Concept Exploration & Refinement BAA

The Great Enterprise™

t/Space Final Briefing
CA-1
March 2, 2005

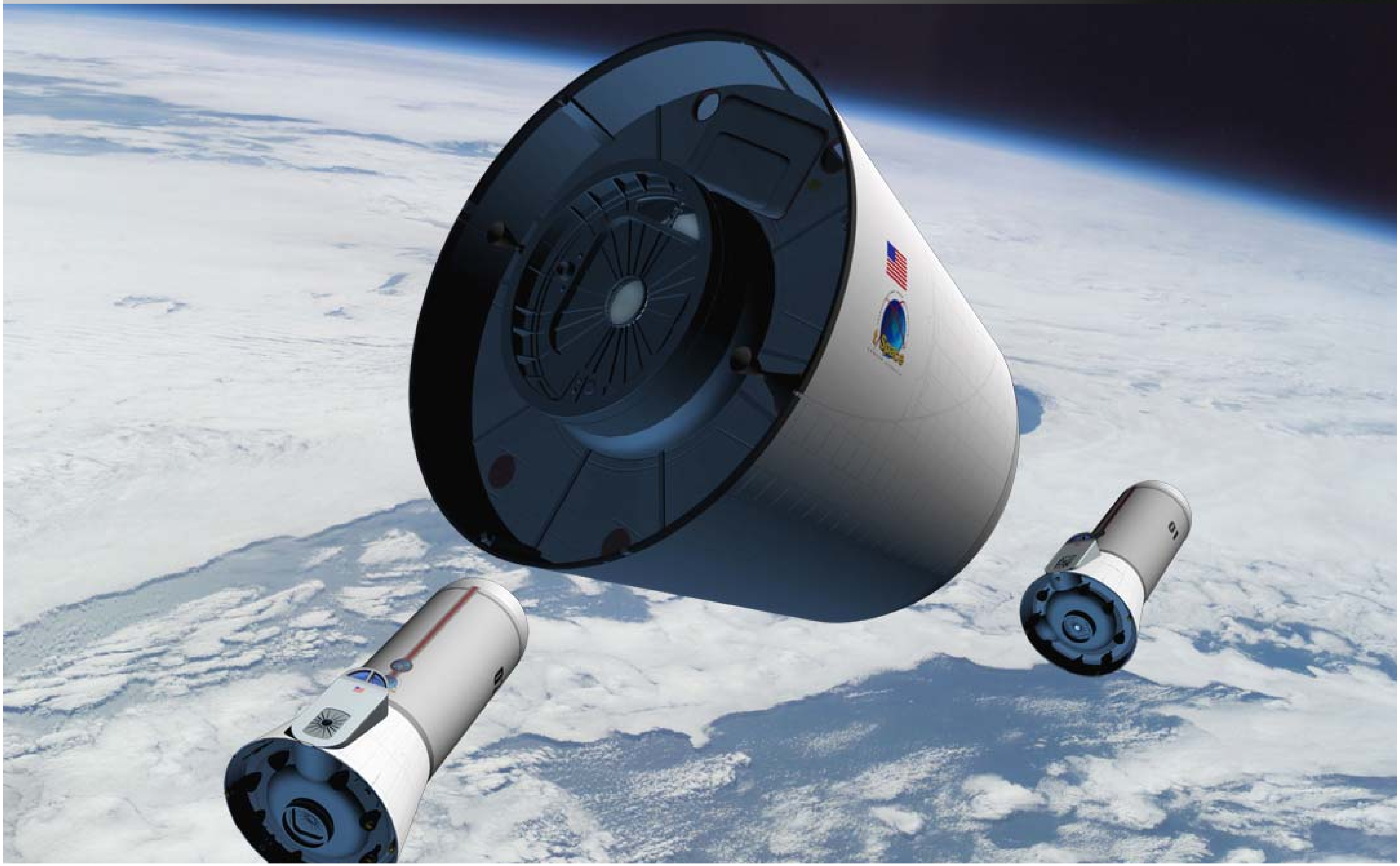
"The Right Stuff at the Right Price"

First-Order Goals

We should aim to create a true frontier

- The public instantly "gets" the frontier concept…
- … new resources, knowledge creation and opportunities
- Critical to achieving affordability and sustainability
- **A commercial infrastructure is required for a frontier to flourish, even if its initial parts are funded by government purchases**

New Results in Final Report



New Results in Final Report

Trajectory analyses & fuel consumption for CEVs traveling directly between LEO and lunar surface

Analysis of lunar propellant from polar ice

Taxonomy of lunar robot types with initial priorities

Market analysis of passenger space travel industry

Work toward a Lunar Industry Directory

Work toward the "standard gauge" consensus among commercial space exploration providers

t/Space Recommended Architecture

Commercial delivery of crew, cargo and propellants to LEO

Space-based CEVs launched on non-human rated vehicles
(boosted without crew on EELVs or new commercial vehicles)

Initial Lunar Expeditions:

Two CEVs go from LEO to lunar surface, return to LEO via aerocapture. Before lunar landing, CEVs refueled by two Tankers.

Post-ISRU Lunar Expeditions, Phase 1:

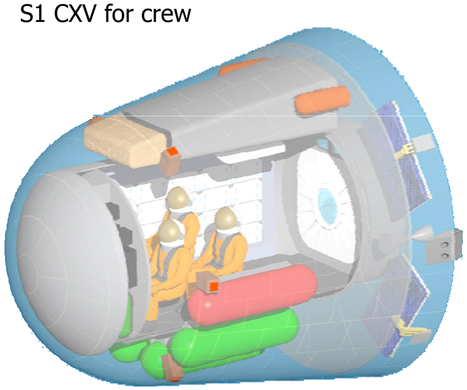
CEVs go LEO to the lunar surface nonstop; refueled there. Payload must be reduced to make LEO-lunar surface run feasible.

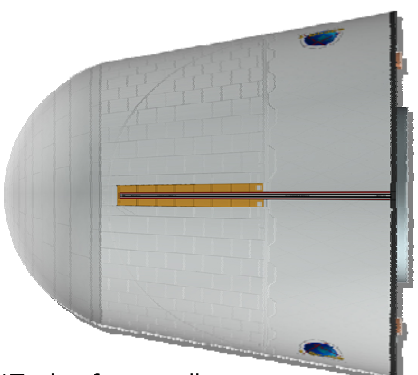
Post-ISRU Lunar Expeditions, Phase 2:

Tankers deliver lunar fuel to lunar orbit and to LEO, allowing full payloads and eliminating the need for Earth-launched propellants.

Taxonomy of Transportation Elements

S1 CXV for crew

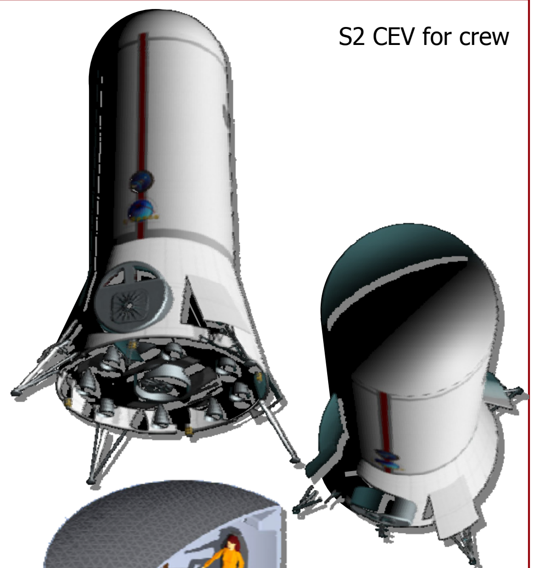


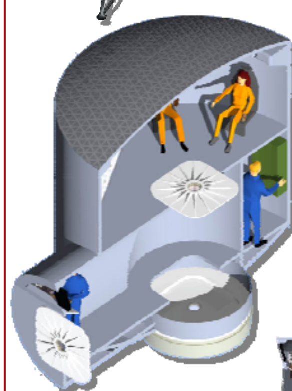


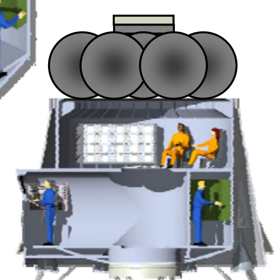
S1Tanker for propellant

S1

S2 CEV for crew

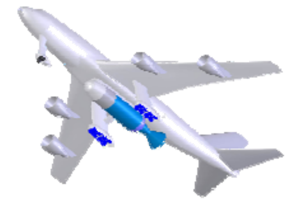




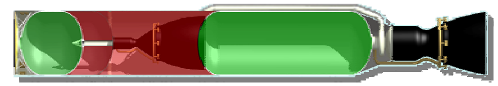


Future LSAM Derivative

S2



Booster for CXV Derived from *QuickReach*



AirLaunch LLC

SpaceX

Kistler

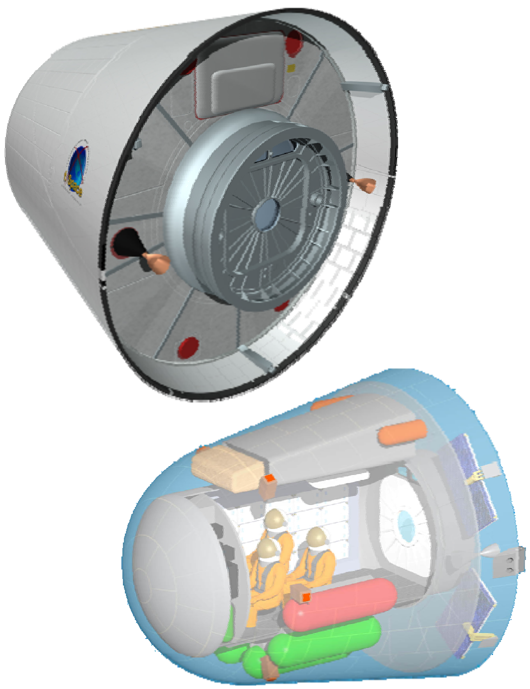
Ground Launch CEV

Launch Elements

Reusable Space Elements

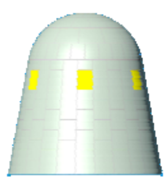
S1 (Spiral 1)

ETO Transfer Vehicle "CXV"



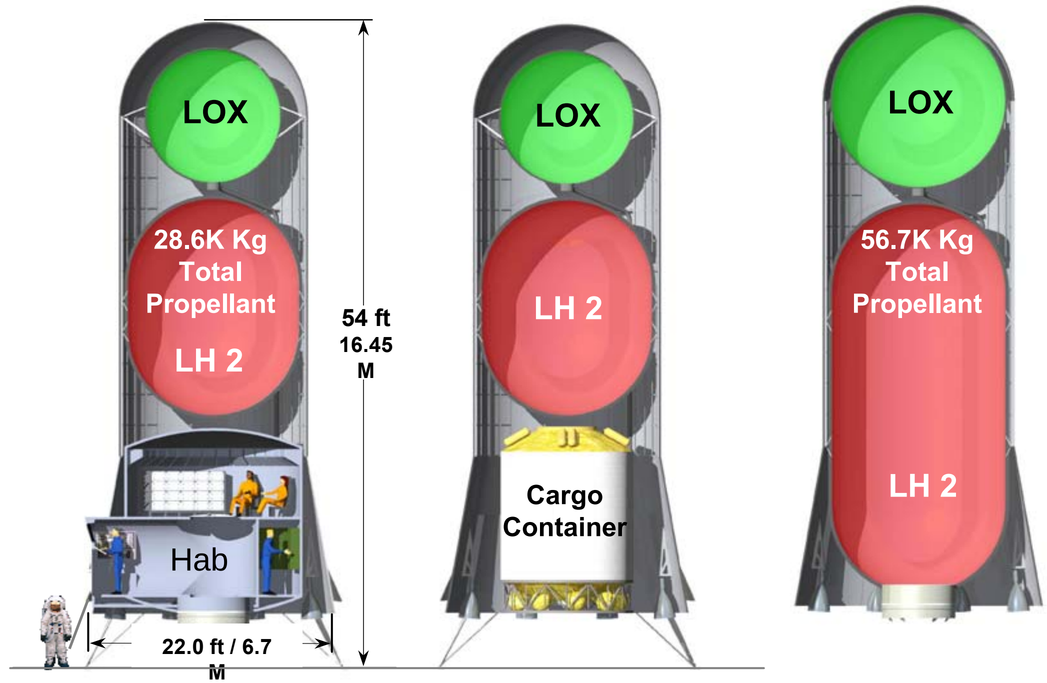
S1T Derived Tanker

(~ 8000 lbs delivered propellant)



S2 (Spiral 2) CEV

6,880 Kg (15K lbs) empty;
4,540 Kg (10K lbs) payload to 5.5Km/sec (18K fps)



S2CEV (Exploration)
About 8 small tanker launches to refuel

S2C (Cargo)

S2T (Tanker)
About 16 small tanker launches to refuel

S2 provides ~1Km/sec ΔV to launch system

(i.e., it acts as a reusable upper or "post-boost" stage)

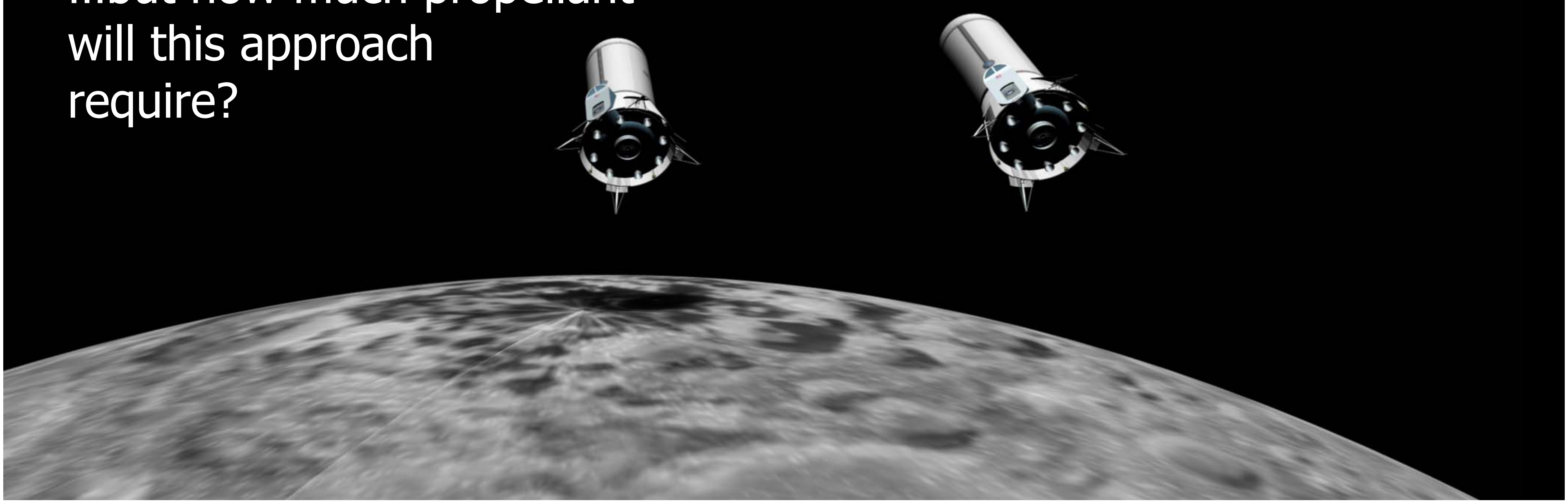
LEO to the Lunar Surface

Drawbacks of a Lunar Surface Access Module:

- LSAM's large cost and significant time to develop
- CEV + LSAM unsuitable for automated cargo system
- Thrown away after each use…
- …or hard to maintain 240,000 miles from Earth

Solution: LEO-direct-to-surface CEV

…but how much propellant
will this approach
require?



CEV Parameters

Tankers refuel CEVs in elliptical lunar orbit (EL50), allowing CEVs to then land directly on Moon without a Lunar Surface Access Module.

	Start	DV1 Leave LEO (200 km) via Hohmann transfer	DV2 Enter elliptical lunar orbit 50 km - 50,000 km	RF Refuel in elliptical lunar orbit via Tanker	DV3 Descend to circular 50-km lunar orbit	DV4+ DV5 Descent +Ascent	DV6 Depart 50-km lunar orbit	DV7 Enter LEO (200 km) using aerocapture
CEV dV	0	3.135	0.310		0.662	3.408	0.973	0.314
Fuel left after action (thousands of kg)	28.6	8.092	6.755	28.6 (+21.845)	22.966	4.330	1.184	0.315*

* Provides **0.119 km/s** for broken plane maneuvers on return trip to match with desired inclinations at LEO; this amounts to plus or minus 1.75 degrees.

Analysis of the Tanker

This performance is possible by Tankers taking a Weak Stability Boundary Transfer from LEO to an elliptical lunar orbit. Almost no deltaV is needed to enter lunar orbit using WSBTs, but the round-trip transit is six months.

	S At LEO200	**DV1** To lunar elliptical orbit via WSB transfer	**DV2** Enter elliptical lunar orbit 50 km - 50,000 km	**RF** Deliver fuel to CEV	**DV3** Leave EL50 via WSB transfer	**DV4** Enter LEO200 using aerocapture
dV	**0**	**3.135**	**0.018**		**0.018**	**0.314**
Tanker fuel left after action (thousands of kg)	**56.7**	**23.426**	**23.296**	**23.296** **- 21.845** **= 1.451**	**1.411**	**0.748**

ISRU Phase 1:
CEVs Refuel on Lunar Surface

When plants begin producing propellants (but before Tankers start exporting propellants), CEVs can be refueled only on the lunar surface.
CEVs won't have the performance to land with a full payload (2.5K kg offloaded)

	Start	**DV1** Leave LEO (200 km) via Hohmann transfer	**DV2** Enter elliptical lunar orbit 50 km - 50,000 km	**DV3** Circularize in 50-km lunar orbit	**DV 4** Descend to surface	**RF** **Refuel on surface w/ISRU**	**DV5** Ascent	**DV6** Depart **50-km** lunar orbit	**DV7** Enter LEO (200 km) using aerocapture
CEV dV	**0**	**3.135**	**0.310**	**0.662**	**1.704**	**0**	**1.704**	**0.973**	**0.314**
Fuel left after (000 of kg)	**28.6**	**9.363**	**8.103**	**5.706**	**0.982**	**28.6**	**16.488**	**11.411**	**10.01***

* Provides **up to 3.287 km/s** for plane changes on contingency return trips to match with desired inclinations at LEO; otherwise, **fuel is available for return to the Moon.**

ISRU Phase 1a:
Lunar-Fueled CEV, with lunar-orbit top-off

Shortfall in CEV payload abilities can be solved when Tankers can export small quantities of lunar propellant to lunar orbit to serve arriving CEVs.

	Start	DV1 Leave LEO (200 km) via Hohmann transfer	DV2 Enter elliptical lunar orbit 50 km - 50,000 km	DV3 Circularize in 50-km lunar orbit	RF1 **Refuel using lunar propellants**	DV 4 Descend to surface	RF2 Refuel on surface	DV5 Ascent	DV6 Depart 50-km lunar orbit	DV7 Enter LEO (200 km) using aerocapture
CEV dV	**0**	**3.135**	**0.310**	**0.662**	**0**	**1.704**	**0**	**1.704**	**0.973**	**0.314**
Fuel left after (000 of kg)	**28.6**	**8.092**	**6.755**	**4.195**	**Add 1.244**	**0**	**28.6**	**15.680**	**10.264**	**8.769***

* Provides **up to 2.488 km/s** for plane changes on contingency return trips to match with desired inclinations at LEO; otherwise, **fuel is available for return to the Moon.**

ISRU Phase 2:
Tankers do surface-to-lunar orbit, and LO-to-LEO

Two-Stage Approach: Lift lunar fuel into elliptical lunar orbit (equivalent trajectory-changing properties as L1) in the same Tankers used in pre-ISRU architecture.

	S At lunar surface	**DV1** Ascend to 50km LLO	**DV2** Enter elliptical lunar orbit 50 km -50,000 km	**RF** Deliver fuel to Tanker or fuel depot in EL50	**DV3** Enter 50km LLO	**DV4** Descend to lunar surface
dV	**0**	**1.704**	**0.662**		**0.662**	**1.704**
Tanker fuel left after action (thousands of kg)	**56.7**	**35.737**	**29.542**	**29.542** **- 23.604** **= 5.938**	**3.874**	**0**

ISRU Phase 2:
Tankers do surface-to-lunar orbit, and LO-to-LEO

Stage Two: Tankers take propellants from lunar orbit to LEO. Each delivers enough to fuel one CEV (19.8K added to the 8.7K kg remaining), and to partially fuel another CEV. Rest of fuel for second CEV comes from a LEO stockpile of lunar fuel, or from Earth.

	S At EL50	**DV1** Leave EL50 via WSB transfer	**DV2** Enter LEO200 using aerocapture	**RF** Deliver fuel to CEV or fuel depot in LEO	**DV3** Leave LEO200 via WSB transfer	**DV4** Enter EL50
dV	**0**	**0.018**	**0.314**		**3.135**	**0.018**
Tanker fuel left after action (thousands of kg)	**56.7**	**56.440**	**51.980**	**51.980 - 27.366 = 24.614**	**0.213**	**0**

Lunar Fuel Required for Export to LEO

Tanker launches from Moon with:	56.7	K kg
Tanker delivers to lunar orbit:	23.6	K kg
Net delivered to lunar orbit:	**41.6%**	
Tanker leaves LO for LEO with	56.7	K kg
Tanker delivers to LEO:	27.366	K kg
Net delivered from LO to LEO:	**48.3%**	
Net fuel delivered Moon to LEO:	**20.1%**	
Fuel left in CEV upon return in LEO:	8.7	K kg
Additional fuel CEV needs in LEO:	19.9	K kg
Fuel needed divided by efficiency of:	20.1%	
Gross fuel Tankers need on Moon:	**99.1**	**K kg**

Total lunar fuel production needed per CEV trip: 127.7 K kg

(99.1 K kg plus the 28.6 K kg loaded onto each CEV on the lunar surface)

CEV Performance
(when using Free Return alternative to EL 50)

	Start	DV1 Leave LEO (200 km) via Hohmann transfer	RF Refuel during coast to Moon in free return trajectory	DV2 Circularize in 50-km lunar orbit	DV3+ DV4 Descent +Ascent	DV5 Depart 50-km lunar orbit	DV6 Enter LEO (200 km) using aerocapture
CEV dV	**0**	**3.156**	**0**	**0.885**	**3.408**	**0.885**	**0.314**
Fuel left after action (thousands of kg)	**28.6**	**8.101**	**28.6** **(+20.499)**	**21.276**	**3.672**	**0.935**	**0.1**

A "free return" scenario was investigated. It requires a minor diminution of payload (0.196K kg out of 11.4K kg dry mass). In EL50 scenario, the CEV has decelerated into an elliptical lunar orbit before the Tanker refuels it, leaving fewer deltaV demands before it returns to LEO.
In the free return scenario, refueling happens before the deceleration burn and thus there are greater post-refueling deltaV demands that require a lighter CEV to accomplish successfully.

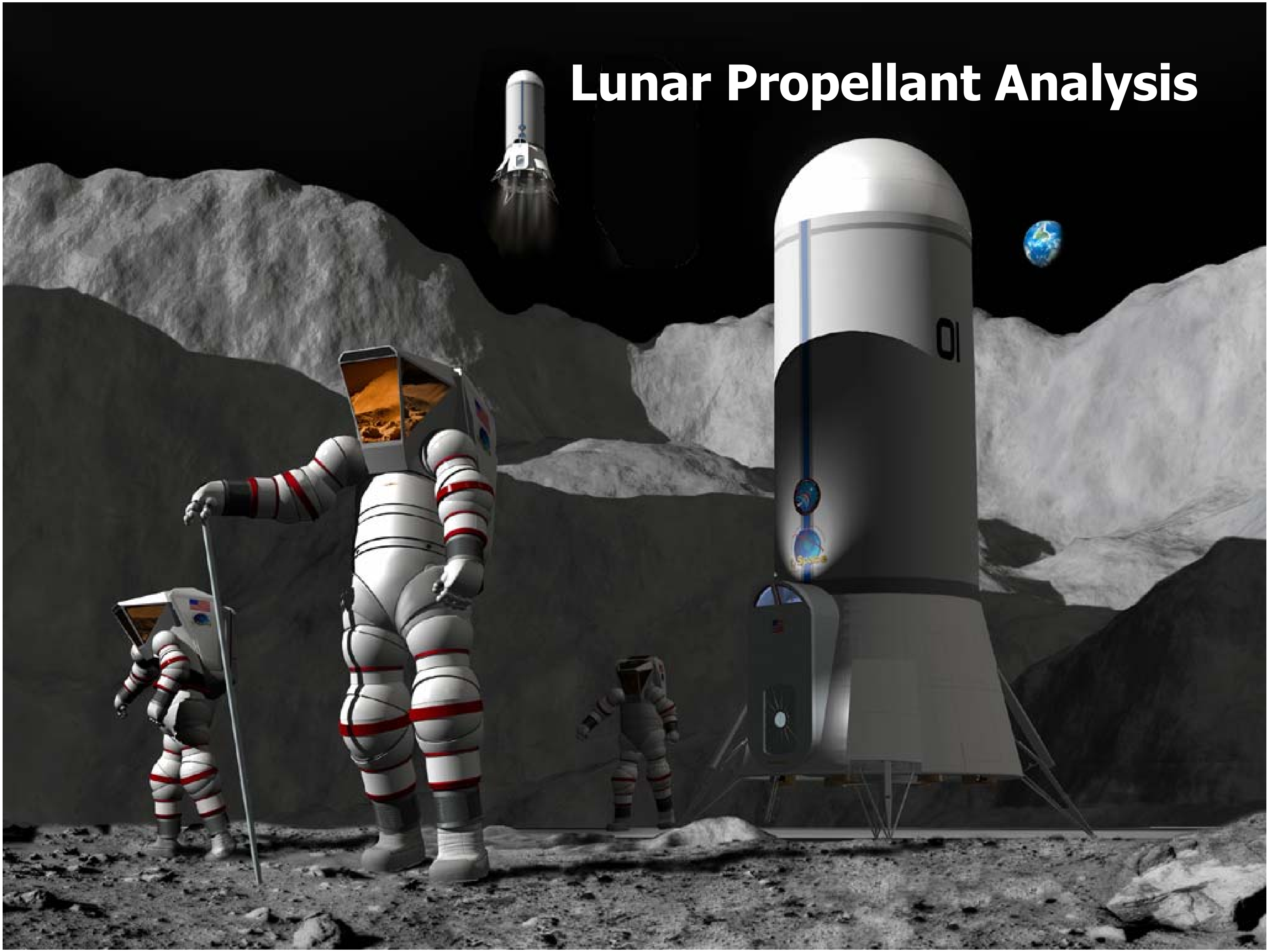
Analysis of the Tanker
(Free Return alternative)

	S At LEO200	**DV1** To lunar free return trajectory (no WSBT)	**RF** Deliver fuel to CEV during outbound coast	**DV2** Margin for course correction after swing-by	**DV4** Enter LEO200 using aerocapture
dV	**0**	**3.156**	**0**	**0.050**	**0.314**
Tanker fuel left after action (thousands of kg)	**56.7**	**23.277**	**23.277** **- 21.845** **= 1.432**	**1.326**	**0.669**

The Tanker in a free-return scenario can transfer up to 21.8K kg to a CEV, but in fact the CEV can take on only 20.5K kg before reaching tank capacity. The 0.669K kg remaining upon return to LEO is equal to 0.342 km/s for plane changes.

Comparison of EL50 Rendezvous vs. Free Return Trajectories

	Rendezvous in Highly Elliptical Lunar Orbit	**Free Return**
Round-trip Tanker transit (Weak Stability Boundary Xfer)	**Six months**	**7 to 10 days**
Tanker launch windows (from a specific LEO orbit)	**Anytime**	**~3-day windows every 14 days**
CEV launch windows (Hohmann Transfer)	**~3-day windows every 14 days** CEV window is not linked to Tanker; Tanker arrival can be delayed in flight by ~15 days	**~3-day windows every 14 days** Requires synchronized launch with Tanker
CEV Dry Mass (crew, ECLSS, structures, etc.)	**11,400 Kg**	**11,204 kg**
CEV fuel margin upon return to LEO	**315 kg**	**100 kg**
Tanker fuel margin upon return to LEO	**748 kg**	**669 kg**


Lunar Propellant Analysis

Trajectory studies established:

- The propellant consumed with direct LEO-to-lunar-surface travel
- The amount of lunar propellant needed to refuel CEVs on the surface and to supply a Tanker route back to LEO

Next: lunar propellant analysis

- The cost of Earth-sourced propellant per Expedition
- The mass needed on the Moon to produce enough propellant to replace Earth-sourced fuel
- Does transporting this mass save money over time?

Earth-to-Orbit Propellant Launch Costs with Space-Based CEVs and Tankers

	Delta 4 Medium	SpaceX Falcon V
ETO launch cost per kg	$5,500	$2,800
Propellant required per CEV (000 of kg)	28.6	28.6
Propellant required per Tanker (000 of kg)	56.7	56.7
Total propellant delivered to LEO per two-CEV Expedtion (000 of kg)	170.6	170.6
Total **ETO** propellant launch cost per Expedition (millions)	$938	$478

These two numbers approximate the recurring costs for second and subsequent lunar expeditions in an architecture based on space-based CEVs and Tankers

Phase 1 ISRU dramatically reduces costs

	Delta 4 Medium	SpaceX Falcon V	**ISRU:** fuel avail. only on Moon*
ETO launch cost per kg	$5,500	$2,800	$2,800
Propellant required per CEV (000 of kg)	28.6	28.6	16.8
Propellant required per Tanker (000 of kg)	56.7	56.7	0
Total propellant delivered to LEO per two-CEV Expedtion (000 of kg)	170.6	170.6	33.6
Total **ETO** propellant launch cost per Expedition (millions)	$938	$478	$94
Total **lunar** propellant production cost per Expedition	NA	NA	?

**CEV payload decreases by 2.5K because it hasn't sufficient performance to go non-stop LEO to surface at full payload*

Phase 2 ISRU:
fuel exported to LEO

Earth launch costs for propellant drop to zero by Phase 2; only crew and cargo are launched to LEO for new expeditions

	Delta 4 Medium	SpaceX Falcon V	**ISRU:** fuel avail. only on Moon*	**ISRU:** fuel also sent to LO & LEO
ETO launch cost per kg	$5,500	$2,800	$2,800	0
Propellant required per CEV (000 of kg)	28.6	28.6	16.8	0
Propellant required per Tanker (000 of kg)	56.7	56.7	0	0
Total propellant delivered to LEO per two-CEV Expedtion (000 of kg)	170.6	170.6	33.6	0
Total **ETO** propellant launch cost per Expedition (millions)	$938	$478	$94	$0
Total **lunar** propellant production cost per Expedition	NA	NA	?	?

**CEV payload decreases by 2.5K because it hasn't sufficient performance to go non-stop LEO to surface at full payload*

What Would Lunar Fuel Be Worth?

Before ISRU

170.6	K kg	Propellant that a two-CEV expedition needs from Earth
$938	mil.	Delta IV ETO launch cost of fuel (per expedition) *= sets maxiumum value of lunar-sourced fuel*
$478	mil.	Future ETO launch cost of fuel (per expedition) *= sets maxiumum value of lunar-sourced fuel*

After ISRU

28.6	K kg	Fuel for each CEV on the lunar surface
99.1	K kg	Fuel sent via Tankers to a CEV in LEO (incl. fuel burned to reach LEO)
255	K kg	Total lunar propellant needed per expedition (two CEVs)
$2,970	**mil.**	Present value at 25% rate of return for plant producing 255,000 kg/year for 7 years (one expedition per year) if output valued at **current** ETO costs
$1,510	**mil.**	Present value at 25% rate of return for plant producing 255,000 kg/year for 7 years (one expedition per year) if output valued at **future** ETO costs

Is Value of Lunar Propellant Greater than Its Cost?

- **Present value: $1.51 billion if output sold at future ETO launch prices ($2,800 kg to LEO) with 25% rate of return**
- **Required production: 255,000 kg per expedition**
  - Compares to 719,000 kg LOX+LH in Shuttle ET
- **CEV refitted as autonomous cargo CEV: 4,500 kg payload**
- **Cargo CEVs would deliver 4,500 kg to the Moon for an ETO propellant cost of $238 million.**
- **Analysis** (following slides) **shows that 3.4 trips of a cargo CEV would deliver 15,500 kg at an ETO propellant cost of $820 million, handily beating the PV limit of $1.5 billion**

Value Analysis, continued

Lunar fuel has other uses; economies of scale from expanding to satisfy these uses will further reduce expedition costs

- **LEO to GEO transfer services for satellites**
- **Restoring station-keeping abilities to GEO satellites**
- **Enhancing DoD spacecraft**
  - Refueling LEO satellites in high-drag low orbits
  - Refueling LEO and MEO satellites after plane changes
  - LEO to GEO transfer services
- **ISS and commercial space stations**
  - Refueling of orbit-maintenance thrusters
  - Water for consumption, hydroponics, sports, sanitation

Lunar ice processing: two potential strategies

(1) Processing in the cold trap

- ***Take power to*** cold trap (mobile nuclear reactor)
- Heat regolith to get water and split into LOX and LH
- Transport just the harvest of LOX and LH to launch site
- Use cryogenic cold in cold trap to support storage

(2) Processing at central base site

- Excavate regolith and haul to base site
- Power source and range of facilities at central base

Conclusion: Process in cold traps

- Ice-dirt mixture may be only 1% ice by volume
- Central base processing would require hauling 100 tons of regolith for 10-20 km for each ton of water to be produced
- Dehydrated regolith then must be moved again to a dump site

(In-situ cold trap processing dumps single loads immediately next to source site)

Volatiles Processing in Cold Trap

- **Scarification of Regolith by 3 rovers**
  2 loads per hour
- **Scoop Bucket Loading by Same Rovers**
- **Bucket Covered and Heated by On-Board Reactor**
  - **Leftover Dry Regolith**
    - **Bucket Emptied, Regolith Disposed**
  - **Volatile Evaporant** (water vapor)
    - **Flows to Cooler Vessels, Liquifies, Capped under Pressure**
      - **Electrolysis**
        - **LOX in Pressurized Vessels on Towed Wagon**
        - **LH in Pressurized Vessels on Towed Wagon**

Same three digging rovers occasionally move fuel wagons up to launch site

Mining and Processing Volatiles in Cold Traps

- **Goal: 255,000 kg of propellant (for annual two-CEV expedition)**
  - 218,500 kg of LOX and 36,500 kg of LH

- **Assumptions**
  - Water content of regolith = 1% by volume; processing losses = 10%

- **Minimum Processing Rates**
  - 63,000 tons (63 million kg) of regolith annually
    - ~ 36,000 m^3/yr (comparable to 26 football fields scraped to 1/3m depth)
    - 7.2 tons/hour or 4.1 m^3/hour (about the volume of large executive desk)

- **Energetics: Heating needed to evaporate volatiles from regolith**
  - Temperature in cold traps ≈ 50 K
  - Gas begins to be released at 120 K and increases exponentially as T approaches 135 K
  - Delta T ≈ 100 K (50 K to 150 K) and specific heat of regolith (basalt) = 0.22 cal/g ^{0}C
  - Heating needed for 63,000 tons = 1.6 million kWhrs (thermal)
    - 1.6 million kWhrs ≈ 26 kWhr/ton; ≈ 45 kWhr/m^3
    - Necessitates reactor heat source putting out 185 kW (thermal)

Mass Budget for Cold Trap Processing

- **Estimated Total Mass from Earth to Moon: 16,500 kg**
- **Gravity stabilized rovers: scarify, load, tow**
  - 3 Rovers make 2 loads/hour (6 loads total) for 4.7 m^3/hr of regolith (need only: 4 m^3/hr)
  - On-board thermal reactor with 185 kW thermal
    - Evaporated water condenses and is deposited into Electrolyzer
    - Easy dumping of dry waste regolith
    - Provides electrical power (5-10 kW) for locomotion (7-15 Hp) and operation
- **Water produced: 45 L/hr ≈ 400,000 L/year ≈ 400,000 kg/year**
  - 5 kg LH/hr (75 L/hr) ≈ 46,000 kg LH/yr (660,000 L/yr)
    - Goal: 36,500 kg LH: margin ≈ 25% for processing losses
  - 40 kg LOX/hr (36 L/hr) ≈ 350,000 kg LOX/yr (320,000 L/yr)
    - Goal: 218,500 kg LOX: margin ≈ 60% for processing losses (excess LOX is produced)
- **Everything on Wheels – Persistent Mobile Operations**
  - Mobile Electrolyzer accumulation vessel: can be towed by rovers (automated quick hitch)
  - LOX and LH pumped into pressure vessels on trailer: towed to destination using rovers

Mass breakdown for Volatile Production

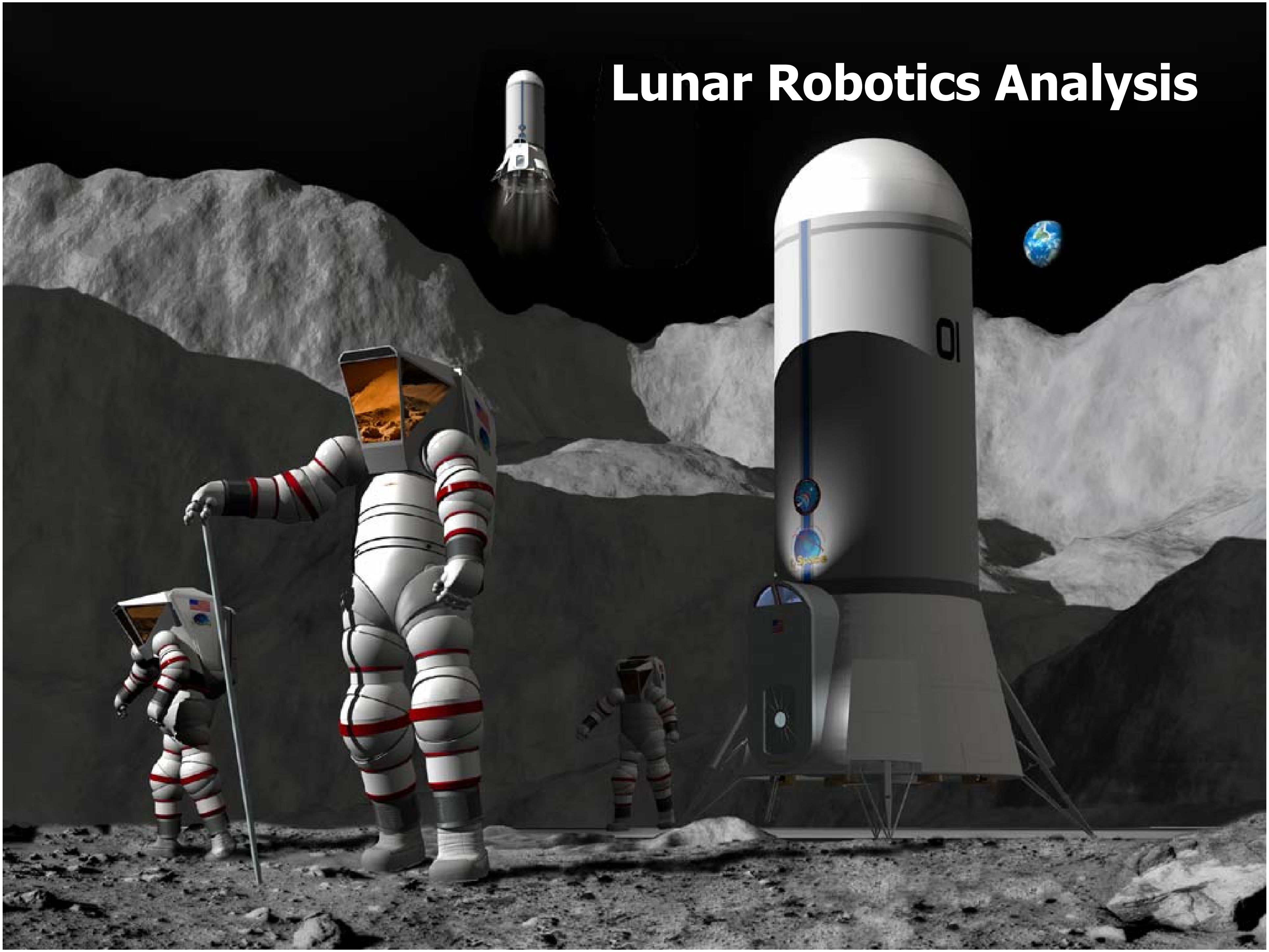
Rover: Modelled after Holland Skid Steer	Mass (Kg)
Scarifier	181
Holland Skid Steer Loader	2,000
Loader size max = 27.9 ft^3 = 0.79 m^3	225
On-board Reactor	500
Other (sensors, computing, manipulators, etc)	800
Single Rover Subtotal	3,707
Total for Three Rovers	**11,121**
System: Processing Water into O and H	
Condensate Accumulation Vessel and Electrolyzer	227
Tankage Required to hold one day's LOX and LH	50
Power source (Reactor)	500
Adding Mobility (System on Wheels)	300
Mobile Electrolyzer Subtotal	**1,077**
Long-term Storage Tanks	**2,765**
Tow Trailer (modeled on wagon gear)	**300**
Miscellaneous (hosing, etc)	**200**
TOTAL kg	**15,463**

Mass budget assumes 2,000 kg weight of a New Holland loader (street model with steel not titanium, etc.)

Conclusion: ISRU Saves Money

- **The Earth-sourced propellant cost of two 2-CEV expeditions is $956 million (at future, lower launch prices)**
- **The mass needed on the Moon to create fuel that eliminates the need for Earth propellants is 15,500 kg**
  - This mass can be transported to the Moon by reusable cargo CEVs at a cost of $53,000 per kg (future launch prices)
- **The mass can be transported for $820 million in ETO costs**
  - For less than the cost of two Expeditions, Earth fuel can be eliminated
  - The present value of eliminating Earth propellants is $1.5 billion, almost twice the $820 million it costs to create lunar fuel capability

Lunar Robotics Analysis



Lunar Robotics Analysis

- **Robots working 24/7 are needed to produce lunar fuel**
- **Robots also are needed for other major Moon activities**
  - Assisting humans in building habitats, greenhouses, observatories, etc.
  - Assisting in building power-generation facilities to support habitation, science, resource extraction, and other applications
  - Exploring that ranges beyond the safe-return limits of humans
  - Supporting Telepresence Tourism
- **Carnegie Mellon University's Field Robotics Center assisted in analysis of required types**

Lunar Robotic Archetypes and Roles

Regional Polar Exploration

- Find cold traps, lava tubes, habitation sites, access routes with sun-runner
- Map and characterize individual lava tubes & cold traps (uses isotope only)
- Dual solar-nuclear rovers: Pragmatic mixing of abundant daylight and cryogenic cold
  - Versatility to enter dark areas using isotopes plus fast travel using solar in the light

Remote Experience Machines

- Tourism & News Media Robots; most NASA-funded robots should include telepresence

Volatiles: Confirm, Characterize, and Extract

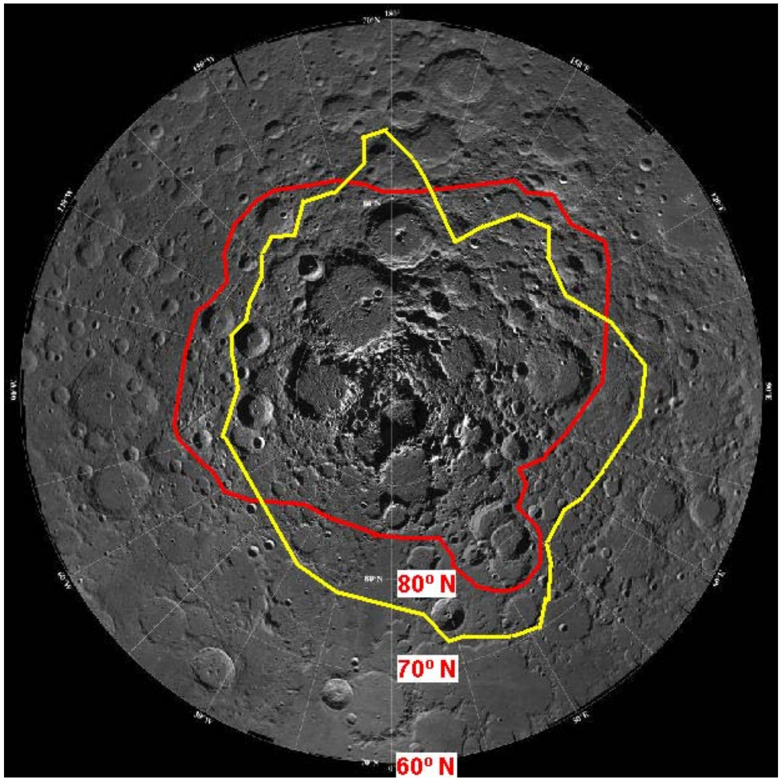
- Cold Trap Assayer with isotope power
- Full ISRU system to produce propellant (hydrogen and oxygen) with isotope power

Site Work: Preparation, Service, and Maintenance

- Base Work: Excavating and Digging
- Inspection, Maintenance, and Servicing of Habitats/Facilities
  - Highly Dexterous Mobile Robonauts and Autonomous Inspection Robots

Solar rovers in sun-synchronous mode can range widely

- Determine ease of entry & exit for cold traps and lava tubes
- Identify landing/habitation/tourism sites
- Establish and map circumpolar routes
- Ready now, little tech-dev



No *point* of eternal sun

But *routes* of eternal sun

Myriad routes exist

Achievable Magellan Route Speeds

Latitude (degrees)	Lunar Circumference (km)	Rover Speed (m/s)
89	191	0.07
87	572	0.22
85	952	0.37
75	2826	1.11
60	5460	2.14
45	7722	3.03

Sun-synch speed shown on Earth by CMU's Hyperion robot: 0.3 m/s

Weaker lunar gravity: gives 6:1 advantage

Stronger sun on Moon: gives 2:1 advantage

TOTAL 12:1 ADVANTAGE

↓

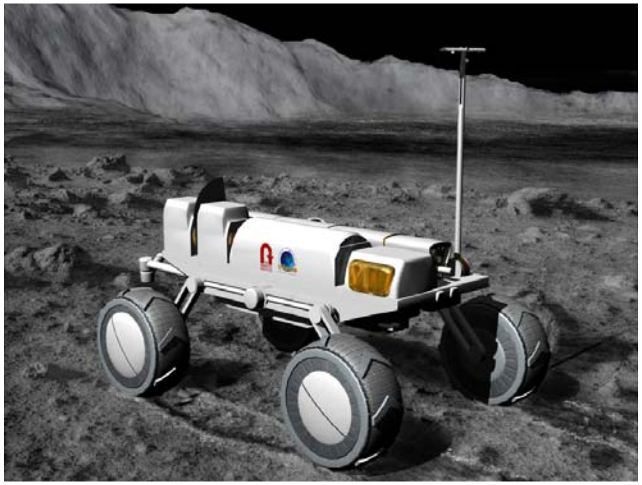
3.6 m/s equivalent lunar speed already demonstrated by Hyperion

Variety of routes viable with ample time for in-situ characterizations

Cold Trap Assayer

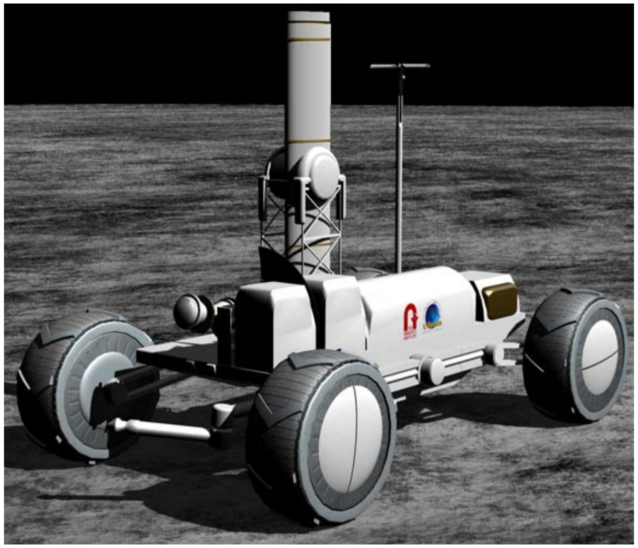
Access cold traps, then analyze lunar ice

- Assayer gets ground truth (single stage drilling up to 2 meters) and distribution maps



Ultra-reliable, slow machine

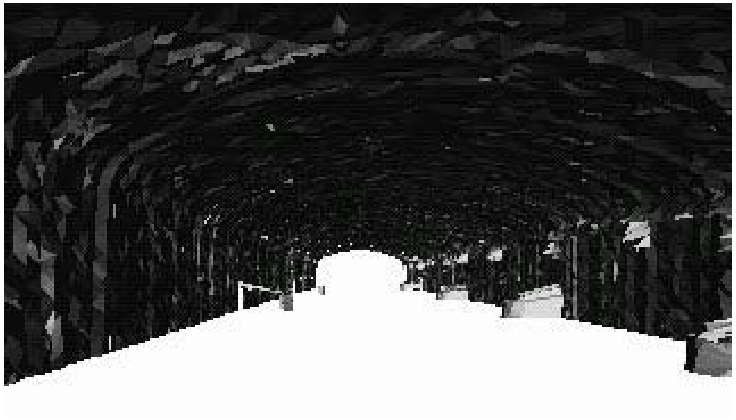
- Long term, multi-year presence in craters/cold traps
- 1,000 km range, but a tortoise – not a hare
  - Designed to exploit any available "easy" crater access & egress, not to overcome all possible barriers
- Isotope power: runs for years without interruption
  - Thermal source (side effect of energy conversion) useful in cryogenic cold – enables "warm-blooded" machine and thermal regulation
  - Eliminates need for large batteries, power cycling, heating units, day/night limitations or the requirement to exit the cold trap to recharge.



Lava Tube Exploration and Characterization

- **Lava Tubes – Incredible assets**
  - Found on Earth when lava flow hardens on the edges but the molten core flows away
  - Rills on the Moon likely are collapsed lava tubes
  - Cost effective (find and occupy vs. build/construct)
  - Inherent radiation and micrometeorite shielding
  - Relatively constant temperature simplifies thermal management systems

- **Robotic void characterization (i.e. mine mapping) is a powerful new technique**
  - Explore incommunicado
  - Astronauts not put at risk



- **Generate 3-D models by occupying voids with autonomous machines**

- **Lunar archetypes would be isotope powered to allow for long expeditions**

Hybrid Rovers for Dark/Light Expeditions

- **Pragmatic lunar scenarios require working in both light and dark**
  - Illuminated-peak to illuminated-peak via dark
    - Two areas on ridge of Shackleton crater (south pole), 10 km apart, are collectively illuminated for more than 98% of the time
  - Versatility to characterize as well as find
    - Find accessible craters, then assay ice levels
    - Discover lava tubes, then enter to map them
- **Hybrid combines strengths**
  - **Solar:** high power density – run fast and far
  - **Isotope:** persistent electric and heat source – operates in cold traps and lunar night
  - Batteries are a poor substitute for isotope power in the cold and dark
    - Charging takes much longer than discharging
    - Batteries are "weakest link" to protect from cold
    - Time in dark always limited by weight of batteries

Rover Power System Comparisons

Power System	Readiness	Pros	Cons
Solar Power (Sun Runner)	Now	• Run fast and far, cover thousands of km • Capable of traversing rugged terrain	• Cannot survive the night, or enter cold traps
Isotope Power (Cold Trap Assayer with Sterling Converter)	Soon – modest effort to improve conversion efficiencies	• Indefinite power • Indefinite thermal source • No power cycling • Operate at night	• Much slower and heavier than solar • Launch risk • Waste heat dissipation
Solar/Isotope Hybrid	Soon – adding solar to an isotope rover is not difficult	• Sustainable operations in dark craters and at night • Able to move faster than isotope when sun is available	• Slower than pure solar due to extra weight of isotope power system • Launch risk • Waste heat

Solar Cell Paver:
Not a priority for early polar outposts

- **Polar location requires solar arrays to be erected vertically; easy paving of cells flat on the lunar surface is only possible near equator**
- **Fusing a glass substrate is easy (at equator), but refining pure cell deposition materials from lunar dirt will be very challenging**

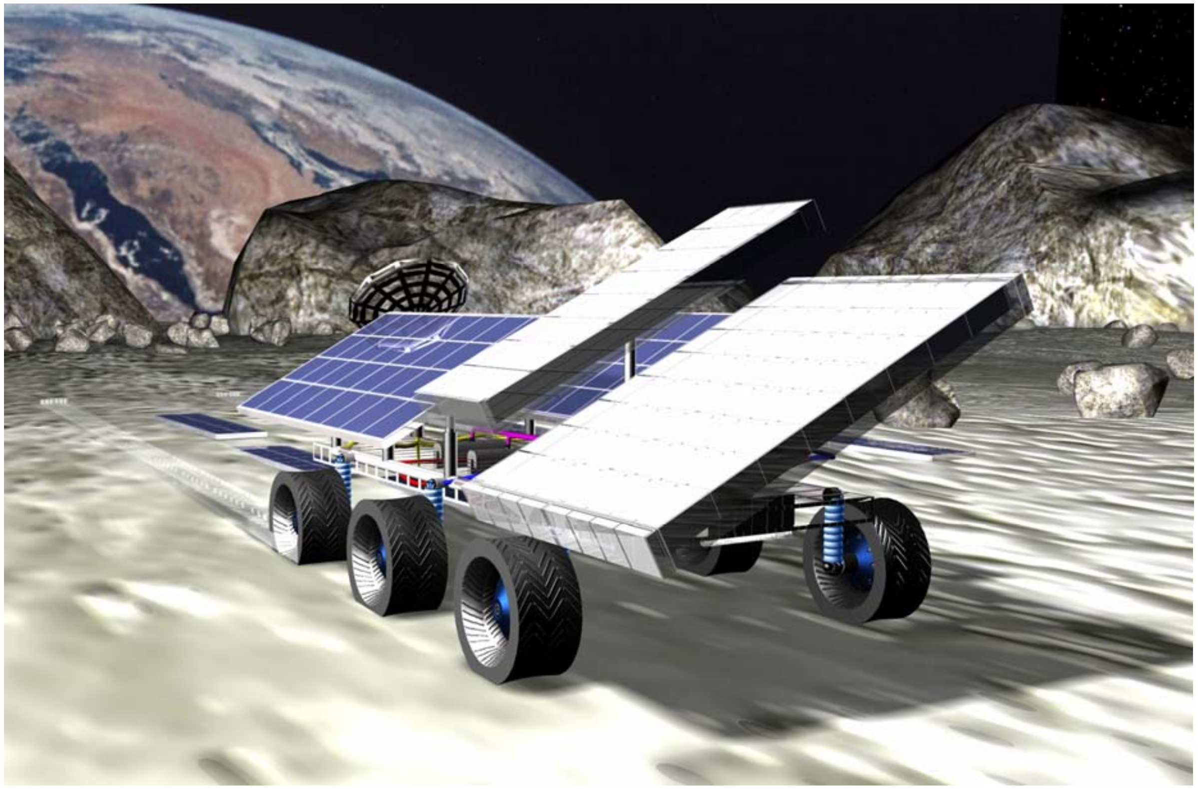
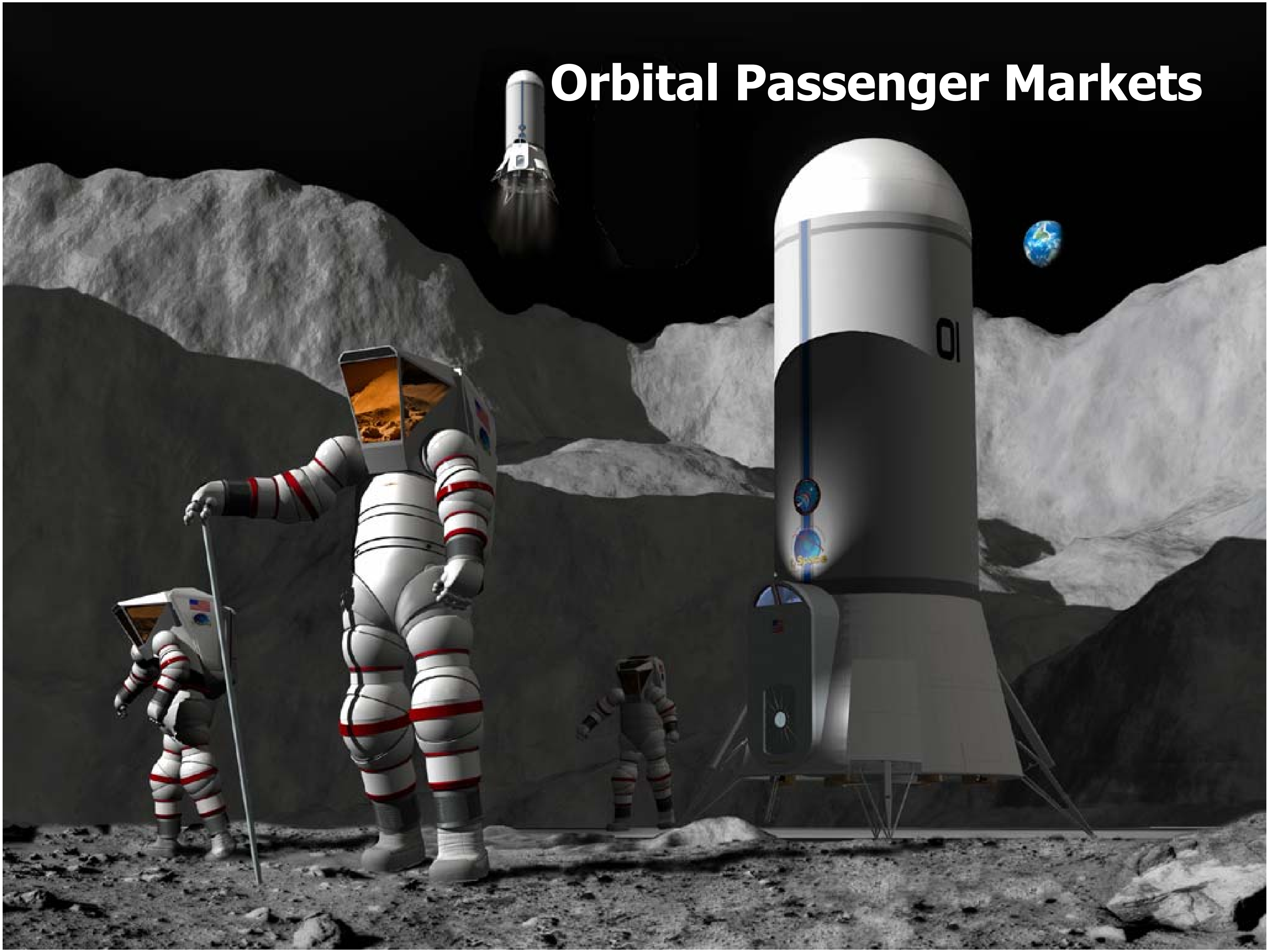


Image shows one unit doing final deposition; unseen are the other units creating lab-pure silicon, aluminum, dopants, etc., using multiple processes in ultra-clean conditions

The Robot Bottom Line

- **First lunar robot:** a wide-ranging sun-synchronous rover for regional polar exploration
  - **Discover and map important resources: cold traps, lava tubes, landing sites, routes of eternal light**
- **Soon thereafter:** a solar-isotope hybrid
  - **Enters cold traps via identified routes to assay the ice deposits**
- **Need:** A ready-to-fly small reactor for ISRU
  - **Add 20% to the Topaz-1 specs (150 kW thermal in 320 kg)**
  - **Poor conversion efficiency to electricity is irrelevant**
- **Need:** A ready-to-fly small reactor for hybrid rover
  - **Requires better-than-Topaz efficiency because electricity is the goal, and waste heat is a problem to shed when sun-running**

Orbital Passenger Markets



Orbital Passenger Markets:
Important for Long-Term Sustainability

- **New t/Space analysis of Futron orbital data**
  - Previous study: $20 million Soyuz ticket, six months training in Russia
  - New forecast: Prices from $1 - $5 million, one month training in U.S.
- **Commercial ETO crew services will spark a new industry**
  - NASA directly benefits as **economies of scale drive down launch costs**
  - **Public support for NASA rises** as spaceflight becomes available
- **Very large market by 2025** (compared to satellite launches)
  - Annual passengers may range from several hundred to several thousand
  - Annual revenues likely to be several billions of dollars

…a thriving industrial base for NASA's Mars Expeditions

Really Rich People Are Rare, So Ticket Prices Are Crucial

Households by net worth:

$1 M	3,500,000	US
$1 M	7,300,000	World
$7 M	1,000,000	World
$20 M	100,000	World
$30 M	58,000	World
$200 M	6,000	World
$1 B	552	World

Dennis Tito and Mark Shuttleworth

Attributes of Millionaire Consumers

- **Willingness to spend**
  - Only 10% spend > $50,000 on a discretionary purchase / 5% of net worth
  - 40% spend $15,000 or more on a discretionary purchase / 1.5% of net worth
  - Soyuz tickets required an est. 7-10% of net worth for Tito, Shuttleworth
- **Time available for space training**
  - 26% spend one month or less on vacation
  - Only 2% spend six months or more on vacation
  - Soyuz tickets require six months of Russian training
- **Openness to risk**
  - 19% have tried skiing
  - 2% have tried mountain climbing
  - 1% have tried sky diving

Available pool by price and net worth spent

Net Worth Spent per Ticket	$5M Ticket Price: Net Worth Needed to Afford	$5M Ticket Price: Size of Global Pool	$2.5M Ticket Price: Net Worth Needed to Afford	$2.5M Ticket Price: Size of Global Pool	$1M Ticket Price: Net Worth Needed to Afford	$1M Ticket Price: Size of Global Pool
5%	$100M	10,000	$50M	50,000	$20M	100,000
1.5%	$333M	4,000	$166M	8,000	$66M	40,000

Potential rich customers adjusted for health, training location and training time

- **Our health screens narrowed the available pool**
  - For respondents 65+, we included only the 11% who are “extremely fit”
  - For folks under 65, we included the 86% who are “average” or above in fitness
  - These two screens leave 61% of the original pool available
- **U.S. location for training widened the available pool**
  - Switching the six months of training from Russia to the U.S. increased the “definitely likely to buy” by 24%
- **Shorter training period widened the available pool**
  - Reducing the training period to one month from six months increased the “definitely likely to buy” by 50%

Conservative definition of customer interest

- **People were read this statement:**

"Space flight is an inherently risky activity… To take the trip, you would have to undergo intensive cosmonaut training in Russia for six months prior to the launch. During the flight you may experience headaches and lower backache. While in space, you might experience some nausea. You would be able to view the Earth through porthole-sized windows. Upon your return to Earth and normal gravity, you might experience some dizziness for a few days and have difficulty standing."

Would you be definitely likely, very likely, somewhat likely, not very likely, or definitely not likely to buy a ticket?

Cummulative "definitely likely" at these prices:				
$20m	$10m	$5m	$2.5m	$1m
7%	16%	20%	26%	30%

Net Effect of Adjustments, Lower Prices

Net Worth Spent per Ticket		$5M Ticket Price	$2.5M Ticket Price	$1M Ticket Price
5%	Global pool	10,000	50,000	100,000
	Fitness (x61%)	6,100	30,500	61,000
	Intention to buy	20%	26%	30%
	Likely Customers	1,220	7,930	18,300
	Switch to U.S. (+24%)	1,512	9,833	22,692
	Less training (+50%)	**2,269**	**14,749**	**34,038**
1.5%	Global pool	4,000	8,000	40,000
	Fitness (x61%)	2,400	4,900	24,400
	Intention to buy	20%	26%	30%
	Likely Customers	480	1,274	7,320
	Switch to U.S. (+24%)	607	1,579	9,076
	Less training (+50%)	**907**	**2,359**	**13,614**

Analysis of Potential Annual Passenger Traffic

Trip Prices	% Net Worth	Peak Demand	2009 1%	2010 1%	2011 2%	2012 3%	2013 4%	2014 6%	2015 8%	2020 40%	2025 83%	2030 97%
			30-year S-curve of acceptance, showing Passengers Per Year									
$5M	5%	2,269	22	25	45	68	90	136	181	907	1,883	2,200
	1.50%	907	8	10	18	27	36	54	72	362	752	879
$2.5M	5%	14,749	147	160	294	442	589	884	1,179	5,899	12,241	14,306
	1.50%	2,359	24	30	47	70	94	141	188	943	1,957	2,288
$1M	5%	34,038	340	375	680	1,021	1,361	2,042	2,723	13,615	28,251	33,016
	1.50%	13,614	136	149	272	408	544	816	1,089	5,445	11,299	13,205

Annual Passenger Revenue

30-year S-curve of acceptance, showing Revenue Per Year

Trip Prices	% Net Worth	Peak Demand	2009 1%	2010 1%	2011 2%	2012 3%	2013 4%	2014 6%	2015 8%	2020 40%	2025 83%	2030 97%
$5M	5%	2,269	22	25	45	68	90	136	181	907	1,883	2,200
	Revenue (millions)		$110	$125	$225	$340	$450	$680	$905	$4,535	$9,415	$11,000
	1.50%	907	8	10	18	27	36	54	72	362	752	879
	Revenue (millions)		$40	$50	$90	$135	$180	$270	$360	$1,810	$3,760	$4,395
$2.5M	5%	14,749	147	160	294	442	589	884	1,179	5,899	12,241	14,306
	Revenue (millions)		$368	$400	$735	$1,105	$1,473	$2,210	$2,948	$14,748	$30,603	$35,765
	1.50%	2,359	24	30	47	70	94	141	188	943	1,957	2,288
	Revenue (millions)		$60	$75	$118	$175	$235	$353	$470	$2,358	$4,893	$5,720
$1M	5%	34,038	340	375	680	1,021	1,361	2,042	2,723	13,615	28,251	33,016
	Revenue (millions)		$340	$375	$680	$1,021	$1,361	$2,042	$2,723	$13,615	$28,251	$33,016
	1.50%	13,614	136	149	272	408	544	816	1,089	5,445	11,299	13,205
	Revenue (millions)		$136	$149	$272	$408	$544	$816	$1,089	$5,445	$11,299	$13,205

Passenger Travel Changes the Economics and Politics of Mars Expeditions

- **Industry revenue of several billions likely by 2025**
  - **Drives down NASA's ETO costs**
  - **Creates LEO services for NASA (habs, fuel, supplies)**
  - **Turns thousands of the world's wealthiest, most influential people into active space supporters**

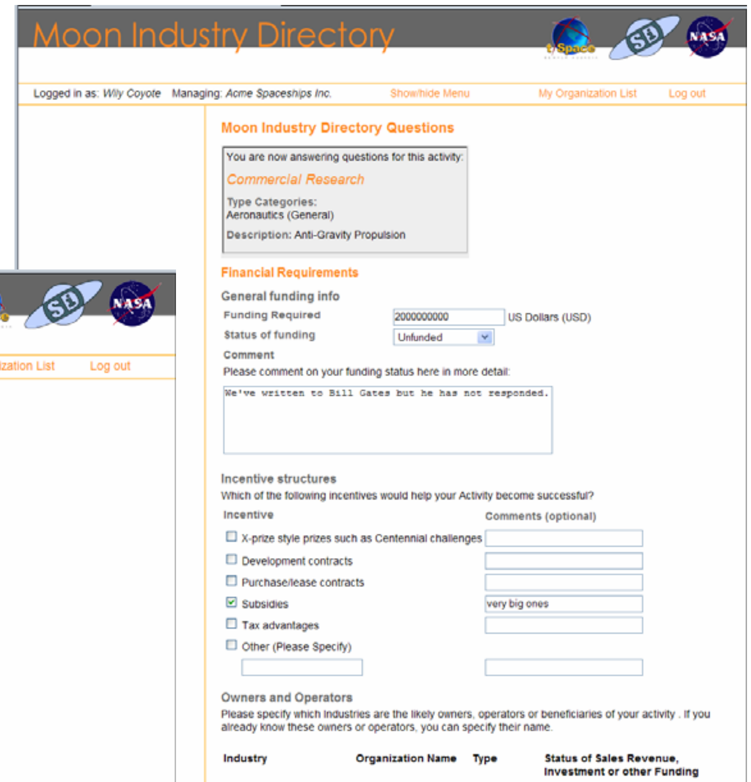

Lunar Commerce Directory
& a VISCO for Space

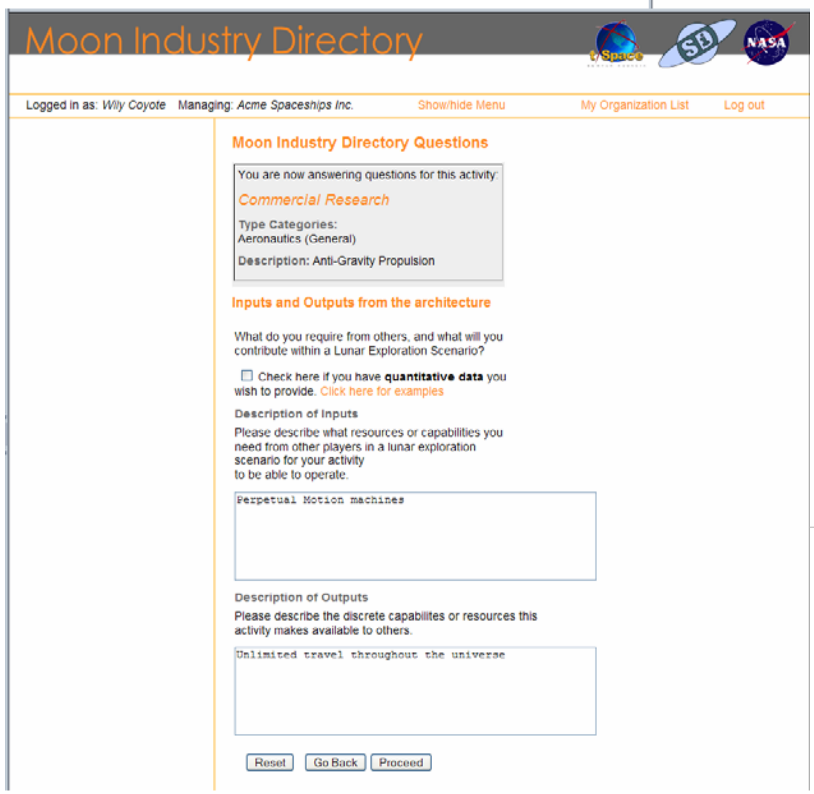
Coming: A Lunar Commerce Directory

- **t/Space is creating an open registry for companies interested in lunar commercial activities**

- **t/Space will do outreach to populate the directory, and will also invite companies to enter their data directly**

- **Available to NASA and to companies seeking partners and suppliers**





Under way: a VICSO for Space

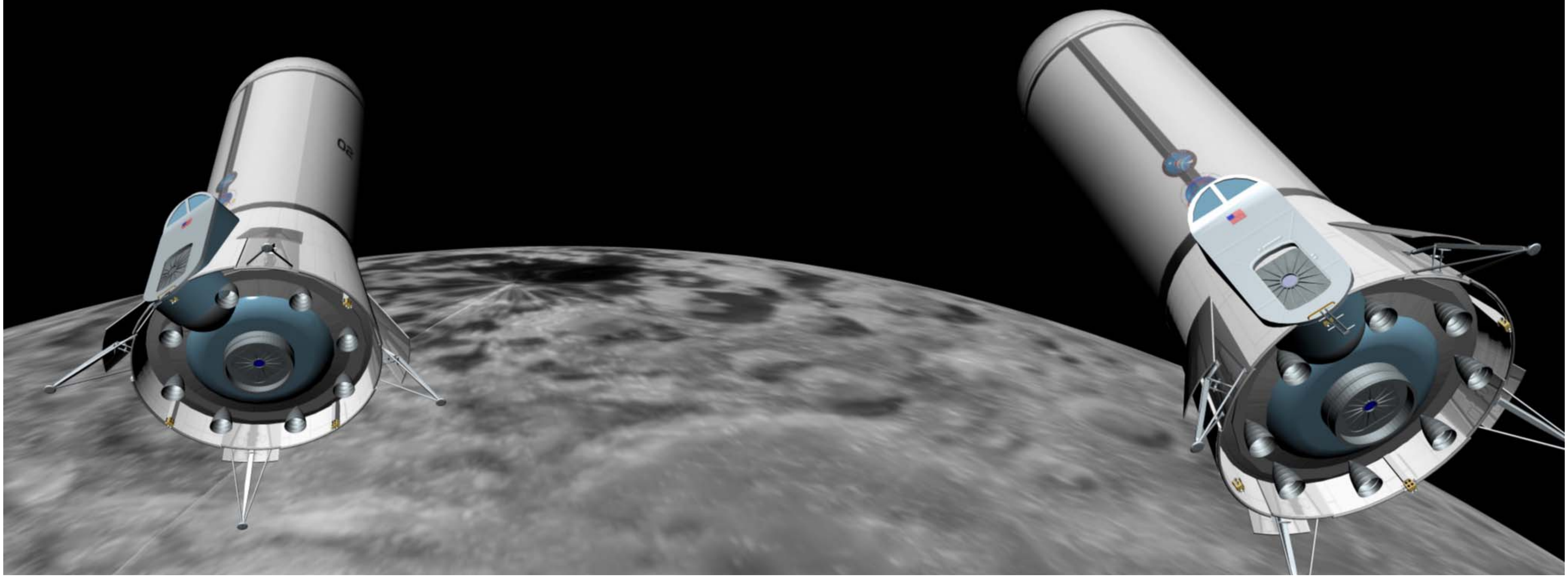
- **t/Space contract with NASA calls for effort to seek out "standard gauge" approaches to harmonizing the products and services of commercial space companies**
- **First step achieved: formation of a Voluntary Personal Spaceflight Industry Consensus Standards Organization**
  - t/Space played strong role in VICSO formation
  - Open to all U.S. non-profit and commercial entities developing commercial space passenger travel
  - Founders include John Carmack, Armadillo Aerospace; Burt Rutan, Scaled Composites; Elon Musk, SpaceX; Alex Tai, Virgin Galactic; Jeff Greason, XCOR; Dr. Peter Diamandis, X PRIZE Foundation; Gary Hudson, t/Space; George French, Pioneer Rocketplane; Stuart Witt, Mojave Spaceport; Eric Anderson, Space Adventures; and Michael S. Kelly, Chairman, RLV Working Group, a DOT industry advisory panel.

Results Summary

CEVs that can land on Moon enable early lunar fuel use and cargo-variant CEVs with 4,500-kg payloads

Lunar fuel production saves money

A robust orbital passenger market is likely by 2025



Policy Summary

- **Commercial ETO will reduce costs**
  - NASA-only service can put four-person crews into LEO for less than $20 million
  - Enabling a passenger industry will drive that price down
  - Avoids the cost of human-rating the CEV launch vehicle
- **Commercial service can eliminate the 2010–2014 gap in U.S. human spaceflight**
- **Commercial ETO broadens NASA's base of support**
  - Shows Congress that NASA is looking beyond the standard approaches that often are very expensive and very slow
  - Thousands of wealthy passengers become space enthusiasts