A New Architecture to Explore the Potential of Lunar Resource Utilization

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Outline

Change the template of spaceflight

Previous architecture: Robots mine the Moon and set-up outpost

Features of modified architecture:
- SLS launch of robotic assets and cargo
- Reusable, space-based elements (cislunar transfer stage, landers)
- Co-located propellant depots and habitats in LEO and LLO
- Transport of crew to and from LEO by commercial providers

Results: same total cost, greater propellant production, permanent human presence on Moon. Builds a cislunar, space-based transportation system for people and cargo

Conclusion: Create long-term space faring capability through lunar resource harvesting and use. Program is scalable and affordable. Creates wealth instead of consuming it.
Spacefaring: Changing the Rules

Current template
- Custom-built, self-contained, mission-specific spacecraft
- Launch on expendable vehicles
- Operate for set lifetime
- Abandon after use
- Repeat, repeat, repeat

New template
- Incremental, extensible building blocks
- Extract material and energy resources of space to use in space
- Launch only what cannot be fabricated or built in space (smart mass)
- Build and operate flexible, modular, extensible in-space systems
- Reuse, Maintain, Expand, Repeat
Moon: Pertinent Facts

Material resources
- Bulk regolith (shielding, ceramics, aggregate for construction)
- Metals (iron, aluminum, titanium)
- Water (chemically unbound), 5-10 wt.% measured; more?

Energy resources
- Areas near poles in quasi-permanent sunlight, close to water deposits (>90% per yr.)

Environmental conditions
- Thermal cold traps (~30-40 K)
- Hard vacuum (10^{-12} torr)
- Exposed to Solar Radiation
- Fractional gravity (0.17 Earth)

Operational benefits
- Close (3 days by crew, 3 seconds by communication)
- Outpost location close to water ice ore and extended sunlight at poles
Mission
Create a permanent human-tended lunar outpost to harvest water and make propellant

Approach
Small, incremental, cumulative steps
Robotic assets first to document resources, demonstrate production methods
Teleoperate robotic mining equipment from Earth. Emplace and build outpost assets remotely
Use existing commercial LV, HLV if it becomes available

Assumptions
Average 10 wt.% water ore, within 10 km of 80% sunlight

Cost and Schedule
Fit under existing run-out budget (< $7B/year, 16 years, aggregate cost $87 B, real-year dollars)
Resource processing outpost operational halfway through program (after 18 missions); end stage after 30 missions: produce 150 tones water/year

Benefits
Create permanent space transportation system
Routine access to all cislunar space by people and machines

Strategic Approach

Characterize ice ore and scout prospects
   Missions to both North and South Pole

Once location is chosen, use SLS to:
   Land robotic elements and systems to mine, process, electrolyze, and store water and propellant
   Employ multiple elements for the same function to mitigate failures

Place transitional nodes at LEO and LLO
   Fuel and crew exchange/short dwell times

Reuse transportation system elements
   Develop reusability for space-based assets, not launch vehicles
   Human lander, Cislunar Crew Stage, Robotic Water Tank Lander

Robotic emplacement of habitation elements at the outpost prior to crew arrival
   Experiment with ceramics, aggregate, 3-D printing, metal extraction, engine servicing, refueling
Launch Vehicles
Previously Atlas 551 for robotic elements
plus unnamed HLV for crew
Now use SLS for cargo; Commercial crew to LEO and return

Crew Rotations
Human tended, change out every 6 months
Previous: 120 crew months dwell over 16 years vs. 216 crew months for new plan

Cost and Schedule
Essentially same total cost ($88B); phasing is a little different
Cost of crew rotation is cut roughly in half
Significant leverage by IP and CP contributed assets (suggested $16B in donated elements)

Benefits
All space-based elements are reusable
More accessible, more crew time on Moon
More water produced (500 t/yr. vs. 150 t/yr.)

Features of New Architecture: SLS

Launch Vehicle Strategy

Use SLS for Cargo (what a big launcher is best suited for); direct to Moon
SLS Block 1: 25 t (net payload) to TLI; 5 t to lunar surface direct
Regular launch cadence, but no more than 5 every 2 years
No on-orbit assembly (too hard to plan to stage habitats, tools, checkout is difficult)
Orbit fueling at LLO for Cargo Lander (~11 t payload to lunar surface)
Preserve both Block 1 and Block 1B capability

Fairing size

Block 1- 5 m fairing (bigger elements, especially landers)
Use Block 1B (EUS) with 8.5-10 m fairing diameter (helps packaging for the big stuff)
Human Lander, Reusable Water Tank Lander, Cargo Lander, Depots with Block 1B

Orion

Use Orion as lifeboat
Station at LLO Hab-Depot for “quick ride home”
Features of New Architecture: CCS

Cislunar Crew Stage (CCS)
- Reusable Crew transport from LEO Hab-Depot to LLO Hab-Depot and back
- Uses aero-assist to shed Earth-approach velocity ($\Delta v$)
- Fuels for one leg at a time (save mass)
- Outbound leg (to Moon) is most propellant consumptive
- Fuels at each depot for upcoming leg
- Maintains zero boil-off (< few % per leg)
- Integral propulsion with cryo RCS
- Use propellant as pressurants (minimize gases)
- Pressurized docking port(s)
- Use common engine cluster (common with reusable landers) with single engine out full capability

Characteristics
- Dry Mass: 17.5 t
- Crew Mass + cargo: 4 + 2 t
- Prop Mass: ~34 t (LEO to LLO)
Features of New Architecture: Hab-Depots

**LEO and LLO Hab-Depots**

- Crew transition points; one at 400 km LEO and one at 100 km LLO orbits
- Capable of fueling any transportation element that can dock to it
- Ingests water and produces LOX and LH₂
- Contains pressurized habitats for short crew layovers (8 crew, typically 1-2 days)
- Pressurized docking ports (for crew ingress/egress)
- Common engine cluster (common with reusable landers) with engine change out on-orbit capability
- Provides power to docked elements
- Requires near-zero boil-off technology (cryo-cooler)

**Characteristics**

- Dry Mass: 29 t
- Crew capacity: 8, generally less than 2-3 days
- Required Storage: 30 t LOX (~27 m³), 4 t H₂ (~57 m³), 10 t water (10 m³)
- Required Power: 200 kW (150 kW for electrolysis)
- Propellant production rate: 14 t/month
Features of New Architecture: Crew Rotation

**Lunar outpost crew change (every 6 months)**

- Commercial Crew (CC) Capsule launches to LEO Depot – Cislunar Crew Stage (CCS) is docked at LEO Hab-Depot in wait state (departing CC Capsule also there)
- Outbound crew transfers to CCS; CCS performs TLI (4-5 day trip to low lunar orbit)
- CCS orbits Moon and rendezvous with LLO Hab-Depot
- Inbound crew launches in reusable lander to rendezvous with LLO Hab-Depot
- Crews exchange at LLO Hab-Depot
- New inbound crew immediately departs and lands on Moon via reusable Human Lander
- Departing Crew refuels CCS at LLO Depot and performs TEI (interim orbits to align planes)
- Outbound crew Earth return 4-5 days later. CCS performs 2 orbit aero-assist passes to shed Δv, then rendezvous with LEO Hab-Depot
- Returning crew transfers to CC Capsule, deorbits and returns to Earth.

**Reusable transportation elements**

**Permanent human presence on Moon**
Architecture Results

**Cost:** commensurate with previous study ($88 B over 16 years), ~$16 B less with international and commercial contributions

**Human Reach:** Expansion of human presence throughout cislunar space with Lunar Outpost and LEO and LLO hab-depots

**In Situ Resources:** Access provided by lunar produced propellant
Shallow gravity well of Moon will eventually provide resources to Earth orbit more efficiently

**Enables:** Human missions to Mars and other Solar System destinations utilizing lunar-derived propellants

**Enables:** Large communications complexes, distributed aperture systems in cislunar and GEO utilizing lunar-derived resources (materials), Space Solar Power (SSP) satellites
Benefits

Determine the degree to which humans can reliably and affordably live and work off-planet using in-situ resources while enhancing the overall benefit to the country and world.

Measure progress and keep focus by creating new spaceflight capabilities from lunar resources.
- Not just water – other volatiles, *in situ* structures, metals, ceramics and aggregate.

Embrace both international partners and commercial interests (early involvement, early transition to private sector).

Create permanent, space-based transportation system for cislunar space and beyond (part of our transportation infrastructure).

Focus on national strategic benefits not public “excitement.”
Money, Money, Money

Era of lunar flight
Era of Low Earth Orbit (LEO) flight
Era of no flight

NASA budget as a percentage of federal budget

0.0% 0.5% 1.0% 1.5% 2.0% 2.5% 3.0% 3.5% 4.0% 4.5% 5.0%
What Kind of Space Program?

Two Visions

The #Journey to Mars

- No viable architecture, but lots of pretty pictures
- Everything launched from Earth (Apollo mindset)
- “Stunt” missions of no lasting value (ARM)
- Flags and footprints forever
- Chronically underfunded (and will remain so for the foreseeable future)

Become a true space faring species

- Reusable, maintainable, extensible space systems
- Incremental, cumulative, steady progression outward from LEO
- Fit under any budget envelope; return value for money spent
- Government develops and demos technology; commerce follows
- Create a permanent and expanding space transportation infrastructure
- Less hype, more substance