Comparative Assessment of Delivering Consumable Resources versus In-Situ Resource Utilization for Moon and Mars Habitats Life Support Systems

LEAG 2015 Annual Meeting

- Gregory Gentry, Matthew Duggan, Kurt Klaus – The Boeing Company
- Tim Scull, Mike Heldmann – UTC Aerospace Systems
- William West, Darren Samplatsky – UTC Aerospace Systems

- October 20-22, 2015

Study Objectives

- Estimate life support oxygen, nitrogen and water losses for a crewed lunar or Martian surface habitat as a baseline for resupply needs
- Identify ***early*** viable lunar and Mars ECLSS ISRU candidates for life support consumables to conduct conceptual value trades
- Conduct conceptual value trades to identify a crossover point for each constituent where ISRU supplied solutions become more advantageous than resupply from earth
- Inform architects and planners with study results

Basis of Analysis

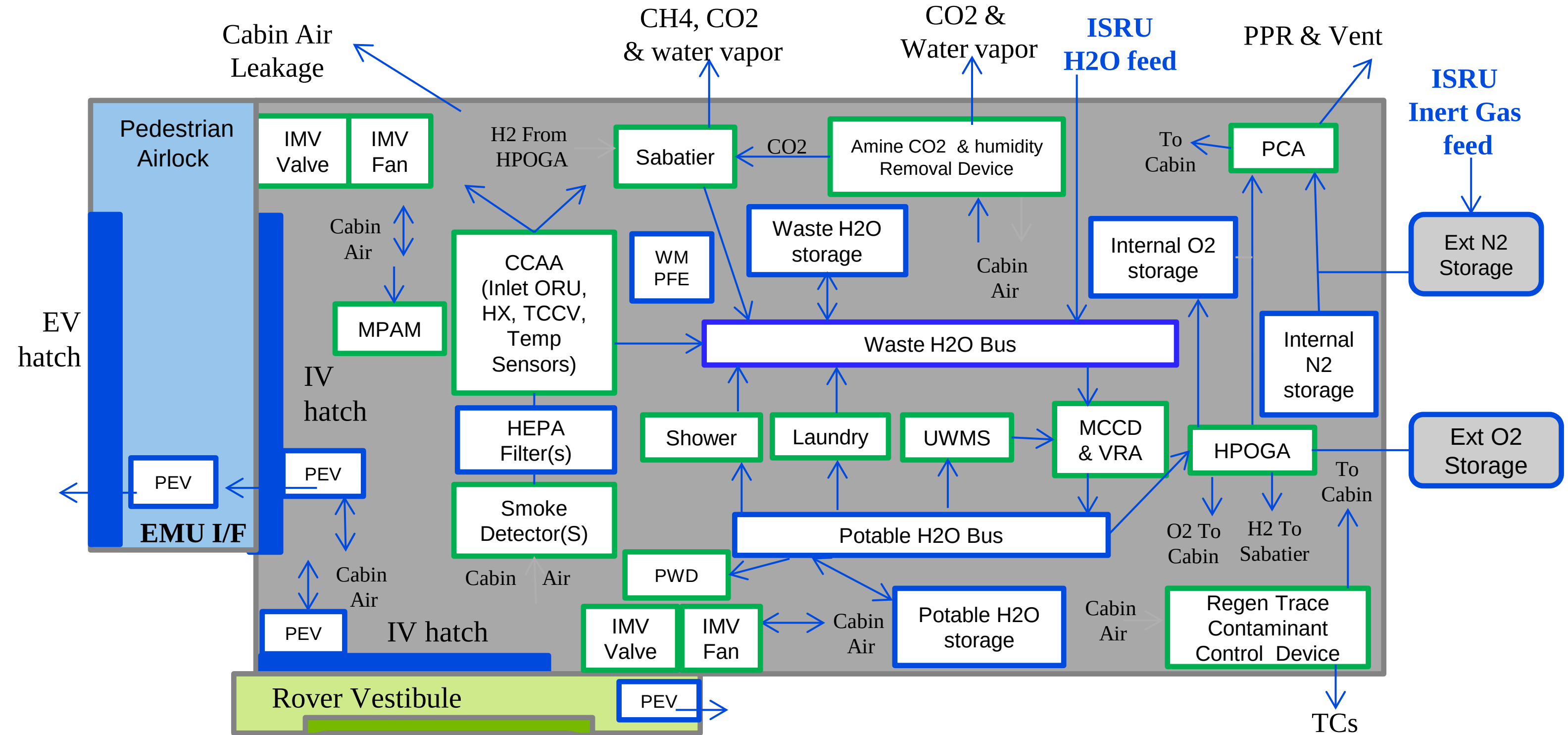
- 4 crew members: lunar stays: 30 - 180 days, Mars stays: 30 & 575 days
- 85 m^3 (3000 ft^3) habitat
  - Includes all the basic life support functions typically expected of a habitat
  - Includes one pedestrian airlock and one rover docking port
  - Includes a shower and laundry **(*Hint: not a big driver*)**
- 8.5 m^3 (300 ft^3) pressurized volume rover with 2 suit ports
- 8-hour Pedestrian Surface Excursions (PSEs) will occur from the rover suit ports while docked to the habitat or during Rover Surface Excursions (RSEs)
  - PSE rate – variable (2 & 7 PSEs/week), **(*Hint: Big driver*)**
  - RSE rate – 1/month for 3 days (conservative)
  - Suits assumed to use Spacesuit Water Membrane Evaporator (SWME) for cooling & Solid Amine regenerative system for CO2 removal
    - Next generation systems (better than sublimators & LiOH or METOX used today)
- As-delivered food water content – variable (0, 50% water)
- Utilization of lunar polar resources (ice only, no oxygen from regolith)
- Utilization of Mars atmospheric constituents (primarily inert gasses)
- Potential for utilization of Mars water resources (icy regolith)
- Technology selection (next slide)

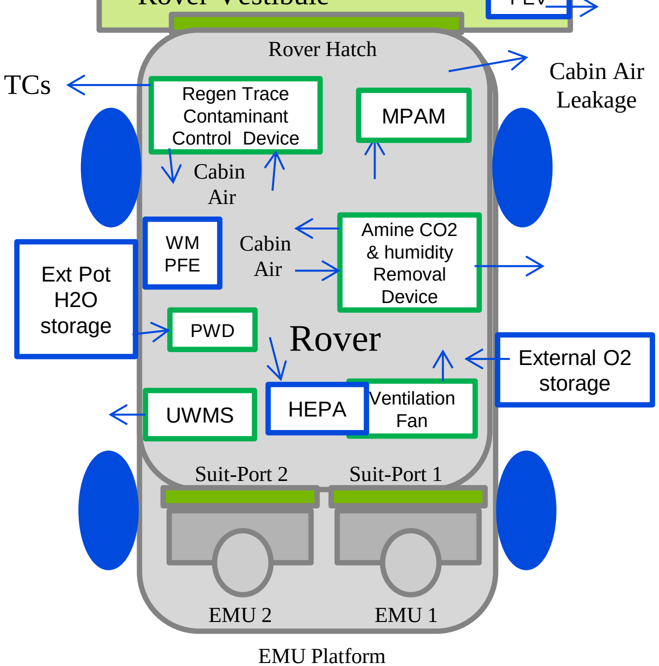
Technology Selection

System	ISS Technology	TRL	Recommended Technology	TRL
O_2 Generation	OGA	9	HPOGA	4
CO_2 Removal	CDRA	9	Solid amine, thermal swing w/water save	7
Water Processing	WPA	9	Modified COTS Commercial Distillation (MCCD) w/ VRA	4
Urine Processing	UPA	9		
Brine water recovery	N/A	N/A	Brine Bag	4
Trace Contaminant Control	Condensing Hx	9	Condensing Hx	9
	Non-regen carbon sorbent	9	Elec. Regen sorbent (RTCCS)	9
	HTCO	9	High Temperature Catalytic Oxidation (HTCO)	9
Temp. & Humidity Control	CHX	9	CHX	9
Atmosphere Monitoring	MCA	9	MPAM	7
Atmosphere Supply & Control	Separate N_2/O_2	9	Mixed N_2/O_2	9
Waste Management	Russian ASU	9	UWMS	7
CO_2 Reduction	Sabatier	9	Sabatier	9
Laundry	N/A	N/A	Water vapor/microwave	3
Shower	N/A	N/A	Enclosed water mist w/ vacuum dry	7
			Average TRL	**6.9**

Extension of ISS experience & enhancements needed to achieve robust, reliable systems

Conceptual Architecture - Habitat & Rover ECLSS Systems





Green outline denotes powered component

Location	Volume M^3	Total Pressure kPa	ppO2 kPa
Habitat	85	77	17-21
Airlock	4.24	0-77	17-21
Suit Port	0.03	0-77	17-21
Vestibule	1.42	0-77	17-21
Rover	8.5	55-77	17-21
Suit	0.2	32.4	32.4

Baseline Consumables & Waste

Consumables	Kg/person/day		Waste	Kg/person/day
Oxygen	0.82		CO_2	1.04
Drinking	2.50		Urine	1.82
Water in food	0.50		Perspiration/ Respiration	1.92
Food Prep water	0.50		Fecal water	0.1
Hygiene	0.2		Hygiene	0.2
Flush	0.4		Flush	0.4
Shower	3.63		Shower	3.63
Clothes wash	1.13		Clothes wash	1.13
Food	0.67		Urine	0.06
			Feces	0.03
			Perspiration	0.02
Total 1 person	10.35		Total 1 person	10.35
Total 4 persons	41.40		Total 4 persons	41.40

Reference: NASA Baseline Values and Assumptions Document (BVAD)

Analysis Results - Gas & Water Losses

Item or Function	Loss Mechanism	Nitrogen Kg/month		Water Kg/month			
Case Variables		**2 PSEs/Wk 1 RSE/Mo**	**7 PSEs/Wk 1 RSE/Mo**	**50% WIF* 2 PSEs/Wk 1 RSE/Mo**	**0% WIF* 2 PSEs/Wk 1 RSE/Mo**	**50% WIF* 7 PSEs/Wk 1 RSE/Mo**	**0% WIF* 7 PSEs/Wk 1 RSE/Mo**
Hab structure	Leakage	0.36	0.36	0.006	0.006	0.006	0.006
Airlock	Ullage vent	0.47	0.47	0.008	0.008	0.008	0.008
Vestibule	Ullage vent	0.16	0.16	0.003	0.003	0.003	0.003
R-TCCS	Ovbd Vent	0.11	0.11	0.01	0.01	0.01	0.01
Sabatier	Ovbd Vent	---	---	2.79	2.79	3.26	3.26
Suit	Leakage	---	---	0.03	0.03	0.11	0.11
Suit cooling	Ovbd Vent	---	---	70.7	70.7	247.6	247.6
Suit CO2 rmvl	Ovbd Vent	---	---	44.9	44.9	157.1	157.1
Rover structure	Leakage	0.22	0.22	0.22	0.22	0.22	0.22
Rover Suit Ports	Ullage Vent	0.02	0.02	0.02	0.02	0.02	0.02
Rover CO2 removal	Ovbd Vent	---	---	5.73	5.73	5.73	5.73
Total:		**1.34**	**1.34**	**124.42**	**124.42**	**414.07**	**414.07**

*% Water in food

Evaporative suit cooling drives water losses

Analysis Results – Water Summary

Water Needs				
	50%* + 2 PSEs/Wk 1 RSE/Mo	**0%*+ 2 PSEs/Wk 1 RSE/Mo**	**50%* + 7 PSEs/Wk 1 RSE/Mo**	**0%* + 7 PSEs/Wk 1 RSE/Mo**
Crew Usage	33.44 kg/day	35.44 kg/day	33.44 kg/day	35.44 kg/day
Equipment Losses	4.19 kg/day	4.19 kg/day	13.71 kg/day	13.71 kg/day
HPOGA usage	3.99 kg/day	3.99 kg/day	4.66 kg/day	4.66 kg/day
Total	**41.62 kg/day**	**43.62 kg/day**	**51.81 kg/day**	**53.81 kg/day**
Water Supplies				
Humidity Condensate	7.32 kg/day	7.32 kg/day	6.41 kg/day	6.41 kg/day
MCCD	26.96 kg/day	26.96 kg/day	26.96 kg/day	26.96 kg/day
Sabatier	1.99 kg/day	1.99 kg/day	2.33 kg/day	2.33 kg/day
Water from brine	1.60 kg/day	1.60 kg/day	1.60 kg/day	1.60 kg/day
Total	**37.88 kg/day**	**37.88 kg/day**	**37.30 kg/day**	**37.30 kg/day**
Delta:	**(3.74 kg/day)**	**(5.74 kg/day)**	**(14.51 kg/day)**	**(16.51 kg/day)**

*% Water in food

MCCD Recovery = 90%, Sabatier recovery = 50%, Brine Bag recovery = 80%; Total recovery = 99%

Regen systems help substantially, but they can’t do it all!

Resupply Needs

^Mission Resupply Needs in kg						
Duration	Nitrogen 2 PSEs/Wk 1 RSE/Mo	Nitrogen 7 PSEs/Wk 1 RSE/Mo	Water 50%* + 2 PSEs/Wk 1 RSE/Mo	Water 0%*+ 2 PSEs/Wk 1 RSE/Mo	Water 50%* + 7 PSEs/Wk 1 RSE/Mo	Water 0%* + 7 PSEs/Wk 1 RSE/Mo
30 days	1.34	1.34	112	172	435	495
90 days	4.02	4.02	337	517	1306	1486
180 days	8.04	8.04	673	1033	2612	2972
365 days	16.08	16.08	1366	2096	5297	6027
575 days	25.33	25.33	2151	3301	8345	9495
730 days	32.16	32.16	2731	4191	10,594	12,054

^ Not including tank and secondary structure mass, which could shift results substantially in our favor

*Amount of water in delivered food; water is used to generate oxygen so no separate column for oxygen is needed

With reasonable assumptions for water in food & PSE rate
water needs add up fast!

Initial Supplies Estimates

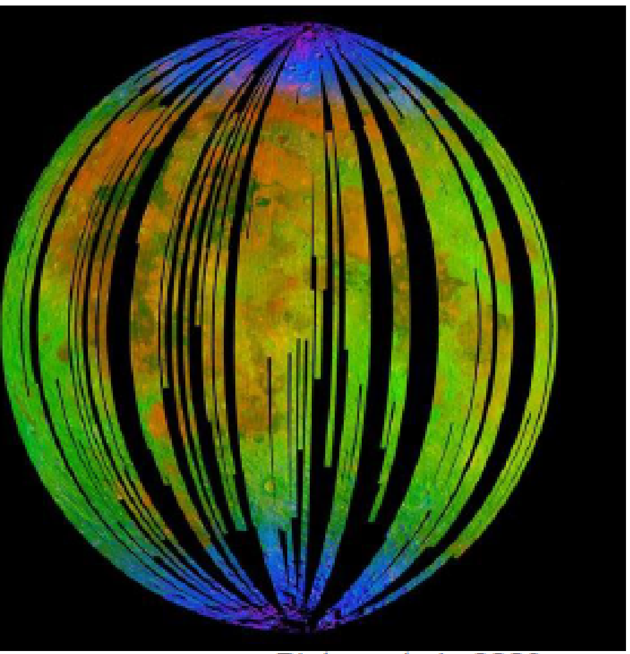
Supply Period	1 Week	1 Month	3 Months
Crew Size	4	4	4
Oxygen - kg	22.96	98.4	295.2
Habitat initial fill gas (air) - kg	68.18	68.18	68.18
Potable water - kg	232.4	996	2988
Leakage makeup - N2	1.23	5.28	15.84
Lithium Hydroxide - kg	28	120	360
Total:	352	1287	3727

Adding contingency supplies or planned replenishment of initial consumables consumption to re-supply need increases ISRU justification!

Multiple Lines of Evidence for Lunar Polar Water

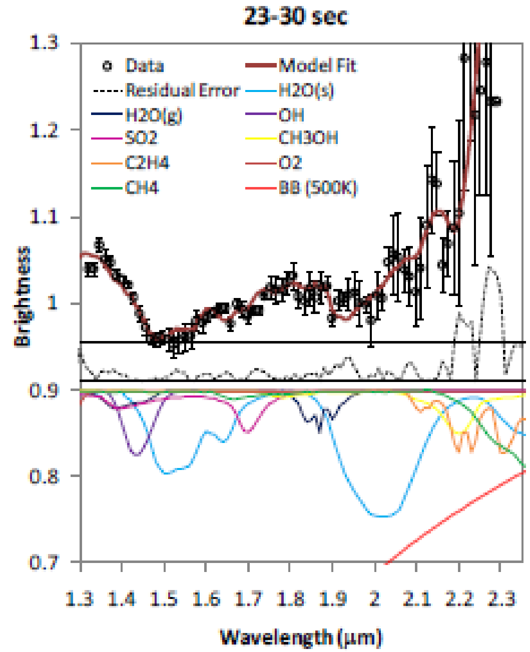
A range of forms, distributions and concentrations

~0.1-1%



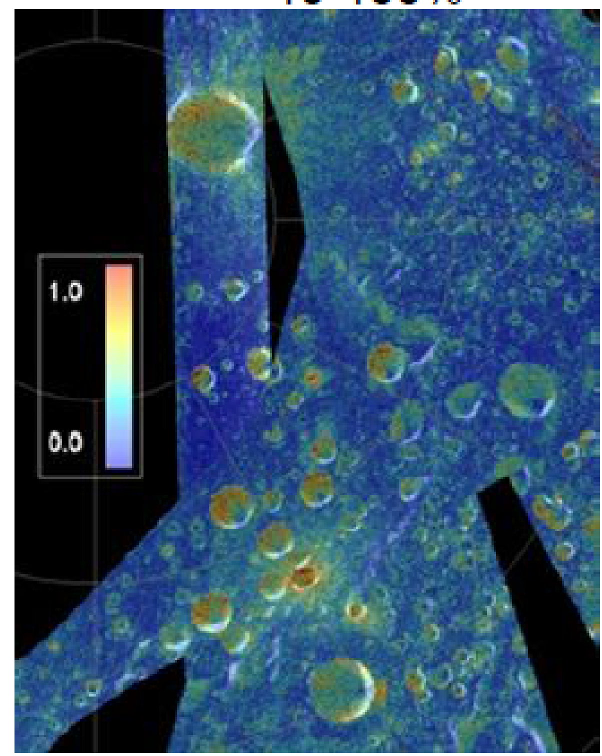
Pieters et al., 2003

~1-10%



Colaprete et al., 2010

~10-100%



Spudis et al., 2010

We know that water (and other H-bearing compounds) are there…

Colaprete et.al., LEAG 2013

Multiple Lines of Evidence for Low-Mid Latitude Ice on Mars

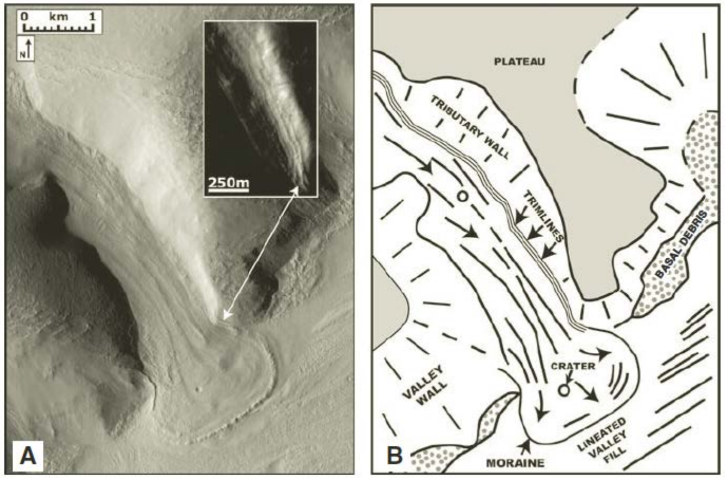


Figure 4. Debris-covered, glacier-like lobe emerging from a tributary on the southern wall of massif A (Fig. 1A; also see image in Fig. 2A). A: Mars Reconnaissance Orbiter Context Camera image. B: Sketch map showing main features and relationships. Note that the lobe extends out onto the floor, crosscutting linear trends in the lineated valley fill (LVF), and appears topographically superposed on the LVF. The inset shows evidence for lateral moraines along the tributary wall, suggesting the progressive loss of ice down to the present topographic level.

Head, et.al 2008

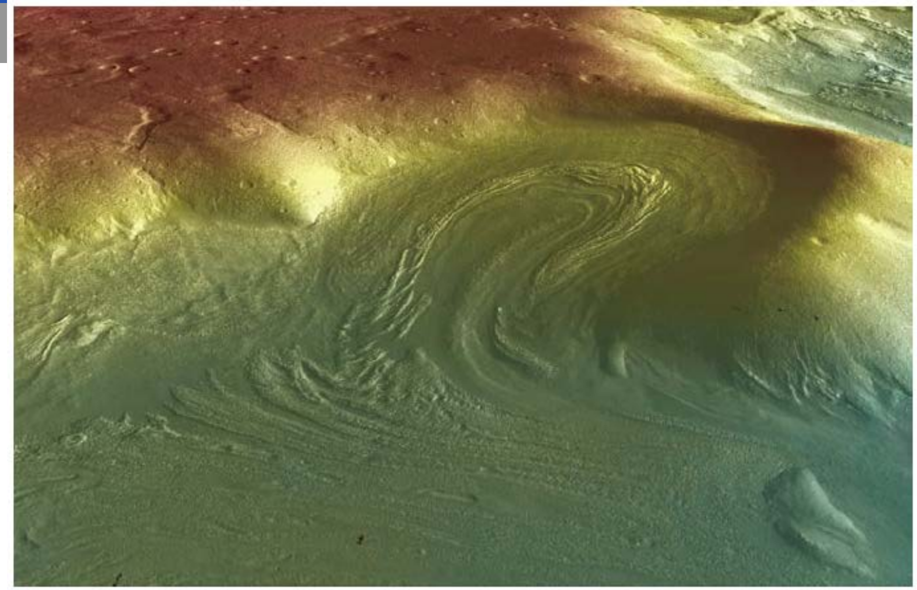


Figure 3. Perspective view from the valley into the box canyon (along a profile shown in Fig. DR1) showing flow features that now trend upslope (see Fig. DR3 for detailed patterns). Mars Reconnaissance Orbiter Context Camera image draped on High Resolution Stereo Camera topography from orbit h2908. No vertical exaggeration.

Head, et.al 2008

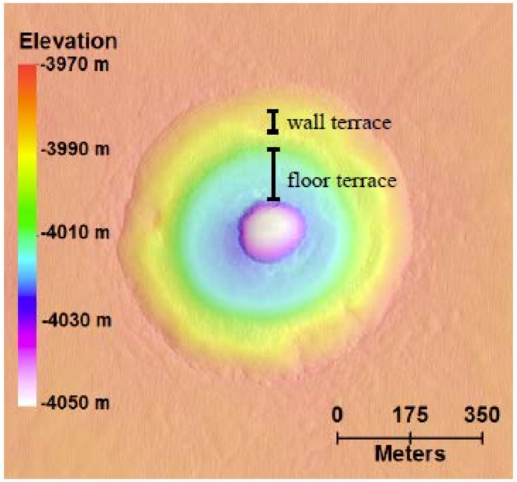


Figure 1: A terraced crater at 46.581°N, 194.85°E with colors representing elevations. The DTM was made using HiRISE stereo pairs ESP_018522_2270 ESP_019010_2270

Bramsom, et.al 2015

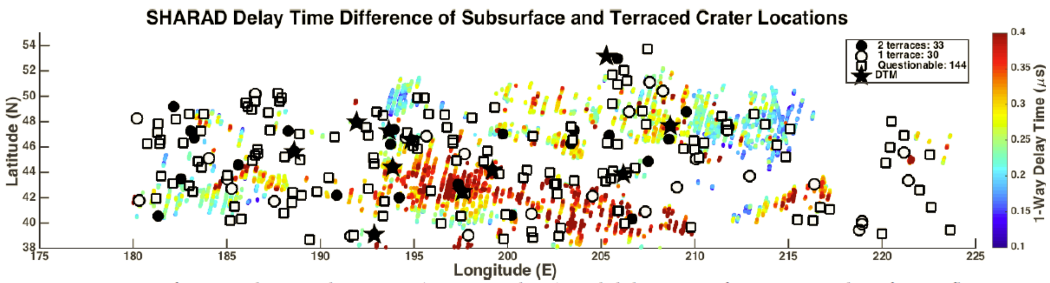
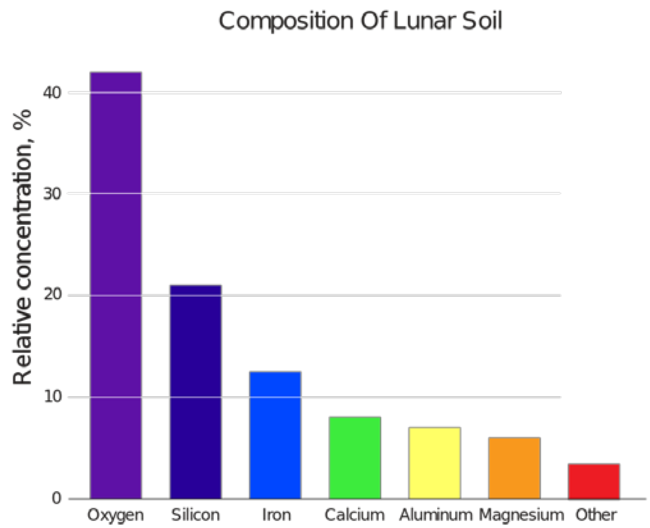


Figure 2: Map of terraced crater locations (B&W markers) and delay time of SHARAD subsurface reflectors.

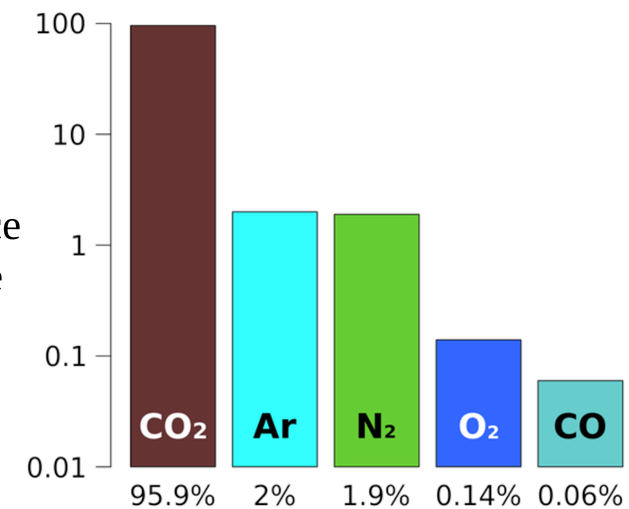
Lunar & Mars ECLSS ISRU Opportunities

- Lunar regolith has abundant oxygen, however it is difficult to extract and therefore was not considered for ***early mission*** ISRU opportunities
- Lunar regolith has minimal inert gasses available for ISRU, although further study is warranted
- LCROSS experiment in 2009 detected 5.6% ± 2.9% total mass of water in a lunar impact ejected plume at Cabeus Crater in the lunar south polar region



Composition of Lunar Soil.

- Mars atmosphere has inert gasses available for ISRU and evidence for ice at low-mid latitudes
- Martian subsurface ice in the mid-lower latitudes has been directly detected but not characterized, and abundant water ice at the Phoenix landing site was detected very near the surface



Average Martial Atmosphere Composition.

ISRU ECLSS Regolith Processing Equipment & Sizing

- A **digger/transporter** device gets “new” processing material (icy regolith) and bring it to the pre-processor
  - This is considered to be tele-robotically operated by an on-site crew member in the habitat
- A **hopper** accepts the load from the transporter and feeds it into the pre-processor
- A **pre-processor** traps and heats the regolith to drive off the water vapor, then condenses the water vapor and pumps the liquid water into a holding (waste tank) for later feeding into the habitat water processor for processing into potable water

- The **digger/transporter** then accepts the “used” regolith and transports it to a disposal site (or location useful for radiation shielding)

Regolith Processor	
Component	Estimated Mass
Tele-robotic digger/transporter	420 kg
Hopper	150 kg
Pre-Processor	250 kg
Total:	**820 kg**

- Assuming regolith water/ice component of 5.6% by mass, 17 kg of regolith (0.013 m^3) would produce 1 liter of water
- A water make-up need of 3.74 kg/day (min. analysis result), would require 63 kg (0.05 m^3) of regolith processed per day

Note: Simplified process equipment shown to demonstrate initial mass assumptions. Actual equipment may be somewhat more complex.

ISRU ECLSS Mars Atmosphere Processing Equipment & Sizing

- A high performance **compressor** collects and compresses atmospheric gas into a **processing tank**
- A thermal process separates the atmospheric CO2 from the inert gas constituents
- The compressor pumps the inert gasses into a **storage tank** (through appropriate filters) for habitat use

- Assuming inert gas component of 3.9% by volume, 24.2 (earth std) m^3 of Martian Atmosphere processed would produce 1.5 kg of inert gas
- An inert gas make-up need of 5 kg/month (analysis result), would require 4 process cycles/month

Mars Atmosphere Processor		
Component	Initial Est. Mass	Reduced Mass
Compressor	300 kg	200
Processing tank	200 kg	100
Storage tank	100 kg	100
Total:	**600 kg**	**400 Kg**

Results Crossover

Constituent	Analysis Results - Need	Processor Mass	Analysis Crossover Point	Crossover w/tank mass W 1.14/ G 2.92	Crossover w/tk & strge W 996/ G 136
Water (50% in food, 2 PSEs/Wk)	3.74 kg/day	820 kg	219 days	192 days	Immediate
Water (50% in food, 7 PSEs/Wk)	5.74 kg/day	820 kg	143 days	125 days	Immediate
Water (0% in food, 2 PSEs/Wk)	14.51 kg/day	820 kg	57 days	50 days	Immediate
Water (0% in food, 7 PSEs/Wk)	16.51 kg/day	820 kg	50 days	44 days	Immediate
Inert gas (Mars only, 2 PSEs/Wk)	1.34 kg/month	600 kg	448 months	153 months	52 months
Inert gas (Mars only, 7 PSEs/Wk)	1.34 kg/month	600 kg	448 months	153 months	52 months

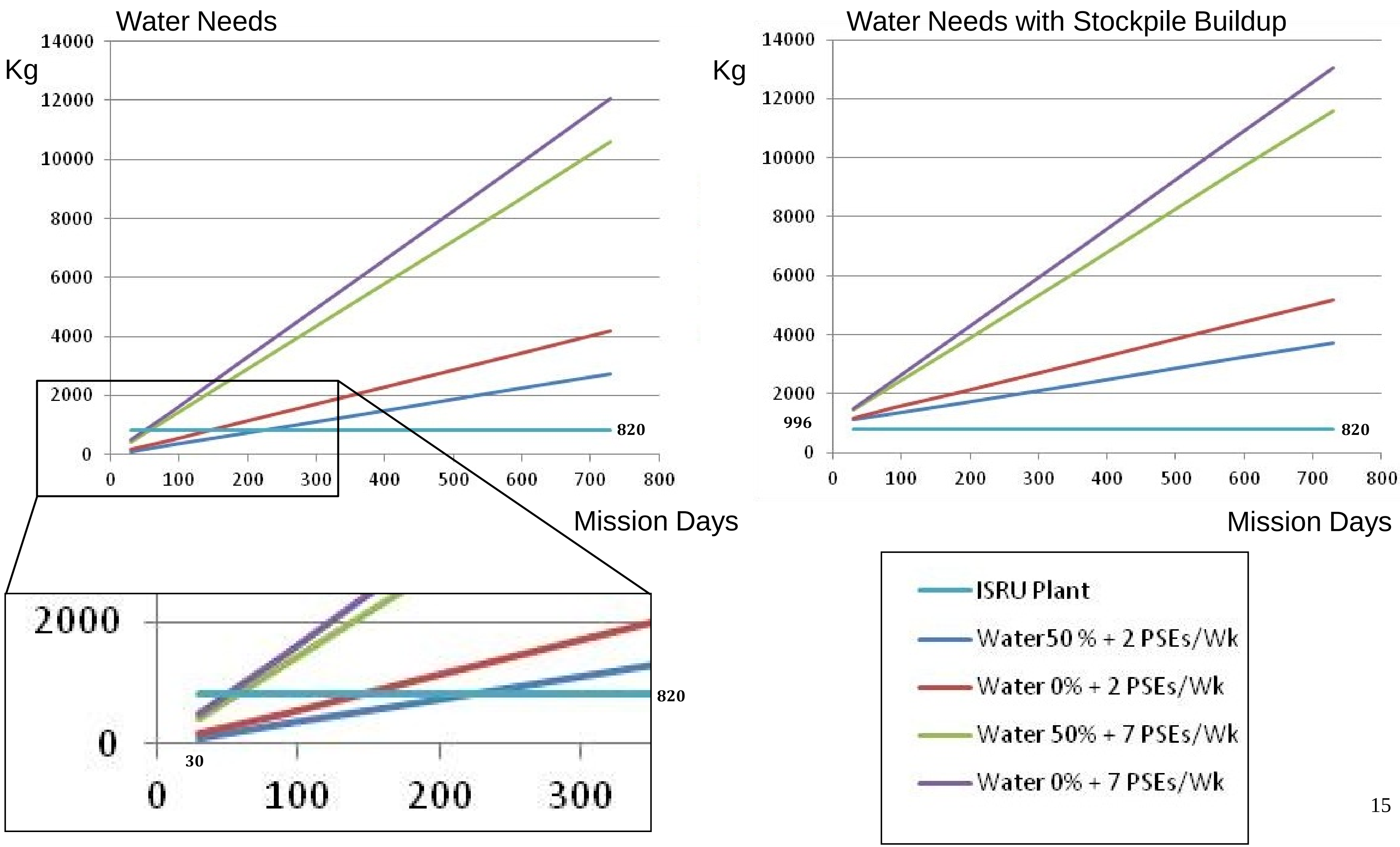
Water: Water resupply needs become sufficiently large to consider developing a pilot ISRU capability for even ***relatively short duration*** missions, assuming a plant mass of 820 kg

- Adding in tank mass and the desire for contingency water stockpile buildup (e.g. 1 month = 996 kg), the crossover point becomes ***immediate***

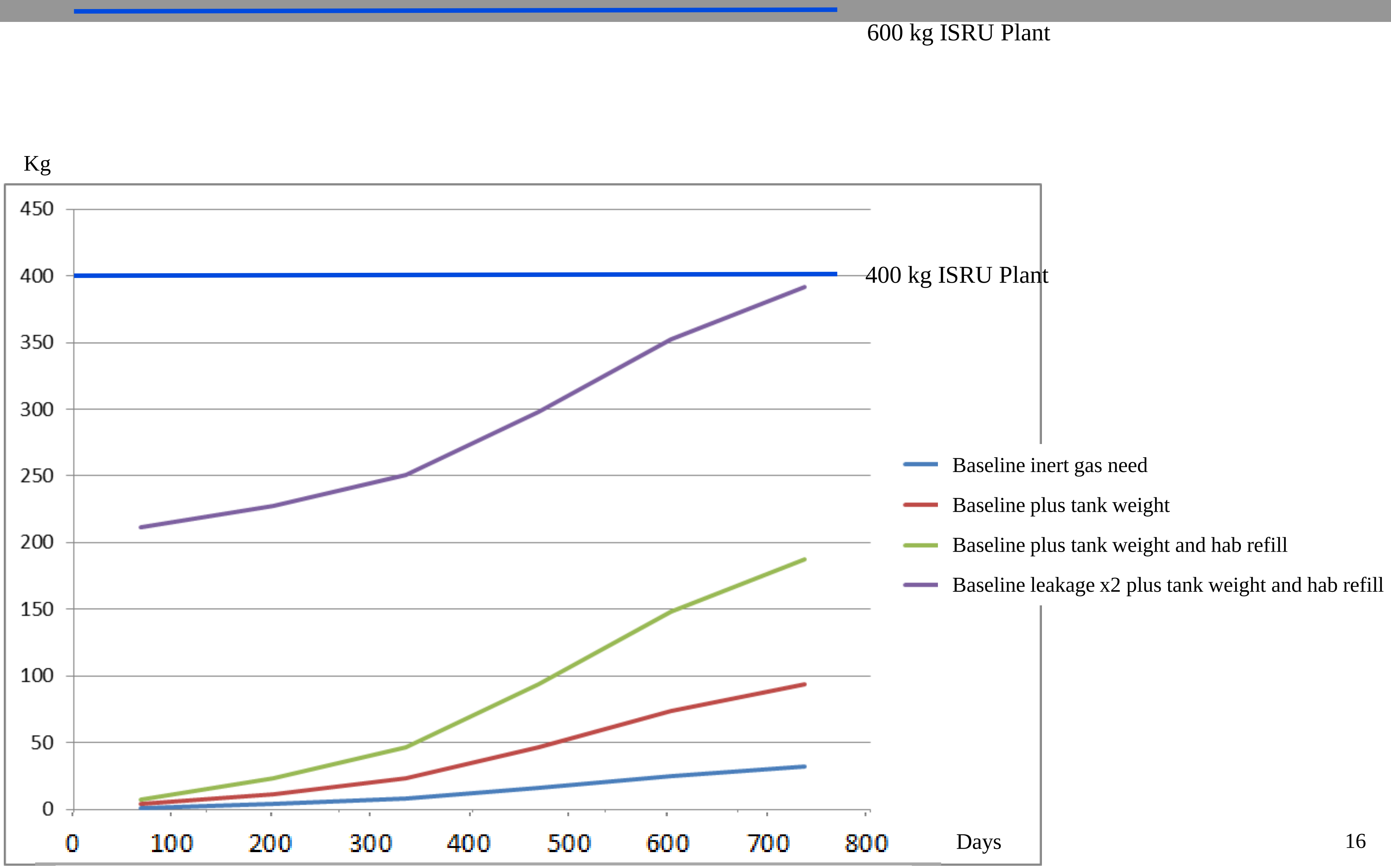
Inert gas (Mars only): ISRU is technically feasible, but based on analysis results only becomes value-added on Mars at 448 months (~37 years), assuming a plant mass of 600 kg. ***However:***

- Adding in ***tank mass*** the crossover point ***is reduced to 153months (~ 13 years)***
- Adding habitat fill replenishment and contingency inert gas stockpile (2 hab represses), the crossover point ***is reduced to 52 months (~ 4 years)***
- Doubling the daily leakage rate results in ***26 month crossover (~ 2 years)***
- Using the above + Reducing plant mass to 400 kg the crossover point is ***immediate***

Results: Water Needs *With Regen* by Mission Duration



Results: Inert Gas Needs by Mission Duration

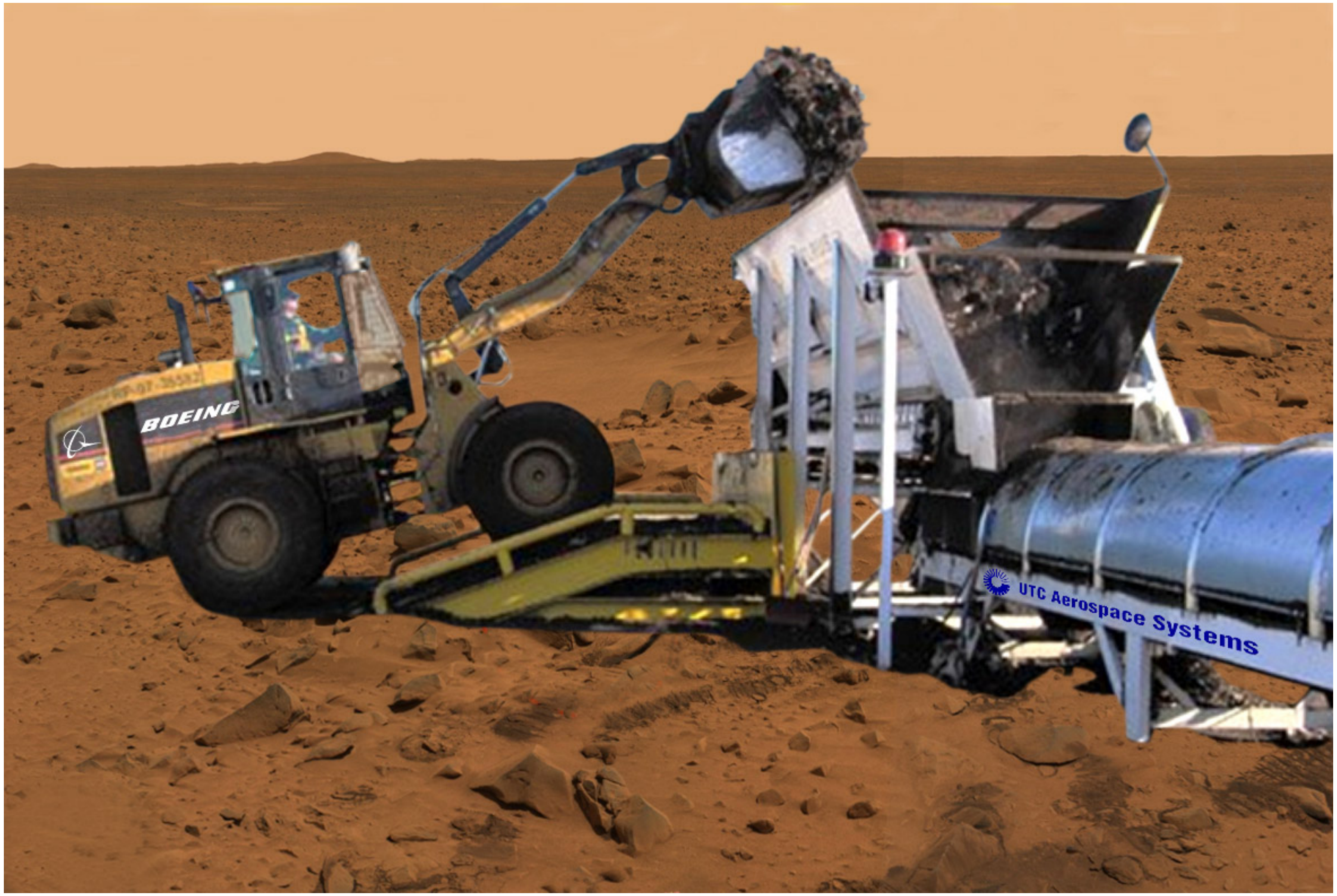


Conclusion

- ISRU water & inert gas resupply would be beneficial within the first mission
- Water mining from icy regolith on both moon and Mars would provide direct benefit to consumable logistics
  - For Mars this would mean landing near the poles or prospecting for water sources in the mid-low latitudes
- Inert gas utilization may not be an option on the moon but provides benefit to consumable logistics on Mars, particularly when stored gas replenishment and contingencies are considered
- Terrestrial industrial analogs for bulk material drying, thermal soil remediation, etc., and gas compression abound
  - New technology development is needed, merely adaptation of existing technology to the local environments is likely not enough, especially for the moon

ISRU technology for Life Support consumables should be developed as an expected subsystem for any lunar or Mars habitat

Questions?



Acronyms

- *ACS* = Atmosphere Control & Supply
- *AR* = Atmosphere Revitalization
- *BVAD* = Baseline Values and Assumptions Document
- *CAMRAS* = CO_2 and Moisture Removal Assembly
- *CCAA* = Common Cabin Air Assembly
- *CDRA* = Carbon Dioxide removal Assembly
- *CHX* = Condensing Heat Exchanger
- *CRD* = Cascade Rotary Distillation
- *ECLSS* = Environmental Control and Life Support Systems
- *EMU* = Extra-vehicular Mobility Unit
- *EVA* = Extravehicular Activity
- *FWM* = Fine Water Mist
- *FDS* = Fire Detection and Suppression
- *HEPA* = High Efficiency Particle Air
- *HPOGA* = High Pressure Oxygen Generator Assembly
- *HTCO* = High Temperature Catalytic Oxidation
- *I/F* = Interface
- *IMV* = Inter-Module Ventilation
- ISRU = In Situ Resource Utilization
- ISS = International Space Station
- MCA = Major Constituent Analyzer
- MCCD = Modified COTS Commercial Distillation
- MPAM = Multi-Platform Air Monitor
- OGA = Oxygen Generation Assembly
- PEV = Pressure Equalization Valve
- PFE = Portable Fire Extinguisher
- PPR = Positive Pressure Relief
- PSE = Pedestrian Surface Excursion
- PWD = Potable Water Dispenser
- RTCCS = Regenerative Trace Contaminant Control System
- RSE = Rover Surface Excursion
- TCs = Trace Contaminants
- THC = Temperature & Humidity Control
- TRL = Technology Readiness Level
- UPA = Urine Processing Assembly
- USOS = United States Operational Segment
- UWMS = Universal Waste Management System
- VCD = Vapor Compression Distillation
- VRA = Volatiles Removal Assembly
- WM = Waste Management
- WP = Water Processor
- WPA = Water Processing Assembly
- WRM = Water Recovery & Management

Basis of Estimate: Digger/Transporter

Reference example:
Hysoon HY 380 mini-digger
Lift capacity: 200 kg (441 lbs.)
Lift volume: 0.15 m3 (5.33 ft3)
Equipment weight: 890 kg (1958 lbs.)

Deltas:
1/3 capacity needed
Electrically driven vs gas motor & hyd
Telerobotic vs direct human control
Lightweight space flight materials

Proposed device:
Lift capacity needed: 68 kg (150 lbs.)
Lift volume needed: 0.05 m3 (1.76 ft3)
Estimated equipment weight: 420 kg (924 lbs.)

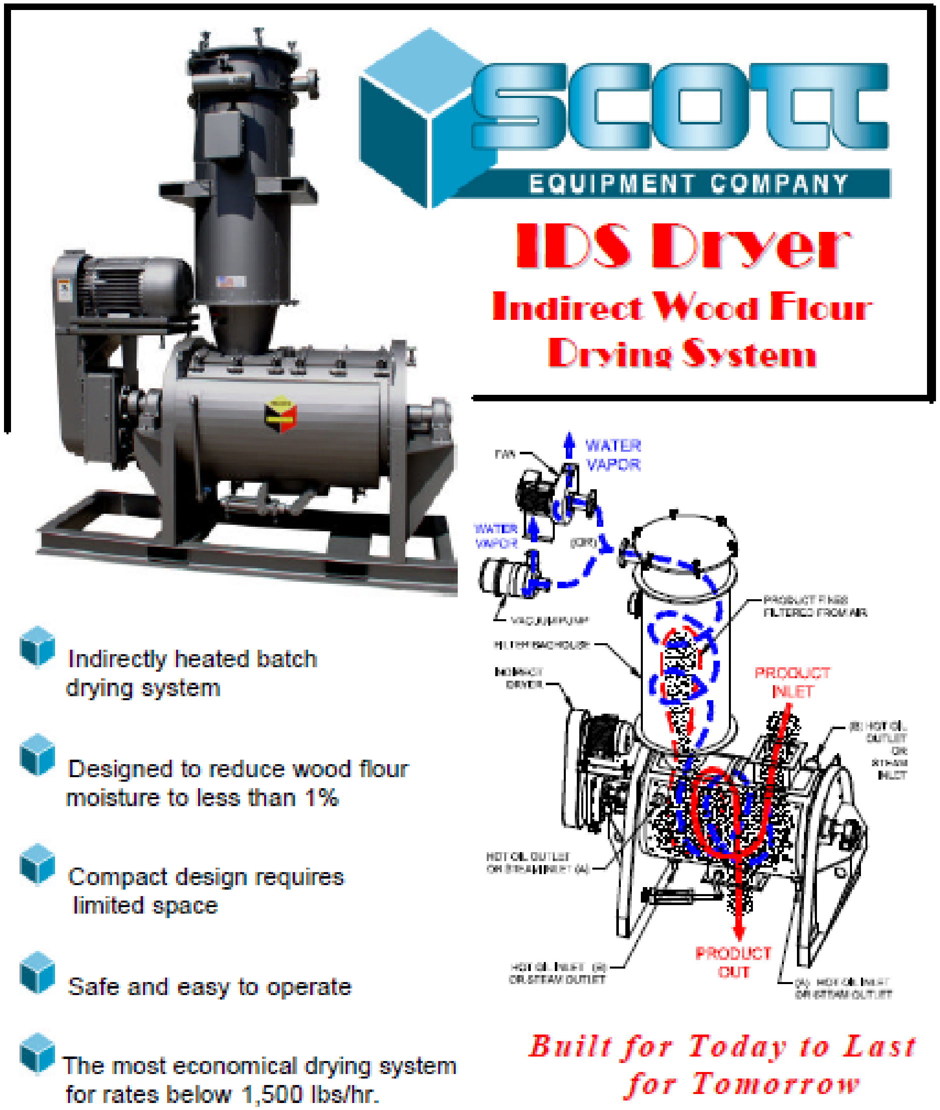
Basis of Estimate: Hopper

Reference example:
Star Industries Model 151
Batch volume: 1 m3 (27 ft3)
Equipment weight: 254 kg (558 lbs.)

Deltas:
1/15 capacity needed
Lightweight space flight materials

Proposed device:
Batch volume needed: 0.05 m3 (1.76 ft3)
Estimated equipment weight: 150 kg (330 lbs.)

Basis of estimate: Pre-Processor



Reference example:
Scott IDS Dryer
Batch Capacity: 0.368 m3 (13 ft3)
500 kg (1100 lbs.)
Equipment weight: 2500 kg (5500 lbs.)

Deltas:
1/8 capacity needed
Lightweight space flight materials

Proposed device:
Batch capacity needed: 68 kg (150 lbs.)
Batch volume needed: 0.05 m3 (1.76 ft3)
Estimated eq. weight: 250 kg (550 lbs.)

Basis of estimate: SCUBA Tank Compressor

19 in x 29 in x 14.5 in
(48 x 74 x 37 cm)

Reference example:
Nuvair MCH6 / 3.5 E
SCUBA tank fill device
Inlet: Earth ambient Outlet: 4500 PSI
4-Stage compression
3-Phase electric motor driven
Equipment weight: 49 kg (108 lbs.)

Deltas:
Lower inlet pressure
Lower discharge pressure
Lightweight space flight materials

Proposed device:
Electric Diaphragm Compressor
Inlet: Mars ambient Outlet: 1000 psia
Estimated eq. weight: 100 kg (220 lbs.)

Basis of estimate: Storage Tanks

3 sizes to choose from 4500,5000,6000

NUVT4500
4500 psi, ultrasonic tested, leak-before-break, DOT cylinders that can be used horizontally or ve

Specification	DOT-E10869-4500/ TC-SU4369-310
Outside Diameter	9.4"
Height	55"
Weight (empty)	155 lbs.
Service Pressure	4500 psi
Test Pressure	6750 psi
Air capacity at service pressure and 70 F (cubic feet)	437
Minimum water capacity(cubic inch)	2750
Tapping	3/4-14 NGT
Collar and Cap	3-1/2" Diameter 11 TPI
Re-test Period	10 years International

Reference example:
Nuvair NUVT4500
Volume: 437 Std Ft^3
Equipment weight: 70 kg (155 lbs.)

Deltas: N/A

Proposed device:
Use as-is

Terrestrial Analogs

For terrestrial industrial analogs for regolith processing for water look at:

- Thermal soil remediation systems
- Sand drying
- Bulk material drying
- Soil Vapor Extraction (SVE) process
- Vacuum dewatering technique
- In Situ Thermal Desorption (ISTD)

For terrestrial analogs for atmosphere compression and storage look at:

- SCUBA tank filling systems