LEAG Workshop on Enabling Exploration: The Lunar Outpost and Beyond

October 2, 2007

ISRU and Potential Mass and Cost Impacts on Sustained Lunar Exploration

Based on: LAT2 In-Situ Resource Utilization (ISRU) Architecture and Economics Analysis Final Report August 2007

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- **Key Ideas**

  Many uncertainties remain with regard to Lunar ISRU. But the potential exists to provide major savings in Launch mass needed for a given Lunar architecture, or alternatively, major increases in useful payload landed on the Moon for a given number of launches. This presentation will briefly review quantitative results of some analyses carried out in support of the recent LAT II activity, and suggest how current uncertainties might be addressed.

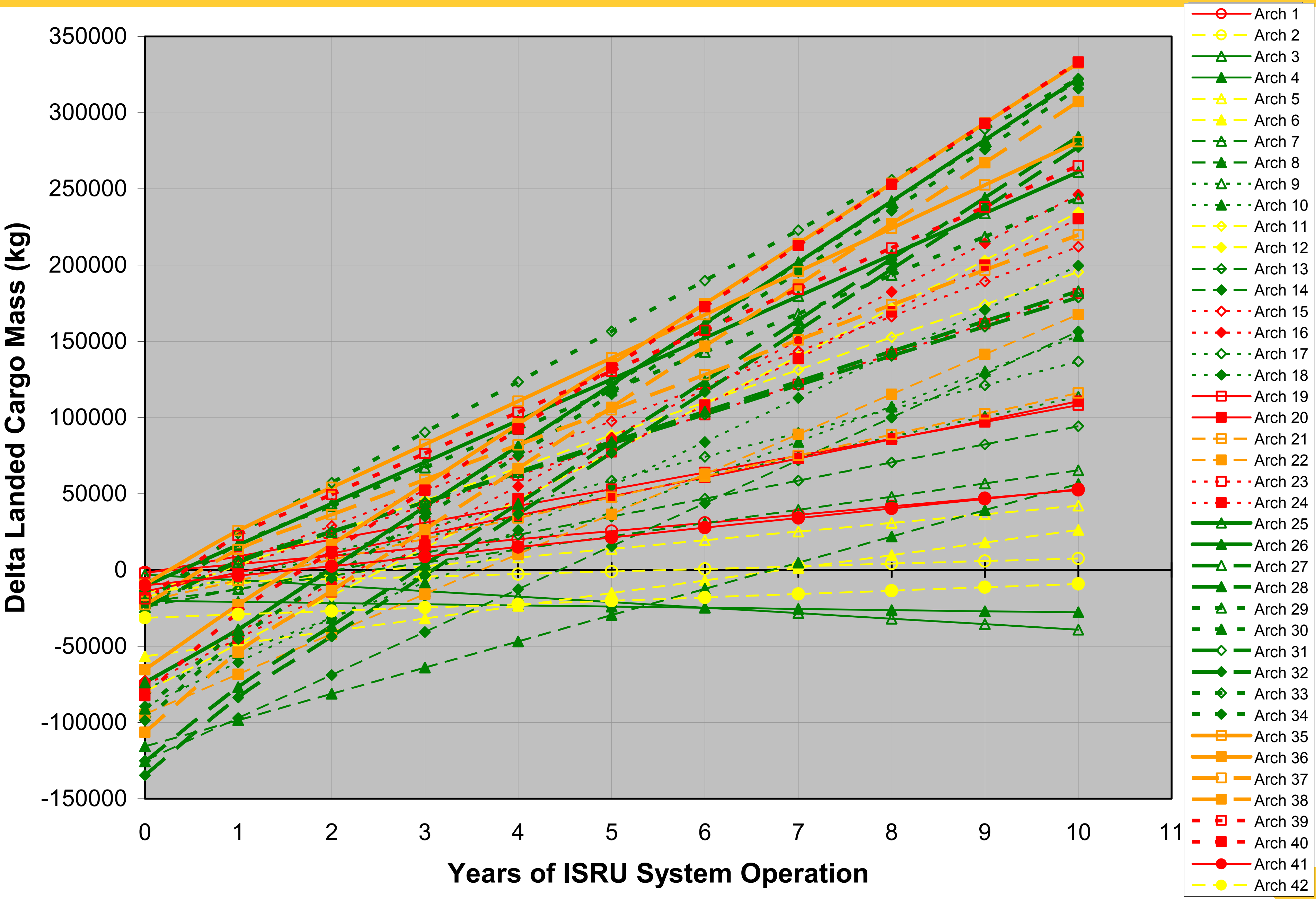
- **Contents**
  - Architecture Trades & Analysis: Transportation Architectures and Campaign Architectures
  - Economics Trades & Analysis
  - Study Results and Conclusions
  - ISRU & Uncertainty

Architecture Trades and Analysis

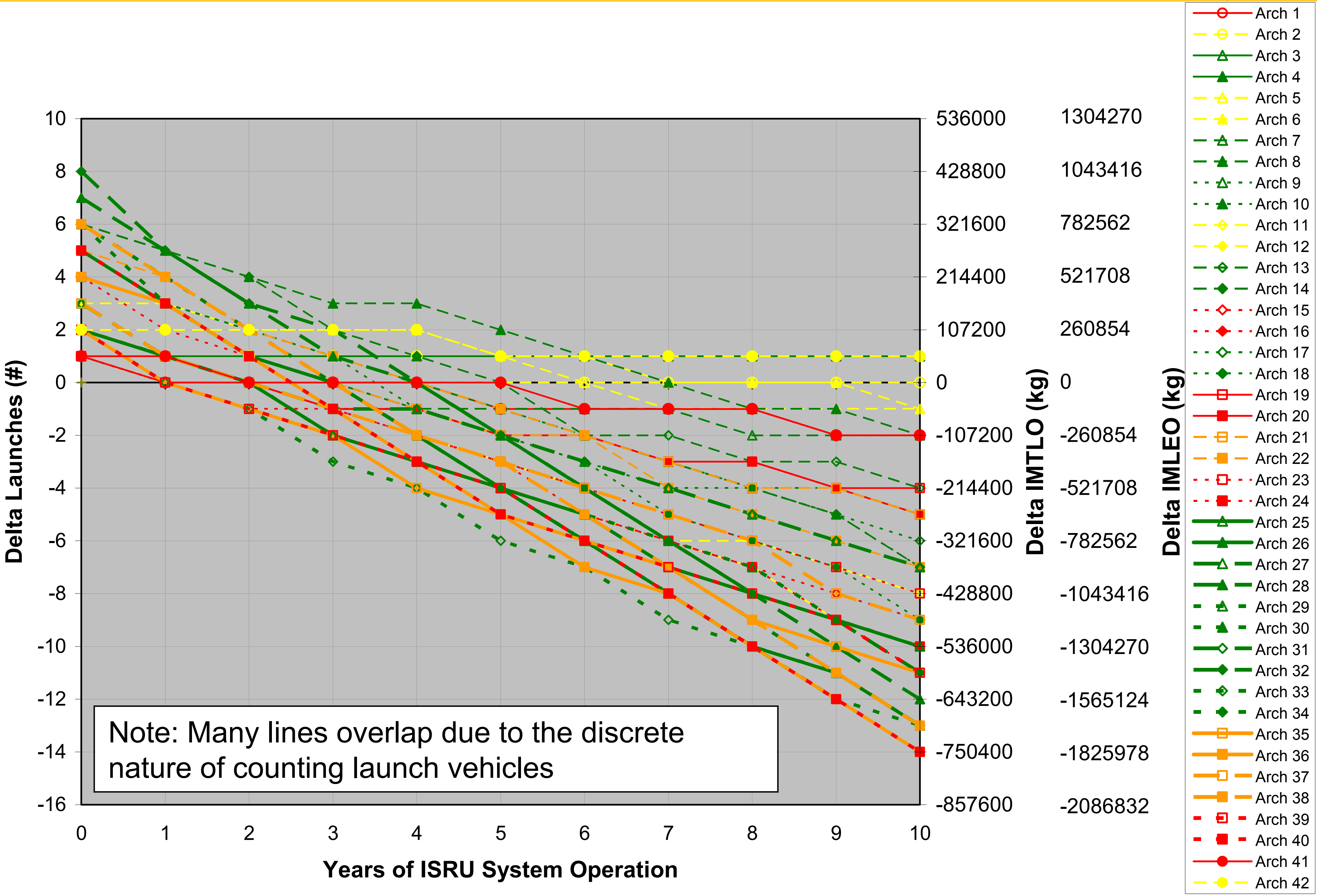
Transportation Architectures Studied-Preliminary Screen

ID #	Return	Reusable LSAM	(Re)Fueled	Where	For	With	Descent Abort	Ascent Abort
1	LOR	No	AS	Surface	Ascent	Oxygen	No	No
2	LOR	No	AS	Orbit	Ascent	Oxygen	Yes	No
3	LOR	No	DS	Surface	Ascent	Oxygen	Yes	Yes
4	LOR	No	DS	Surface	Ascent	Both	Yes	Yes
5	LOR	No	DS	Orbit	Descent	Oxygen	Yes	No
6	LOR	No	DS	Orbit	Descent	Both	Yes	No
7	LOR	No	DS	Orbit	Descent/Ascent	Oxygen	Yes	Yes
8	LOR	No	DS	Orbit	Descent/Ascent	Both	Yes	Yes
9	LOR	No	DS	Orbit & Surface	Descent & Ascent	Oxygen	Yes	Yes
10	LOR	No	DS	Orbit & Surface	Descent & Ascent	Both	Yes	Yes
11	LOR	No	AS & DS	Orbit	Descent/Ascent	Oxygen	Yes	No
12	LOR	No	AS & DS	Orbit	Descent/Ascent	Both	Yes	No
13	LOR	No	AS & DS	Orbit	Descent/Ascent/Abort	Oxygen	Yes	Yes
14	LOR	No	AS & DS	Orbit	Descent/Ascent/Abort	Both	Yes	Yes
15	LOR	No	AS & DS	Orbit & Surface	Descent & Ascent	Oxygen	No	No
16	LOR	No	AS & DS	Orbit & Surface	Descent & Ascent	Both	No	No
17	LOR	No	AS & DS	Orbit & Surface	Descent/Abort & Ascent	Oxygen	Yes	Yes
18	LOR	No	AS & DS	Orbit & Surface	Descent/Abort & Ascent	Both	Yes	Yes
19	LOR	No	ADS	Surface	Ascent	Oxygen	No	No
20	LOR	No	ADS	Surface	Ascent	Both	No	No
21	LOR	No	ADS	Orbit	Descent/Ascent	Oxygen	Maybe	No
22	LOR	No	ADS	Orbit	Descent/Ascent	Both	Maybe	No
23	LOR	No	ADS	Orbit & Surface	Descent & Ascent	Oxygen	No	No
24	LOR	No	ADS	Orbit & Surface	Descent & Ascent	Both	No	No
25	LOR	Yes	DS	Surface	Ascent/Descent	Oxygen	Yes	Yes
26	LOR	Yes	DS	Surface	Ascent/Descent	Both	Yes	Yes
27	LOR	Yes	DS	Orbit	Descent/Ascent	Oxygen	Yes	Yes
28	LOR	Yes	DS	Orbit	Descent/Ascent	Both	Yes	Yes
29	LOR	Yes	DS	Orbit & Surface	Descent & Ascent	Oxygen	Yes	Yes
30	LOR	Yes	DS	Orbit & Surface	Descent & Ascent	Both	Yes	Yes
31	LOR	Yes	AS & DS	Orbit	Descent/Ascent/Abort	Oxygen	Yes	Yes
32	LOR	Yes	AS & DS	Orbit	Descent/Ascent/Abort	Both	Yes	Yes
33	LOR	Yes	AS & DS	Orbit & Surface	Descent/Abort & Ascent	Oxygen	Yes	Yes
34	LOR	Yes	AS & DS	Orbit & Surface	Descent/Abort & Ascent	Both	Yes	Yes
35	LOR	Yes	ADS	Surface	Ascent/Descent	Oxygen	No	Maybe
36	LOR	Yes	ADS	Surface	Ascent/Descent	Both	No	Maybe
37	LOR	Yes	ADS	Orbit	Descent/Ascent	Oxygen	Maybe	No
38	LOR	Yes	ADS	Orbit	Descent/Ascent	Both	Maybe	No
39	LOR	Yes	ADS	Orbit & Surface	Descent & Ascent	Oxygen	No	No
40	LOR	Yes	ADS	Orbit & Surface	Descent & Ascent	Both	No	No
41	LOR	No	AS	Surface	Ascent	Both	No	No
42	LOR	No	AS	Orbit	Ascent	Both	Yes	No

ΔLC Compilation- Preliminary Screen



ΔLaunches Compilation-Preliminary Screen



Note: Many lines overlap due to the discrete nature of counting launch vehicles

Transportation Architecture (TA) Elements & Trade Space-2nd Round

Element	Abbr.	Type	Description
Crew	Crew	Inert	4 person crew, descends and ascends in an AM or EM
Samples	Samples	Inert	100 kg of lunar samples, ascends in an AM or EM
Cargo (DM, CDM, or DAM)	Cargo ( )	Inert	Cargo carried to the lunar surface by a DM, CDM, or DAM
Liquid Hydrogen (Element-Maneuver)	LH2 ( )	Inert	LH2 isn't produced by ISRU, it will be brought from Earth for reusable elements
Liquid Oxygen (Element-Maneuver)	LOX ( )	Inert	LOX is sometimes transported before being used, requiring it to be an element
Methane (Element-Maneuver)	CH4 ( )	Inert	CH4 isn't produced by ISRU, it will be brought from Earth for reusable elements
Crew Exploration Vehicle	CEV	Inert	Not split into CM & SM. TLI mass assumed to be 20,000kg
Ascent Module	AM	Propulsive	An AM ascends Crew and Samples
Escape Module	EM	Inert	An EM is used for abort while descending or ascending on a DAM or RDAM
Descent Module	DM	Propulsive	A DM descends an AM and Cargo - If there is no AM, then it is actually a CDM
Cargo Descent Module	CDM	Propulsive	A CDM descends only Cargo - If there is an AM, then it is actually a DM
Descent Ascent Module	DAM	Propulsive	A DAM descends and ascends an EM and Cargo
Reusable Descent Ascent Module	RDAM	Propulsive	A RDAM descends and ascends an EM multiple times
Reusable Propellant Module	RPM	Propulsive	A RPM ascends propellant to a depot and descends itself multiple times
Lunar Orbital Depot	LOD	Inert	An orbital depot holds LOX and LH2 to fuel elements in orbit
Combined Earth Departure Stage	CEDS	Propulsive	Assumed capability is 79.5mt to TLO for 1.5 Launch & 69.7mt for 1.0 Launch
ISRU System	ISRU	Inert	Includes all the components necessary to extract oxygen from the lunar regolith

	Ph. II ID	LOI	Crew Desc.	Cargo Desc.	Ascent	Fueling Location	Module Fueled (Maneuver)	Descent Abort	Ascent Abort
Baseline	A	DM	DM	DM	AM	Orbit (LLO)	None	AM	None
						Surface	None		
Refuel AM w/ ISRU	C	DM	DM	DM	AM	Orbit (LLO)	None	No	No
						Surface	AM (Ascent)		
Refuel DM w/ ISRU	D	DAM	DAM	DAM	DAM	Orbit (LLO)	None	EM	EM
						Surface	DAM (Ascent)		
Orbital & Surface Depot	E	DAM	DAM	DAM	DAM	Orbit (LLO)	DAM (Descent)	EM	EM
						Surface	DAM (Ascent)		
Orbital Depot	F	DM	DM	DM	AM	Orbit (LLO)	AM (Ascent), DM (Descent)	AM	None
						Surface	None		
Orbital & Surface Depot	G	DAM	DAM	DAM	DAM	Orbit (LLO)	DAM (Descent), EM (Abort)	EM	EM
						Surface	DAM (Ascent)		
Reusability Added	H	CDM	RDAM	CDM	RDAM	Orbit (LLO)	None	EM	EM
						Surface	RDAM (Ascent, Descent)		
	I	CDM	RDAM	CDM	RDAM	Orbit (LLO)	RDAM (Descent), CDM (Descent), EM (Abort)	EM	EM
						Surface	RDAM (Ascent)		
	J	CDM	RDAM	CDM	RDAM	Orbit (LLO)	RDAM (Descent), EM (Abort)	EM	EM
						Surface	RDAM (Ascent)		
	K	CDM	RDAM	CDM	RDAM	Orbit (LLO)	CDM (Descent), EM (Abort)	EM	EM
						Surface	RDAM (Ascent, Descent)		

TA Figures of Merit (FOMs)

Preliminary Screening used Delta landed Cargo and Delta # of Launches

During Second round two main FOMs investigated:

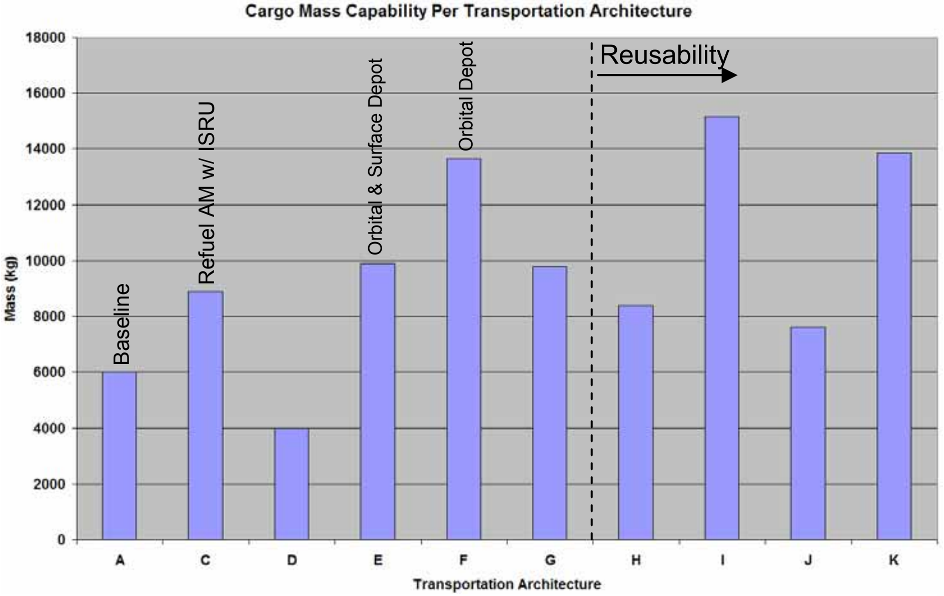
1. Absolute Landed Cargo – How much total cargo a given architecture can carry
2. Delta Landed Cargo Mass (ΔLC) – How much additional cargo a given architecture can carry over the baseline crewed architecture

- $\Delta LC = LC - LC_B$
  - ΔLC: Delta Landed Cargo Mass
  - LC: Absolute Landed Cargo Mass for the candidate TA
  - LC_B: Absolute Landed Cargo Mass for the baseline TA

Using ISRU can reduce launch mass required for the transportation elements, by *either* allowing for a smaller launch vehicle, *OR* allowing additional cargo can be put on the Moon. This analysis evaluates TAs from the latter point of view.

TA Results – Baseline Lander Cargo Capability (6 mT) w/ ISRU O2

Absolute Landed Cargo Mass



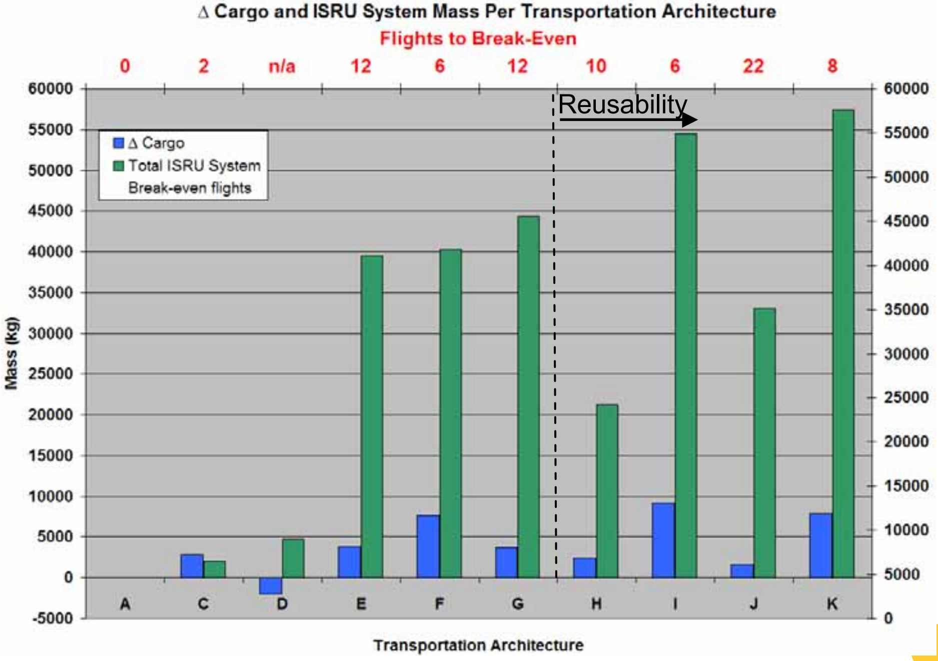
Absolute Landed Cargo Mass Results

- ISRU can significantly increase the landed payload to the surface by 1.3-2.5x the baseline, with exception of D.
- I & K provide the most landed mass and make use of a reusable descent/ascent module (RDAM), in orbit and surface depots/refueling, and have descent and ascent abort capability.
- F is the same as LAT Baseline except orbital fueling of the AM and DM is utilized and provides >100% increase in landed mass.
- C (refueling AM on surface) increases payload capability by >50% over Baseline.

Delta Landed Cargo Mass Results

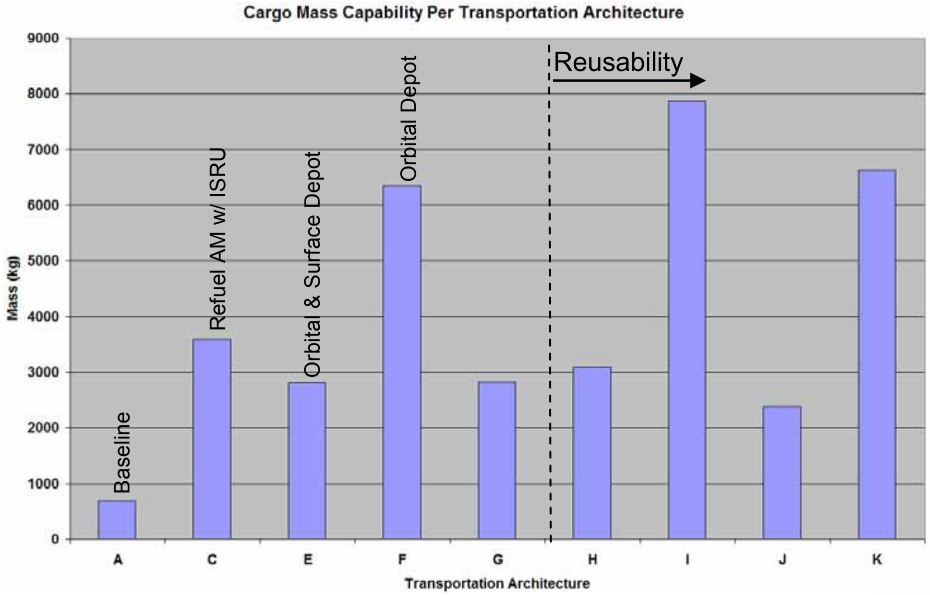
- Total ISRU System includes masses of depots and propellant delivery systems.
- Surface refueling for ascent (C) provides fewest flights to break-even at 2 flights.
- Lunar orbit depot fueling for descent (F & I) provides breakeven in 6 flights.
- TAs E, G, H, K (“Full ISRU”) can provide break-even in 8-12 flights.
- TA D is the only architecture incapable of breaking even as the landed cargo is less than that of the baseline (6 MT).

Delta Landed Cargo Mass



TA Results – Reduced Lander Cargo Capability (0.7 mT) w/ ISRU O2

Absolute Landed Cargo Mass for Each TA



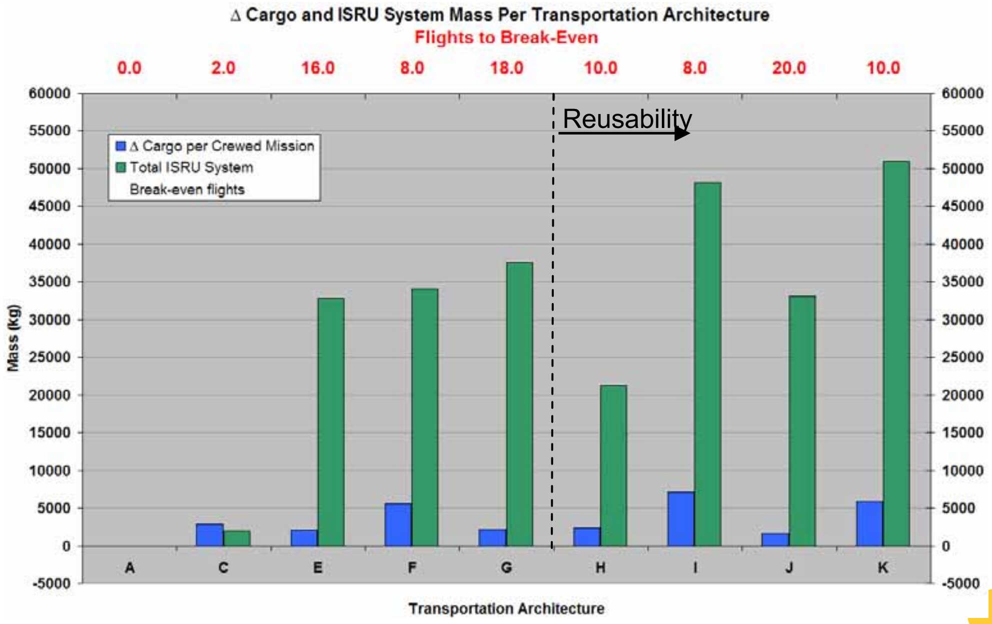
Delta Landed Cargo Mass Results

- Total ISRU System includes masses of depots and propellant delivery systems.
- Surface refueling for ascent (C) provides fewest flights to break-even at 2 flights.
- Architectures F & I (Lunar orbit depot fueling for descent) provides a reasonable break-even in 8 flights.
- TAs E, G, H, K ("Full ISRU") can provide break-even in 10-18 flights.

Absolute Landed Cargo Mass Results

- Use of ISRU can increase the landed payload by 3.4-11x the 0.7 mT baseline.
- I & K provide the most landed mass and make use of a reusable descent/ascent module (RDAM), in orbit and surface depots/refueling, and have descent and ascent abort capability.
- F is the same as LAT Baseline except orbital fueling of the AM and DM is utilized and provides an increase of landed mass 9x that of the baseline.
- C (refueling AM on surface) increases payload capability by 500% over the baseline.

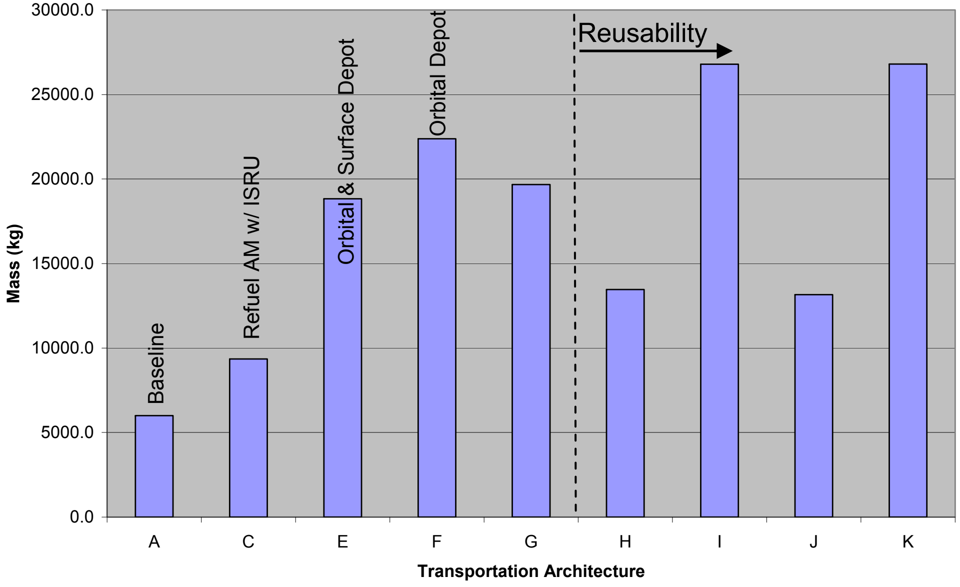
Delta Landed Cargo Mass



TA Results – Baseline Lander Cargo Capability (6 mT) w/ ISRU H2O

Absolute Landed Cargo Mass for Each TA

Cargo Mass Capability Per Transportation Architecture



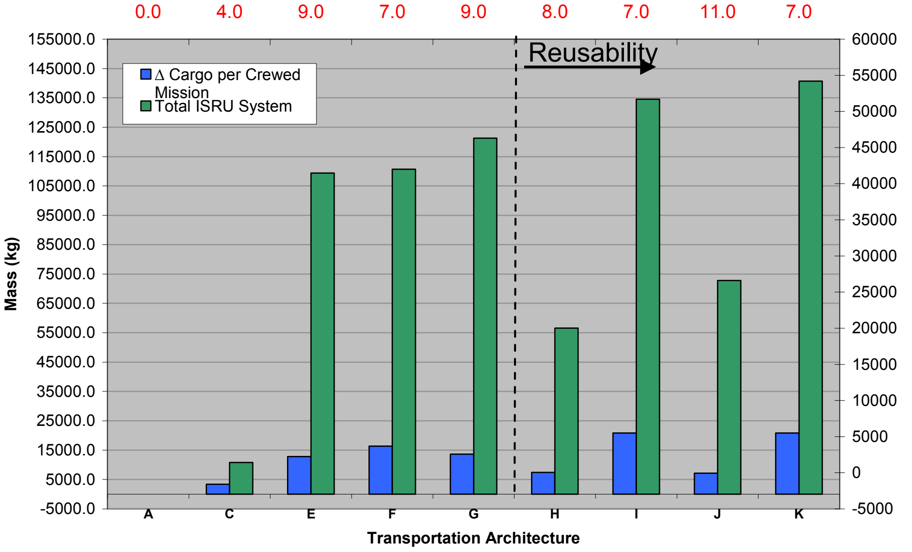
Absolute Landed Cargo Mass

- H2O production systems enable an increase of lander cargo capability over those enabled by O2 production systems:
- 10% increase for TA C (Refuel AM for ascent)
- 60-100% increase for more aggressive TAs (E-K) since H2 for RPM (vehicle for refueling orbital depot) no longer needs to be brought from Earth, and reusable elements can be resized smaller.

Delta Landed Cargo Mass

Δ Cargo and ISRU System Mass Per Transportation Architecture

Flights to Break-Even



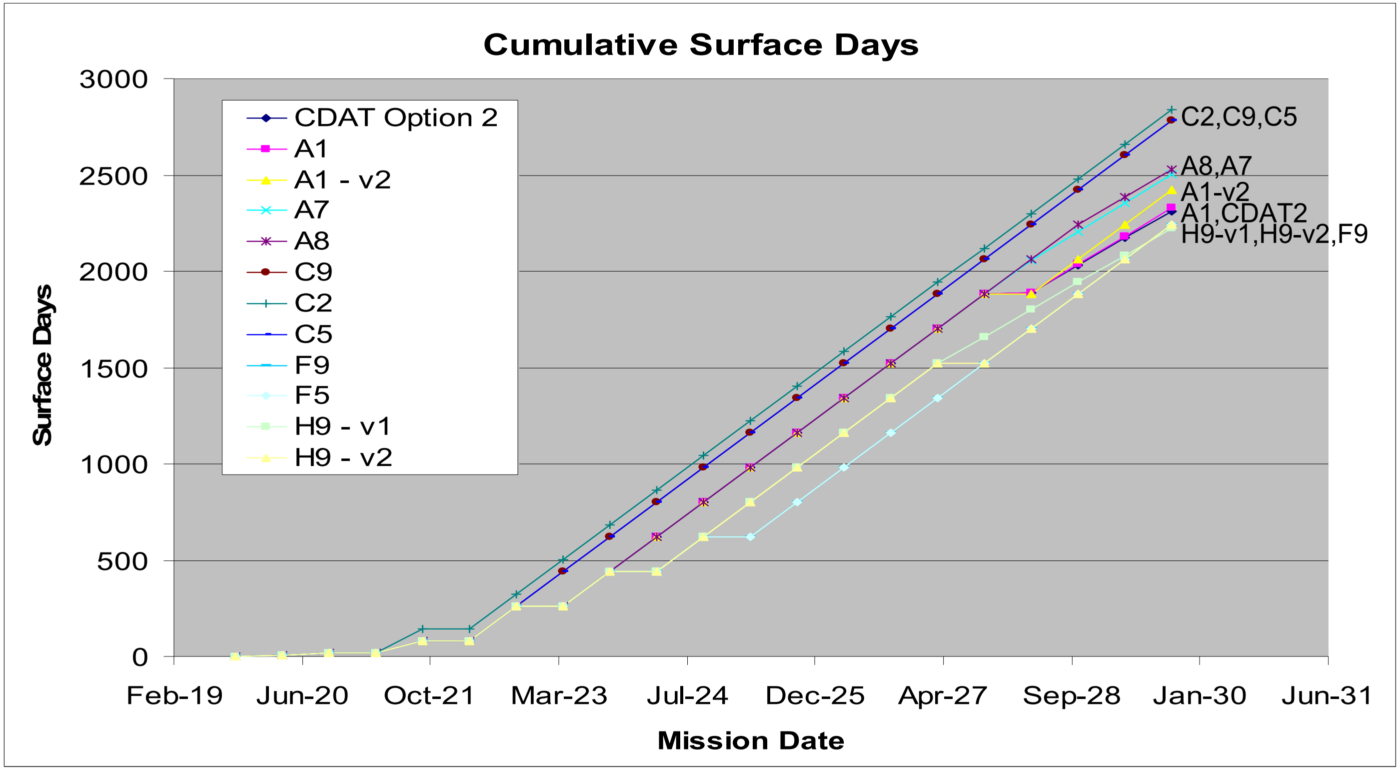
Delta Landed Cargo Mass

- H2O production system break even time is doubled for TA C (Refuel AM for ascent) over O2 production break even time
- H2O break even times for TAs F, I, K comparable to those for O2 production
- H2O break even times for E, G, H, J reduced by 20%-50% compared to O2 break even times

Candidate Campaign Architecture Options

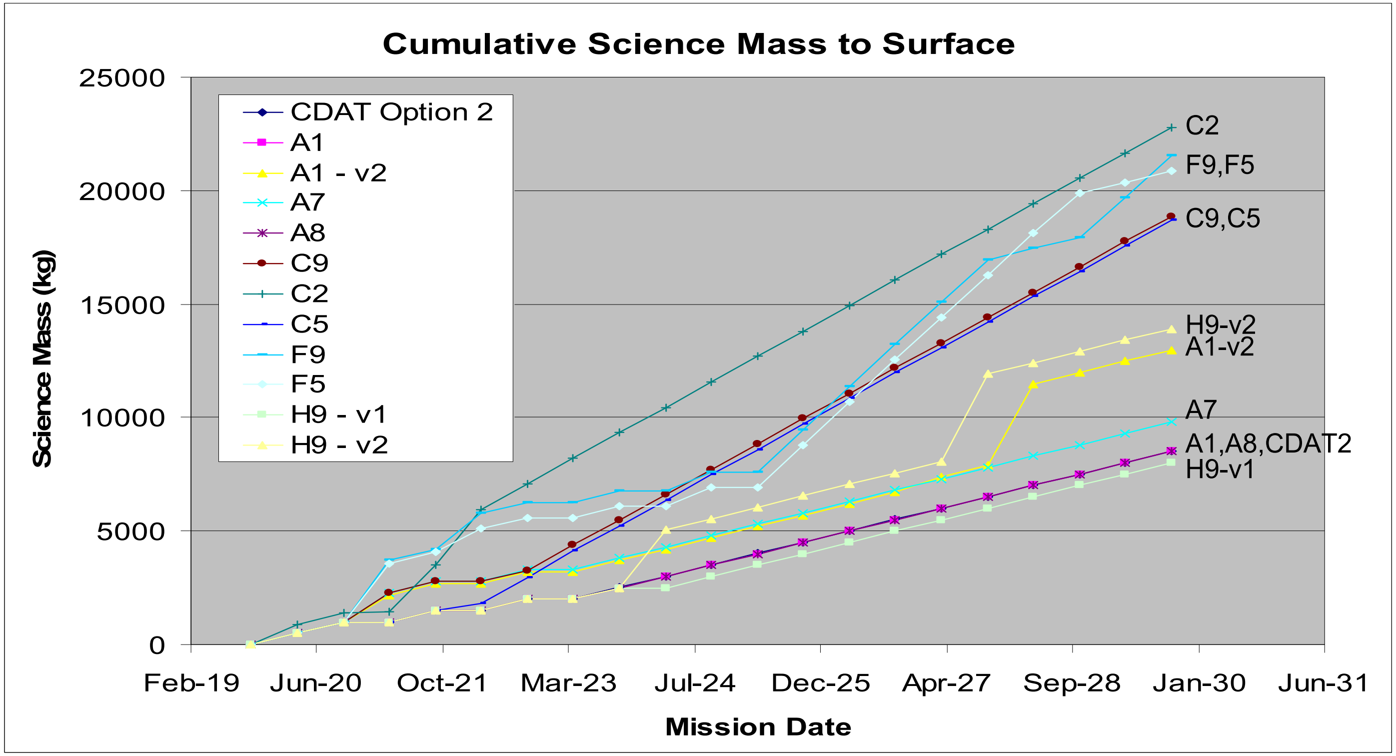
ID	Description	Op #	ISRU Product	ISRU Use(s)	Deployment Schedule	Performance Increase	Rationale for Variation
1	CDAT Campaign 2 ("Baseline")	2	None	N/A	N/A	N/A	Baseline for comparison purposes
2	Campaign 2, Early, Crew Stay	2	O2	ECLS & EVA, TA prop	Early	Crew Stay	Effect of performance allocation on "early" architectures
3	Campaign 2, Early, Single-Launch	2	O2	ECLS & EVA, TA prop	Early	Single-Launch	
4	Campaign 2, Early, Resize LV	2	O2	ECLS & EVA, TA prop	Early	Resize LV	
5	Campaign 2, Late, Crew Stay	2	O2	ECLS & EVA, TA prop	Late	Crew Stay	Effect of performance allocation on "late"
6	Campaign 2, Late, Single-Launch	2	O2	ECLS & EVA, TA prop	Late	Single-Launch	
7	Campaign 2, Early, ECLS/EVA	2	O2	ECLS & EVA	Early	Crew Stay	Effect of deployment schedule for O2 ISRU
8	Campaign 2, Late, ECLS/EVA	2	O2	ECLS & EVA	Late	Crew Stay	
9	Campaign 2, Phased	2	O2	Early: ECLS & EVA Late: TA prop	Phased	Crew Stay	
10	Campaign 2, H2O, Late	2	H2O	ECLS & EVA, TA prop	Late	Crew Stay	Effect of different uses & deployment schedule for H2O ISRU
11	Campaign 2, H2O, Late, Surface Mobility Fuel Cells	2	H2O	ECLS & EVA, Surface mobility fuel cells	Late	Crew Stay	
12	Campaign 2, H2O, Late, Surface Mobility Hoppers	2	H2O	ECLS & EVA, LSAM as hopper	Late	Crew Stay	
13	Campaign 2, H2O, Phased	2	H2O	Early: ECLS & EVA Late: TA prop	Phased	Crew Stay	
14	Campaign 2, H2O, Early, ECLS/EVA	2	H2O	ECLS & EVA	Early	Crew Stay	
15	Campaign 2, H2O, Early	2	H2O	ECLS & EVA, TA prop	Early	Crew Stay	
16	CDAT Campaign 4 (Mobile Landers)	4	None	N/A	N/A	N/A	Baseline for comparison purposes
17	Campaign 4, Late	4	O2	ECLS & EVA, TA prop	Late	Crew Stay	Effect of deployment schedule for Mobile Lander options
18	Campaign 4, Phased	4	O2	Early: ECLS & EVA Late: TA prop	Phased	Crew Stay	
19	Campaign 4, Early	4	O2	ECLS & EVA, TA prop	Early	Crew Stay	
20	CDAT Campaign 6 (Nuclear Reactor)	6	None	N/A	N/A	N/A	Baseline for comparison purposes
21	Campaign 6, Late	6	O2	ECLS & EVA, TA prop	Late	Crew Stay	Effect of deployment schedule for nuclear reactor options
22	Campaign 6, Phased	6	O2	Early: ECLS & EVA Late: TA prop	Phased	Crew Stay	
23	Campaign 6, Early	6	O2	ECLS & EVA, TA prop	Early	Crew Stay	

Combined Architecture Results – Cumulative Surface Days



- Immediate use of ISRU (2019 delivery date) for ascent propellant (C2): 23% increase in surface days
- Late adoption of ISRU (2022 delivery date) for ascent propellant (C5, C9): 20% increase
- 2 mT/yr ISRU plant for ECLSS + LSAM H2 scavenging (A7, A8): 8-9% increase over CDAT Option 2 with 1 mT/yr ISRU plant and no H2 scavenging
- Immediate delivery (2019) of 2 mT/yr ISRU plant shows little benefit over later delivery (2022).
- More aggressive ISRU TAs with reusability and/or orbital depots (F, H) do not show surface time benefit because the time horizon explored (until 2030) is too short to show the potential benefit. However, launches could be eliminated if crew flight durations were permitted to exceed 180 days.
- Flat sections on the graph indicate either a very short crewed mission duration or a cargo launch; more aggressive ISRU TA's may require 1-2 additional cargo launches over CDAT baseline. Refueling AM for ascent (TA C) eliminates one cargo launch.

Combined Architecture Results – Cumulative Science Payload



- Immediate use of ISRU (2019) for ascent propellant (C2): 168% increase in total science payload delivered
- Late adoption of ISRU (2022) for ascent propellant (C5, C9): 120% increase
- 2 mT/yr ISRU plant for ECLSS + LSAM H2 scavenging (A7): 15% increase over CDAT Option 2 with 1 mT/yr ISRU plant and no H2 scavenging
- Immediate delivery (2019) of 2 mT/yr ISRU plant shows little benefit over later delivery (2022). However, benefits of early delivery are large with use of ISRU for ascent propellant (TA C).
- More aggressive ISRU TAs with reusability and/or orbital depots (F, H) do not show much science payload benefit because the time horizon explored (until 2030) is too short to show the potential benefit.
- Large jumps indicate either a crew launch where additional science equipment could be brought rather than exploration equipment or consumables, or a cargo launch with much space available for science payload.
- When only a short mission (e.g. 7 days) is possible due to lack of stockpiled food, etc., it may be beneficial to send a cargo flight instead. This enables longer mission durations in the future, and/or delivery of additional science payload. Cases above where a short-duration crewed mission is replaced by a cargo mission are indicated with “v2” appended to the case number.

Economics Trades and Analysis

Outpost Development Cost Puts and Takes

Some Ops Cost Analyses

Software Costs

ISRU LCC: Some Possible Development Cost Impacts

- ISRU will only sell if it can be shown to address the budget peak that precedes Outpost emplacement (caused by development costs)
- Some *possible* qualitative impacts of ISRU on overall development costs are tabulated here
- Complex relationship: Many aspects of ISRU overlap with development of other outpost elements; ISRU development shares some development costs, displace some, and increase others…

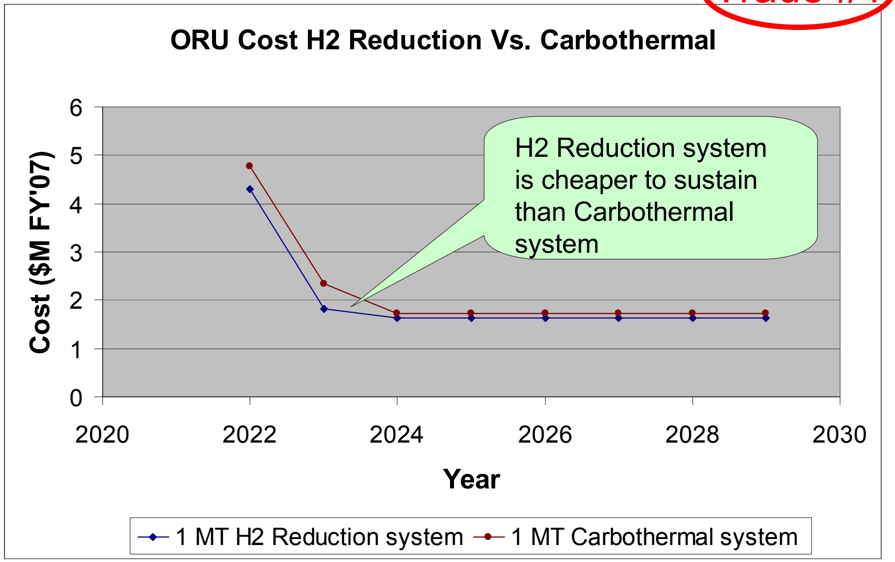
Outpost Element	**Some Possible Impacts of ISRU on Overall Outpost Development Cost**	**Notes**
1-ISRU	**Unavoidable increases due to "PEPSU" ISRU elements development costs**	▪These are heavily architecture-dependent, e.g. less for architectures with mobile landers, more for orbital depots
2-LUNAR LANDERS	**Increases: Reuse/refuelability to retain abort capability** **Decreases: reduction in cargo capacity requirement**	▪Mobile landers have a different set of attributes ▪*Possible* reduced need for investment in Lander manufacturing and ops capability
3-HABITATS	**Decreases: reduced ECLSS closure, shielding replaced by regolith**	▪O2 or O2/H2O
4-POWER /ENERGY	Increases: increased power generation requirement Decreases: avoided solar energy storage	▪.Modular approach may minimize development cost increase ▪.ISRU could provide/share H2O electrolysis; other functions
5-LAUNCH VEHICLES	**Decreases: reduced lift capacity needed**	*Possible* reduced need for investment in LV manufacturing and ops capability
6-SURFACE C3/NAV	**Increases: increased surface ops complexity-> more C3 & Nav capability**	
7-SURFACE MOBILITY	Decreases: improved performance per DDT&E dollar via ISRU reactant(s)	ISRU-powered fuel cells vs. batteries (?)
8-SCIENCE CAPABILITY	Decreases: shareable assets for ISRU prospecting and science of condensed volatiles	Premise is that SMD might help develop

Operations Cost Analysis Process

- Method: Use Exploration Architectures Operations Cost Model (ExAOCM)
  - Evolved from ISS operations model (MESSOC), Model Lead: Robert Shishko
  - Incorporates spares-modeling capability derived from SpaceNet (logistics model also led by Robert Shishko.)
- Data collected:
  - Flight Manifest for LAT Option 2
  - Elements characteristics from MEL for each ISRU implementation option
  - Outpost Replacement Units (ORUs) characteristics
  - Human EVAs involved in sustaining operations
  - Additional data (e.g. ECLSS MEL and ORU data)
- Trades performed (numbered on following slides):
  1. Compare H_2 Reduction vs. Carbothermal 1 MT systems
  2. Compare 1, 5, 10 & 50 MTs H_2 Reduction
  3. 5 x 1 MT H_2 Reduction vs. 1 x 5 MT H_2 Reduction
  4. Reduce flight rate and extend crewed mission duration
- Analysis of Trades 1-3 provides useful information for making design decisions about ISRU system construction
- Analysis of Trade 4 demonstrates cost reductions potentially enabled by ISRU

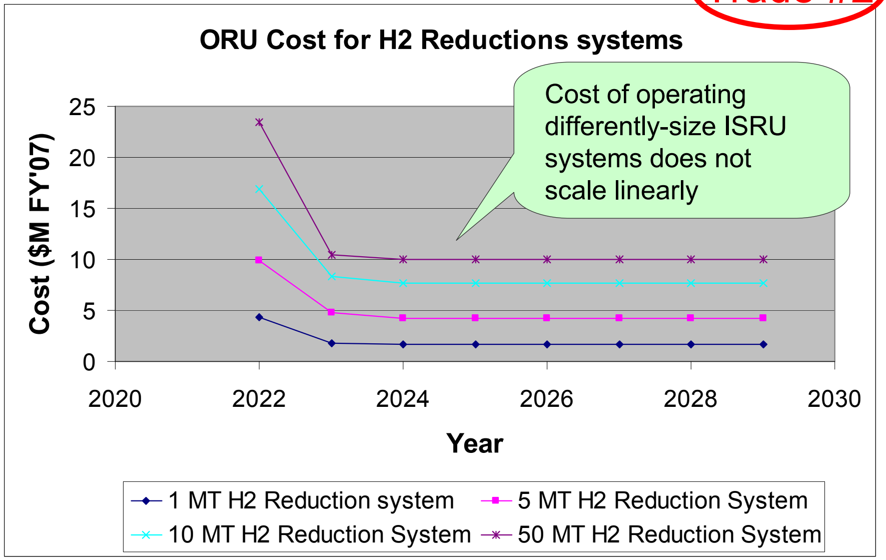
Operations Cost Results (1 of 2)

Trade #1


ORU Cost H2 Reduction Vs. Carbothermal

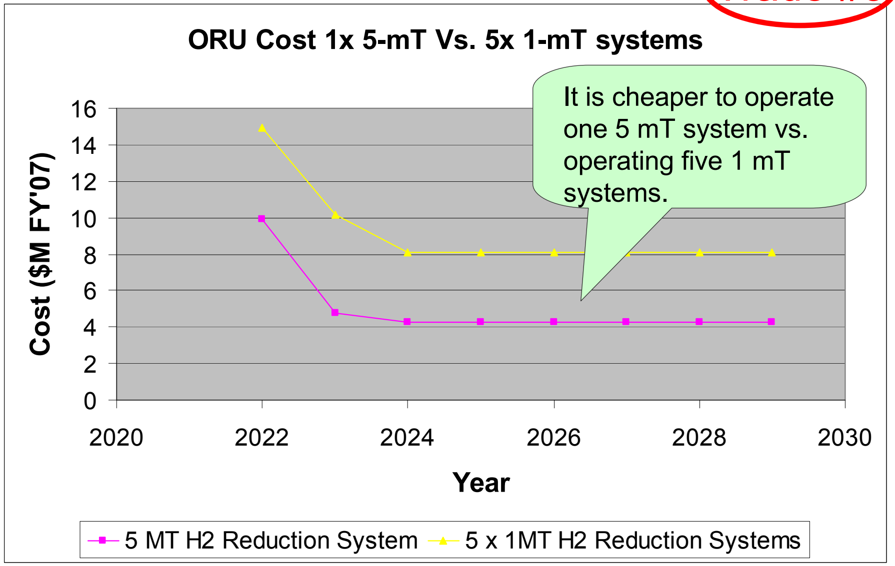
H2 Reduction system is cheaper to sustain than Carbothermal system

Trade #2


ORU Cost for H2 Reductions systems

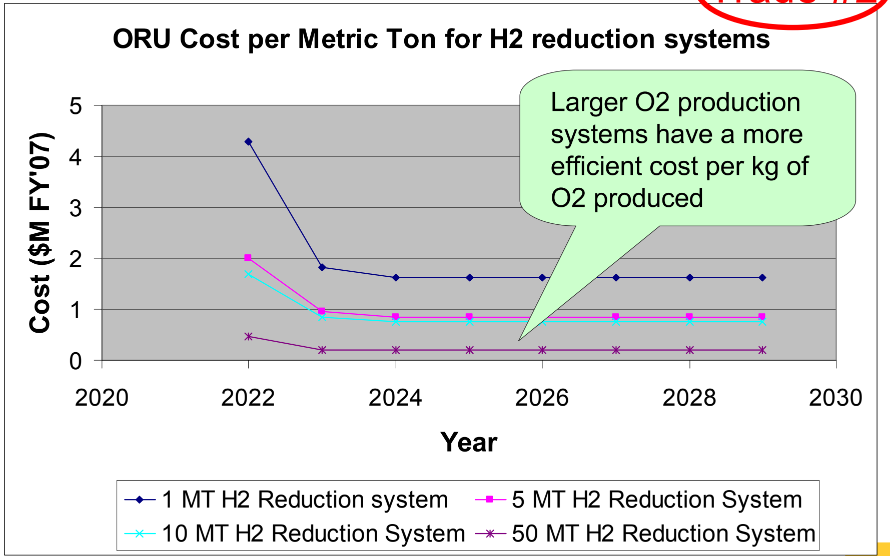
Cost of operating differently-size ISRU systems does not scale linearly

Trade #3


ORU Cost 1x 5-mT Vs. 5x 1-mT systems

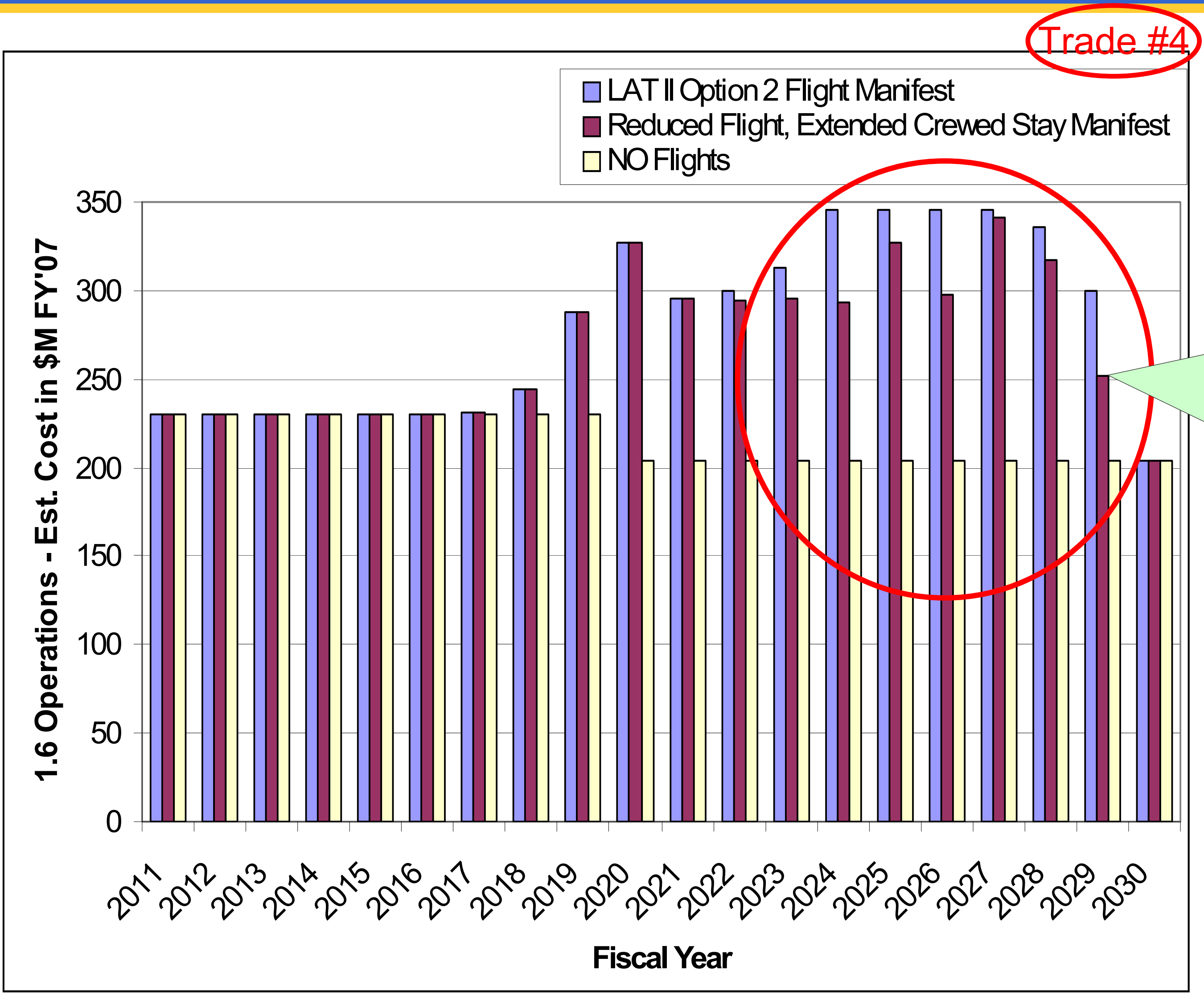
It is cheaper to operate one 5 mT system vs. operating five 1 mT systems.

Trade #2


ORU Cost per Metric Ton for H2 reduction systems

Larger O2 production systems have a more efficient cost per kg of O2 produced

Operations Cost Results (2 of 2)



ISRU enabled flight reduction and longer crew stays result in operational cost savings.

Notes:

- Flight rate was reduced from every 6 months to every 8 months
- Cost savings largely from reduced astronaut training

ISRU Software Cost Estimating Methodology

- **Obtained historical software size and effort data for analogous estimating (in priority order)**
  - Primary data source – JPL/NASA Centers
  - NASA contractors
  - Industry data
- **Used parametric software cost and schedule estimating models (SEER-SEM) to estimate the software development cost**
  - Minimal data required to create estimates
  - Used default Knowledge Bases
  - Provides quick turnaround (to support trade studies)
  - Can be calibrated to project-specific data
  - Well established and accepted within NASA
- **Used the JPL-developed ExAOCM model to estimate the annual software maintenance cost**
- **Documented groundrules and assumptions**
- **Provided analysis and results**

Study Results and Conclusions

Architecture Conclusions

Transportation Architectures

- ISRU can significantly increase the landed payload to the surface
  - By a factor of 1.3-2.5x the baseline for baseline cargo capability (6 mT) and a factor of 3.4-11x with reduced lander cargo capability (0.7 mT)
  - C (refueling AM on surface) increases payload capability by >50% (6 mT lander) or up to 500% (0.7 mT lander)
  - With reduced lander cargo capability induced by the Manager's Reserve, ISRU becomes an enabling technology
- Surface refueling for ascent (C) provides fewest flights to break-even at 2 flights.
- H_2O production systems enable 10%-100% increase of lander cargo capability over those enabled by O_2 production
- H_2O production systems mostly have comparable or improved break-even times over O_2 production scenarios

Combined Architectures

- 2 mT/yr ISRU plant for ECLSS + LSAM H_2 scavenging provides significant benefits
  - 8-9% increase in crew stay time
  - Up to 15% increase in science payload
- Refueling AM on surface provides significant increases in crew stay and science payload
  - 23% more crew stay time
  - 168% more science payload
- Inclusion of lunar orbit propellant depot can significantly increase payload and Outpost sustainability beyond the 2030 timeframe, and possibly decrease launches by increasing maximum sustainable crewed mission duration

Economics Conclusions

Operations Costs

- Operations costs can be lowered by:
    - Choosing H2 Reduction ISRU rather than Carbothermal ISRU
    - Operating a smaller number of large ISRU systems rather than a larger number of small ISRU systems
    - Reducing the flight rate of crewed missions (e.g 3 missions every 2 years)

Software Development & Maintenence

- ISRU software development would cost ~$35M and software maintenance would cost ~$3M/yr

Life Cycle Costs

- Lack of an integrated outpost life cycle cost model led to an inability to model life-cycle costs as a whole – therefore this study is unable to conclusively understand the economic impact of ISRU on the Lunar Exploration Outpost.

- **Until we're able to develop a useful life cycle costing capability, the full potential of ISRU will be difficult to adjudge.**

ISRU & Uncertainty

ISRU UNCERTAINTIES

- **One KISS way to look at uncertainties:**

F = B P / C, where

F = Feasibility ~ expected return / investment ; should be greater than one for any investment

B = Benefit associated with employing ISRU , eg launch mass savings or IMLEO saved or additional useful cargo landed for given # of launches, and/or avoided development costs, if any (eg, less closed ECLSS)

– **You've seen some of our results regarding the potential benefits -- the "B's"**

P = Probability of capturing that benefit

C = Cost of capturing the benefit, eg cost of ISRU system development & operation over the benefit period; includes additional non-ISRU costs as consequence of ISRU, eg more complex surface ops.

ISRU UNCERTAINTIES, cont

- **P can't be higher than one; what can it be?**

- **Assume P ~ f (Pr, Pp, 1- Pf)**
  - **Pr = probability that resource is available in quantities and concentrations assumed**
  - **Pp = probability that ISRU system performs as designed (efficiency, life, maintainability)**
  - **Pf = Probability that system fails "un-gracefully", eg with LOM or LOC possibilities**
  - **RIGHT NOW:**

Probability	H2O Based	Regolith-based
Pr	Lo	Med
Pp	Med	Lo
1-Pf	**Med-Lo** **Architecture dependent** (Pf ~ complexity)	**Med -Lo** **Architecture dependent** (Pf ~ complexity)
P	too low…	too low…

REDUCING ISRU UNCERTAINTIES

- **INCREASING P:**
  - **Increasing Pr (probability that resource is available in quantities and concentrations assumed):**
    - **“Prospecting”: eg robotic and/or crewed activities to carry out surface and subsurface measurements**
  - **Increasing Pp (probability that ISRU system performs as designed (efficiency, life, maintainability)):**
    - **System Modeling, Testing on Earth, and Testing on the Moon**
  - **Decreasing Pf (probability that system fails “un-gracefully”, eg with LOM or LOC possibilities):**
    - **Architecture Trades to balance complexity , cost and benefit; Modeling and Testing; Evolutionary growth in complexity**
    - **The right way to do this: Look at overall risk-- eg, small, simple ISRU system decreases Pf, but more complex, larger system with higher Pf can reduce LOM, LOC by reducing number of launches needed…**