Cost and Market Modeling for Lunar Mining and Drilling

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International Cost Estimating and Analysis Association (ICEAA) Southern California Chapter Workshop
100 North Pacific Coast Highway, Building 100, El Segundo, CA, December 11, 2019

Overview

Value Basis for Lunar In-Situ Resource Utilization (ISRU)

Demand Modeling - Emerging Markets

Costing and Operations Models

Public Private Partnerships

VALUE BASIS

The Moon in Context

The Moon has an “Earth 2.0” worth of mineralization

- Earth has seven continents – a geologic orebody the size of an “8th continent” lies right next door
- The Moon is made of the same source materials as Earth with a different set of geologic processes
- Relaxed thermal and ropeway constraints enable going 8x deeper on the Moon using current tech

Crushing and grinding consume half of the energy of a ‘typical’ terrestrial mine – the lunar surface is already highly fragmented, giving mineral processing a head start

Extreme cold and ultra high vacuum enable low-cost industrial processes that are very expensive on Earth

The Moon is a “Real Asset” and can naturally expand the global economy using well-understood tools

Real Assets have Intrinsic Value

There is a **tangible basis** for valuing lunar resources:

> *"Real assets are **physical assets** that have an **intrinsic worth** due to their substance and properties. Real assets include precious metals, commodities, **real estate**, **land**, equipment, and **natural resources**. They are appropriate for inclusion in most diversified portfolios because of their relatively low correlation with financial assets, such as stocks and bonds."* https://www.investopedia.com/terms/r/realasset.asp

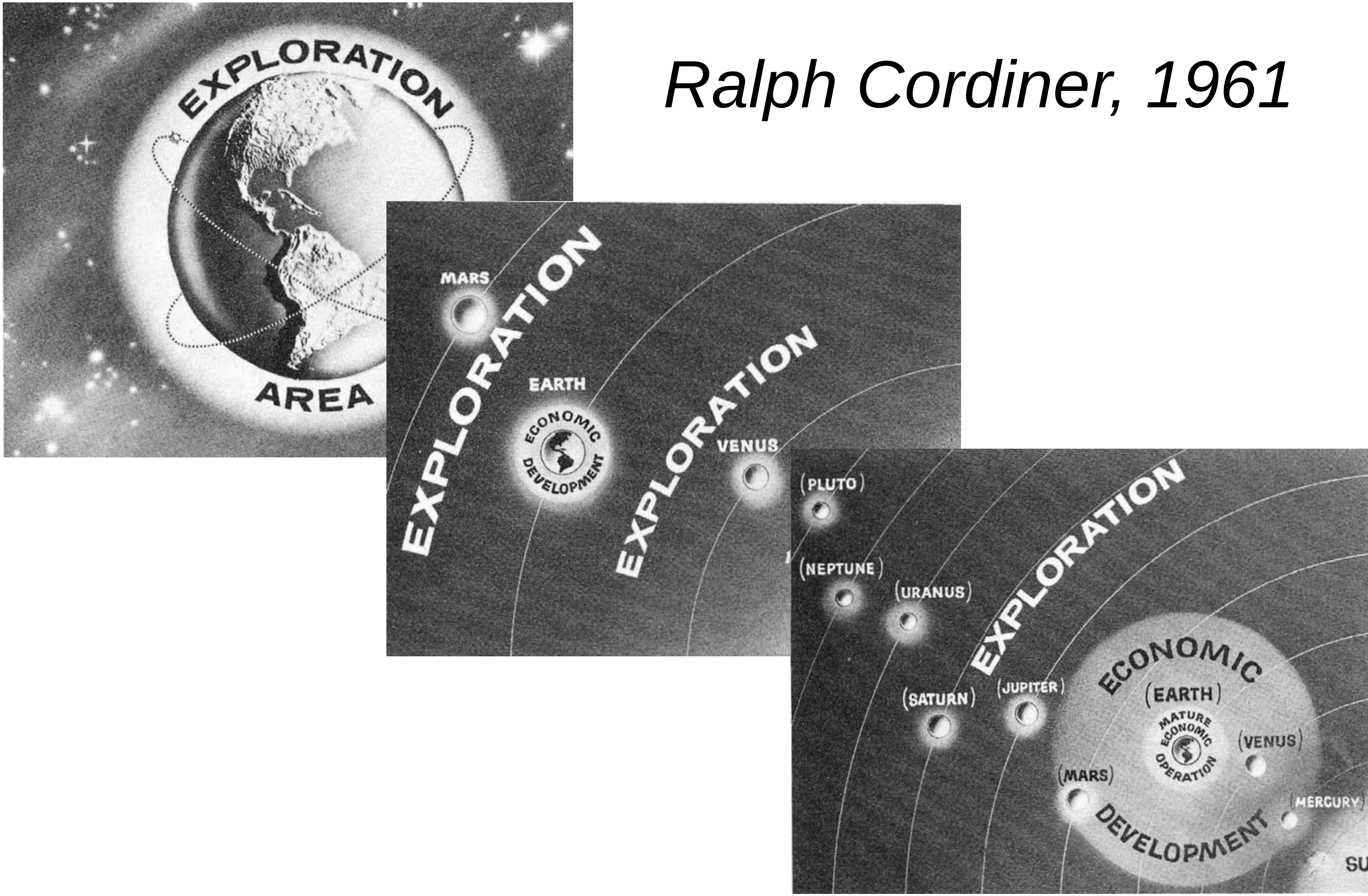
With the right kind of legal cover, the Moon could become very attractive to private and commercial investors

How to Get Started

- Mapping the Tipping Point
  - It is called “bootstrapping”
  - The ISRU community has being doing this for decades
- Activating the Tipping Point
  - Long-term, patient capital is required
  - PPPs are an excellent choice for mechanism
  - Private capital can augment the NASA budget
  - First mover advantage may be difficult to overcome (think about China in this context)
- The Billionaire space race has already begun...

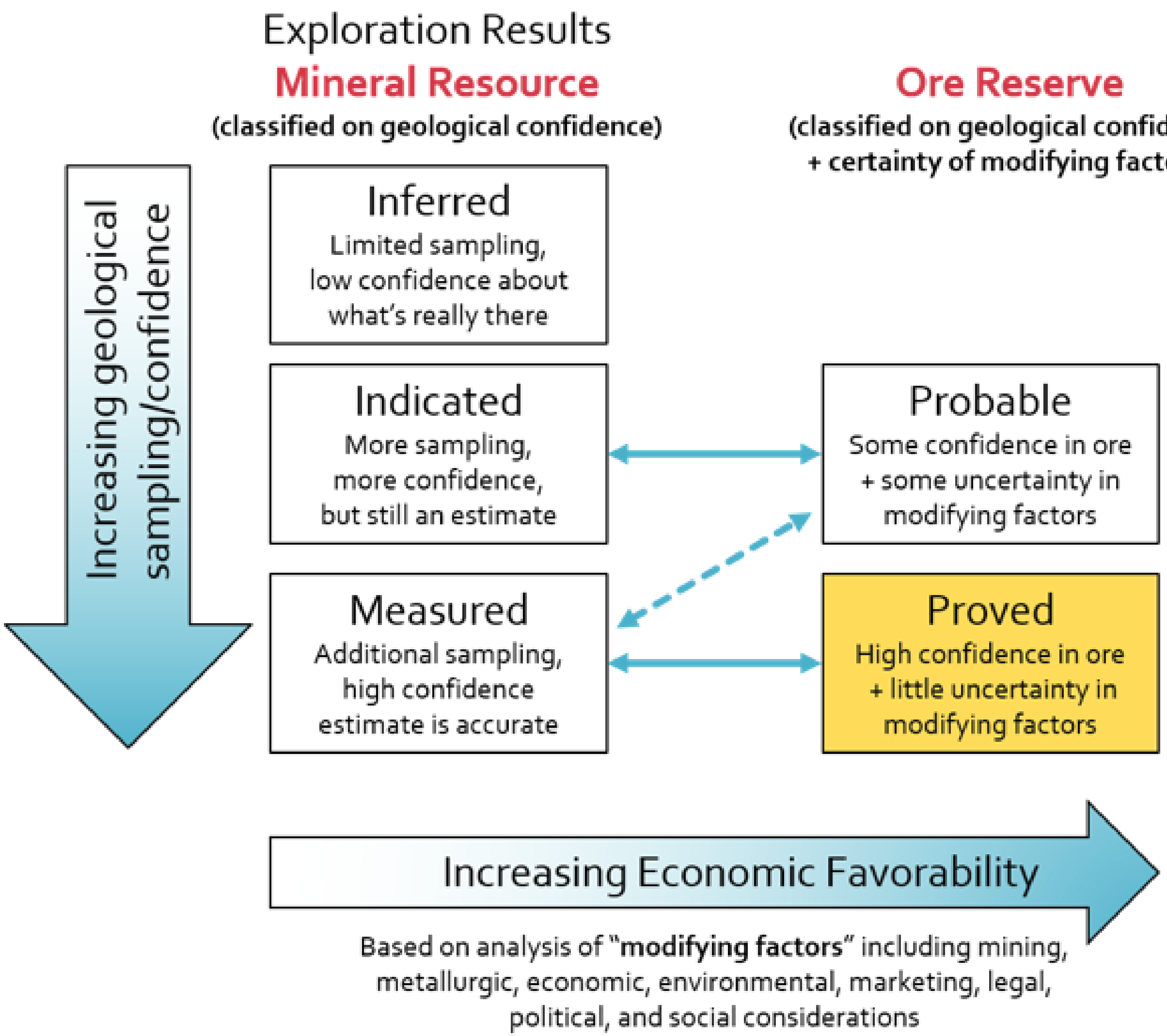
Resources Enable Economic Expansion

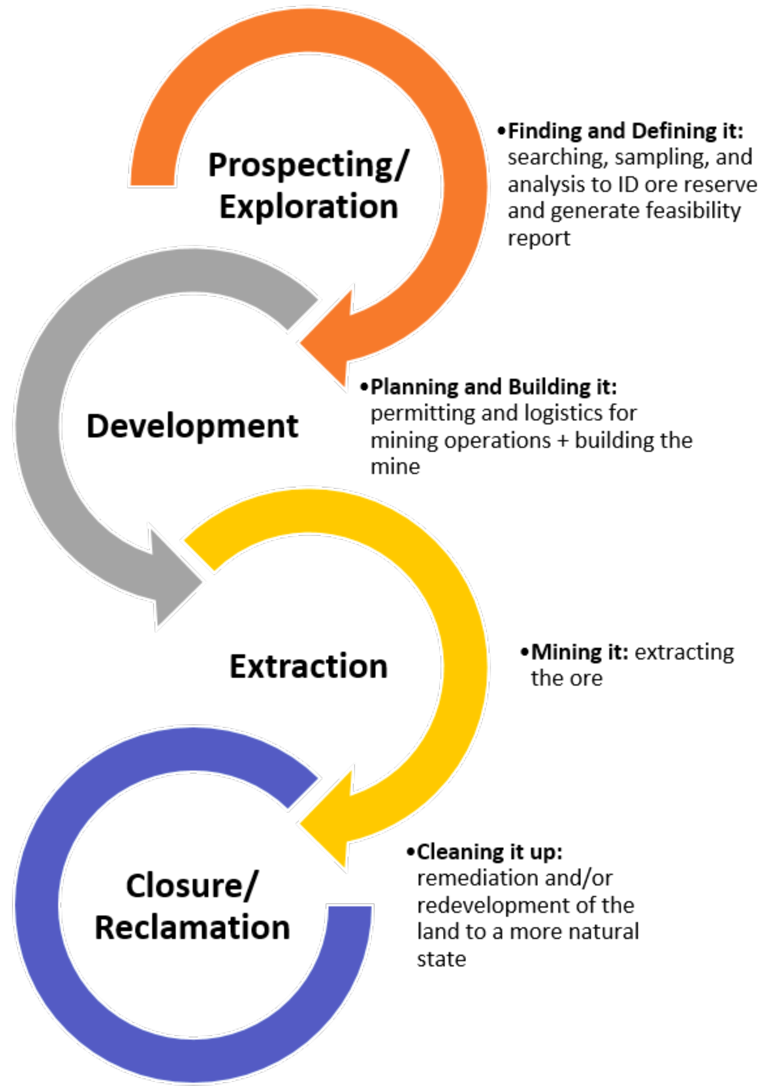
Ralph Cordiner, 1961



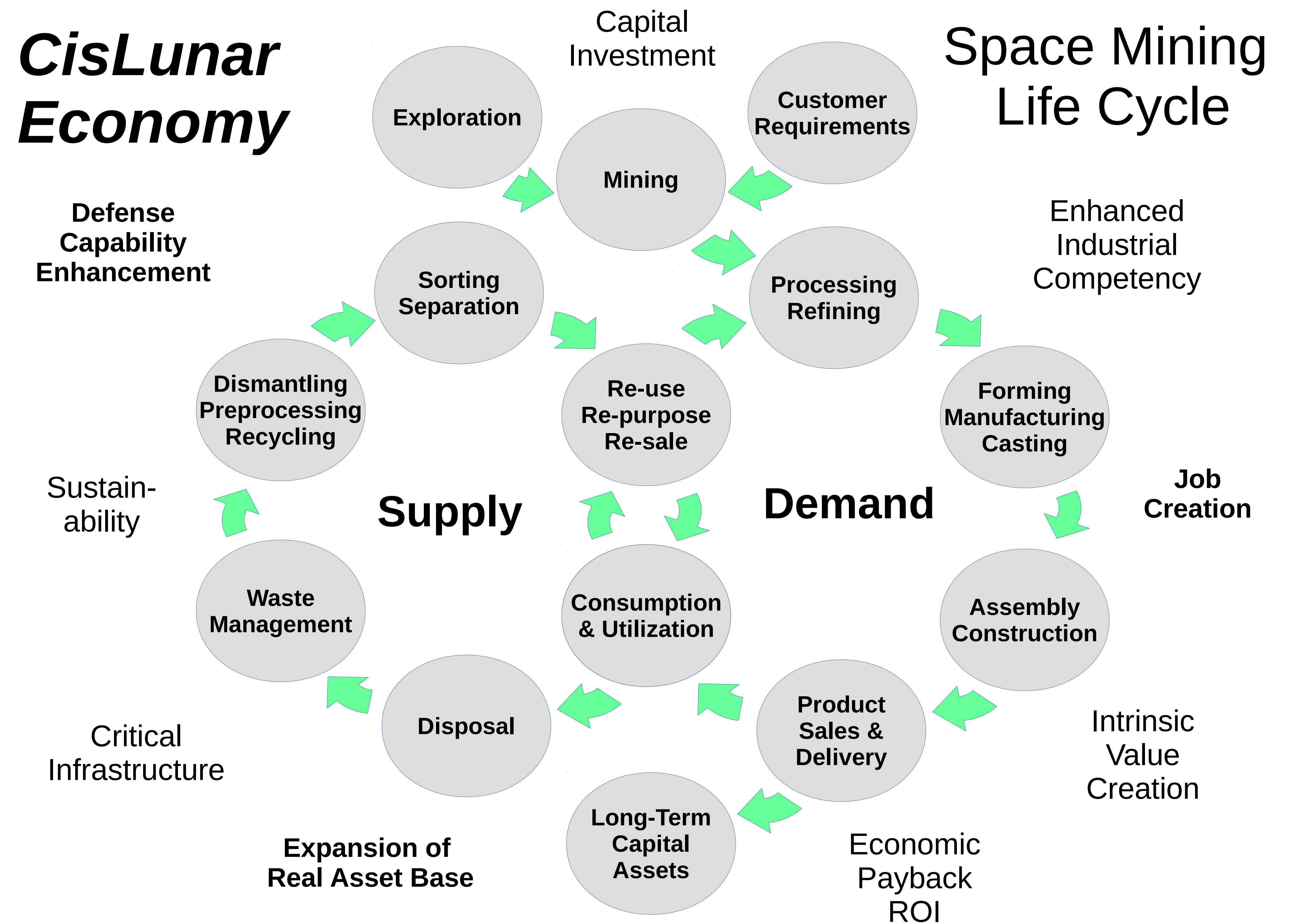
https://denniswingo.wordpress.com/2014/04/01/the-economic-development-of-the-solar-system-lessons-from-1961/

A Mining Industry Framework

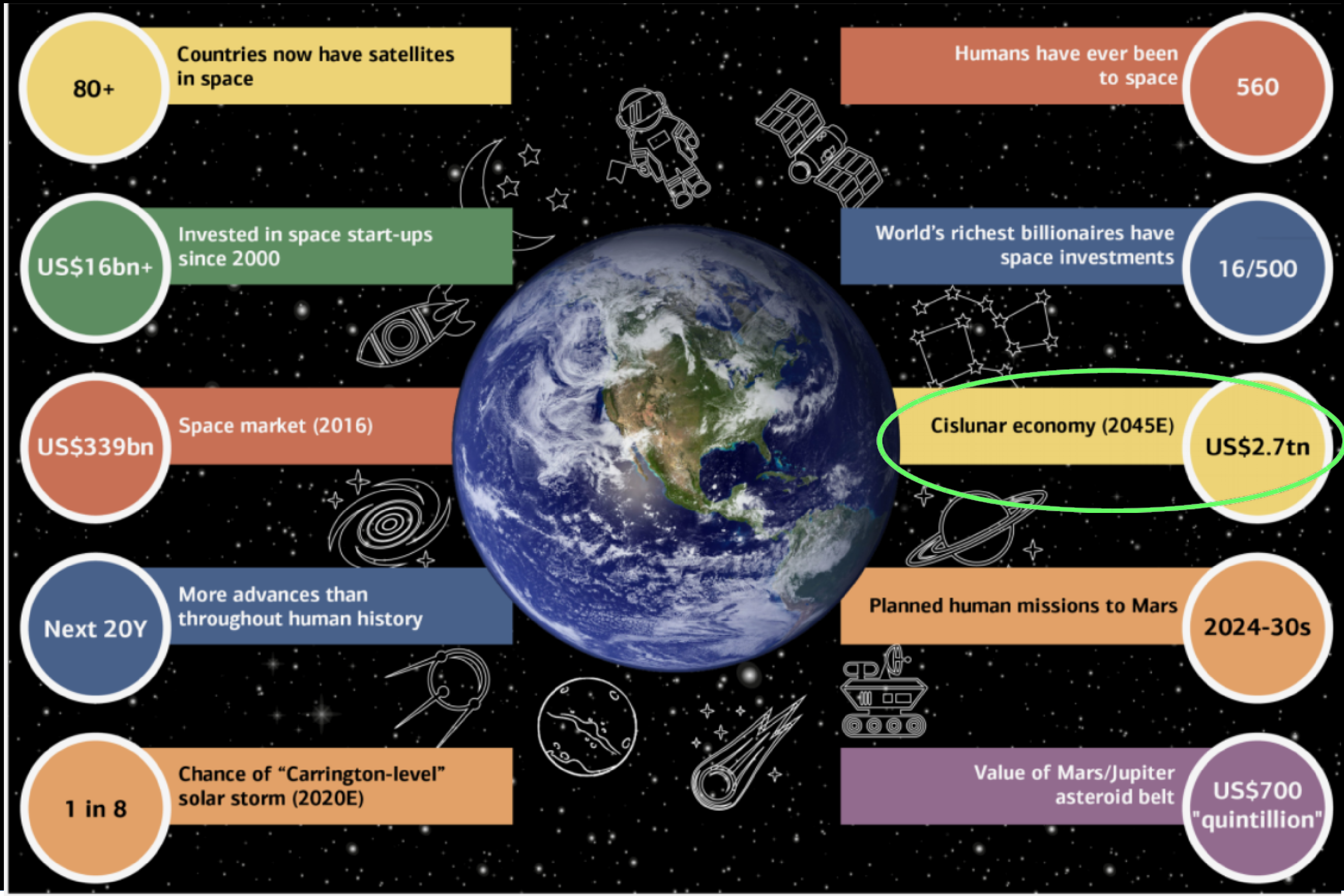




https://superfund.arizona.edu/learning-modules/tribal-modules/copper/mine-life-cycle


CisLunar Economy
Space Mining Life Cycle
Capital Investment
Exploration
Mining
Customer Requirements
Defense Capability Enhancement
Sorting Separation
Processing Refining
Enhanced Industrial Competency
Dismantling Preprocessing Recycling
Re-use Re-purpose Re-sale
Forming Manufacturing Casting
Sustain-ability
Supply
Demand
Job Creation
Waste Management
Consumption & Utilization
Assembly Construction
Disposal
Product Sales & Delivery
Intrinsic Value Creation
Critical Infrastructure
Long-Term Capital Assets
Expansion of Real Asset Base
Economic Payback ROI

BofAML Global Research 2017



Source: BofAML Global Research based on various sources

BofA RIC-Report-November-2017.pdf

DEMAND MODELING

Lunar Surface Propellant Interest

https://www.cnbc.com/amp/2019/06/19/jeff-bezos-blue-origin-will-refuel-lunar-lander-with-moon-ice.html

CNBC

MENU

Bezos says Blue Origin will one day refuel its lunar lander with ice from the moon

Michael Sheetz | @thesheetztweetz

Military Demand - Propulsion

USG ASSETS RESULTS

Based on ~130 military assets, it was estimated:

- Current demand is ~45 tons of water per year
- 333 kg of water per asset per year

A future water propelled U.S. military asset would require:

- 3,000 kg for deployment
- 130 kg for disposal
- 610 kg per year for station keeping

Supply chain demand:

- ~40% Fuel for LEO
- ~20% Fuel for MEO
- ~40% Fuel for GEO

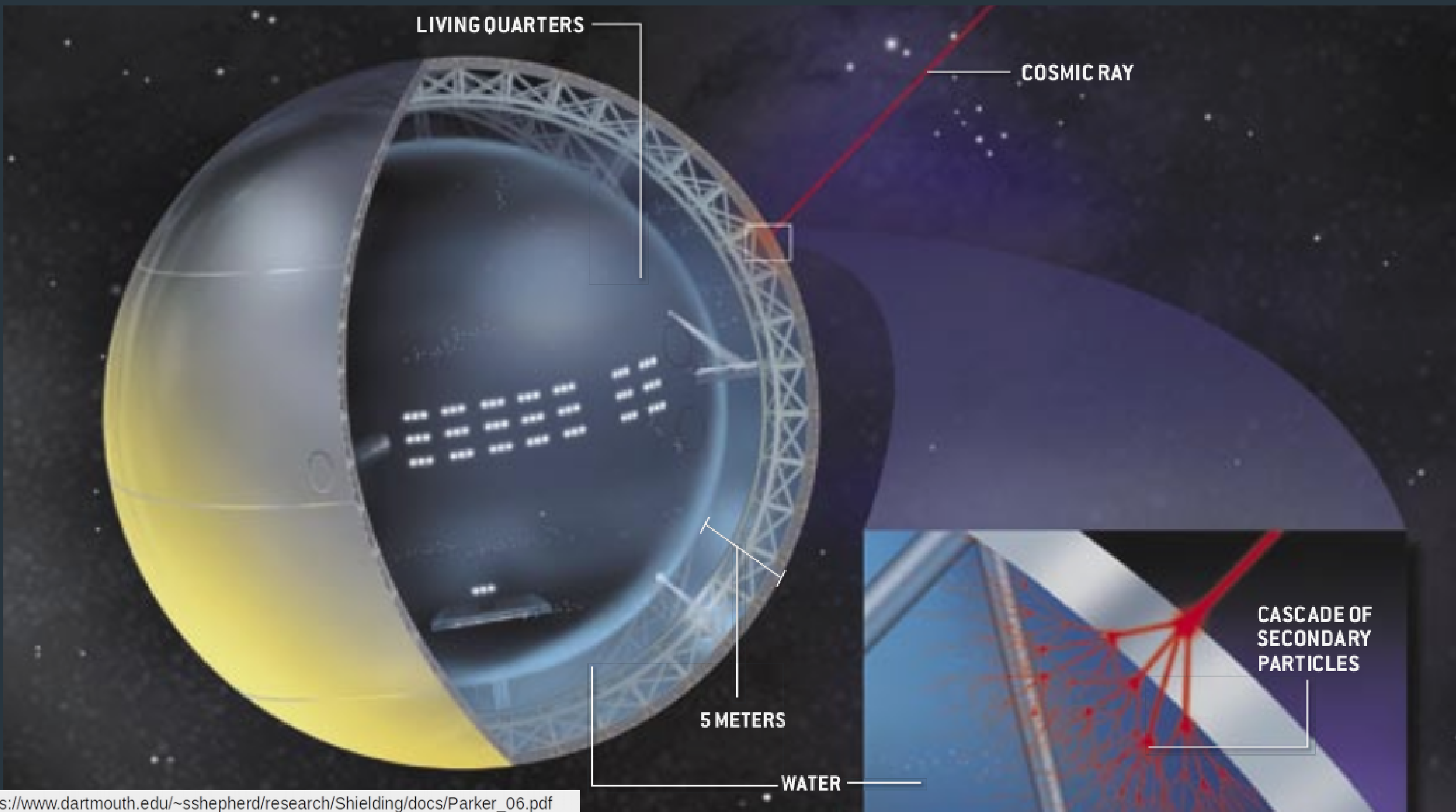
Transportation to destination orbit needs 50% for LH2/LOX and 10% for ion/plasma

https://isruinfo.com/public/docs/srr20_ptmss/2-4%20Military%20supply%20and%20demand%20for%20in-space%20water-based%20fuel-Aspiotis%20&%20Oleary.zip

H_2O based Radiation Shielding

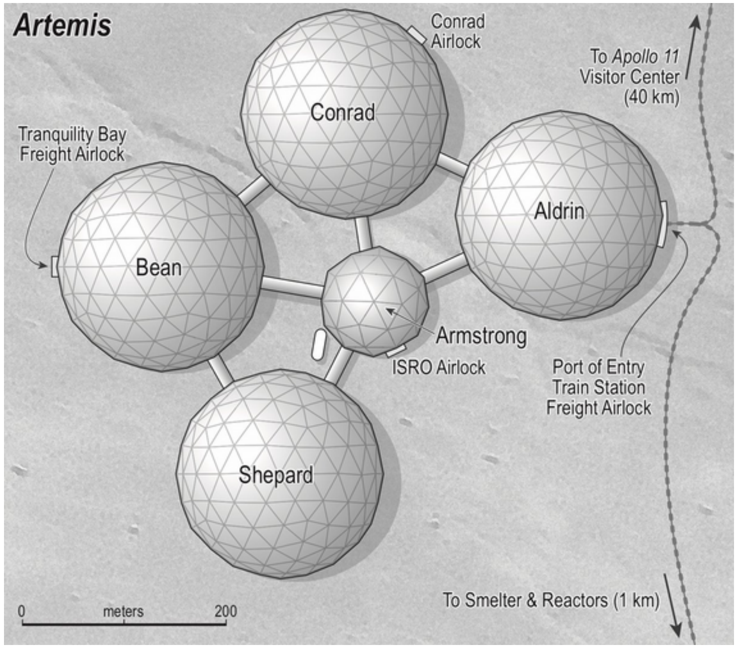
PLAN 1: MATERIAL SHIELD

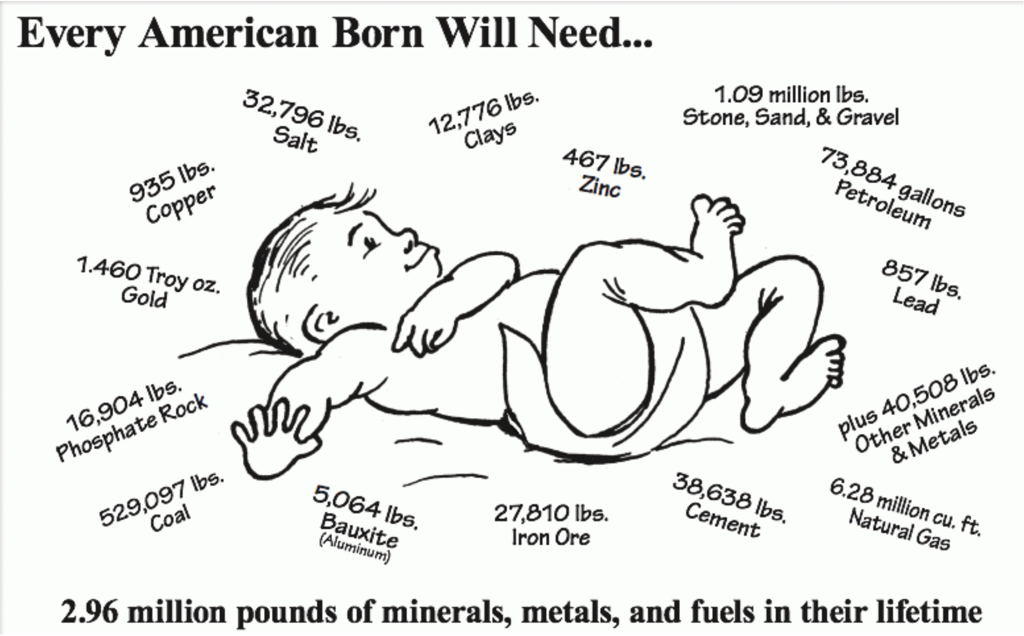
A large mass around the astronauts absorbs incoming radiation and the secondary particles it produces. A spherical shell of water five meters thick provides the same protection that Earth's atmosphere offers at an altitude of 5,500 meters (18,000 feet).



https://www.dartmouth.edu/~sshepherd/research/Shielding/docs/Parker_06.pdf

Two ways to estimate future demand





Bottoms-up design
(engineering approach)

Analogy
(per capita approach)

This approach requires a significant engineering effort

Terrestrial Supply of Moonbase?

***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

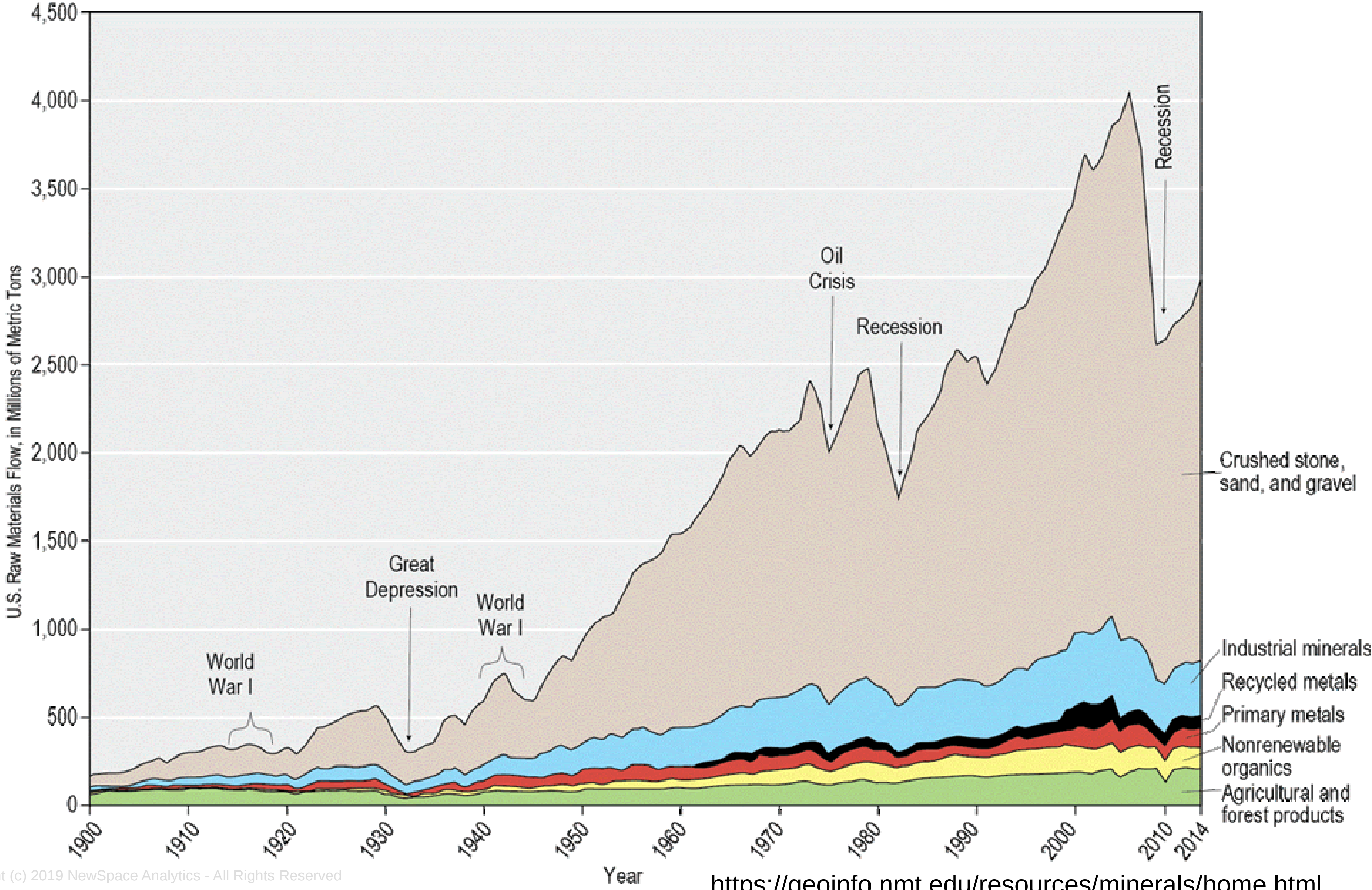
Including These Energy Fuels

- 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—

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

Terrestrial Consumption Analogy

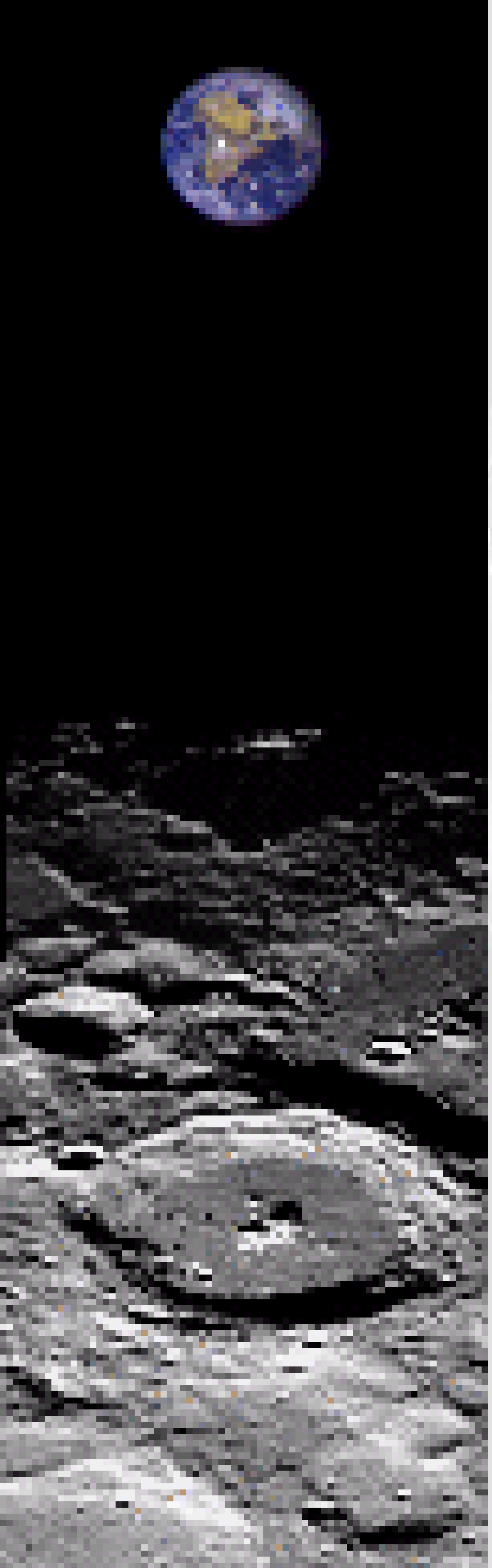


https://geoinfo.nmt.edu/resources/minerals/home.html

CONCEPT OF OPERATIONS
and
ISRU SYSTEMS COSTING

ISRU Trade Studies

- FY89 Eagle Engineering models
  - Apollo engineers generate first complete model of lunar mining, including cost
- FY02 Lunar ISRU Economic Model (CSM)
  - NExT model identified *feasible conditions for lunar commercial investment*
- FY03 DARPA Lunar Manufacturing Fresh Start
  - CSM & MDA (Canada) quantitative model for military applications of ISRU
- FY04 RASC Study
  - Applications of ISRU to lunar basing and Mars propellant cases
- FY05 NASA CE&R
  - NASA Concept Evaluation & Refinement contract – four ISRU-centric lunar architectures developed by Lockheed, Boeing, Raytheon and tSpace
- FY07 Georgia Tech ISRU Study
  - A.C. Charania is now V.P. of Business Development at Blue Origin
- FY12 Spudis / MSFC
  - ISRU applications to a Constellation lunar surface architecture
- FY15 Evolvable Lunar Architecture (ELA)
  - Commercial model
- FY18 CSM-ULA Engineering Model for Polar Ice Mining
  - Outgrowth of CisLunar 1000 architecture



The Case for Commercial Lunar Ice Mining

by

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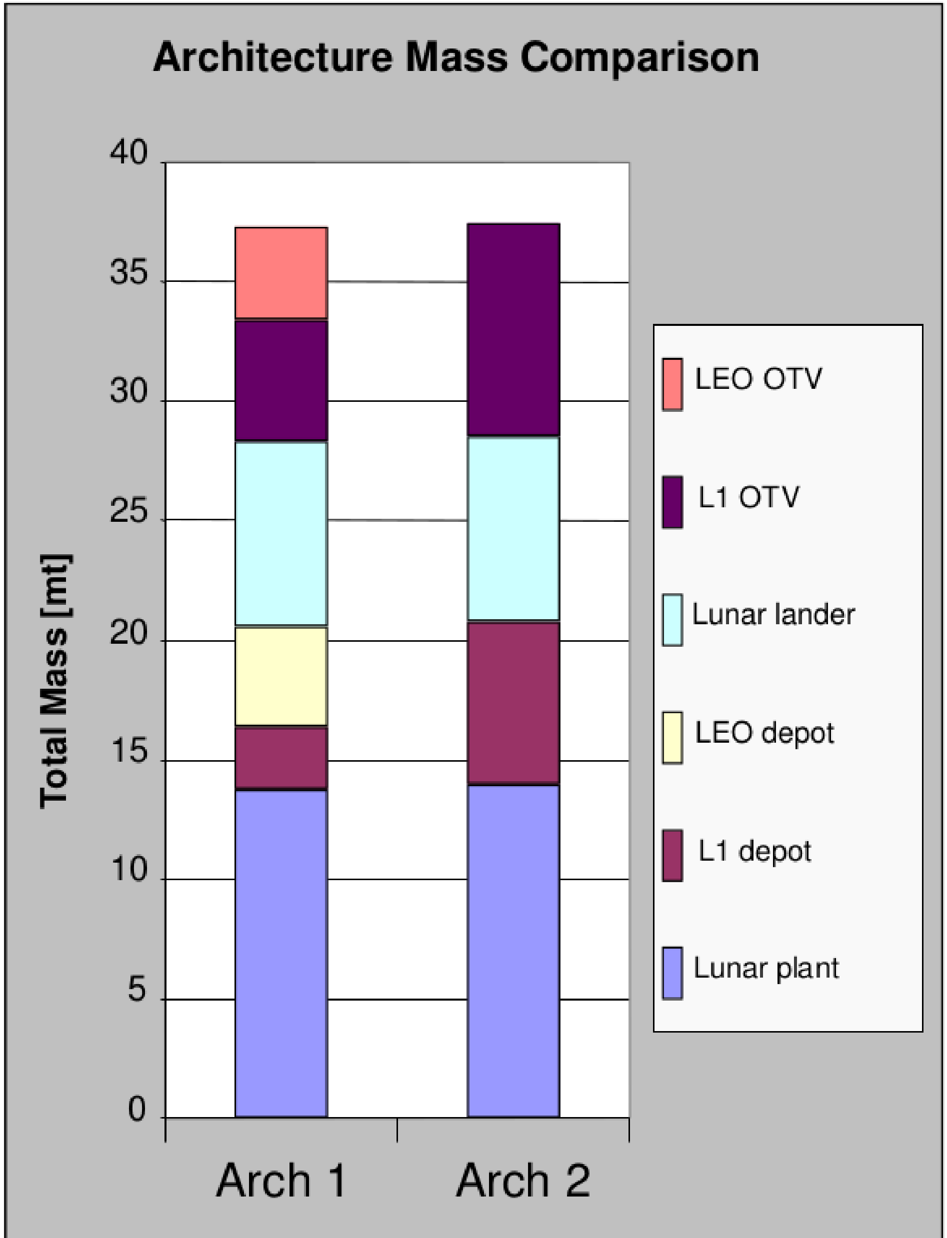
December, 2002

http://www.isruinfo.com//docs/LDEM_Draft4-updated.pdf

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

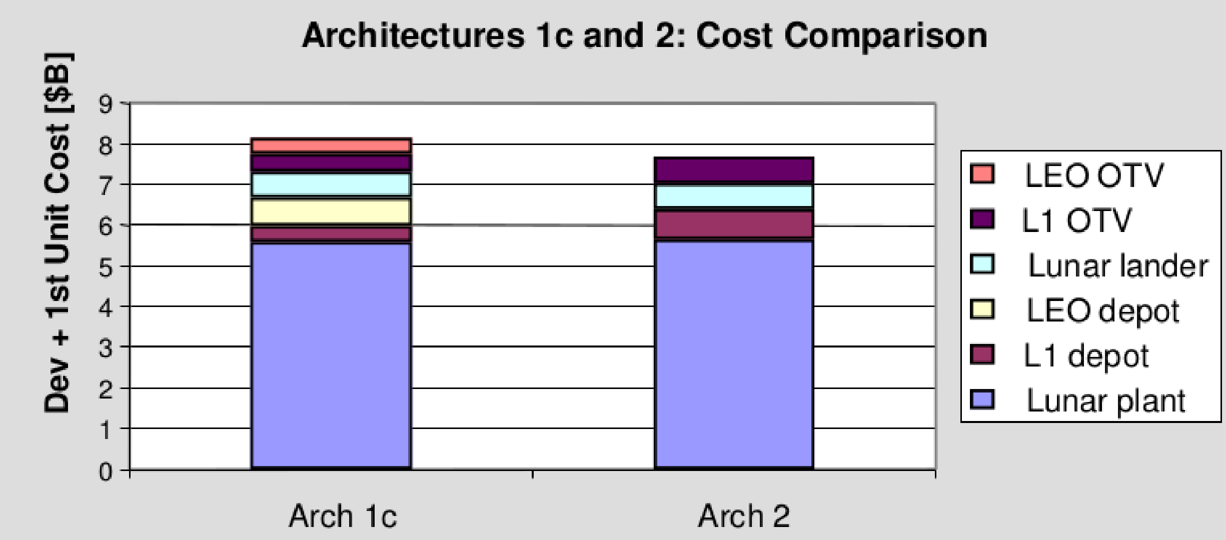
Vehicle	mass (kg)
Moon - L1 (Lander / fuel carrier)	7869
Propulsion system	2180
Telecomm	10
water storage (0.01%)	256
C&DH	3
Structures	3482
Power	15
Landing System	1801
L1-LEO-L1 Vehicle (fuel carrier)	1424
Propulsion system	636
Telecomm	10
water storage (0.01%)	200
C&DH	3
Structures	560
Power	15
L1-LEO 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 Cost Model Assumptions

- Tools that were used to build the cost model
  - NAFCOM (NASA and Air Force Cost Model)
    - Cost model for space hardware development and production
    - Reports DDT&E and Production Unit costs
    - Includes integration costs, overhead, program management, and fees
    - Analogy database includes numerous manned and unmanned NASA program system elements and has a high level of detail
  - SOCM (Space Operations Cost Model)
    - Cost model for operations related to architecture
    - Estimates operating costs and FTEs for discreet systems
  - Launch Costs ($10,000/kg to LEO; $40,000 to L-1; $90,000 to the lunar surface)
  - Refurbishment Costs
- Cost are rolled-up into Annual Cost basis
  - Annual costs are discounted at 8%
  - Integrates output of NAFCOM, SOCM, and launch cost models
  - Aggregates cost elements into temporal format (e.g., annual costs)
  - Includes 10% replacement hardware (fabrication and launch)
- Costs were estimated for the ISRU Architecture, and compared to a Baseline Fully Expendable Architecture

Definition of “Improvement Factors”

A number of parametric factors were defined for the purpose of simplifying the analysis of the effect of certain major assumptions in the cost model

- Extraction efficiency: The proportion of a resource that can be extracted from the raw material
- Transportation cost factor: A factor applied to obtain possible future costs compared to current transportation costs (e.g. cost of Earth to LEO transportation)
- Development cost factor: A factor that can be used to represent the possibility of lower production costs than those included in the government NAFCOM model
- Production cost factor: A similar factor for the production costs modeled by NAFCOM
- Operation cost factor: A factor relating possible future costs in comparison to the current SOCM operations model
- Transfer demand factor: A linear multiplier to represent possible future levels of demand for transfer of payloads from LEO to GEO in comparison to those of this model
- Refueling demand factor: A linear multiplier to represent possible future levels of demand for resupply to satellites in Earth orbit in comparison to those of this model
- Technology factors: Multipliers to represent possible future improvements to technologies (excavators, reactors, power systems)

Baseline results are derived by setting all factors to 1.0

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

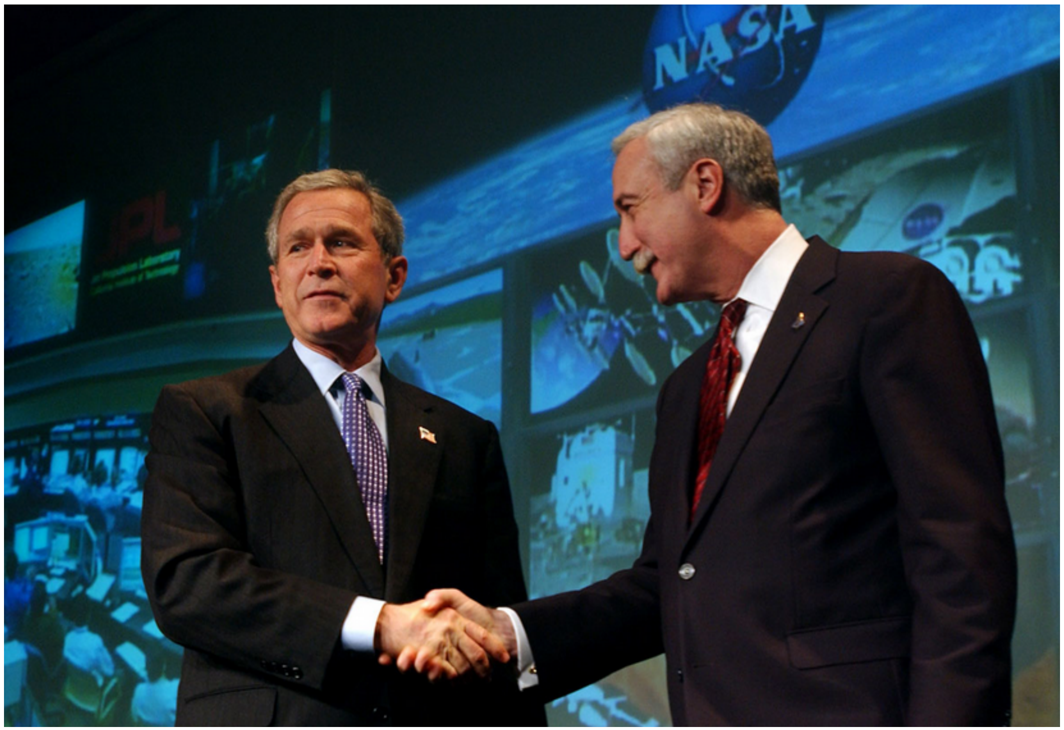
Table 4.3. Model results (key financial metrics) by version for Architectures 1 and 2.

	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 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

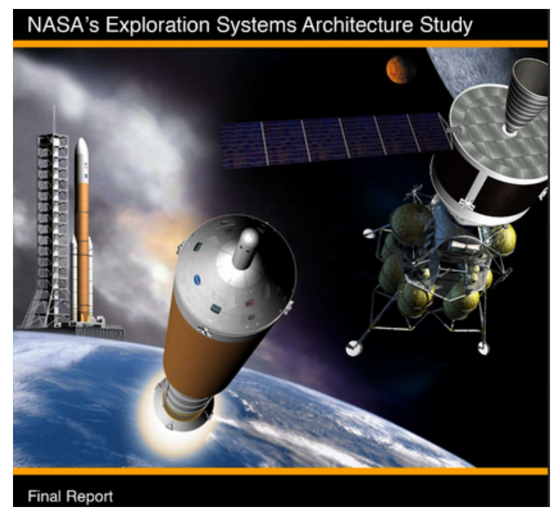
2004 Vision for Space Exploration



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

FY07 ISRU Cost Model (Charania)

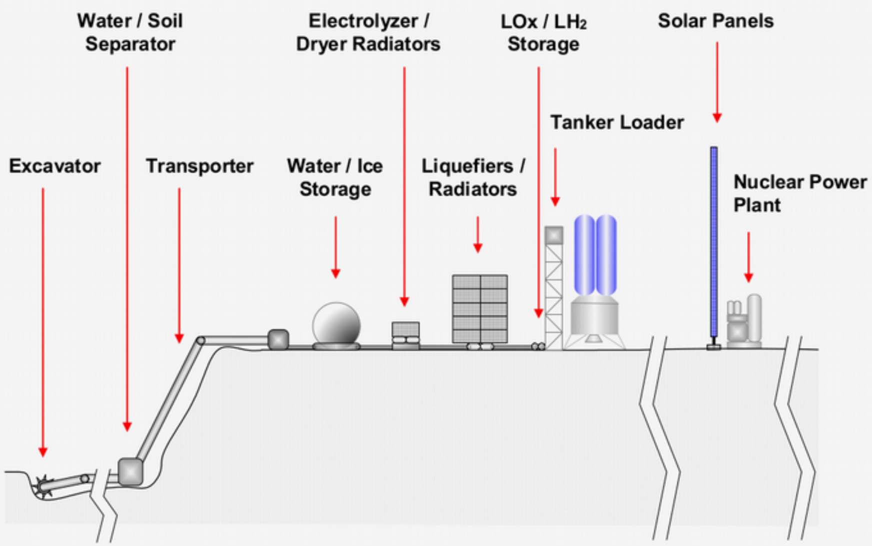
Table 1. Lunar ISRU Plant Size for 21 MT Lunar Lander

Components	Size (stowed) [m]	Mass [MT]
Excavator	2x0.1x0.1	1.00
Separator	D0.6x3	0.80
Transporter	6x0.15x0.15	1.60
Water Storage	D2.0x1.7	1.43
WTM Loader	-----	-----
Wheel Loader	-----	-----
Wheel Crane	2.5x1.6x2	4.80
Nuclear Power Station	D8.6x2	5.40
Power and Transport Sub-Total		**15.03**
Electrolyzer	1x1x1	1.08
Dryer Radiators	3x3.1x0.05	0.04
Liquefiers LOX	0.6x0.7x1	0.13
Liquefiers LH2	0.5x1x1	0.42
Radiators LOX	5x3x0.1	0.21
Radiators LH2	5x3x0.3	0.58
Storage LOX	D1.6x2.1	1.23
Storage LH2	D1.6x4.3	2.15
Solar Panels	D8.6x0.45	0.07
Lunar Habitat Module	-----	-----
Soil and Water Management Sub-Total		**5.91**
Lunar ISRU Plant Systems Total		**20.94**

Table 2. Monte Carlo Simulation: Triangular Distributions for Various Cost Uncertainty Parameters

Parameter	Deterministic/ Most Likely: Case 1: Lunar Surface	Deterministic/ Most Likely: Case 2: LLO	Deterministic/ Most Likely: Case 3: GEO	Minimum: All Cases	Maximum: All Cases
DDT&E Cost [$M, FY2006]	**$957 M**	**$ 2,157 M**	**$ 2,557 M**	-25%	+75%
Nuclear Power Plant*	$200 M	$200 M	$200 M		
Excavation/Processing/Storage Facility Cost*	$595 M	$595 M	$595 M		
Mass of Excavation/Processing/Storage Facility*	$162 M	$162 M	$162 M		
Lunar Tanker Vehicle**	-	$1,200 M	$1,200 M		
Orbital Tanker Vehicle**	-	-	$400 M		
Acquisition Cost [$M, FY2006]	**$319 M**	**$ 1,019 M**	**$ 1,044 M**	-25%	+75%
Nuclear Power Plant*	$67 M	$67 M	$67 M		
Excavation/Processing/Storage Facility Cost*	$198 M	$198 M	$198 M		
Mass of Excavation/Processing/Storage Facility*	$54 M	$54 M	$54 M		
Lunar Tanker Vehicle**	-	$700 M	$700 M		
Orbital Tanker Vehicle**	-	-	$25 M		
Transportation Cost to Lunar Surface [$M, FY2006]	**$1,445 M**	**$2,220 M**	**$2,240 M**	-10%	+25%
Cargo Launch Vehicle (CaLV)***	$560 M	$1,120 M	$1,120 M		
Earth Departure Stage (EDS)****	$215 M	$430 M	$430 M		
Lunar Surface Access Module (LSAM)****	$670 M	$670 M	$670 M		
Falcon V or similar launch of OTV	-	-	$20 M		
Mission Operations Cost [$M/year, FY2006]	**$35 M**	**$35 M**	**$35 M**	**-10%**	**+50%**

Notes:
United States Dollars FY2006 unless otherwise noted
* - Source: Shimizu Corporation (75% development cost, 25% acquisition cost)
** - Source: SEI internal cost estimates derived from previous work; development cost to the commercial company is for modification of existing stages, not for complete development of a new vehicle
*** - Source: Charania, A., "The Trillion Dollar Question: Anatomy of the Vision for Space Exploration Cost," AIAA-2005-6637, Space 2005, Long Beach, California, August 30 - September 1, 2005[7].
**** - Source: Exploration Systems Architecture Study (ESAS) Draft Report, Section 12[6].



Credit: Shimizu Corporation
*Elements shown are not to scale, but represent those that are included in the plant landed by the lunar cargo lander

Figure 4. Notional Elements of a Lunar ISRU Plant and Storage Depot

Table 2. Monte Carlo Simulation: Triangular Distributions for Various Cost Uncertainty Parameters

Parameter	Deterministic/ Most Likely: Case 1: Lunar Surface	Deterministic/ Most Likely: Case 2: LLO	Deterministic/ Most Likely: Case 3: GEO	Minimum: All Cases	Maximum: All Cases
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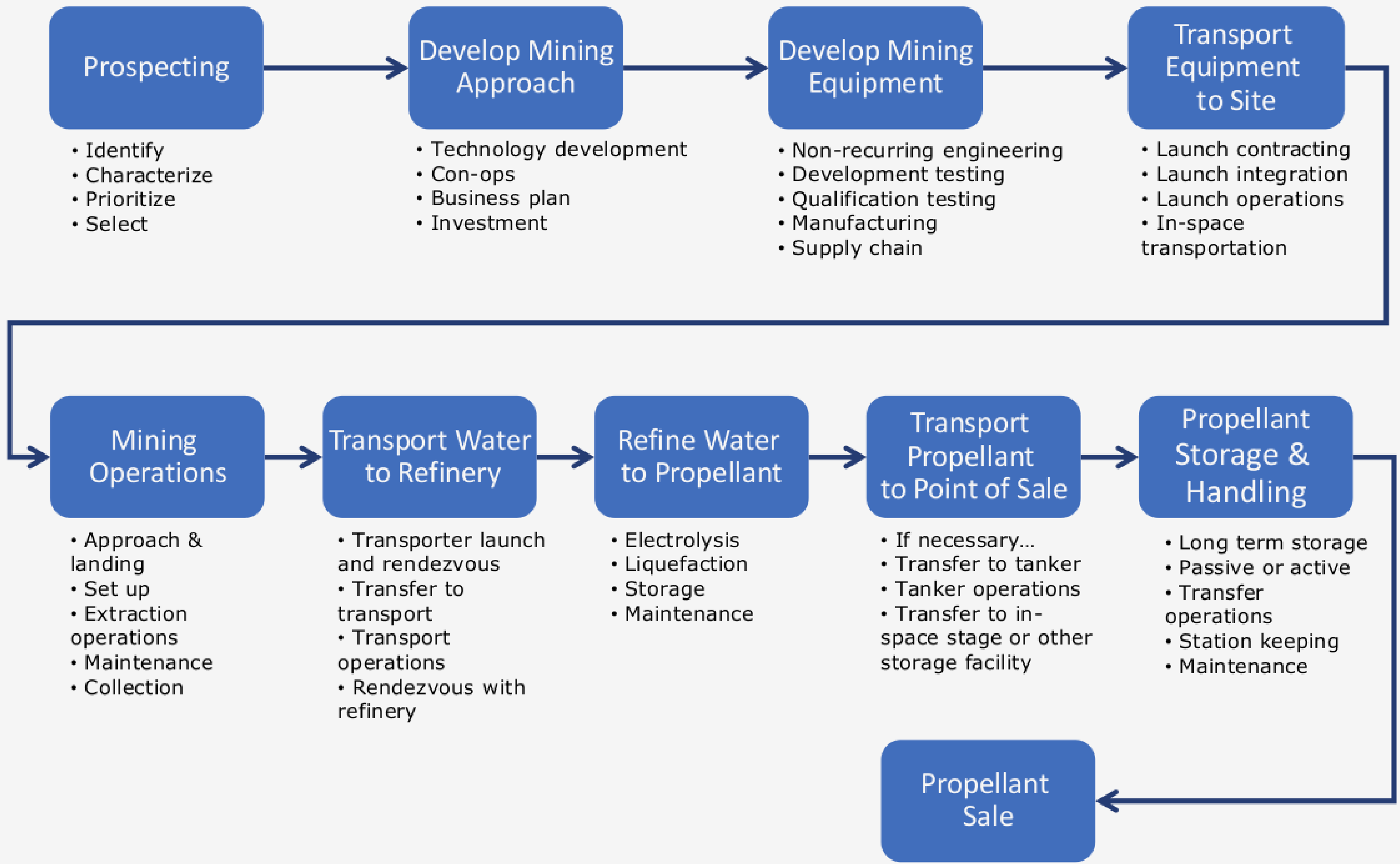
CSM-ULA Mining Architecture



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.

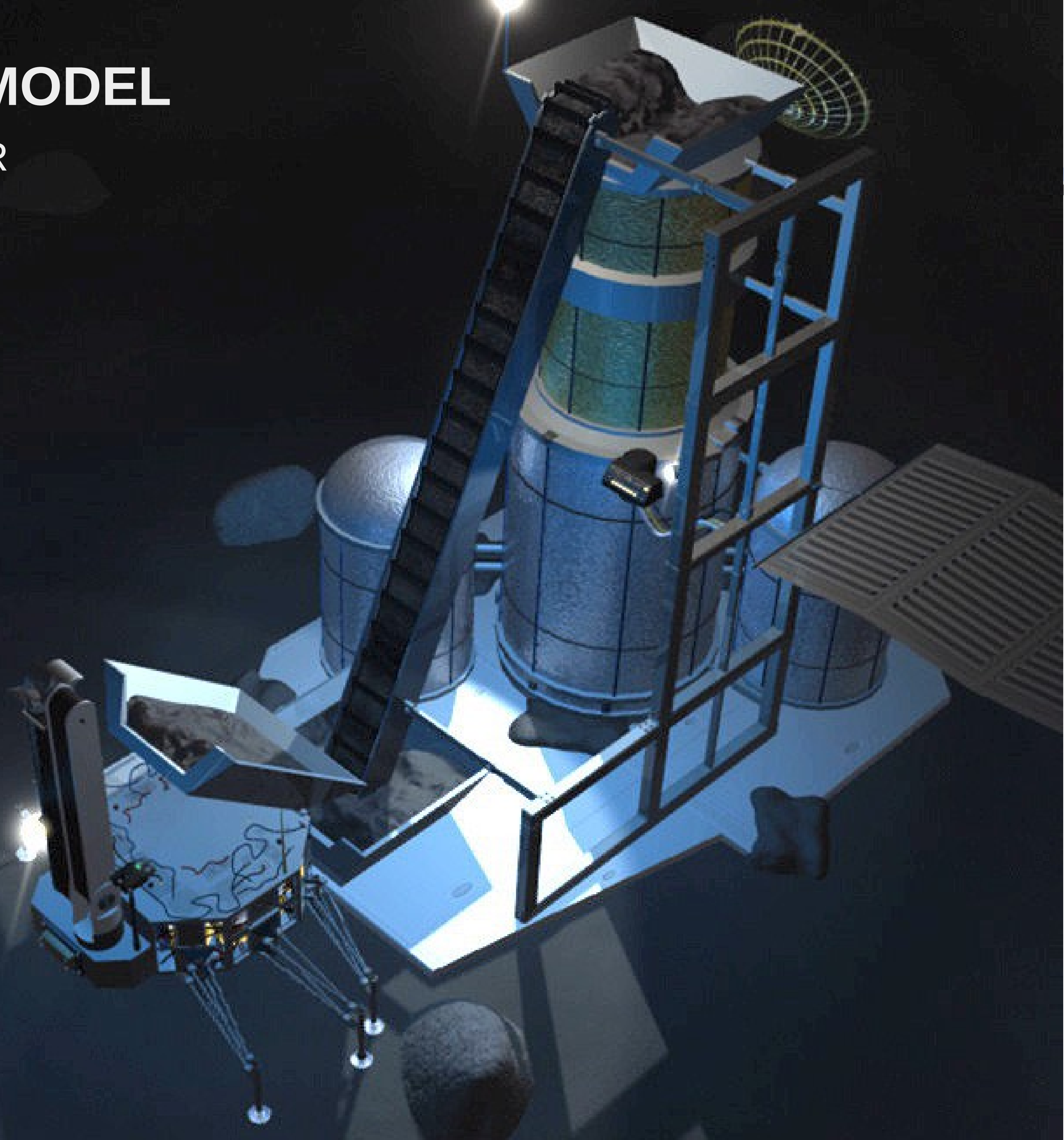
Colaprete et al. (2010)

VOLATILE PROCESS MODEL

- PRIMARY HEATING REACTOR
- WATER ELECTROLYSIS
- OXYGEN LIQUEFIER
- HYDROGEN LIQUEFIER
- NITROGEN LIQUEFIER
- FRACTIONAL DISTILLATION
- SABATIER REACTOR
- SULFUR EXTRACTION
- 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

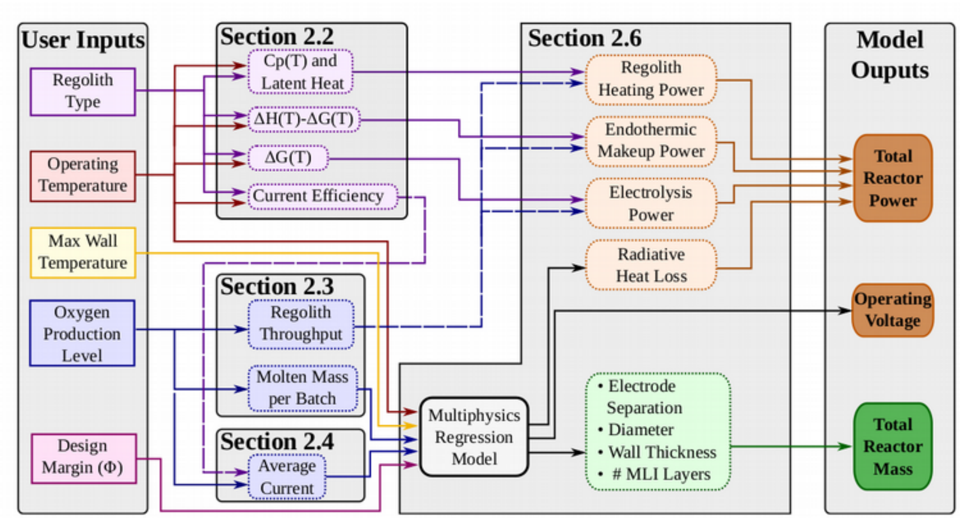


Figure 2.1 of [Schreiner and Hoffman, 2015]

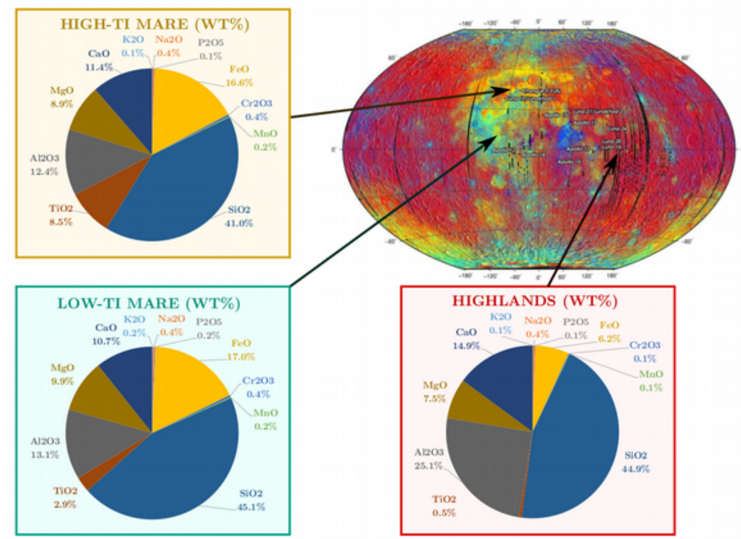


Figure 2.2 of [Schreiner and Hoffman, 2015]

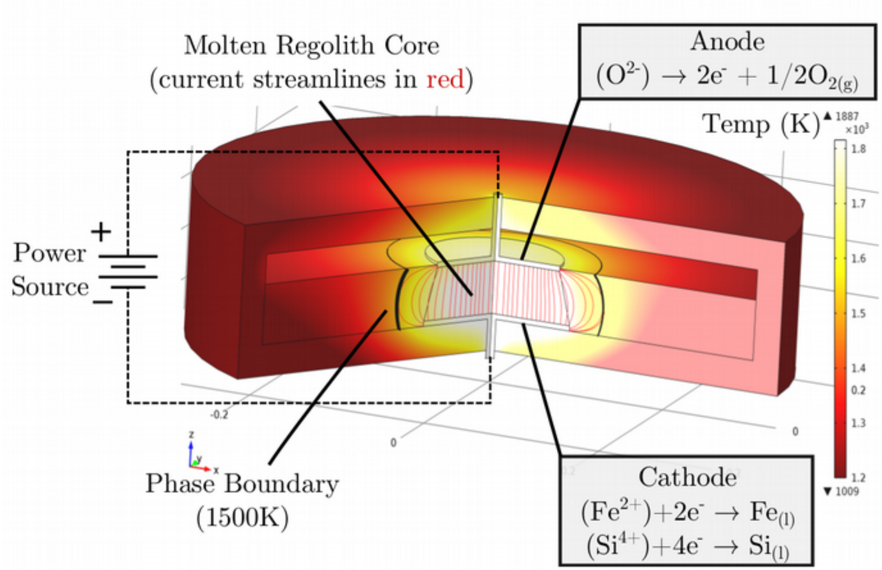


Figure 1.2 of [Schreiner and Hoffman, 2015]

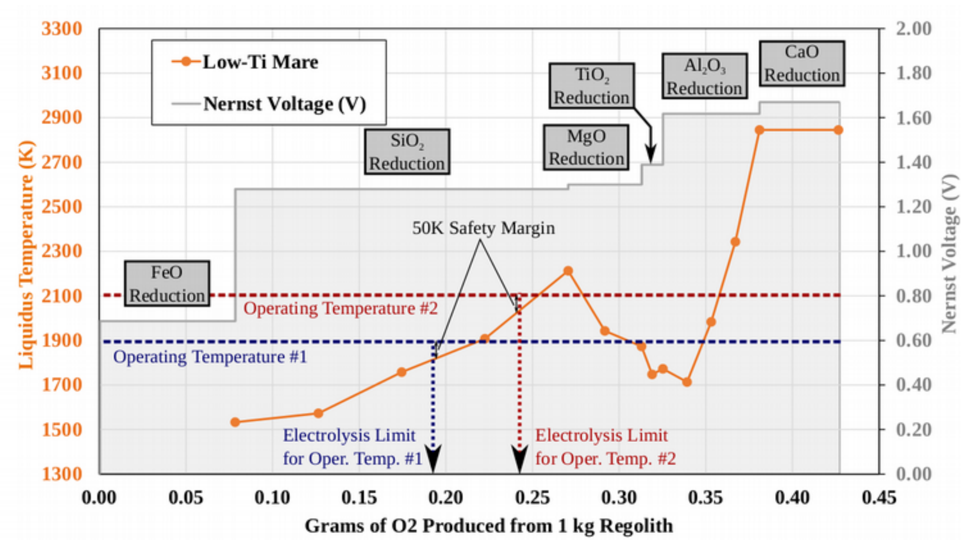


Figure 2.9 of [Schreiner and Hoffman, 2015]

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

Price per Unit Weight

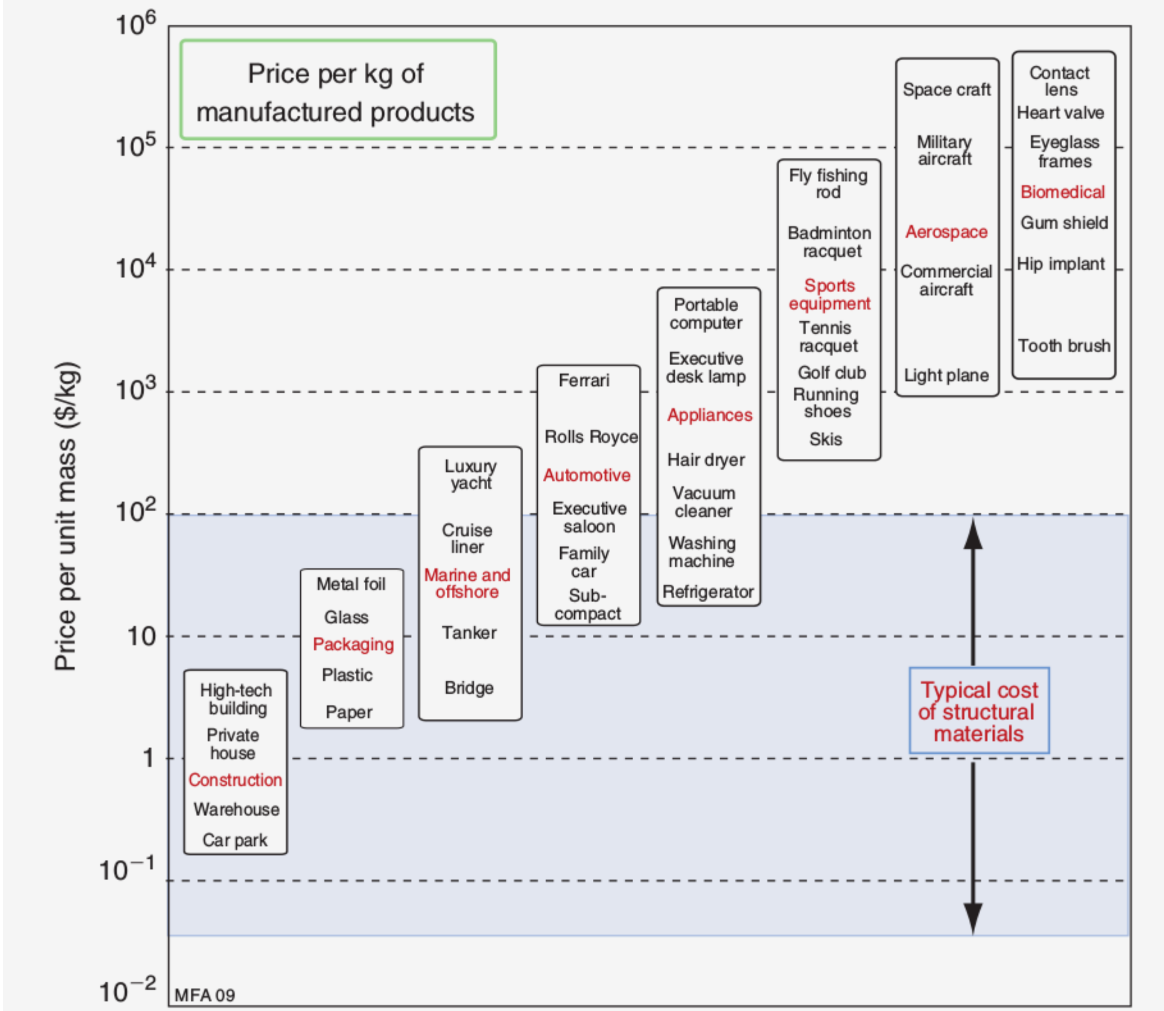
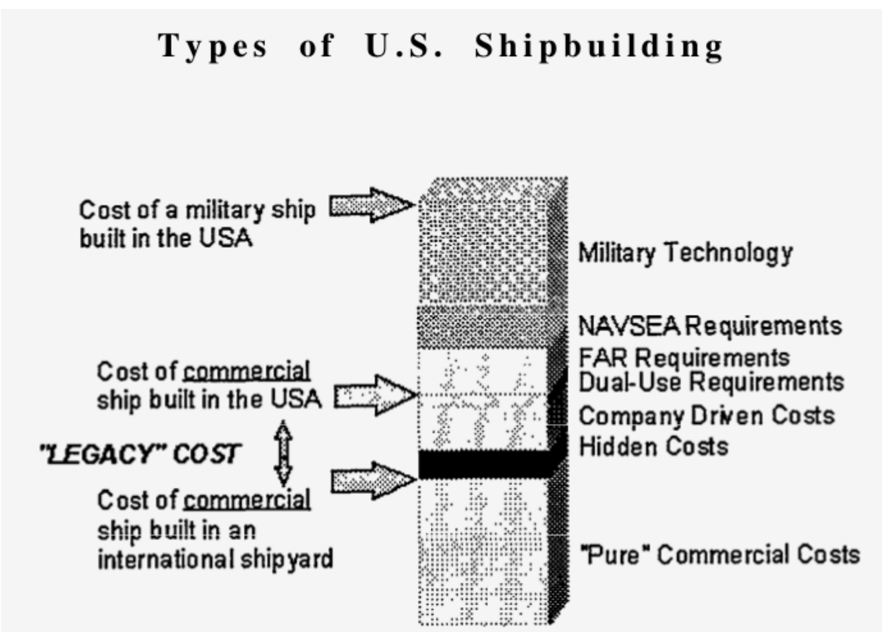


FIGURE 11.4 *The price-per-unit weight diagram for products. The shaded band spans the range in which lies most of the material of which they are made. Products in the shaded band are material intensive; those above it are not.*

Materials and the Environment (1st edition) Figure 11.4 by Ashby 2009
https://adminimages.muhandes.net/content/library/628007254b8e4bb5bdc1a25ba21b4d51.pdf

Unit Costs for Drilling Ships



NSRP, "Shipyard Cost Model Using Activity-Based Costing Methods," National Shipbuilding Research Program (NSRP) Report #0478, Naval Surface Warfare Center in cooperation with National Steel and Shipbuilding Company, October 1996, www.dtic.mil/dtic/tr/fulltext/u2/a451193.pdf

Jackup design class properties and newbuild cost (2011).

Design	Number	Price (million $)	Water depth (ft)	Harsh	VDL (tons)
Friede & Goldman JU-2000E	11	190-220	400	Y	7,000
LeTourneau Super 116E Class	12	159-210	200-375	N	3,750
KFELS B Class	20	180-210	350-400	N	4,500
PPL Shipyard Pacific Class 400	3	190	400	N	3,750
Friede & Goldman JU-2000A	4	220-229	350	Y	4,500
Friede & Goldman JU-3000N	6	220-245	400	N	7,000
KFELS Super A Class	5	230-260	400	Y	7,000
LeTourneau 240-C Workhorse	3	194-257	400	N	3,000
GustoMSC CJ70	3	500-530	492	Y	7,000

Source: Bailey and Sullivan, 2011; Industry press.

Semisubmersible design class properties and newbuild cost (2011).

Design	Number	Price (million $)	Water depth (ft)	Harsh	VDL (tons)	Displacement (tons)
GVA 7500-N	2	526-709	10,000	Y	8,250	62,000
F&G ExD	3	599-771	7,500-10,000	N	10,000	58,000
Ensco 8500	2	537-560	8,500	N	8,000	
CS-50 MkII (N)	2	510-526	9,843-10,000	Y	6,800	47,000
Sevan Drilling 650	3	526-685	10,000	N	22,000	61,000
GM 4000	2	460-560	1,640-4,000	Y	5,000	42,000
GVA 4000 NCS	2	565	1,640	Y		60,000

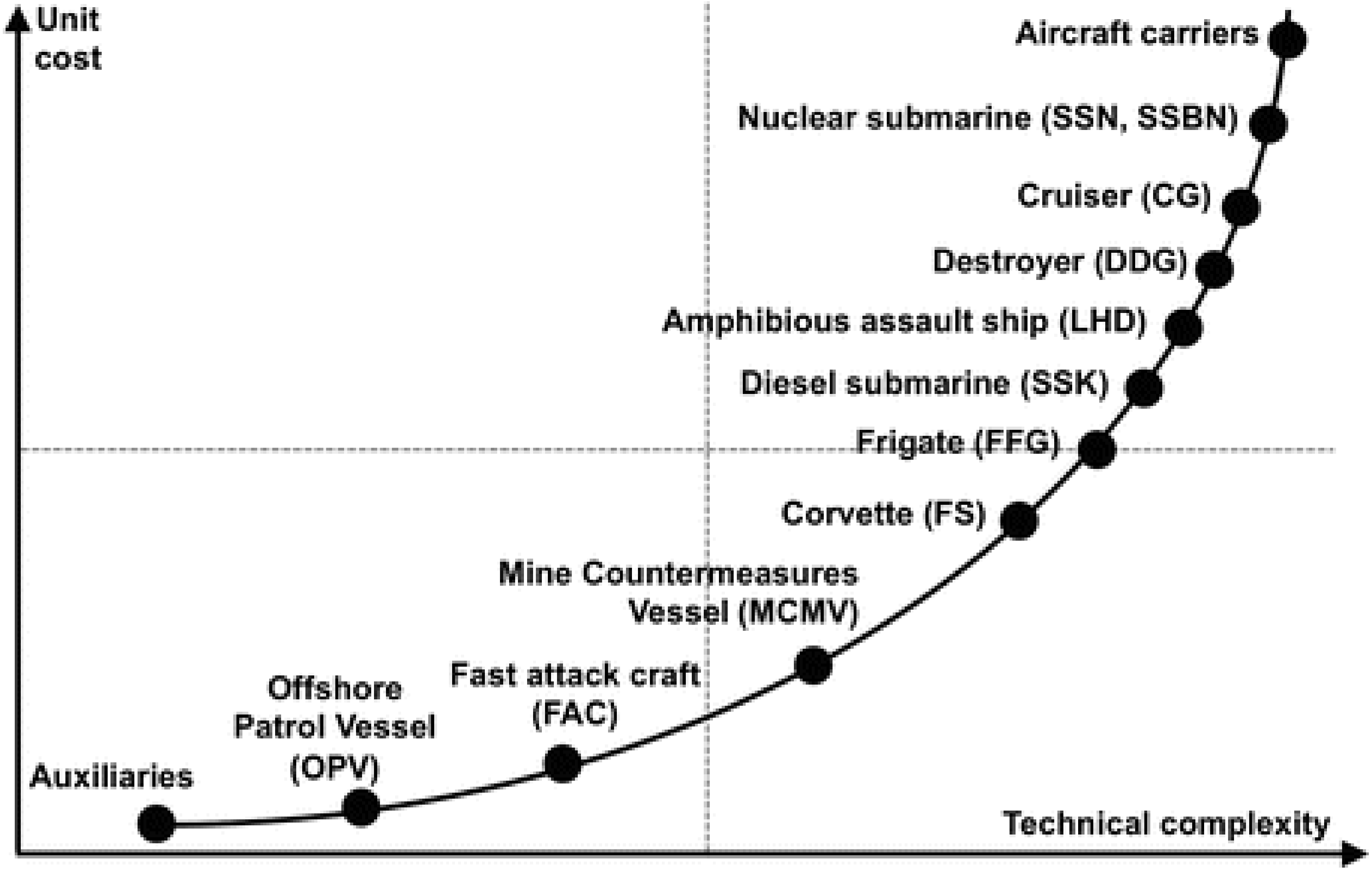
Source: Bailey and Sullivan, 2011; Industry press.

Drillship design class properties and newbuild cost (2011).

Design	Number	Price (million $)	Water depth (ft)	Harsh	VDL (tons)	Displacement (tons)
DSME 10000	2	579	10000	N	24,000	112,000
DSME 12000	6	590-782	10,000-12,000	N	24,000	112,000
GustoMSC P10000	11	590-630	10,000-12,000	N	20,000	75,000
GustoMSC PRD12,000	1	632	12,000	N	15,000	45,000
Samsung 10000	17	638-820	10,000-12,000	N	22,000	105,000
Samsung 12000	8	550-650	10,000-12,000	N	22,000	105,000
Stena/Samsung	1	1,150	7,500	Y	19,000	108,000
Huisman GT-10000	2	550-585	10,000	N	20,000	60,000

Source: Bailey and Sullivan, 2011; Industry press.

Unit Costs for Navy Vessels



Source: Estimation based on various reports in the *Defense News*, *Jane's Navy International*, *Jane's Defense Weekly* over several years, and interviews with various naval shipbuilding representatives, March 2013

https://link.springer.com/chapter/10.1007/978-3-662-47127-2_3

https://www.google.com/imgres?imgurl=https%3A%2F%2Fmedia.springernature.com%2Flw785%2Fspringer-static%2Fimage%2Fchp%253A10.1007%252F978-3-662-47127-2_3%2FMediaObjects%2F303825_1_En_3_Fig6_HTML.gif&imgrefurl=https%3A%2F%2Flink.springer.com%2Fchapter%2F10.1007%2F978-3-662-47127-2_3&docid=BAWXlVn04f0qmM&tbnid=m-GRHmolK_BKKM%3A&vet=10ahUKEwjgiKq6w-3cAhWL4IMKHT06Dw0QMwg_KAAwAA..i

Scaling Laws in Unit Costing

Comparative Costs per Kilogram for Manufactured Systems

Spacecraft	dry mass (t)	cost $M	**$k/kg**	source
MSL Rover (Curiosity)	3.8	2500	**658**	https://en.wikipedia.org/wiki/Mars_Science_Laboratory
GOES-16 weather satellite	5.2	2750	**529**	https://spacepolicyonline.com/news/noaas-newest-weather-satellite-goes-s-ready-for-launch/
Telstar 19V	3.0	100	**33.0**	https://spacenews.com/maxar-considering-quitting-geo-satellite-manufacturing-business/
Aircraft				
F-22 Raptor	19.7	339	**17.2**	https://en.wikipedia.org/wiki/Lockheed_Martin_F-22_Raptor
B-2 Stealth Bomber	71.7	1152	**16.1**	https://en.wikipedia.org/wiki/Northrop_Grumman_B-2_Spirit
F-18E	13.4	120	**8.9**	https://www.defense-aerospace.com/dae/articles/communiques/FighterCostFinalJuly06.pdf
F-35A	13.2	94.6	**7.2**	https://en.wikipedia.org/wiki/Lockheed_Martin_F-35_Lightning_II
F-15E	20.4	136	**6.7**	https://www.defense-aerospace.com/dae/articles/communiques/FighterCostFinalJuly06.pdf
Navy Ship (nuclear powered)				
Virginia Class Submarine	7900	3200	**0.41**	https://en.wikipedia.org/wiki/Virginia-class_submarine
Ford-class Aircraft Carrier	100000	13000	**0.13**	https://en.wikipedia.org/wiki/Gerald_R._Ford-class_aircraft_carrier
Mining Equipment				
Rear Dump Truck (55t)	41.2	0.938	**0.023**	http://costs.infomine.com/costdatacenter/miningequipmentcosts.aspx
Wheel Loader (7 cu m)	50	0.912	**0.018**	http://costs.infomine.com/costdatacenter/miningequipmentcosts.aspx
Hydraulic Shovel (4 cu m)	60	1.025	**0.017**	http://costs.infomine.com/costdatacenter/miningequipmentcosts.aspx
Drill Ship				
GustoMSC PRD12,000 Drillship	45000	710	**0.016**	https://www.offshore-mag.com/articles/print/volume-72/issue-7/rig-report/reviewing-rig-construction-cost-factors.

Published ISRU Cost Estimates	Mining & Hauling				Processing Plant + Storage					Power Plant			
	ore type	mass	dev cost	mfg cost	ISRU plant type	kg/yr	mass	dev cost	mfg cost	type	mass	dev cost	mfg cost
Blair (2002)	polar ice	630	47.2	33.2	ice heating & electrolysis	245000	7134	771	54.5	nuclear	3421	565	341
Charania (2007)	unspecified	2600	162	54	unspecified	57600	5910	595	198	nuclear	5400	200	67
Spudis (2011)	polar ice	2300	1065	725	ice heating & electrolysis	30000	2400	4420	1400	solar	1100	n/s	n/s
Lavoie (2016)	polar ice	4000	350	250	ice heating & electrolysis	140000	5000	1000	250	solar	1900	n/s	785

PUBLIC PRIVATE PARTNERSHIPS

Maximizing ISRU Benefits

Defining the Objective Function

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 MYa

PPP Opportunity

- 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.
- 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 1.5 years until the next potential reset (remember - three strikes and you are out).*

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

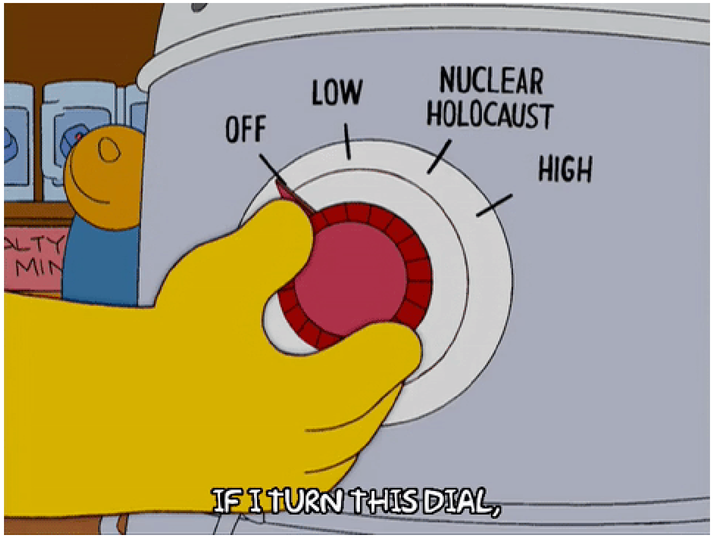
Enterprise Modeling: Study Goals

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

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*

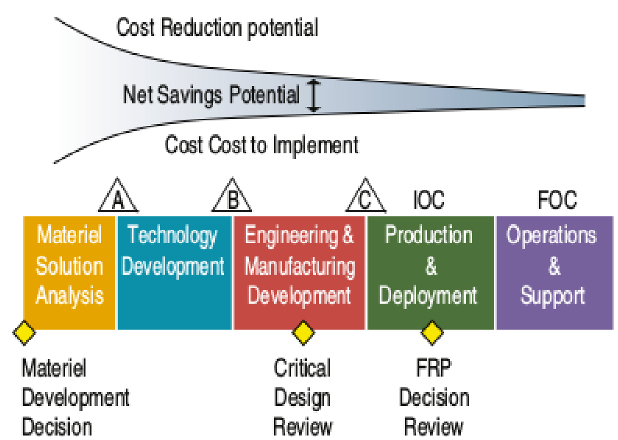


- **<u>Changing government policy and regulatory risks are existential</u>**
  - Focus: Substantial USG co-investment "skin-in-the-game"
  - Model: Choose % of each CapEx category to be government funded
- **<u>Technical obsolescence and/or competition risks boost ROI requirements</u>**
  - Fucus: Lower 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)**



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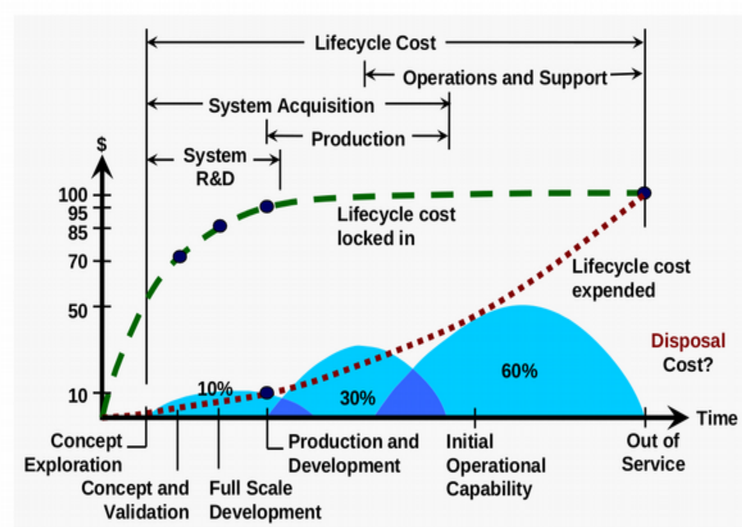
Percentage of Cost Locked In by Phase



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

Resilient Architectures

- “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.

Conclusions & Discussion Points

- 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