Quantitative Approaches to Lunar Economic Analysis

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Introduction

Human Space Exploration is currently at Risk

"The U.S. human spaceflight program appears to be on an unsustainable *trajectory …" "… pursuing goals that* do not match *allocated resources …" Augustine II*

"… Constellation Program cost and schedule will remain uncertain *until a* sound business case *is established" GAO*

Solutions include

- Reduce expectations
- Increase NASA budget (ask Congress for a bailout)
- International collaboration
- Innovative commercial partnerships

Sustainability has *multiple aspects*

- Biological
- Logistical
- Economic

Overview

- Economic value *framework* for lunar resources
- Prior art: Quantitative lunar economic modeling at Colorado School of Mines (CSM)
- Recommendations for development of a "sustainable" lunar exploration architecture

Acknowledgements

- Researchers and Staff at the CSM Center for Space Resources *(formerly the Center for Commercial Applications of Combustion in Space or CCACS)*
- Our NASA sponsors at JSC, JPL and KSC
- Canadian Partners (MDA and Norcat)
- A special thanks to Dr. Mike Duke

The 'Expendable Honda' model

(an analogy for how we currently conduct space transportation)

- Model Assumptions
  - Replacement car must be purchased when fuel tank is empty
  - Standard driving conditions = 12,000 miles per year
  - Standard options, Minimum vehicle price
  - Fuel tank capacity + MPG used in analysis
  - Assume highway mileage applies through life of vehicle

2006 Ridgeline $27,700 MSRP
Fuel Tank Capacity: 22.0 (gal.)
EPA Mileage Estimates:
16 mpg / 21 mpg (Cty/Hwy)
Payload Capacity: 1,550-lb.

2005 Civic $13,675 MSRP
Fuel Tank Capacity: 13.2 gal.
EPA Mileage Estimates:
32 mpg / 38 mpg (Cty/Hwy)
Payload Capacity: 13 cubic ft

2005 Insight $19,845 MSRP
Fuel Tank Capacity: 10.6 gal.
EPA Mileage Estimates:
60 mpg / 66 mpg (Cty/Hwy)
Payload Capacity: 16 cubic ft

EH Model – Annual Results

- Annual capital cost of driving: $330,000-$720,000
- Not included: Operations, maintenance, fuel cost
- Question: How would this change automobile demand?
- ***Rocket Stages are Discarded after their first use!***

The Expendable Honda model (B. Blair, CSM-CCACS, 4-14-05)

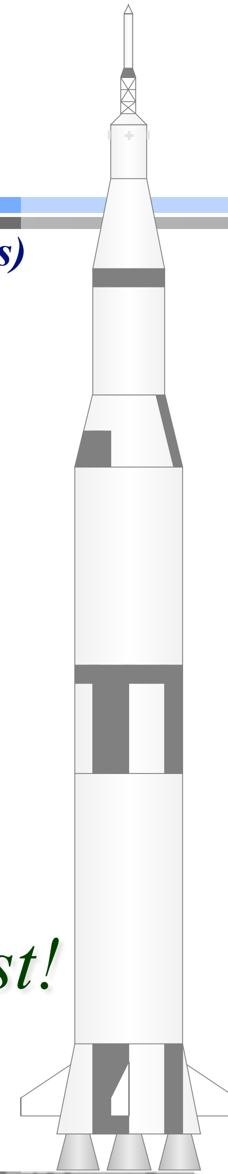
Model	Ridgeline	Civic	Insight
Type	truck	sedan	hybrid
Year	2006	2005	2005
2005 MSRP	$ 27,700	$ 13,675	$ 19,845
Fuel Cap (gal)	22.0	13.2	10.6
MPG-H	21	38	66
Annual number of vehicles purchased (12,000 miles per year)			
	26.0	23.9	17.2
Total Annual Cost (FY05 US$)			
	$ 719,481	$ 327,153	$ 340,395

Extending EH range to >500mi

Systems Requirements for a single cross-country road trip (remember - no filling stations)

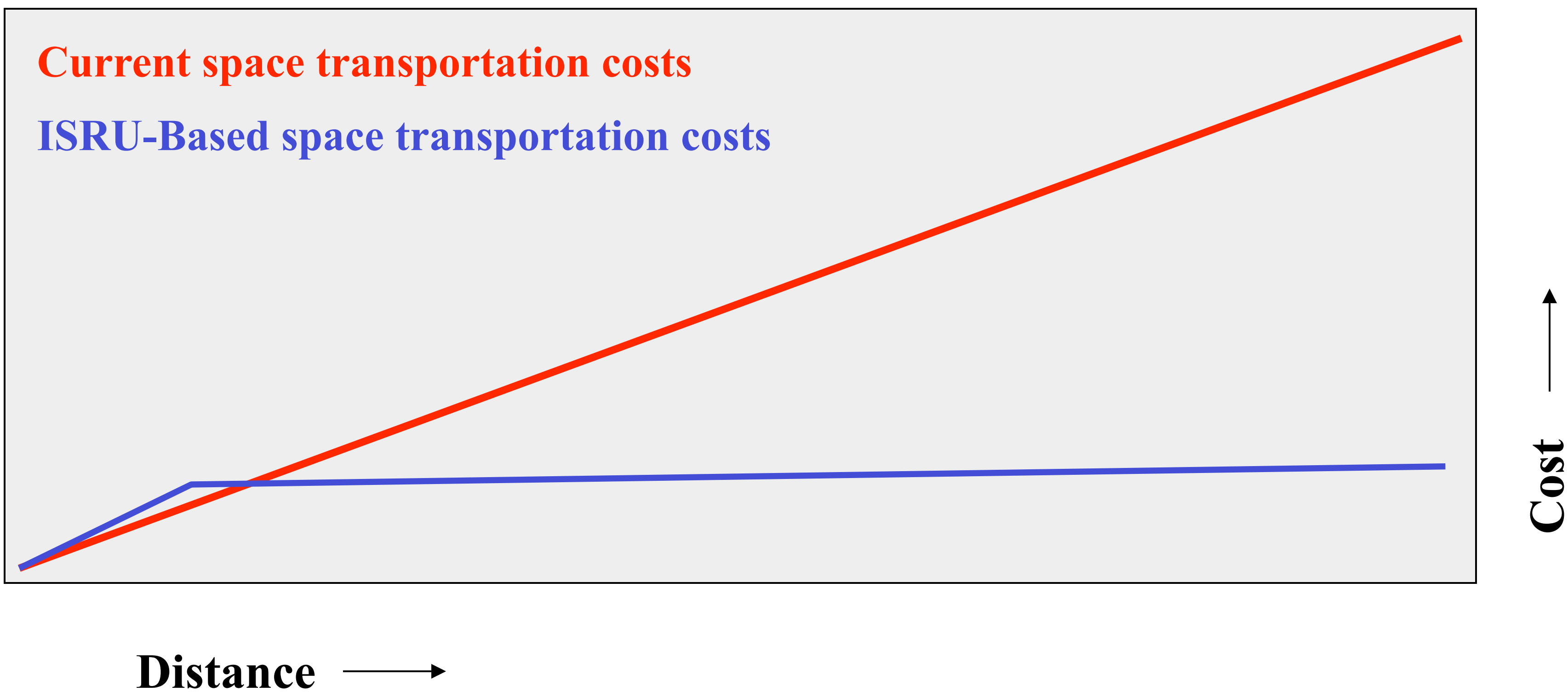
Action	Range	Cost
Load passenger into EH	**500mi**	**$15,000**
Load onto expendable flatbed	**1000mi**	**$50,000**
Load flatbed onto tractor-trailer	**2000mi**	**$250,000**
Load tractor-trailer onto train	**3500mi**	**$1,250,000**

A linear increase in distance incurs an exponential cost!



Transportation Cost vs. Distance (notional)

- Assumptions
  - Cost = production + ops + fuel
  - Ops cost is constant
  - Production cost is incurred once
  - Fuel cost follows previous chart



“What if” ISRU were available during Apollo?

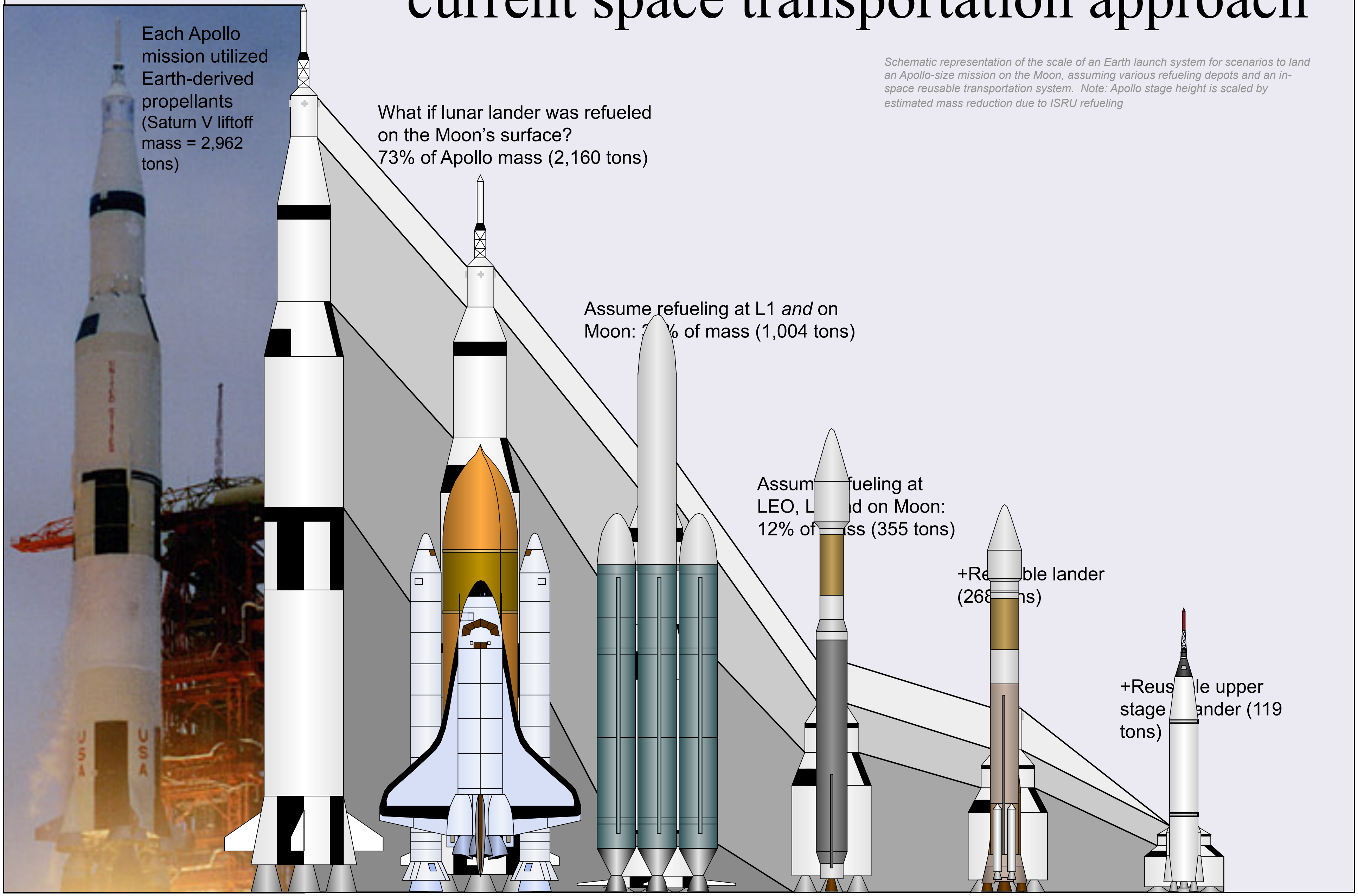
The Saturn V model

Imbedded excel spreadsheet tool used to estimate reduction of launch stack based on refueling and spacecraft element reuse assumptions (scenario tool shows set points)

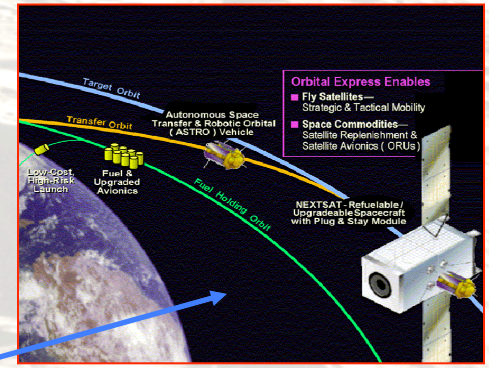
mult			kgs						
total	Name	Dry Mass	Wet Mass	Prop Mass	Interstage	Cum	Isp	Delta V (m/s)	cum
100.0%	S-IC (first stage)	132791	2285713	2152922	4536	2961668	304	3867	3867
100.0%	S-II (second stage)	36923	492564	455641	3629	671419	421	4683	8550
100.0%	LE (launch escape sys)	4128	4128	0	0	175226			
100.0%	S-IVB (third stage)	12111	120703	108592	2041	171098	421	4155	12705
100.0%	LD (lunar descent)	2790	11658	8868	0	48354	311	2423	15128
100.0%	LA (lunar ascent)	2132	4513	2381	0	36696	311	2286	2286
100.0%	LMA (adaptor)	1814	1814	0	0	32183			
100.0%	SM (service module)	6101	24517	18416	0	30369	314	2869	5155
100.0%	CM (command module)	5851	5851	0	0	5851			

SCENARIO	Mass of Stack (ton)	Percent of Apollo	Reduced Systems	Reduction Percent	Refueled Systems	# refuels	Reused Systems	# reuses	Removed Systems	Fuel Required	Total Fuel
Refuel M	2,160	72.9%	S-IC	65.5%	LA	1	n/a		LD	2381	2381
Refuel M+L1	1,004	33.9%	S-IC	16.0%	LA	2	n/a		LD	4763	23179
					SM	1	n/a			18416	
Refuel M+L1+LEO	355	12.0%	S-II	60.0%	LA	2	n/a		LD, S-IC	4763	55757
			S-IVB	30.0%	S-IVB	0.30	n/a			32578	
					SM	1	n/a			18416	
Refuel M+L1+LEO, Reuse LA	268	9.0%	S-II	45.0%	SM	1	LA	2	LMA, LA,	23179	48155
			S-IVB	23.0%	S-IVB	0.23	n/a		LD, S-IC	24976	
fuel M+L1+LEO, Reuse LA+S-IVB	119	4.0%	S-II	20.0%	n/a		LA	2	SM, LMA, LA,	4763	29739
			S-IVB	11.5%	S-IVB	0.12	S-IVB	0.12	LD, LE, S-IC	24976	

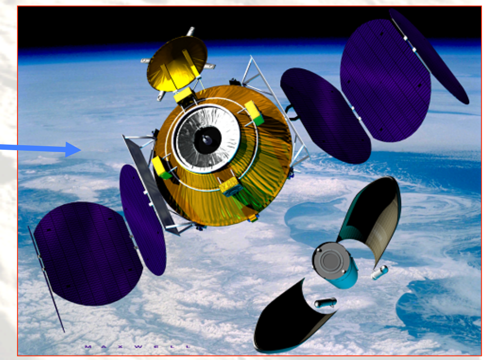
Propellant from the Moon could revolutionize our current space transportation approach

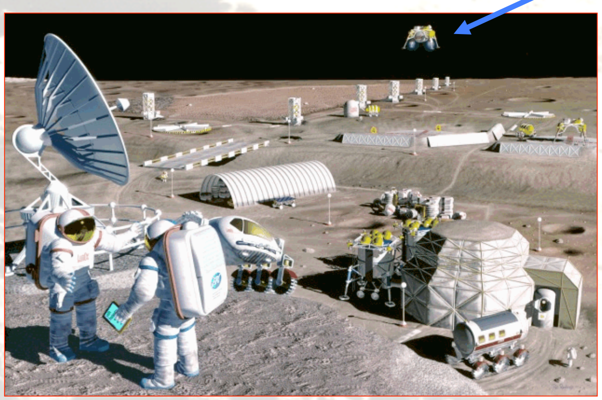


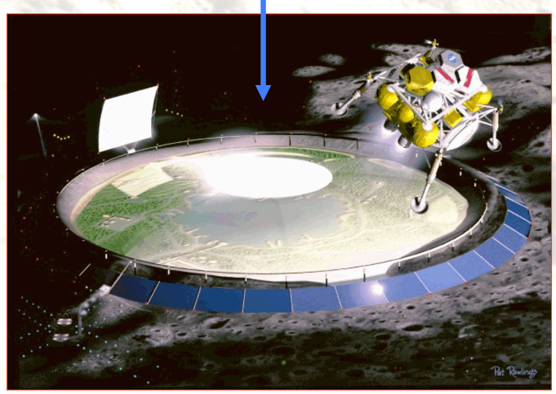
Markets for Lunar Propellant

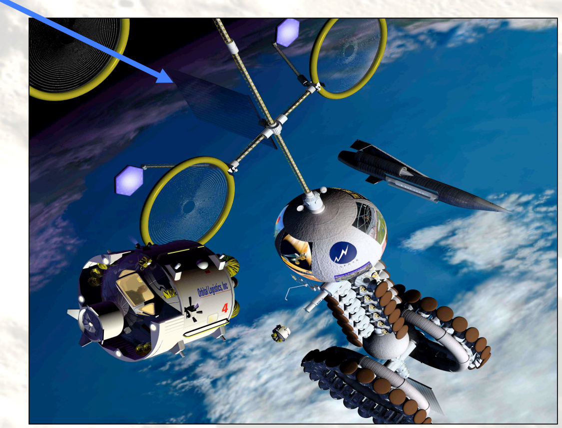


NASA-Science
Military Missions
Debris Management
Satellite Servicing & Refueling
International Space Station
Human Exploration
Space Solar Power
Self-Sustaining Colonies



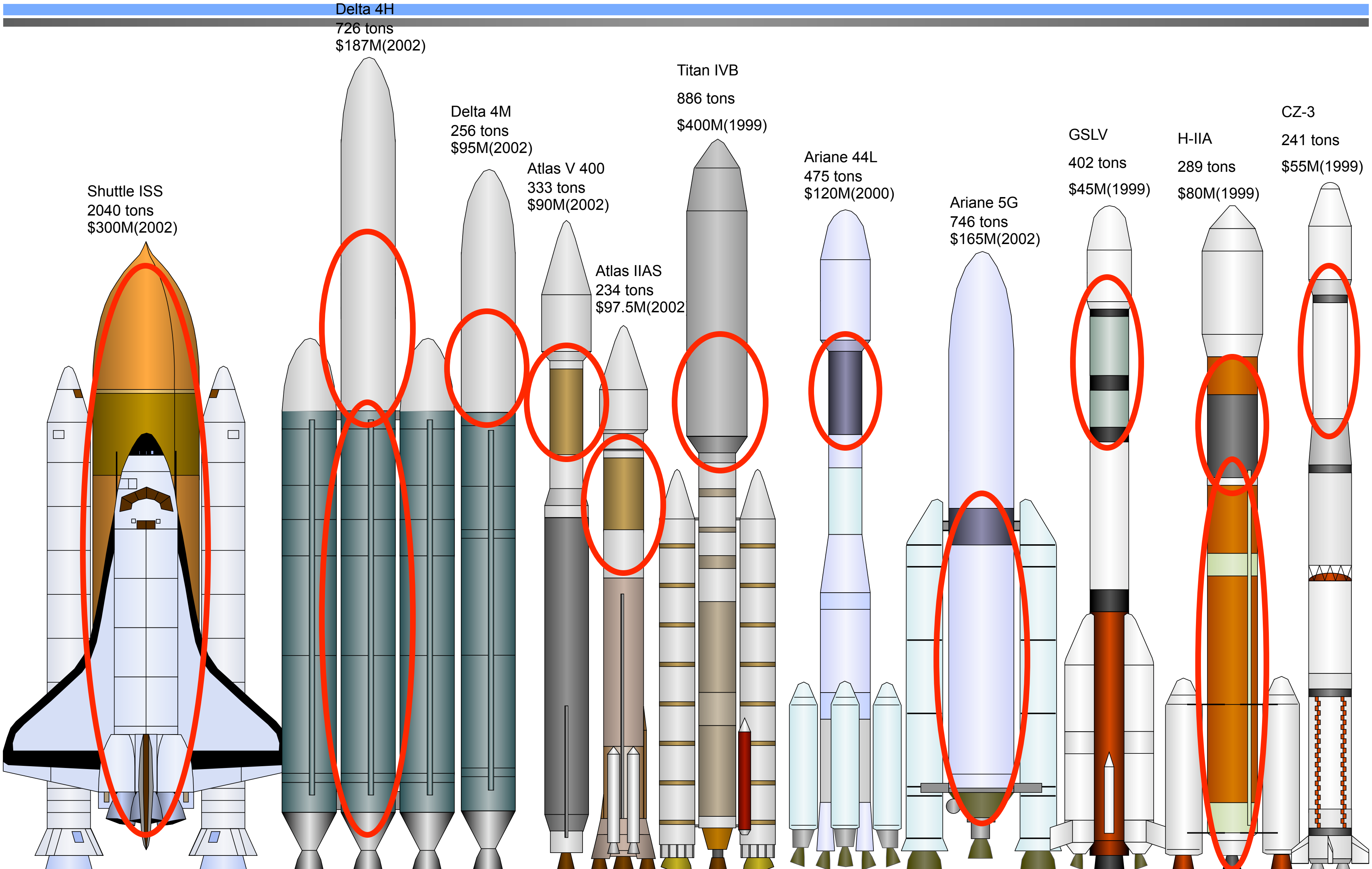




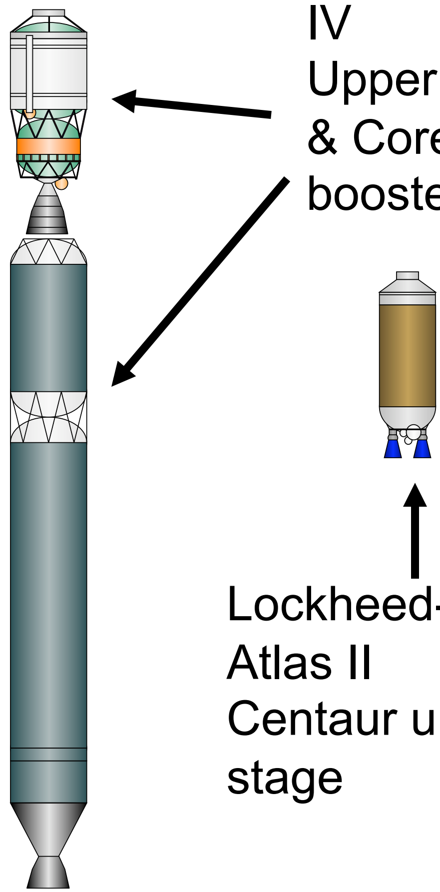


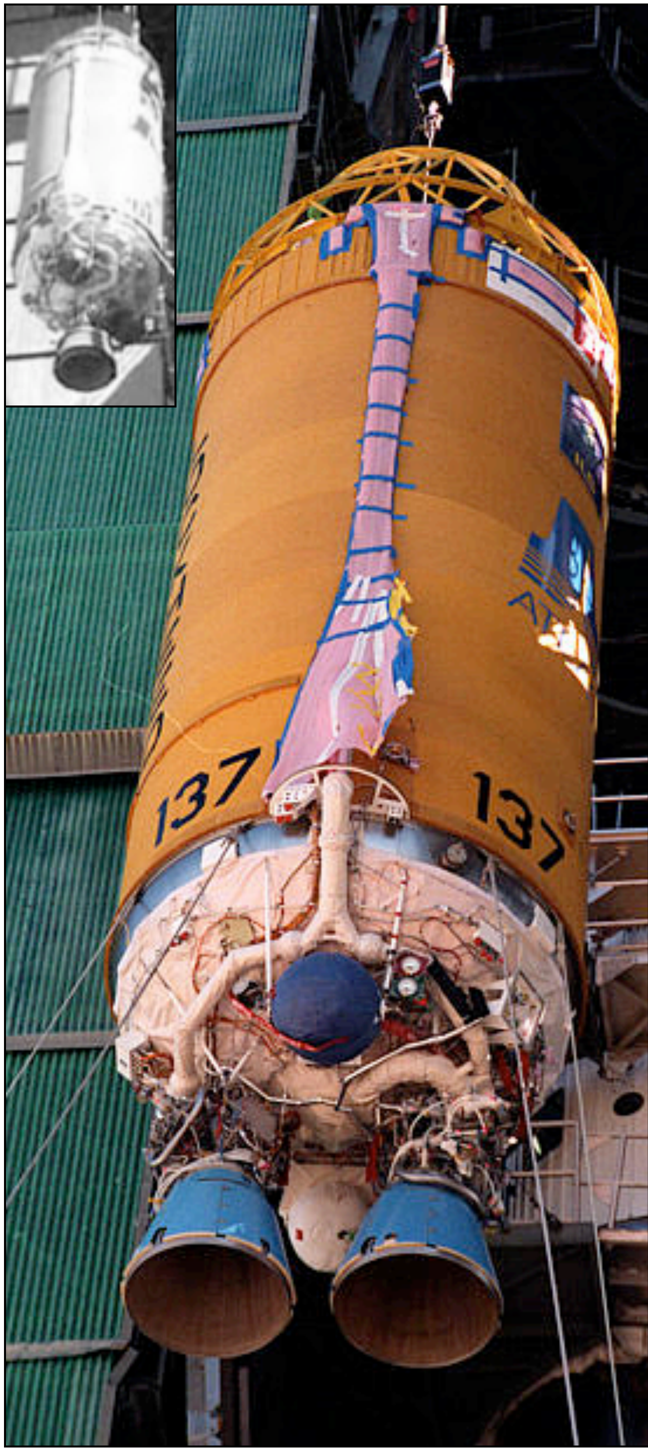
Potentially reusable elements in today's launch fleet

(LOX / LH2 cryo stages)



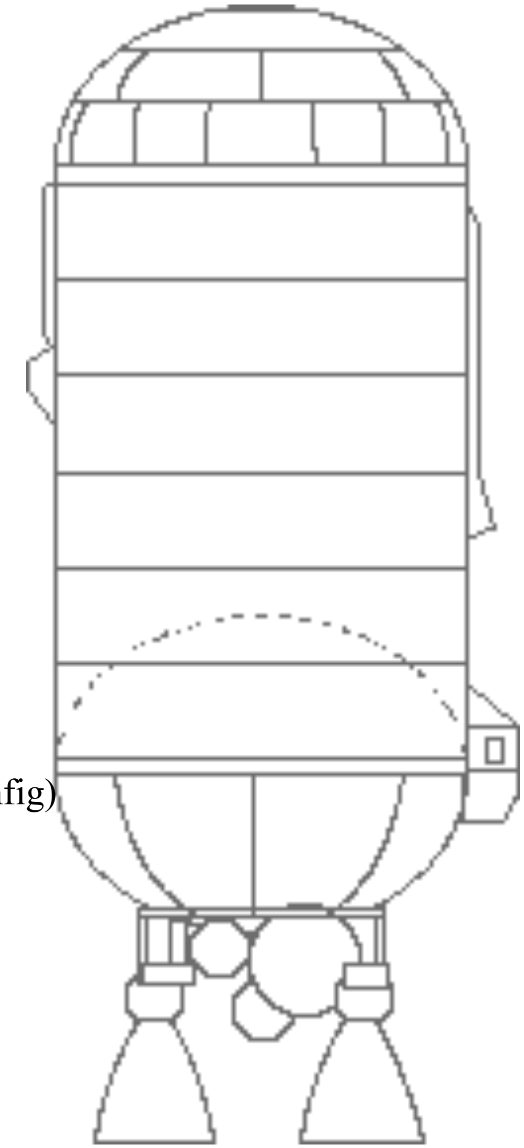
Three elements will be examined in detail





The Centaur Upper Stage

Currently discarded when empty!



<u>Atlas Centaur II-A upper stage</u>

- Gross mass
  19,100kg
- Empty mass
  2,300kg
- Propellant mass
  16,800kg
- ISP
  449 sec
- Standard payload to LEO
  8,600kg (Atlas IIAS, standard config)

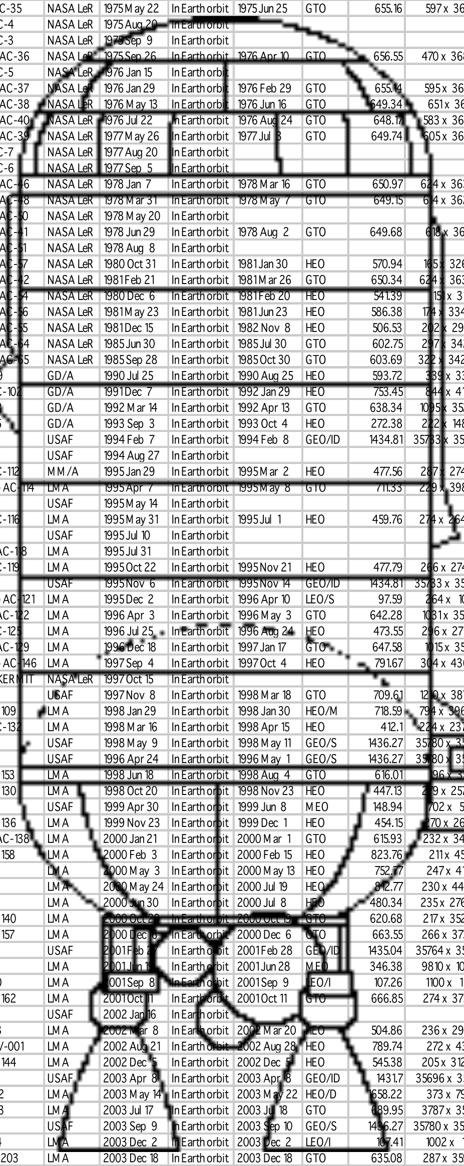
Centaur Reuse

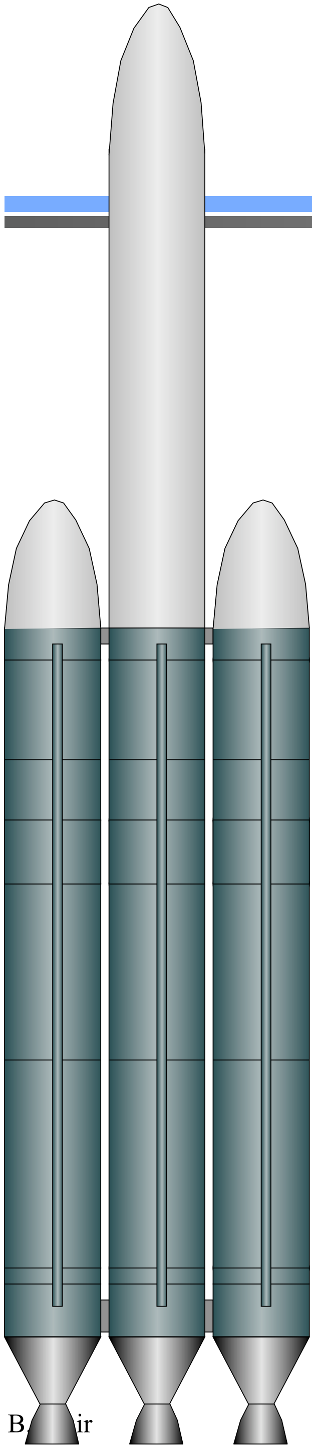
- **Approximate payload of a fully fueled Centaur IIA in LEO**
  - **To GEO – 7,700kg**
  - **To LLO – 8,900kg**
- Centaur upper stages are currently classified as "orbital debris"
- Number of Centaurs remaining in orbit > 90 (out of more than 170 launches)
- Location

LEO	GTO	GEO	MEO	HEO	Unknown	Other
6	31	7	2	24	18	1

- Conclusion
  - Transportation infrastructure is already accumulating in Earth orbit
  - These *could be* stranded assets

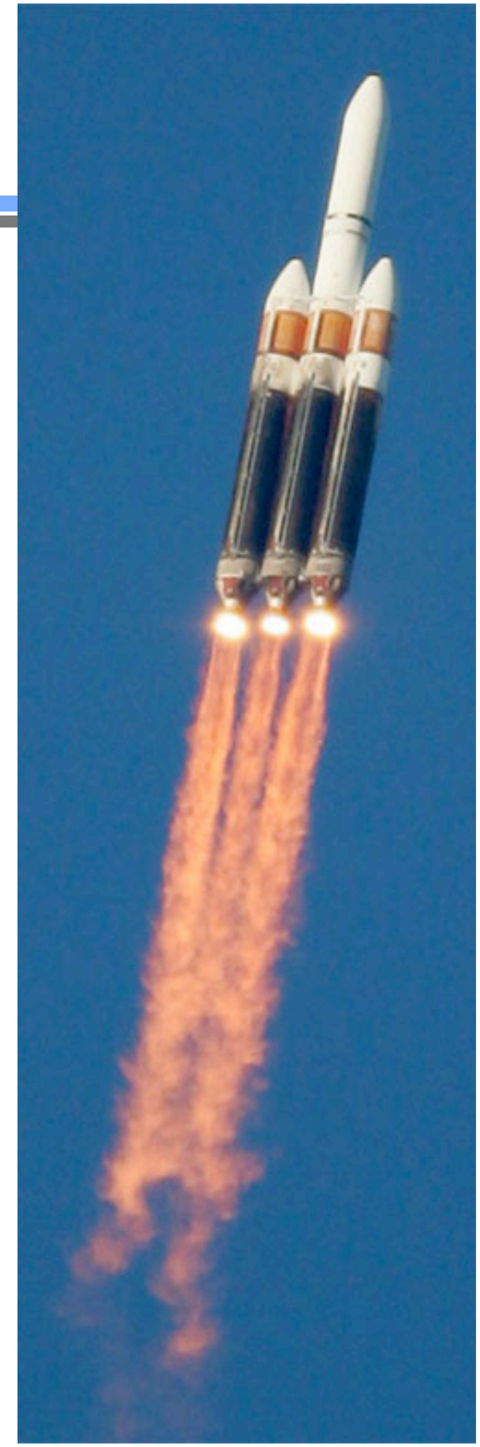
S000694	196	3-047A	Centaur AC-2	Centaur 2B	NASA LeR	1963 Nov 27	In Earth orbit	1963 Dec 31	LEO/I	107.89	485 x 1773 x 30.3
S002764	196	7-035B	Centaur D AC-12	Centaur D AC-12	NASA LeR	1967 Apr 17	In Earth orbit				
S002883	196	7-068B	Centaur D AC-11	Centaur D AC-11	NASA LeR	1967 Jul 14	In Earth orbit	1967 Jul 14	CLO	15937.92	167 x 406653 x 30.5
S003598	196	8-110B	Centaur AC-16	Centaur 13D	NASA LeR	1968 Dec 7	In Earth orbit	1969 Jan 14	LEO/I	100.21	722 x 815 x 35.0
S003760	196	9-014B	Centaur AC-20	Centaur 17D	NASA LeR	1969 Feb 25	In Earth orbit				
S003845	196	9-030B	Centaur AC-19	Centaur 16D	NASA LeR	1969 Mar 27	In Earth orbit				
S004069	196	9-069B	Centaur AC-18	Centaur 15D	NASA LeR	1969 Aug 12	In Earth orbit	1969 Sep 25	GTO	703.18	2237 x 37394 x 17.4
S004882	197	1-006B	Centaur AC-25	Centaur 20D	NASA LeR	1971 Jan 26	In Earth orbit	1971 Mar 1	GTO	654.37	598 x 36580 x 28.1
S005267	197	1-051B	Centaur AC-23	Centaur 21D	NASA LeR	1971 May 30	In Earth orbit				
S005816	197	2-003B	Centaur AC-28	Centaur 20D	NASA LeR	1972 Jan 23	In Earth orbit	1972 Feb 23	GTO	654.35	560 x 36618 x 28.3
S006058	197	2-041B	Centaur AC-29	Centaur 26D	NASA LeR	1972 Jun 13	In Earth orbit	1972 Jul 13	GTO	653.29	558 x 36565 x 27.0
S006155	197	2-065B	Centaur D AC-22	Centaur 19D	NASA LeR	1972 Aug 21	In Earth orbit	1972 Sep 20	LEO/I	99.59	698 x 780 x 35.0
S006779	197	1-116	Centaur AC-26	Centaur 23D	NASA LeR	1971 Dec 20	In Earth orbit				
S006797	197	3-058B	Centaur D-1A AC-31	Centaur D-1A AC-31	NASA LeR	1973 Aug 23	In Earth orbit	1973 Sep 24	GTO	655	609 x 36601 x 27.5
S007545	197	4-093B	Centaur D-1A AC-32	Centaur D-1A AC-32	NASA LeR	1974 Nov 21	In Earth orbit	1974 Dec 28	GTO	654.27	569 x 36605 x 25.8
S007902	197	5-042B	Centaur D-1A AC-35	Centaur D-1A AC-35	NASA LeR	1975 May 22	In Earth orbit	1975 Jun 25	GTO	655.16	597 x 36621 x 26.1
S008111	197	5-075B	Centaur TC-4	Centaur D-1T TC-4	NASA LeR	1975 Aug 20	In Earth orbit				
S008272	197	5-083B	Centaur TC-3	Centaur D-1T TC-3	NASA LeR	1975 Sep 9	In Earth orbit				
S008331	197	5-091B	Centaur D-1AR AC-36	Centaur D-1AR AC-36	NASA LeR	1975 Sep 26	In Earth orbit	1976 Apr 10	GTO	656.55	470 x 36820 x 21.6
S008583	197	6-003B	Centaur TC-5	Centaur D-1T TC-5	NASA LeR	1976 Jan 15	In Earth orbit				
S008621	197	6-010B	Centaur D-1AR AC-37	Centaur D-1AR AC-37	NASA LeR	1976 Jan 29	In Earth orbit	1976 Feb 29	GTO	655.14	595 x 36623 x 21.7
S008840	197	6-042B	Centaur D-1AR AC-38	Centaur D-1AR AC-38	NASA LeR	1976 May 13	In Earth orbit	1976 Jun 16	GTO	649.34	651 x 36271 x 21.8
S009329	197	6-073B	Centaur D-1AR AC-40	Centaur D-1AR AC-40	NASA LeR	1976 Jul 22	In Earth orbit	1976 Aug 24	GTO	648.17	583 x 36279 x 21.8
S010025	197	7-041B	Centaur D-1AR AC-39	Centaur D-1AR AC-39	NASA LeR	1977 May 26	In Earth orbit	1977 Jul 3	GTO	649.74	605 x 36337 x 21.8
S010272	197	7-076B	Centaur TC-7	Centaur D-1T TC-7	NASA LeR	1977 Aug 20	In Earth orbit				
S010322	197	7-084B	Centaur TC-6	Centaur D-1T TC-6	NASA LeR	1977 Sep 5	In Earth orbit				
S010722	197	8-002B	Centaur D-1AR AC-46	Centaur D-1AR AC-46	NASA LeR	1978 Jan 7	In Earth orbit	1978 Mar 16	GTO	650.97	624 x 36382 x 21.2
S010779	197	8-035B	Centaur D-1AR AC-48	Centaur D-1AR AC-48	NASA LeR	1978 Mar 31	In Earth orbit	1978 May 7	GTO	649.15	614 x 36299 x 21.9
S010912	197	8-051B	Centaur D-1AR AC-50	Centaur D-1AR AC-50	NASA LeR	1978 May 20	In Earth orbit				
S010976	197	8-068B	Centaur D-1AR AC-41	Centaur D-1AR AC-41	NASA LeR	1978 Jun 29	In Earth orbit	1978 Aug 2	GTO	649.68	618 x 36321 x 21.9
S011003	197	8-078C	Centaur D-1AR AC-51	Centaur D-1AR AC-51	NASA LeR	1978 Aug 8	In Earth orbit				
S012069	198	0-087B	Centaur AC-57	Centaur D-1AR AC-57	NASA LeR	1980 Oct 31	In Earth orbit	1981 Jan 30	HEO	570.94	165 x 32674 x 26.2
S012363	198	1-018B	Centaur AC-42	Centaur D-1AR AC-42	NASA LeR	1981 Feb 21	In Earth orbit	1981 Mar 26	GTO	650.34	624 x 36349 x 20.5
S012445	198	0-098B	Centaur AC-54	Centaur D-1AR AC-54	NASA LeR	1980 Dec 6	In Earth orbit	1981 Feb 20	HEO	541.39	151 x 31101 x 23.5
S012497	198	1-050B	Centaur AC-56	Centaur D-1AR AC-56	NASA LeR	1981 May 23	In Earth orbit	1981 Jun 23	HEO	586.38	174 x 33483 x 24.4
S013007	198	1-119B	Centaur AC-55	Centaur D-1AR AC-55	NASA LeR	1981 Dec 15	In Earth orbit	1982 Nov 8	HEO	506.53	202 x 29139 x 23.5
S015874	198	5-055B	Centaur AC-64	Centaur D-1AR AC-64	NASA LeR	1985 Jun 30	In Earth orbit	1985 Jul 30	GTO	602.75	297 x 34219 x 23.2
S016102	198	5-087B	Centaur AC-65	Centaur D-1AR AC-65	NASA LeR	1985 Sep 28	In Earth orbit	1985 Oct 30	GTO	603.69	322 x 34243 x 22.9
S020713	199	0-065B	Centaur AC-69	Centaur I AC-69	GD/A	1990 Jul 25	In Earth orbit	1990 Aug 25	HEO	593.72	339 x 33705 x 18.1
S021804	199	1-083B	Centaur AC-102	Centaur II(3) AC-102	GD/A	1991 Dec 7	In Earth orbit	1992 Jan 29	HEO	753.45	844 x 41255 x 16.6
S021907	199	2-013B	Centaur AC-72	Centaur I AC-72	GD/A	1992 Mar 14	In Earth orbit	1992 Apr 13	GTO	638.34	1095 x 35264 x 19.6
S022788	199	3-056B	Centaur AC-75	Centaur I AC-75	GD/A	1993 Sep 3	In Earth orbit	1993 Oct 4	HEO	272.38	222 x 14859 x 26.9
S022989	199	4-009B	Centaur TC-12	Centaur TC-12	USAF	1994 Feb 7	In Earth orbit	1994 Feb 8	GEO/ID	1434.81	35733 x 35790 x 12.0
S023247	199	4-054B	Centaur TC-11	Centaur TC-11	USAF	1994 Aug 27	In Earth orbit				
S023468	199	5-003B	Centaur AC-112	Centaur II(3) AC-112	MM/A	1995 Jan 29	In Earth orbit	1995 Mar 2	HEO	477.56	287 x 27433 x 26.9
S023554	199	5-019B	Centaur AC-114	Centaur IIA(4N) AC-114	LMA	1995 Apr 7	In Earth orbit	1995 May 8	GTO	711.33	229 x 39807 x 26.4
S023568	199	5-022B	Centaur TC-17	Centaur TC-17	USAF	1995 May 14	In Earth orbit				
S023590	199	5-027B	Centaur AC-116	Centaur II(3) AC-116	LMA	1995 May 31	In Earth orbit	1995 Jul 1	HEO	459.76	274 x 26434 x 26.9
S023610	199	5-034B	Centaur TC-8	Centaur TC-8	USAF	1995 Jul 10	In Earth orbit				
S023629	199	5-038B	Centaur AC-118	Centaur IIA(4) AC-118	LMA	1995 Jul 31	In Earth orbit				
S023697	199	5-057B	Centaur AC-119	Centaur II(3) AC-119	LMA	1995 Oct 22	In Earth orbit	1995 Nov 21	HEO	477.79	266 x 27467 x 26.9
S023713	199	5-060B	Centaur TC-13	Centaur TC-13	USAF	1995 Nov 6	In Earth orbit	1995 Nov 14	GEO/ID	1434.81	35733 x 35790 x 9.8
S023727	199	5-065B	Centaur AC-121	Centaur IIA(4N) AC-121	LMA	1995 Dec 2	In Earth orbit	1996 Apr 10	LEO/S	97.59	264 x 1023 x 97.9
S023840	199	6-020B	Centaur AC-122	Centaur IIA(4) AC-122	LMA	1996 Apr 3	In Earth orbit	1996 May 3	GTO	642.28	1031 x 35530 x 21.9
S023968	199	6-042B	Centaur AC-125	Centaur II(3) AC-125	LMA	1996 Jul 25	In Earth orbit	1996 Aug 24	HEO	473.55	296 x 27198 x 26.8
S024675	199	6-070B	Centaur AC-129	Centaur IIA(4) AC-129	LMA	1996 Dec 18	In Earth orbit	1997 Jan 17	GTO	647.58	1015 x 35817 x 22.5
S024937	199	7-050B	Centaur AC-146	Centaur IIA (1N) AC-146	LMA	1997 Sep 4	In Earth orbit	1997 Oct 4	HEO	791.67	304 x 43636 x 19.0
S025009	199	7-061B	Centaur TC-21	Centaur TC-21 KERMIT	NASA LeR	1997 Oct 15	In Earth orbit				
S025035	199	7-068B	Centaur TC-16	Centaur TC-16	USAF	1997 Nov 8	In Earth orbit	1998 Mar 18	GTO	709.61	1210 x 38740 x 64.7
S025149	199	8-005B	Centaur AC-109	Centaur IIA AC-109	LMA	1998 Jan 29	In Earth orbit	1998 Jan 30	HEO/M	718.59	794 x 39600 x 63.4
S025259	199	8-016B	Centaur AC-132	Centaur II(3) AC-132	LMA	1998 Mar 16	In Earth orbit	1998 Apr 15	HEO	412.1	224 x 23708 x 26.9
S025337	199	8-029B	Centaur TC-18	Centaur TC-18	USAF	1998 May 9	In Earth orbit	1998 May 11	GEO/S	1436.27	35780 x 35800 x 0.1
S025349	199	6-026B	Centaur TC-15	Centaur TC-15	USAF	1996 Apr 24	In Earth orbit	1996 May 1	GEO/S	1436.27	35780 x 35800 x 0.1
S025372	199	8-037B	Centaur AC-153	Centaur IIA AC-153	LMA	1998 Jun 18	In Earth orbit	1998 Aug 4	GTO	616.01	[illegible]96 x 35011 x 23.1
S025502	199	8-058B	Centaur AC-130	Centaur IIA AC-130	LMA	1998 Oct 20	In Earth orbit	1998 Nov 23	HEO	447.13	279 x 25703 x 26.9
S025725	199	9-023B	Centaur TC-14	Centaur TC-14	USAF	1999 Apr 30	In Earth orbit	1999 Jun 8	MEO	148.94	702 x 5156 x 28.2
S025968	199	9-063B	Centaur AC-136	Centaur IIA AC-136	LMA	1999 Nov 23	In Earth orbit	1999 Dec 1	HEO	454.15	270 x 26116 x 26.9
S026053	200	0-001B	Centaur AC-138	Centaur IIA(4) AC-138	LMA	2000 Jan 21	In Earth orbit	2000 Mar 1	GTO	615.93	232 x 34971 x 25.9
S026072	200	0-007B	Centaur AC-158	Centaur IIA AC-158	LMA	2000 Feb 3	In Earth orbit	2000 Feb 15	HEO	823.76	211 x 45250 x 18.7
S026353	200	0-022B	Centaur AC-137	Centaur IIA	LMA	2000 May 3	In Earth orbit	2000 May 13	HEO	752.77	247 x 41819 x 20.1
S026370	200	0-028B	Centaur AC-201	Centaur IIIA	LMA	2000 May 24	In Earth orbit	2000 Jul 19	HEO	812.77	230 x 44713 x 20.3
S026389	200	0-034B	Centaur AC-139	Centaur IIA	LMA	2000 Jun 30	In Earth orbit	2000 Jul 8	HEO	480.34	235 x 27642 x 26.9
S026576	200	0-065B	Centaur AC-140	Centaur IIA AC-140	LMA	2000 Oct 20	In Earth orbit	2000 Oct 19	GTO	620.68	217 x 35232 x 26.0
S026636	200	0-080B	Centaur AC-157	Centaur IIA AC-157	LMA	2000 Dec 6	In Earth orbit	2000 Dec 6	GTO	663.55	266 x 37378 x 26.5
S026716	200	1-009B	Centaur TC-22	Centaur TC-22	USAF	2001 Feb 27	In Earth orbit	2001 Feb 28	GEO/ID	1435.04	35764 x 35768 x 4.5
S026858	200	1-026B	Centaur AC-156	Centaur AC-156	LMA	2001 Jun 19	In Earth orbit	2001 Jun 28	MEO	346.38	9810 x 10110 x 44.8
S026906	200	1-040B	Centaur AC-160	Centaur AC-160	LMA	2001 Sep 8	In Earth orbit	2001 Sep 9	LEO/I	107.26	1100 x 1100 x 63.0
S026949	200	1-046B	Centaur AC-162	Centaur IIA AC-162	LMA	2001 Oct 11	In Earth orbit	2001 Oct 11	GTO	666.85	274 x 37538 x 26.5
S027169	200	2-001B	Centaur TC-19	Centaur TC-19	USAF	2002 Jan 16	In Earth orbit				
S027390	200	2-011B	Centaur AC-143	Centaur AC-143	LMA	2002 Mar 8	In Earth orbit	2002 Mar 20	HEO	504.86	236 x 29012 x 27.0
S027500	200	2-038B	Centaur AV-001	Centaur SEC AV-001	LMA	2002 Aug 21	In Earth orbit	2002 Aug 28	HEO	789.74	272 x 43575 x 17.9
S027567	200	2-055B	Centaur AC-144	Centaur IIA AC-144	LMA	2002 Dec 5	In Earth orbit	2002 Dec 5	HEO	545.38	205 x 31262 x 26.9
S027712	200	3-012B	Centaur TC-23	Centaur TC-23	USAF	2003 Apr 8	In Earth orbit	2003 Apr 8	GEO/ID	1431.7	35696 x 35705 x 3.7
S027812	200	3-020B	Centaur AV-002	Centaur AV-002	LMA	2003 May 14	In Earth orbit	2003 May 22	HEO/D	658.22	373 x 79685 x 17.5
S027853	200	3-033B	Centaur AV-003	Centaur AV-003	LMA	2003 Jul 17	In Earth orbit	2003 Jul 18	GTO	689.95	3787 x 35186 x 17.6
S027938	200	3-041B	Centaur TC-20	Centaur TC-20	USAF	2003 Sep 9	In Earth orbit	2003 Sep 10	GEO/S	1436.27	35780 x 35800 x 2.0
S028096	200	3-054B	Centaur AC-164	Centaur AC-164	LMA	2003 Dec 2	In Earth orbit	2003 Dec 2	LEO/I	107.41	1002 x 1211 x 63.6
S028118	200	3-057B	Centaur AC-203	Centaur IIA AC-203	LMA	2003 Dec 18	In Earth orbit	2003 Dec 18	GTO	635.08	287 x 35905 x 27.0
S028155	200	4-003B	Centaur AC-165	Centaur IIA AC-165	LMA	2004 Feb 5	In Earth orbit	2004 Feb 14	GTO	628.85	221 x 35650 x 12.5
S028185	200	4-007B	Centaur AC-202	Centaur IIIA	LMA	2004 Mar 13	In Earth orbit				



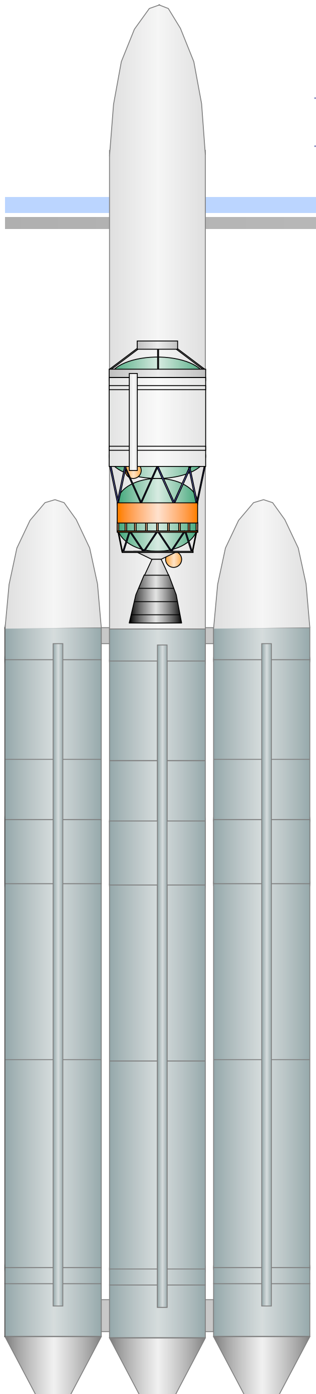


Boeing Delta IV-Heavy

- Largest vehicle in the international launch fleet
  - All components utilize LOX/LH2 cryogenic propellants
  - The HDCUS upper stage is potentially reusable
  - The central core stage can be put into LEO, and is also a candidate for reuse
- The potential LLO payload of a LEO refueled Delta-IV core booster is more than 3x the LLO payload of the Saturn V



Boeing Delta IV-Heavy: Upper Stage

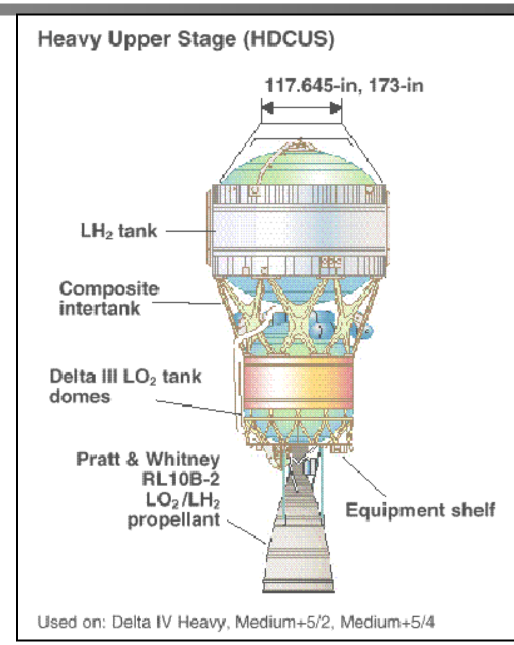


Technical Specifications

- Gross Mass – 30,200kg
- Empty Mass – 3,500kg
- Propellant Mass – 27,000kg
- ISP – 462 sec

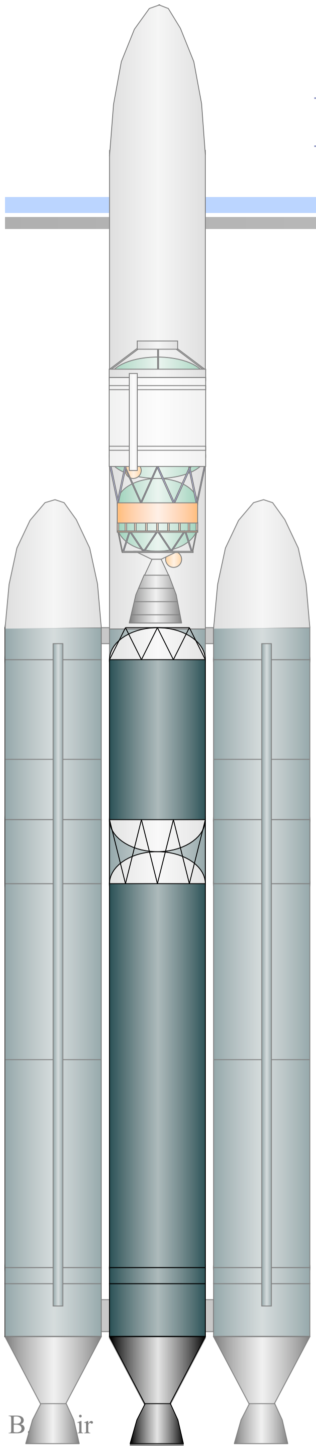
Delta IV Standard Payload

- LEO – 25,800kg
- GTO – 10,800kg
- LLO – 6,700kg (est)



Refueled in LEO: Extended Payload

- **GEO – 13,200kg**
- **LLO – 15,000kg**
- **L1 – 17,000kg**



Boeing Delta IV-Heavy: Core Booster

Technical Specifications

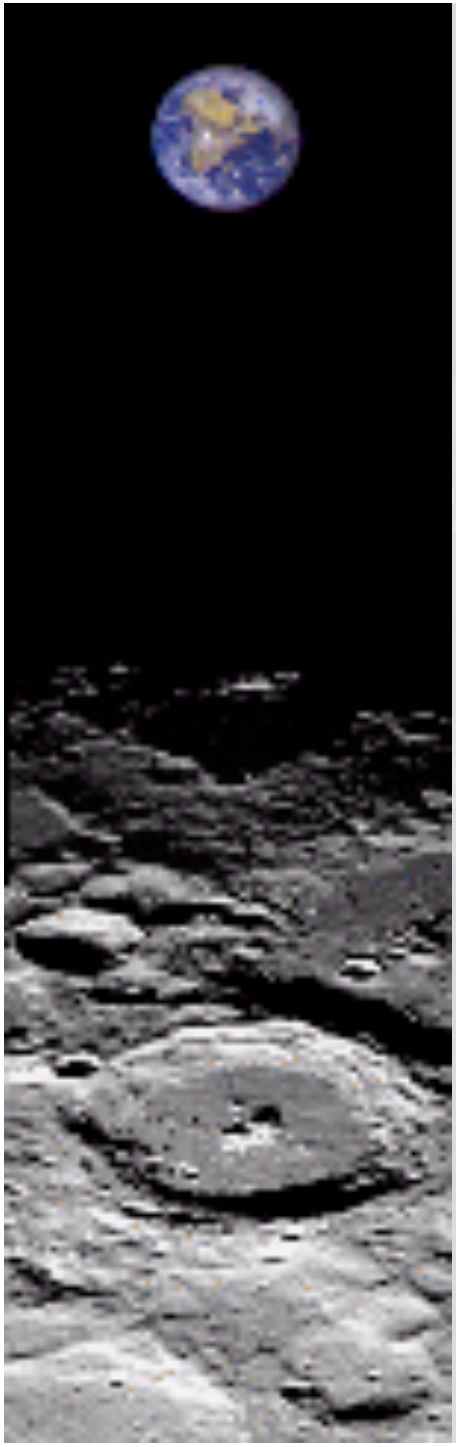
- Gross Mass – 226,400kg
- Empty Mass – 26,800kg
- Propellant Mass – 199,600kg
- ISP – 420 sec

Delta IV Standard Payload

- LEO – 25,800kg
- GTO – 10,800kg
- LLO – 6,700kg (est)

Refueled in LEO: Extended Payload

- **GEO – 80,600kg**
- **LLO – 93,100kg**
- **L1 – 106,600kg**



The Case for Commercial Lunar Ice Mining

by

Brad R. Blair, Javier Diaz, Michael B. Duke,
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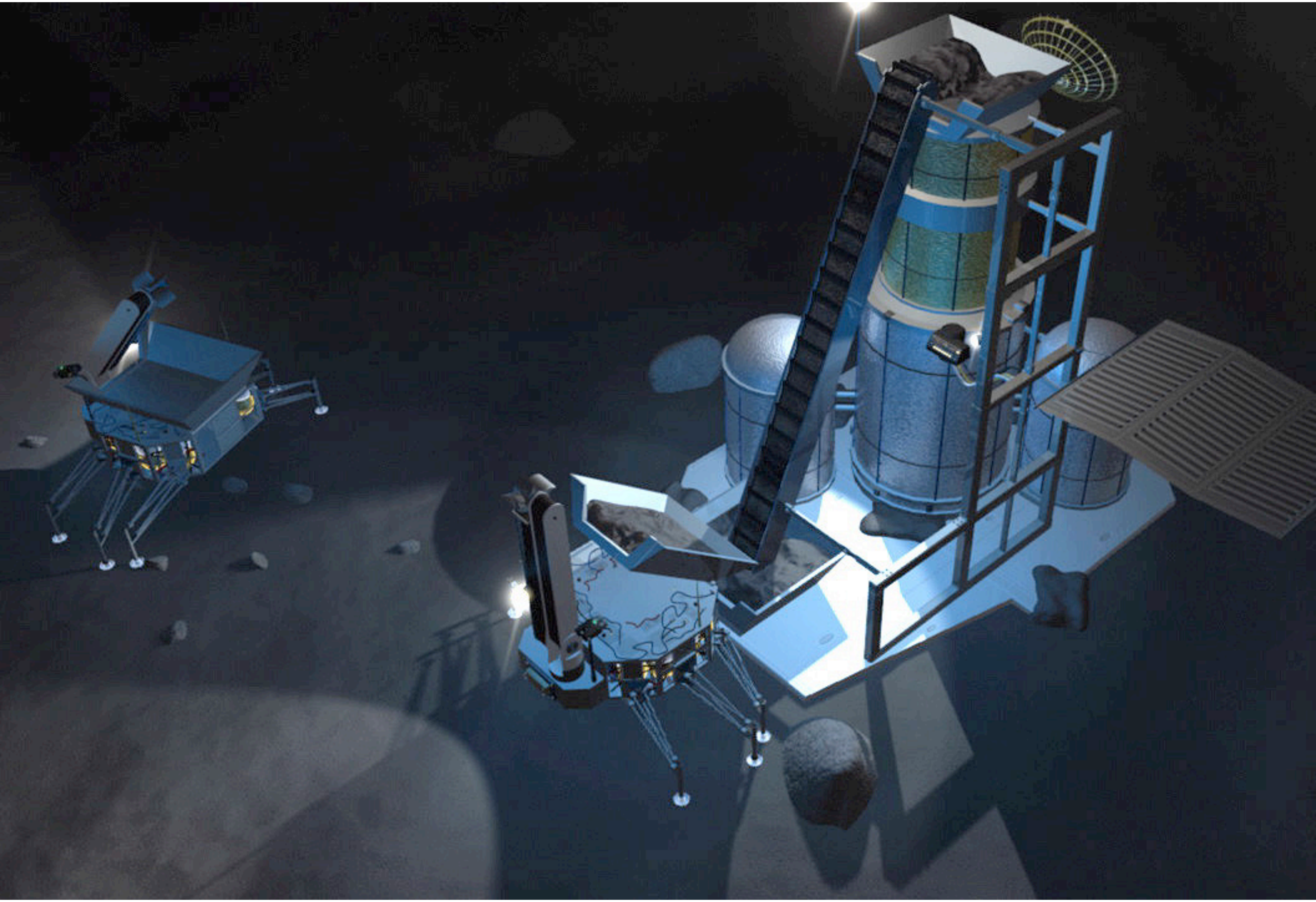
December, 2002

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



Architectures Studied

<u>Two architectural variants were modeled:</u>

Architecture 1

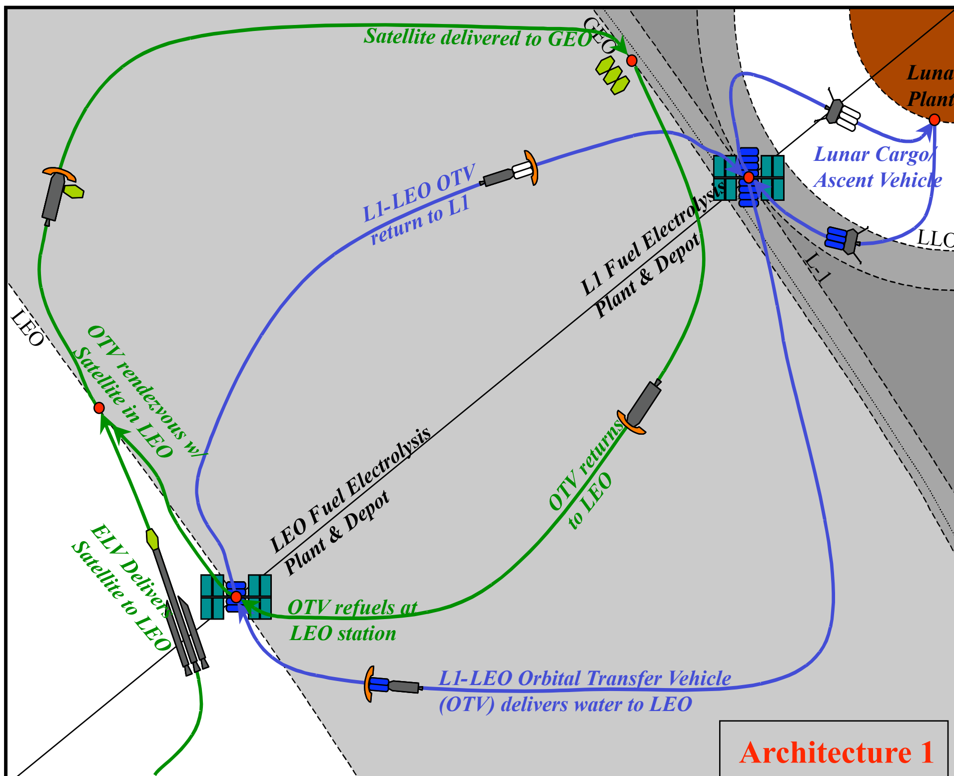
- Has an L1-based transportation system for getting payloads from LEO to GEO

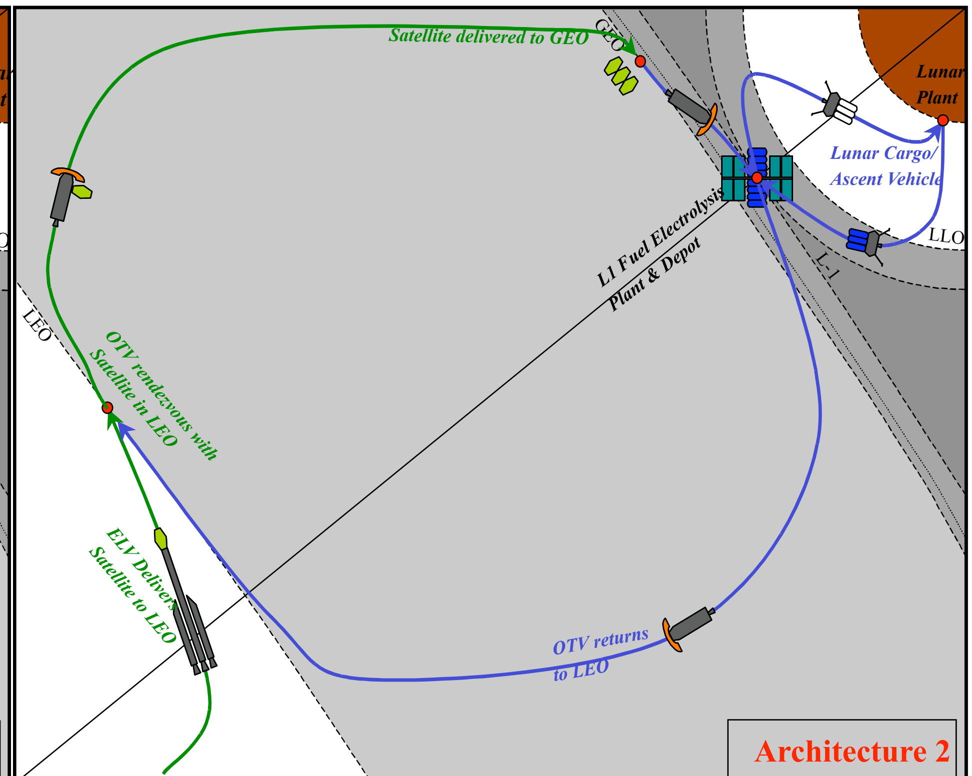
Architecture 2

- Is a LEO-based system, which requires that propellant be shipped to LEO

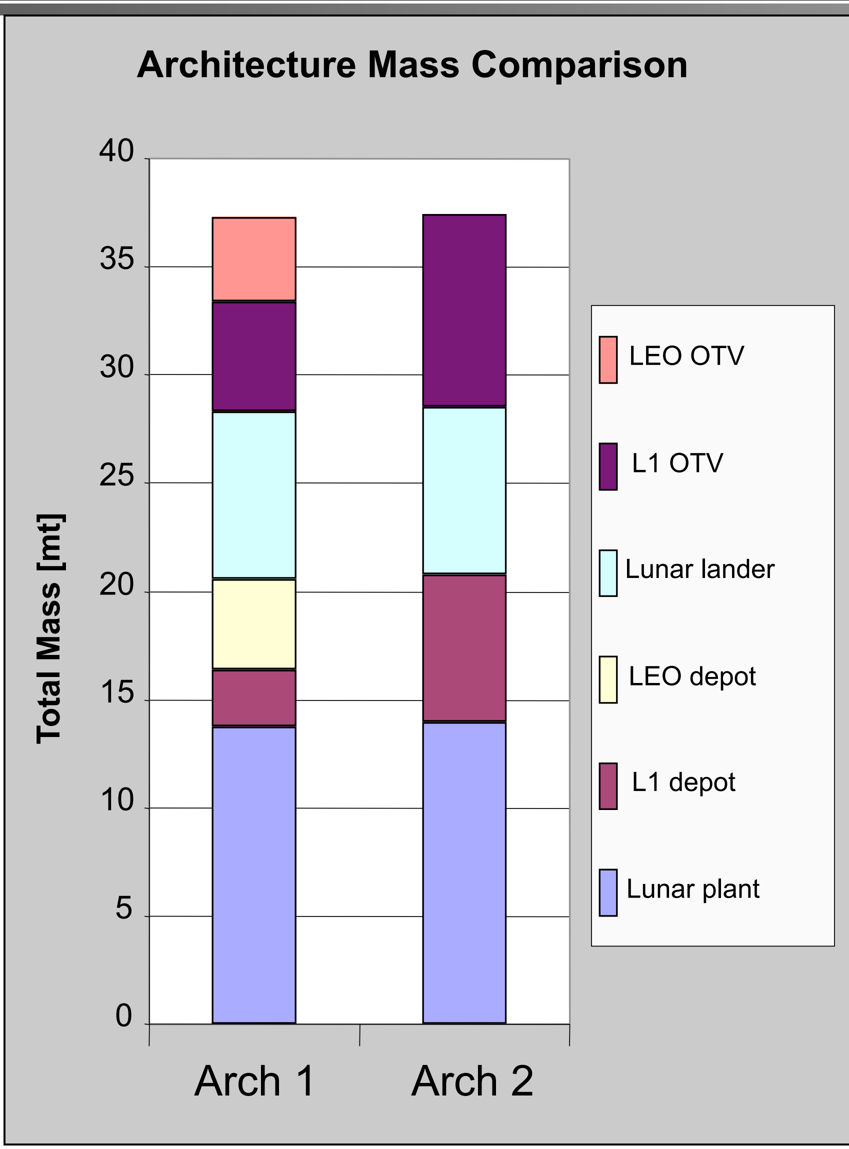
<u>Conservative Technology assumptions:</u>

- 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





FY02 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

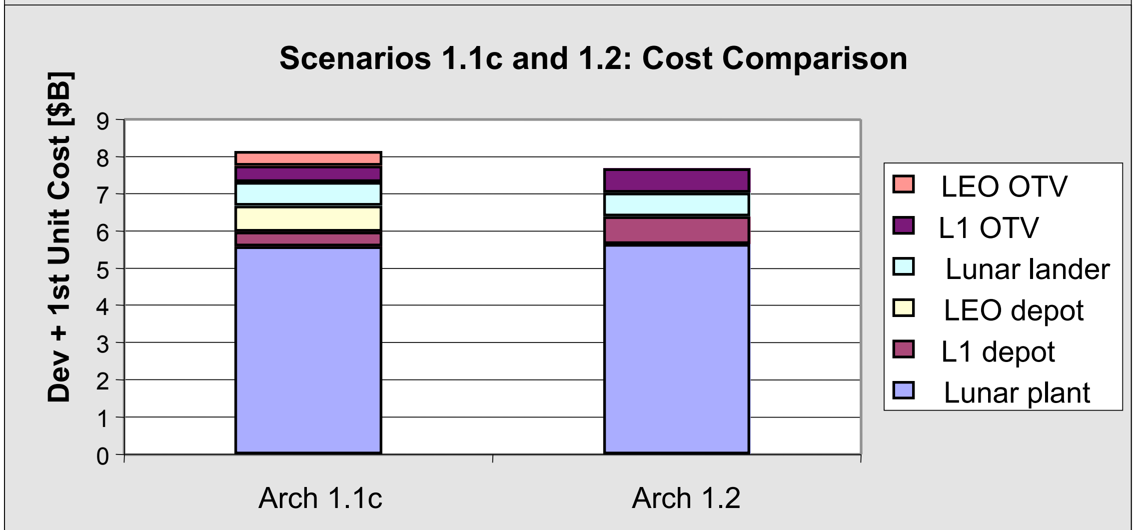
Vehicle	mass (kg)
Moon - L1 (Lander / fuel carrier)	7869
Propulsion system	2180
Telecomm	10
water storage (0.01%)	256
C&DH	3
Structures	3482
Power	15
Landing System	1801
L1-LEO-L1 Vehicle (fuel carrier)	1424
Propulsion system	636
Telecomm	10
water storage (0.01%)	200
C&DH	3
Structures	560
Power	15
L1-LEO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

FY02 Cost Model Development

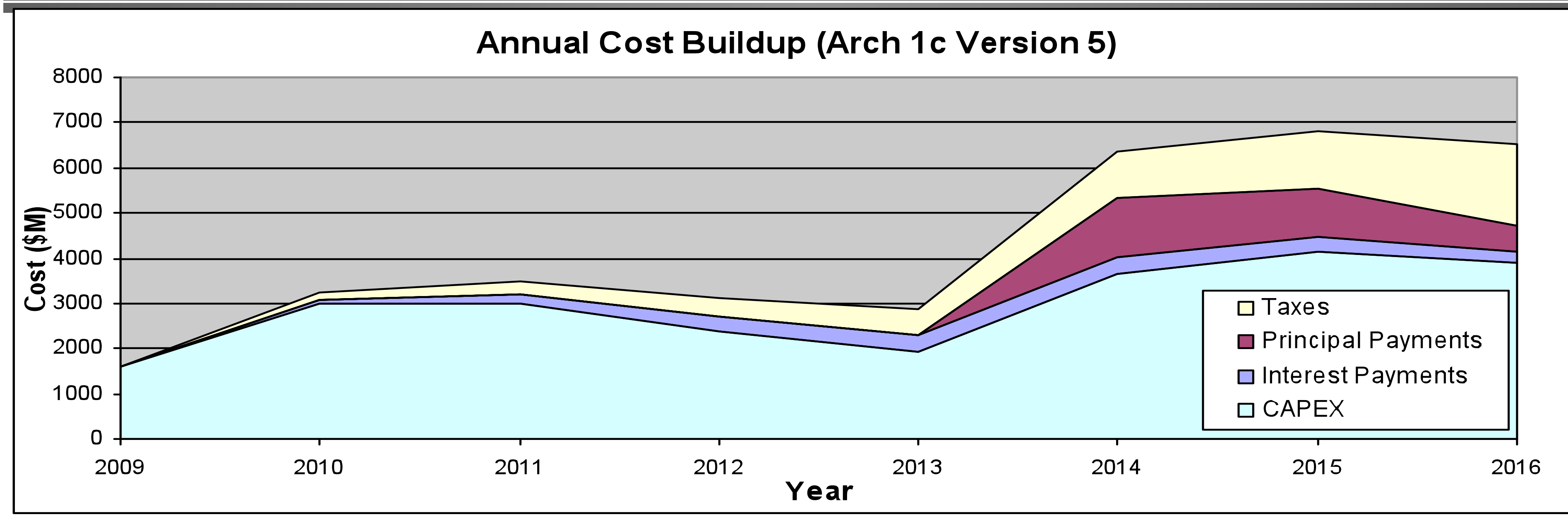
- NAFCOM99: Analogy-based cost model
  - Architecture 2 WBS shown on right panel
  - Conservative methodology used
- SOCM: Operations cost model
  - Estimates system-level operating costs
  - Conservative methodology used
- Launch Costs: $90k/kg Moon, $35k/kg GEO, $10k/kg LEO

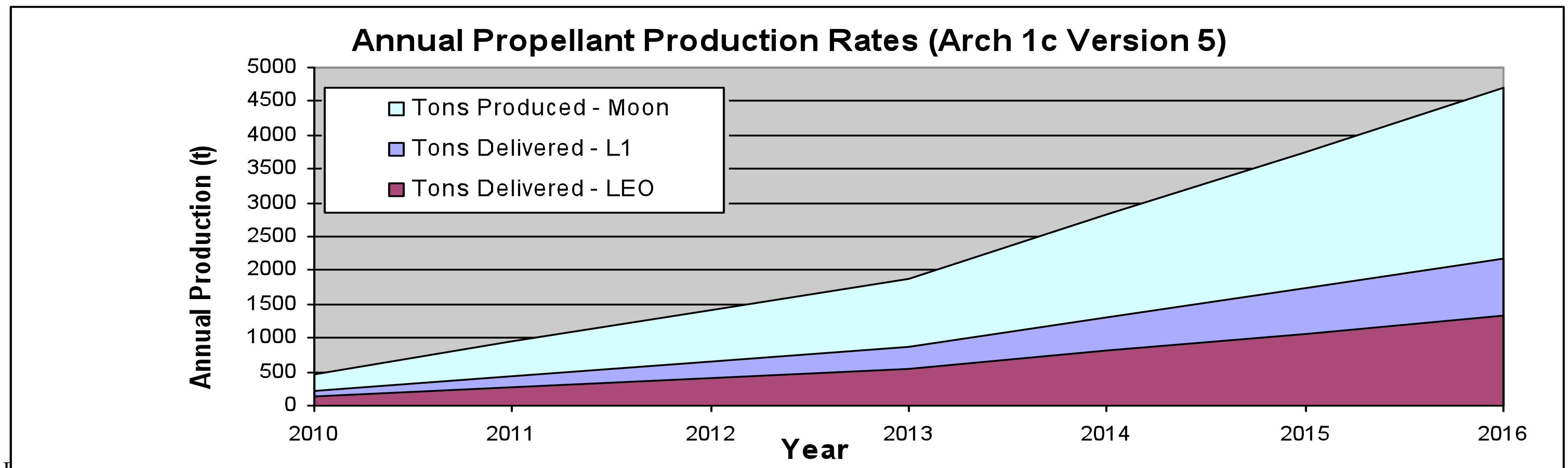
SRD Architecture 2 Cost Model ($M FY02 NAFCOM Estimate)	Mass (kg)	D&D	STH	FU	Prod	Total Cost
GRAND TOTAL	37470.2	5393.2	1018.1	1264.5	1264.5	7675.8
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	13980.7	3972.1	750.5	927.1	927.1	5649.7
SYSTEM 2: L1 Depot	6806.8	569.1	74.2	93.8	93.8	737.1
SYSTEM 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



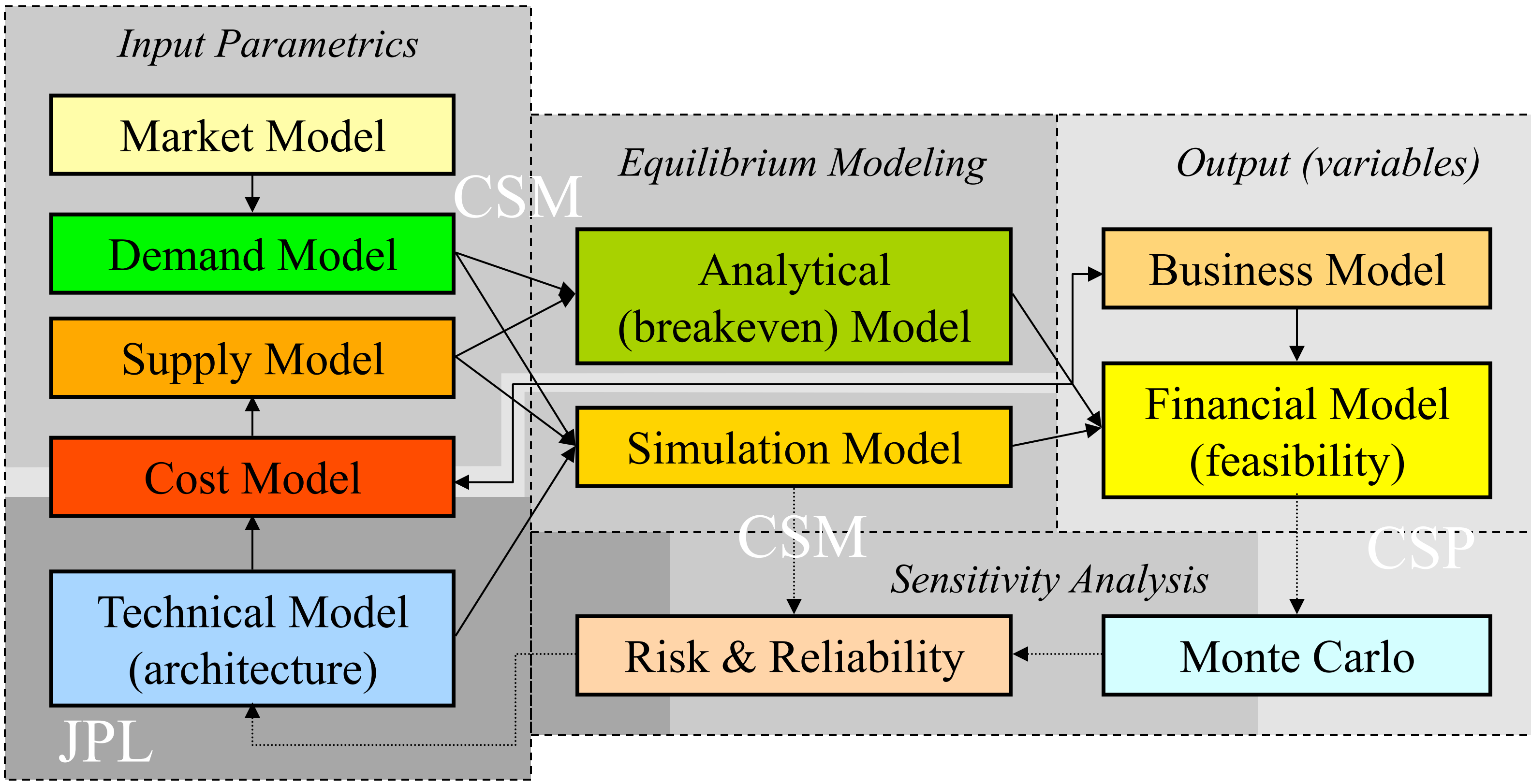
SRD Architecture 2 Cost Model ($M FY02 NAFCOM Estimate)	Mass (kg)	D&D	STH	FU	Prod	Total Cost
GRAND TOTAL	37470.2	5393.2	1018.1	1264.5	1264.5	7675.8
SYSTEM 1: Lunar Surface Mining & Procesing Equipment	13980.7	3972.1	750.5	927.1	927.1	5649.7
HARDWARE TOTAL	13980.7	1861.6	750.5	577.3	577.3	3189.5
Regolith 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

Cost Buildup & Production Rates





Economic Model Integration



Market Breakdown Structure

Market Breakdown Structure				Orbit Utilization (Note: Bold X indicates potential location for fuel or materials demand)								
				LEO	MEO	GTO	GEO	Polar	L1	Moon	Mars	Asteroid
1			Communications Market (commercial)									
	1		Fixed Satellite Service	**X**		X	**X**					
	2		Direct Broadcast Service	**X**		X	**X**					
2			Space Manufacturing (potential)									
	1		Space Manufacturing	**X**								
	2		Space Processing	**X**								
3			Government Missions									
	1		Existing Government Missions									
		1	NASA Missions (Excluding Station)	**X**	X	X	X	X	**X**	X	X	X
		2	DOD Missions	**X**	X	X	X	X				X
	2		Increased Space Station Missions									
		1	Station Deployment	**X**	X							
		2	Station Resupply	**X**	X							
		3	Station Reboost	**X**	X							
	3		Human Planetary Exploration									
		1	Lunar Base Program	**X**		X				**X**		
		2	Mars Design Reference Missions	**X**		X			X		X	
		3	Asteroid Exploration	**X**		X			X			**X**
	4		Asteroid Detection/Negation	**X**		X			X			**X**
	5		Technology Development Testbed	**X**		X	X					
4			Transportation									
	1		Space Servicing and Transfer	**X**	X	X	X		**X**			
	2		Hazardous Waste Disposal	**X**		X			X	**X**		
	3		Space Tourism	**X**		X			**X**	**X**	**X**	
5			New Missions									
	1		Space Debris Management	**X**	X	X	**X**	X	**X**			
	2		Multiuse LEO Business Park	**X**								
	3		Space Settlements	**X**			X		**X**	**X**	**X**	X
6			Space Utilities									
	1		GEO Solar Power Satellites	**X**		X	**X**					
	2		Lunar Based Power Station	**X**		X			X	**X**		
	3		Space to Space Power Beaming	**X**	X		**X**	X	X			

MBS Timeframe & Description

			MBS Item	Time Frame (modeled markets in bold)			Market Description
				Short-Term	Medium-Term	Long-Term	
1			Communications Market (commercial)				
	1		Fixed Satellite Service	**X**	X	X	Orbital Transfer (Deployment)
	2		Direct Broadcast Service	**X**	X	X	Orbital Transfer (Deployment)
2			Space Manufacturing				
	1		Manufacturing			X	Feedstock, Construction Materials
	2		In-Space Processing		X	X	Mineral Feedstock
3			Government Missions				
	1		Existing Government Missions				
		1	NASA Missions (Excluding Station)	**X**			Orbital Transfer (Deployment)
		2	DOD Missions	**X**			Orbital Transfer (Deployment + Missions)
	2		Increased Space Station Missions				
		1	Station Deployment		X	X	Orbital Transfer
		2	Station Resupply	**X**	X	X	Life Support
		3	Station Reboost		X	X	Stationkeeping
	3		Human Planetary Exploration				
		1	Lunar Base Program			X	Orbital Transfer, Life Support, Construction Materials
		2	Mars Design Reference Missions		X	X	Orbital Transfer, Life Support
		3	Asteroid Exploration			X	Orbital Transfer, Life Support
	4		Asteroid Detection/Negation (robotic)		X	X	Orbital Transfer (Deployment + Missions)
	5		Technology Development Testbed	**X**	X	X	Experimental (e.g., DARPA Orbital Express program)
4			Transportation				
	1		Space Servicing	**X**	X	X	Orbital Transfer (Deployment + Missions)
	2		Hazardous Waste Disposal			X	Orbital Transfer (Deployment)
	3		Space Tourism		X	X	Orbital Transfer, Life Support
5			New Missions				
	1		Space Debris Management	**X**	X	X	Orbital Transfer (Deployment + Missions)
	2		Multiuse LEO Business Park		X	X	Stationkeeping, Life Support
	3		Space Settlements			X	Construction Materials, Life Suppport, Fuels
6			Space Utilities				
	1		GEO Solar Power Satellites		X	X	Orbital Transfer (Deployment), Construction Materials
	2		Lunar Based Power Station			X	Construction Materials
	3		Space to Space Power Beaming			X	Orbital Transfer (Deployment), Construction Materials

Revenue Model

- Baseline Market Model
  - Commercial **GEO payload delivery** (Note: this is an existing market)
  - Modeled quantity = 150 tons/yr of GEO Satellite delivery mass 2010-2016 (Based on FAA/OCST 1999 and 2002 forecasts)
  - Market capture function starts at 10% in 2010 and ends at 100% in 2016
  - Modeled price = $20,000/kilogram of Satellite delivered to GEO

- Other near-term cryogenic fuel / H_2O markets
  - *Not included in current version of model*
  - Satellite servicing (Orbital Express bus)
  - ISS / Commercial business park (fuel + consumables)
  - DOD Missions (Orbital Express bus)
  - Orbital debris management
  - Human exploration missions (fuel + consumables)
  - Space materials processing/manufacturing (fuel, metals, ceramics, etc.)
  - Asteroid detection/negation
  - Solar powered satellites

FY02 Feasibility Modeling

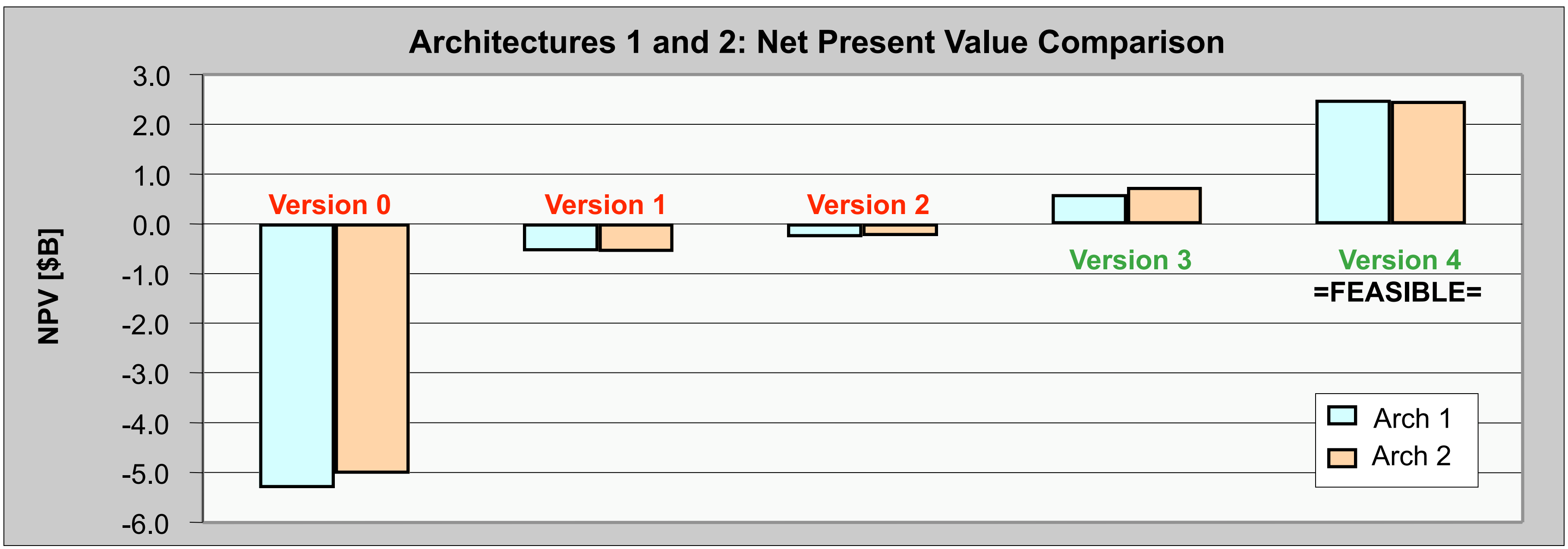
<u>Feasibility Process Summary:</u>

- Version 0 = Baseline (most conservative)
- Versions 1-3: Relax assumptions…
- Version 4 shows a *positive rate of return for private investment* (6%)

<u>Version 4 Assumes:</u>

- Zero non-recurring costs (DDT&E)
- 30% Production cost reduction
- 2% Ice concentration
- 2x Demand level (i.e., 300T/yr)

Version	Summary	Description
1.1c.0 1.2.0	Baseline	Baseline Version -all assumptions the same as previously except for demand and architecture changes
1.1c.1 1.2.1	No Non-Rec. Investments	Assumes the public sector pays for the Non-Recurring Investments (design, development and first unit cost)
1.1c.2 1.2.2	No Non-Rec. Investments, 30% Production Cost Reduction	Assumes the above, and Reduces the First unit production cost of all elements by 30%
1.1c.3 1.2.3	No Non-Rec. Investments, 30% Production Cost, 2x Lunar Water Concentration Reduction	Assumes all the above, and a Concentration of Water in Lunar Regolith twice higher than the current best estimate.
1.1c.4 1.2.4	No Dev. Cost, 30% Production Cost Reduction, 2x More Water on Moon, 2x Demand	Same as above, and Double the Demand



FY02 Commercial Model Results

CSP Financial Summary (Architecture 2, Version 4)

INCOME STATEMENT	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Revenues	$ 0	$ 0	$ 0	$ 600	$ 1,200	$ 1,800	$ 2,400	$ 3,600	$ 4,800	$ 6,000	$ 20,401
Gross Profit	$ 0	$ 0	$ 0	$ 539	$ 1,078	$ 1,617	$ 2,155	$ 3,233	$ 4,311	$ 5,388	$ 18,321
EBITDA	$ (4)	$ (9)	$ (10)	$ 527	$ 1,065	$ 1,604	$ 2,142	$ 3,219	$ 4,296	$ 5,373	$ 18,205
EBIT	$ (4)	$ (9)	$ (10)	$ 373	$ 610	$ 910	$ 1,257	$ 1,970	$ 2,195	$ 3,272	$ 10,565
Net Income	$ (4)	$ (9)	$ (10)	$ 184	$ 225	$ 337	$ 510	$ 924	$ 1,058	$ 1,708	$ 4,924

CASH FLOW	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Cumulative
Net Cash From Operations	$ (4)	$ (9)	$ (10)	$ 338	$ 680	$ 1,031	$ 1,395	$ 2,173	$ 3,159	$ 3,809	$ 12,563
Net Changes in Working Capital	$ 0	$ 0	$ 0	$ (45)	$ (45)	$ (45)	$ (45)	$ (90)	$ (90)	$ (90)	$ (448)
CAPEX/NRE	$ 0	$ 0	$ 1,548	$ 3,018	$ 3,013	$ 2,384	$ 1,910	$ 3,649	$ 4,105	$ 4,410	$ 24,039
Taxes	$ -	$ -	$ -	$ 107	$ 150	$ 225	$ 340	$ 616	$ 706	$ 1,138	$ 3,282
Annual Cash (Shortfall) Surplus	$ (4)	$ (8)	$ (1,557)	$ (2,725)	$ (2,378)	$ (1,399)	$ (560)	$ (2,928)	$ (2,224)	$ (1,391)	$ (15,174)
Equity Financing	$ 104	$ 8	$ 1,557	$ 1,363	$ 1,189	$ 699	$ 280	$ 1,464	$ 1,112	$ 695	$ 8,472
Debt Financing	$ -	$ -	$ -	$ 1,363	$ 1,189	$ 699	$ 280	$ 1,464	$ 1,112	$ 695	$ 6,802
Principal and Interest Payments	$ -	$ -	$ -	$ 82	$ 235	$ 348	$ 407	$ 1,792	$ 1,620	$ 1,126	$ 5,610

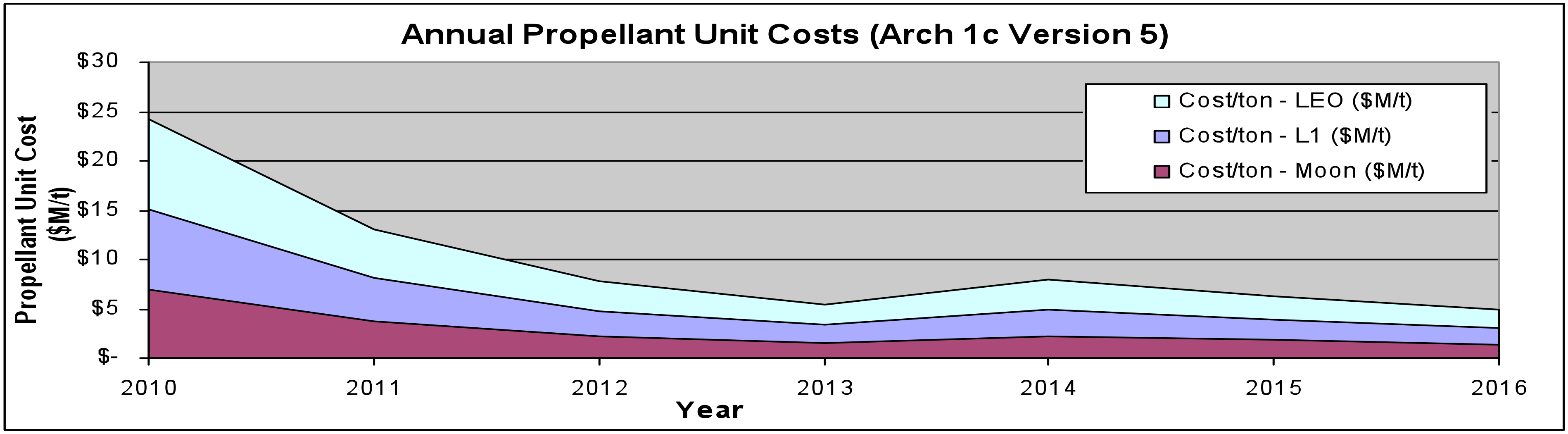
BALANCE SHEET	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Total Assets	$ 100	$ 100	$ 1,648	$ 4,562	$ 7,170	$ 8,911	$ 9,987	$ 12,486	$ 14,590	$ 16,999
Short and Long Term Liabilities	$ 0	$ 1	$ 1	$ 1,369	$ 2,563	$ 3,267	$ 3,552	$ 3,664	$ 3,597	$ 3,603
Shareholder Equity	$ 104	$ 112	$ 1,670	$ 3,032	$ 4,221	$ 4,921	$ 5,200	$ 6,665	$ 7,777	$ 8,472
Retained Earnings	$ (4)	$ (13)	$ (23)	$ 161	$ 386	$ 724	$ 1,234	$ 2,158	$ 3,216	$ 4,924

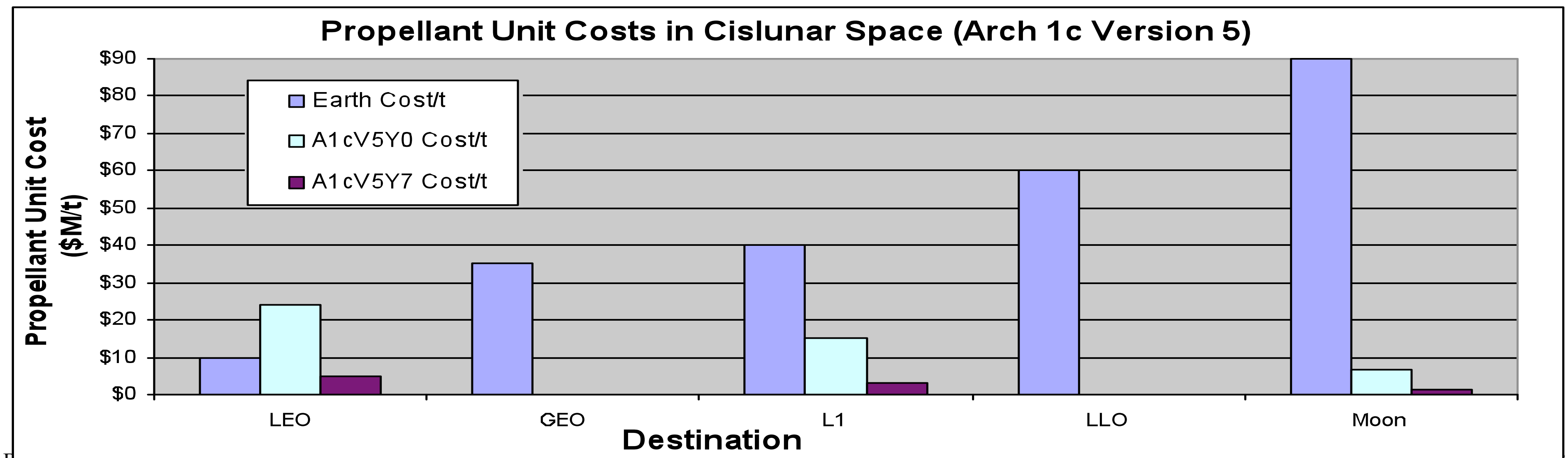
Production and delivery rates for water at Lunar cold trap and L1 (Architecture 2, Version 4)

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Total Market Demand [MT]	300	300	300	300	300	300	300	300	300	300
Market Share and Growth	0%	0%	0%	10%	20%	30%	40%	60%	80%	100%
Actual Demand [MT]	0	0	0	30	60	90	120	180	240	300
Number of deployed production units	0	0	0	2	4	6	8	12	16	20
Non-Recurring Investments (Development) [$M]	$4,378	$2,368	$550	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Recurring CAPital EXpenditures (Production & Launch) [$M]	$ -	$ -	$ -	$1,533	$3,013	$2,384	$1,910	$3,649	$4,105	$4,410
Tons Produced - Moon (MT)	**0**	**0**	**0**	**491**	**981**	**1472**	**1963**	**2944**	**3925**	**4907**
Tons Delivered - L1 (MT)	**0**	**0**	**0**	**225**	**451**	**676**	**902**	**1353**	**1804**	**2255**
Annualized cost/ton - Moon ($M/t)				$ 3.12	$ 3.07	$ 1.62	$ 0.97	$ 1.24	$ 1.05	$ 0.90
Annualized cost/ton - L1 ($M/t)				$ 6.80	$ 6.68	$ 3.53	$ 2.12	$ 2.70	$ 2.28	$ 1.96

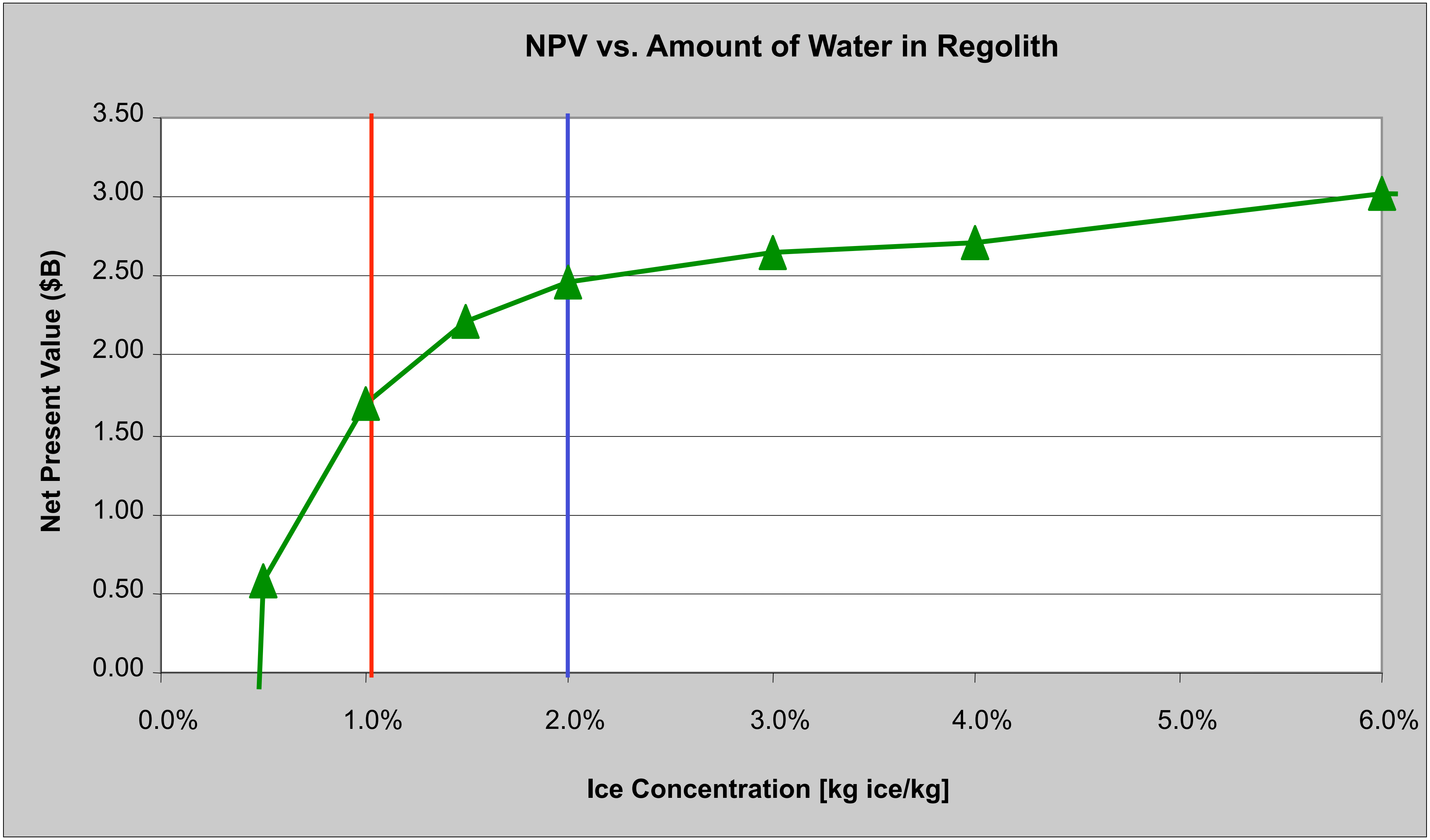
SRD Model Results

- Results provide an *Upper Bound* on Propellant Unit Costs



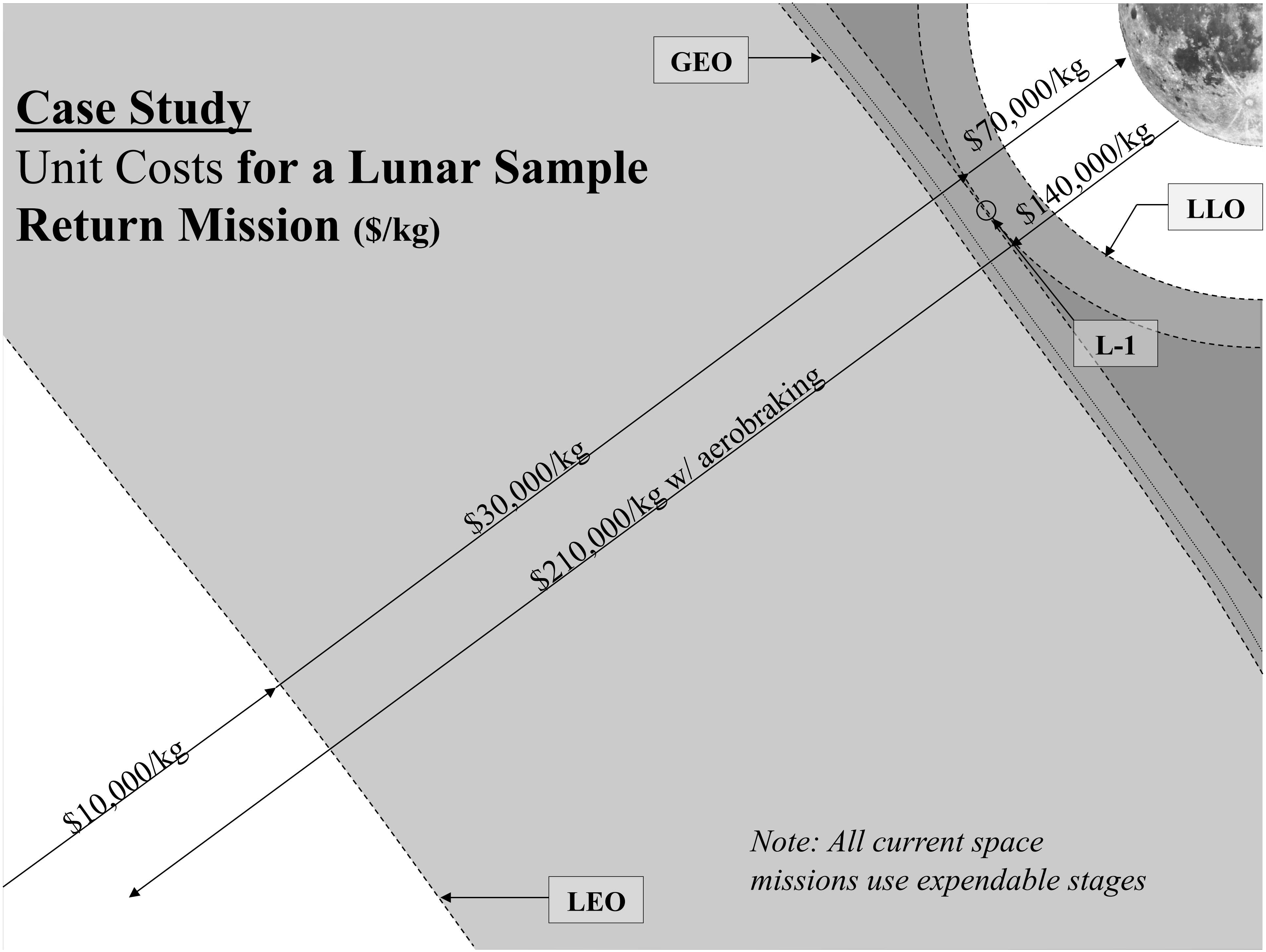


SRD Model Sensitivity to % Ice



Case Study

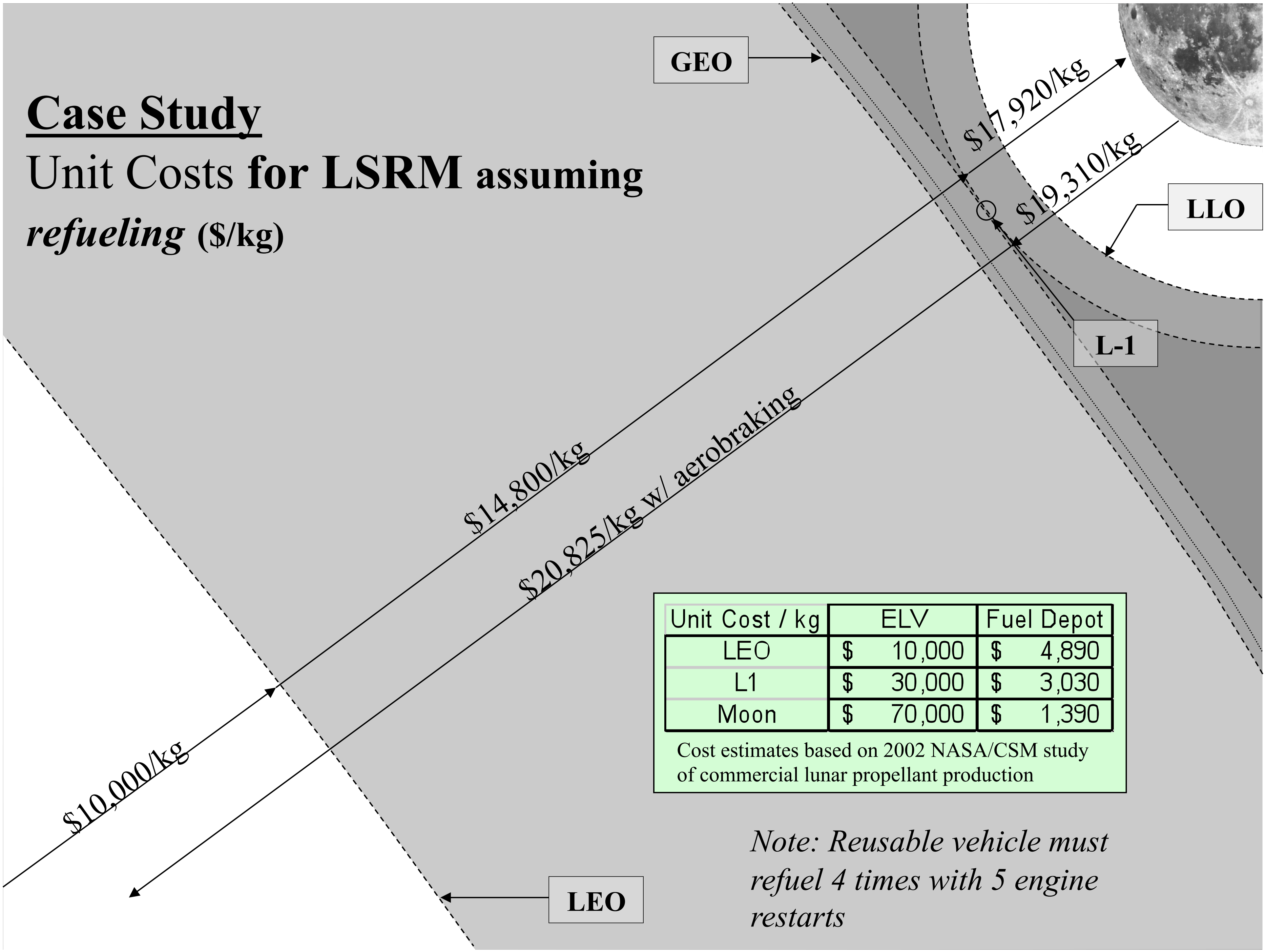
Unit Costs **for a Lunar Sample Return Mission** **($/kg)**



Note: All current space missions use expendable stages

Case Study

Unit Costs **for LSRM assuming** ***refueling*** **($/kg)**



Unit Cost / kg	ELV	Fuel Depot
LEO	$ 10,000	$ 4,890
L1	$ 30,000	$ 3,030
Moon	$ 70,000	$ 1,390

Cost estimates based on 2002 NASA/CSM study of commercial lunar propellant production

Note: Reusable vehicle must refuel 4 times with 5 engine restarts

2003 DARPA Study

- "Lunar Manufacturing" fresh start in Spring 2003
- Partnership between CSM and MDA (U.S. – Canada collaboration)

- Refined architectural assumptions including ISRU and transportation system models
- Expanded propellant market models to include DoD payloads

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

Acknowledgements

- **Johnson Space Center (JSC)**
  - Study Lead
  - Verification/validation of architecture
  - Vehicle sizing and consumables requirements
    - Scott Baird
    - Kris Romig
    - Gerald Sanders
- **Colorado School of Mines (CSM)**
  - Economic modeling
  - Architecture development
  - Excavating (lunar focus)
  - Product integration
  - Final Report
    - Brad Blair
    - Begonia Diaz
    - Javier Diaz
    - Mike Duke
- **Kennedy Space Center (KSC)**
  - Lunar Processing Plants development
  - Mars Processing Plants development
  - Chemical processing methodology
    - Dale Lueck
    - Clyde Parrish
- **Florida Institute of Technology**
  - Assist KSC with processing plant development
    - Jonathan Whitlow

Architecture Elements

- **Earth surface-to-LEO transportation**
  - Existing Capabilities: Shuttle, Delta IV Heavy, Atlas V
  - New "Magnum" class heavy lift expendable

- **LEO Station**
  - ISS

- **Near-Earth Neighborhood and Earth-Mars Transfer Vehicles**
  - Hybrid Propulsion Module (HPM)
  - Chemical Transfer Module (CTM)
  - Nuclear Electric Propulsion (NEP)
  - Solar-Electric Rocket
- **Crew Transport Vehicle**
  - Crew Exploration Vehicle (CEV)

- **Lagrange Point Stations [E-ML1,2, S-EL1,2, S-ML1,2]**
  - Earth-Moon L1 will act as a staging point for Mars bound missions
    - Propellants and other consumables supplied from lunar surface
  - Fuel Depots at Earth-Moon L1, Mars-Sun L1
  - Gateway Station (L1)

- **Lunar Surface Base**
  - Manned habitats and surface excursion vehicles
  - Surface production plants

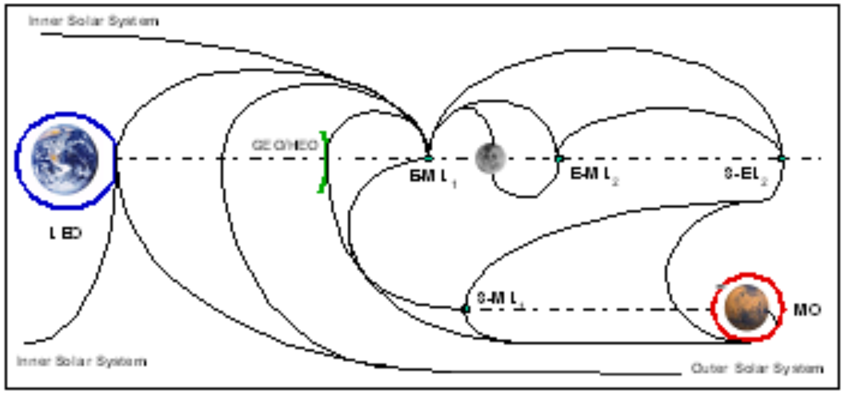
- **Lunar surface-to-Lunar Orbit transportation**
  - Single Use
  - Reusable
- **Mars Surface Base**
  - Manned habitats and surface excursion vehicles
  - Surface production plants

- **Mars surface-to-Mars Orbit transportation**
  - Single Use
  - Reusable

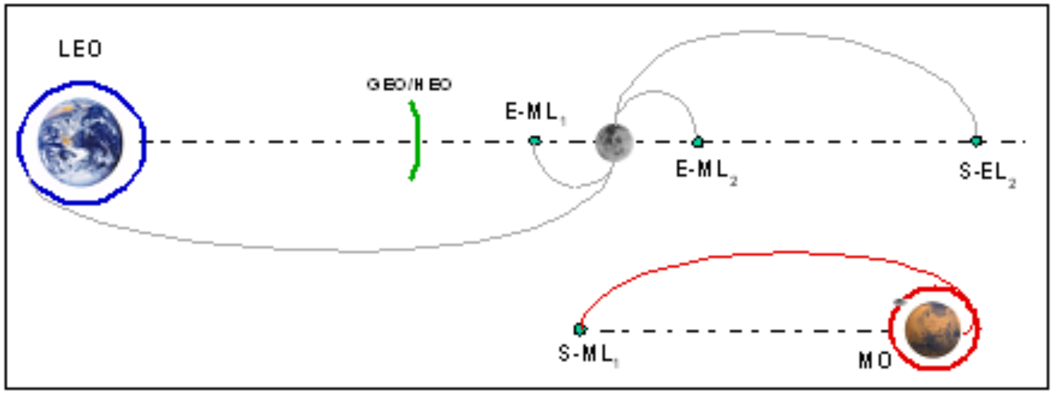
Mission Design

- **Mission Destinations & Staging Points**

ISRU Supportable Missions



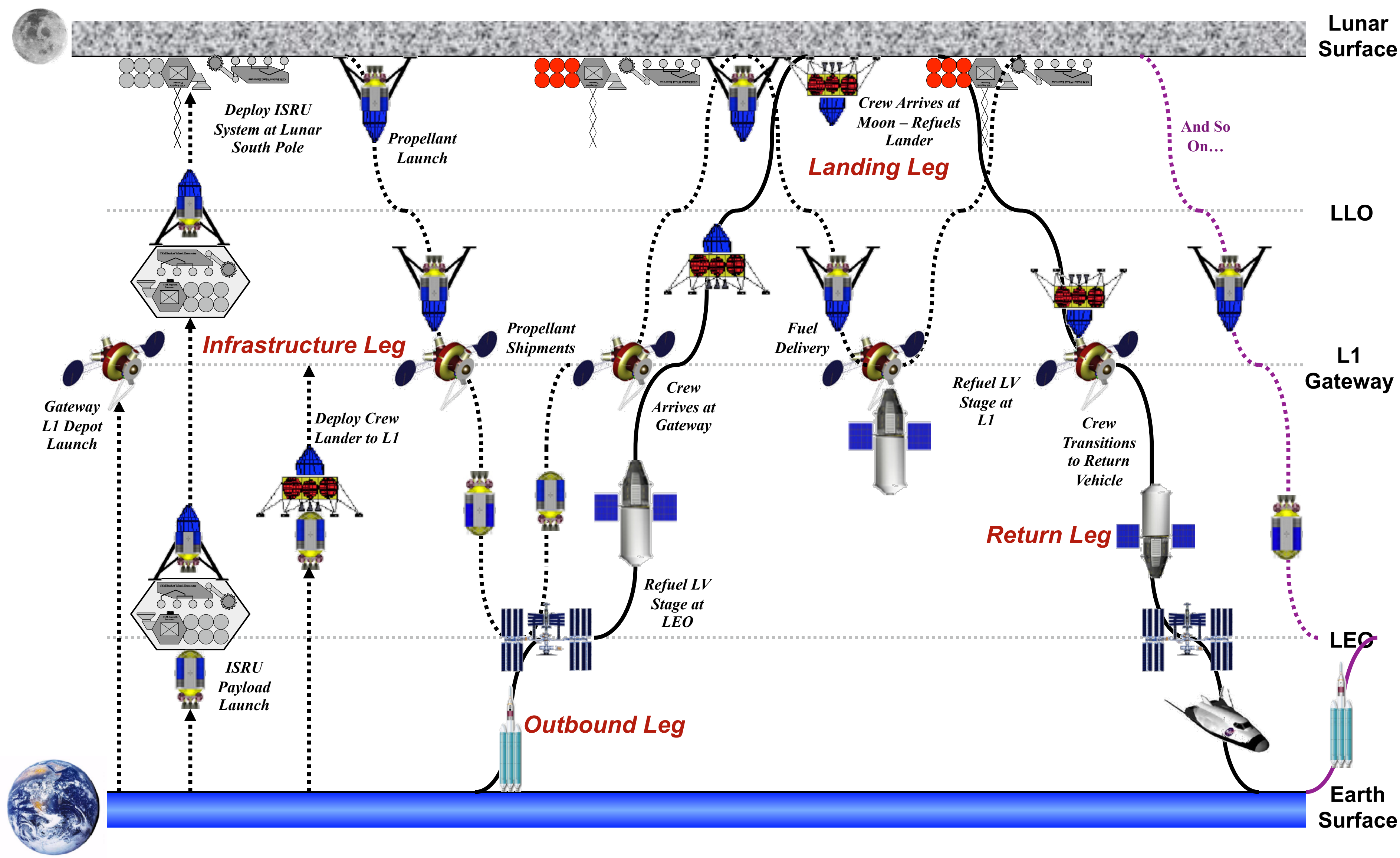
ISRU Supplied Resources Architecture – Resupply Nodes



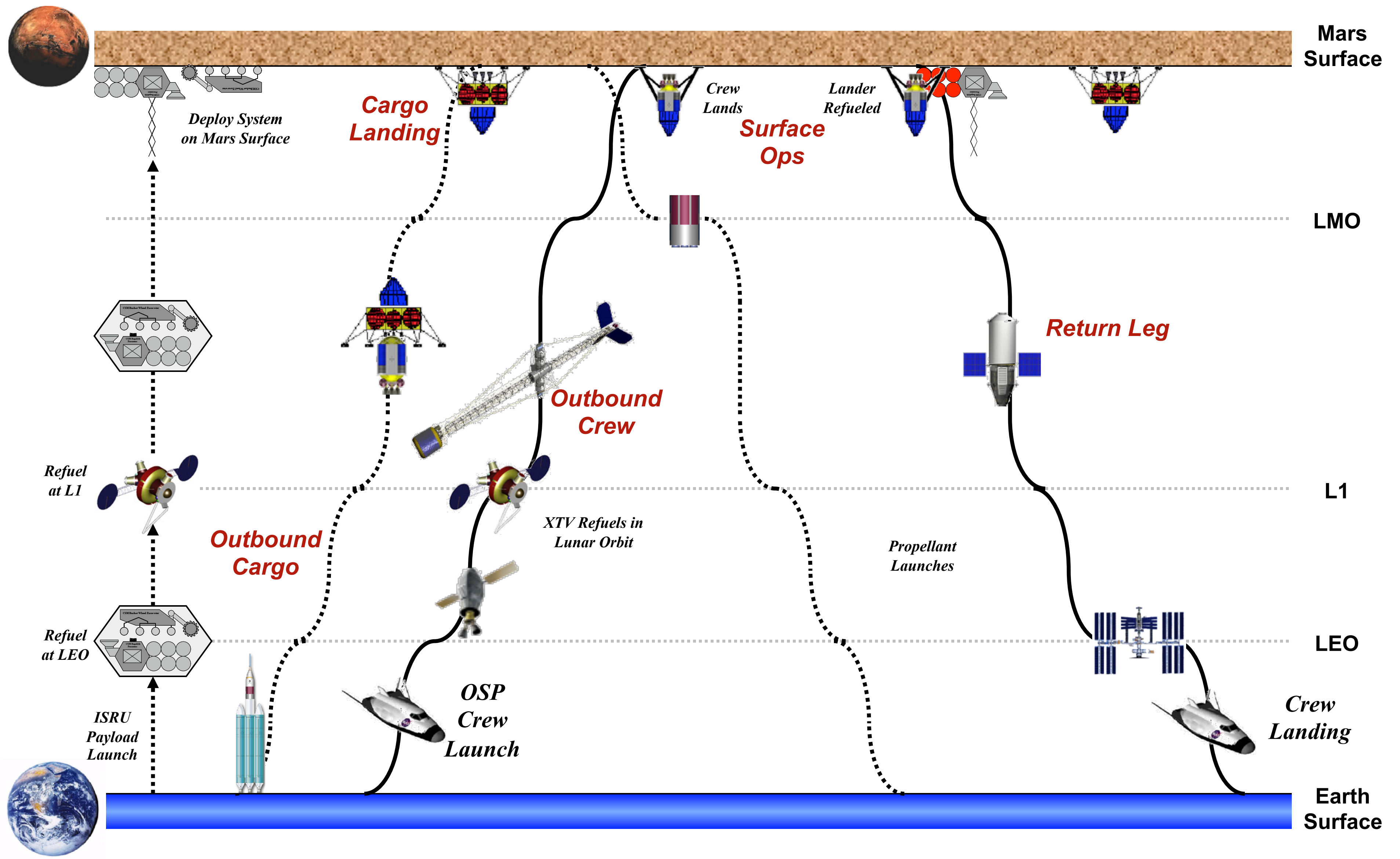
- **Mission Velocity Requirements (ΔV)**

TO: FROM	ES	LEO	GEO HEO	E-ML	S-EL	LS	S-ML	MO	MS
ES		**12,000**	**15,000**	-	-	-	-	-	-
LEO	**114**		**2,700**	**4,040**	**3,150**	**5,930**	**TBD**	**5,600**	**4,800**
GEO/HEO	-	**2,700**		**TBD**	-	-	-	-	-
E-ML	-	**4,040**	**TBD**		**TBD**	**2,620**	**7,450**	**TBD**	**TBD**
S-EL	-	**TBD**	**TBD**	**TBD**		**TBD**	**TBD**	**TBD**	**TBD**
LS	-	**2,740**	-	**2,700**	**TBD**		-	-	-
S-ML	-	**TBD**	-	**7,450**	**TBD**	-		**TBD**	**6,000**
MO	-	**1,800**	-	**TBD**	**TBD**	**3,200**	**TBD**		**850**
MS	-	**5,800**	-	**TBD**	**TBD**	-	**TBD**	**4,000**	

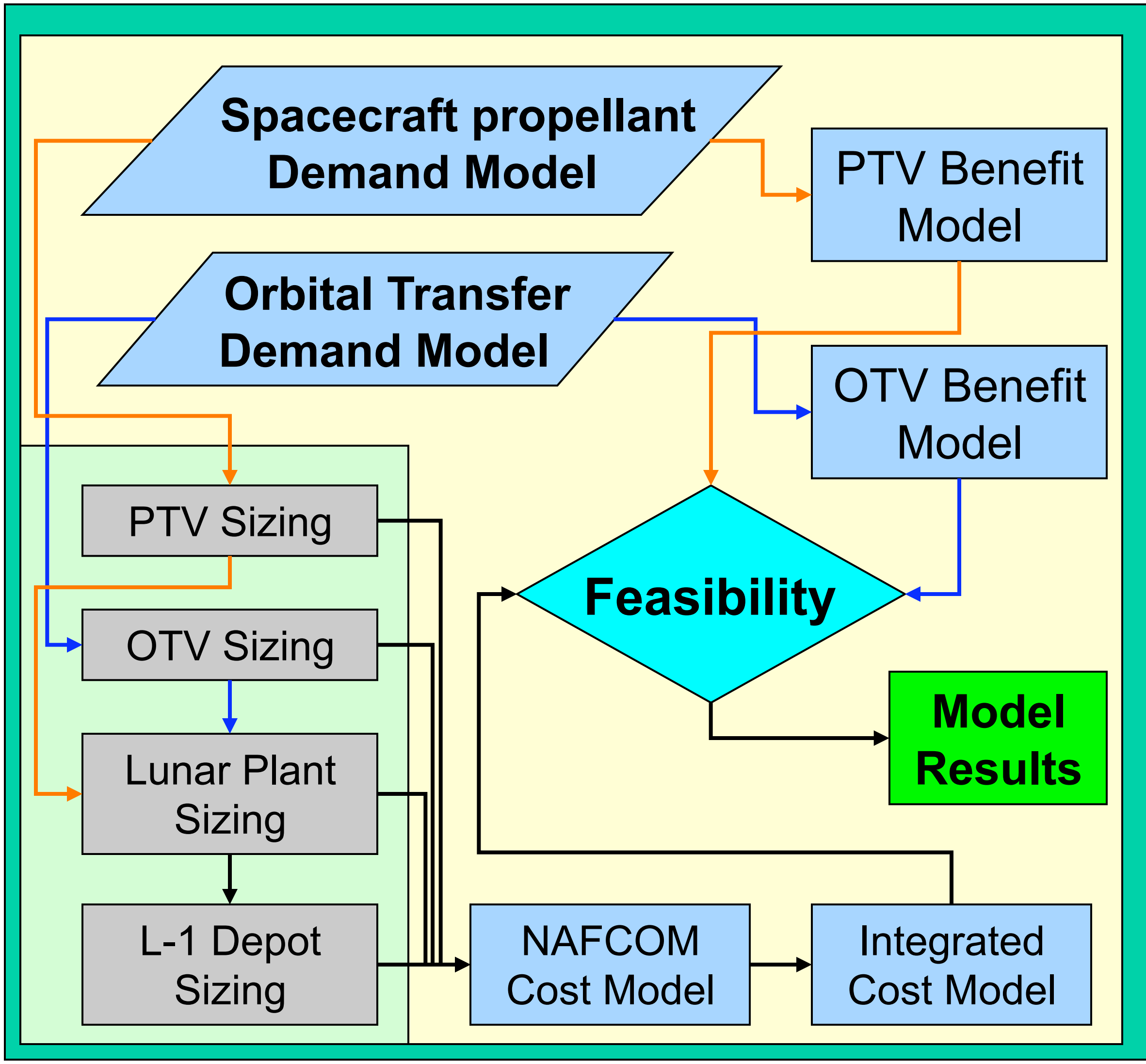
Lunar ISRU Architecture



Mars ISRU Architecture

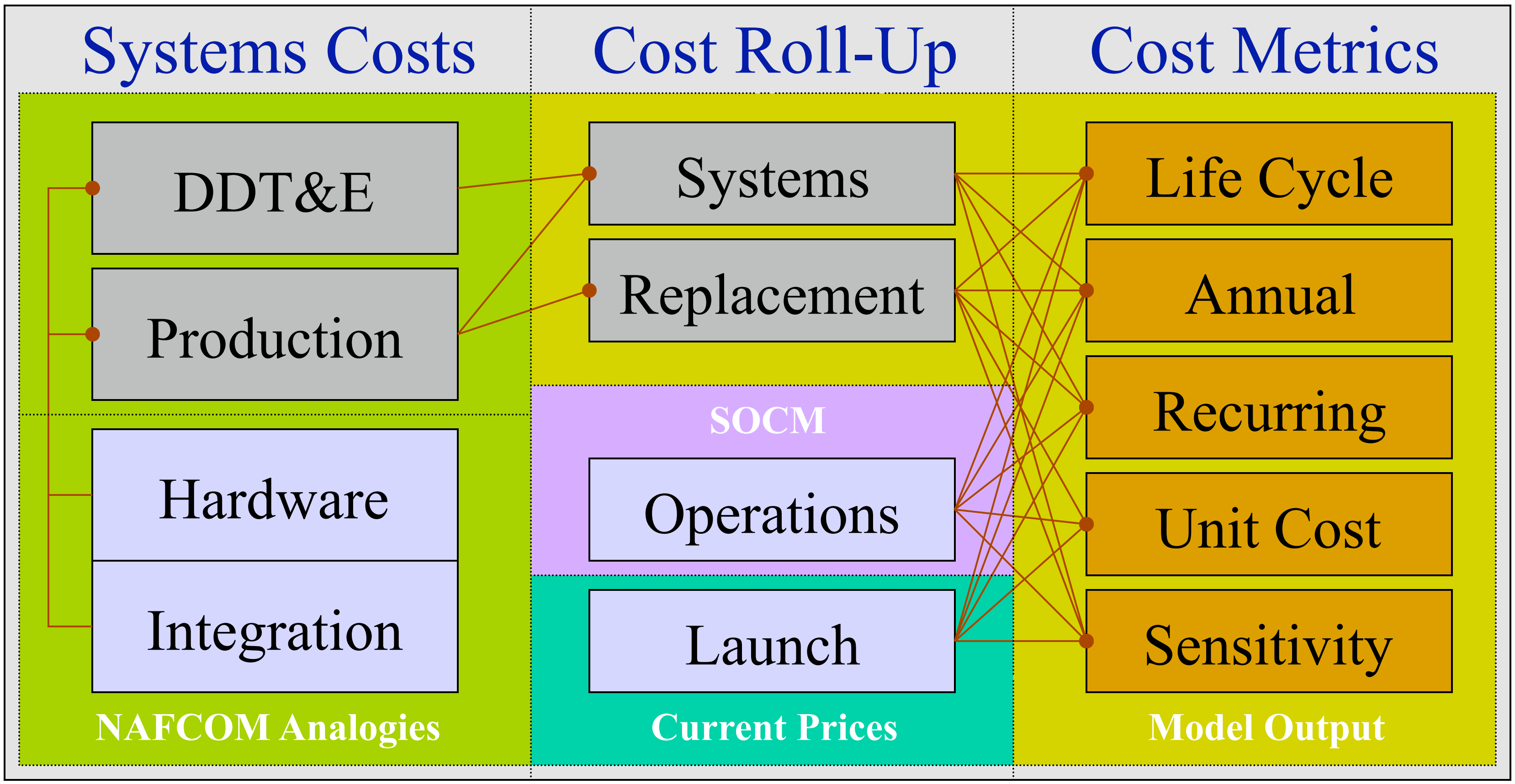


Functional Layout of CSM Models



- Model Structure
  - Architecture
  - Parametric sizing
  - Demand models
  - Cost model
  - Feasibility
- Goals of Modeling
  - Determine feasible conditions (Go / No Go)
  - Insight into critical assumptions
  - Insight into systems dynamics (sensitivity)
  - Identification of critical risk factors
  - Technology sensitivity analysis (investment prioritization)

Cost Modeling Flowsheet



A Bold Vision for Space Exploration

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2014 (goal of 2012)
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

"It is time for America to take the next steps.

Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We'll make steady progress – one mission, one voyage, one landing at a time"

President George W. Bush – January 14, 2004

Cost/Benefit Modeling

(lunar 10yr scenario)

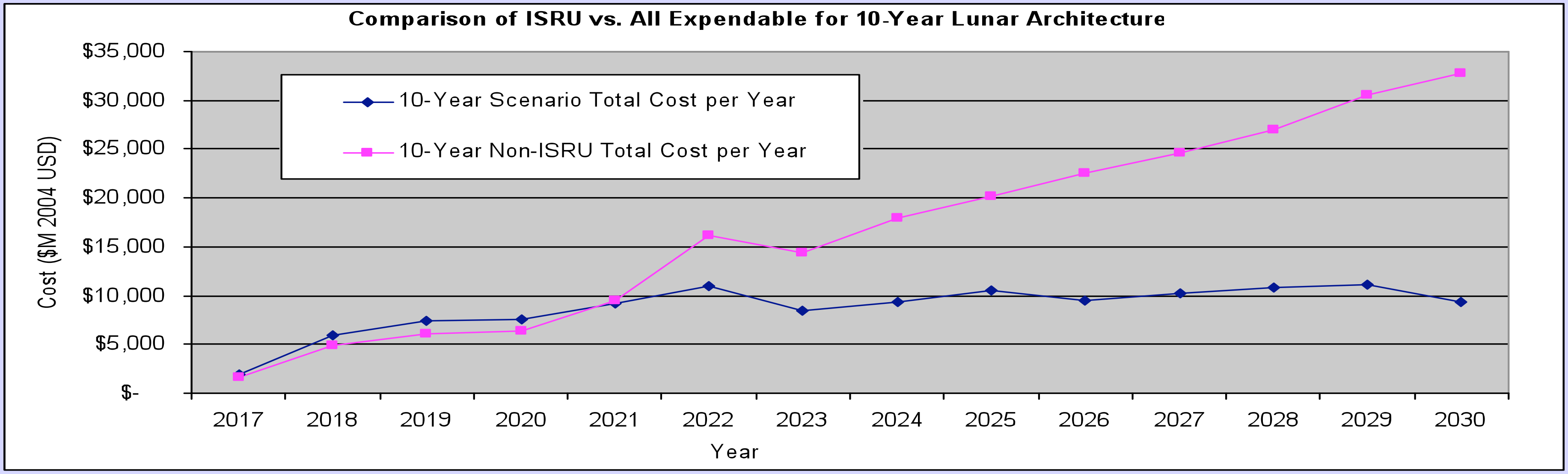
- Cost Model includes
  - DDT&E, Production & Integration costs from NAFCOM
  - Operations cost of $57M per element per mission
  - Launch costs, including options for Saturn V, Delta 4, Atlas 3
  - Discounting of out-year costs at 8%
- Comparison of ISRU to Baseline
  - Baseline assumes Apollo-style expendable systems
  - Choice of Saturn, Delta, Atlas for cargo missions
- Benefit Model includes
  - Rate of return, comparing relative benefit of ISRU model to Baseline

Cost/Benefit Results for Lunar ISRU

- Discounted Rate of Return (ROR) vs. Baseline = 49.4%
  - ISRU 10-yr mission cost = $40.1 Billion
  - Baseline 10-yr mission cost = $59.9 Billion

- Suggested Model Improvements Include
  - Add/improve links for sensitivity analysis
  - Preliminary technology improvements modeling
  - Review & update launch cost roll-ups

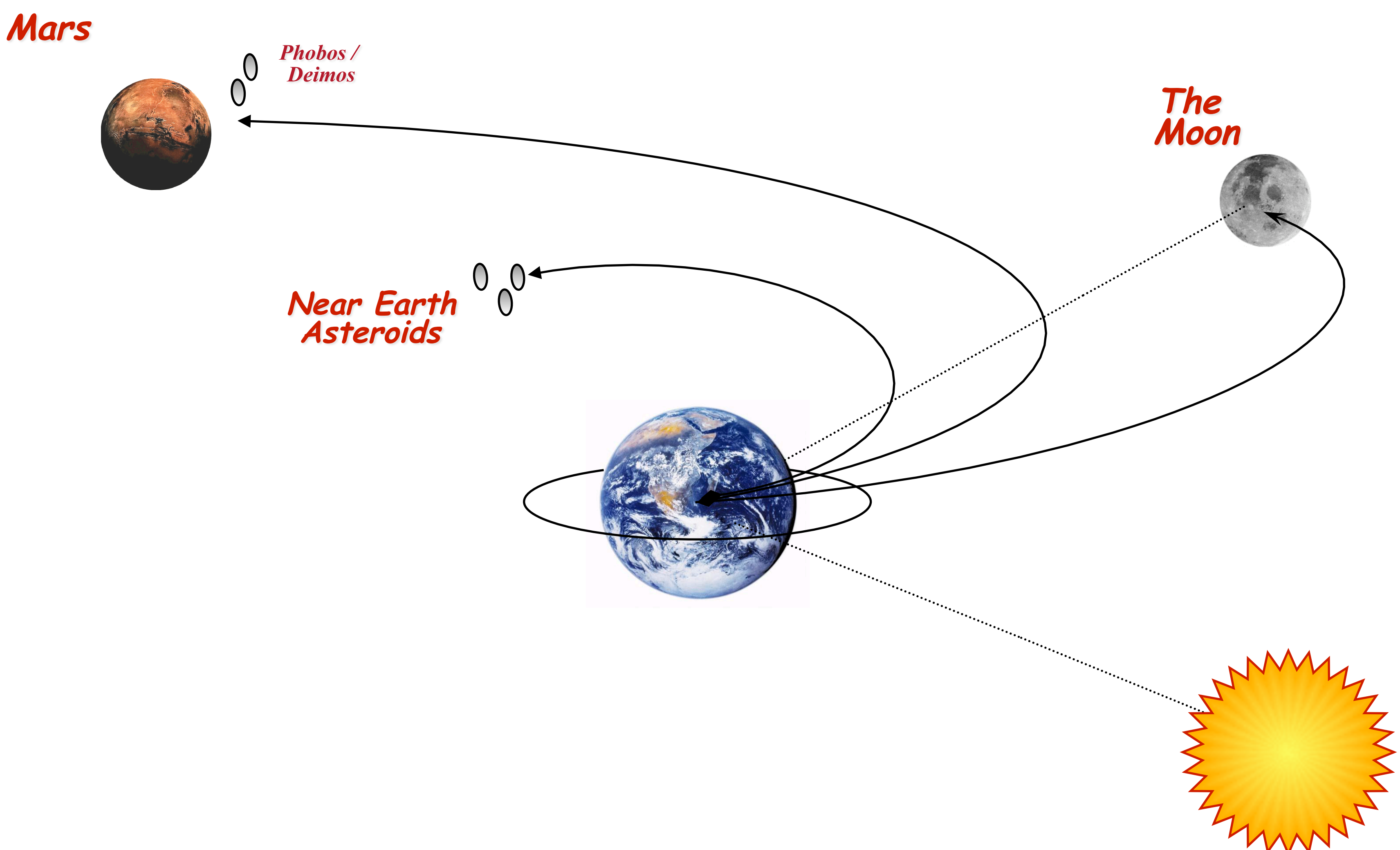
Lunar ISRU cost crossover point



10 Year ISRU Scenario Cost Summary	Date	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Development Cost		$1,927	$ 5,935	$ 7,472	$ 4,593	$ 1,370	$ 530	$ 814	$ 641	$ 149	$ -	$ -	$ -	$ -	$ -
Production Cost		$ -	$ -	$ -	$ 1,309	$ 3,917	$ 4,625	$ 2,712	$ 2,708	$ 3,320	$ 2,843	$ 3,033	$ 3,119	$ 3,247	$ 2,250
Launch Cost		$ -	$ -	$ -	$ 1,281	$ 2,722	$ 3,807	$ 2,510	$ 3,294	$ 3,623	$ 2,720	$ 2,697	$ 2,770	$ 2,168	$ 1,193
Operations Cost		$ -	$ -	$ -	$ 192	$ 696	$ 1,200	$ 1,368	$ 1,584	$ 1,992	$ 2,352	$ 2,712	$ 3,144	$ 3,648	$ 3,936
Replacement Cost		$ -	$ -	$ -	$ 120	$ 431	$ 823	$ 1,010	$ 1,173	$ 1,393	$ 1,563	$ 1,725	$ 1,855	$ 1,987	$ 2,029
10-Year Scenario Total Cost per Year		$1,927	$ 5,935	$ 7,472	$ 7,495	$ 9,135	$10,985	$ 8,414	$ 9,401	$10,477	$ 9,478	$10,167	$10,888	$11,051	$ 9,408
Discounted Annual Cost (2004=base year)		$ 558	$ 1,563	$ 1,789	$ 1,631	$ 1,807	$ 1,976	$ 1,376	$ 1,397	$ 1,416	$ 1,164	$ 1,135	$ 1,105	$ 1,020	$ 789
Undiscounted Total Cost ($M)	$	122,234													
Net Present Cost ($M)	$	18,727													
10-Year Non-ISRU (all expendable) Baseline															
10-Year Non-ISRU Total Cost per Year		$1,568	$ 4,850	$ 6,149	$ 6,324	$ 9,493	$16,153	$14,394	$17,895	$20,213	$22,525	$24,689	$27,001	$30,530	$32,832
Discounted Annual Cost (2004=base year)		$ 454	$ 1,277	$ 1,472	$ 1,376	$ 1,878	$ 2,905	$ 2,354	$ 2,660	$ 2,731	$ 2,767	$ 2,757	$ 2,741	$ 2,818	$ 2,755
Crossover point		0	0	0	0	0	1	1	1	1	1	1	1	1	1
Breakeven		$ (359)	$(1,443)	$(2,766)	$(3,868)	$(4,328)	$ (1,846)	$ 3,149	$ 9,593	$17,264	$26,461	$37,001	$49,051	$61,990	$77,430
Undiscounted Total Cost ($M)	$	234,616													
Net Present Cost ($M)	$	30,946													
Rate of Return of ISRU vs. Expendable		39.5%													

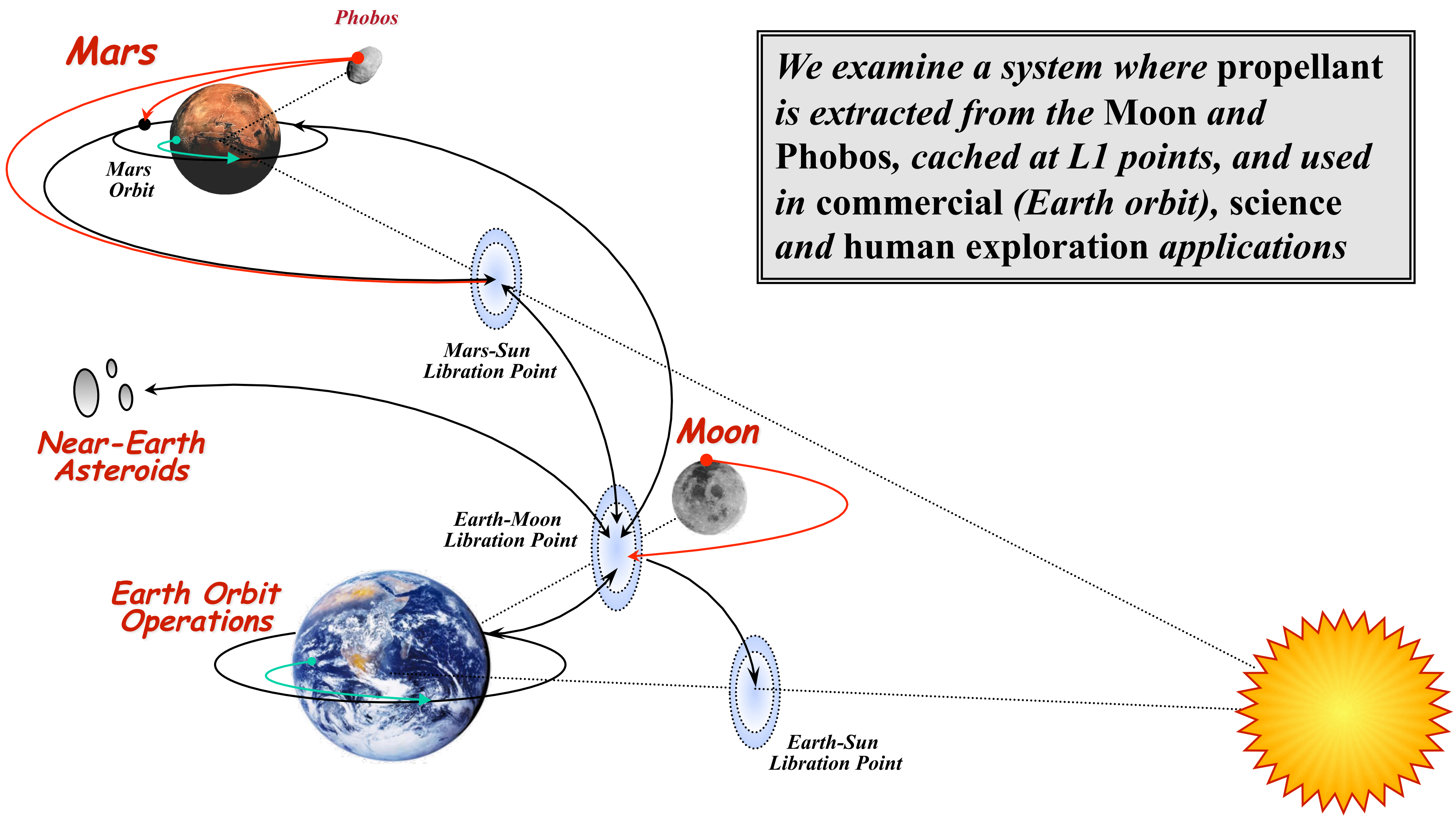
The Current (Expendable) Paradigm

One-way missions with no transportation system reuse



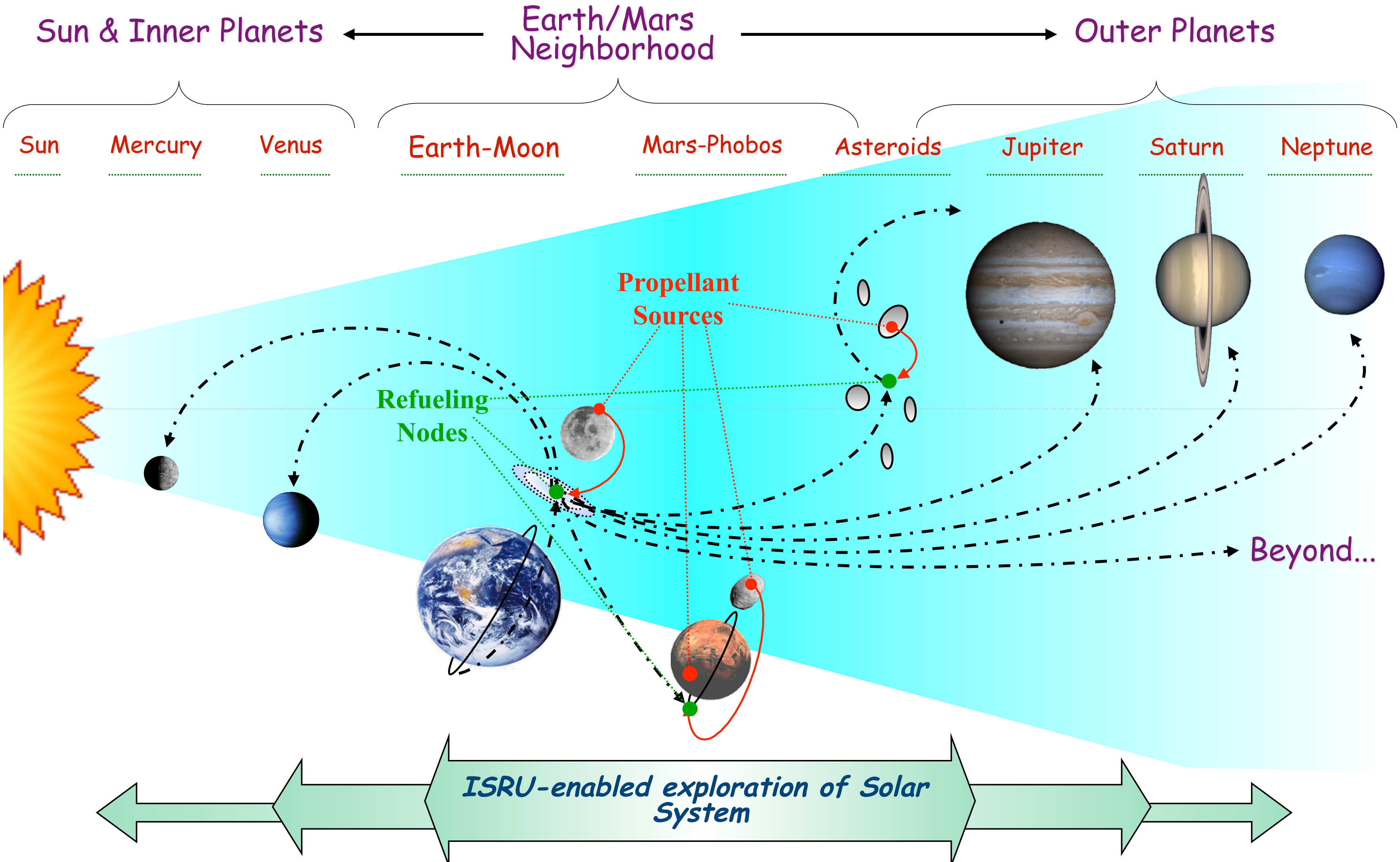
ISRU-Enabled Transportation Nodes

Libration-based Fuel Depots



We examine a system where **propellant** *is extracted from the* **Moon** *and* **Phobos,** *cached at L1 points, and used in* **commercial** *(Earth orbit),* **science** *and* **human exploration** *applications*

Libration Fuel Depots enable *Solar System Access*



Conclusions

- ISRU is an up-front Investment that could generate long-term returns, but it depends on developing a *sustainable market* for lunar-derived products

- Return on investment (ROI) can be quantitatively demonstrated for lunar propellant under certain conditions

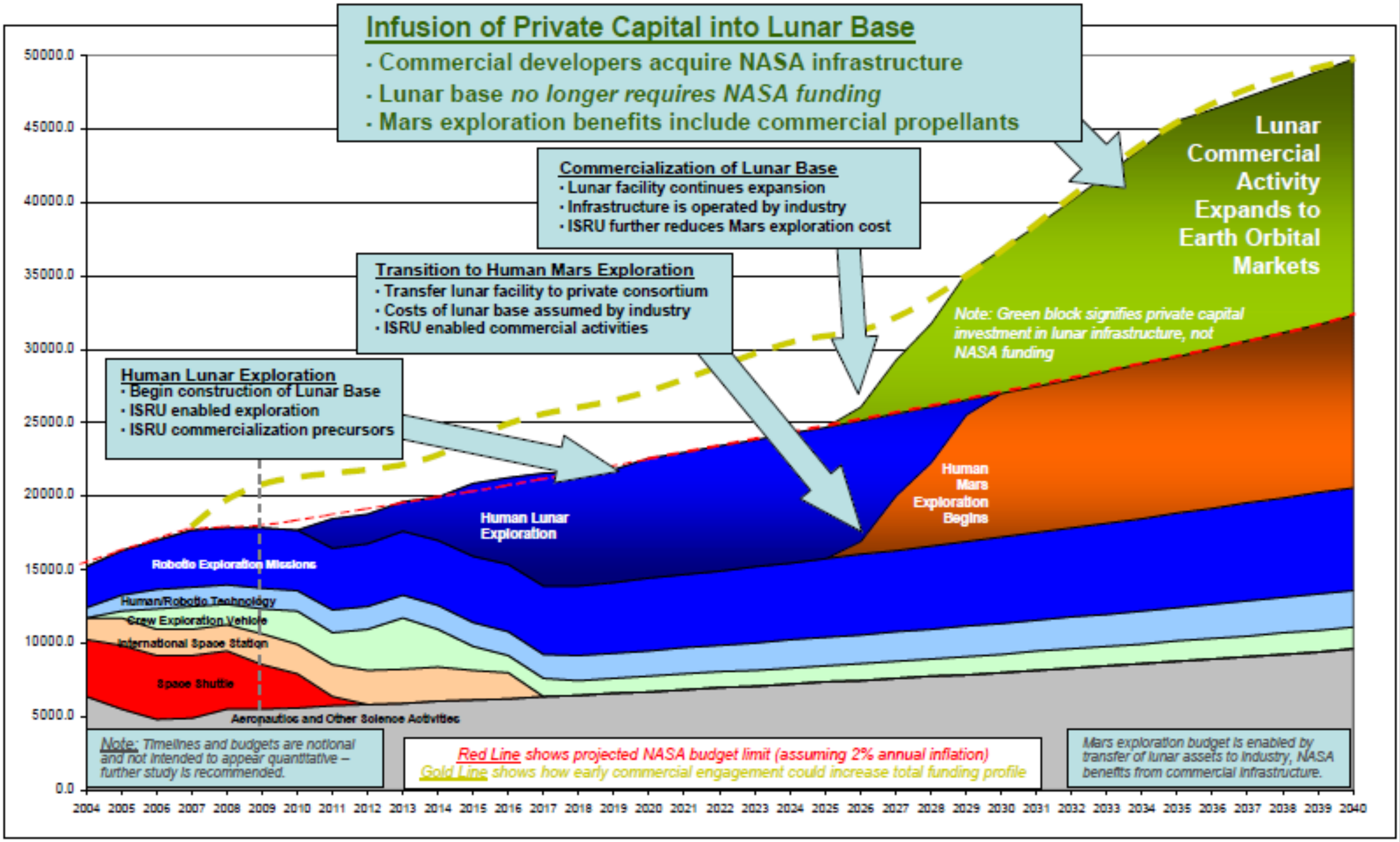
- NASA has the ability to help create or enhance those conditions

Necessary v. Sufficient Conditions

- Is space commercialization a **necessary** condition for human space exploration?
  - Yes. It is a necessary element of a **rational cost reduction** plan.
  - Leveraged capabilities and cost effectiveness could dramatically increase.

- Is space commercialization a **sufficient** condition for space colonization?
  - No. There is still a dependence on NASA to **lead the way**, reduce risks and build infrastructure that can be later privatized.
  - Technologies with space *and* terrestrial applications are a potential offsetting factor and are currently attracting industry investment.

Lunar Commercialization Could Enable Budget for Mars



	Amounts (Billions) Limit	Current
Total	$12,798.14	$4,169.71
Federal Reserve Total	$7,765.64	$1,678.71
Primary Credit Discount	$110.74	$61.31
Secondary Credit	$0.19	$1.00
Primary dealer and others	$147.00	$20.18
ABCP Liquidity	$152.11	$6.85
AIG Credit	$60.00	$43.19
Net Portfolio CP Funding	$1,800.00	$241.31
Maiden Lane (Bear Stearns)	$29.50	$28.82
Maiden Lane II (AIG)	$22.50	$18.54
Maiden Lane III (AIG)	$30.00	$24.04
Term Securities Lending	$250.00	$88.55
Term Auction Facility	$900.00	$468.59
Securities lending overnight	$10.00	$4.41
Term Asset-Backed Loan Facility	$900.00	$4.71
Currency Swaps/Other Assets	$606.00	$377.87
MMIFF	$540.00	$0.00
GSE Debt Purchases	$600.00	$50.39
GSE Mortgage-Backed Securities	$1,000.00	$236.16
Citigroup Bailout Fed Portion	$220.40	$0.00
Bank of America Bailout	$87.20	$0.00
Commitment to Buy Treasuries	$300.00	$7.50
FDIC Total	$2,038.50	$357.50
Public-Private Investment*	$500.00	0.00
FDIC Liquidity Guarantees	$1,400.00	$316.50
GE	$126.00	$41.00
Citigroup Bailout FDIC	$10.00	$0.00
Bank of America Bailout FDIC	$2.50	$0.00
Treasury Total	$2,694.00	$1,833.50
TARP	$700.00	$599.50
Tax Break for Banks	$29.00	$29.00
Stimulus Package (Bush)	$168.00	$168.00
Stimulus II (Obama)	$787.00	$787.00
Treasury Exchange Stabilization	$50.00	$50.00
Student Loan Purchases	$60.00	$0.00
Support for Fannie/Freddie	$400.00	$200.00
Line of Credit for FDIC*	$500.00	$0.00
HUD Total	$300.00	$300.00
Hope for Homeowners FHA	$300.00	$300.00

he FDIC's commitment to guarantee lending under the Legacy Loan Program and the Legacy Asset Program includes a $500 billion line of credit from the U.S. Treasury.

Recommendations for NASA

- Continue development of ISRU technology
- Conduct focused research and modeling related to *In-Space Markets* for ISRU products
- Support and nurture small-scale robotic ISRU demonstration missions (commercial and international partnerships)
- Nurture entrepreneurial enterprise through prizes, competitions and outsourcing