Space Mineral Resources

(IAA Cosmic Study 3.17)

Chapter 6: **MARKET MODELING AND PROPELLANT DEMAND FORECASTING**

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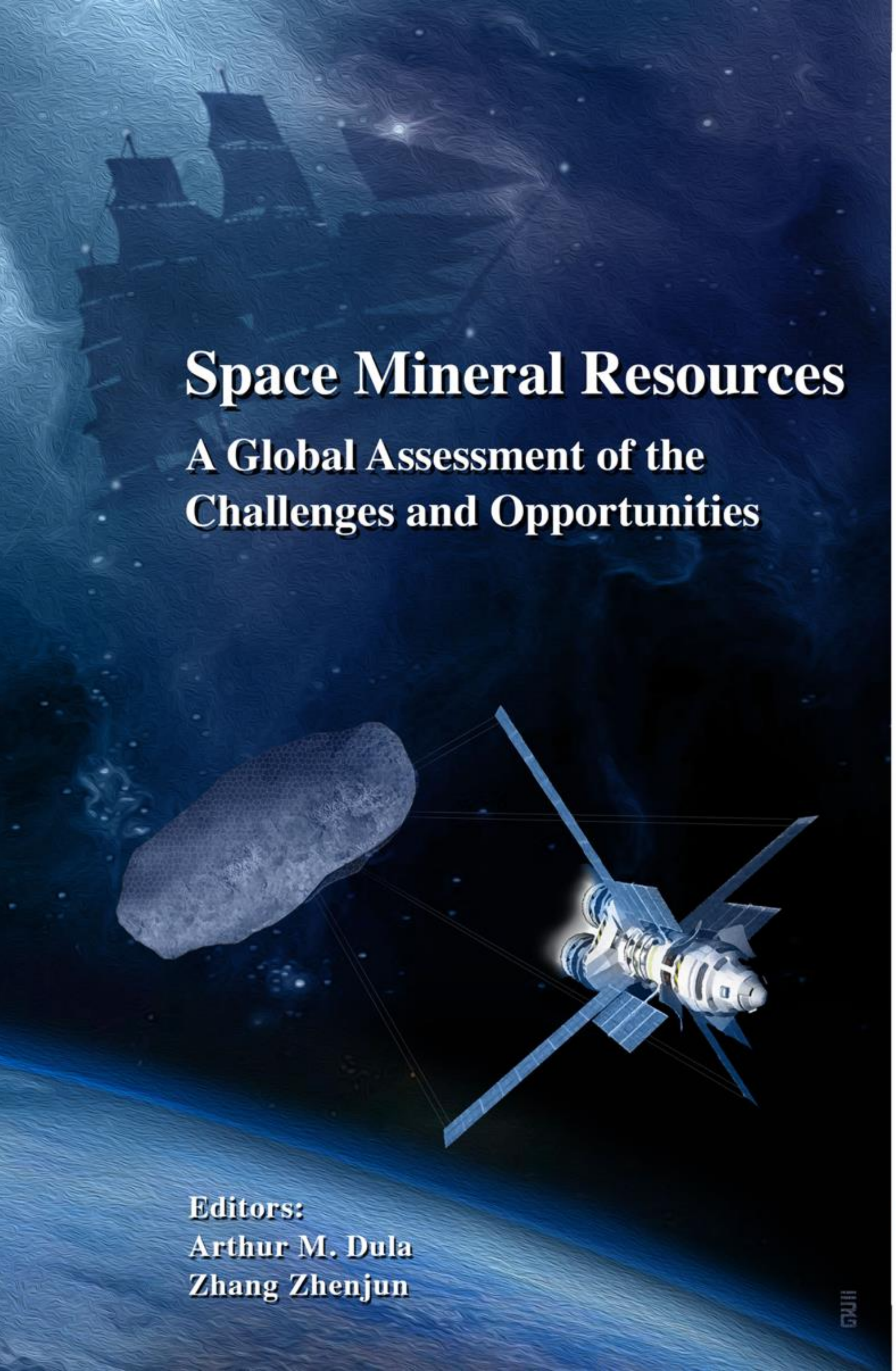

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https://www.amazon.com/Space-Mineral-Resources-Assessment-Opportunities-ebook/dp/B018OJD95Q

What the study provides

- Technical information
- Policy and legal analyses
- Economic context and opportunity analyses
- Recommended next steps
- International roadmap
- Conclusions and recommendations

Chapter Outline

SMR Study Leadership

Arthur M Dula

- Space lawyer and patent attorney
- Literary executor for Robert A. Heinlein
- Chairman and founder of Excalibur Almaz

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11 organizations provided study content

Heinlein Prize Trust
U.S. National Space Society
International Space Development Conference
Texas A&M University – Aerospace Engineering Department
European Space Conference – Turino
Newspace Conference
International Space University
International Space Elevator Consortium
Chinese Society of Astronautics
Canadian Space Society
Australian Space Society

5 firms provided business road maps

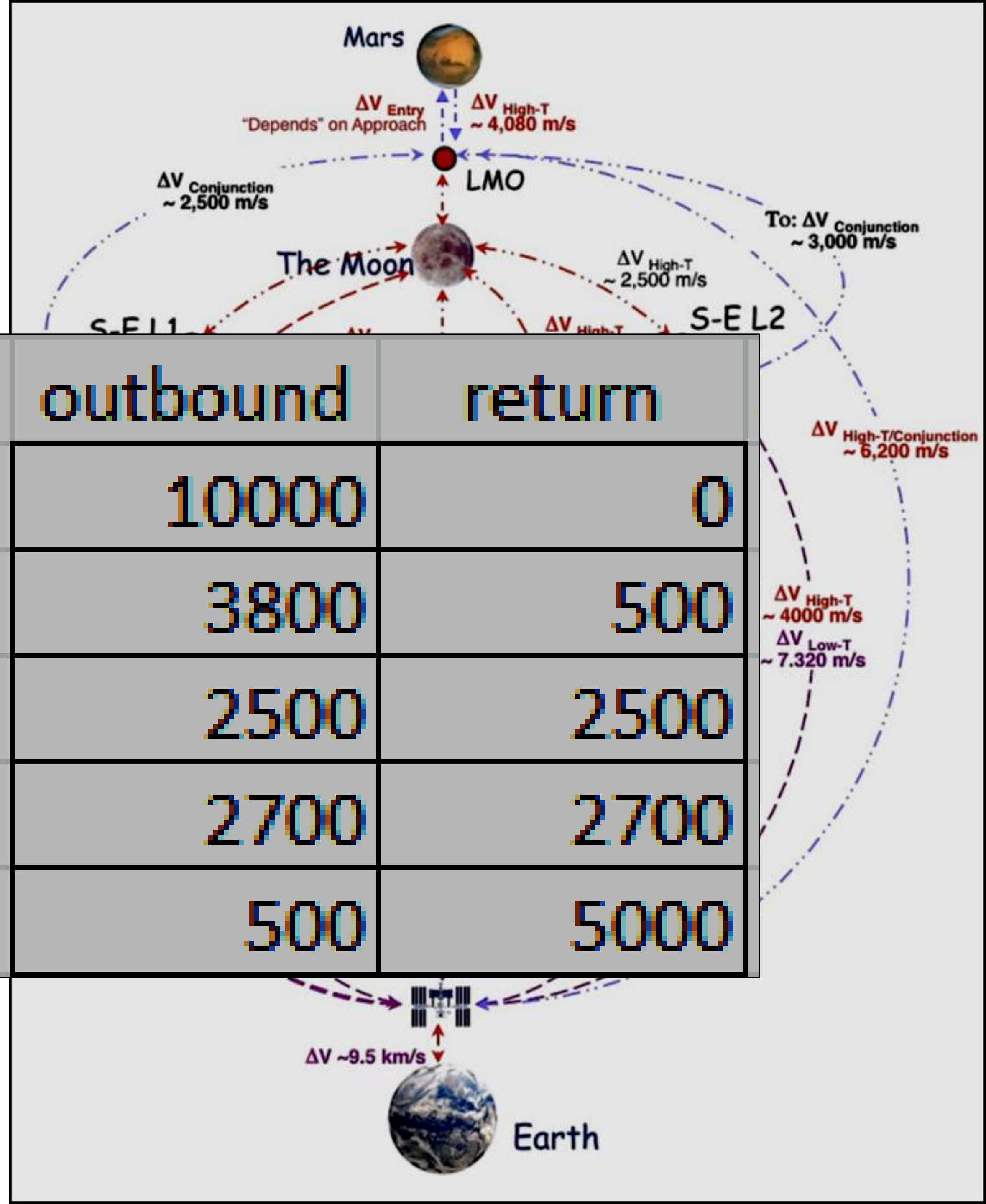
Moon Express
Excalibur Exploration Limited
Deep Space Industries
Ad Astra Rocket Company
Shackleton Energy Corporation

SMR Ch 6 **Modeling and Analysis**

Economic Assumptions

- Water is the “propellant of choice”
- Customers: Space propellant and consumables
- Population forecast = 10,000 people on Mars
- Estimated unit consumption *per human*
- Estimated in-space logistics flows
- Simple approximations are favored vs. high model fidelity (comprehensibility bias)

Model **Delta-V** assumptions



	outbound	return
Earth-LEO	10000	0
LEO-L1	3800	500
L1-Moon	2500	2500
L1-Phobos	2700	2700
Phobos-Mars	500	5000

Mass and Consumption from Inspiration Mars

TABLE VII. CREW METABOLIC INTERFACE VALUES (HANFORD, 2006, TABLE 3.3.8) [18]

Interface	Avg. Single Crew-Member per Day		Total 2CM 500d*	
Overall Body mass	70	kg	140	Kg
Respiratory Q				
Air				
Ca				
Ox				
Water				
Po				
Fe				
Re				
Ur				
Me				
Food				
Dr				
Thermal				
N/				
Waste				
Fe				
Perspiration Solid Waste (dry basis)	0.018	kg /CM-d	18	kg
Urine Solid Waste (dry basis)	0.059	kg /CM-d	59	kg

*Does not include packaging and storage containers.

unit masses		
person	70	kg
food (per day)	0.62	kg
water (per day)	3.91	kg
oxygen (per day)	0.84	kg
O2 ratio in water	80%	
pesonal equipment	559	kg

Mars Surface **Population Forecast** basis: 10,000 people by 2070 (WAG)

SMR-Space Infrastructure Forecast / In-Space Population Model					
year	**2010**	**2025**	**2040**	**2055**	**2070**
growth rate per period (specified)		15%	15%	15%	15%
number of people in space	6	49	397	3233	26304
population ratios through time		100%	100%	100%	100%
LEO outpost	100%	75%	55%	35%	30%
EML1 outpost		20%	20%	10%	10%
Moon Surf outpost		4%	17%	20%	20%
Phobos outpost		1%	3%	5%	5%
Mars Surf outpost			5%	30%	35%
in-space population distribution	2010	2025	2040	2055	2070
LEO outpost	6	37	218	1131	7891
EML1 outpost	0	10	79	323	2630
Moon Surf outpost	0	2	68	647	5261
Phobos outpost	0	0	12	162	1315
Mars Surf outpost	0	0	20	970	9206

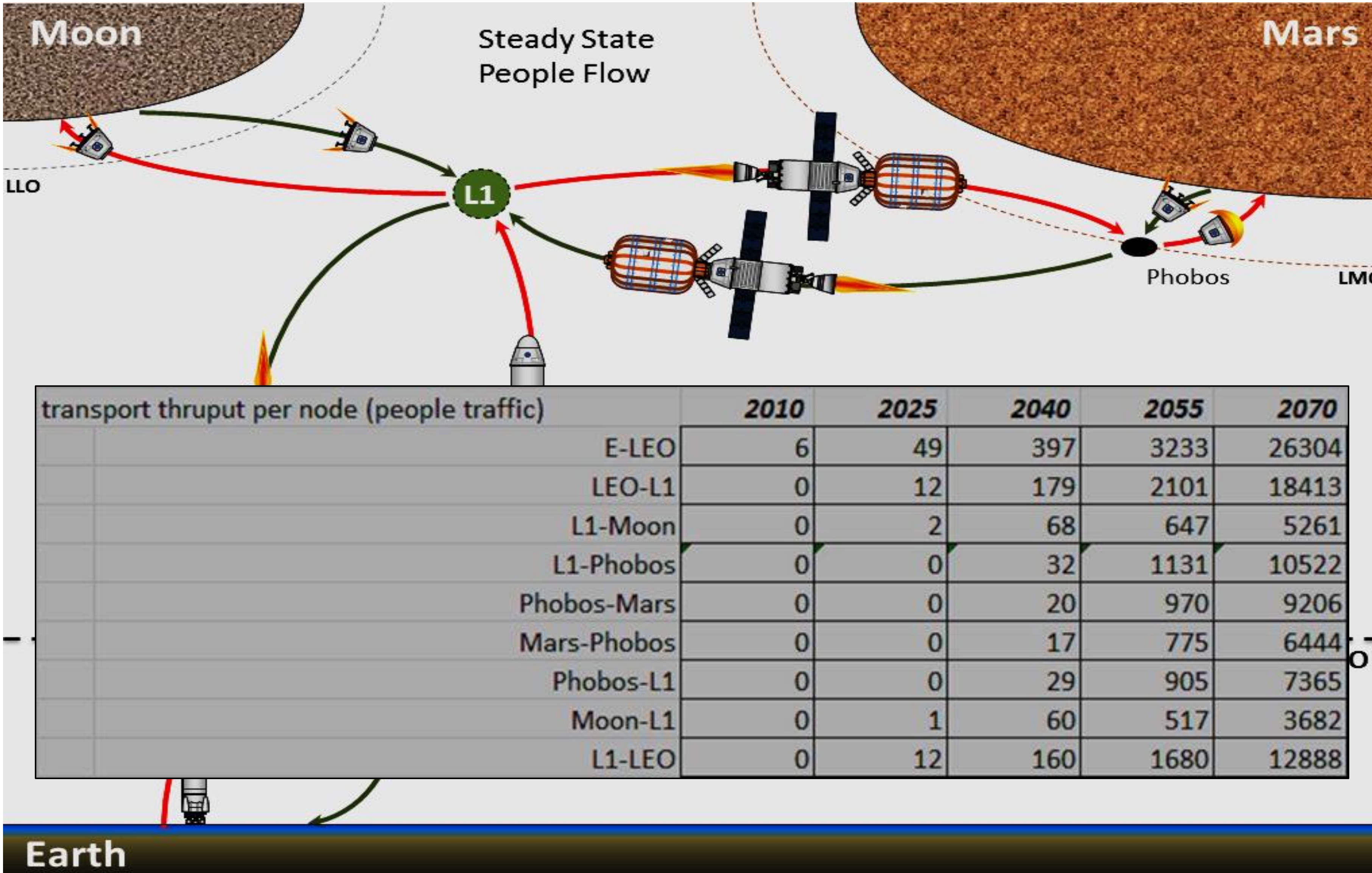
averages per year per person	2010	2025	2040	2055	2070
trip frequency (per yr)	0	0.5	0.5	1	1
trip duration (yrs)	0	2	2	1	1
food, air & water multiplier (days)	365	365	180	50	20
luxury multiplier for water use	1	2	4	8	20
hab & ECLSS equip/person ratio	5	40	30	25	20
SMR / industrial equip multiplier ratio	0	0.5	1.5	5	8
settler retention factor	1	1	0.9	0.8	0.7

annual mass buildup (per person)	2010	2025	2040	2055	2070	year
mass of person	70	70	70	70	70	kg
mass of LS equip	350	2800	2100	1750	1400	kg
mass of food	226	226	112	31	12	kg
mass of water	1427	2854	2815	1564	1564	kg
mass of air (oxygen)	383	383	189	53	21	kg
mass of outbound industrial/SMR equip	0	35	105	350	560	kg (ba

outbound propellant per node per person (kg)	2010	2025	2040	2055	2070
LEO-L1	0	24332	9804	1090	1043
L1-Moon	0	12295	4954	681	652
L1-Phobos	0	13789	5556	741	709
Phobos-Mars	0	0	710	126	121

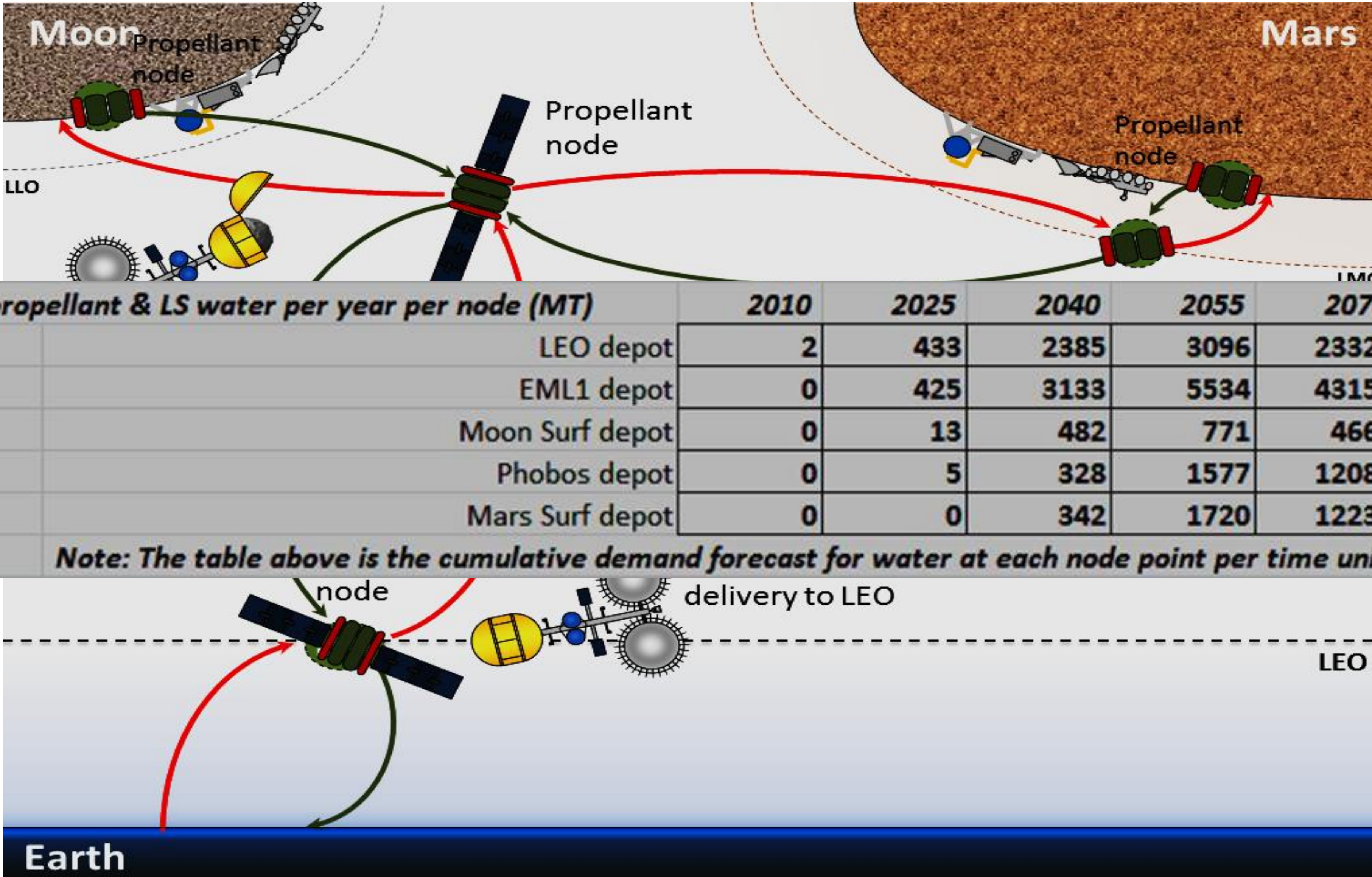
return propellant per destination per person (kg)	2010	2025	2040	2055	2070
L1-LEO	0	822	684	111	97
Moon-L1	0	5740	4774	601	521
Phobos-L1	0	6437	5354	654	567
Mars-Phobos	0	0	16714	1328	1152

Population Flow (cumulative demand)



transport thruput per node (people traffic)	2010	2025	2040	2055	2070
E-LEO	6	49	397	3233	26304
LEO-L1	0	12	179	2101	18413
L1-Moon	0	2	68	647	5261
L1-Phobos	0	0	32	1131	10522
Phobos-Mars	0	0	20	970	9206
Mars-Phobos	0	0	17	775	6444
Phobos-L1	0	0	29	905	7365
Moon-L1	0	1	60	517	3682
L1-LEO	0	12	160	1680	12888

Propellant Flow (quantity)



propellant & LS water per year per node (MT)	*2010*	*2025*	*2040*	*2055*	*2070*
LEO depot	2	433	2385	3096	23321
EML1 depot	0	425	3133	5534	43158
Moon Surf depot	0	13	482	771	4665
Phobos depot	0	5	328	1577	12084
Mars Surf depot	0	0	342	1720	12230

Note: The table above is the cumulative demand forecast for water at each node point per time unit

Propellant Cost Model

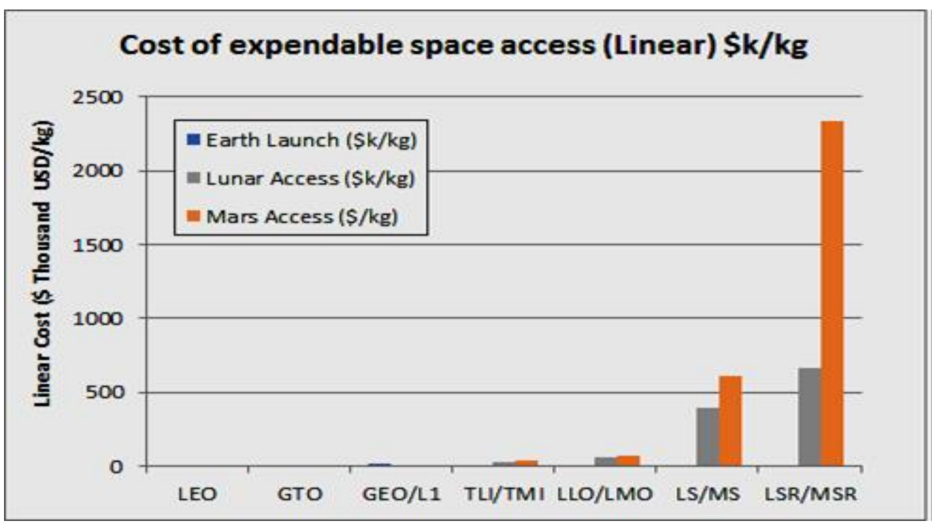
(approximated from prior economic studies)

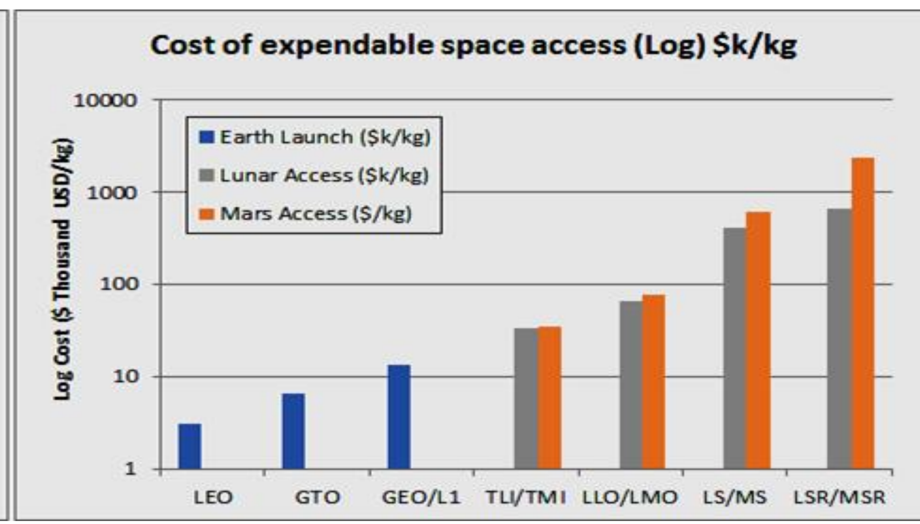
est unit water product cost $k/kg	2010	2025	2040	2055	2070	steady state	
LEO depot	1.2	0.8	0.6	0.4	0.3	0.2	WAGs
EML1 depot		5.1	2.5	1.5	0.9	0.8	RAP
Moon Surf depot		6.9	4.2	1.4	0.9	0.4	LDEM/Starlite
Phobos depot		6.9	4.2	1.4	0.9	0.4	LDEM/Starlite (assume applies to Phobos)
Mars Surf depot		6.9	4.2	1.4	0.9	0.4	LDEM/Starlite (assume applies to Mars surf)

product cost $k/kg	2010	2025	2040	2055	2070	steady state
LEO depot	1.2	0.8	0.6	0.4	0.3	0.2
EML1 depot		5.1	2.5	1.5	0.9	0.8
Moon Surf depot		6.9	4.2	1.4	0.9	0.4
Phobos depot		6.9	4.2	1.4	0.9	0.4
Mars Surf depot		6.9	4.2	1.4	0.9	0.4

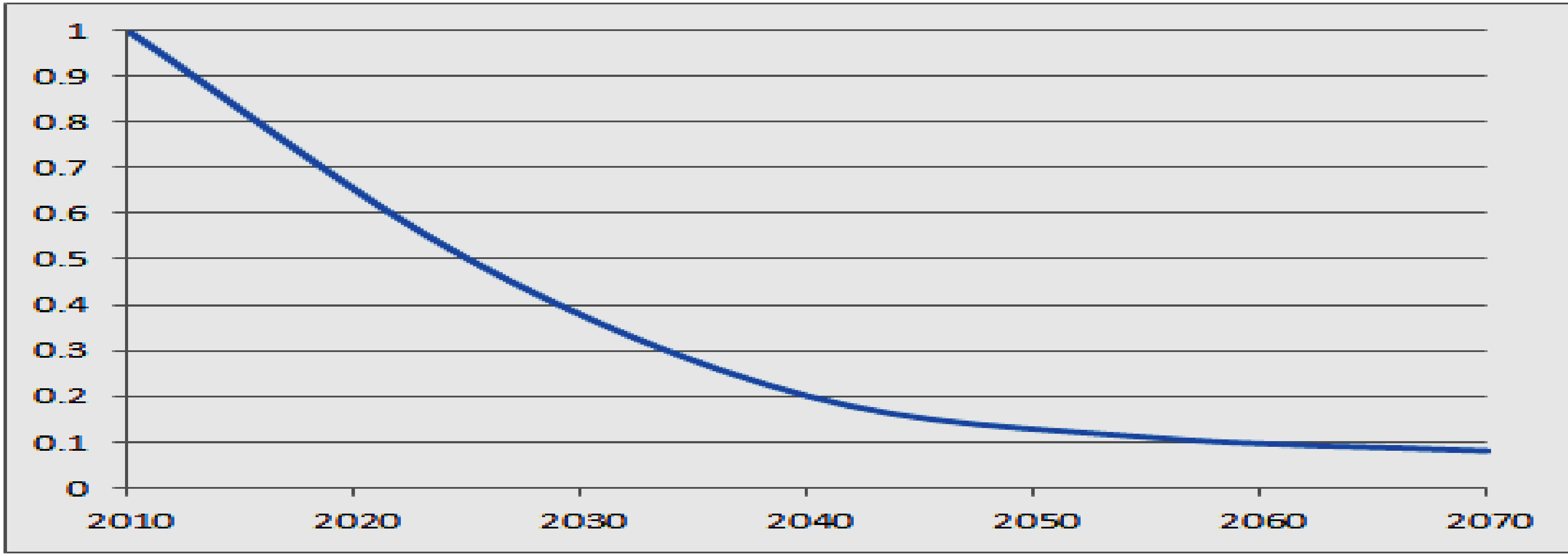
Flown Mission Unit Cost = Initial **Price** of Resources

					discount ratio	0.33333
source	mass-kg	total cost-$M	unit cost-k/kg	destination	**Modified unit cost ($k/kg)**	
Delta IV-H	27569	254	9.2	LEO		**3.1**
Delta IV-H	12999	254	19.5	GTO		**6.5**
Delta IV-H	6365	254	39.9	GEO/L1		**13.3**
Astrobotic price list	663	65.6	99.0	TLI	TLI stage payload	**33.0**
Astrobotic price list	515	102.0	198.0	LLO	LLO payload	**66.0**
Astrobotic price list	270	324	1200.0	LS	lander payload	**400.0**
Astrobotic price list	120	240	2000.0	LSR	rover payload	**666.7**
MER rovers unit cost est	6000	60	10.0	EL		**3.3**
MER rovers unit cost est	1062	110	103.6	TMI	TLI stage payload	**34.5**
MER rovers unit cost est	827	190	229.7	LMO	aeroshell payload	**76.6**
MER rovers unit cost est	174	320	1839.1	MS	lander payload	**613.0**
MER rovers unit cost est	50	350	7000.0	MSR	rover payload	**2333.3**





Price reduction as a function of time & competition



price of water supply $k/kg	2010	2025	2040	2055	2070	year
asymptote for converging on cost	*1*	*0.5*	*0.2*	*0.11*	*0.08*	*steady state*
LEO depot	3.1	1.6	0.8	0.5	0.4	0.2
EML1 depot	13.3	7.1	3.3	2.2	1.8	0.8
Moon Surf depot	400.0	200.2	80.3	44.4	32.4	0.4
Phobos depot	76.6	38.5	15.6	8.8	6.5	0.4
Mars Surf depot	613.0	306.7	122.9	67.8	49.4	0.4

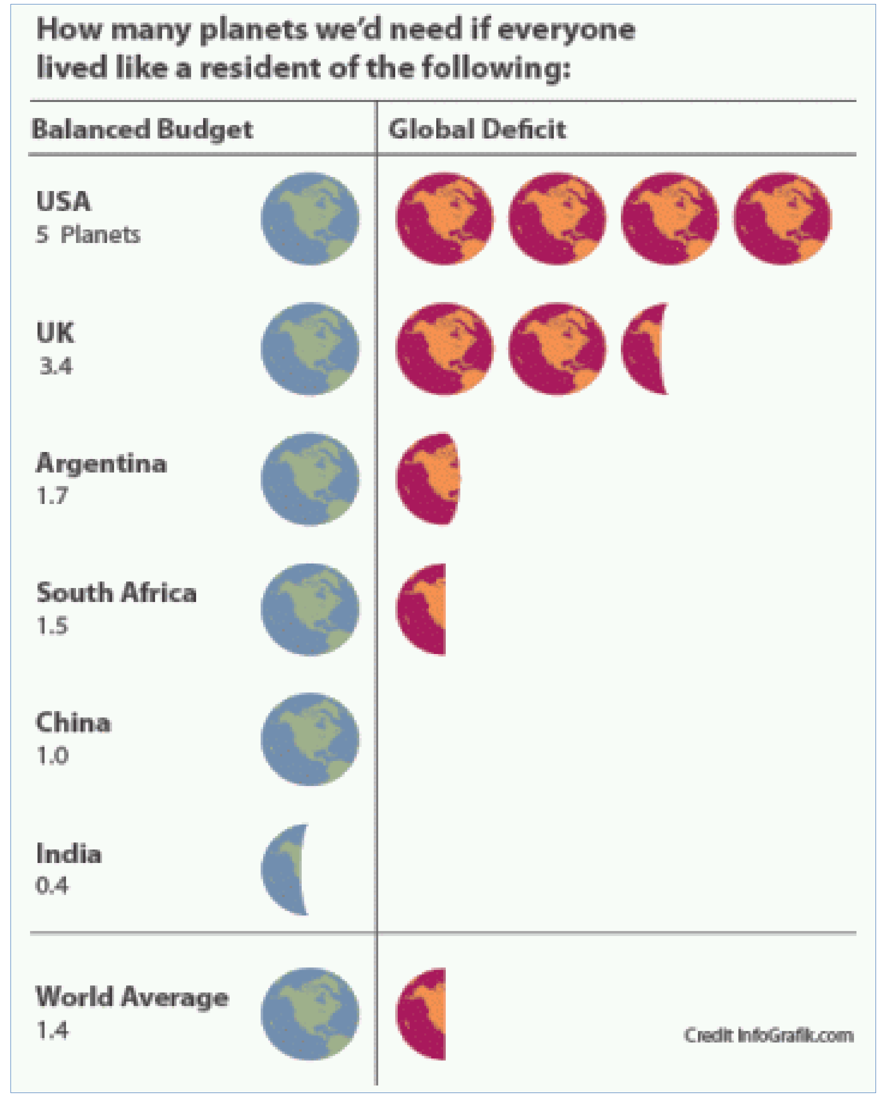
Net Present Value ($B)

discounted net revenue (price-cost) in target yr $B			*discount rate*		*25%*	*=WACC*
yr	2010	2025	2040	2055	2070
LEO depot	4.3	12.7	0.5	0.016	0.005
EML1 depot		29.2	3.1	0.16	0.06
Moon Surf depot		88.3	45.4	1.4	0.2
Phobos depot		5.5	4.7	0.5	0.1
Mars Surf depot			50.2	5.0	0.9

Conclusions

Why Space?

- Unlimited Resources & Energy
- Rapidly maturing Technologies
- Private Capital is becoming available
- Factors of Production are underutilized
- It will be the next HUMAN FRONTIER



Why Now?

- Space provides **solutions** that avert *global systemic collapse* scenarios
  - Identifies and mitigates asteroid impact hazards
  - Redirects corporate and military aggression
  - Provides a way out of the financial crisis
  - Offers a feasible path for non-hydrocarbon energy

rank	name	age	net worth	source	space investment
19	Jeff Bezos	49	$25.20	Amazon	Blue Origin
21	Sergey Brin	40	$22.80	Google	Google Lunar X Prize
20	Larry Page	40	$23.00	Google	Google Lunar X Prize, Planetary Resources
53	Paul Allen	60	$15.00	Microsoft	SpaceShipOne, SETI telescope array
138	Eric Schmidt	58	$8.20	Google	Planetary Resources
272	Sir Richard Branson	63	$4.60	Virgin Group	Virgin Galactic
527	Elon Musk	42	$2.70	PayPal, Tesla Motors	SpaceX
831	Guy Laliberte	53	$1.80	Cirque du Soleil	Visitor to ISS
922	K Ram Shriram	56	$1.65	Google	Planetary Resources
1031	Ross Perot, Jr.	54	$1.40	Oil & Gas	Planetary Resources
			$106.35	**Total Net Worth**	

HEINLEIN PRIZE TRUST

What are the facts? Again and again and again — what are the facts? Shun wishful thinking, ignore divine revelation, forget what “the stars foretell,” avoid opinion, care not what the neighbors think, never mind the unguessable “verdict of history” — what are the facts, and to how many decimal places? You pilot always into an unknown future; facts are your single clue. **Get the facts!**

R. A. Heinlein

US Naval Academy Class of 1929

Addendum: Space Mining Law

US legislation on space mining aroused **heated debate** at the UN COPUOS Legal Subcommittee (4-15 April, 2016)

- The Subcommittee agreed that a single issue for discussion entitled **“General exchange of views on potential legal models for activities in exploration, exploitation and utilization of space resources”** should be included on the agenda of the Subcommittee at its fifty-sixth session in 2017 (the intent is to provide an opportunity for a constructive, multilateral exchange of views on SMR activities, including economic aspects)
- **Vigorous debate** on this subject is also expected during the Main Committee session of COPUOS in Vienna (8-17 June 2016)

http://www.unoosa.org/oosa/en/ourwork/copuos/schedule.html

Mitigating SMR Legal Risk and Uncertainty

- Space policy is built around ratified treaties, universally accepted principles, and internationally established customs
  - What is NOT in place is just a widely accepted legal framework to regulate relevant national and international activities
  - Both the commercial space industry and the academia of space law await the legal vacuum to be filled as soon as practicable
- National legislation consistent with the principles of international law will be of paramount significance in protecting the legitimate rights of space miners
- Important elements will include how to assert SMR rights, discharge obligations and avert legal risks in an internationally competitive sphere under the rule of law

Our Voice Matters

There is an urgent need to create a sound legal environment for SMR exploration and mining from both national and international perspectives

- IAA SG3.17 (SMR) participants expect that commercial pioneers would contribute to the development of international space mining law for the benefit of all humankind
- This legal framework should be developed with adequate participation of the SMR community itself
- The study also predicts that non-state actors, especially when they are organized, stand the chance of becoming one of the most significant influencers if not creators of new Customary International Law in the field of commercial space, including the endeavor of SMR harvesting and utilization for the benefit and in the interest of all countries