Modeling Lunar Partnerships for the NASA Emerging Space Office

Brad R. Blair
NewSpace Analytics

12 June, 2018

Space Resources Roundtable, Colorado School of Mines, Golden, Colorado, 12-15 June, 2018

Status Update

The NASA Emerging Space Office (ESO) selected a proposal entitled **PPP framework for multi-commodity lunar ISRU** for award under NRA Solicitation NNA15ZBP0001N-B1.

PI: Brad Blair
Co-I: David Cheuvront
Consultants: Hoyt Davidson and Hannah Rens

The Current Opportunity

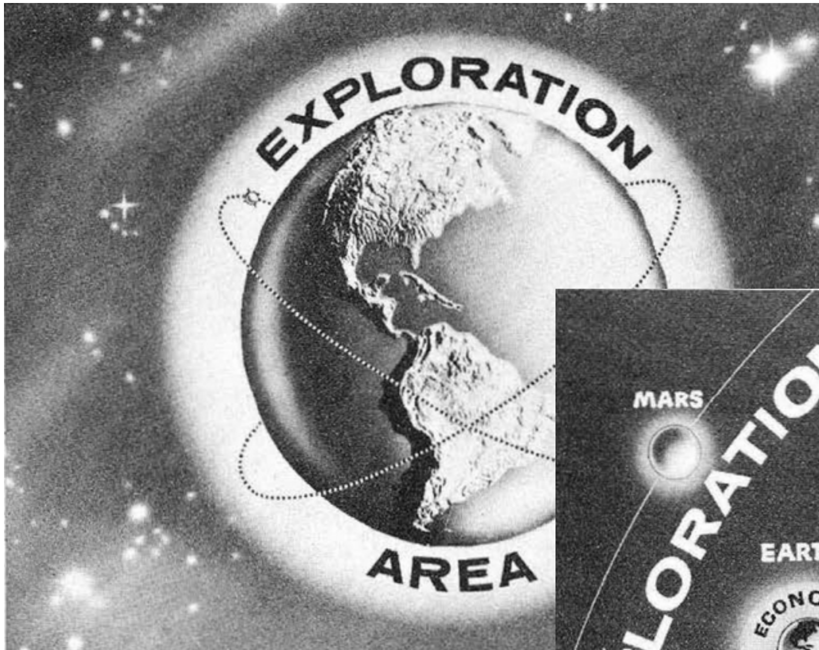
A robust, ***private-sector commercial lunar ecosystem*** will prove invaluable to NASA, *provisioning* propellant, life support consumables and other *materials* to NASA as one customer among many. This would *increase the robustness* of NASA's human space exploration missions by providing sustainable, affordable, complementary options that *reduce* NASA's science and spaceflight *costs*.

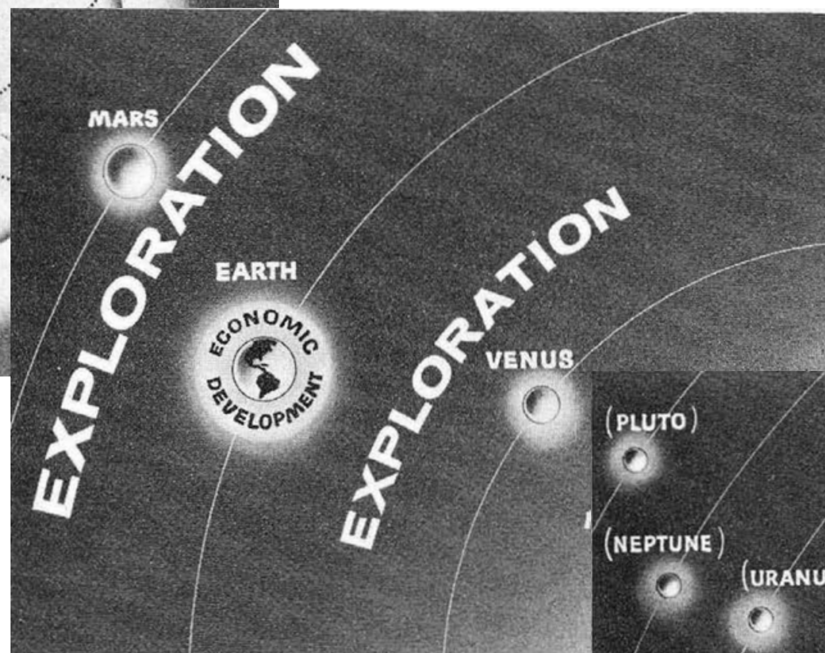
A commercial-off-the-shelf approach could also ***lower the risk of NASA program failure and/or requirements creep*** that typically accompanies cyclical regime change – which is especially troubling for long duration programs (indeed, a lack of fully considering economic factors may be the leading cause of agency regime change).

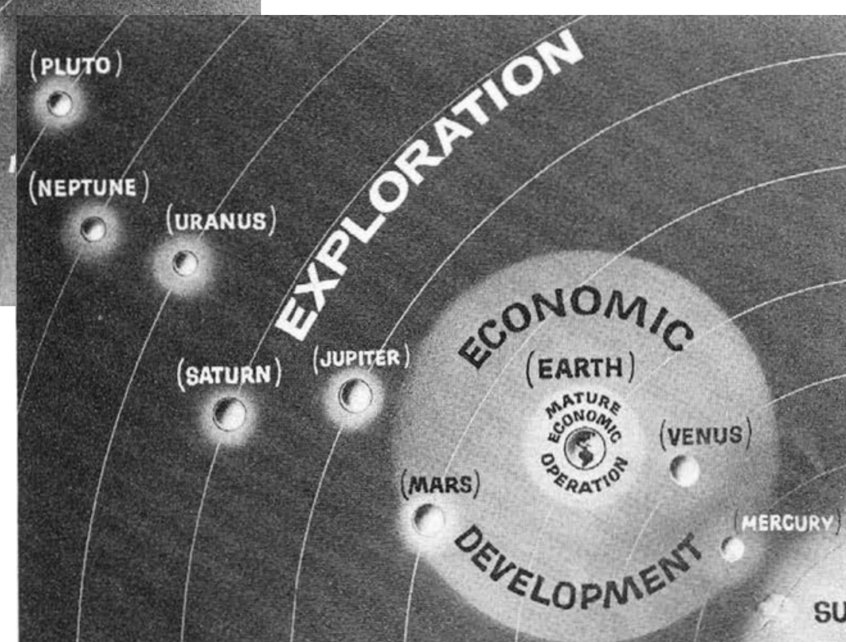
There is a sense of urgency: We have 2.5 years until the next potential reset (remember - three strikes and you are out).

ISRU Enables Economic Expansion

Ralph Cordiner, 1961







https://denniswingo.wordpress.com/2014/04/01/the-economic-development-of-the-solar-system-lessons-from-1961/

Maximizing PPP Benefits

Public Benefits
-Ops Risk Reduction (consumables + propellant)
-Lower Costs (off-budget capital)
-Programmatic Risk Reduction (Insurance)

Constellation, Circa 2007

Private Benefits
-Economic Profit
-Historical Legacy
-Risk Appetite (aggression)

Ichthyostega, Circa 374–359 Ma

Study Objectives

Primary Study Objective:

- Build and utilize a *commercial lunar mining* model to **estimate the effectiveness of PPP scenarios in *accelerating* lunar development**

Secondary Objectives:

- Examine lunar resource *byproduct scenarios* that may be synergetic or of low incremental cost to obtain high economic benefit
- Identify comparisons to *terrestrial mining* activities, where byproducts often generate more operating profit than the primary commodity

Stretch goal: This work could also *generate a method* to steer near term prospecting and ISRU technology demonstration missions toward ‘commercially useful results’ by using a risk analysis framework to ‘buy down’ uncertainty

The Challenge

What makes you think you can do all of that?

- We had a head start
- We have a pretty good network to ask for help
- We kept the “core innovation” simple
- We have a really good team
- We have a really good reason to do it

Motivation

- We could wait and ask for a proper budget to 'do the job right'
- It might delay PPP readiness for another year or more
- We need to act fast to converge and move forward (three strikes)
- A motivated and capable team can often make big progress

The Team

Core Team

- Brad Blair
  - Built first commercial ISRU model in 2002
  - Background in mining and economics
- Dave Cheuvront
  - 40+ years aviation & space, retired NASA, multi-disciplines
  - ISS development, R&M, T&V; exploration system engineering, S&MA
- Hannah Rens
  - 2x SSDC winner, UT Austin Sophomore
- Hoyt Davidson
  - Near-Earth LLC, 400p. report in 2010 on Commercial Space
  - Investment banking / private equity experience in commercial satellite industry

Extended Team

- Space Portal: Lynn Harper, Bruce Pittman, Allison Zuniga
- Space Settlement Specialist Anita Gale
- LaRC Roger Lepsch (landers & space transport)
- KSC Edgar Zapata (commercial costing)
- Tony Muscatello, Nathan Davis, Larry Baxter (chemical engineering / extractive metallurgy)
- George Sowers (lunar mining systems design / commercial landers)
- Guest Appearances: Dan Rasky, John Patterson, Richard Godwin, Geoff Sheerin, Daniel Faber, Jim Keravala, Bernard Kutter, Dennis Stone, Angel Abbud-Madrid, Bruce Cahan, Koki Ho

The Head Start

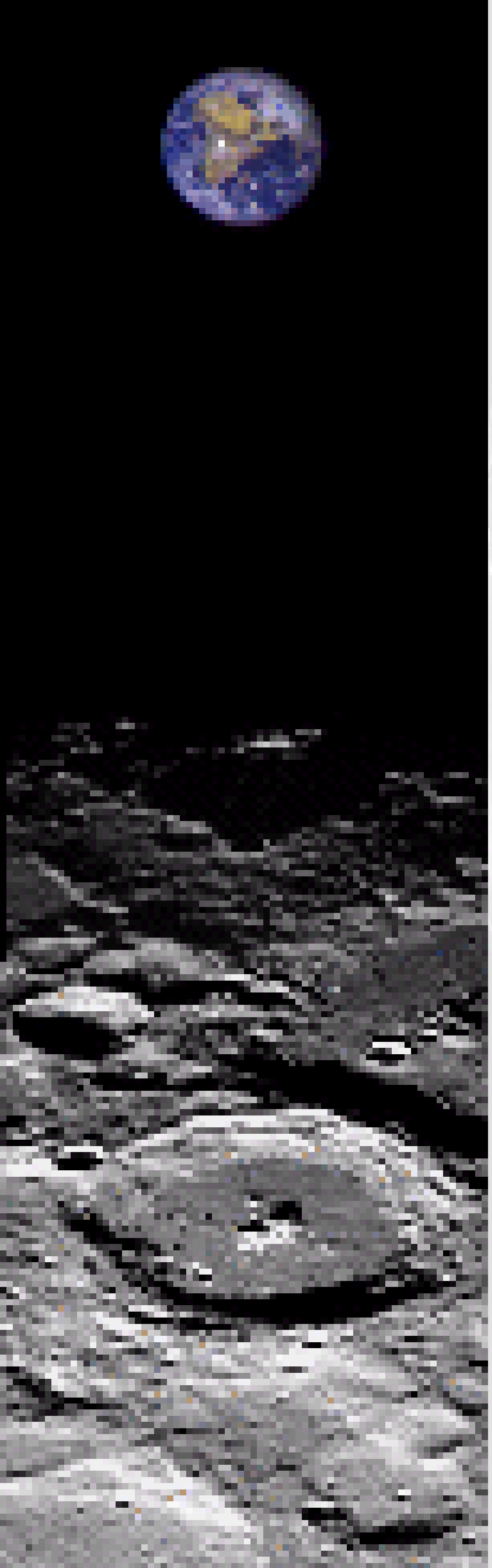
FY02 Lunar ISRU Economic Model (CSM – Mike Duke)

- Solved for feasible conditions for *lunar commercial investment*

FY04 RASC ISRU Study

- Two NASA Centers
- Two Universities
- Canadian Team
- Multiple Consultants

- Absorbed into CE&R / VSE



The Case for Commercial Lunar Ice Mining

by

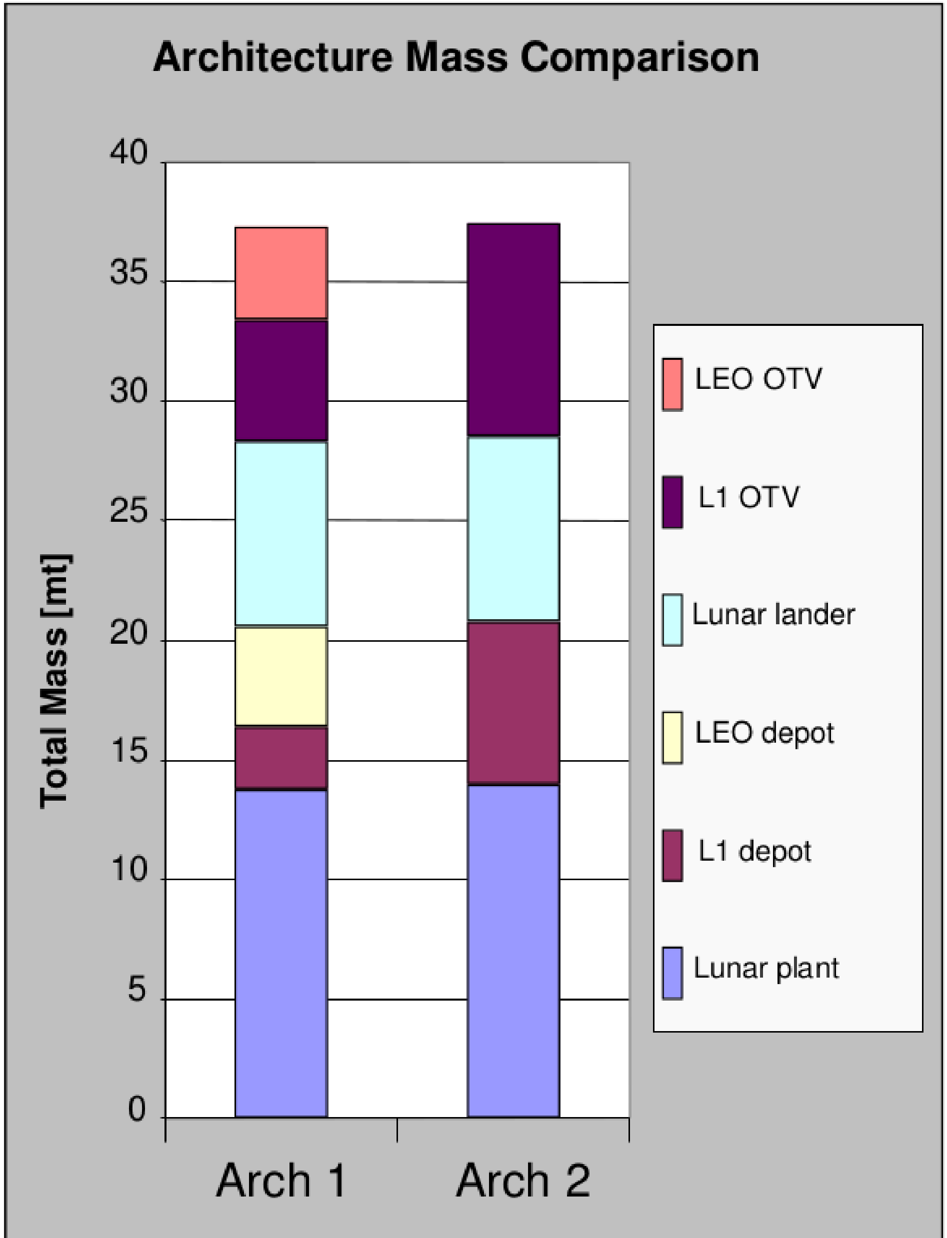
Brad R. Blair, Javier Diaz, Michael B. Duke,
Center for the Commercial Applications of Combustion in Space, Colorado School of Mines, Golden, Colorado

Elisabeth Lamassoure, Robert Easter,
Jet Propulsion Laboratory, Pasadena, California

Mark Oderman, Marc Vaucher
CSP Associates, Inc., Cambridge, Massachusetts

December, 2002

Parametric Engineering Model



Technology assumptions

Cryogenic Vehicles (H_2/O_2 fuel)
- Lunar Lander
- Orbital Transfer (OTV)

Fuel Depot(s)
- Solar Power
- Electrolysis (fuel cell)
- Tanks for H_2, O_2 and H_2O

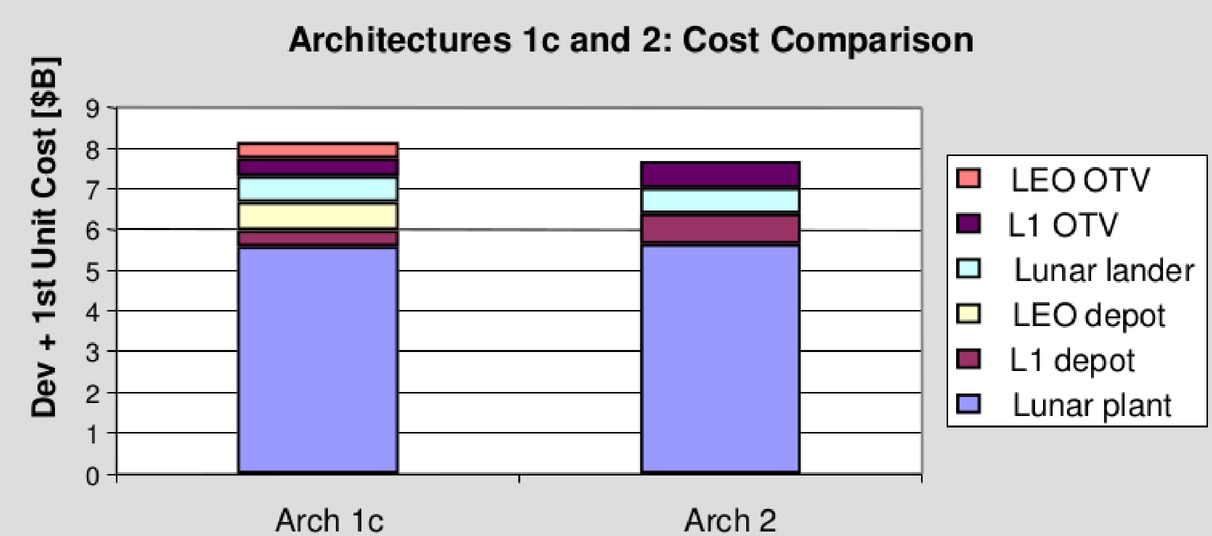
Vehicle	mass (kg)
Moon - L1 (Lander / fuel carrier)	**7869**
Propulsion system	2180
Telecomm	10
water storage (0.01%)	256
C&DH	3
Structures	3482
Power	15
Landing System	1801
L1-LEO-L1 Vehicle (fuel carrier)	**1424**
Propulsion system	636
Telecomm	10
water storage (0.01%)	200
C&DH	3
Structures	560
Power	15
L1-LEO Aerobrake	3214
LEO-GEO-LEO Vehicle (payload transport)	**3422**
Propulsion system	1362
Telecomm	10
C&DH	3
Structures	2032
Power	15
LEO-GEO-LEO Aerobrake	513
L1-LEO-L1 Vehicle (fuel carrier)	**5431**
Propulsion system	2088
Telecomm	10
C&DH	3
Structures	3315
Power	15
LEO-L1-LEO Aerobrake	3504

	ARCH 1	ARCH 2
Lunar Surface Plant	Mass (kg)	Mass (kg)
Excavators	210	272
Haulers	273	354
Extractors	2099	2724
Electrolyzers	564	732
Hydrogen liquefiers	19	24
Hydrogen liquefier radiators	326	423
Oxygen liquefiers	70	91
Oxygen liquefier radiators	100	130
Water tanks	554	554
Hydrogen tanks	497	497
Oxygen tanks	2119	2119
Aerobrake production system	0	0
Power system (nuclear)	2624	3405
Ancillary equipment (25% of total)	2364	2832
Total	11820	14158
Annual refurbishment	660	847
L-1 Fuel Depot	Mass (kg)	Mass (kg)
Electrolyzers	195	690
Hydrogen liquefiers	18	63
Hydrogen liquefier radiators	308	1092
Oxygen liquefiers	66	235
Oxygen liquefier radiators	66	235
Water tanks	316	368
Hydrogen tanks	193	613
Oxygen tanks	823	2616
Power system (solar)	72	255
Ancillary equipment	206	617
Total	2264	6783
Annual refurbishment	86	293
LEO Fuel Depot	Mass (kg)	Mass (kg)
Electrolyzers	673	0
Hydrogen liquefiers	22	0
Hydrogen liquefier radiators	389	0
Oxygen liquefiers	84	0
Oxygen liquefier radiators	84	0
Water tanks	180	0
Hydrogen tanks	299	0
Oxygen tanks	1277	0
Power system (solar)	91	0
Ancillary equipment	310	0
Total	3409	0
Annual refurbishment	170	0

Cost Model Development

- NAFCOM99: Analogy-based cost model
  - Architecture 2 WBS shown on right panel
  - Conservative methodology used (to model worst-case results)
- SOCM: Operations cost model
  - Estimates system-level operating costs
  - Conservative methodology used
  - Hardware replacement at 10%/yr
- Launch Costs: $90k/kg Moon, $35k/kg GEO, $10k/kg LEO

SRD Architecture 2 Cost Model ($M FY02 NAFCOM Estimate)	Mass (kg)	D&D	STH	FU	Prod	Total Cost
GRAND TOTAL	37470.2	5393.2	1018.1	1264.5	1264.5	7675.8
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	13980.7	3972.1	750.5	927.1	927.1	5649.7
SYSTEM 2: L1 Depot	6806.8	569.1	74.2	93.8	93.8	737.1
SYSTEM 3: Lunar Lander	7747.8	446.8	83.5	105.4	105.4	635.7
SYSTEM 4: OTV (LEO-GEO-L1)	8934.8	405.2	109.8	138.2	138.2	653.2



SRD Architecture 2 Cost Model ($M FY02 NAFCOM Estimate)	Mass (kg)	D&D	STH	FU	Prod	Total Cost
GRAND TOTAL	37470.2	5393.2	1018.1	1264.5	1264.5	7675.8
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	13980.7	3972.1	750.5	927.1	927.1	5649.7
HARDWARE TOTAL	13980.7	1861.6	750.5	577.3	577.3	3189.5
Regolith Excavator	274.0	19.5	17.7	13.6	13.6	50.8
Structure	68.5	8.2	5.7	4.4	4.4	18.3
Mobility	68.5	3.9	6.4	4.9	4.9	15.3
Excavation	68.5	0.8	1.4	1.1	1.1	3.3
Soil Handling	65.5	6.1	3.7	2.8	2.8	12.6
CC&DH	3.0	0.5	0.4	0.3	0.3	1.3
Regolith Hauler	356.0	27.7	25.5	19.6	19.6	72.8
Structure	117.7	10.0	6.7	5.2	5.2	22.0
Mobility	117.7	5.3	9.3	7.2	7.2	21.8
Soil Handling	117.6	11.0	8.3	6.4	6.4	25.8
CC&DH	3.0	1.3	1.1	0.9	0.9	3.3
Thermal Extraction	2736.9	602.3	24.1	18.5	18.5	644.8
Water Electrolysis	736.0	90.6	38.2	29.4	29.4	158.2
Hydrogen Liquefier	25.0	2.9	0.6	0.4	0.4	3.9
Hydrogen Liquefier Radiators	425.0	26.9	1.6	1.3	1.3	29.8
Oxygen Liquefier	92.0	5.6	1.6	1.2	1.2	8.4
Oxygen Liquefier Radiators	131.0	14.9	0.6	0.5	0.5	16.1
Water Tanks	520.0	7.0	1.0	0.8	0.8	8.7
Hydrogen Tanks	469.0	6.6	0.9	0.7	0.7	8.2
Oxygen Tanks	1999.0	14.6	2.2	1.7	1.7	18.6
Power System (Nuclear)	3420.9	565.1	442.7	340.5	340.5	1348.3
Maintenanace Facility	1000.0	374.1	152.6	117.4	117.4	644.0
Mobility	200.0	78.9	10.4	8.0	8.0	97.3
Sensors	200.0	140.2	51.7	39.8	39.8	231.6
Manipulators	200.0	7.1	13.5	10.4	10.4	31.1
CC&DH	200.0	108.6	61.3	47.1	47.1	217.0
Spare Parts	200.0	39.4	15.6	12.0	12.0	67.0
Ancillary Equipment	1796.0	103.9	41.3	31.7	31.7	176.9
SYSTEM INTEGRATION		2110.5		349.7	349.7	2809.9
SYSTEM 2: L1 Depot	6806.8	569.1	74.2	93.8	93.8	737.1
HARDWARE TOTAL	6806.8	280.3	74.2	57.1	57.1	411.6
Water Electrolysis	692.0	154.4	48.7	37.4	37.4	240.5
Hydrogen Liquefier	63.0	4.6	1.2	0.9	0.9	6.7
Hydrogen Liquefier Radiators	1096.0	43.2	3.5	2.7	2.7	49.4
Oxygen Liquefier	236.0	8.9	3.4	2.6	2.6	14.9
Oxygen Liquefier Radiators	236.0	20.1	1.0	0.8	0.8	21.9
Water Tanks	369.0	5.8	0.8	0.6	0.6	7.2
Hydrogen Tanks	615.0	7.6	1.1	0.8	0.8	9.6
Oxygen Tanks	2624.9	17.0	2.6	2.0	2.0	21.6
Power System (solar)	256.0	2.7	5.3	4.1	4.1	12.2
Ancillary Equipment	619.0	15.9	6.6	5.1	5.1	27.6
SYSTEM INTEGRATION		288.8		36.7	36.7	362.3
SYSTEM 3: Lunar Lander	7747.8	446.8	83.5	105.4	105.4	635.7
HARDWARE TOTAL	7747.8	208.1	83.5	64.2	64.2	355.9
Propulsion System	2180.0	56.4	24.9	19.2	19.2	100.5
Water Tanks	239.0	4.5	0.6	0.5	0.5	5.7
CC&DH	13.0	1.6	1.5	1.1	1.1	4.2
Structure	3481.9	68.8	42.4	32.6	32.6	143.8
Power	15.0	7.2	0.2	0.1	0.1	7.5
Landing System	1819.0	69.6	14.0	10.8	10.8	94.4
SYSTEM INTEGRATION		238.6		41.2	41.2	321.0
SYSTEM 4: OTV (LEO-GEO-L1)	8934.8	405.2	109.8	138.2	138.2	653.2
HARDWARE TOTAL	8934.8	173.2	109.8	84.5	84.5	367.5
Propulsion System	2088.0	55.1	24.3	18.7	18.7	98.0
CC&DH	13.0	1.6	1.5	1.1	1.1	4.2
Structure	3314.9	67.0	40.9	31.5	31.5	139.4
Power	15.0	7.2	0.2	0.1	0.1	7.5
Aerobrake	3503.9	42.4	43.0	33.1	33.1	118.4
SYSTEM INTEGRATION		232.0		53.7	53.7	339.5

FY02 Commercial ISRU Model Feasibility

Table 4.2. Model versions relative to baseline.

Version	Description	Summary
0	Architecture 1&2 Baseline. All assumptions set to most conservative level.	Baseline
1	Baseline w/ No Non-Recurring Investments. (assumes that the public sector pays for design, development and first unit cost)	Remove DDT&E from Baseline
2	No Non-Rec. Investments + Reduce the production cost of all elements by 30%.	Add 30% Production Cost Reduction
3	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith from 1% to 2%.	Add 2x Lunar Water Concentration
4	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith + Double demand.	Add 2x Demand
5	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith + Double demand + Price Increase	Add 1.25x Price

Table 4.3. Model results (key financial metrics) by version for Architectures 1 and 2.

	Year 1 Return on Equity		Project Rate of Return		Net Present Value	
	Arch 1	Arch 2	Arch 1	Arch 2	Arch 1	Arch 2
Version 0	N/A	N/A	N/A	N/A	$ (5,275)	$ (5,006)
Version 1	-30.3%	-30.5%	-11.9%	-11.9%	$ (553)	$ (561)
Version 2	-9.8%	-10.1%	-5.0%	-5.2%	$ 255	$ 240
Version 3	-2.3%	1.6%	-1.7%	-0.3%	$ 593	$ 726
Version 4	15.0%	15.2%	6.2%	5.9%	$ 2,484	$ 2,461
Version 5	26.1%	26.3%	12.8%	12.6%	$ 4,156	$ 4,134

FY04 Space Transportation Architecture Based On ISRU Supplied Resources Study

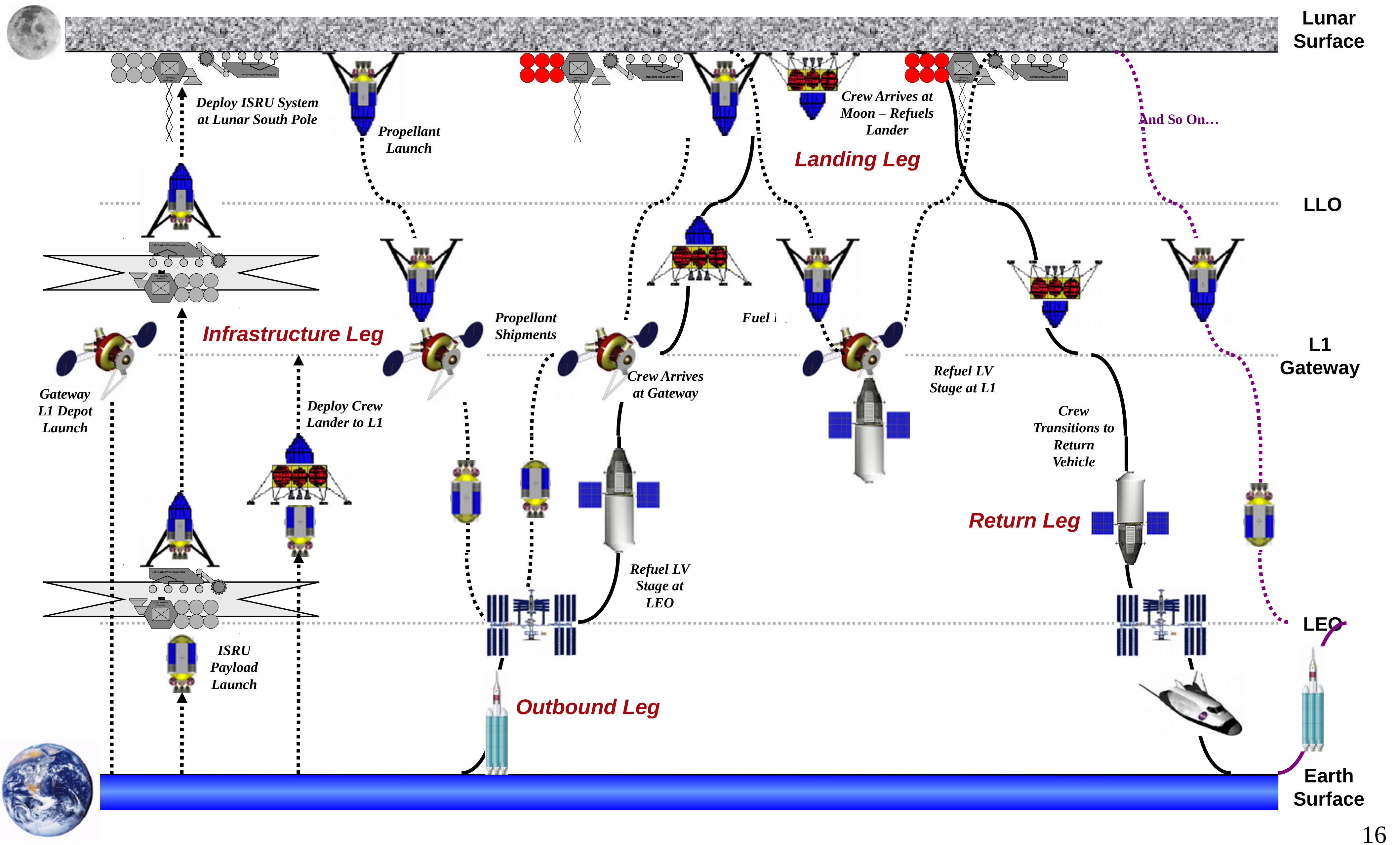
Scott Baird,
Kris Romig,
Jerry Sanders
JSC

January 2004

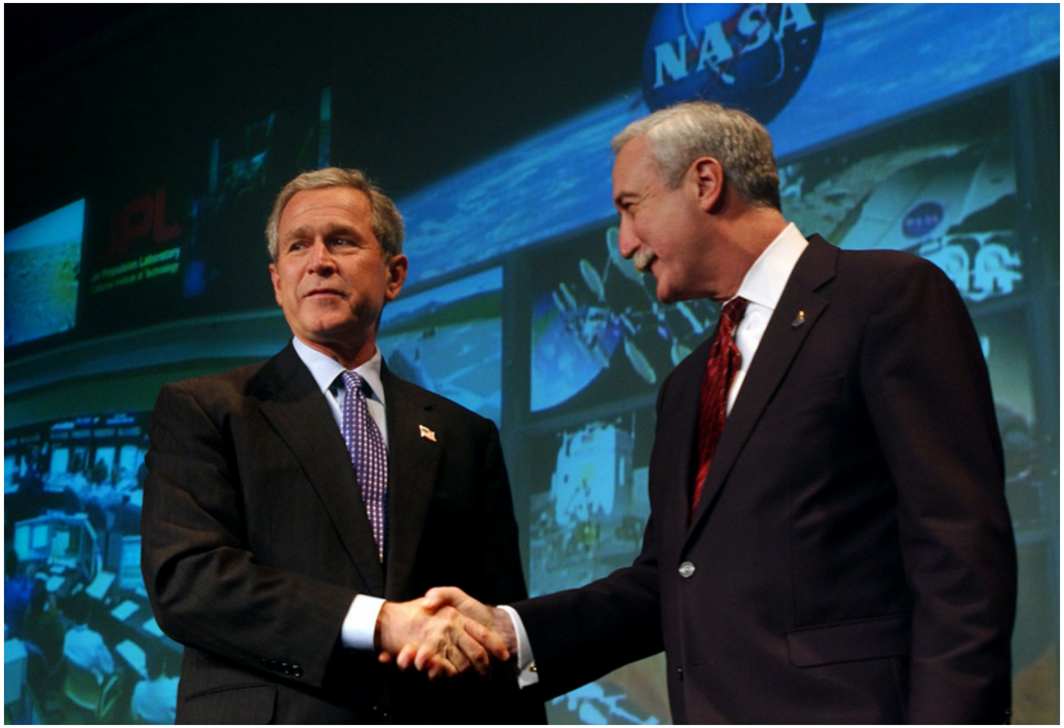
FY04 Executive Summary

- **Project Title:** **Space Transportation Architecture Based On ISRU Supplied Resources Study**
- **Purpose**
  - Identify ISRU-based space transportation scenarios and compare them to Earth supplied scenarios to provide architecture trade crossover points for cost, mass, and schedule
  - Identify architecture sensitivities and drivers
  - Identify key technology needs/drivers to help prioritize ISRU technology development
- **Scope**
  - Develop & model ISRU production and product transportation and storage architecture options
  - Define & model elements for space transportation architecture options
  - Define & evaluate emplacement and buildup scenarios
  - Model & evaluate architecture option operations, costs, and business/commericial potential
  - Perform technology driver and cost analysis sensitivity studies
- **Study Summary: Preliminary Findings & Conclusions**
  - Development of ISRU and transportation elements still in work (study end date 6/04)
  - Earth-Moon L1 point is most optimal position for propellant depot for Earth orbit satellite servicing and satellite delivery tugs from Low Earth Orbit (LEO) to Geostationary Orbit (GEO)
  - Commercial potential of combined ISRU propellant/L1 Depot could significantly influence architecture and reduce cost to NASA
- **Application to NASA Future Mission Needs**
  - ISRU and transportation element concepts, models, and databases developed in this study can be applied to future Design Reference Missions (DRMs)
  - In-situ production of mission critical consumables (propellants, life support, fuel cell reagents, science gases) provides early mission benefits with minimal infrastructure requirements

FY04 Lunar ISRU Architecture



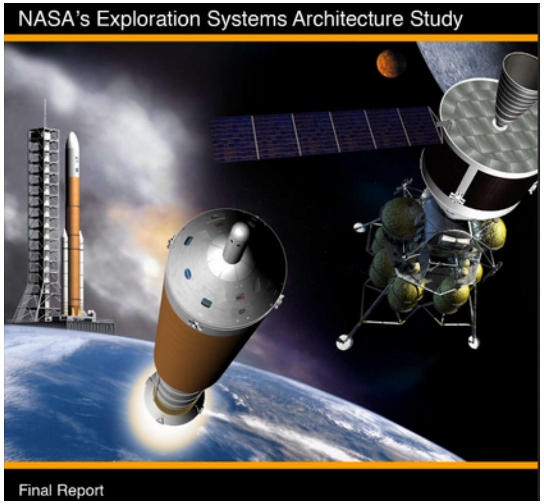
2004 Vision for Space Exploration



http://www.spudislunarresources.com/blog/the-vision-for-space-exploration-a-brief-history-part-1/

Concept Evaluation & Refinement

11 Teams
4x ISRU-centric architectures



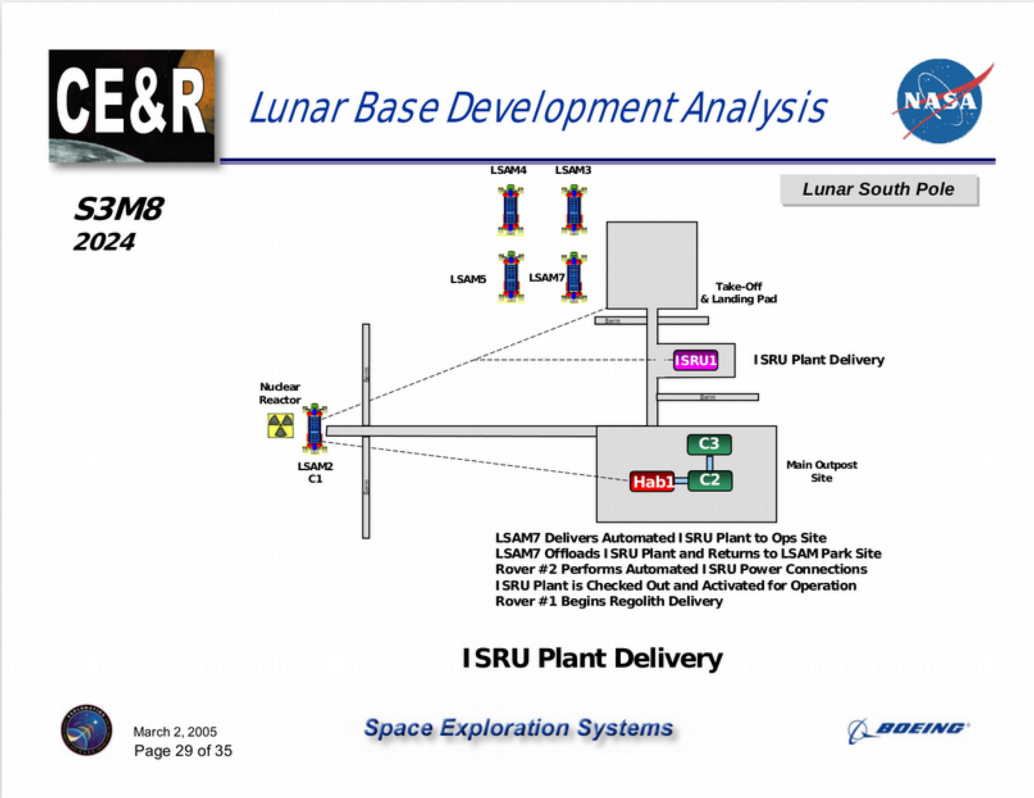
Exploration Systems Architecture Study (ESAS)

Constellation

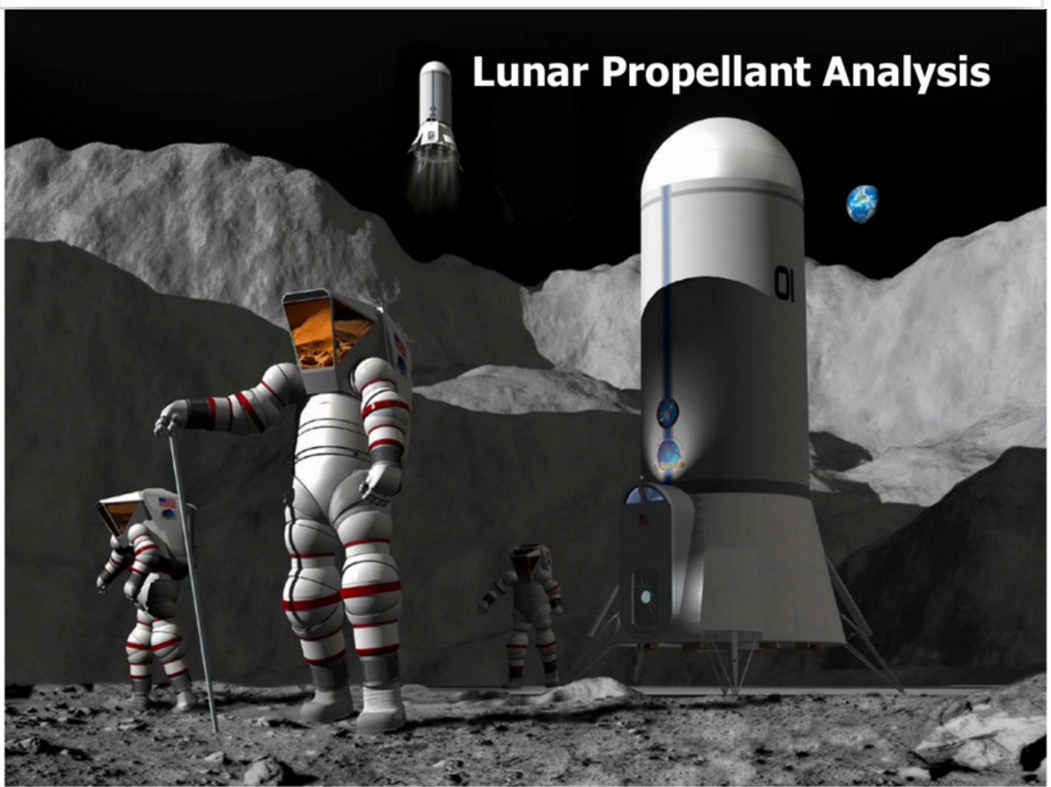
Fully Expendable

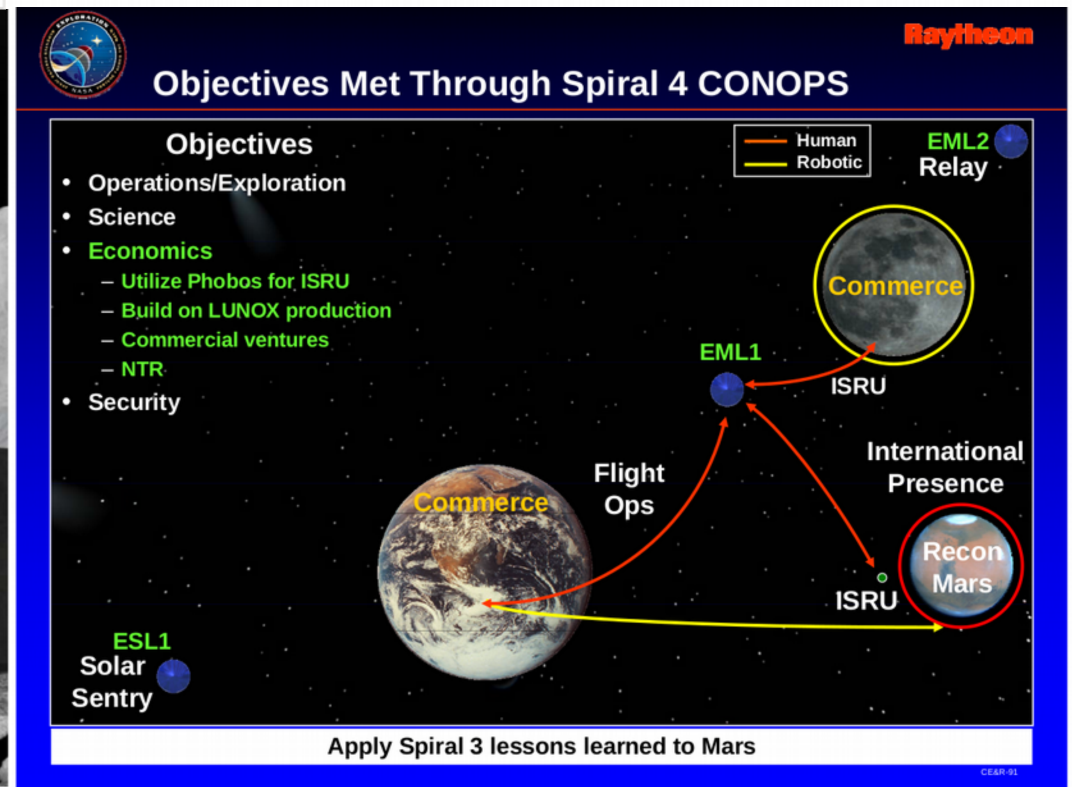
ISRU-Centric Lunar Architectures: Raytheon, Lockheed-Martin, Boeing, tSpace

Link to CE&R Midterm Reports
https://www.nasa.gov/missions/solarsystem/vision_concepts.html


CE&R
Lunar Base Development Analysis
NASA
S3M8
2024
Lunar South Pole
LSAM4
LSAM3
LSAM5
LSAM7
Take-Off & Landing Pad
ISRU1
ISRU Plant Delivery
Nuclear Reactor
LSAM2 C1
C3
Hab1
C2
Main Outpost Site
LSAM7 Delivers Automated ISRU Plant to Ops Site
LSAM7 Offloads ISRU Plant and Returns to LSAM Park Site
Rover #2 Performs Automated ISRU Power Connections
ISRU Plant is Checked Out and Activated for Operation
Rover #1 Begins Regolith Delivery
ISRU Plant Delivery
March 2, 2005
Page 29 of 35
Space Exploration Systems
BOEING


Lockheed Martin's
Systems-of-Systems
Lunar Architecture
Point-of-Departure Concept
CE&R BAA Open Forum
CA-1 (Basic Period)
Final Briefing
01 March 2005
ORBITEC
BIGELOW
ARES


Lunar Propellant Analysis


Raytheon
Objectives Met Through Spiral 4 CONOPS
Objectives
Operations/Exploration
Science
Economics
– Utilize Phobos for ISRU
– Build on LUNOX production
– Commercial ventures
– NTR
Security
Human
Robotic
EML2
Relay
Commerce
EML1
ISRU
International
Presence
Flight
Ops
Commerce
Recon
Mars
ISRU
ESL1
Solar
Sentry
Apply Spiral 3 lessons learned to Mars

Innovator’s Dilemma

- A heritage integrated ISRU model has the right structure
- Innovator’s Dilemma: What is needed? (the new stuff) and What can be upgraded later?
- The primary goal is **connecting** the technical content with an enterprise model – one with **PPP switches** and dials
- Technical numbers can be upgraded from a baseline
- The FY02 and FY04 models provide a useful scaffold to connect commercial ideas and a PPP tool to a heritage NASA ISRU-supplied lunar base study

Diagramming model blocks

- Explain in block diagram FY02 modules and which ones fed into FY04 framework
- Explain which parts of FY04 work fed which CE&Rs and include Shackleton biz model +yr
- Show how the FY02 enterprise model by CSP was replaced by a more detailed model by NE-LLC, supported by 350p two part study summary
-

Model Upgrades

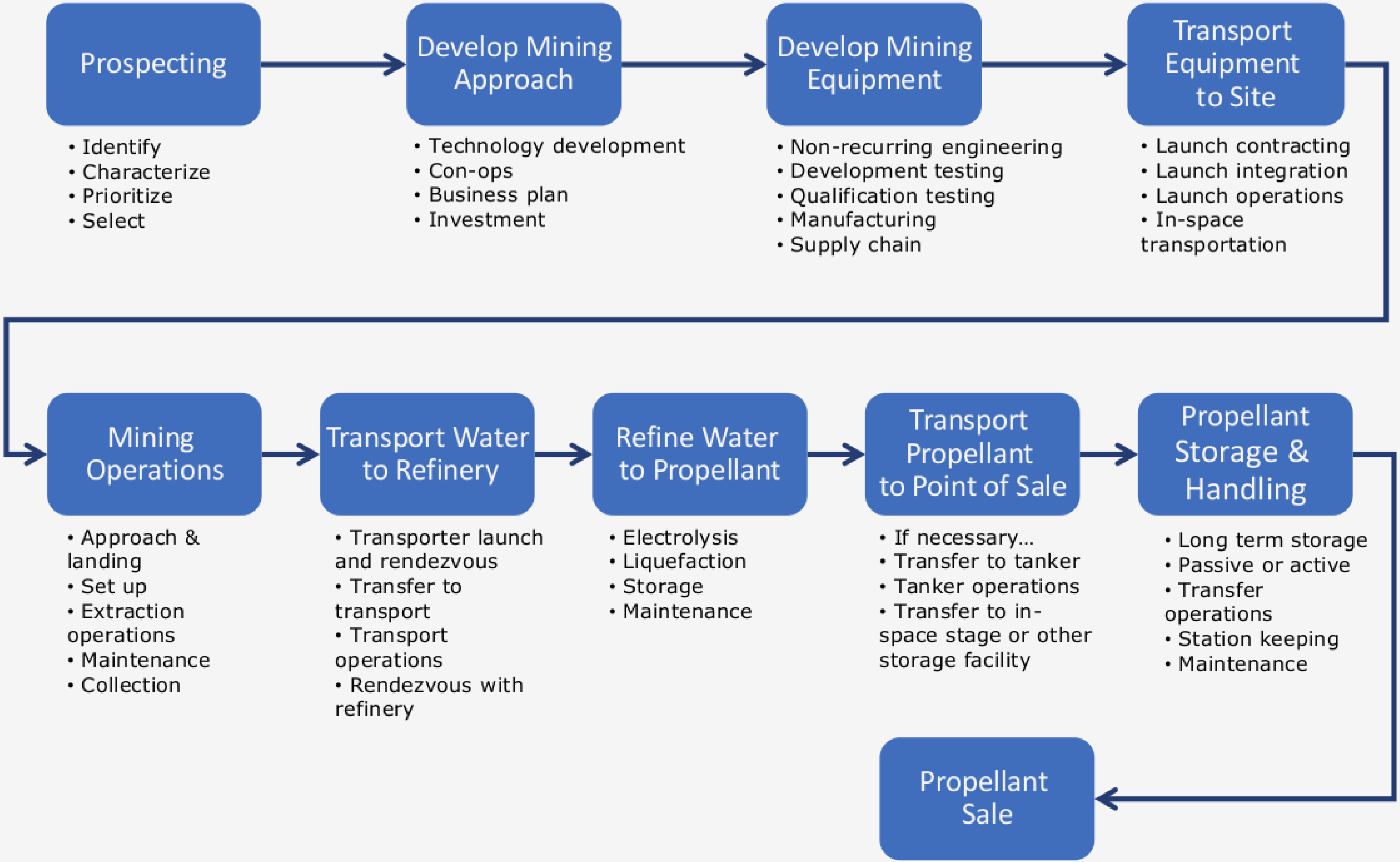
Heritage (FY04)

- Reusable Landers, Transfer Stages, CEV
- Lunar ISRU
  - Nitrogen from regolith
  - Ice from poles
  - Glass
  - Solar Cells
- Cost model (NAFCOM, SOCM, Launch & Logistics)

Upgrades in Place

- ISRU Plant
  - +mixed volatiles
  - +metals
  - +CSM/ULA mining model
- Demand Scenarios (Cislunar 1000, Mars Exploration, CH4, Defense propellant)
- Price Forecast
- Competitive Scenarios (Market share & Price)
- Enterprise Layer
- PPP options

CSM-ULA Mining Architecture



Adjusted LCROSS Results for Volatiles

Table 1. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV. Values shown are the average value across the averaging period, and errors are 1 SD.

	Water mass (kg)			
Time (s)	Gas	Ice	Dust mass (kg)	Total water %
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Table 2. Abundances derived from spectral fits shown in Fig. 3. The uncertainty in each derived abundance is shown in parenthesis [e.g., for H_2O: 5.1(1.4)E19 = $5.1 \pm 1.4 \times 10^{19}$ cm^{-2}] and was derived from the residual error in the fit and the uncertainty in the radiance at the appropriate band center.

Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$*
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

*Abundance as described in text for fit in Fig. 3C.

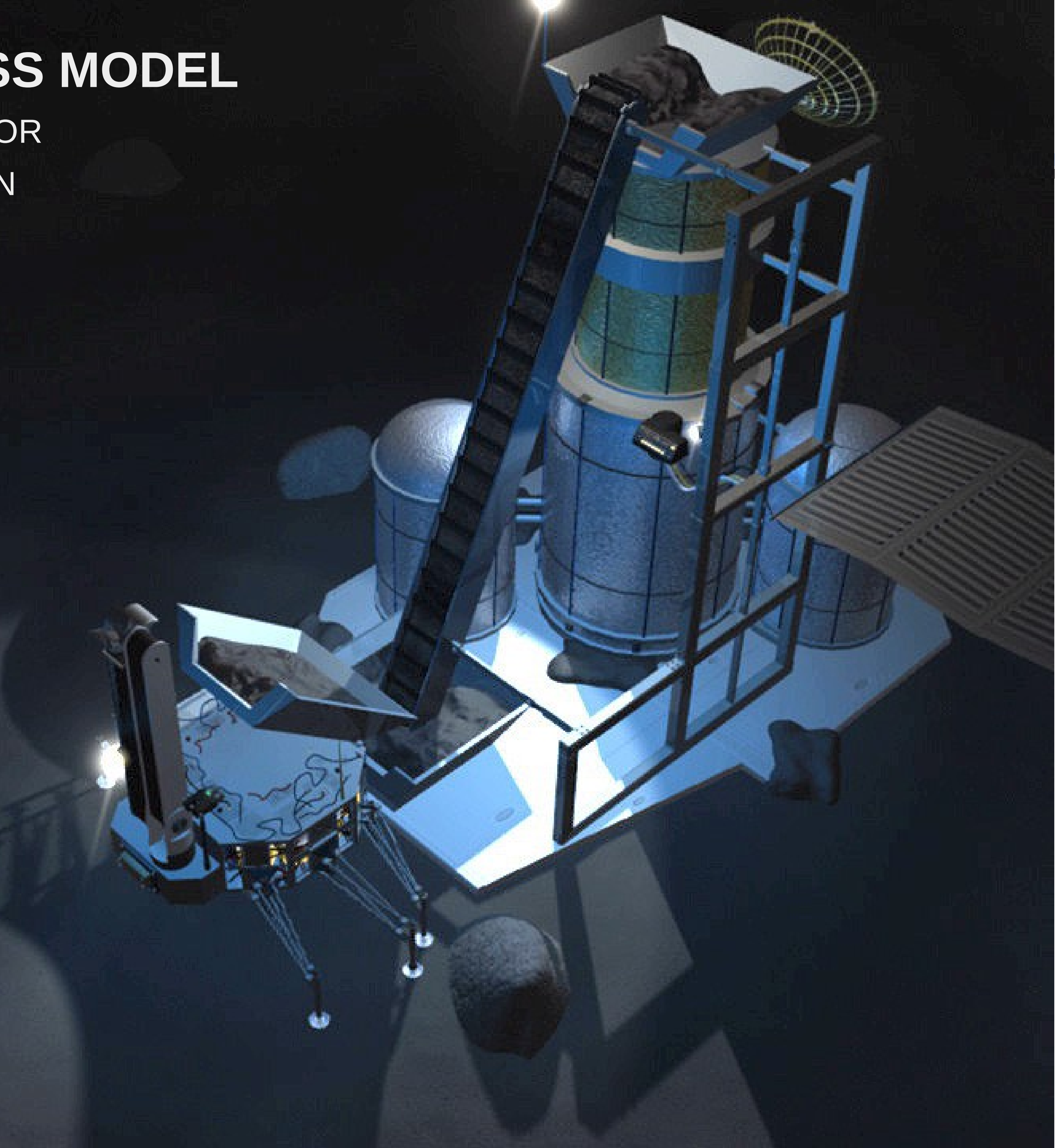
Colaprete et al. (2010)

VOLATILE PROCESS MODEL

PRIMARY HEATING REACTOR
+ FRACTIONAL DISTILLATION
+ CARBON COMBUSTION
+ SABATIER REACTOR
+ SULFUR EXTRACTION
WATER ELECTROLYSIS
OXYGEN LIQUEFIER
HYDROGEN LIQUEFIER
+ NITROGEN LIQUEFIER
+ METHANE LIQUEFIER
+ AMMONIA LIQUEFIER
+ MERCURY SEPARATOR

TANK FARM

WATER TANK
OXYGEN TANK
HYDROGEN TANK
+ NITROGEN TANK
+ METHANE TANK
+ AMMONIA TANK
+ MERCURY TANK



Molten Oxide Electrolysis model

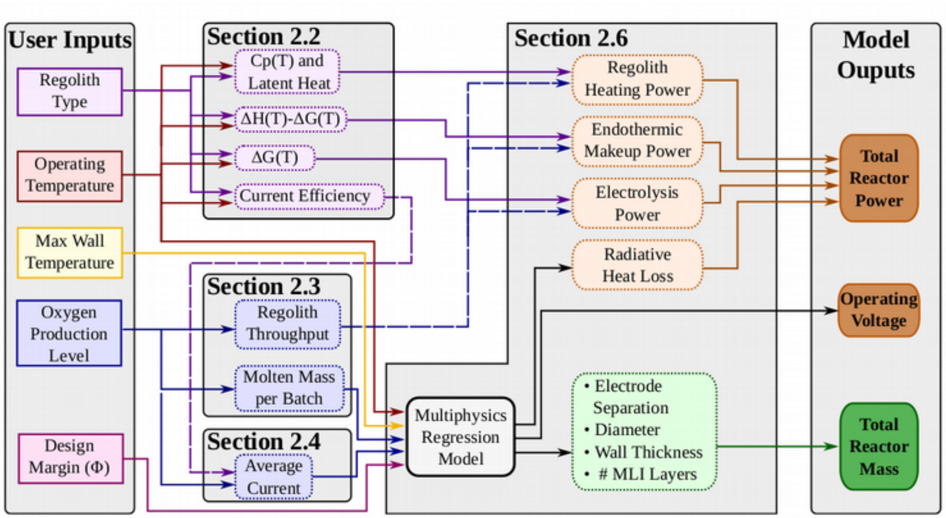


Figure 2.1 of [Schreiner and Hoffman, 2015]

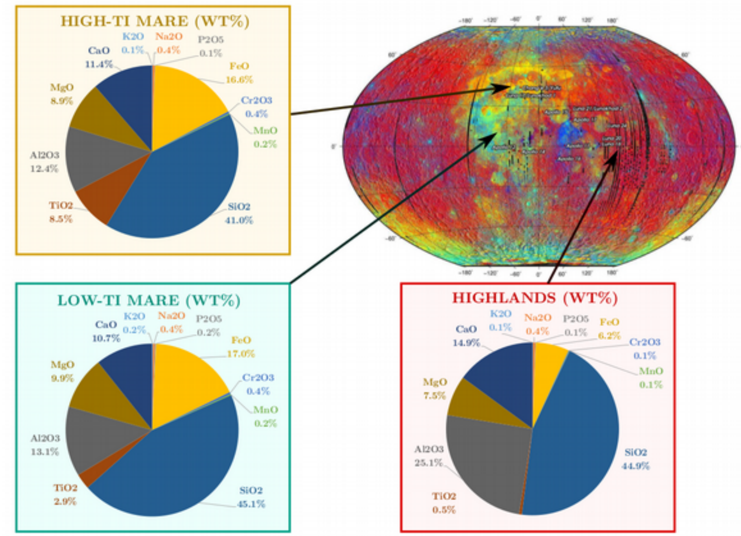


Figure 2.2 of [Schreiner and Hoffman, 2015]

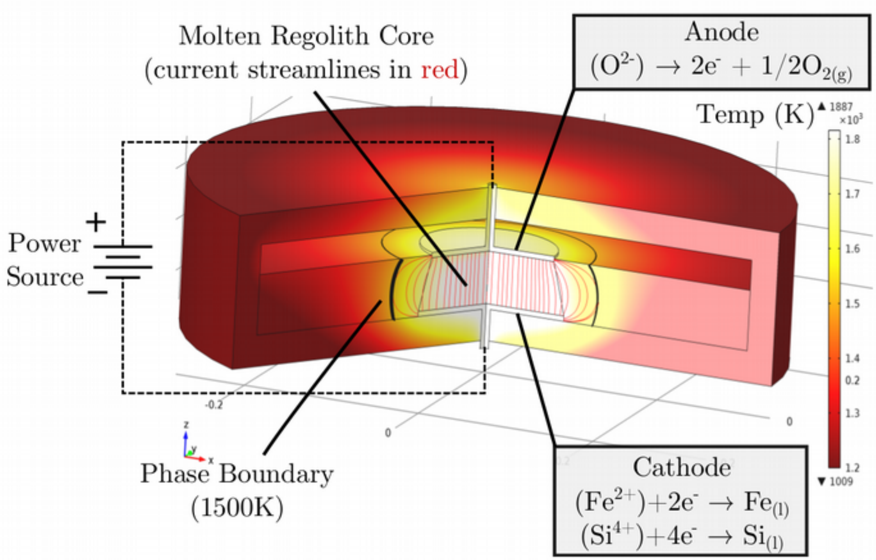


Figure 1.2 of [Schreiner and Hoffman, 2015]

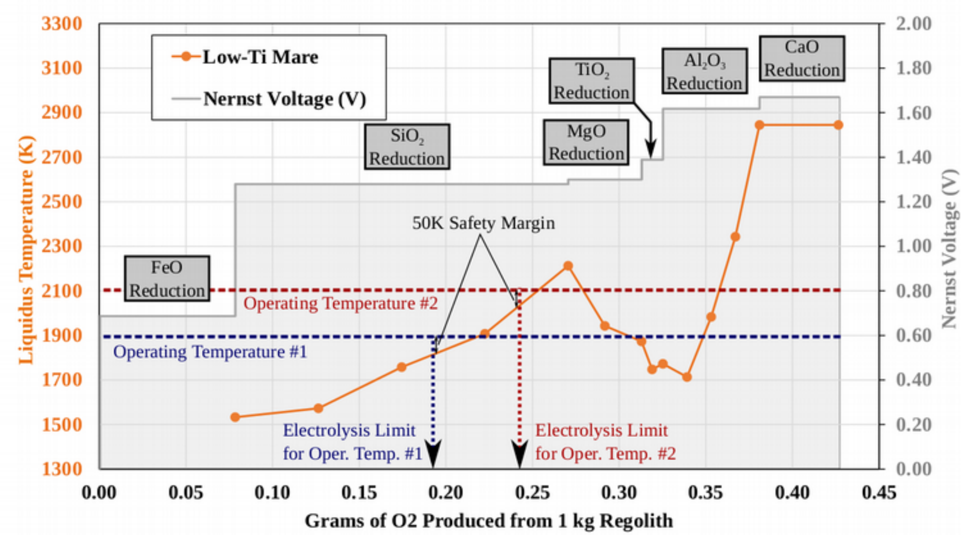
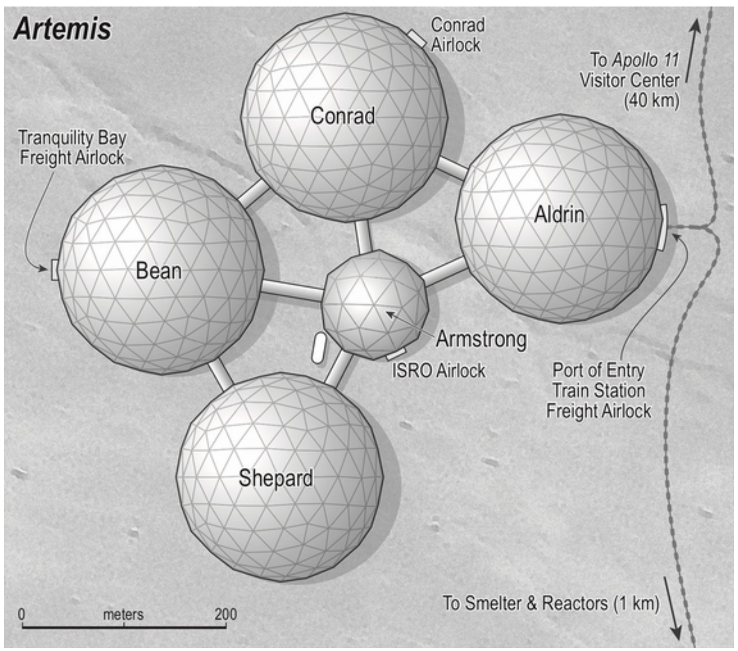


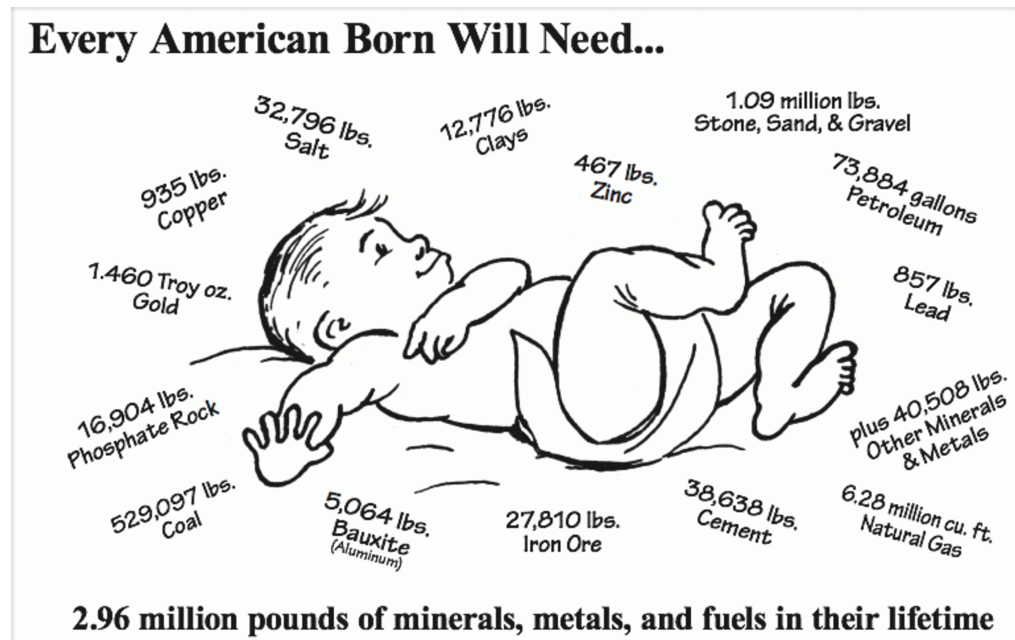
Figure 2.9 of [Schreiner and Hoffman, 2015]

http://ssl.mit.edu/files/website/theses/SM-2015-SchreinerSamuel.pdf

Have you seen my customer?

Two ways to estimate future demand





Bottoms-up design
(engineering approach)

Analogy
(per capita approach)

This approach requires a significant engineering effort

Terrestrial Consumption

Every Year— 38,052 pounds of new minerals must be provided for every person in the United States to make the things we use every day

- 8,509 lbs. **Stone** used to make roads, buildings, bridges, landscaping, and for numerous chemical and construction uses
- 5,599 lbs. **Sand & Gravel** used to make concrete, asphalt, roads, blocks and bricks
- 496 lbs. **Cement** used to make roads, sidewalks, bridges, buildings, schools and houses
- 357 lbs. **Iron Ore** used to make steel— buildings; cars, trucks, planes, trains; other construction; containers
- 421 lbs. **Salt** used in various chemicals; highway deicing; food & agriculture
- 217 lbs. **Phosphate Rock** used to make fertilizers to grow food; and as animal feed supplements
- 164 lbs. **Clays** used to make floor & wall tile; dinnerware; kitty litter; bricks and cement; paper
- 65 lbs. **Aluminum (Bauxite)** used to make buildings, beverage containers, autos, and airplanes
- 12 lbs. **Copper** used in buildings; electrical and electronic parts; plumbing; transportation
- 11 lbs. **Lead** 87% used for batteries for transportation; also used in electrical, communications and TV screens
- 6 lbs. **Zinc** used to make metals rust resistant, various metals and alloys, paint, rubber, skin creams, health care and nutrition
- 36 lbs. **Soda Ash** used to make all kinds of glass; in powdered detergents; medicines; as a food additive; photography; water treatment
- 5 lbs. **Manganese** used to make almost all steels for construction, machinery and transportation
- 332 lbs. **Other Nonmetals** have numerous uses: glass, chemicals, soaps, paper, computers, cell phones
- 24 lbs. **Other Metals** have the same uses as nonmetals but also electronics, TV and video equipment, recreation equipment, and more

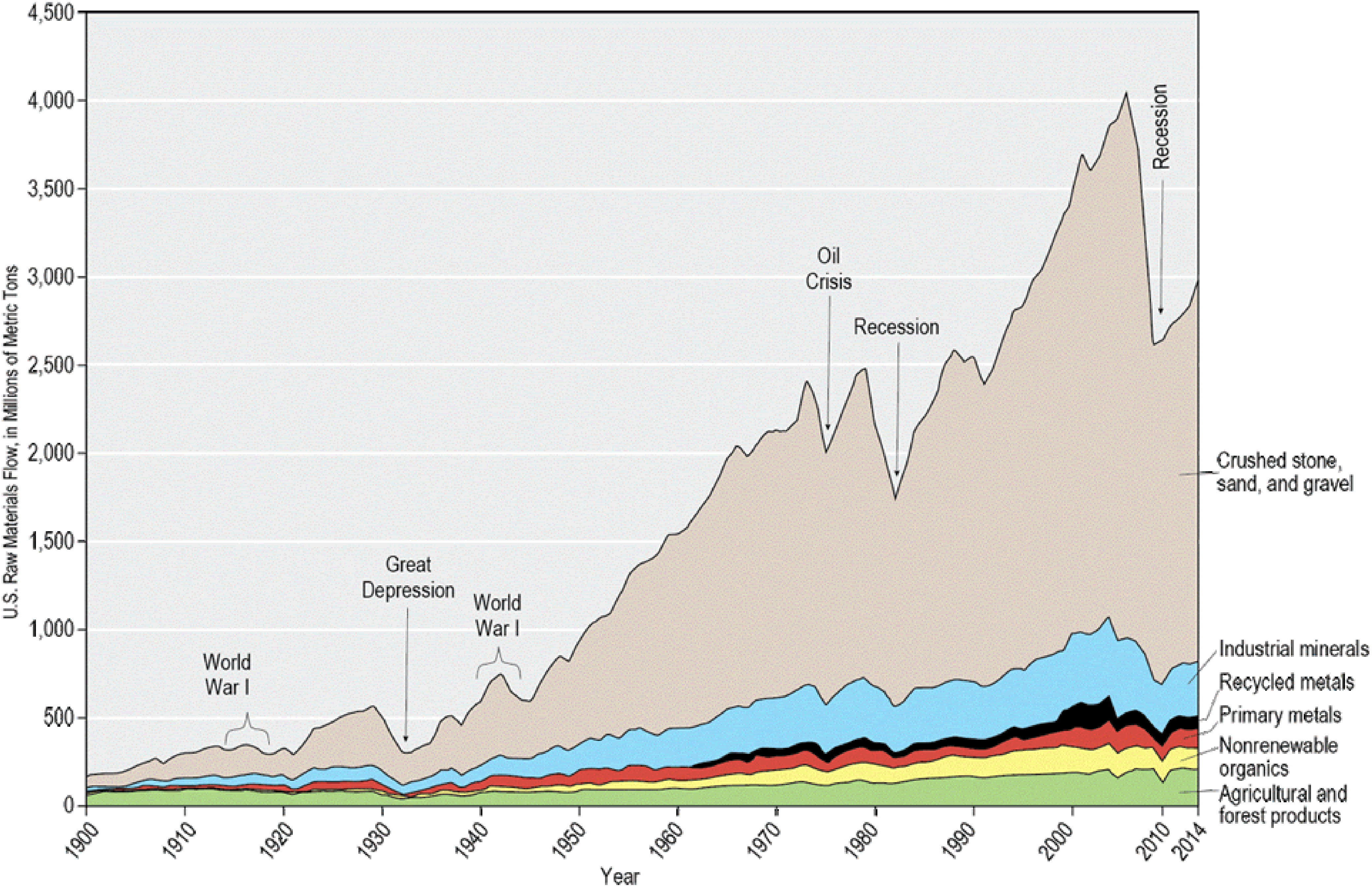
Including These Energy Fuels

- 951 gallons of **Petroleum**
- 6,792 lbs. of **Coal**
- 80,905 cu. ft. of **Natural Gas**
- 1/4 lb. of **Uranium**

To generate the energy each person uses in one year—

© 2011, Mineral Information Institute, SME Foundation

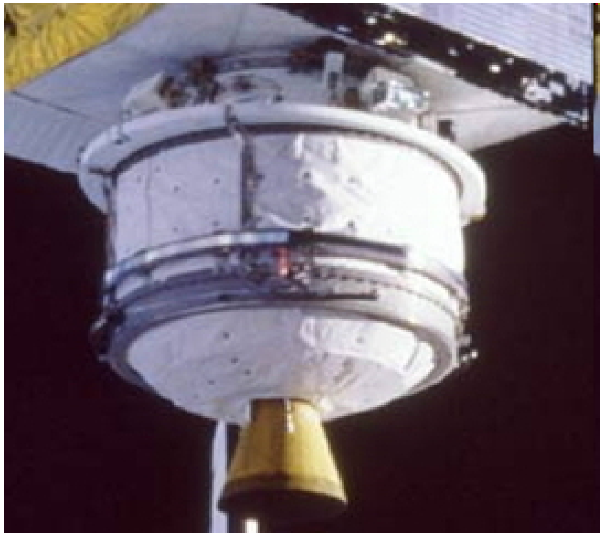
https://mineralseducationcoalition.org/mining-minerals-information/mining-mineral-statistics/



https://geoinfo.nmt.edu/resources/minerals/home.html

LEO-GEO Transfer

- Tech / Cost
  - Refuelable cryo upper stage
  - Cost should be very low – they are currently thrown away



- Bizop / Market Size
  - Baseline market model for 2002 study
  - Onramps are straightforward because of existing demand for GEO access

- Schedule & Risks
  - Risk of cannibalize existing markets

Plane Change Missions

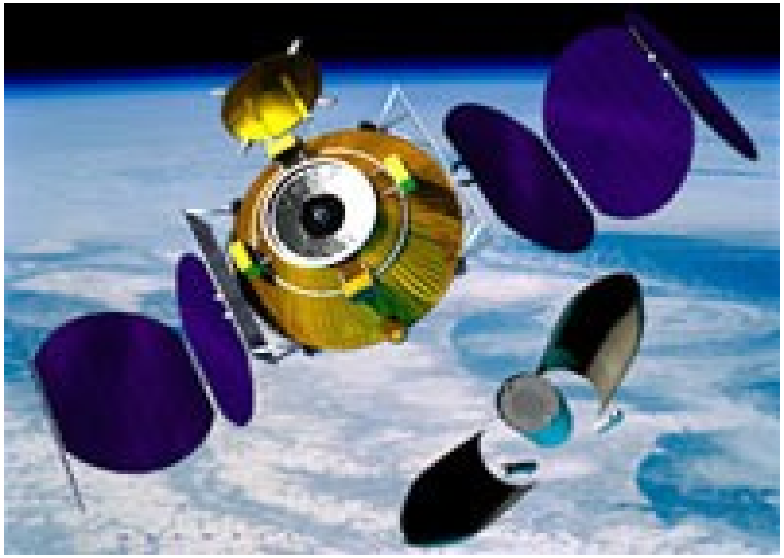
- Tech / Cost
  - Refuelable cryo upper stage
  - Ops cost only (existing hardware reuse)

- Bizop / Market Size
  - Market can be estimated by extrapolating existing instances
  - The market exists today for satellites requiring a plane change

- Schedule & Risks
  - Risk of alienation of existing industry (cannibalize existing markets)
  - We should consider co-opting aerospace industry by helping build new markets & customers

Satellite Servicing

- Tech / Cost
  - Commercial business plans are under development
  - Tech is enabled by miniaturization of electronics
  - Cost structure is well understood

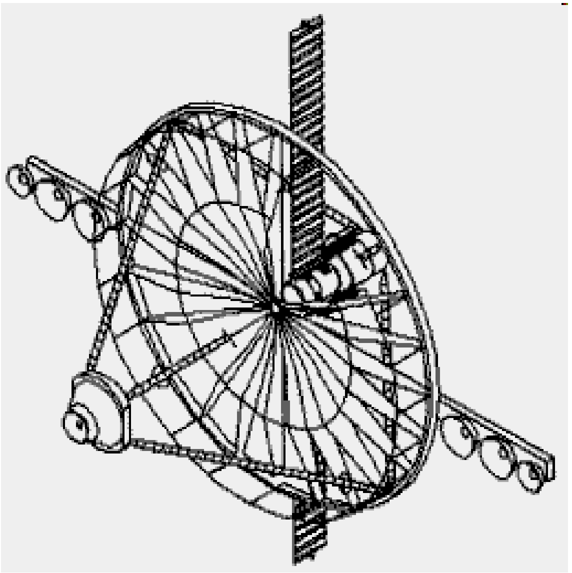


- Bizop / Market Size
  - Repair and refueling of satellites can extend mission life and increase capability

- Schedule & Risks
  - Market risk dominates over technical risks
  - Assured customers could emerge from govt sector

Large GEO Placement

- Tech / Cost
  - 20 ton GEO satellites have been discussed in the past
  - Expendable system approach would require HLLV
  - Refueled upper stages could also achieve the same objective

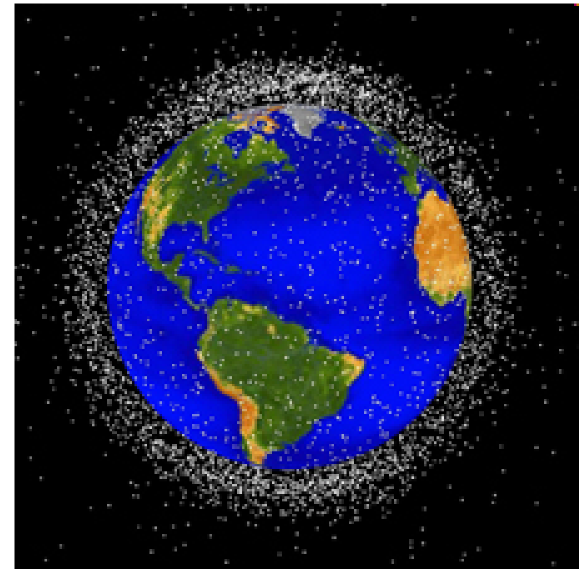


- Bizop / Market Size
  - Globis 20t concept
  - Comsat companies would be a target customer group provided economies of scale can be shown to exist

- Schedule & Risks
  - The handoff in LEO would be perceived to be risky compared to conventional alternatives
  - No existing large comsat bus is under development

Debris Removal

- Tech / Cost
  - Refueling puts a robust debris removal capability into the affordable range for a government program



- Bizop / Market Size
  - There are almost 40,000 space objects tracked today
  - The debris problem is at the threshold of a runaway chain reaction
  - There are good reasons to solve the problem sooner rather than later

- Schedule & Risks
  - Accountability for debris has not been allocated to any party
  - Government agencies will be reluctant to promote an unfunded liability

ISS Propellant & Supply

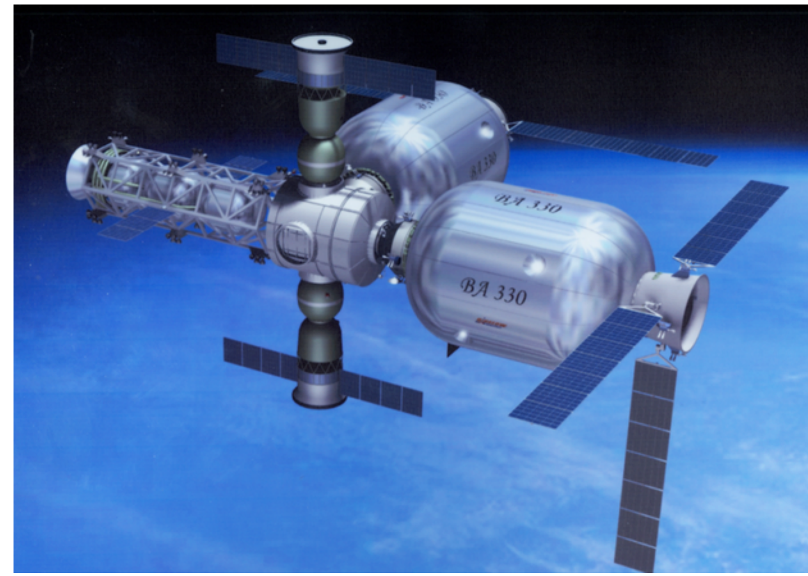
- Tech / Cost
  - Russian Progress resupply modules currently send propellant, water and consumables to ISS

- Bizop / Market Size
  - Function of current size & projected growth
  - Consumables are correlated with crew size (up to 6)
  - May be possible to move ISS to a higher orbit using a reusable tug

- Schedule & Risks
  - Customer would be low risk
  - Anchor tenancy for delivery of products could help reduce business risk

Space Business Park

- Tech / Cost
  - Bigelow has a substantially lower cost structure than standard NASA procurement
  - Progressive capability demos on orbit are underway



- Bizop / Market Size
  - The market vision for Bigelow habitats / stations includes industrial activities, tourism and exploration

- Schedule & Risks
  - Partnership or delivery contracts with Bigelow would be perceived to reduce market risk

Space Science Missions

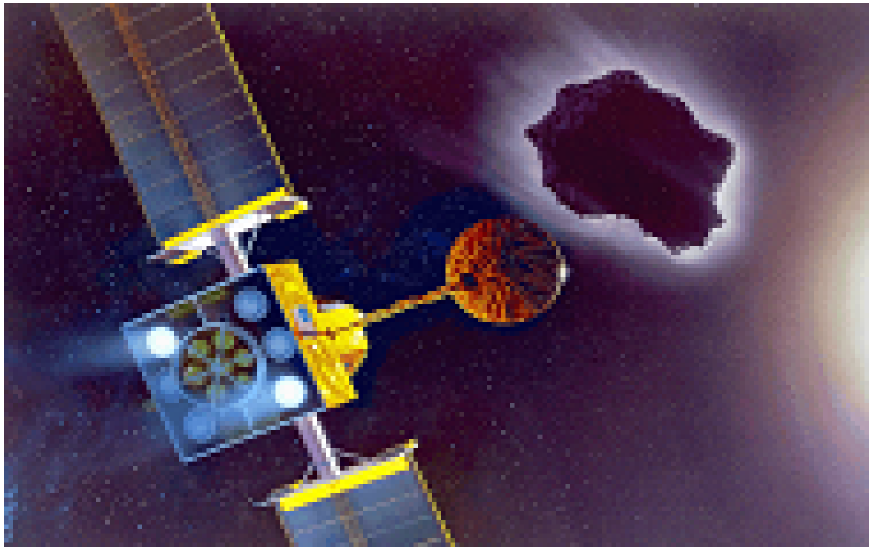
- Tech / Cost
  - NASA planetary exploration
  - Uses refulable upper stage for added high thrust “reach”
  - Faster missions to outer planets

- Global Market
  - Enables large outer solar system missions
  - Refueling capability for Earth Neighborhood missions

- Schedule & Risks
  - Govt budget determines schedule
  - Tradeoff between increased performance and risk

Planetary Protection

- Tech / Cost
  - ISRU is a critical enabling technology offering a series of response options
  - Cost will scale with scope of response



- Bizop / Market Size
  - Customers could emerge for both assessment and response

- Schedule & Risks
  - ISRU is a response to risk, not a source of it (framing is critical here)
  - Schedule will be determined by PHA discovery rate & results of trajectory modeling

NASA Human Missions

- Tech / Cost
  - Determined by architecture (e.g. ESAS vs CE&R)

- Bizop / Market Size
  - 800MT per Mars Mission

- Schedule & Risks
  - Determined by architecture
  - 2024 start date (at best)
  - ISRU is a significant risk reduction strategy

Planetary surface markets

- Safe harbor
- Habitation-related services (rental condos & home sales)
- Radiation protection services (underground facility access)
- Industrial / academic Research & Development
- Food lodging entertainment tourism
- Transport (hoppers, rovers)
- Physics-based (cryo & vacuum) science & manufacturing
- Teleoperation time sales (equipment rental)
- Offshore banking services
- Archive facility (Longnow foundation)
- Private telescope (sell data)
- Infrastructure construction services

Public Private Partnerships

A rich set of public-private partnership (PPP) options are available to government. A tool is needed to help select the PPP strategy that could *maximize the rate of lunar commercialization* by ***attracting private capital*** into the development of critical ***infrastructure*** and robust ***capabilities*** that directly serve government needs.

A successful lunar industrial development program would be good for the country, offering a path to ***revitalize the US economy*** by opening up whole new worlds of resources while ***increasing national employment*** in aerospace and other high technology sectors.

PPP options

Investor Risks	LCRATS	NASA Contracts	Tech Demo Missions	SAAs	Patent License	CRADA	SBIR / STTR	IPP Seed	Centennial Challenges	COTS Type
Technical: Developing new technologies	High		High	High	High	High	Moderate	High	High	Moderate
Technical: Manufacturing difficulty	Moderate		Moderate	Moderate	Moderate	Moderate		Moderate	Moderate	High
Market: Size	High	Moderate		Moderate	Moderate	Moderate			Moderate	Moderate
Market: Quality and reliability	Moderate									Moderate
Market: Development timing	High	Moderate						High		High
Market: Uncertainty	Moderate							Moderate		Moderate
Financial: Magnitude of capital required	High	High	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate		High
Financial: Timing of capital needs	High							High	Moderate	High
Financial: Uncertainty	Moderate		Moderate					Moderate		High
Financial: ROI hurdle	Moderate	Moderate		Moderate		Moderate	Moderate			High
Political / Regulatory: Policy & budgets	High									High
Political / Regulatory: Regulatory compliance	High									Moderate
Political / Regulatory: Treaties & indemnification	Moderate									Moderate
Perception	Moderate		Moderate	Moderate	Moderate	Moderate			High	High

Investor Risks	LCRATS	Tax Credits	Loan Guarantees	Anchor tenancy	Other purchase agreements	Direct Investment	Government Trust Fund (SPIC)	Super SBIR	Super Competitions	Customer #1 Procurement	Free Flight Challenge	Bounties on orbital debris
Technical: Developing new technologies	High					High		High	Moderate		Moderate	
Technical: Manufacturing difficulty	Moderate					Moderate		Moderate	High			
Market: Size	High			Moderate	Moderate				Moderate	Moderate		High
Market: Quality and reliability	Moderate			High	Moderate				Moderate			High
Market: Development timing	High			Moderate						High	Moderate	High
Market: Uncertainty	Moderate			Moderate	High					Moderate		High
Financial: Magnitude of capital required	High	High	High			Moderate	High	Moderate		Moderate	High	Moderate
Financial: Timing of capital needs	High	Moderate	High				High			Moderate	Moderate	Moderate
Financial: Uncertainty	Moderate	Moderate	Moderate	Moderate		High	High					Moderate
Financial: ROI hurdle	Moderate	High	High	Moderate		Moderate	Moderate		Moderate	Moderate	Moderate	Moderate
Political / Regulatory: Policy & budgets	High	Moderate	High	Moderate	Moderate	Moderate	High					High
Political / Regulatory: Regulatory compliance	High											Moderate
Political / Regulatory: Treaties & indemn.	Moderate											High
Perception	Moderate	Moderate	High	High	Moderate	Moderate	High		High	Moderate	Moderate	Moderate

Davidson, Hoyt, et al. "Supporting Commercial Space Development Part 2: Support Alternatives versus NASA Commercialization Priorities", Near Earth LLC, NASA Contract NNH11CD08D, November 2010, https://www.nasa.gov/sites/default/files/files/SupportingCommercialSpaceDevelopmentPart2.pdf

Enterprise Modeling: Study Goals

1. **Create flexible enterprise modeling tool**
   - Easy link to production models
   - Take market demand time series
   - Take market share and pricing data
   - Take capital expenditure costs
   - Take production & operating costs
   - Assume PPP factors
   - Create financial statements
   - Calculate NPV and IRRs
   - Determine sensitivities

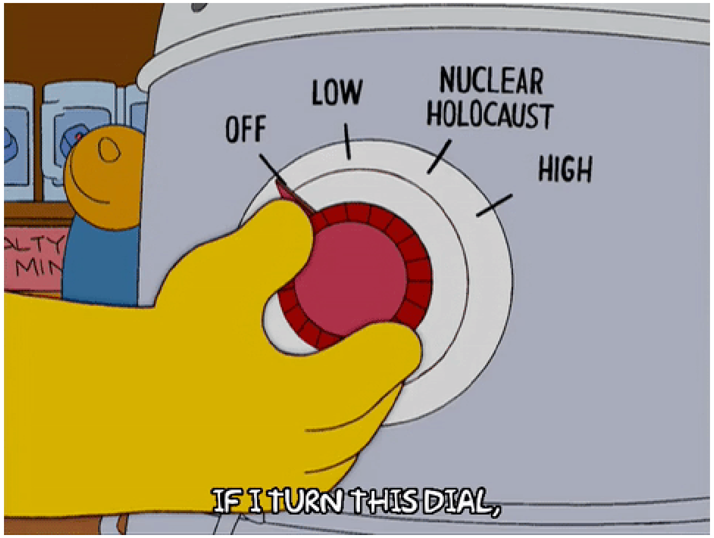
2. **Estimate economic viability of various production models**
   - With varying production processes, byproducts, strategies
   - With varying market demand and pricing assumptions
3. **Estimate optimal PPP support**
   - Required types and levels of support to attract private capital
   - Best alternatives for government

Status vs. Goals

1. **<u>Create flexible enterprise modeling tool</u>**
   - Done: Interface to production models
   - Done: Version 1 of Enterprise model
   - Done: Key PPP parameters modeled
   - Done: Full financial statements
   - Done: Calculates NPV and IRRs
   - CIP: Sensitivity analysis & data tables
   - TBD: Add price elasticity formulas
   - TBD: Add accelerated depreciation
   - TBD: Add more inventory cost methods
   - TBD: Add more equity & debt securities

2. **<u>Estimate economic viability of various production models</u>**
   - Tested conceptually, viability seems possible for some cases
   - Need better cost and market data to run accurate cases
3. **<u>Estimate optimal PPP support</u>**
   - Tested conceptually, PPP support can work
   - Need better cost and market data to optimize PPP structures

4 Big PPP Knobs to Turn

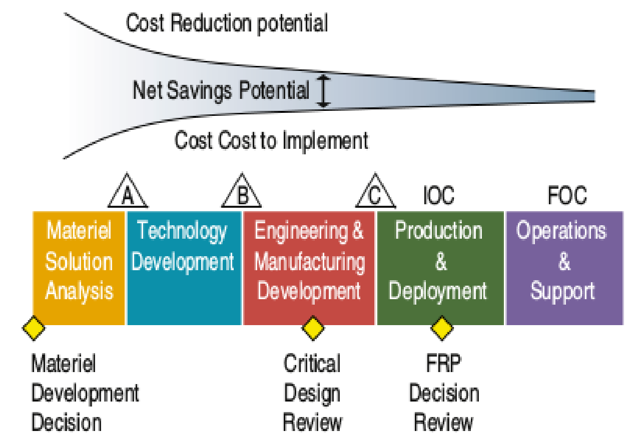


- **<u>Uncertain demand for commodities is biggest challenge to enterprise</u>**
  - Focus: "prime the pump" as 1st customer
  - *Model: Choose unit purchase guarantees by commodity by year*
- **<u>Changing government policy and regulatory risks are existential</u>**
  - Focus: Substantial USG co-investment "skin-in-the-game"
  - Model: Choose % of each CapEx category to be government funded
- **<u>Technical obsolescence and/or competition boost ROI requirements</u>**
  - Fucus: Lower WACC thru USG loan guarantees and rate subsidies
  - *Model: Choose % of total up front capital to be government backed*
- **<u>Operating risks and challenges reduce profit margins</u>**
  - Focus: Tax credits to balance extreme operating risk and high R&D
  - *Model: Choose which expense line items to qualify for credits*

Managing Risk: Common Pitfalls and their Results

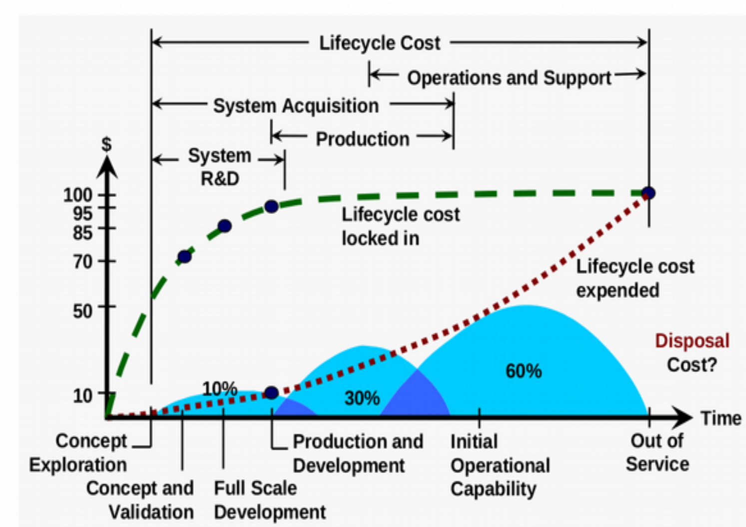
- Imposing risk requirements after making key decisions
  - Precludes implementation of the most effective options
  - Similar to Value Engineering & Supportability principles
- Focus on a specific risk to the exclusion of others
  - Sub-optimal solutions for integrated end-to-end risk
- Imbalance of risks to different parties
  - Win/lose rather than win/win
- Unappreciated and under-appreciated risks
  - Unprepared to manage the consequences
- Over-design to extent that risk increases
  - Adding complexity to reduce risk

Figure 2. **VE Savings Potential During the Life of a Typical System. (Adapted from E. D. Heller, General Dynamics Corporation)**



DefenseATL-MayJune-2009-VE-Reed-Mandelbaum

Percentage of Cost Locked In by Phase



From W. J. Larson & L. K. Pranke (1999) Human Spaceflight: Mission Analysis and Design

Application of Resilient Architecture Concepts *

- “Resilience” - Complex systems that stably operate within their normal design parameters and through unexpected events or changing needs
  - Common interfaces and standards to interconnect components, elements, systems, and sub-systems in multiple ways making them less vulnerable to failures
  - Different kinds of components, elements, and subsystems, provided by different organizations, nationalities, cultures, and individuals
  - Start with small scale tests and demos, develop modular capabilities (e.g., resource location, characterization, extraction, ISRU processing, power, life support, propellant delivery), replicate to increase capacity
  - Adapt in response to failures, evolutionary learning & discovery of new knowledge about what works (or not)/other changing needs.

* Metropolis: Point of View / March 2013 / Toward Resilient Architectures 1: Biology Lessons, www.metropolismag.com/Point-of-View/March-2013/Toward-Resilient-Architectures-1-Biology-Lessons

Integrated Risk Strategies

- Multiple small prospector scouts by multiple providers per launch
- Use of contingency launches and other operations (“M of N” reliability)
- Unused contingency hardware from one mission subsequently assigned as next primary
- Highly manufacturable, upgradeable, modular designs, mfg in quantity
- Standard interfaces and interoperability
- Multiple launches, time-phased to incorporate learning cycles
- Large population of small multiples and high flight rates to leverage reliability growth
- Early revenue-generating flights with cargo prior to crew
- Initial use of polar-capable landers in equatorial region with larger margins

Integrated Risk Strategies (Cont'd)

- Start ISRU production sized for small scale reusable landers or hoppers
- Consider early demo/Minimum Viable Product with LOX only (use terrestrial LH2/fuel)
- Use of reusable landers in non-reusable or terrestrially-resupplied mode until ISRU propellant is available, then resupply it on the lunar surface in an uncrewed demonstration mode
- Scale up ISRU production to practically any level desired by adding more units/capability
- Add the ability to capture by-products at low incremental additional cost to improve economics and enabling additional infrastructure development
- Early depot or stage refueling in LEO with terrestrial propellants so an L-1 depot can be ready when lunar ISRU products are available
- Terrestrial propellant can supplement or make up for any ISRU shortfalls

Costing the Mining Architecture

- Cost + Government contracting is easy to estimate with NAFCOM analogies, but are useful in establishing a conservative baseline
- Commercial costs are hard to predict
  - Bottoms-up approach works, but requires more information that we have
  - Commercial analogies are sparse
  - Cost risk (exceeding budget expectations) is high
- "Assuming that you can keep DOE and NASA from turning them into white collar welfare programs, ..."
- Cost as an Independent Variable (CAIV) approach is recommended

Existential comments

- Unless something catastrophic happens, humanity has the potential to expand into space using geometrically abundant mineral and energy resources
- The current pool of assets over next 50 years is the Moon, Mars and asteroids
- Costs from Earth stack exponentially in an expendable paradigm
- ISRU linearizes costs: Where it crosses the line is interesting
- A lunar base is accessible multiple times per year and is close LEO and sited near the edge of Earth's gravity well
- Mars is accessible every 2 years, and is the size of a continent
- Asteroids can provide inputs to the Earth economy after a calculable threshold
- What is the risk of doing nothing? What is the risk of losing the opportunity?
- If we succeed with a demo program, it gets everything started
- A calibrated and sufficiently detailed model can identify the point where commercial crosses the line into feasibility