Commercial Lunar Propellant Opening a Gateway to the Solar System

ASCE Earth and Space

Tom Moser

April 12, 2016

Situation

- Desire to advance Human Space Exploration
- Current Assets
  - Experience, tools and capabilities developed over 55+ years
  - Private sector space transportation systems
  - Public/private sector partnerships
  - International partnerships
- Needs
  - Commitment by U.S. and foreign leaders and the public
  - Affordable and reliable funding
  - New free market opportunities
  - Development of space systems and processes for utilizing lunar resources.

Human Space Exploration Past, Present and Future

The Past

NASA has made 3 major attempts in the last 45 years to recreate the magic of Apollo.

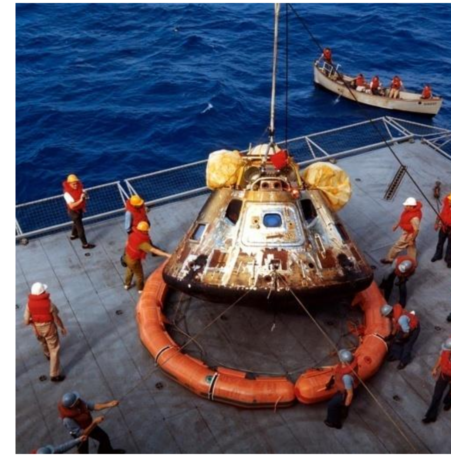
- Each of the attempts has failed because of affordability
- Every previous attempt cost hundreds of billions

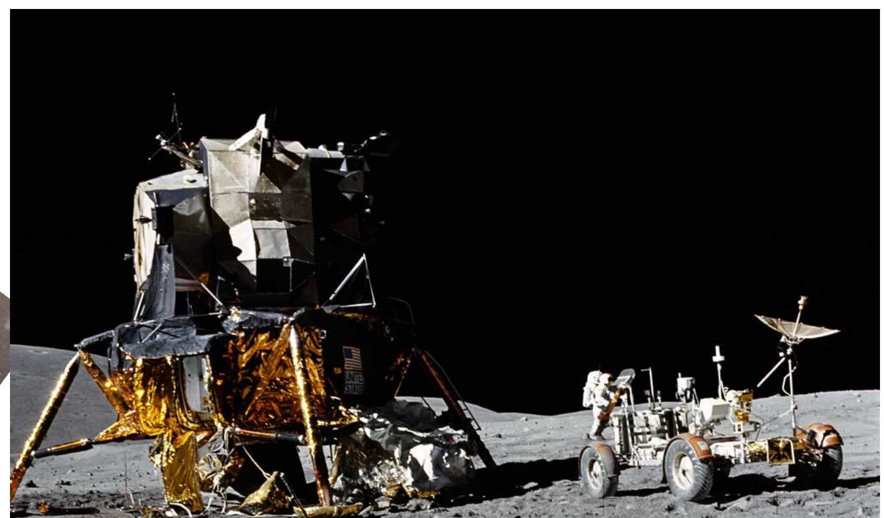
NASA’s Apollo Program

Kennedy Moon Speech

May 1961

“before this decade is out,
land a man on the Moon
and return him safely to Earth.”





Apollo Program

Mission – Send humans to the moon and safely return them earth (within the decade of the 60’s)

We did not know how to do it.

We had the determination.

We didn’t know what we didn’t know.

The Apollo Challenges

Total new designs for

- A launch vehicle to lift 6.4 million lbs.
- A crew transportation vehicle (earth to moon)
- A lunar landing and launch vehicle
- An inertial guidance system
- A communication and control system

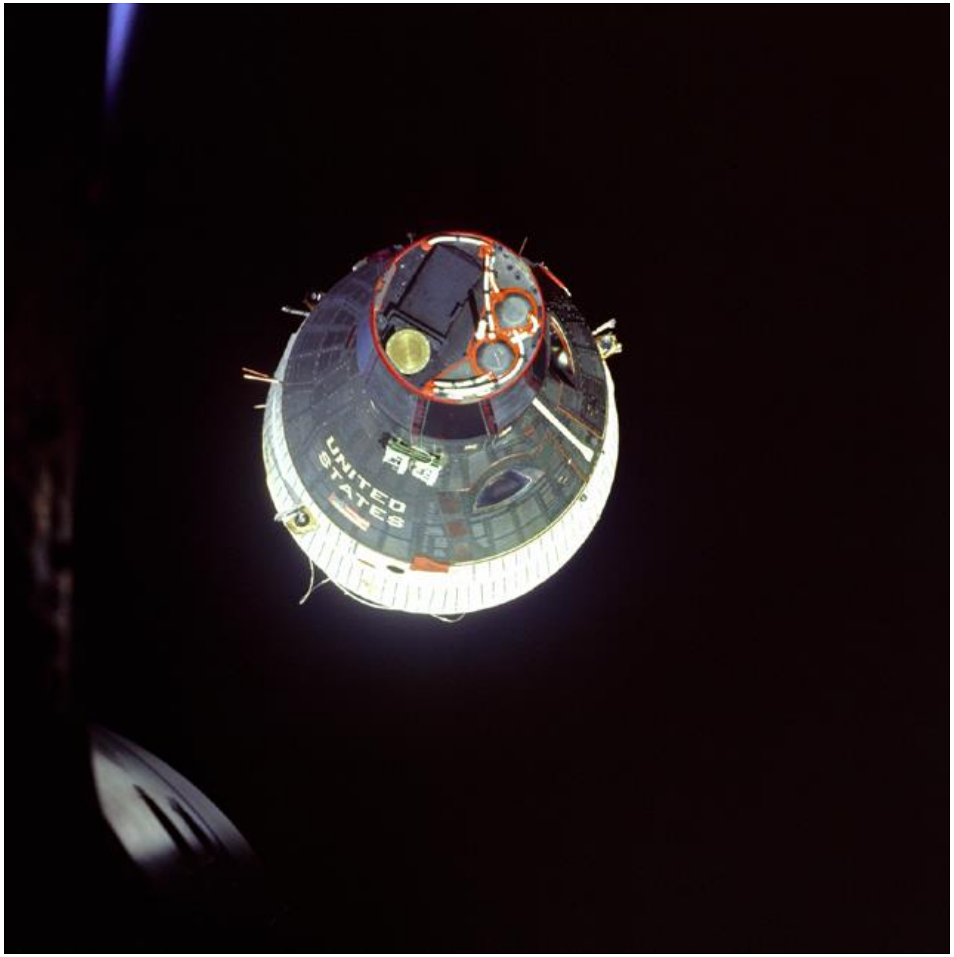
How to rendezvous and dock in space

Testing the systems on earth (thermal, vacuum, vibrations, loads, radar, etc.)

Determining if humans could live and work in space for weeks

Could Humans Live and Operate in Space?
Project Mercury

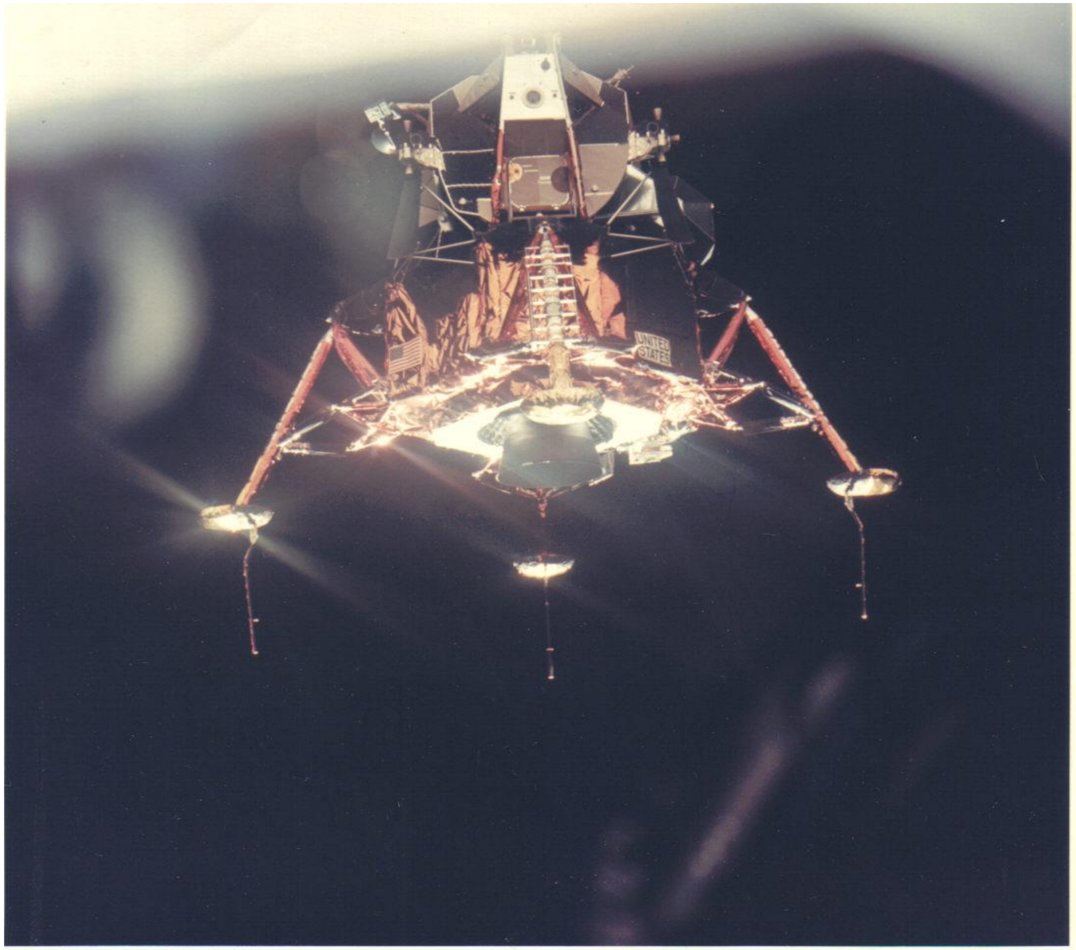
Project Gemini
Demonstrate Rendezvous and Docking in Space



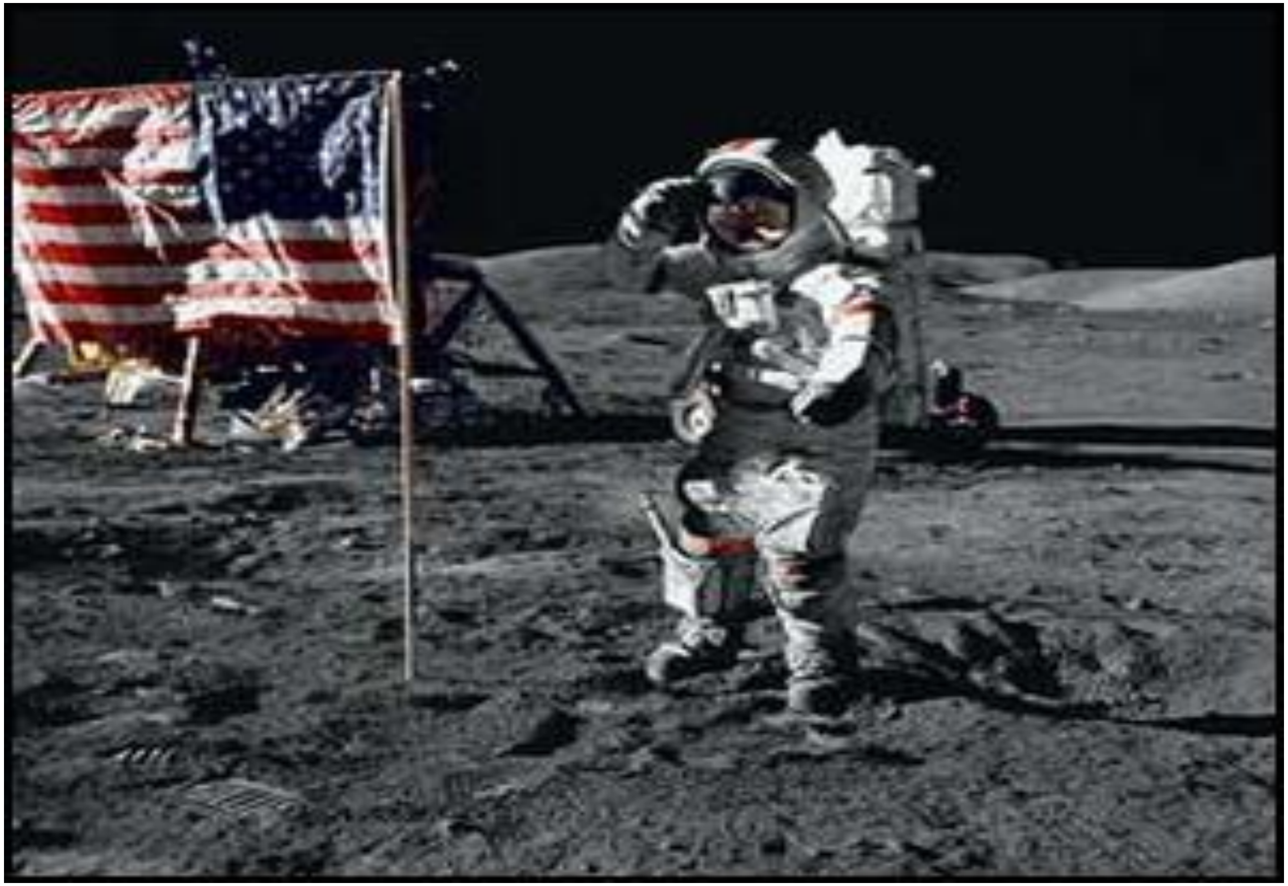
Saturn V Launch Vehicle

Lunar Module

Challenge – Develop a vehicle to land on the Moon and a launch vehicle from the Moon

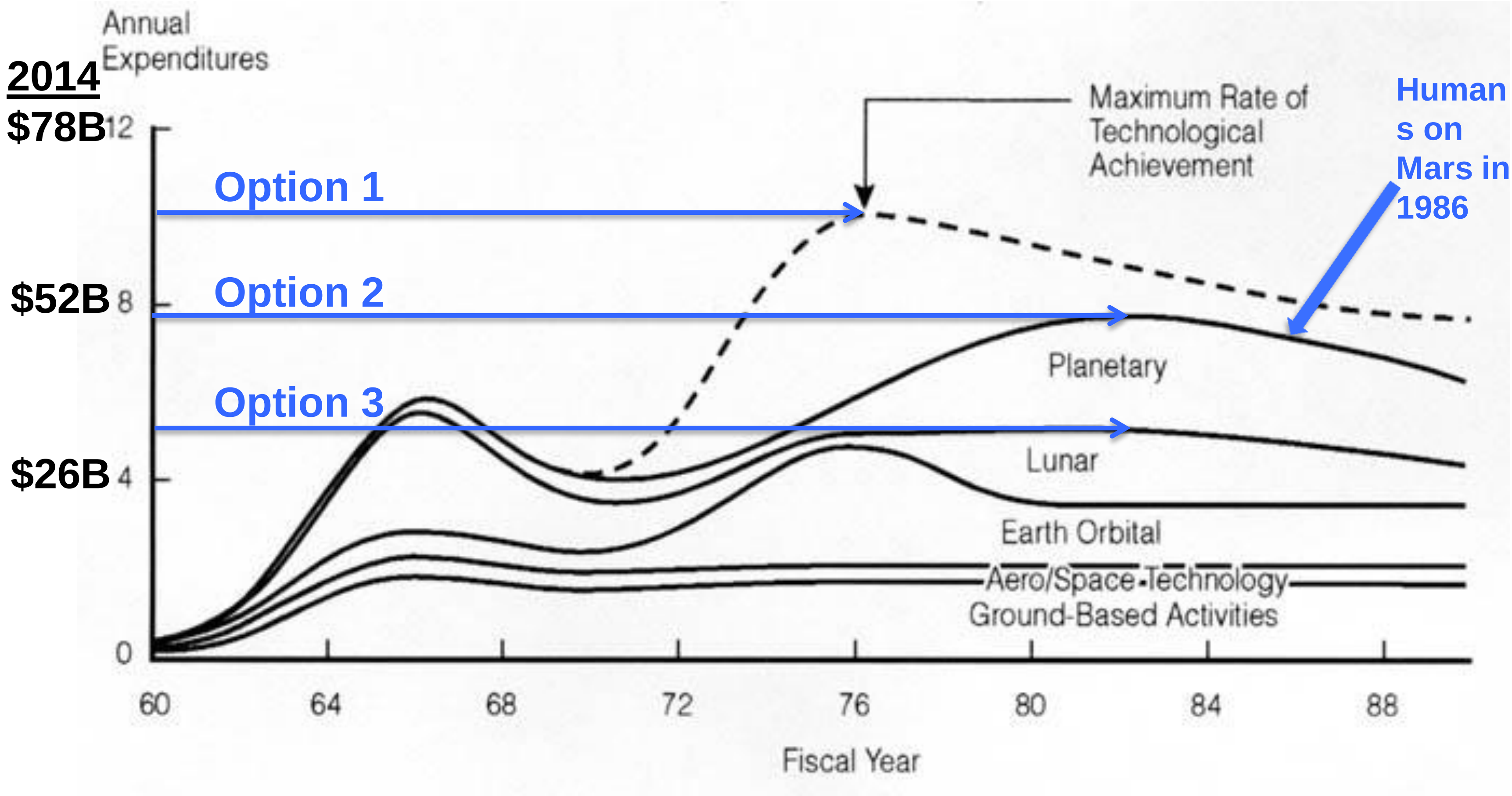


Mission Accomplished



Apollo Lunar and Mars Funding Plans

Three levels of space activity studied by Space Task Group in 1969. (NASA)



Reaction from Nixon White House

- Cancellation of final three flights to the Moon
- Cut NASA's budget to a low of $14.5 billion (FY2014)
  - Less than half of STG's recommended minimum
- On March 7, 1970, released following statement:
  - ***Space expenditures must take their proper place within a rigorous system of national priorities … What we do in space from here on in must become a normal and regular part of our national life and must therefore be planned in conjunction with all of the other undertakings which are important to us.***
- Approval to build reusable launch vehicle (RLV) that would fly 50 times per year at $10 million per launch

Project Skylab

Mission – Long periods of human space research

Space Shuttle

Mission:

- Develop a space system that is a launch vehicle, spacecraft, re-entry vehicle, and airplane
- Carry a “school bus size” payload weighing 65,000lb to and from space
- Reuse the space vehicles 100 times
- Turn-around time: Two weeks

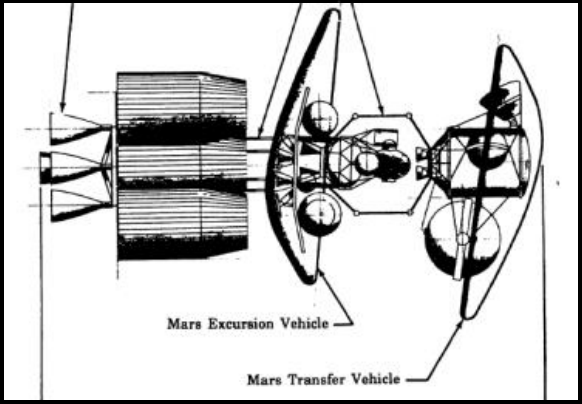
Space Shuttle

Installing 25,000 Tiles

Announcing Space Exploration Initiative (SEI)

July 20, 1989 on steps of the National Air & Space Museum

- Begin operation of the International Space Station in the 1990s
- A permanent Base on the Moon (2009)
- A Human Mission to Mars (2019)
- Tasked Vice President and White House National Space Council to develop options



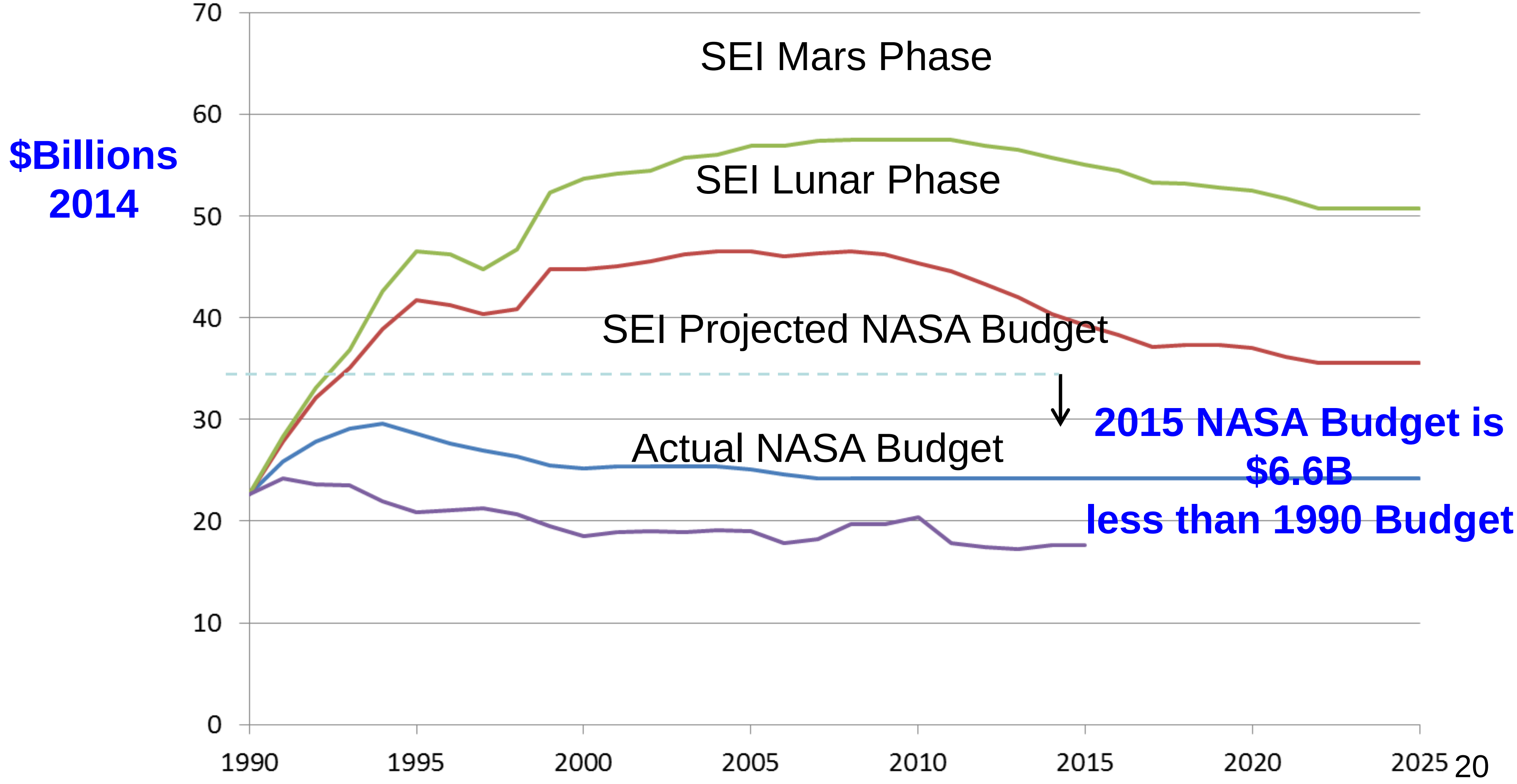
We must commit ourselves anew to a sustained program of manned exploration of the Solar System, and yes the permanent settlement of space. We must commit ourselves to a future where Americans and citizens of all nations will live and work in space.

To seize this opportunity I am not proposing a 10-year plan like Apollo, I am proposing a long-range continuing commitment.

President George H. W. Bush – July 20, 1989

1991 Space Exploration Initiative

Required $25B/year increase to NASA budget for lunar (only)



Response to SEI

- NASA 90-day study estimated SEI's long-term cost
  - **Approximately $983 (2014) billion dollars**
- White House and Congressional reaction to NASA plan was hostile
  - primarily due to the cost estimate
- Clinton Administration officially removed human exploration from the national agenda in 1996.

Reactions from Bush 41 White House

- Mark Albrecht, Executive Secretary, National Space Council
  - *“We were just stunned, felt completely betrayed.* ***Vice President Quayle was furious.*** *The 90-day Study was the biggest ‘F’ flunk, you could ever get in government.*
  - *The real problem with the NASA plan was not that we didn’t think the technology was right, but that it was just the most expensive possible approach.* ***It was just so fabulously unaffordable, it showed no imagination.”***
- Former President George H. W. Bush
  - ***“I got set up”***

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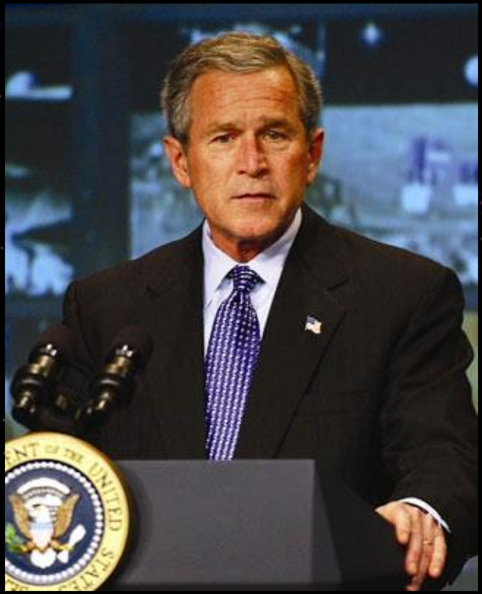
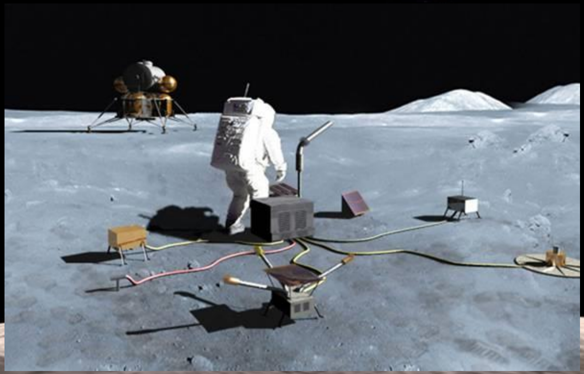
A Bold Vision for Space Exploration Jan. 2004
leading to the "Constellation Program"

- 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



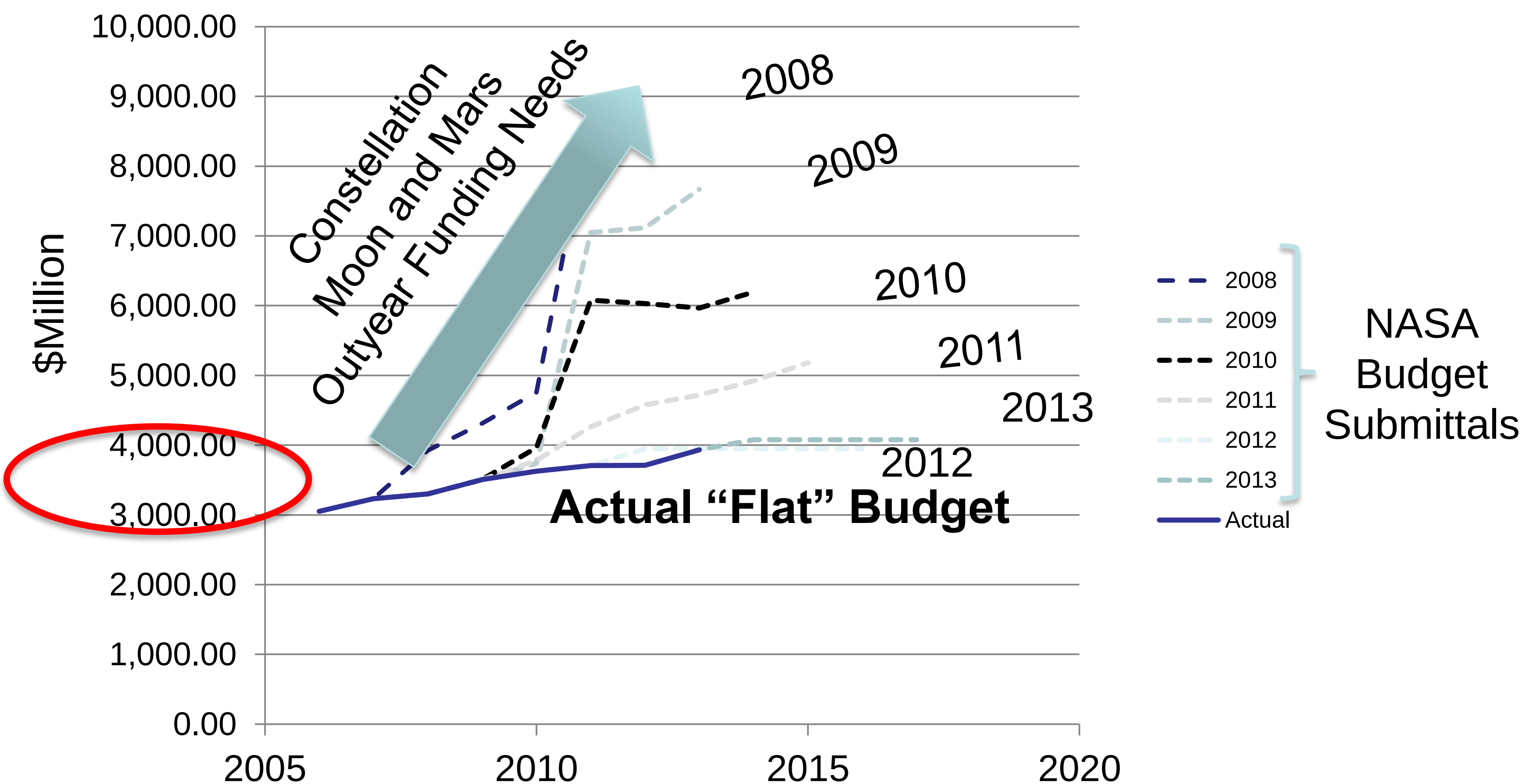


"It is time for America to take the next steps.

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"

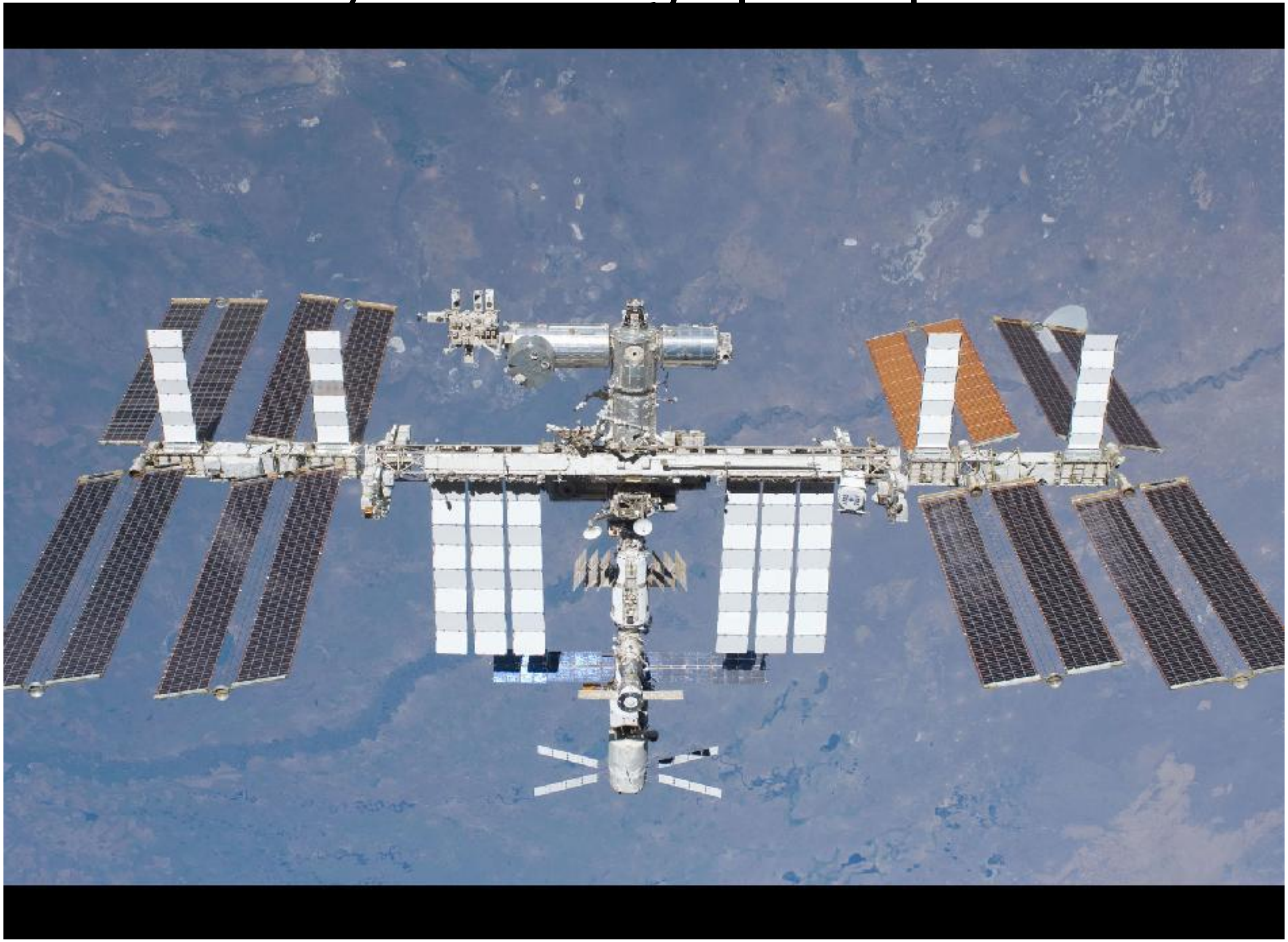
President George W. Bush – January 14, 2004

NASA's Deep Space Human Exploration program
Encounters Budget Reality (Again)



Space Station

Mission-Develop a 6 person micro-gravity research facility with foreign participation



Try Strategy of Last 3 Decades (Again)
Ask Uncle Sam for more $$

Develop a New Strategy based on what the U.S. can Afford

- Congress has clearly & repeatedly said
  - $3-4 Billion per year is affordable

What If?

- What if we could develop a permanent human settlement on the Moon
- For about $3 Billion per year (FY2014)
- By leveraging commercial partnerships?

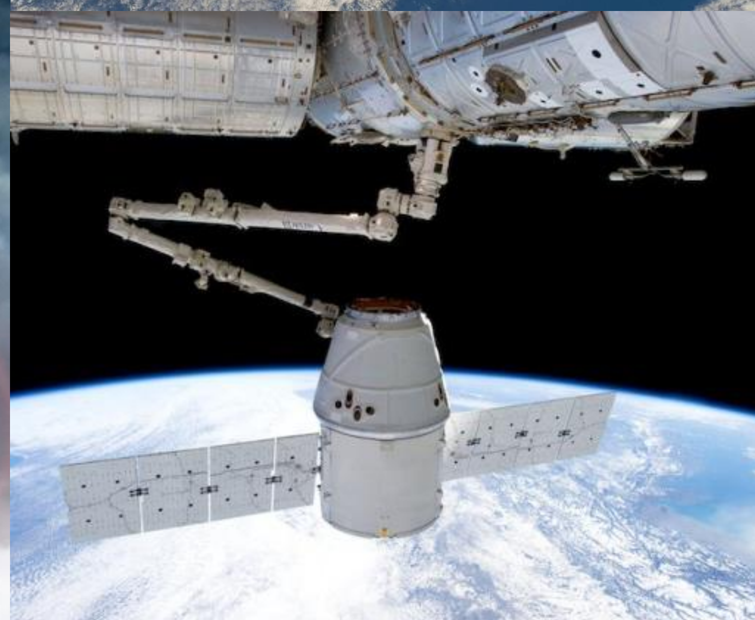
What If?

- We could develop a lunar “export”
  - that would pay enough to cover ALL costs of operating that permanent lunar base?

What If?

- We applied lessons learned from NASA’s highly-successful public-private-partnerships?
  - ISS Commercial Orbital Transportation Services (COTS)
  - ISS Commercial Resupply Services (CRS)
  - ISS Commercial Crew

COTS/CRS Produced two New Rockets and two New Spacecraft at radically lower costs

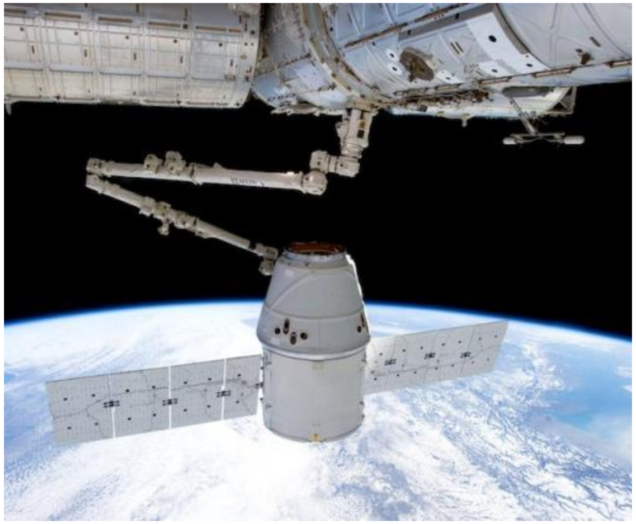


Lessons Learned from Partnership Approach to NASA ISS Cargo Requirements

- Started in 2006
  - Dec. 2010 - SpaceX first private company to successfully launch & return a spacecraft from orbit
  - May 2012 - SpaceX first private company to launch a capsule that docks with the ISS & safely return
  - Jan. 2014 – OSC Cygnus arrives at the ISS

- **Total NASA Up-front investment = ~$740M.**

- Private Investment
  - SpaceX invested **~$200M** = Musk ~$100M + Founders Fund, Draper Fisher Jurvetson ~$100M
  - OSC invested **~$150M**



- NASA Investment yielded 2 new launchers & 2 new spacecraft
  - NASA audits confirm up-front development costs for the Falcon 9 were ~ $300M total

Traditional vs NewSpace
Cost Comparisons

- In 2011, NASA estimated cost of …
  - Developing Falcon 1, Falcon-9, and Dragon
  - Using NASA-Air Force Cost Model (NAFCOM)
- PURPOSE:
  - Compare traditional development vs commercial partnerships
- RESULTS:
  - NASA estimated cost, using traditional methods, at $3.977B
  - Actual cost was $400-500M
- CONCLUSION:
  - **Traditional development estimated 8-10 times the actual cost for SpaceX to develop these same systems**
    - Falcon 9 Launch Vehicle NAFCOM Cost Estimates, August 2011, NASA Associate Deputy Administrator for Policy: http://www.nasa.gov/pdf/586023main_8-3-11_NAFCOM.pdf

Evolvable Lunar Architecture

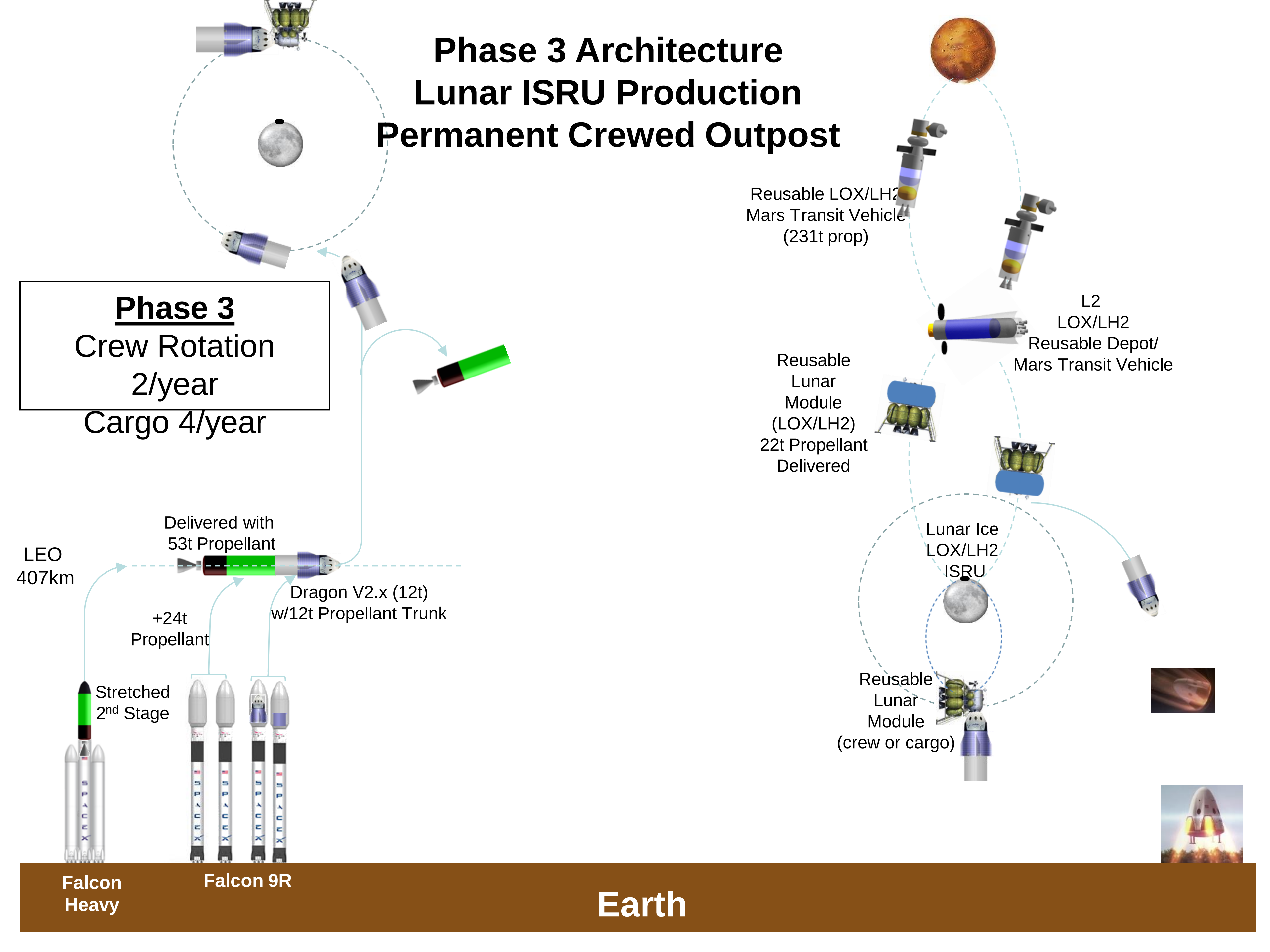
A Way to Affordably Continue Human Space Exploration

Evolvable Lunar Architecture

- Incrementally develop a lunar base and the capability to use the moon as a stepping stone to go to Mars
- Start with existing experience and capabilities
- Create an International Lunar Authority
- Enable commercial development of critical elements of ELA
- Develop the enabling technologies

Evolvable Lunar Architecture

- Three Phases to the Evolvable Lunar Architecture
  - Phase 1: Human Sorties to Equator / Robotic Prospecting Poles
    - Key transition point to Phase 2 – When LEO on-orbit propellant storage and transfer is available (LOX-H2 or LOX-Kero)
  - Phase 2: Sorties to Poles & ISRU Capability Development
    - Key transition point to Phase 3 – When Lunar ISRU, storage and transfer (LOX-H2) & a reusable lunar lander (LOX-H2) is available
  - Phase 3: Permanent Lunar Base transporting propellant to L2
    - Assume transport for 200+ MT of propellant to L2 every year for Mars EDS



Phase 3 Architecture
Lunar ISRU Production
Permanent Crewed Outpost
Phase 3
Crew Rotation
2/year
Cargo 4/year
Reusable LOX/LH2
Mars Transit Vehicle
(231t prop)
L2
LOX/LH2
Reusable Depot/
Mars Transit Vehicle
Reusable
Lunar
Module
(LOX/LH2)
22t Propellant
Delivered
Lunar Ice
LOX/LH2
ISRU
Reusable
Lunar
Module
(crew or cargo)
Delivered with
53t Propellant
LEO
407km
Dragon V2.x (12t)
w/12t Propellant Trunk
+24t
Propellant
Stretched
2nd Stage
Falcon
Heavy
Falcon 9R
Earth

Leverage Commercial Partnerships

- A partnership with NASA using proven commercial methods, practices and suppliers
  - NASA as a customer of “propellant” to lunar orbit for going to Mars
  - Privately-owned and –operated. NASA never acquires ownership of lunar infrastructure.
  - Use methods proven by COTS, CRS and Commercial Crew
  - Leverage and use existing technologies to maximum extent possible
  - Two independent partner-solutions to provide redundancy, align incentives and drive innovation across the lunar architecture
  - Transition to “International Lunar Authority” to reduce risk to both USG and private industry, to efficiently manage lunar operations, and to seamlessly integrate our international partners

Lunar Governance Options Analysis

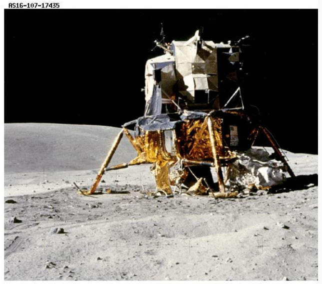
Governance Models / Figures of Merit	Baseline (ISS, Shuttle, Constellation)	NASA Partnerships (COTS, LSP, Comm'l Crew)	Lead U.S. Corporation (AT&T/Bell)	International Authority (PA-NYNJ, TVA, CERN)	International Corporation INTELSAT/Fannie Mae/Freddie Mac
International Partners					
Private Investment					
Quick Debt Capital					
Economic Benefit					
Innovation					
Non-govt Customers					
Management Efficiency					
Econ Valuable Use Rights					
Political Sustainability					
Strategic Flexibility					

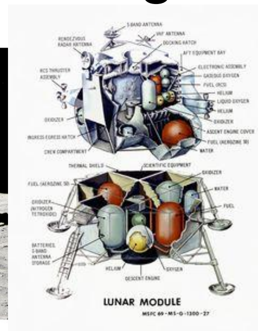
Case Study: CERN
(European Organization for Nuclear Research)

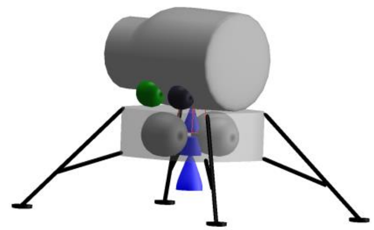
- Founded in 1954 by 12 nations by treaty out of a position of weakness
  - Because no one European nation could afford to finance world-class research
  - Operated today by 21 European nation states, with U.S. participation
- CERN is now world's leading high-energy research institution
  - Large Hadron Collider operates at 8 trillion electron volts (TEV)
    - Upgrade to 20 trillion electron volts in process
  - United States is now clearly in second place
    - U.S. Superconducting Supercollider (SSC) collapsed in 1993
    - America's largest existing collider (Fermilab Tevatron, 1 TeV) retired in 2011
- CERN approach is proven to be both affordable & politically sustainable
- Other CERN features include:
  - Politicians have limited ability to micromanage design and operations
  - Streamlined procurement and management processes, as organization is not subject to many "national" laws and regulations.
  - Bifurcated Council Structure: National governments manage finances, but scientists manage research priorities
  - Director General (i.e., CEO) manages operations

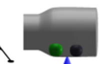
Lunar Lander

Based on existing Commercial Rocket Engines









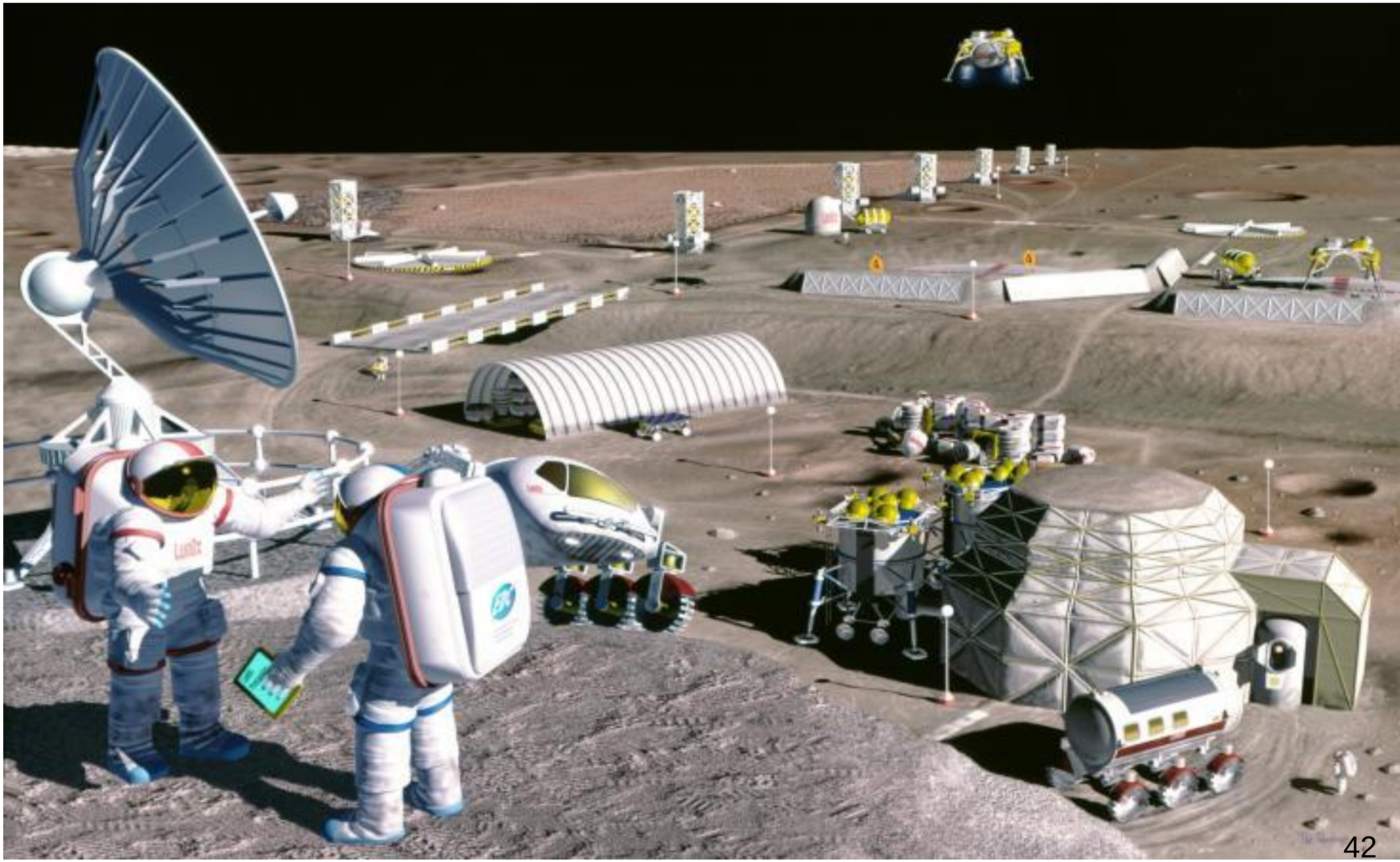
	Lunar Module Descent	Lunar Module Ascent
Body Structure, kg	444	473
Induced Envir Protection, kg	149	155
Lnch Recov & Dkg, kg	218	23
Main Propulsion, kg	505	213
Orient Control Sep & Ullage, kg	6	156
Prime Power Source, kg	260	167
Power Conv & Distr, kg	30	210
Guidance & navigation, kg	20	35
Instrumentation, kg	3	58
Communication, kg	6	50
Environmental Control, kg	44	132
(Reserved), kg	150	277
Personnel Provisions, kg	24	44
Crew Sta Contrl & Pan, kg	1	108
Mass Growth Allowance, kg		
SUBTOTALS (Dry Weight), kg	1,859	2,102
Personnel, kg	-	325
Non Cargo, kg		
Cargo, kg	-	-
Ordnance, kg	12	12
Resid Prop & Serv Items, kg	122	54
Inflight Losses, kg	148	314
RCS Propellant, kg		
SUBTOTALS (Inert Weight), kg	2,141	2,808
Full Thrust Propellant, kg	7863	2258
TOTAL (Gross Weight), kg	10004	5066
Total with Payload, kg	15070	5066

Isp, s	315	315
DeltaV available, m/s	2278	1823

	Descent Lander	Ascent Lander
Body Structure	829	536
Induced Environmental Protection	35	19
Main Propulsion	409	219
Orient Control Separation	0	136
Prime Power	182	157
Power Conversion and Distribution	36	70
Guidance and Navigation	38	38
Instrumention	32	32
Communication	97	97
Thermal Control	170	166
Personnel Provisions	0	699
Crew Station Control Panel	0	141
Range Safety and Abort	71	71
Mass Growth Allowance	577	819
Personnel	0	325
Ordanance	23	23
SUBTOTALS (Dry Mass), kg	**2,499**	**3,549**
Residual Propellant	178	69
Reserves	178	69
RCS Propellant	0	263
SUBTOTALS (Inert Mass), kg	**2,856**	**3,950**
Cargo	**7,385**	
Full Thrust Propellant	8,906	3,435
Total (Gross Mass), kg	**19,147**	**7,385**
Total wo/Cargo, kg	**11,762**	**7,385**

Isp, s	324	324
DeltaV, m/s	1988	1988

Lunar Colony

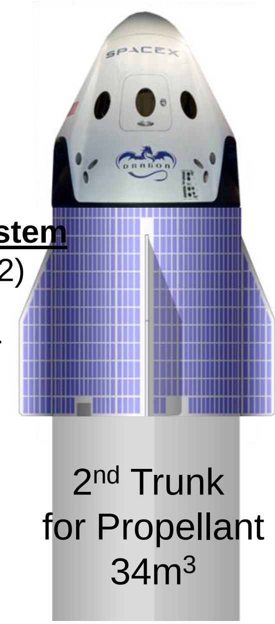


Reusable Crew Transportation

Modified SpaceX Dragon V2 or Boeing CST 100

Inert	6,350	kg
Prop	1,456	kg
Payload	4,694	kg
Gross	12,500	kg
Isp	315	s
DV	371	m/s
DV - Apollo LES	107	m/s
Landing DV	269	m/s

<u>Long Duration Crew System</u>
-4 crew assumed (study=2)
-20 days assumed
-5t (payload) allocated for
personnel provisions
and consumables

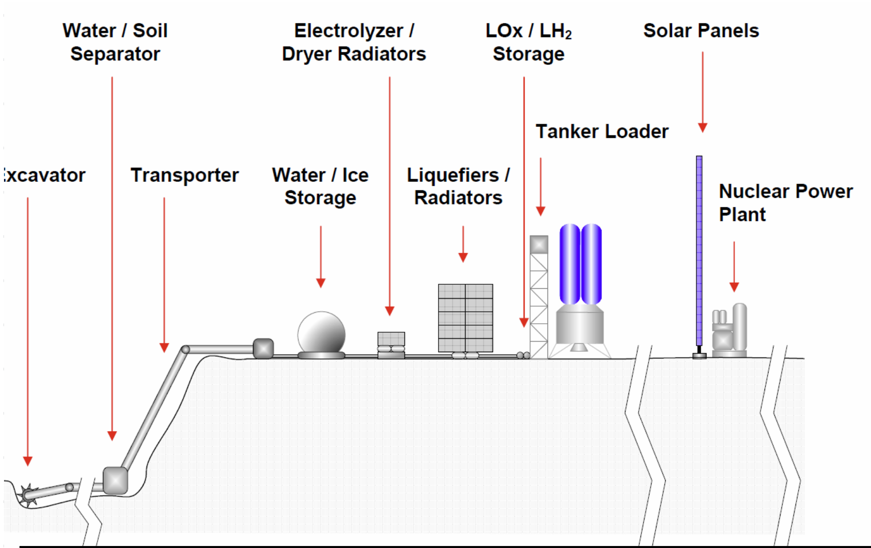


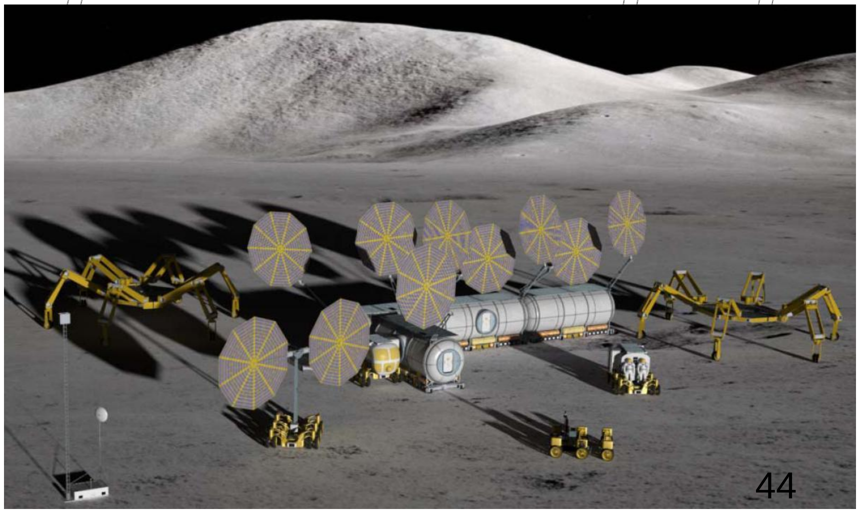
Inert V2	6,350
Prop1	1,456
Prop2	10625
Inert Trunk	1875
Payload	4,694
Prop Total	12,081
Gross	25,000
Isp	315
DV capability, m/s	2039
DV TEI + Landing	1,535

Prop Trunk Mass

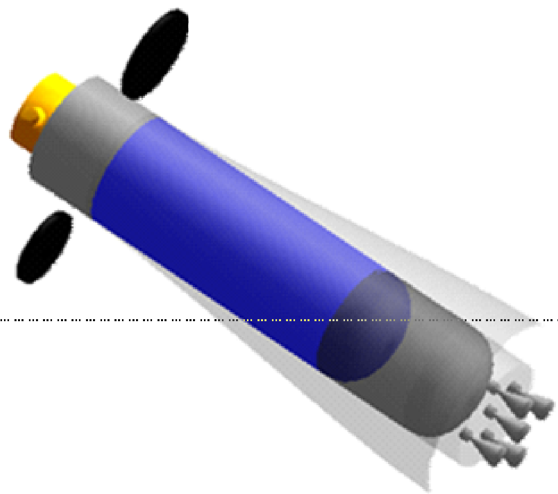
Lunar ICE ISRU Plant and Infrastructure

Propellant (LOX/LH2; 20% margin)	772,000 kg
Oxidizer/Fuel	5.5
Water (3.52kg/day; 4-crew; 20% margin)	6,167 kg
Oxygen (0.84kg/day; 4-Crew; 20% margin)	1,472 kg
Ice Concentration	1.00%
Mining Equipment	
Front Loader	1,078 kg
Hauler	889 kg
Low Pressure Feed Hopper	13 kg
High Pressure Feed Hopper	88 kg
Regotith Thermal Processing	561 kg
Electrolysis	2,728 kg
Oxygen Liquefier	1,559 kg
Hydrogen Liquefier	566 kg
Water Tank	234 kg
Oxygen Tank	935 kg
Hydrogen Tank	2,306 kg
Nuclear Power System (SNAP-50)	12,131 kg
Total ISRU Plant	23,088 kg





Representative (EM L2) Propellant Depot, LOX/LH2



Propellants	**LOX/LH_2**
Stage Diameter	**6 m**
Stage Length	**28 m**
Oxidizer Boiloff	**0%/month**
Fuel Boiloff	**0%/month**
Suborbital T/W	**0.72**
Orbital T/W	**0.20**
Power	**3736 W**
Cryocooler Power	**2636 W**
Mass Growth	**30%**
#engines/type	**5/RL10B-2**
Engine Isp	**464s**

	Mass, kg
2. Body Structure	8,835
3. Induced Environmental Protection	485
5. Main Propulsion	1,764
6. Orient Control Separation	193
7. Prime Power	261
8. Power Conversion and Distribution	52
9. Guidance and Navigation	38
10. Instrumention	32
11. Communication	97
12. Thermal Control	2,193
16. Range Safety and Abort	69
16a. Mass Growth Allowance	4,212
19. Ordanance	20
Dry Mass	**18,252**
21. Residual Propellant	4,616
23. Inflight Losses	30
25a. RCS Propellant	5,938
25. Total Propellant inc Boiloff	230,799
IMLEO	**315,208**

Propellant Burn 1	187,354
Payload Burn 1	55,574
DeltaV Burn 1	4,228
Propellant Burn 2	31,273
Payload Burn 2	55,574
DeltaV 2	1,342
Propellant 3	6,978
Payload 3	48,281
DeltaV 3	395

Description:

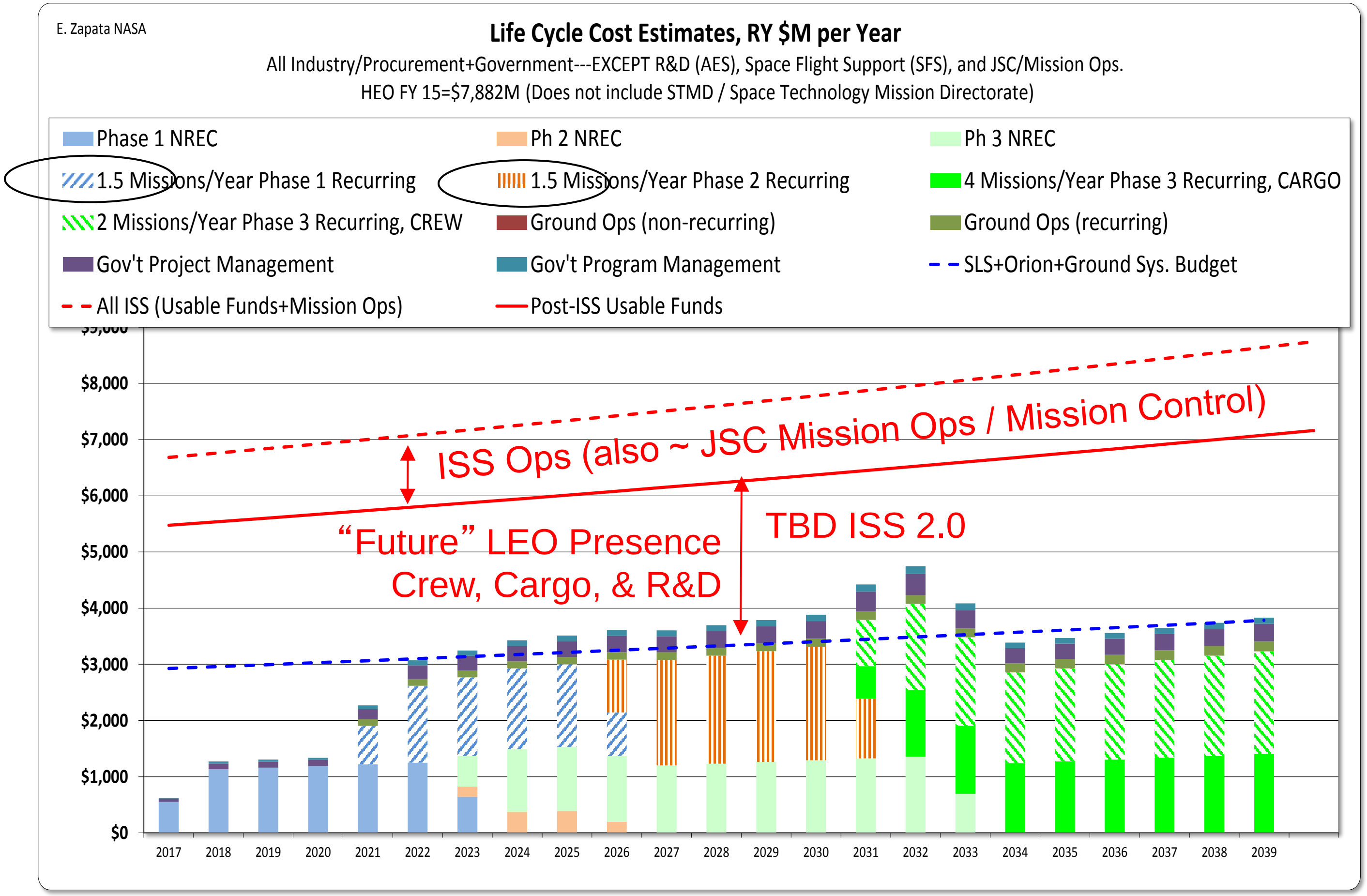
The combined propellant depot and CPS stage is capable of holding enough O2 and H2 (225MT) to perform NEA missions requiring up to 7 km/s of delta-V when used as a CPS stage. Both the Depot and CPS have MLI (SOFI for ground hold and 60 layer MLI), cryocoolers, and sunshield. Power is with Ultraflex solar cells.

Both the Depot and Depot-Derived CPS can be launched from a Falcon Heavy or Delta IV Heavy replacing the second stage of the launch vehicle and using the RL 10 engines to place itself into a 407 km, 28.5 deg inclination circular orbit.

CryoMech AL 325 has sufficient cooling capacity for LH_2 – 70W @ 20K, 196kg, 11kW, 1m^3, $47k

Life Cycle Costs – ELA Scenario (Variant)

Variant: 1.5 Missions per year (Phase 1 and 2)



- Reduce operational missions in Phases 1 & 2 to fit within budget constraints

- We don't assume any efficiency in a continuing NASA LEO presence (pre and post-ISS), which could cover the ELA life cycle cost profile slightly overshooting a ~$3B a year cap

Study Conclusions

- Technically feasible to return humans to the surface of the Moon within a period of 5-7 years from authority to proceed.
- Estimated cost is $10 Billion (+/- 30%) for <u>two independent commercial providers</u>, or about $5 Billion for each provider.
- Permanent lunar base by early 2030s producing years 200 MT of propellant/year for NASA Mars missions
  - Total cost of about $40 Billion (+/- 30%).
  - Achievable within NASA's existing deep space human spaceflight budget
  - Assumes innovative partnership is set up to mitigate business risks.
- Lunar propellant could reduce costs & risks NASA Mars missions.
- A permanent commercial lunar base might substantially pay for its operations by exporting propellant to lunar orbit for sale to NASA.
- Private "commercial" trips to lunar surface become affordable for many nations, and many private citizens (US economic growth)

ELA Study Team

Charles Miller (Principal Investigator, Business & Economic)

- Nearly 30 experience in space industry
- Former NASA Senior Advisor for Commercial Space
- Co-founder Nanoracks LLC, and former President and CEO of Constellation Services International, Inc.

Dr. Alan Wilhite (Co-Principal Investigator, Technical)

- 40 years of systems engineering at NASA and Georgia Tech
- More than 60 published articles and several book chapters on space systems engineering.
- Former Director of the NASA's Independent Program Assessment Office

Edgar Zapata, KSC (Life Cycle Cost Analysis)

- Has worked with NASA at KSC since 1988 with responsibility for Space Shuttle cryogenic propellant loading systems, and related flight and ground propulsion systems.
- For last 20 years has translated real-life human spaceflight operational experience and lessons learned into improvements in flight and ground systems design, technology, processes and practices. He has participated in most major agency-level human exploration studies.

David Cheuvront (Risk, Safety & Mission Assurance)

- David Cheuvront has 37 years of aerospace experience, including 19 years at NASA JSC. At Rockwell International, Cheuvront solved key maintenance challenges in the preliminary design of the Space Station *Freedom*, and was hired by NASA JSC to solve problems in reliability and maintainability in human spaceflight.

Robert Kelso (Lunar Robotics & ISRU)

- 37 years at NASA-Johnson Space Center, including serving as a Shuttle Flight Director in JSC's Mission Control Center. Kelso led NASA's efforts to leverage commercial lunar robotics developments for several years.

American University (AU) School of Public Affairs & Dr. Howard McCurdy

- Dr. McCurdy is an AU Professor of Public Policy and has authored seven books on the American space program, including *Faster-Better-Cheaper: Low-Cost Innovation in the U.S. Space Program*, *Inside NASA: High Technology and Organizational Change*, and *Space and the American Imagination*.

ELA
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- Joe Rothenberg (Chairman)
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