Lockheed Martin’s Systems-of-Systems Lunar Architecture Point-of-Departure Concept

CE&R BAA Open Forum
CA-1 Midterm Briefing

30 November 2004

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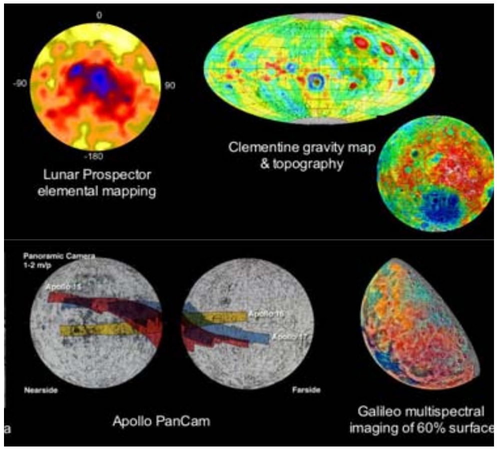
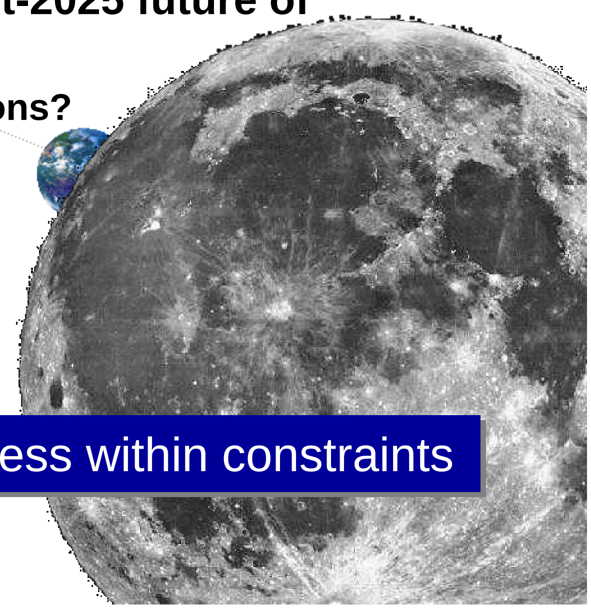
Exploration Objective Decomposition and Relationships to POD Architecture

- Guiding principles
- Mars exploration approach
- Why-go-where on the Moon
- Science objectives
- ISRU objectives
- Testbed objectives
- Relationship of objectives to POD architecture
- POD Lunar campaign
- POD affordability
- POD objective satisfaction vs. time



Guiding Principles for Lunar Exploration

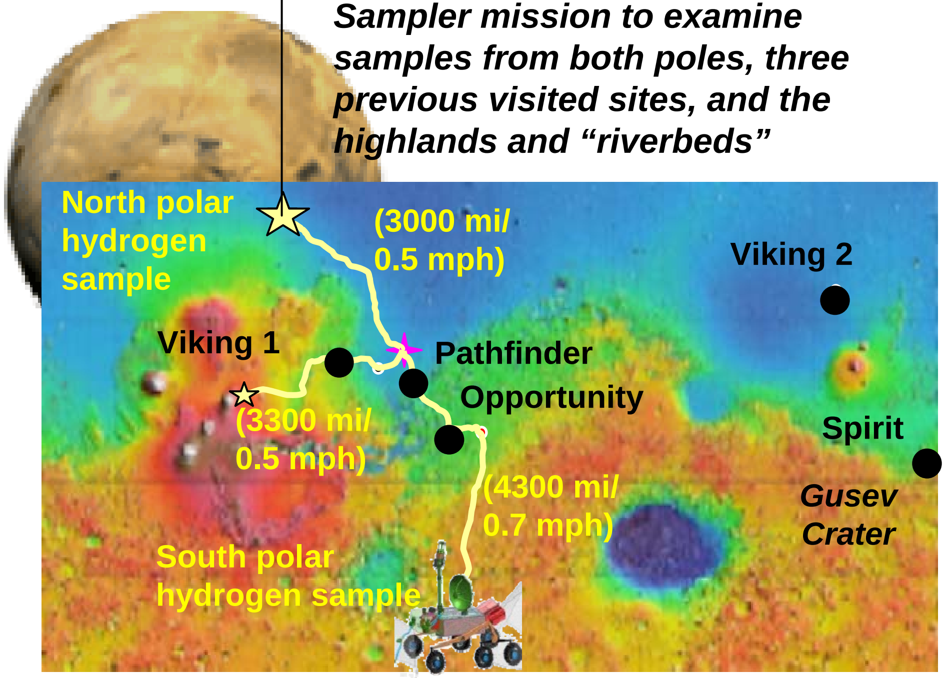
- **Simultaneously address each of the Vision Objectives**
  - **Continuous testbed, science, and ISRU returns support program sustainability across the widest spectrum of stakeholders**
  - **Utilize synergistic combination of humans and robotics**
  - **Satisfy objectives in a safe and affordable manner**
  - **Enable extension to commercial activities in post-exploration era**
- **Start with Mars and work backwards**
  - **Mirror the exploration strategy likely for Mars**
  - **Lunar exploration testbed on critical path towards humans on Mars by 2030**
    - **Lunar testbed results required by at least 2025 to incorporate into Mars system developments (i.e., >5 years prior to sending humans to Mars)**
- **Answer the fundamental questions to determine the post-2025 future of exploration on Moon, Mars, and Beyond**
  - **Can humans live/work safely and effectively for long durations?**
  - **Can the promise of lunar ISRU be realized?**
  - **Is there a viable, long-term mission model?**
    - **Stimulus for permanent space infrastructure**
    - **Enables transition of government-sponsored to commercially- driven activities**



Objective-driven approach maximizes exploration progress within constraints

Mars Exploration Approach

Example of first Roving Robotic Sampler mission to examine samples from both poles, three previous visited sites, and the highlands and "riverbeds"



Of 153 candidate landing sites identified for geochemistry/geology, exobiology, metrology, and seismology, 59% are near-equator, 35% in mid-latitudes, and 6% at poles*

*World-wide survey by Arizona State University

- **Mars robotic precursors (orbiters and landers) already leading the way**
  - **Pursuing water/life clues**
  - **Providing the global access to H20 ice at poles/near poles**
  - **Soon to be performing combined science, ISRU, engineering testbed missions**
  - **Improving rover duration and speed**
- **Human missions likely to use fixed, near-equatorial site for surface stays of 30-630 days**
  - **Near the most desirable sites**
  - **Low altitude to minimize entry/descent/landing difficulty**
  - **Enables incremental build-up**
  - **Most energy/mass efficient location**
  - **More favorable thermal environment (20°C to -140°C)**
  - **Safest approach**
  - **Best solar fluence**

Fixed equatorial outpost approach to exploration high probability for Mars

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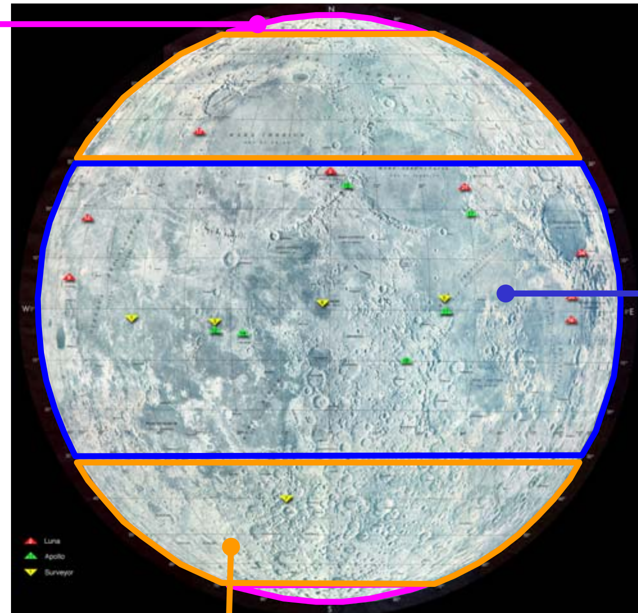
Lunar Exploration – Why go where?

Polar (70°- 90°)

- **6% of surface area**
- **5% of top sites (3/60*)**
  - **High H concentrations but *questionable H_20 ice* (if not ice then H_2/O_2 extraction more difficult given dark/cold)**
  - **Terrain limited mostly to highlands; rich in Al and Ca/poor in FeO and TiO2**
  - **Craters as deep as 4km (Grand Canyon)**
- **Near-continuous sun <u>only on 5 km mountain tops</u>**
  - **Mild thermal variation where sun is continuous (-63 to -43°C); extreme cold in shadows (-223°C)**
- **70-90+% communication connectivity to earth <u>only on 5 Km mountain tops</u>**
- **10-45% delta-V penalty for anytime abort**



Mid-latitudes (30°- 70°)

- **44% of surface area**
- **26% of top sites (21/60*)**
- **Very similar to equatorial for terrain, illumination, etc.**
- **Most severe access limitations; 10- 55% delta-V penalty for anytime abort and/or access**

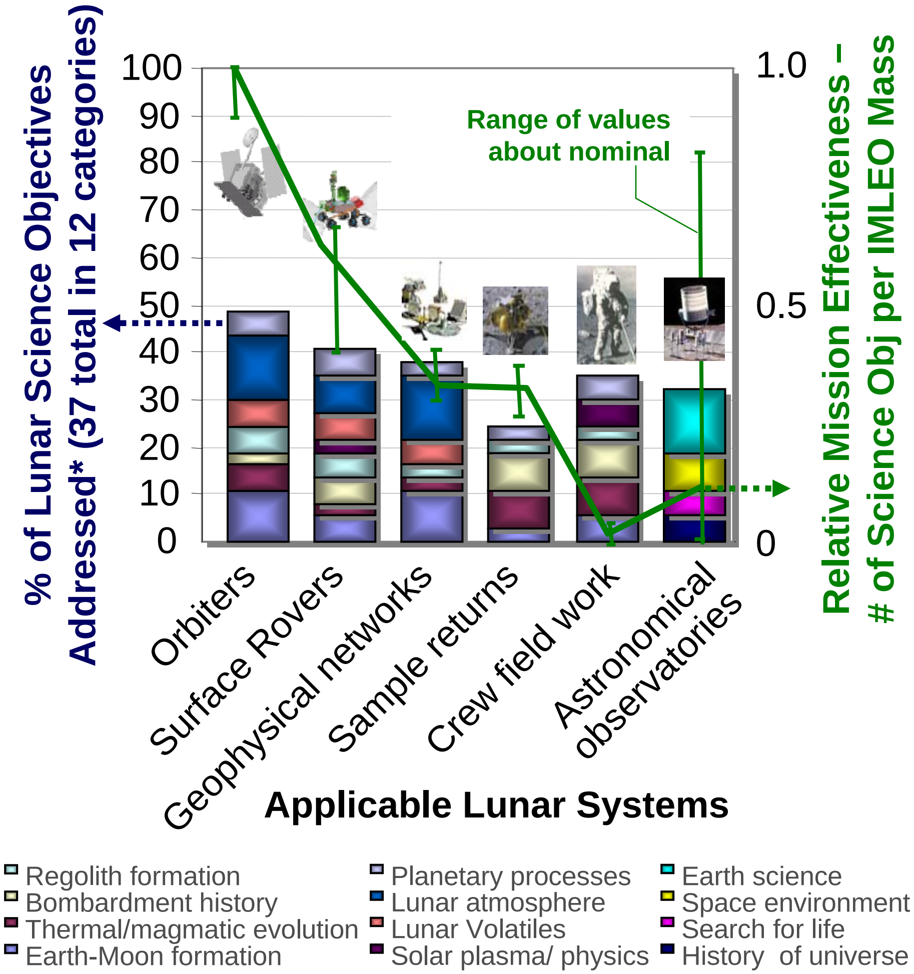
Equatorial (+/-30°)

- **50% of total 28M km^2 surface area**
- **69% of top science/ISRU sites (41/60*)**
  - **All possible terrains**
  - **All possible resources available except H_20 ice**
- **All types of terrain including both mares and highlands**
- **14 days in sun followed by 14 days in dark**
- **Significant temperature swings; slightly larger than Mars (121°C to -159°C)**
- **100% communication connectivity to earth**
- **Access via minimum delta-V; anytime abort without delta-V penalty**

Human any-time, global access desirable but is it required to meet objectives?

***As defined by Lunar and Planetary Institute (1988)**

Lunar Science Objectives



*Each objective may be addressed by one or more systems

- **Science objectives can be accomplished at any time, in any sequence**
  - **Not on critical path to Mars or lunar commercialization**
- **Up to 80% of science may be accomplished by robotic systems**
  - **Non-human science not an architectural mass or cost driver**
    - **Up to the point that astronomical observatories remain proof of concept vs. operational systems**
  - **Moving forward with LRO ('08), LSI ('09), and Moonrise (Aitken Basin sample return in '10)**
  - **International participation with SMART 1 ('04), Lunar A ('05), and Selene ('06)**
- **Humans perform critical science functions but at significant cost**
  - **Global access/any time abort a major driver**
- **Synergistic with ISRU characterization**

Global robotic support effectively addresses majority of science needs

Lunar ISRU Objectives

Ranking:
▲ = High
● = Medium
▼ = Low
Priority:
1=High,
5=Low

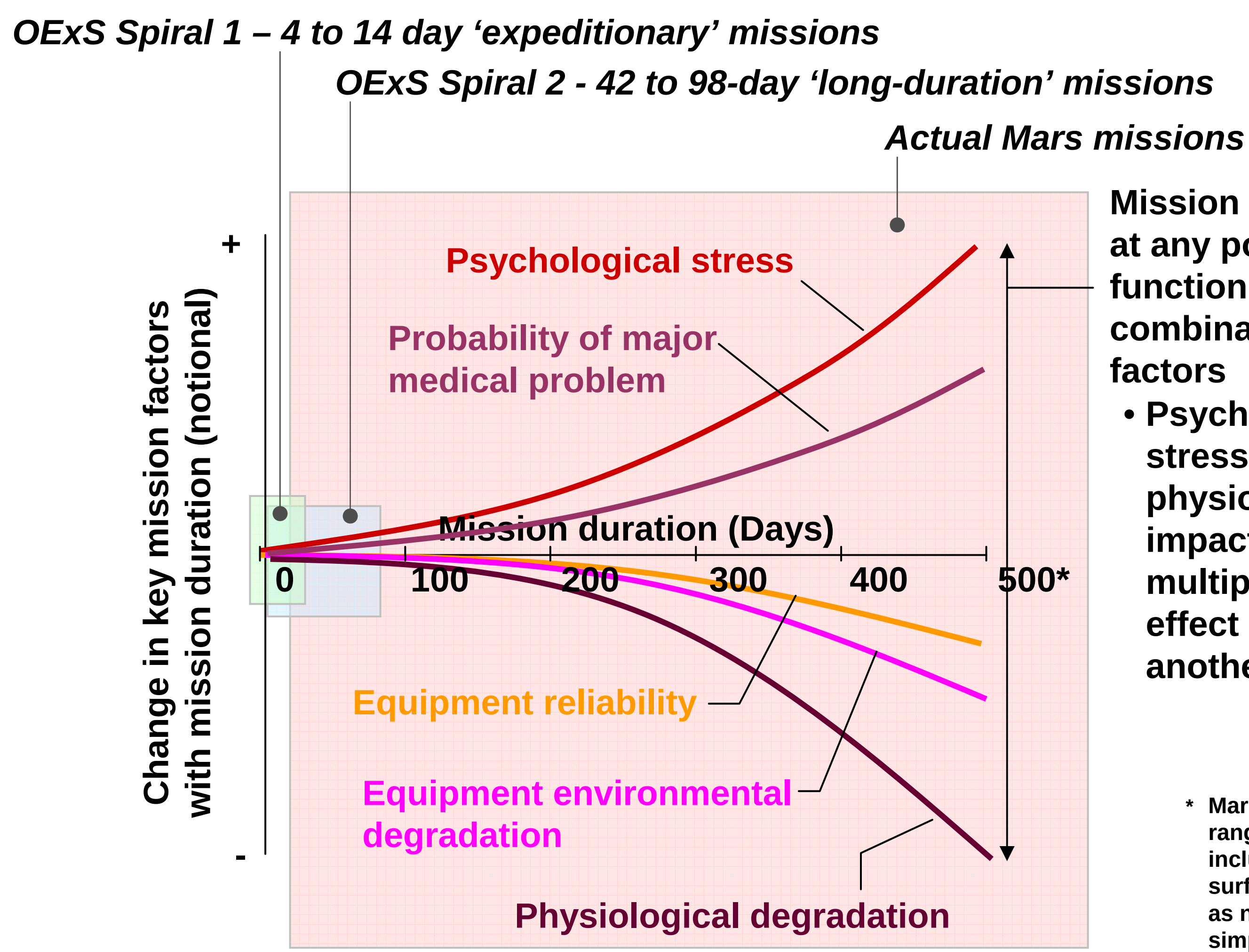
	ISRU Application						Rankings						Relative priority*
	Shielding/ building mat.	Propellant	Life support	Press. vessels	Mfg/parts	Energy	Tech readiness	Robotic appl.	Efficiency	Simplicity	Mission benefits	Mtrl availability	
Regolith	■						▲	▲	▲	▲	▲	▲	1
O_2 (regolith)		■	■				▲	▲	▼	●	▲	●	1
H_2 (regolith)		■	■				▼	▲	▼	●	●	▼	2
$H_2/0_2$ (H_2O ice)		■	■				▼	▲	●	▲	▲	●	1
C (regolith)		■	■				▼	▲	▼	●	▲	▼	2
N_2 (regolith)			■				▼	▲	▼	●	▲	▼	4
Fiberglass/et al	■			■	■		●	▲	●	●	●	▲	2
Molded glass	■			■	■		▼	▲	●	●	●	▲	2
Simple ceramics	■			■	■		▼	▲	●	●	●	▲	2
Complex ceramics					■		▼	▲	●	▼	●	●	4
Metallic Iron (CVD)	■				■		▼	▲	●	●	●	▲	2
Aluminum/Ti/etc.	■				■	■	●	▲	▼	●	▲	●	1
Silicon						■	▼	▲	●	●	●	▲	3
Solar cells						■	●	▲	▼	▼	▲	●	3
^3He						■	▼	▲	▼	●	▼	▼	5

- **Enabler for both human Mars exploration or permanent Lunar settlement/ commercialization**
  - **Self-sufficiency potential well documented**
  - **Near-term challenge to demonstrate performance, reliability, and cost effectiveness**
- **Key architectural driver**
  - **Basing locations**
  - **Power requirements**
  - **Mission durations (slow processes)**
  - **Mass delivered to surface**
  - **Robotics/automation**
- **Significant synergies**
  - **Science and ISRU mapping/ characterization**
  - **ISRU and Testbed activities (e.g., propellants, life support, *etc*.)**

*** CSM / CCACS**

Potential game-changing capabilities warrant incremental demonstration

Exploration Testbed Objectives - Problem Space



Mission effectiveness at any point in time a function of the combination of factors

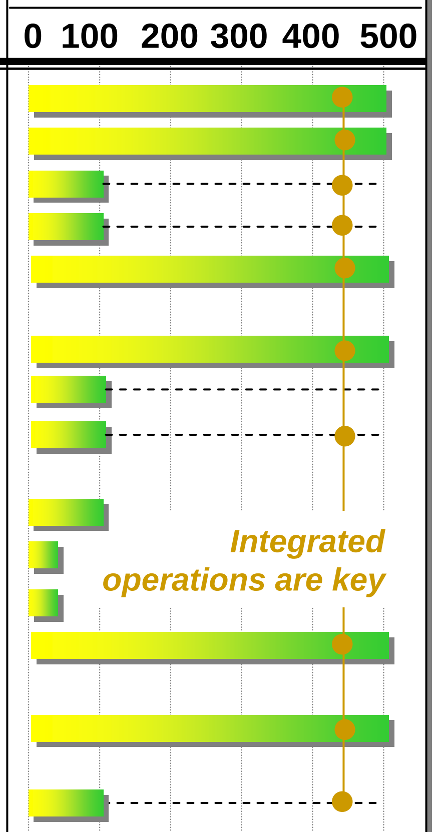
- **Psychological stress and physiological impacts have a multiplicative effect on one another**

* Mars mission may typically range from 400 to 900 days including both transit and surface stay; 500 days used as nominal value for simplification

Long-duration crew and equipment demonstrations necessary prior to Mars

Exploration Testbed Objectives

Testbed objectives	Testbed location*				Testbed duration (days)
	Earth	ISS	Moon	Other	
Crew physiology		P	MR	IS	
Crew psychology	P	P	MR	IS	
Remote mission operations			MR		
Human-robotic collaboration	P	P	MR	P	
Long-duration habitation and surface operations	P	P	MR	IS	
Advanced life support	P	P	MR	IS	
Energy-rich surface power	P		MR		
Extended reach surface mobility	P		MR		
EVA effectiveness	P	P	MR		
Precision landing/launch			P	R	
Navigation/timing	P		MR		
Non-earth logistics, maintenance, and repair	P	P	MR		
Environmental characterization/abatement			MR	R	
ISRU integration	P		MR		



* P=partial test, MR=most representative test, IS=In-space transit test, R=robotic test

- A ‘must’ prior to taking next steps in human exploration
  - Sending humans to Mars
  - Initiating more permanent settlement/ commercialization
- Key architectural driver
  – Mission sequence/ spiral definitions
  – Mission durations
  – Basing strategy
  – Mass delivered to the surface
- Earth and ISS-based testing helpful but not sufficient
  – Moon provides best test-like-you-fly verification

Confidence available only through full-duration, integrated effects simulation

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Relationships of Objectives to LMC's POD

Degree of influence
- (gray) = related
- (black) = driver
- (blue) = primary driver

Key architecture features	Level 0 lunar objectives: Safety	Affordability	Sustainable	Develop tech.	Robotic msn	Mars testbed	Lunar ISRU	Lunar science	Transportation	International	Commercial	Inspiration	Resulting LMC POD baseline
Exploration approach (i.e., expeditionary, testbed, or settlement)	primary driver	primary driver	primary driver	driver	driver	primary driver	primary driver	related		related	driver	primary driver	Testbed exploration-focus (address all objectives simultaneously)
Mission durations	related	related	driver			primary driver	primary driver				related	related	4 to 500 days
Mission timing/sequence		related	driver	driver	driver	primary driver	driver			driver		primary driver	Testbed satisfied by 2023
Crew size	primary driver	driver			driver	driver	related	related	driver		related		4
Robotic/intelligent systems	driver	primary driver	driver	related	primary driver	driver	driver	primary driver				related	Maximized, start in 2008
Basing approach/site	driver	driver	driver	related	related	primary driver	primary driver		related		driver	related	Fixed, equatorial Outpost
Surface access	primary driver		related	related	related	related	driver	driver	related			related	Global access
Safety measures	primary driver	primary driver	primary driver		related	related	related	related	driver		related	driver	Fault tolerance, aborts, etc.
Useable mass to surface	driver	driver	driver	driver	related	primary driver	primary driver	related	driver		driver	driver	70mT HLVs; cryo prop
Surface power		related	related	primary driver	related	related	primary driver				driver		Nuclear preferred
Staging/assy locations	driver	primary driver		driver					driver		related		LEO assembly; LLO staging
Reusable systems	driver	primary driver		driver	related		driver		driver		driver	related	Expendable (TBR)
In-space infrastructure (comm, refueling, etc.)	driver	primary driver	related	related	related		driver		related		driver		Minimized

Testbed and ISRU (vs. Science) are keys to most architecture decisions

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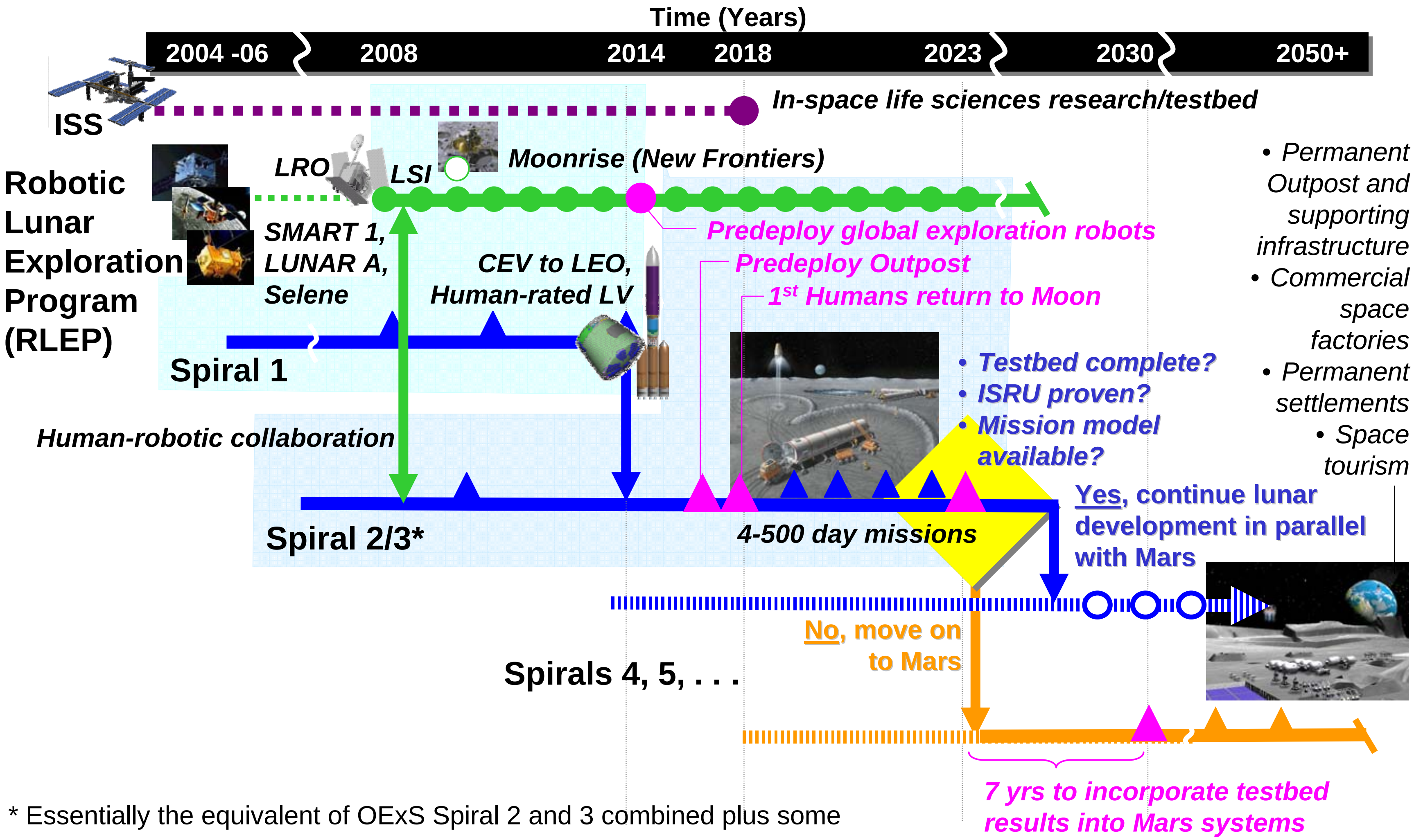
LMC's POD Lunar Campaign/Spirals



* Essentially the equivalent of OExS Spiral 2 and 3 combined plus some

Combined Spiral 2/3 approach addresses <u>all</u> objectives/enables future paths

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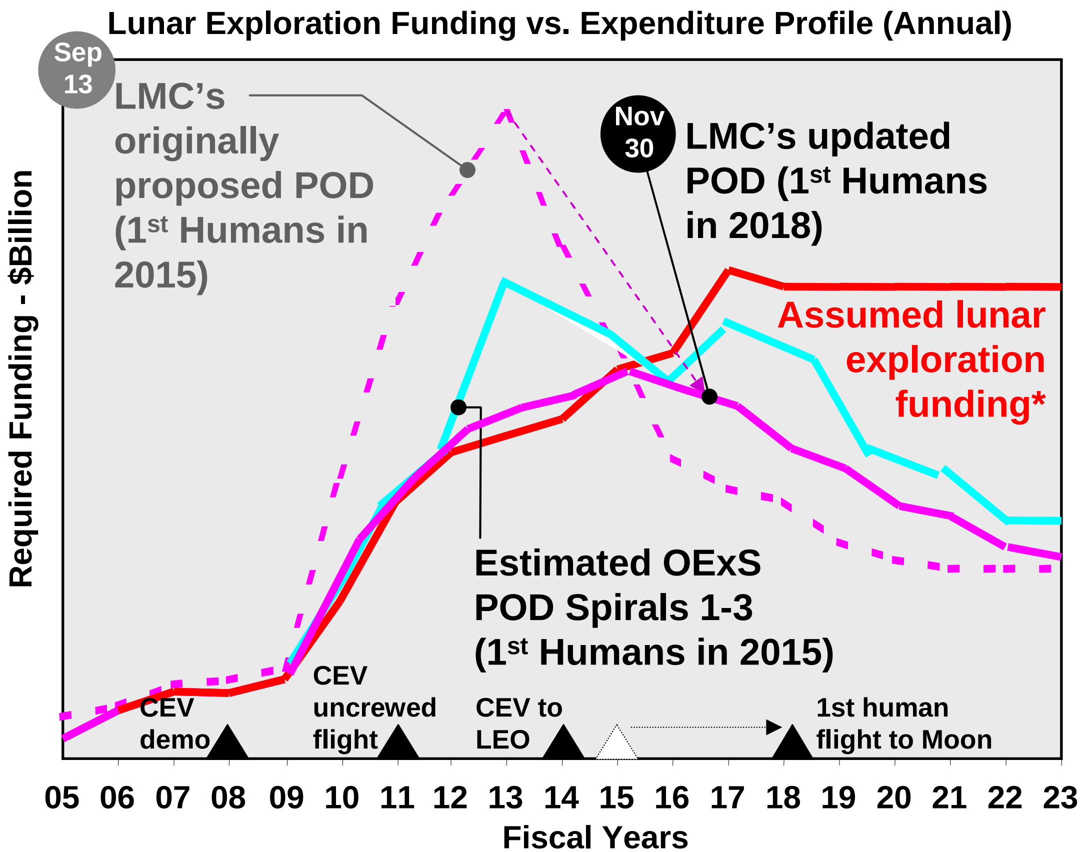
POD Affordability

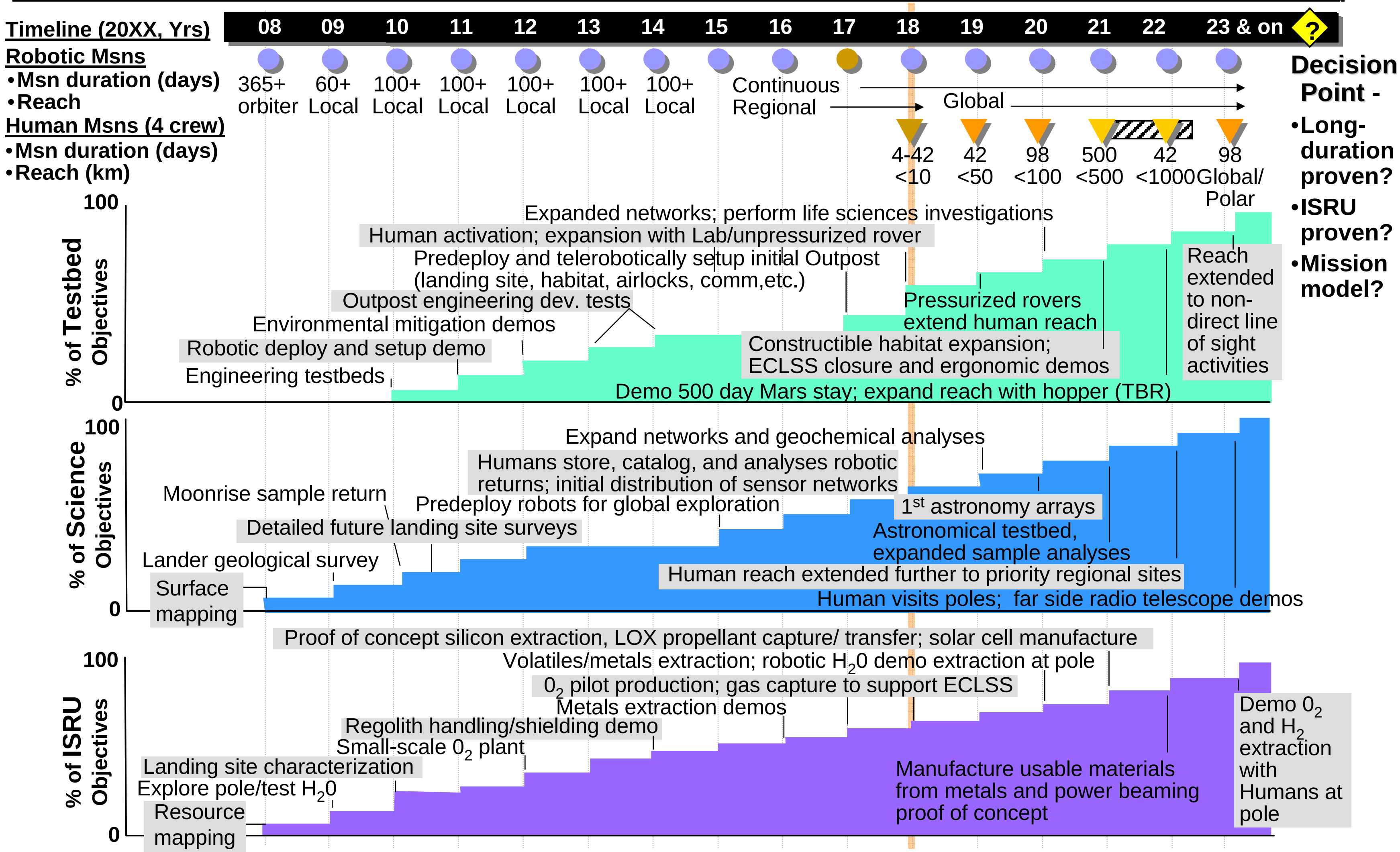


*Human exploration + RLEP less Government funds; no H&RT included to date

- Funding significantly constrained in early years
  - HLV development starts in 2006
  - CEV testing accomplished on existing fleet of LVs
- Delaying 1st human mission to 2017/2018 satisfies 'go as you can pay' affordability constraint
  - Independent of POD
  - Driven by the 2014 milestone
- Sufficient funding available to support LMC's more aggressive approach to objective satisfaction
  - 7 years to incorporate testbed results prior to 1st Mars mission in 2030

POD all objectives in less time while remaining affordable

LMC POD Objective Satisfaction vs. Time



Continuous returns meet objectives, remain affordable, and ensure sustainability

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Architecture Overview/Definition

- Assumptions and groundrules
- POD architecture overview
- POD architecture comparison to OExS POD
- CONOPS definition (transportation, surface operations)
- Top-level development timeline
- Alternatives still to be traded/evaluated

Assumptions and Groundrules (1 of 2)

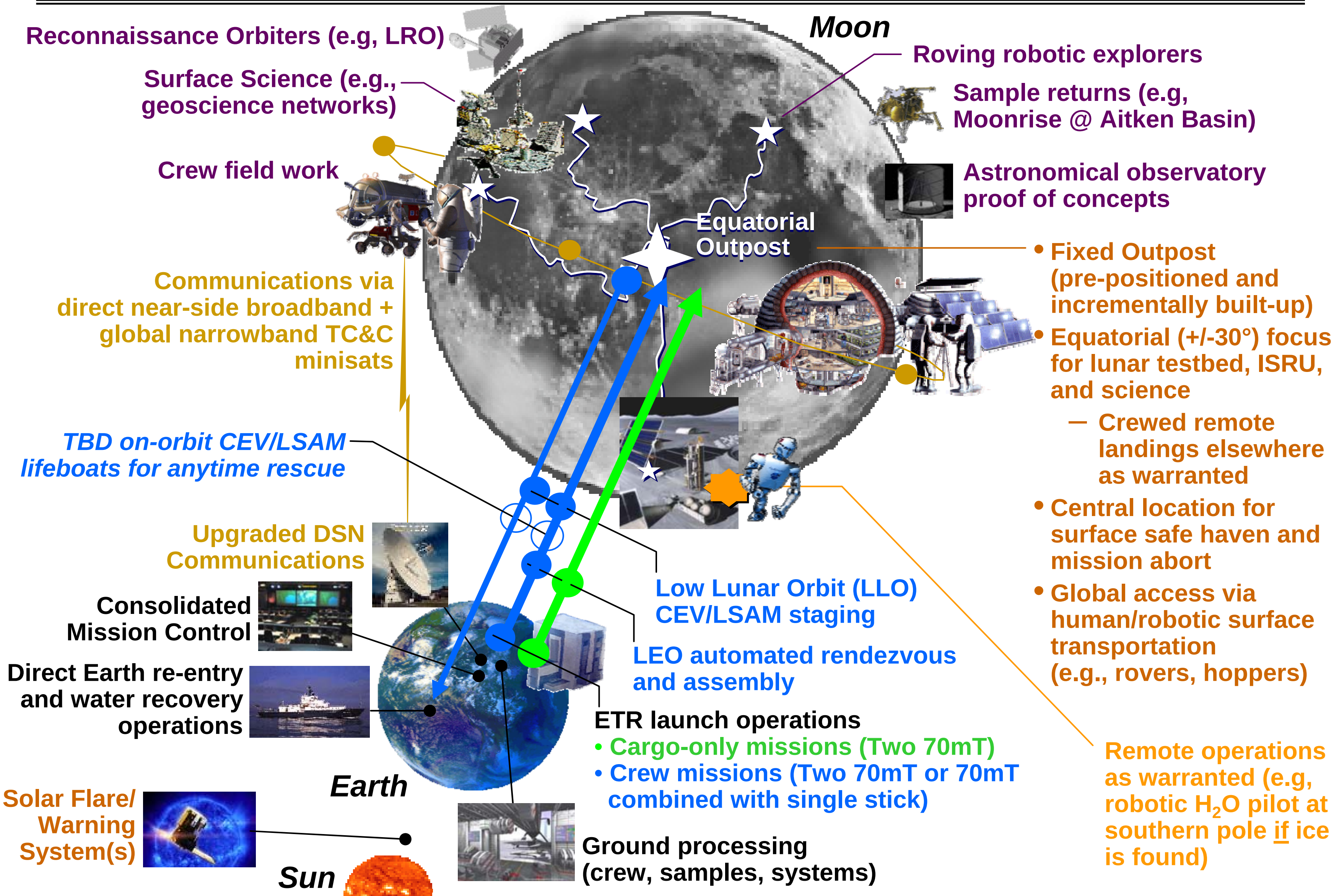
- Develop balanced and sustainable exploration framework
  - Go beyond simply repeating Apollo fifty-years later
  - Apply lessons learned from Shuttle and ISS
  - Maximize amount of usable mass delivered to lunar surface
    - Maximize the payload/transportation system IMLEO ratio
  - Incrementally add to surface infrastructure with each mission
  - Provide continuous returns to address broadest spectrum of stakeholders
- Use combination of CAIV-driven solutions and spiral development to match scope, schedule, and risk to available budget profile
  - Yearly robotic missions start in 2008; yearly human missions including CEV in LEO NLT 2014, Moon between 2015-2020, and Mars NLT 2030
    - Deployment of capabilities sooner is highly desirable
    - Address all objectives and answer fundamental questions within 5 years of human return to the Moon (see objectives discussed earlier)
  - Invest in selective innovative, beneficial technologies
    - Technology at TRL 6 five years prior to IOC
    - Nuclear power acceptable
  - Address total life cycle cost equation at the very start

Assumptions and Groundrules (2 of 2)

- **Simultaneously maximize crew safety and effectiveness**
  - **Satisfy NPR 8705.2a human rating guidelines**
    - **Two-failure tolerance, design for minimum risk, abort and/or safe haven during all mission phases**
  - **Maximize use of robotics/intelligent systems**
    - **Minimize crew size required for effective operations**
    - **Provide global access to Mars/Moon surface**
    - **Minimize the number of missions required to accomplish objectives (e.g., single rover can collect more samples and cover more miles in one year then six Apollo missions)**
  - **Deployment/returns occur day or night at any time during year**
- **Maximize extensibility/evolvability to Mars and Beyond**
  - **Use same exploration approach for both Moon and Mars**
  - **Provide open solutions to accommodate certain change**
  - **Right-size and right-time solutions (e.g., deliver long-term infrastructure elements only after decision is made to whether to stay or not)**

Seeking balanced solution that is sustainable over the long run

POD Lunar Architecture Features (2018-2023)



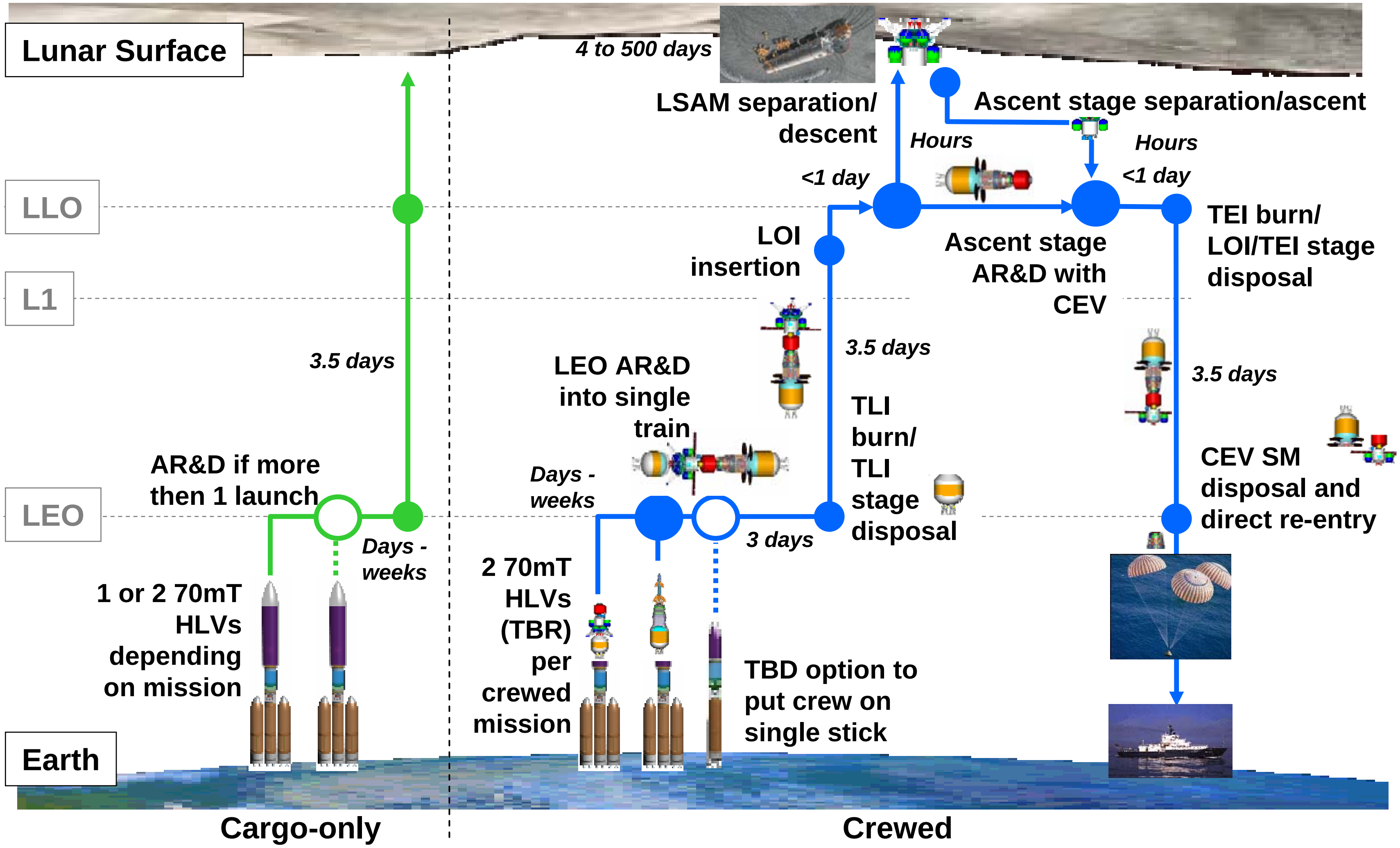
POD Comparison

Key Architecture Attribute		Assumed OExS POD	LMC POD
Exploration approach		Expeditionary/transportation focused, limited testbed later	Balance of all objectives, testbed focus sooner vs. later
Mission duration		4-98 days	4-500 days
Staging location		LLO	Same
Surface access		Global	Same
Primary base location		Southern Pole	Fixed equatorial Outpost
Reusability		None (TBR)	Same (TBR)
HLV	ETO crew/cargo sep.	Yes	Yes
	Size/#of launches	TBD/4+ per crewed mission	70mT*/2 per crewed mission (TBR)
CEV	Crew size	4	Same
	Functionality	Crew to/from LLO; TEI burn	Same except no TEI burn
Transfer	Number of stages	1 (TBR)	2 with TLI, LOI, and TEI burns
	Propellant types	LOX/LH2 or LOX/CH4 (?)	LOX/LH2 (common for all prop)
LSAM	Functionality	Transportation and habitat	Transportation to fixed Outpost
	Configuration	2 stage	2 stage (TBR)
Cargo to surface/crewed mission		0.5mT	~7mT or short duration habitat
Surface systems		Delayed until Spiral 3 post-2020	Predeploy w/1st human mission
Re-entry		Direct re-entry w/water recovery	Same

*Option to launch crew on single stick version of same vehicle

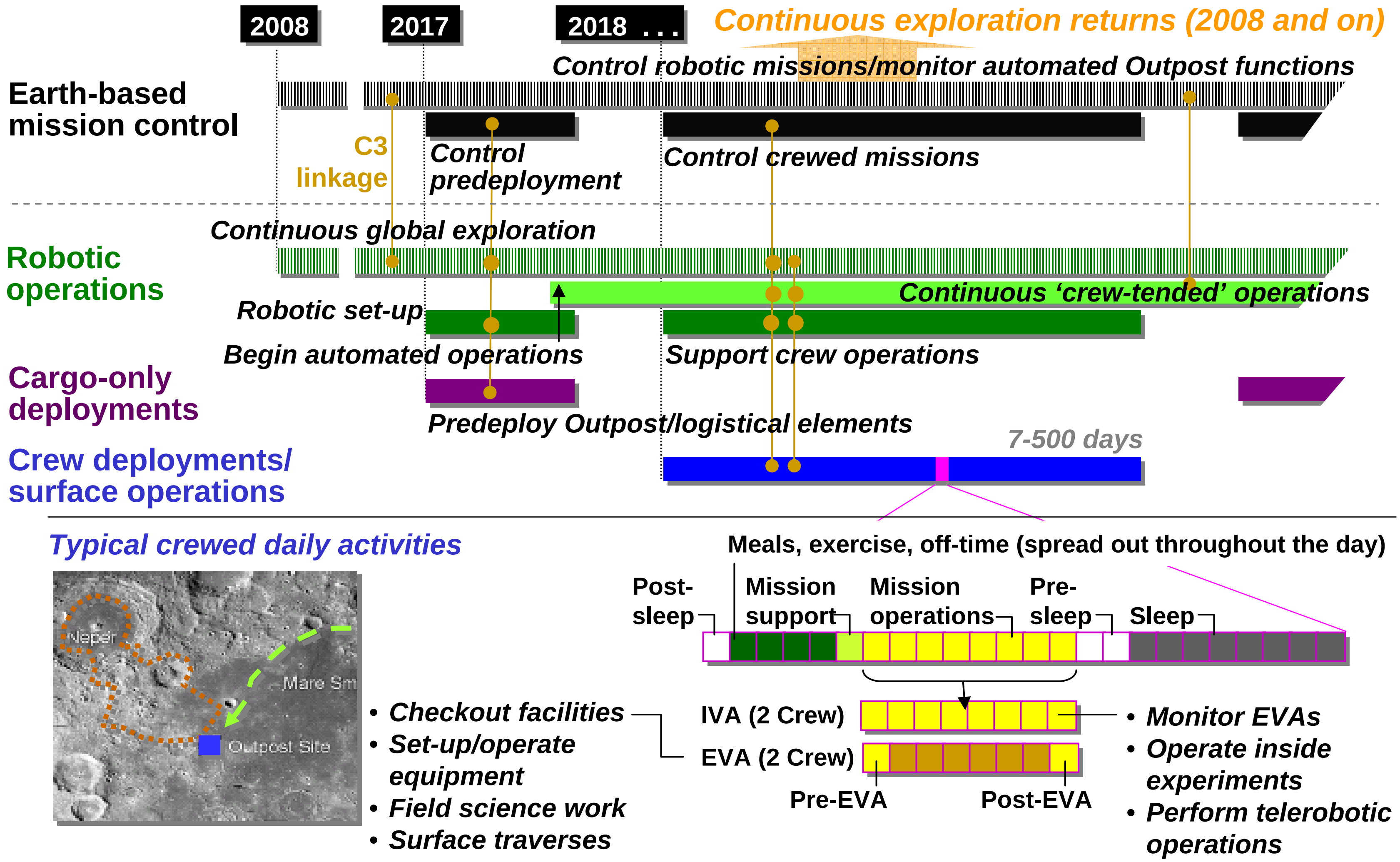
Key differences all primarily relate to basic exploration approach

Transportation CONOPS



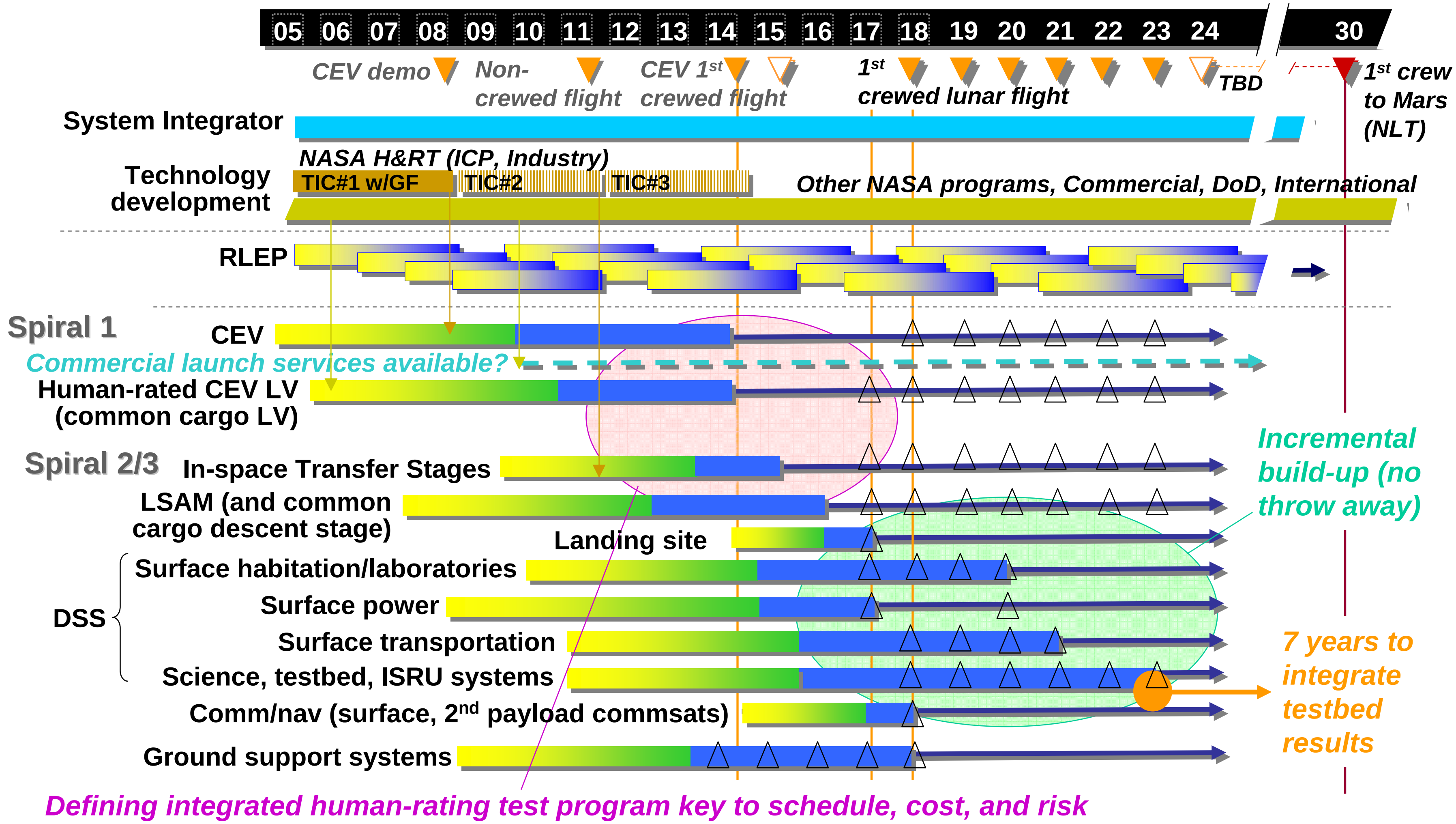
Maximum useable mass to lunar surface within available funding

Surface CONOPS



Continuous returns through robust human-robotic collaboration starting in '08

Top-level Deployment Timelines



Evolutionary incremental development manages risk and funding needs

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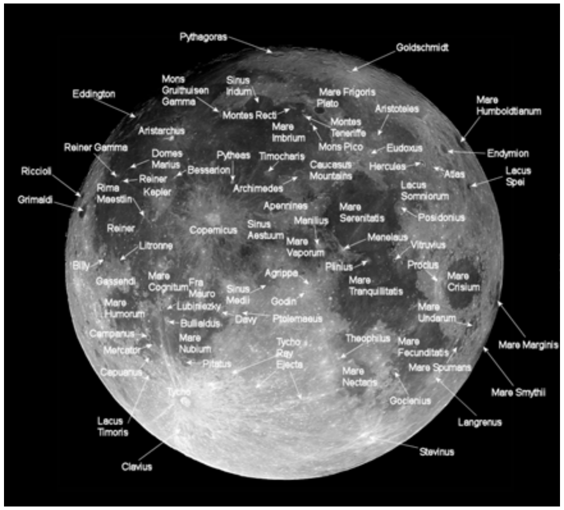
System & Element Requirements

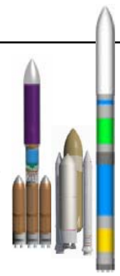
- System and element definitions
- Functional allocations
- Drivers/sensitivities



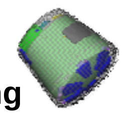
POD (2008-2023) Architectural Systems (1 of 2)

Crew Transportation Systems (CTS)

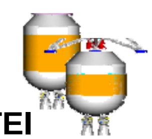
Crew HLV (# of LV/Mission)
- Existing (4 or 5)
- Evolved EELV (2 or 3)
  - *70 mT POD, 24mT crew option*
- Shuttle-derived (2 or 3)
- Clean-sheet (1 to 3)
- Reusables



Crew Exploration Vehicle
- Reference CA-2 Briefing



Departure/Transfer Stages*
- Staging
  - Separate TLI, LOI, TEI
  - TLI/LOI (Separate or combined), TEI w/CEV
  - Optimized 2 stage combination of TLI/LOI/TEI
- Propulsion
  - Chemical (LOX/LH2, LOX/CH4, storables, etc.)
  - Alternative (SEP, NEP, tethers, etc.)



Lunar Surface Access Module (LSAM)*
- Staging (1, 1.5, or 2; using LOI for part of descent)
- Propellants (LOX/LH2, LOX/CH4, Storables)
- Habitat (transportation only, short-term habitat)
- Cargo (minimum for science, maximum possible)

Cargo Delivery Systems (CDS)

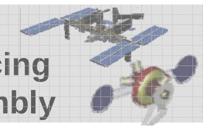
Cargo HLV
- *Common w/Crew*

Departure/Transfer Stages*
- *Common w/Crew*

Cargo Destination Landing System
- Cargo Module
- *Maximum commonality with crew descent stage*

In-Space Support Systems (ISSS)

In-space logistics systems
- Refueling
- In-space servicing
- In-space assembly



Communications/navigation
- Dedicated Lunar constellation @ L1, L2, or LLO
- 2nd payload minisats

Space Environments/ Early Warning Systems

Orbital/access parameters

Assembly locations: none, LEO, L1, LLO
Staging locations: none, LEO, L1, LLO
Transit trajectory: earth-moon plane (free return), other
Surface access: global, partial
Anytime abort access: global, partial
Earth return: direct, aerocapture, LEO

***Currently expendable, reusability being studied**

xxx = options not included in initial POD
xxx = options continuing to be considered

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POD (2008-20230) Architectural Systems (2 of 2)

Destination Surface Systems (DSS)

Basing

- **Fixed Outpost**
  - -Landing site/equipment
  - -Habitats
  - -Laboratories
  - -EVA and airlock (including robotic support elements)
  - -ECLSS
  - -Power (Nuclear primary, regenerative back-up)
  - -Communication/navigation
  - -Logistics support facilities/equipment
- **Alternate Remote Operations**
  - -Integrated habitat
  - -Prepositioned propellants/supplies (TBR)
  - -Prepositioned safe haven capabilities (TBR)

Surface Transportation

- - Manned vehicles
- - Service vehicles
- - ISRU support vehicles (TBR)

Testbed equipment/operations

Science equipment/operations

ISRU equipment/operations

Ground Support Systems (GSS)

Certification & Training

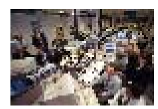
Launch/ Abort

Recovery Operations

- - Water and/or Land

Logistics Support/ Maintenance

Mission Operations



Planetary Surface Operations

Communications Operations (e.g., DSN)

Science/ Outreach Networks

TBD Unique Test Facilities

Robotic Precursor Systems (RPS)

May include comm 2nd payload

2004 – SMART 1 (ESA)
2005 – Lunar A (Japan)
2006 – Selene (Japan)
2008 – LRO I*
2009 – LSI
2010 – Moonrise* (New Frontiers)
2010 – Landing site survey/ environment characterization
2011 - Outpost engineering tests I
2012 – O_2 demonstration
2013 – Outpost engineering tests II
2014 – Regolith handling/shielding demo
2015 – Global robotic explorers I*
2016 – Metals extraction demo*
2017 – LRO II*
2018 – O_2 prototype production
2019 – Materials extraction demo I
2020 – South pole H_2/O_2 extraction
2021 – Global robotic explorers II*
2022 – Materials extraction demo II
2023 - Materials extraction demo III

XXX = options not included in initial POD
XXX = options continuing to be considered

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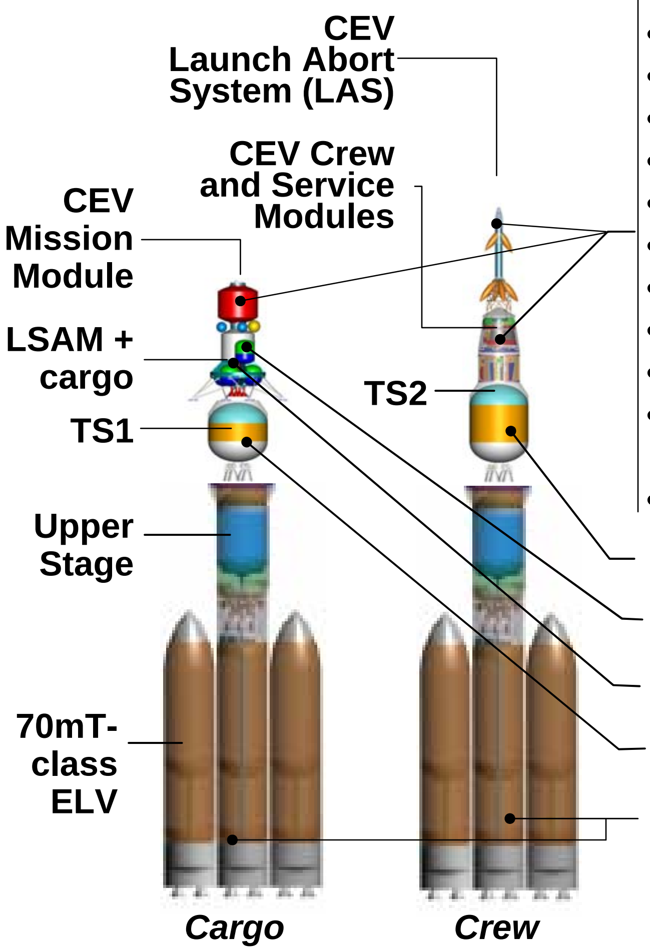
Example Functional Allocations - CTS



- Safe abort during ETO (prior to Upper Stage ignition)
- Crew transfer/abort during ETO
- Mission command, nav, and control from LEO to/from LLO
- Communications
- ECLSS, power, and IVHM
- Close proximity maneuverability
- Autonomous rendezvous/docking with rest of transfer train
- Radiation/solar particle event (SPE) safe haven
- Contingency EVA provisions
- Mission-unique support elements
- LEO orbital maneuver capability and/or destructive re-entry *(TEI burn moved to Transfer Stage 2)*
- Earth re-entry and recovery

- Transfer Stage 2 (Remaining 60% of TLI, LOI, and TEI burns)

- Crew transportation to/from CEV in LLO to Lunar Surface

- Cargo (nominally) or short-term hab depending on mission

- Transfer Stage 1 (1st 40% of TLI)

- ETO propulsion (including circularization)
- IVHM, engine-out, trajectory shaping during ascent for abort, and rapid crew egress while on pad for safety/human-rating

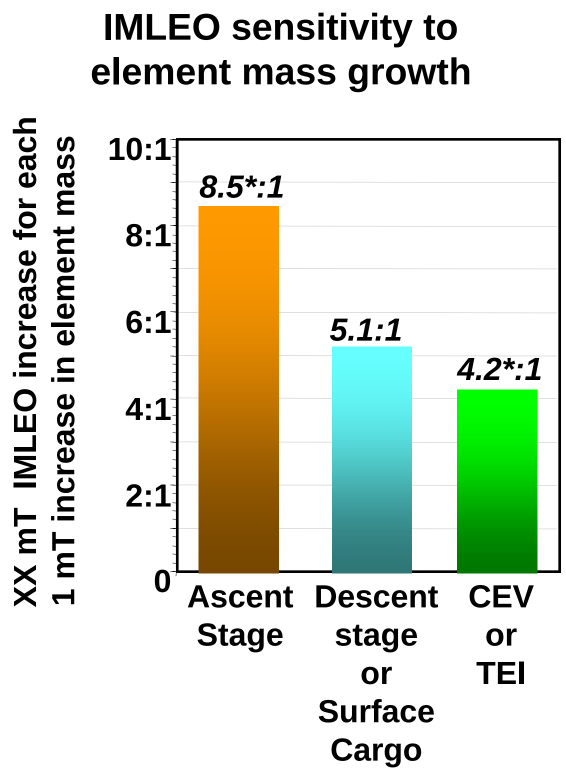
Crew and cargo separation on most cost-effective launch solution

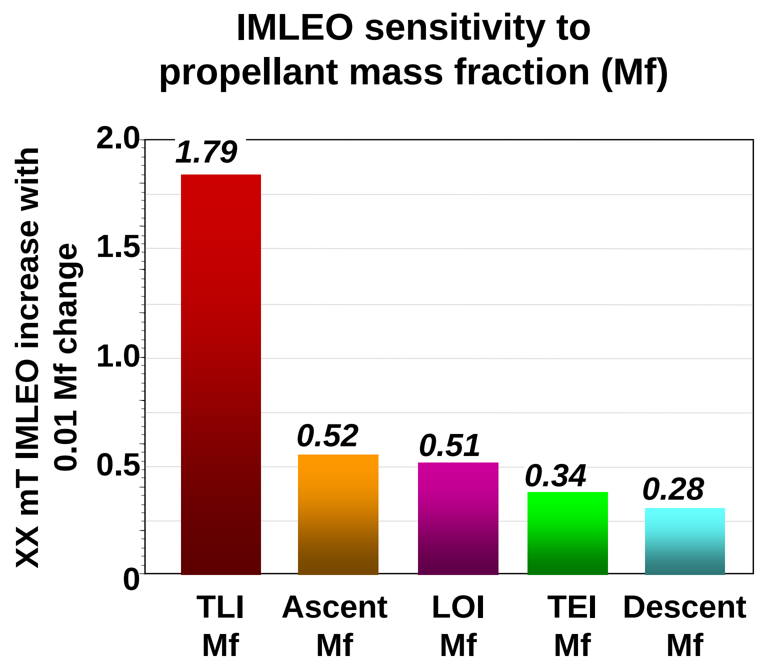
Example Functional Allocation Trade – TEI Delta-V in CEV vs. Transfer Stage

FOMs	Options for Lunar Exploration Approach		
	TEI separate stage	TEI integrated in CEV SM	TEI integrated with LOI
Crew survivability	Smaller CEV has more LV options; added hazards	Heaviest CEV has fewest LV options	TEI always with CEV; smaller CEV has more LV options
Reliability	Likely requires new (unproven) mid-sized engine development; TEI backs up LOI	Likely requires new (unproven) mid-sized engine development; TEI backs up LOI	Engines fired for LOI provides added confidence at TEI; common with proven RL-10 engines
Contingencies	Some abort to orbit capability if launched with CEV	Some abort to orbit capability	If launched with CEV, large stage with higher T/W provides best abort to orbit
Mass (mission effectiveness)	Smaller size results in decreased mass fraction	Allows significant cargo to surface	Slight increase in cargo by eliminating LSAM launch support; better mass fraction
Extensibility	Smaller stage available for wide variety of future missions/architectures	Size and integration in CEV makes it inflexible to lunar architecture variations	Common with stages used by commercial;DOD; adjusts to lunar architecture variations
Affordability	Additional NRE, possible new engine development, additional mgt costs	Likely to require new mid-size engine development	Fewest stages; engine, tanks, and propellants common with ETO upper stage
Development risk	New development; potential to share descent stage development	High-risk that CEV will be continually perturbed by fluctuations in TEI delta-V and mass requirements	Minimum given common design and CEV decoupling; requires long-term cryo storage for extended mission

Decoupling TEI simplifies the CEV and reduces development risk

Two Example Sensitivities Relative to Space Transportation Factors Impact on IMLEO





* Sensitivities are for POD LLO solution and would change for L1, e.g., 8.5:1 for ascent changes to ~14:1 and 4.2:1 for CEV changes to ~3.3:1. Breakeven mass point for LLO and L1 solutions is where CEV mass = ~ 5 x total LSAM mass.

Understanding transportation sensitivities key to optimizing solution space

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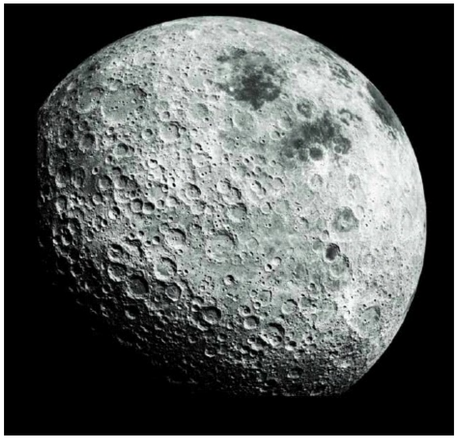
Key Trades and Analyses Results

- Architecture-level
  - Safety/human-rating analyses
    - Anytime abort-to-earth
  - Lunar surface basing location
  - Earth re-entry/landing
- CTS
  - In-space propulsion (i.e., path-to-moon)
    - Propellant types, staging location, reusability, LSAM configuration
  - ETO launch vehicle trade
  - CEV size/mission duration
- Surface Systems
  - Advanced life support systems
  - ISRU O_2 production
  - Rover studies
- In-space Support Systems
  - Communication/navigation



Safety/Human-Rating – Unfinished Business

Architecture applicability	ETO/ LEO	LEO- LLO	Lunar Descent	Lunar Surface	Lunar Ascent	LLO- Earth	Re-entry/ recovery
# of hazards (out of 160)	94	64	45	38	41	51	53
Mitigations/ responses							
- Design for minimum risk	hatched	hatched	hatched	hatched	hatched	hatched	hatched
- Crew I/f and work load	green	green	green	green	green	green	green
- Testing	yellow [3]	green	yellow [3]	green	yellow [3]	green	yellow [3]
- Design margins	hatched	hatched	hatched	hatched	hatched	hatched	hatched
- Failure tolerance	yellow [5]	hatched	hatched	hatched	hatched	hatched	hatched
- P(crew survival)	green						
- Repair		green		green		green	
- Abort*	hatched	hatched	hatched	yellow [4]	red [2]	red [2]	red [2]
- Escape	← Escape systems are not used throughout the architecture →						
- Safe haven		green		green		green	red [2]
- Rescue	red [1,2]	red [1,2]	red [1,2]	red [1,2]	red [2]	red [2]	red [2]

(hatched) = items with reasonable solutions based on contractor interpretations; need gov't concurrence

*Required from 'launch pad to lunar surface' per ESMD-RQ-0013 CTS0110G

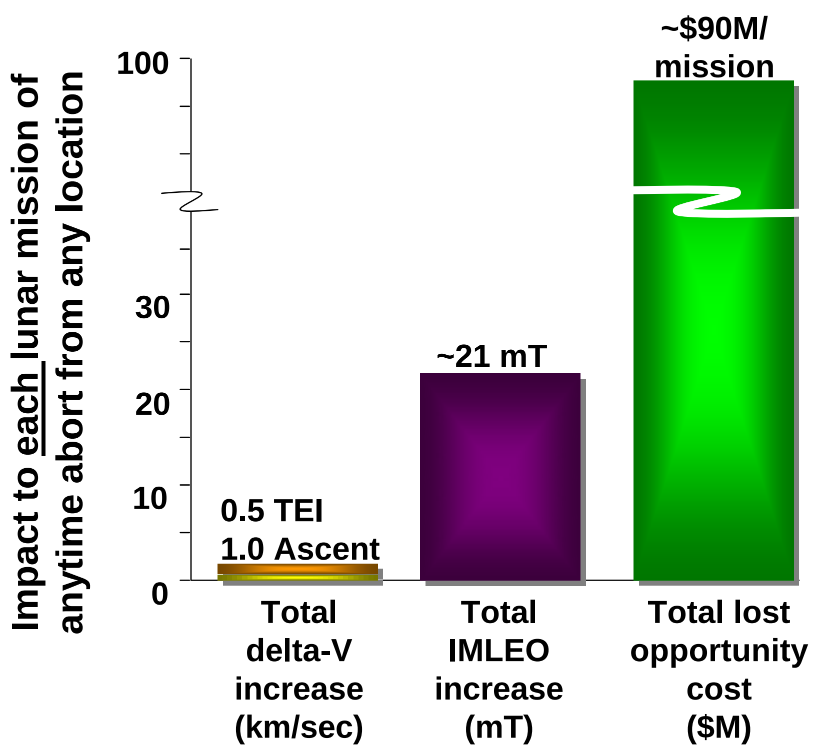
Concerns

1) EMSD-RQ-0013 CTS0405G requires unmanned rescue to LLO and surface.
   - Requires either launch on demand or CEV and LSAM on-orbit storage
2) NPR 8705.2a App D indicates need for abort, safe haven, or rescue during all phases
   - Same as #1 plus need solutions for re-entry
3) Ability to adequate test new LVs and propulsion stages is a concern
4) CTS0110G requires CTS anytime abort from surface; driver depending on surface destinations
5) Use of abort to meet two failure tolerance; TBD if this is acceptable

Architecture selection dominated by 'interpretations' of safety concerns

Anytime Abort-to-Earth*

~ Worst case anytime abort-to-earth impact for mid-latitude and near-polar surface sites



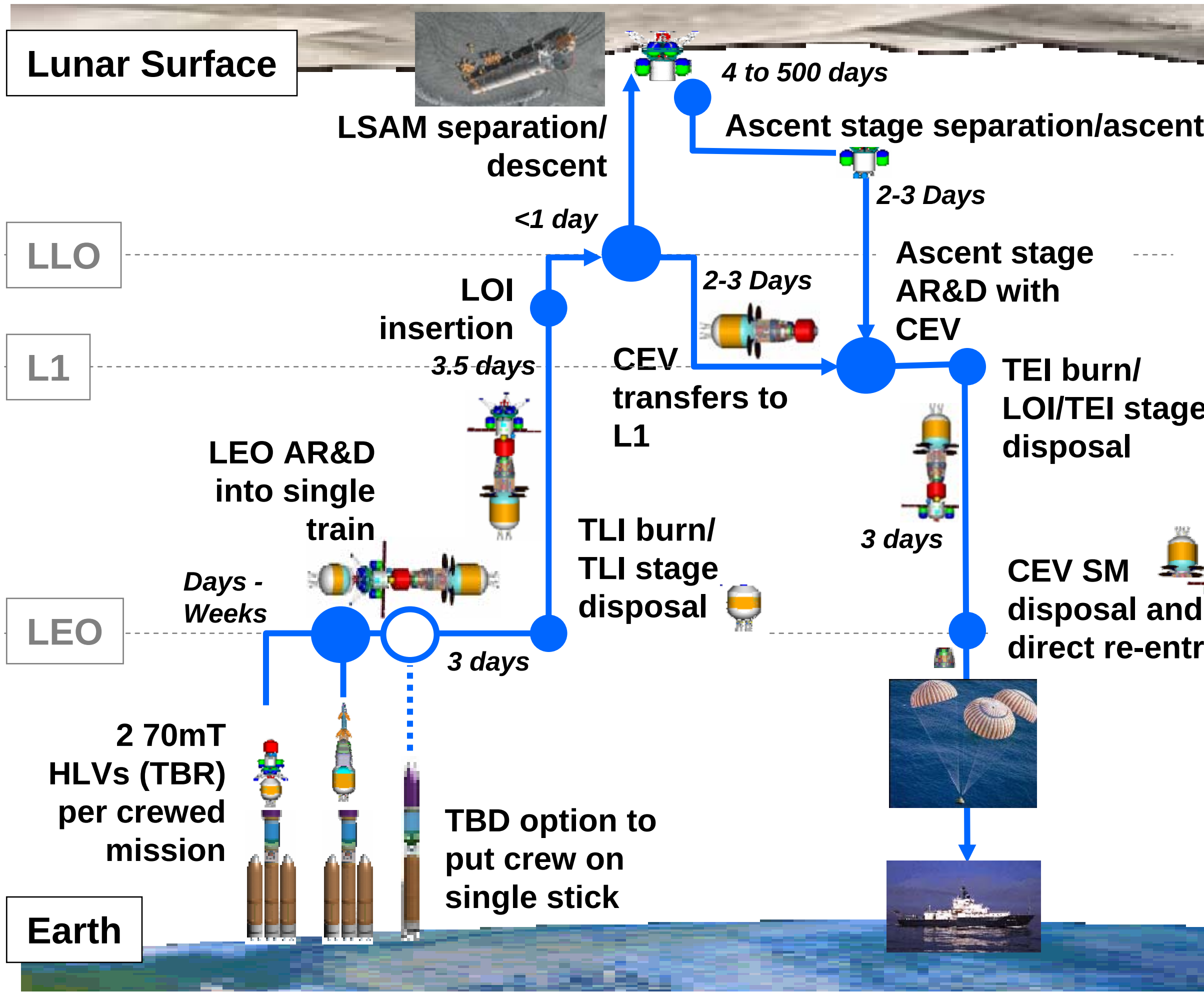
* 1) Return from lunar orbit/surface independent of orbital alignment is required by CTS0110G and was a major driver in POD trade studies.
2) NPR 8705.2a calls for abort, safe haven, or rescue during any mission phase.

Recommendations:

- **Abort-to-surface safe haven is first option**
  - Safe haven approach proven acceptable in Antarctica Station
  - Avoids significantly penalizing each mission
  - Avoids substantial IMLEO/lost opportunity cost impacts
  - Can arrive at safe haven within <3 hrs
- Utilize anytime abort-to-Earth **from equatorial region with no delta-V impact** if surface safe haven not sufficient
- Implement on-orbit 'lifeboats' concepts if rescue is required
  - May not be needed for equatorial Outpost
  - Could be deployed prior to undertaking non-equatorial missions

Anytime abort-to-earth may be a costly design solution

Example Alternative Approach to Anytime Abort From Any Surface Location



- Provides true anytime abort from any lunar surface location regardless of latitude
  - Eliminates any return restrictions but adds 2 days of travel time
- Slight modifications required
  - Requires slightly more robust Ascent Stage
    - Carries 4 day habitat
    - Adds delta-V to get to L1
  - Minor TEI increases to move CEV to L1
- 12mT total IMLEO impact (~50% of worst case LLO abort-anytime-to-earth)

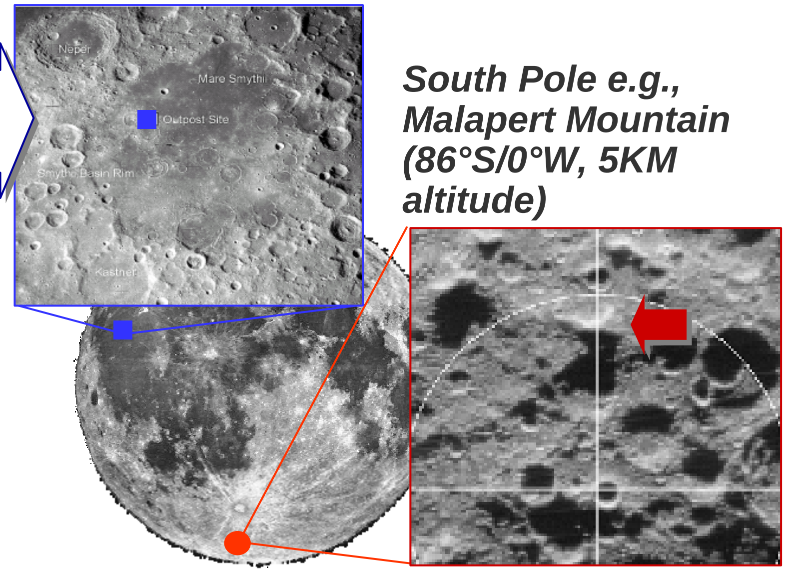
If anytime abort is a requirement, is there a better way?

Primary Base Location - Equatorial Site

- **Most Mars-like environment/exploration strategy**
- **Maximum mass to surface; any orbit accessibility**
- **Maximum safety**
  - **Anytime abort with no added delta-V**
  - **Safe haven/abort option from global expeditions**
  - **Large mares excellent for landing sites**
- **Abundant ISRU possibilities**
  - **Regolith provides for efficient O_2 production**
  - **Ilmenite mining sites (H and Ti)**
  - **Pyroclastic deposits (Fe, Mg, Cu, Pb, Cd, Te)**
  - **KREEP minerals for industry, agriculture, etc.**
  - **Anorthosite (Al metals or rocket fuel; fiberglass, glass, and ceramic products)**
  - **Calcium metal (conductors, easy to machine)**
- **Location for majority of priority science (69% of 61 top science sites within +/- 30º)**
  - **Most primitive lunar rocks**
  - **Unusual volcanic features such as vents**
  - **Volatile history (H, ^{3}He) and traps (e.g., dark halo craters)**
  - **Crater ejecta history (Fe, Mg, Ti in mare basalts)**
  - **Limb sites for maintaining far-side observatories**
  - **Equatorial sites enhance interferometric imaging (i.e., celestial objects never rise or set at poles)**
- **Full-sky viewing w/100% Earth comm coverage**

Equatorial e.g., Mare Smythii (1.7°N/85.8°W)

South Pole e.g., Malapert Mountain (86°S/0°W, 5KM altitude)



- ***Polar site chases potential Hydrogen but . . .***
  - ***Uncertain existence***
  - ***Extraction in extreme terrain/cold***
  - ***May add years to exploration timeline***
- ***Crew locations likely 10-100's km away from potential H deposits, astronomy cold traps, and Aitken Basin (i.e., robotics required)***
- ***Near-constant illumination but . . .***
  - ***Only on mountain tops***
  - ***Low grazing angles unfriendly to crew vision, shadows, energy efficiency***
- ***Only 70-90% comm w/o satellites***

Primary Base Location – Equatorial Site

FOMs	Options for Lunar Exploration Approach	
	South Pole (e.g., Malapert Mountain)	Equatorial (e.g., Mare Smythii)
Safety/Mission Success	Very treacherous terrain, no anytime abort without significant mass impacts	Minimizes hazards; lunar surface first option for safe haven; anytime abort w/o penalty
Mission Effectiveness		
Testbed	Conditions are either milder or worse then Mars	Location, environment, and exploration strategy most representative of Mars
Science	Near <5% of top sites; Aitken Basin distance/size requires robotics to explore regardless of base location	Access to 69% of top sites and all terrain types; preferred for some astronomical observations
ISRU	High H concentrations but uncertain ice; other resources limited	Access to all resources except potential H_2O; O_2 plentiful w/easier extraction/processing
Mass	Significant impact of anytime access and abort	Maximum mass to surface; no anytime abort penalty
Extensibility	Milder continuous sun location may be best for permanent lunar settlement	More mars-like conditions make system/technology more extensible to Mars
Affordability	Added $ for comm, extreme cold/dark conditions, throwaway expeditions	Lowest cost solution for equal scope
Sustainability	Interesting concept; *extreme conditions and/or no ice add yrs to timeline*	Capable of providing most returns for $; Apollo-like issue to contend with
Development risk	Possible to mitigate day/night issue but only in very selected sites	Must develop systems to contend with lunar day/night

Site selection close given unknowns: Equatorial site has more positives

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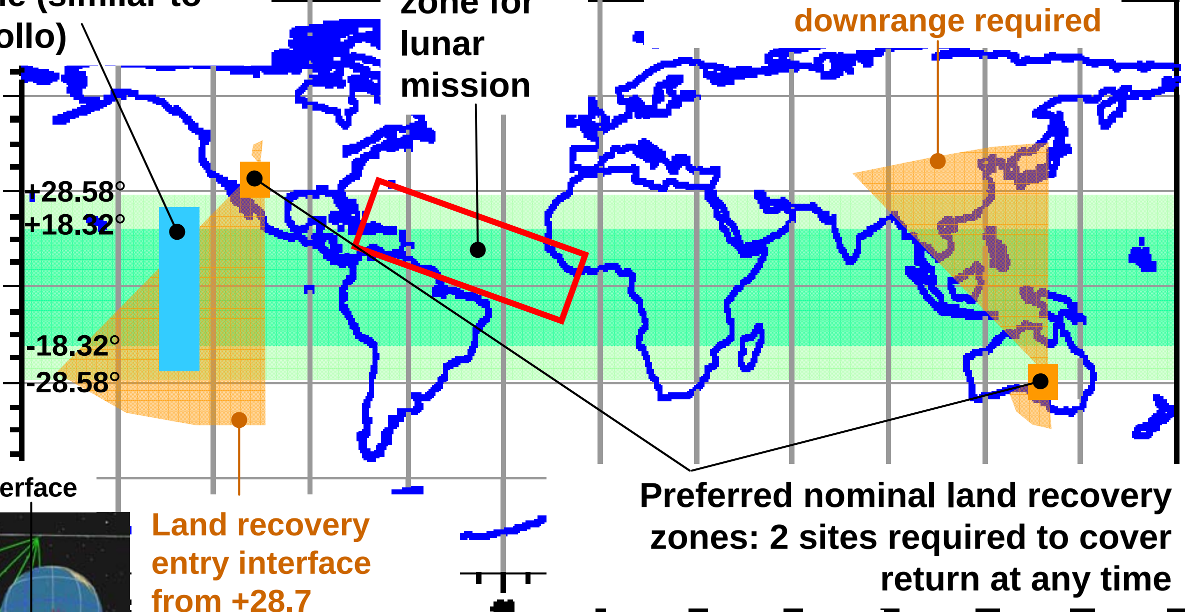
Landing Site – Water vs. Land

Preferred nominal water recovery zone (similar to Apollo)

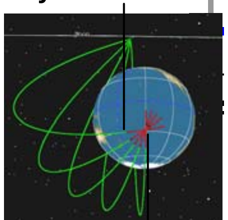
ETO abort zone for lunar mission

Land recovery entry interface from -28.7 declination, ~11,000 km downrange required



Preferred nominal land recovery zones: 2 sites required to cover return at any time

Entry interface



Vacuum perigee

Land recovery entry interface from +28.7 declination, ~11,000 km downrange required

Note: Recovery area for low Lunar latitude departure sites occur within oscillating latitude boundaries ±18.32° and ±28.58° (Period of boundary oscillation is 18.6 years)

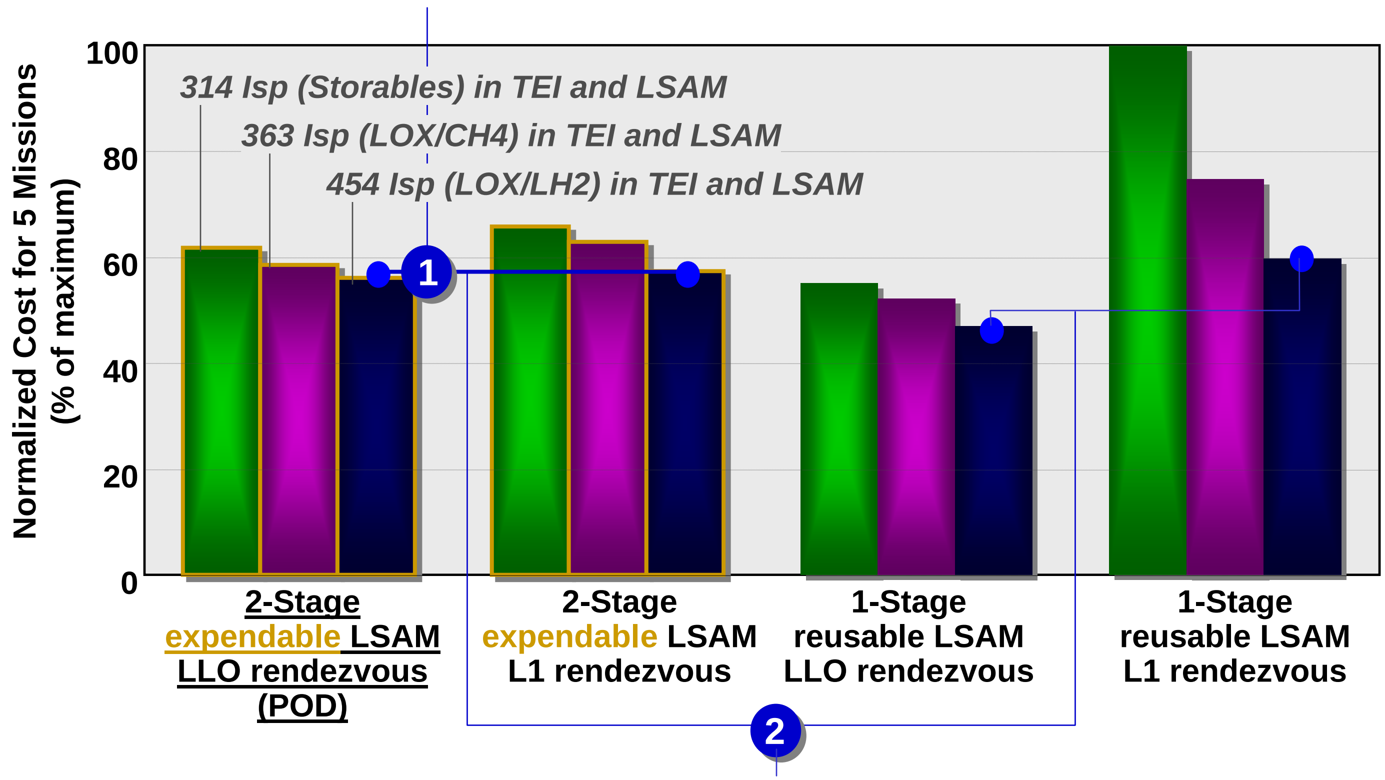
Water recovery is the initial preferred solution

- Requires simplest/ lowest risk CEV design (L/D<0.5)
- Single zone covers all seasonal/daily planned arrivals
- Slight increase in ops costs offset by lower design CEV costs
- Minimizes over flight/ stage disposal concerns
- Maintains potential for passive abort
- Water landing required for abort operations
- Flight rate does not warrant reusability (TBR)
- Avoids ~260m/s delta-V addition to TEI for polar earth return trajectory

Initial results indicate water landing is preferred approach (TBR)

Path-to-Moon – Interim Summary Results

Gross mission costs for expendable LSAM solutions are lowest at LLO but L1 only 3% higher

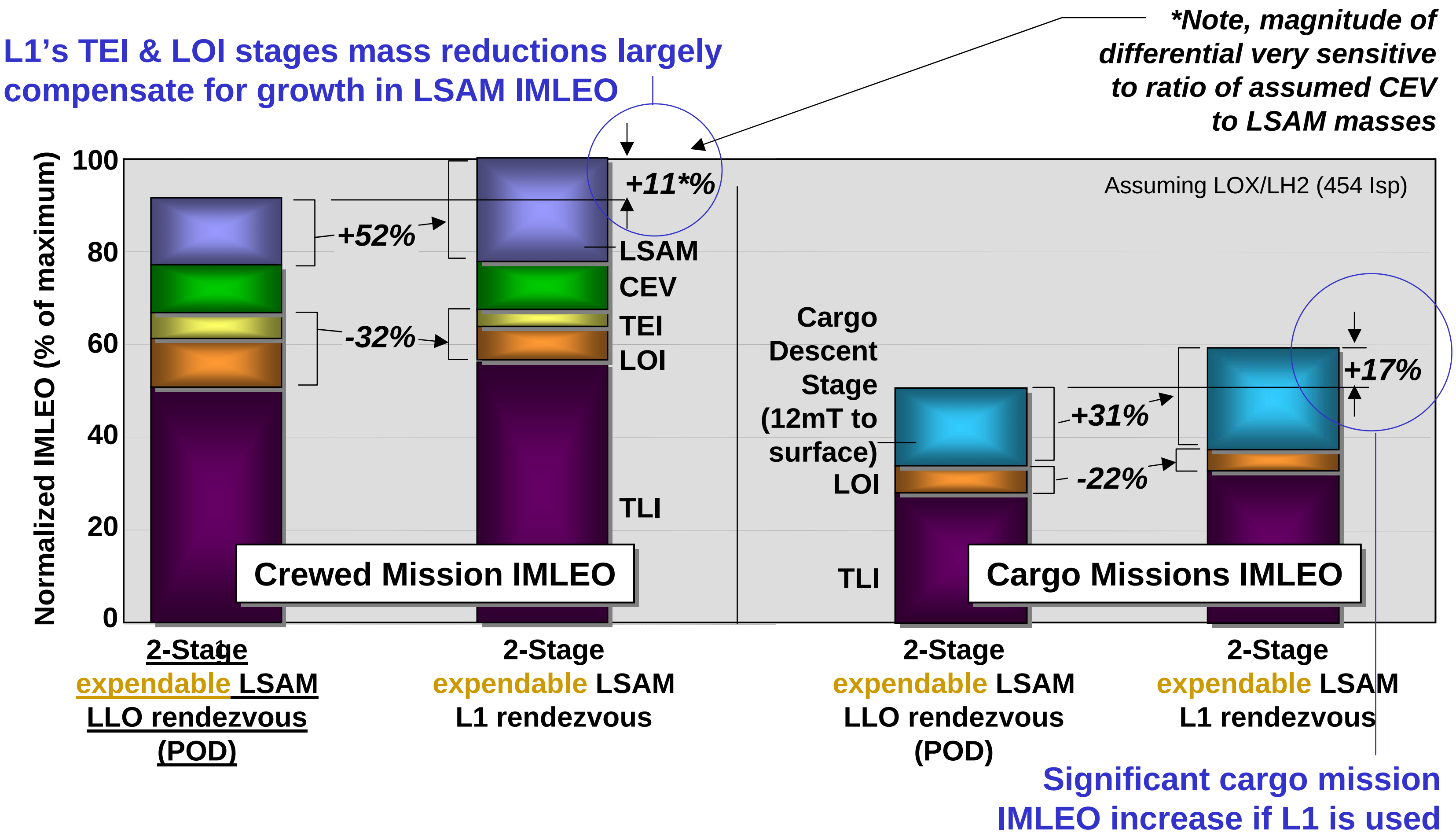


- Cost includes RE for ETO LV, TLI, LOI, TEI, CEV, and LSAM + NRE delta for LSAM reusability
- LOX/LH2 used for TLI & LOI stages
- TEI, ascent, and descent stages use indicated propellant (with different mass fractions)

Reusable LSAMs are cost competitive with expendables (reusable LSAM at LLO least costly option of all)

Expendable LLO optimum but reusability and L1 surprisingly competitive

Path-to-Moon – LLO vs. L1 Mission Mass

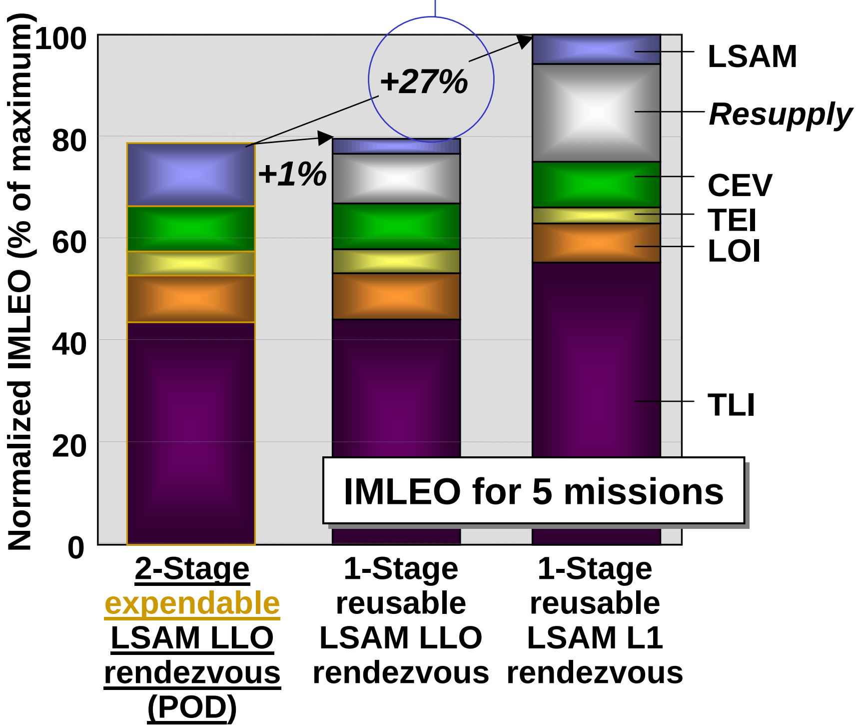


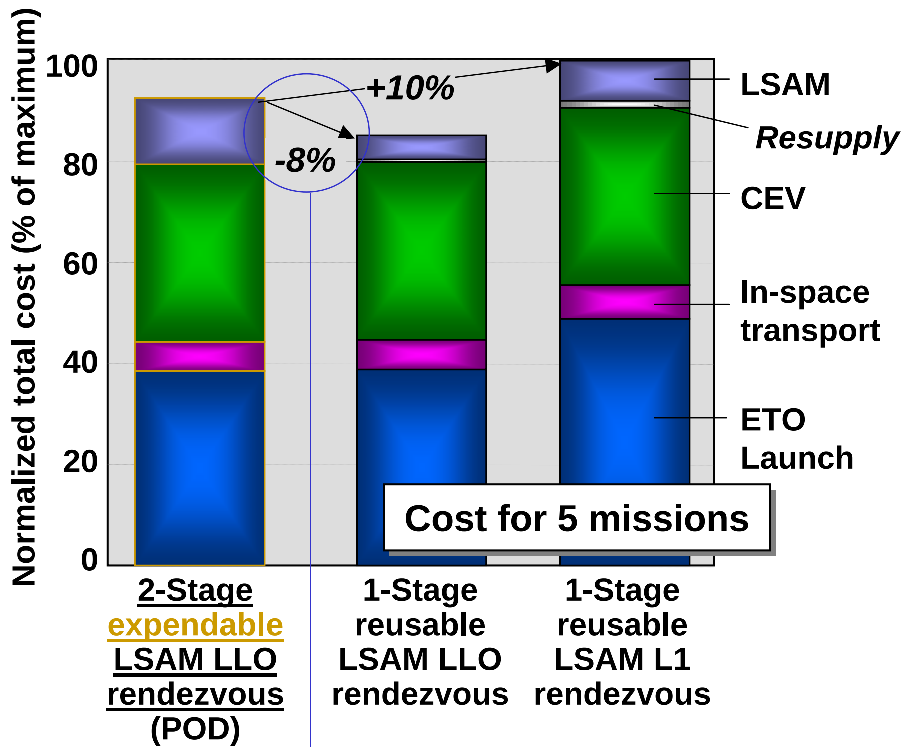
Mass differentials still favor LLO path

Path-to-Moon – IMLEO and Costs of Reusable vs. Expendable LSAM

Crewed missions assuming LOX/LH2 (454 Isp)

L1 increases the IMLEO significantly relative to LLO alternatives



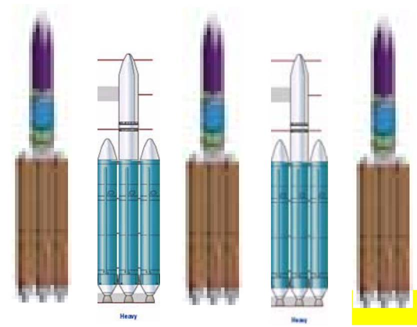


Recurring cost savings of four LSAMs makes reusable LSAMs cost competitive with expendable LSAMs

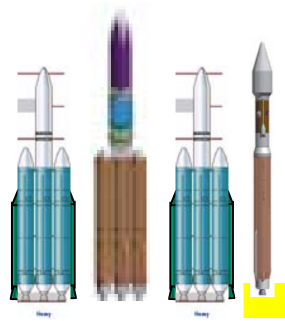
Reusable LLO solution may make sense from mass/cost perspective*

*** Interim analyses; final recommendation must consider other factors (e.g., safety, operations, etc.)**

ETO Launch – Current Trade Space



Option 1: Existing ELVs



1a: Existing/ modified ELVs

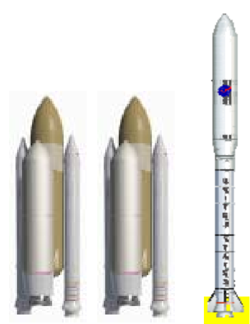
2: Option 2b w/single stick

2a: Option 2 w/ IMLEO match

2b: 70mT-class ELV (Atlas/ Delta)

3: 135mT-class ELV (Atlas/ Delta)

4: Shuttle-derived



5: Hybrid ELV/ Shuttle-derived

6: Clean-sheet

7: Hybrid

Current LMC POD

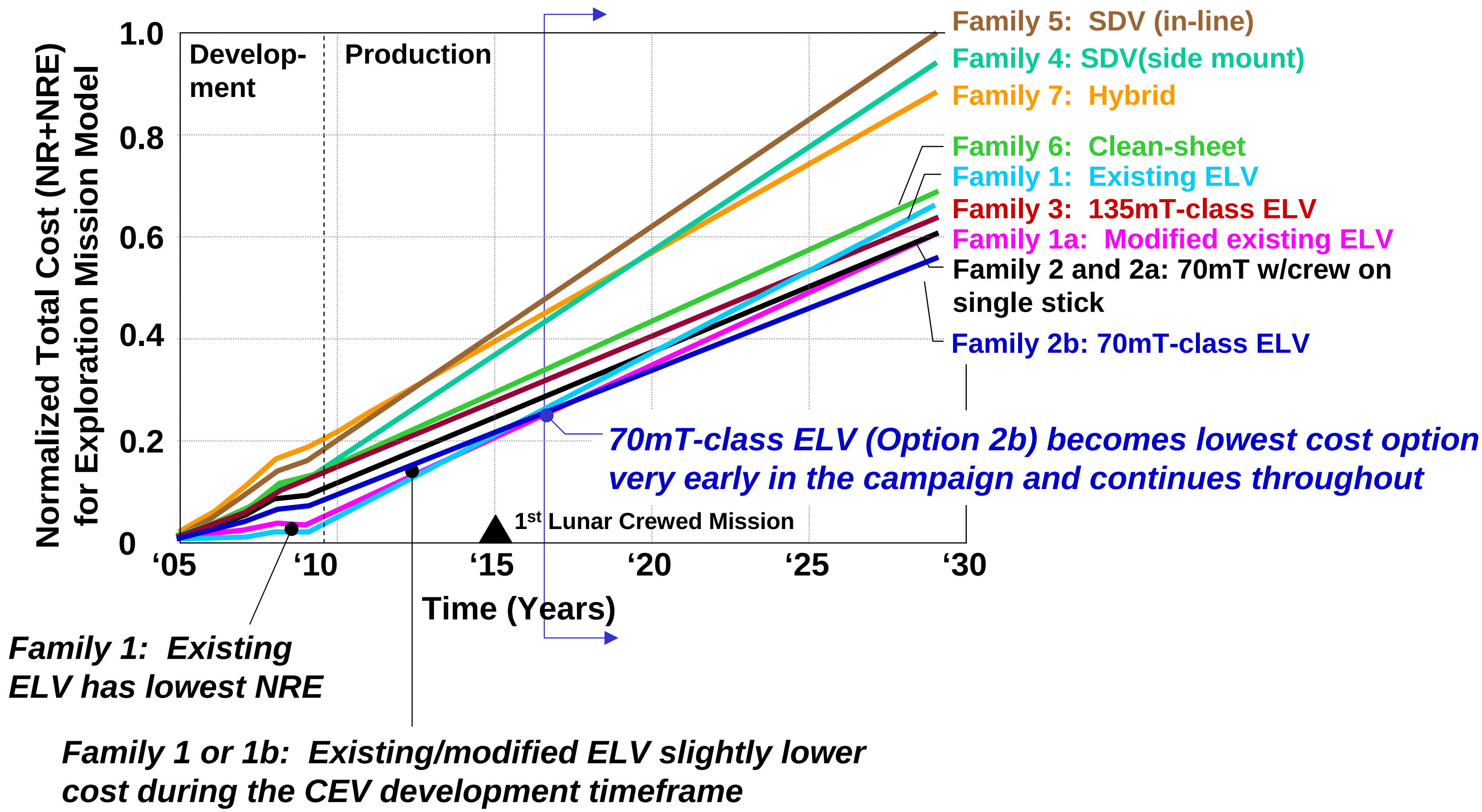
Current preferred "single stick" crew option

Notes:

- Crewed LV highlighted in yellow

Trade to be expanded to include emerging commercial ETO launch options

ETO Launch – 25-70mT Evolved ELV



70mT-class ELV family is most affordable, long-term solution for exploration

ETO Launch – 25-70mT Evolved ELV (TBR)

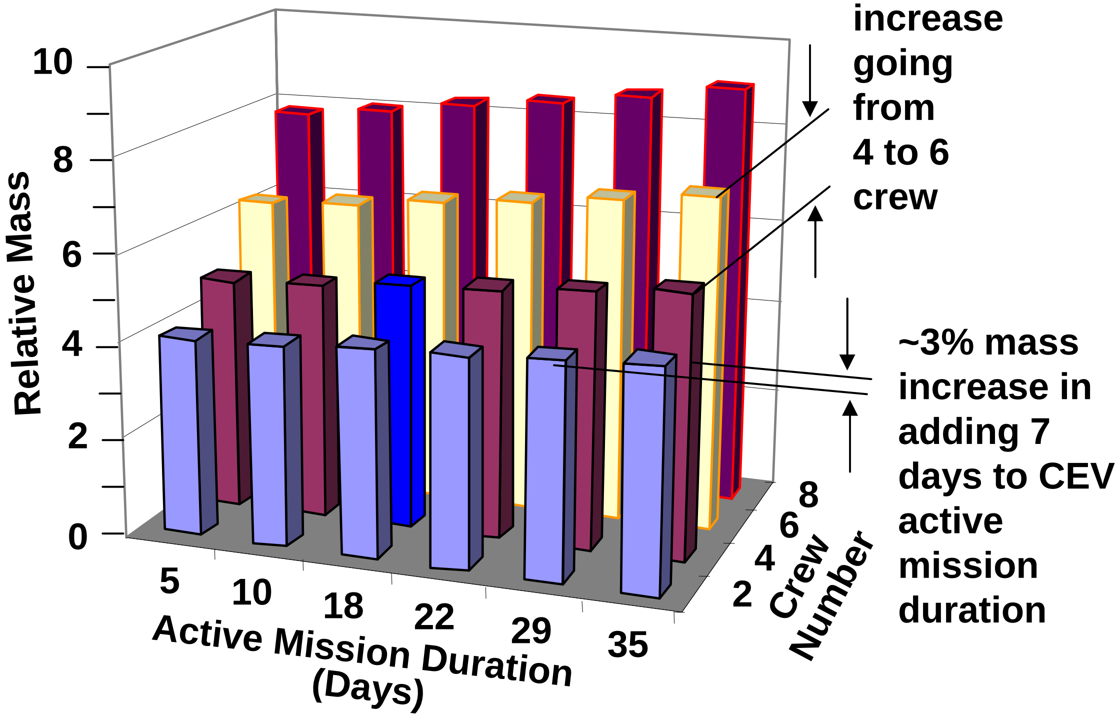
Green = Best
Yellow = Better
Red = Marginal

Crew vehicle/ applicable LV Family	Existing ELV 1	ELV single stick 1a	25 mT-class single stick 2, 2a, 7	70mT-class ELV 2b	135mT-class ELV 3	SDV - SRB 4	SDV (in-line) 5	Clean-sheet 6	Key drivers:
Hazard analyses	Red	Green	Green	Red	Red	Green	Yellow	Yellow	*# of engines & stages*
Probabilistic risk assessment (accounting for mitigations)	Red	Green	Green	Green/Orange	Green/Orange	Green	Red	Yellow	*# of engines & stages, failure rate data*
Capability to provide enough test flights to reduce risk/ensure confidence	Green	Green	Yellow	Yellow	Yellow	U/S Yellow	Red	Red	*Previous history, other users*
Capability to gain component-level demonstrated reliability	Green	Green	Green	Green	Green	U/S Red	Red	Red	*Previous history, other users*
Design margins	Red	Yellow	Green	Green	Green	Yellow	Green	Green	*Original design philosophy*
Interim summary	Yellow	Green	Green	Yellow/Green	Yellow/Green	Yellow	Orange	Orange	

TBD engine-out analyses

Uncertainties in accurately/consistently measuring safety across NASA/industry

Crew Size and Mission Duration Impacts to CEV and IMLEO – 4 vs. 6



- 4 crew optimal number for lunar exploration
  - Ensures safe operations and efficient exploration
  - Small increase in safety and mission effectiveness provided do not warrant the significant disadvantages of 6
    - 25% increase in CEV mass and cost
    - ~25-40mT increase in IMLEO corresponding to a lost opportunity cost of >$300M/mission
    - Higher development risk
    - Requirements for larger crew HLV
- Relatively small sensitivity to mission duration could support potential on-orbit contingency/rescue scenarios if required

IMLEO and affordability very sensitive to crew size

Advance Life Support Systems – Open vs. Partial Closure vs. Full Closure

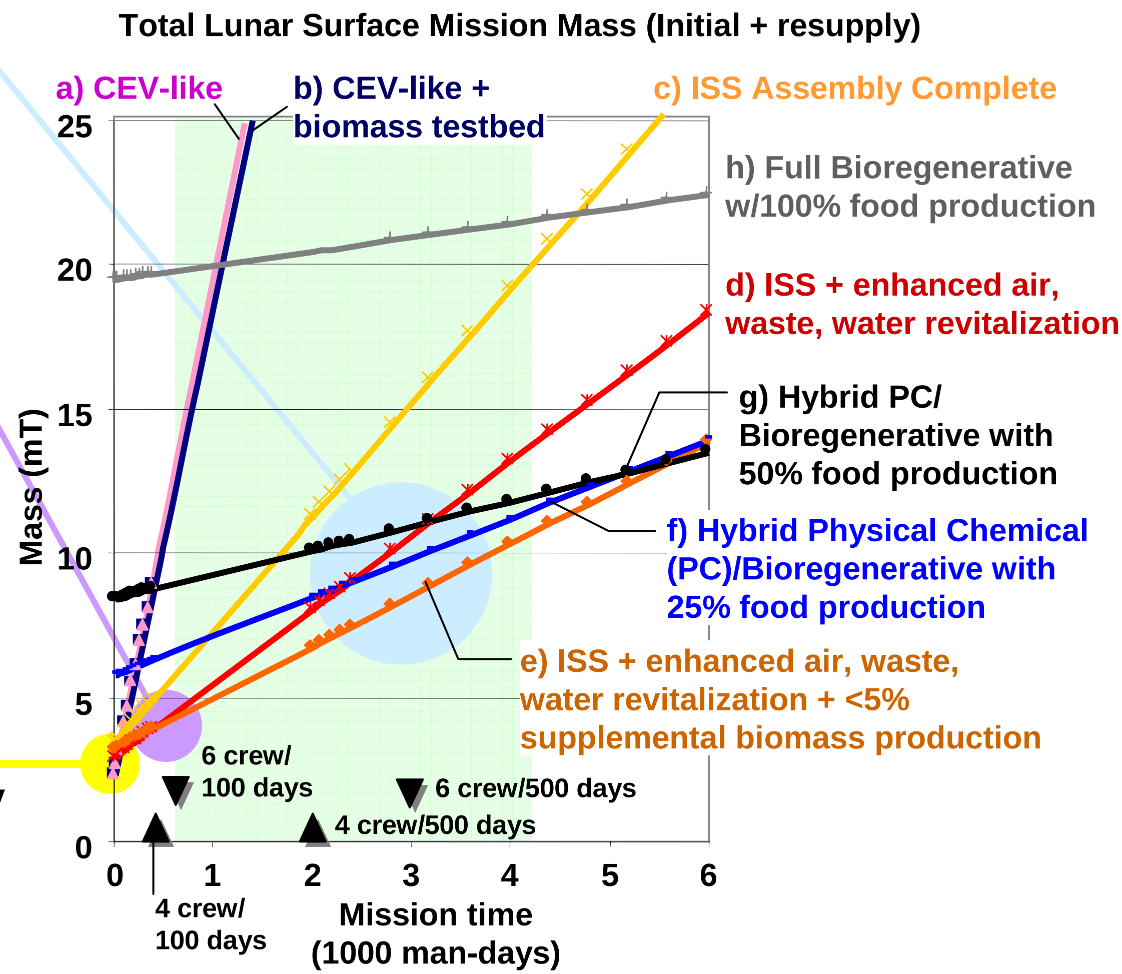
If goal is long duration space missions, this is solution space for Spiral 2

For true Mars-like durations, hybrid/ bioregenerative systems become mass competitive (also may have psychological benefits)

For 'long duration' 40-100 day missions, an enhanced ISS-like solution can save over 50% of the mass compared to the open systems

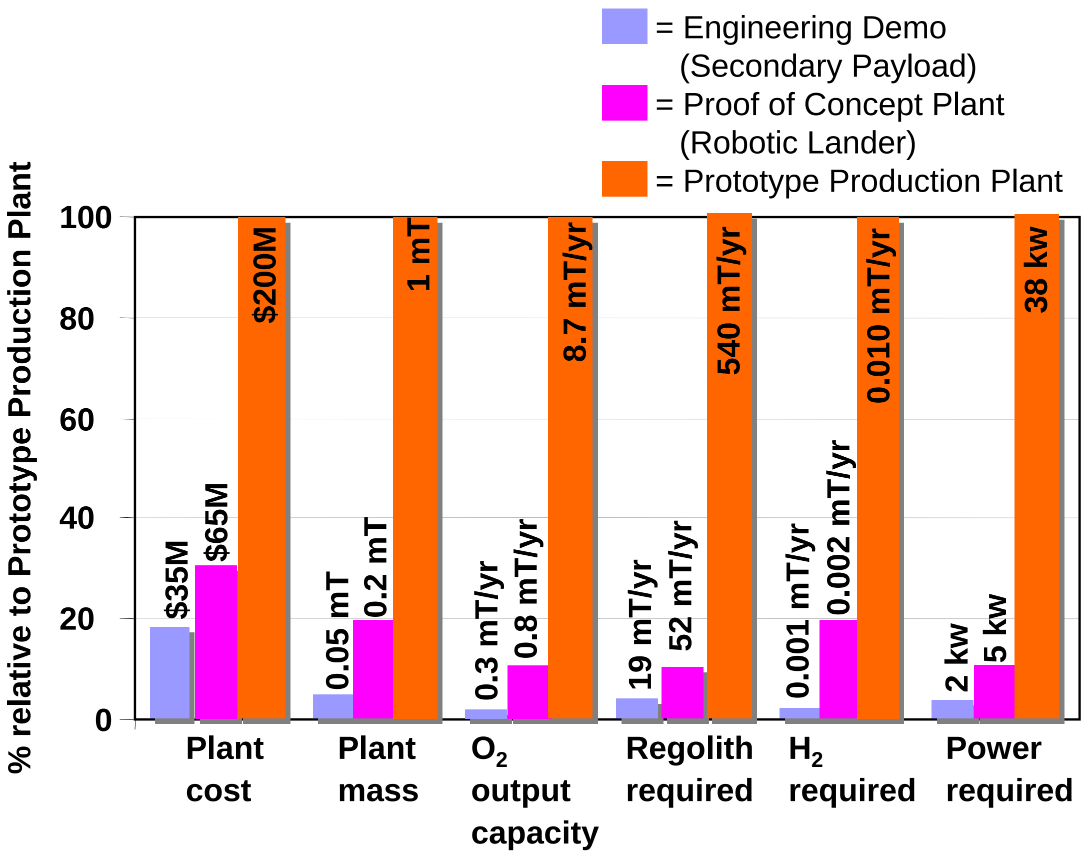
Potential solutions to meet near-term constraints are throw-aways in long-term

For CEV and 4-14 day surface missions, fully open systems are optimal



Long-duration goals may outweigh near-term suboptimization

ISRU O_2 Production – Demonstration Scale

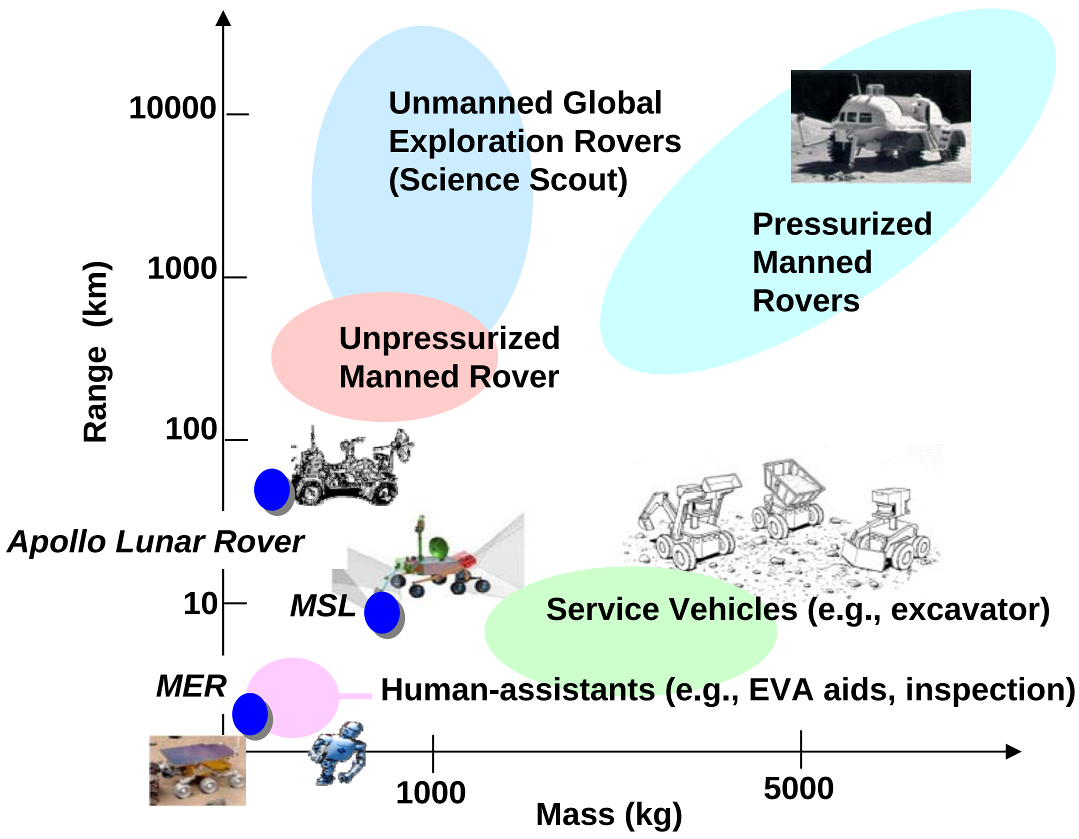


NASA illustration of notional production -class lunar mining effort

- **O_2 produced from equatorial iron-rich mare regolith (either ilmenite-rich or pyroclastic glass)**
- **Utilizes fluidized bed reactor using hydrogen reduction**

Incremental capability demos provide path to potential self-sufficiency

Surface Transportation/Rover - Trade Space

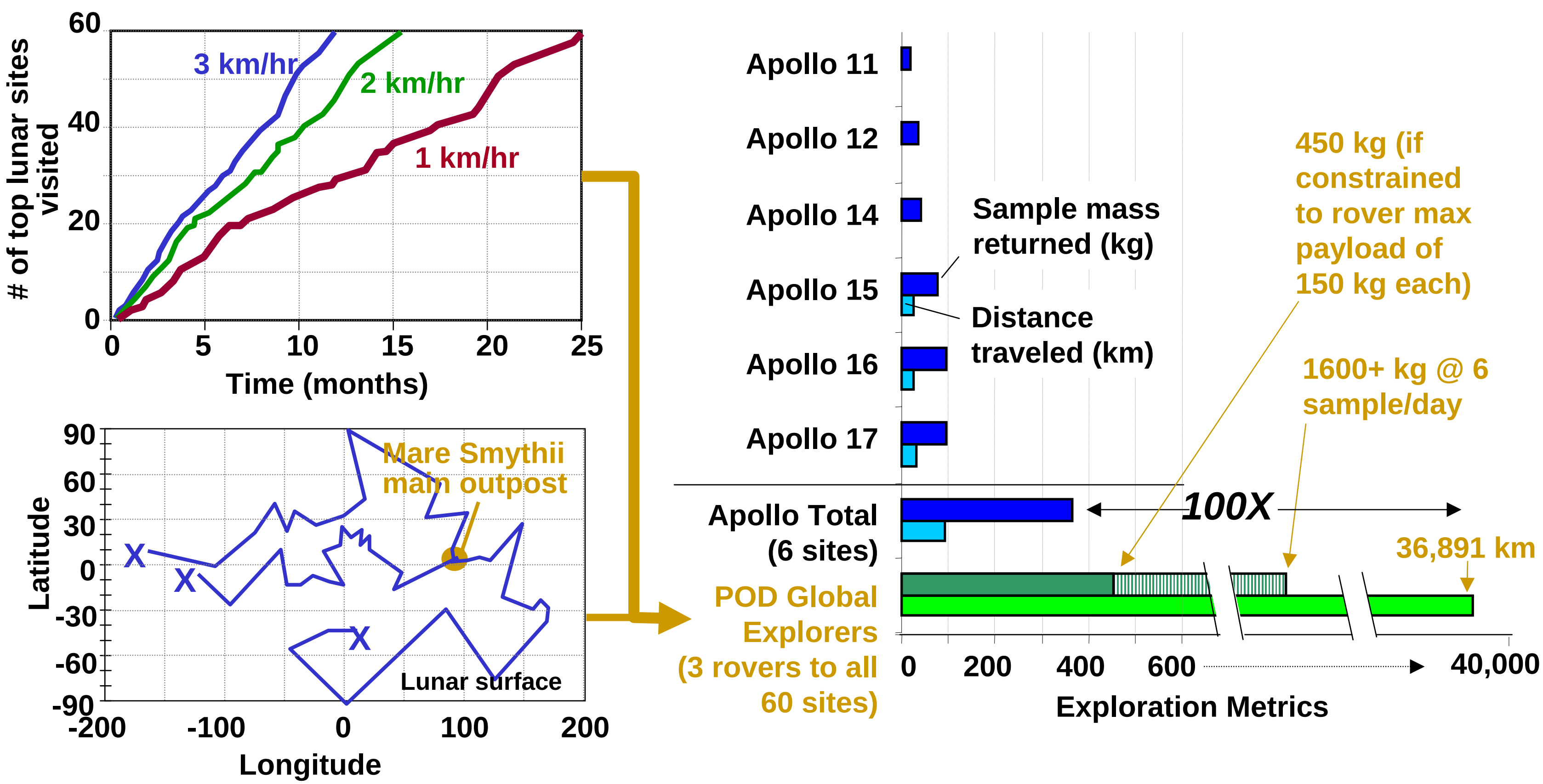


- **Human exploration depends on expanding the capability and range of surface transportation; both human and robotic**
  - **Far greater range and mobility**
  - **Larger payloads**
  - **Multi-functional tasking**
  - **Day/night operations**
  - **Telerobotic/autonomous functionality**
- **Investigating modular approaches to add functions over time and be customizable for different roles on site**
  - **One-sizes-fits-all not feasible technically**
  - **Unique design for each not affordable**
- **<u>Crew safety/rescue is the critical issue to allow humans to move beyond landing site</u>**

Investigating more affordable and safe methods for global reach

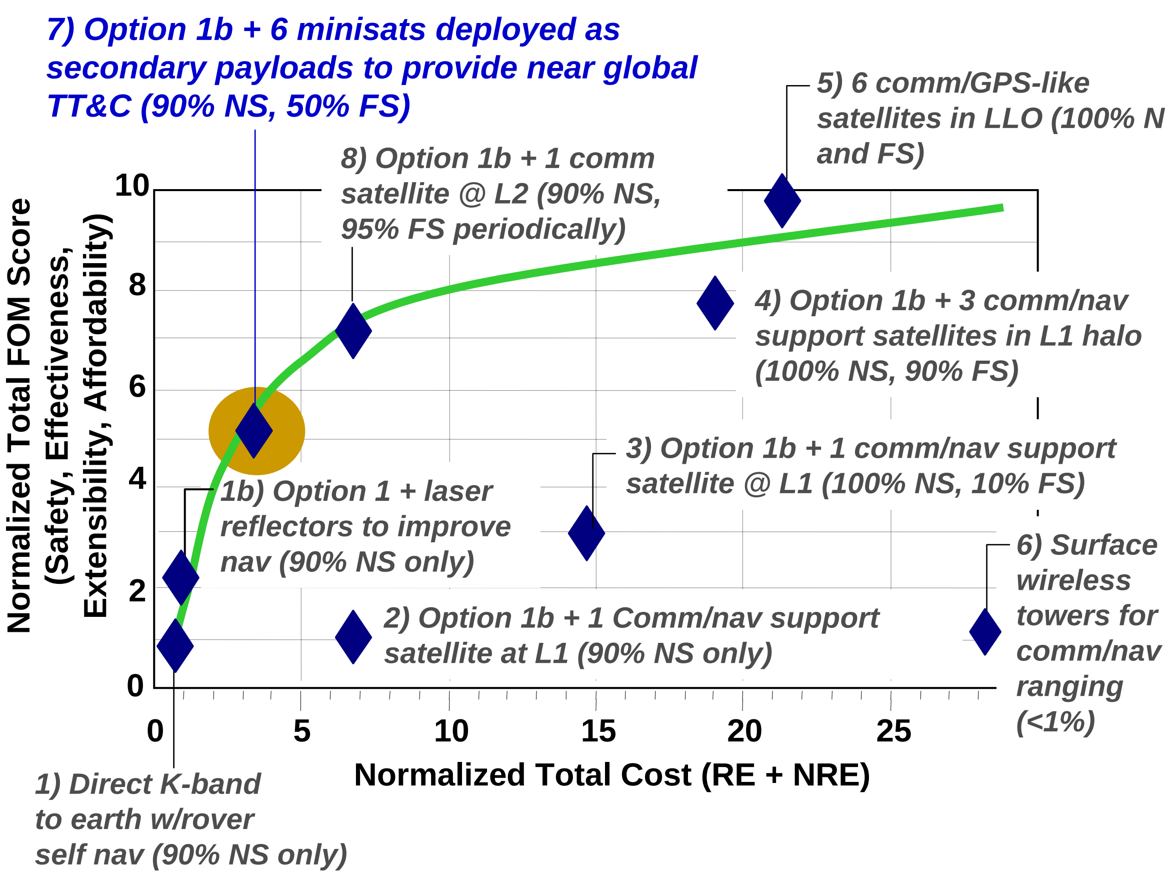
Example Exploration Rovers Capabilities

Global exploration of all top 60 science sites accomplished with 3 rovers within 12 to 24 months (each finishing up at equatorial Outpost to deliver samples)



More science on 1st crewed mission than all of Apollo expeditions

Communications/Navigation – Direct w/Minisats



Note: (x%) = % lunar coverage for near-side (NS) and far-side (FS)

- **Direct wideband earth-moon communications augmented by constellation of narrowband minisats is POD (Option 7)**
  - **Highest benefit/$**
  - **Minimum upfront costs consistent with funding profile**
  - **Sufficient for near-term science and testbed activities**
  - **Provides key safety net to CEV on the far-side**
- **Option 8 best solution for polar coverage (100% coverage available by adding 2 more satellites at L2)**
- **Option 5 provides greater coverage/more precise navigation available if the decision is made to remain at the moon**

POD comm/nav solution best fit with funding and near-term lunar objectives

Remaining Trades/Analyses Focus

- **Safety/Human-rating Analyses**
  - **Continue efforts to analyze NPR 8705.2a implications on architecture including expansion of concepts for anytime abort, safe haven, and/or rescue**
- **ETO LV Trade –**
  - **Finalize all FOMs and expand to include commercial launch alternatives**
- **In-Space Propulsion Trade**
  - **Validate propellant selections and staging location**
  - **Optimization of LSAM configuration and number of stages**
- **Alternative Mission Models**
  - **Further decomposition of testbed requirements to earth, ISS, space, and lunar surface application**
  - **Further optimization of systems scope and timing with funding**
- **Expand reusability analyses**
  - **LSAM, transfer stages, CEV (CM, SM)**

Continuing further efforts to refine/validate initial results across broad spectrum

Technology Requirements

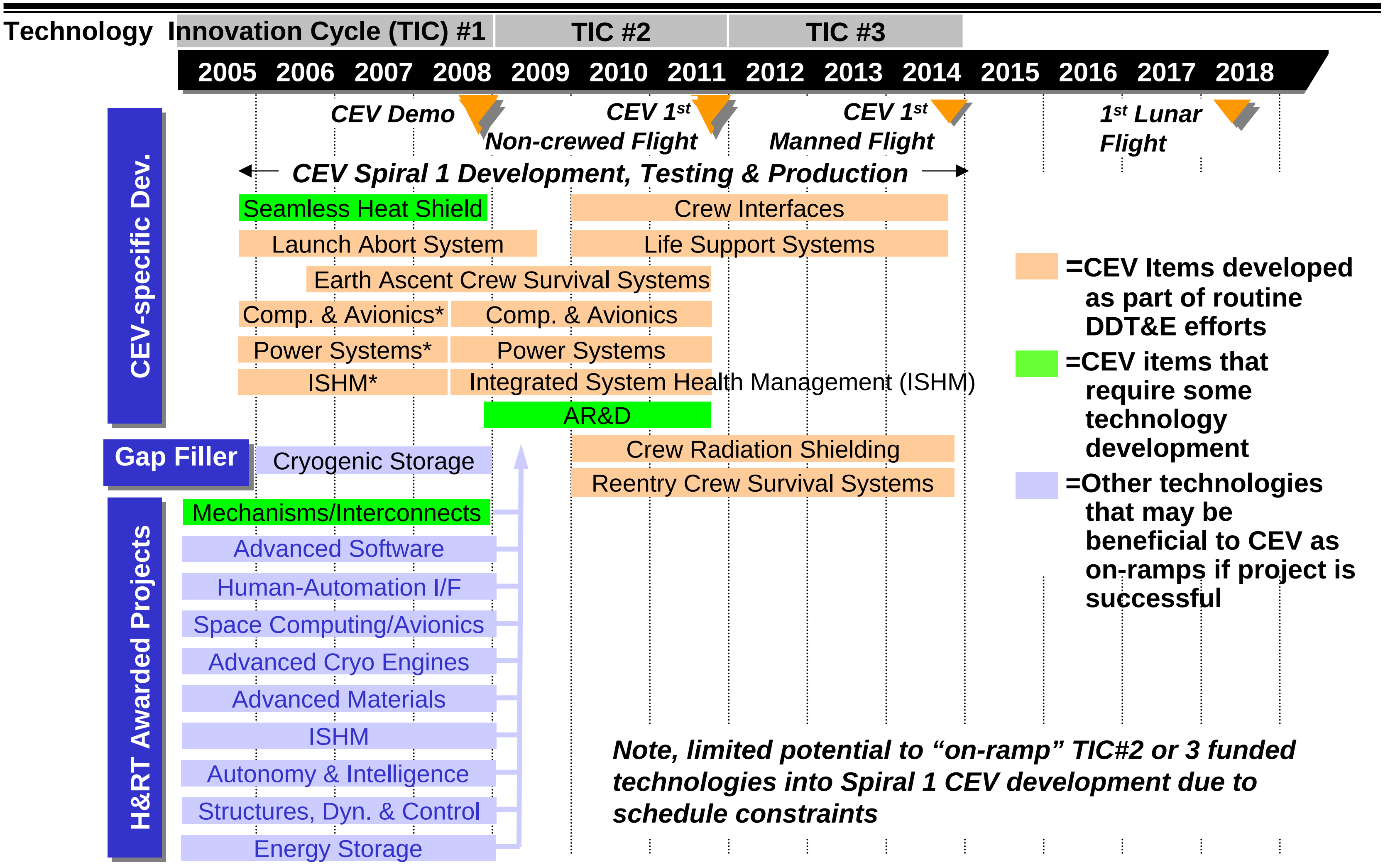
POD High Payoff Technologies (2008-2023)

- Intelligent systems/robotics*
  - Outpost emplacement, science rovers, ISRU emplacement/operations, human-tended operations
- High-ISP cryogenic propulsion*
  - Long-term storage, throttleability, reliability, in-space handling, LOX/H2 and/or LOX/CH4 engines, ISRU propellant production
- On-orbit automated rendezvous and docking*
- Counter measures to long duration space exposure of crew
- Nuclear power for lunar surface
- ISRU for propellant production, life support, and manufacturing
  - Extraction, processing, manufacturing, storage, transport
- Advanced life support systems (maximum resource closure)
- Heavy lift launch vehicle
  - IVHM, engine-out, wide body cryogenic upper stage
- Software (autonomy, reconfigurability, reliability)
- In-vehicle activities (IVAs) vs. EVAs
- Advanced mission operations and life cycle support capabilities
  - Automation, lights-out operations, integrated logistics/maintenance

*Fundamental to solution; significant impact if not available

POD assumes continued development of critical beneficial technologies

Example Technology Roadmap – CEV System-level



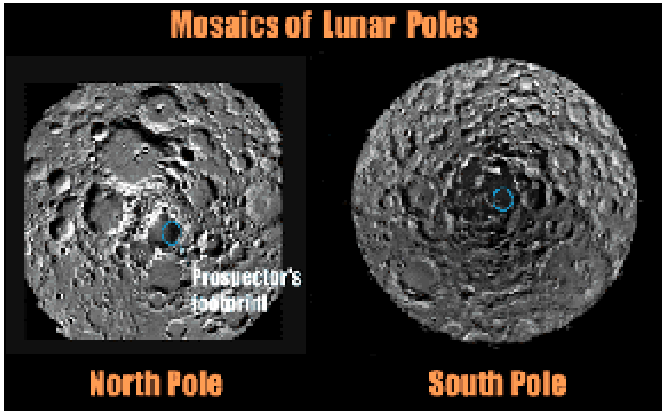
Development efforts effectively leverage existing and emerging technology

Future High Payoff Technologies

Category	Enhanced capabilities	Information to enable implementation
In-space communication/ navigation	Orbiting satellite constellation to provide 100% wideband communications and GPS-like navigation precision	Decision to permanently settle and/or commercialize the moon
In-space refueling/ servicing	Provide in-space refueling/servicing of CEV, LSAM, and transfer stages via either earth or lunar-based propellants	• Decision on permanent settlement • Incorporation of reusable systems • Long-duration cryogenic storage • ISRU propellant production • Proven human-robotic collaboration
Production-class ISRU systems	• Production-class ISRU systems • In-situ construction • In-situ commercial mfg • Etc.	• Decision on permanent settlement • Proven cost effective/reliable ISRU processes • ISRU processes scaled to production-class Viable business case
Reusable systems	Reusable CEV, LSAM, and transfer stages (possibly transition to SEP or NEP vs. chemical propulsion)	• Decision on permanent settlement • Proven ISRU and in-space refueling/servicing • Robust exploration and/or commercial mission model to warrant investments
Commercial lunar operations	Transition from exploration Outpost to long-term settlement including commercial operations, tourism, etc.	• Decision on permanent settlement • Government policies to permit transition of capabilities to private sector • Viable business case to consistent with risks
Super HLV	Extend HLV towards 135mT class to support significant mass to both Moon and Mars	• Decision on permanent settlement • Decision to continue human exploration to Mars

Desirable capabilities for next spirals depending on decision for post-2023

Exploration/Programmatic and Technical Risk Assessment



Top Risks/Example Mitigation Steps (1 of 2)

Risk	Type *	POD unique	Example mitigation strategies
Changing priorities/ programmatics	P, C, S	No	Continuous mission returns; open solutions; spiral development; mission success; CAIV-based decision making; implement ISS/Shuttle lessons learned
Human-rating/safety considerations	P, T, C, S	No	Government consensus on safety requirements; Architecture-level human rating features (e.g., SPE safe havens, back-up life support); robotics; minimum in-space infrastructure
Long duration space impacts to crew	P, T, C, S	No	Early research on Earth and ISS; precursor robotic missions to characterize environments/mitigation strategies; intelligent support/ advanced life support systems; full duration Mars system/crew demo
Intelligent/ robotic system maturity	T, C, S	Some what	Invest in new capabilities early; incrementally demonstrate in precursor robotic missions (e.g., Hubble servicing); leverage extensive commercial and DoD efforts
"Power rich" surface system maturity	P, T, C, S	No	Leverage Project Prometheus efforts into surface systems; develop advanced regenerative systems capable of supplying power and supporting ECLSS in parallel
High-ISP propulsion system maturity	T, C, S	Some what	Next cryogenic systems derived from today's proven technologies, develop long-term storage and in space transfer; invest in parallel in advanced 'game changing' technologies including ISRU or tethers

* P=programmatic, T=technical, C=cost, S=schedule

Top Risks/Example Mitigation Steps (2 of 2)

Risk	Type *	POD unique	Example mitigation strategies
Historically high ops cost for crewed missions	P, T, C, S	No	Implement ISS/Shuttle lessons learned to reduce logistics train and 'standing army'; implement 'man-tended' ops; maximize autonomous functionality; leverage low cost ops from robotic missions in combination with COTS/standards
Current mission model does not warrant reusability investments	P, T, C, S	No	Maximize commonality at subsystem/component levels; selective reusability where cost effective (e.g., surface systems); delay full reusability into later spiral when more robust mission model and lunar ISRU may support (open system designs upfront minimize the impact of later spiral insertion)
Total cost/ mass of new ISRU capabilities	P, T, C, S	Some what	Demonstrate ISRU concepts/technology in early spirals starting with robotic precursor missions; implement small scale pilots during initial spiral; delay large scale commitments (e.g., in space fuel depots) until next spiral
Low cost/safe ETO launch capacity	P, T, C, S	No	Develop HLVs ranging up to at least 70 mT class to minimize # of launches; minimize mass required to lunar surface; seek self sufficiency via use of in space resources and bioregenerative life systems; demonstrate routine autonomous docking/assembly; develop high ISP propulsion

* P=programmatic, T=technical, C=cost, S=schedule

Risks mitigated by our baseline features and future development efforts

Recommendation Summary

- **Reconsider exploration strategy, definition of spirals, and mission durations**
  - **Focus on objective-driven solutions**
  - **Balanced approach (testbed-focused) can be affordable**
- **Reconsider requirements for global access and preferred landing site**
  - **Equatorial location more effective solution given all considerations**
- **Convene Government/Contractor Safety Working Group to better understand human rating requirements/evaluation methods**
  - **Driver for ETO LV selection**
  - **Clarify anytime abort-to-earth and rescue requirements that are key to many CEV and architectural-level decisions**
- **Continue to consider several aspects of architecture, e.g.,**
  - **Reusability, safety alternatives, fuel alternatives, and early HLV development**
- **Consider long-term cryogenic propulsion/storage and nuclear surface power technology developments a top priority for lunar architecture**

Seeking the sustainable approach that ensures journey ends at destination