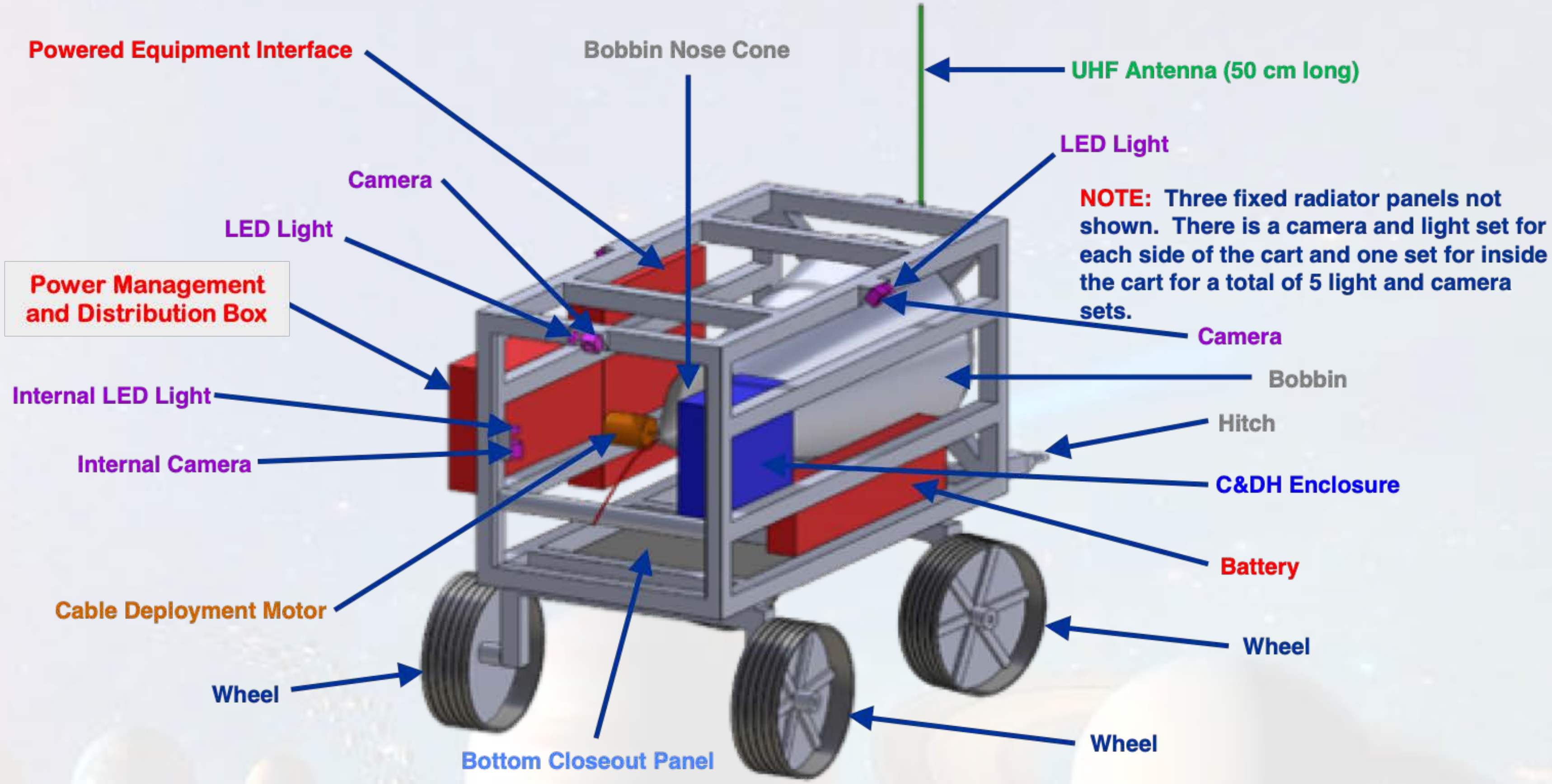
Cable Cart

- Assume nuclear reactor already available in PSR from previous demonstration mission
- Lander also carries a cable cart to deploy power cable between reactor and PSR lander
- Distance determined by landing accuracy and plume ejecta concerns

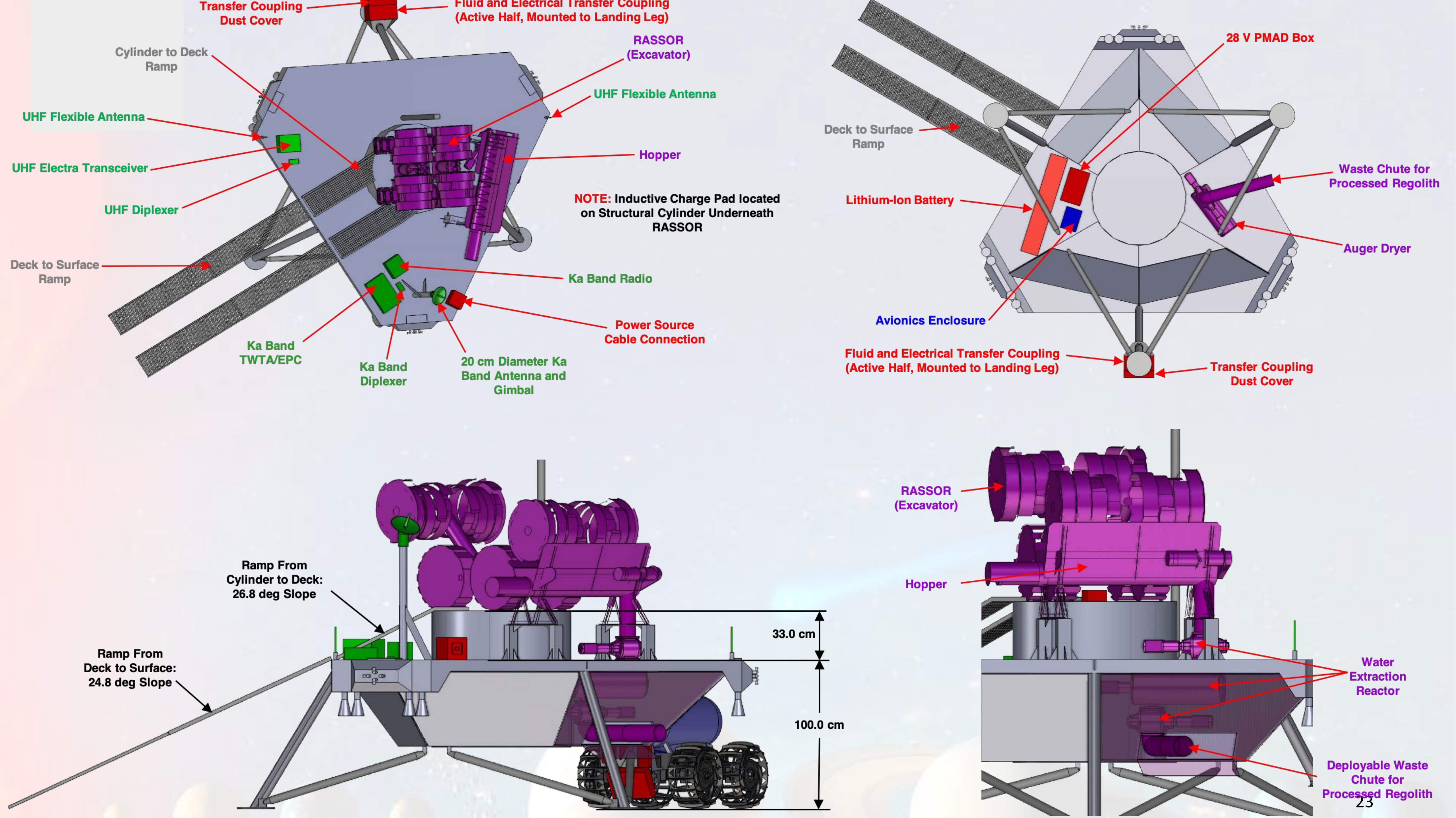


Cable Cart Specifics

- Power transmitted at 1000 VDC to minimize diameter of coaxial cable
  - Cart carries 1000 VDC to 28 VDC converters
- Ice tanker is used to guide cart, aided by motors on the cart’s wheels



Pilot Plant Conceptual Design


Transfer Coupling Dust Cover
Fluid and Electrical Transfer Coupling (Active Half, Mounted to Landing Leg)
Cylinder to Deck Ramp
RASSOR (Excavator)
UHF Flexible Antenna
UHF Flexible Antenna
UHF Electra Transceiver
Hopper
UHF Diplexer
NOTE: Inductive Charge Pad located on Structural Cylinder Underneath RASSOR
Deck to Surface Ramp
Ka Band Radio
Power Source Cable Connection
Ka Band TWTA/EPC
Ka Band Diplexer
20 cm Diameter Ka Band Antenna and Gimbal
28 V PMAD Box
Deck to Surface Ramp
Waste Chute for Processed Regolith
Lithium-Ion Battery
Auger Dryer
Avionics Enclosure
Fluid and Electrical Transfer Coupling (Active Half, Mounted to Landing Leg)
Transfer Coupling Dust Cover
Ramp From Cylinder to Deck: 26.8 deg Slope
Ramp From Deck to Surface: 24.8 deg Slope
33.0 cm
100.0 cm
RASSOR (Excavator)
Hopper
Water Extraction Reactor
Deployable Waste Chute for Processed Regolith

Mass and Power Summary for PSR Plant

	Mass			Power		
	Basic (kg)	Growth[a] (kg)	Total (kg)	Basic (W)	Growth (30%) (W)	Total (W)
PSR Plant	**275**	**50**	**325**	**1809**	**544**	**2353**
Bus	114	24	138	45	14	59
Command & Data Handling	10.3	3.1	13.4	24.3	7.3	31.6
Communications &Tracking	13.5	1.4	14.9	3.8	1.2	5.0
Electrical Power Subsystem	43.0	12.3	55.3	11.5	3.5	15.0
Thermal Control	3.8	0.7	4.5	5.4	1.6	7.0
Water Capture and Transfer	15.7	1.0	16.6			
Structures and Mechanisms	28.1	5.1	33.1			
ISRU System	161	26	187	1764	530	2294
Water extractor and hopper	95	19	114	1475	443	1918
Water tanker hotel/survival				115	35	150
Excavator	66	7	73	174[b]	52	226

[a]Mass growth based on AIAA Standard

[b]Only needed for 5 hrs every 4 days

Mass and Power Summary for Ridge Plant

	Mass: Basic (kg)	Mass: Growth[a] (kg)	Mass: Total (kg)	Power: Basic (W)	Power: Growth (30%) (W)	Power: Total (W)
Ridge Plant	**657**	**182**	**839**	**3311**	**995**	**4306**
Bus	249	51	300	365	111	476
Command & Data Handling	6.5	2	8.5	8.3	2.5	11
Communications &Tracking	42	4.4	46	65	20	85
Electrical Power Subsystem	55	22	77	292	88	380
Thermal Control	39	5	44			
Structures and Mechanisms	106	18	124			
ISRU System	256	85	341	2832	850	3682
Command and data handling	9.1	2.7	12	30	9	39
Electrolyzer	11	4	15	1322	397	1719
Electrolyzer balance-of-plant	32	11	44	59	18	77
Thermal control (electrolyzer)	21	3.7	25			
Hydrogen dryer	6	2	8	24	7	31
Hydrogen tank storage	48	17	64			
Hydrogen liquefaction	87	31	118	1148	345	1493
Oxygen dryer	5	2	7	24	7	31
Oxygen tank storage	28	10	38			
Oxygen liquefaction	9	1	10	225	67	292
Water Ice Tanker (total)	152	46	198	114	34	148
Water Ice Tanker (ea)	76	23	99	50	15	65
Water Ice Tanker recharge*				64	19	83

[a]Mass growth based on AIAA Standard
[b]Only needed for 20 hrs every 9.5 days

Conclusions

- CLPS-style lander can deliver ISRU system to extract 1125 kg of water in a year to produce 1000 kg of oxygen
  - 325 kg ISRU system mass estimate leaves 7.5% margin on 350-kg payload lander
- Taking advantage of PSR environment to freeze extracted water in Ice Tanker reduces power and mass requirements
- Getting power to PSR plant remains key challenge
  - Assumption of dedicated nuclear reactor may be reasonable for full-scale water/oxygen production
  - For pilot plant, prefer scenario where power supply can be landed with either PSR plant or Ridge plant