Mid Term Briefing – CA1

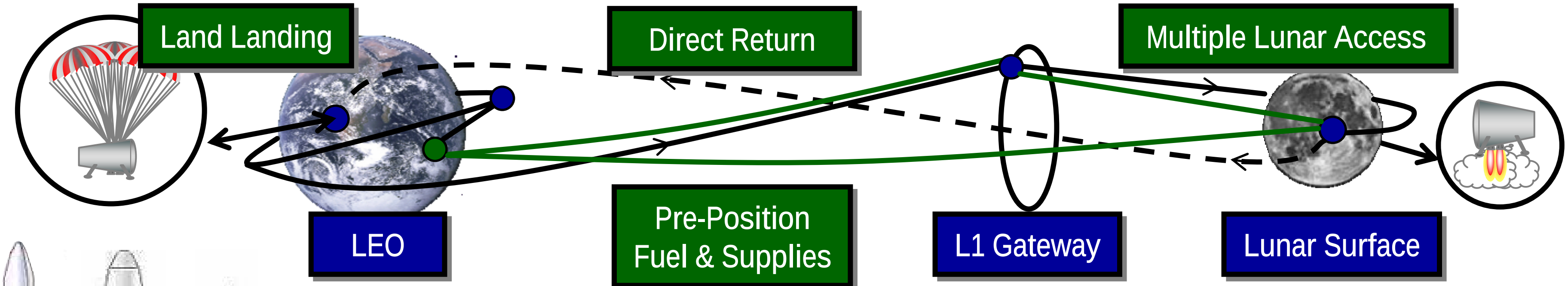
1 December 2004, 10:00 – 11:00 AM

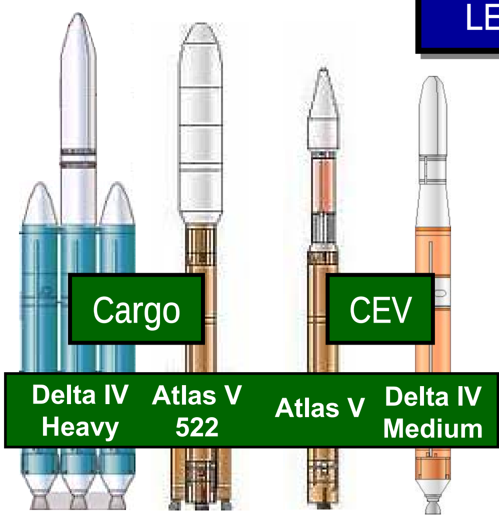
Schafer Corporation
System Engineering and Integration Division

Agenda

1.0 Introduction
2.0 Exploration Objectives
3.0 Architecture Overview And Definition
4.0 System And Element Requirements
5.0 Trade Studies And Analysis For Super System And CEV
6.0 Technology Requirements
7.0 Exploration Programmatic And Technical Risk Assessment
8.0 Summary

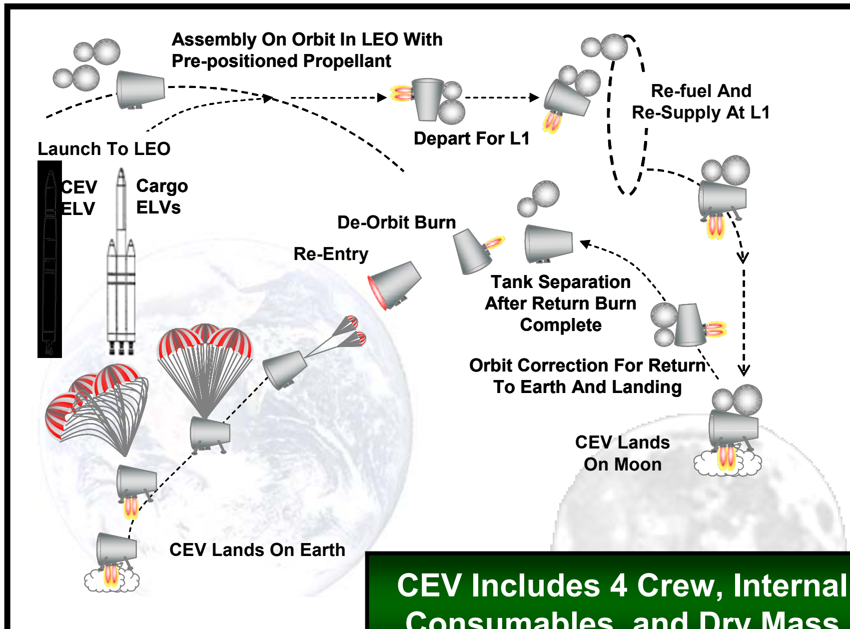
Gateway Architecture





CEV: EELVs With IVHMS And Launch Abort

Cargo: 20 mt EELV To LEO Orbit, 24 Launch/Year



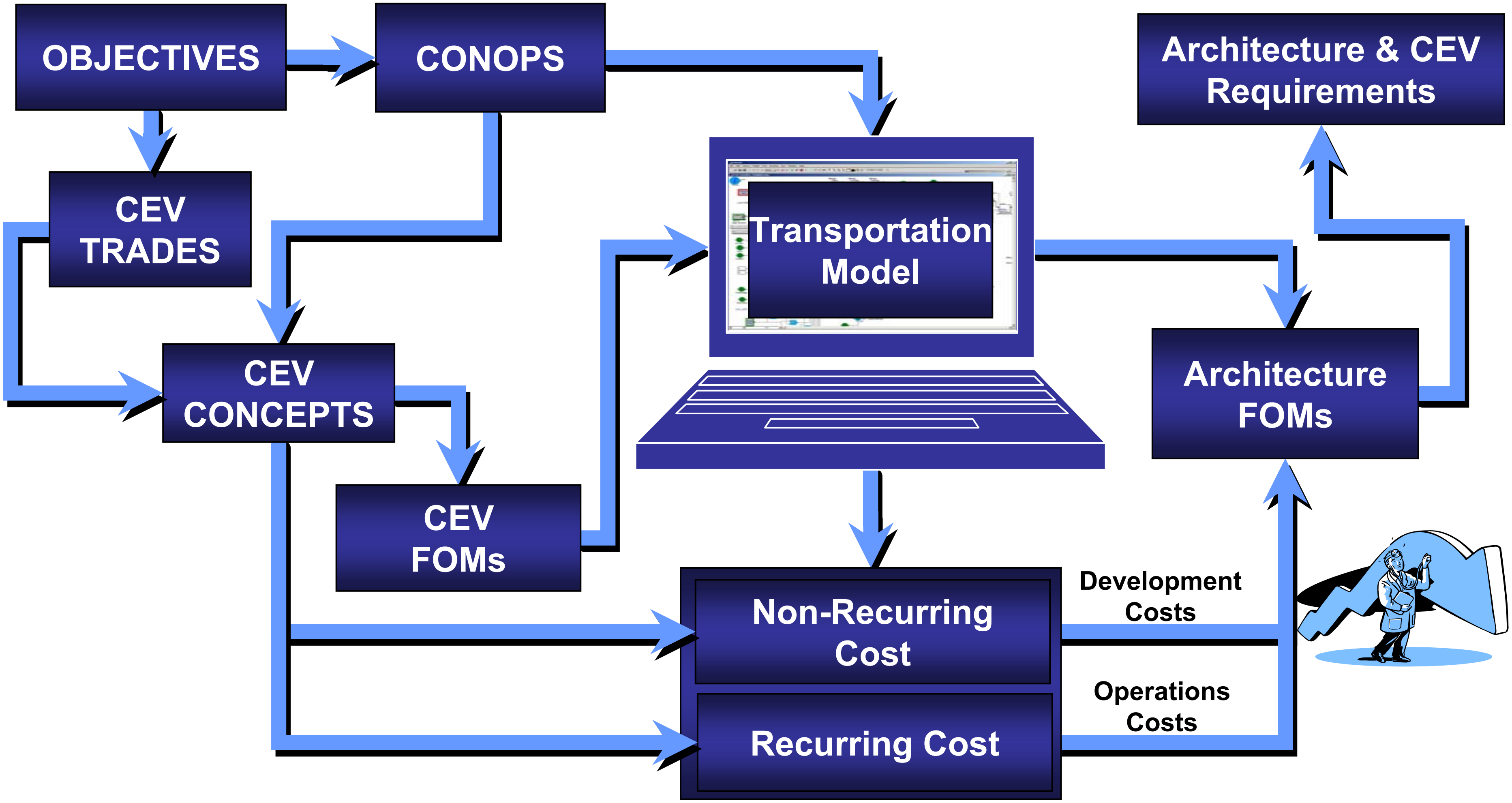
CEV Includes 4 Crew, Internal Consumables, and Dry Mass

Architecture Elements

- CEV
- Human Rated Launch System
- EELV Cargo Launch System
- In Space Cargo Transport
- Safe Haven
- Lunar Habitat
- Cargo Lander
- Lunar Hopper

Through Spiral 3: Gateway Architecture Using ELVs And 8 mt CEV Supports All Missions

Approach



Requirements, CONOPS, Cost, And Performance are Integrated With Our Transportation Model

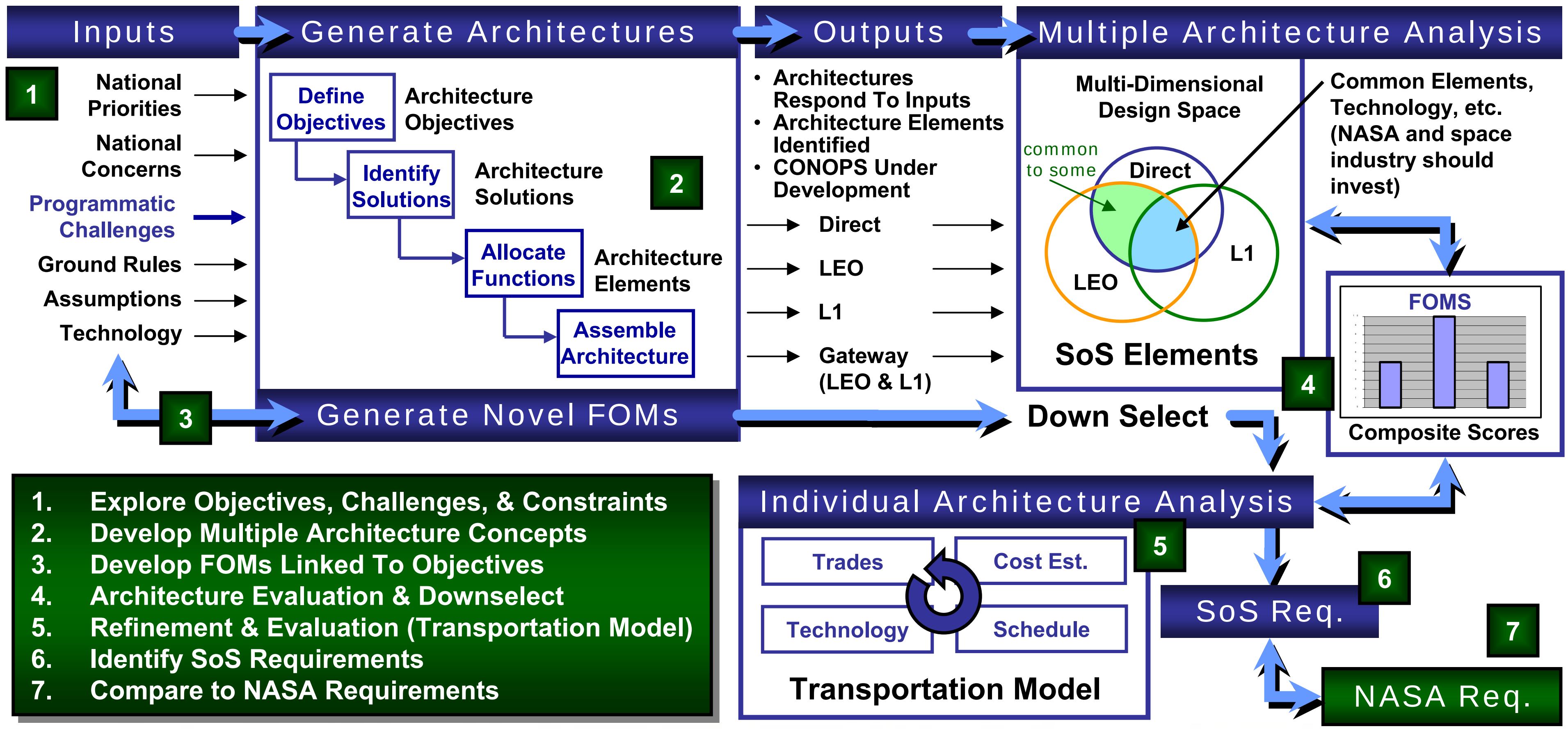
2.0 Exploration Objectives

Decomposition And Maturation

Architecture Achieves Robustness Through Commonality As Inputs Change

Robustness – degree to which architecture successfully responds to changing inputs without the need to change elements, only mission

Commonality – degree to which architecture shares objectives, solutions, elements, and technology with other architectures



1. Explore Objectives, Challenges, & Constraints
2. Develop Multiple Architecture Concepts
3. Develop FOMs Linked To Objectives
4. Architecture Evaluation & Downselect
5. Refinement & Evaluation (Transportation Model)
6. Identify SoS Requirements
7. Compare to NASA Requirements

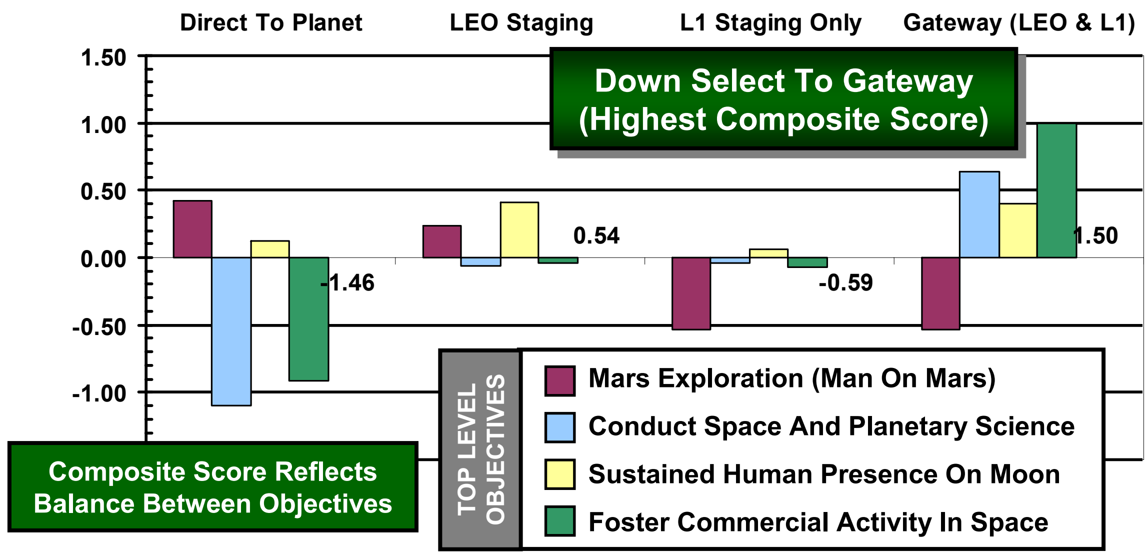
Our Architecture Development Process Is Designed To Accommodate Changes At All Steps And Traces The Impacts Of The Changes Through The Architecture Model

Initial Evaluation Of Architecture Types

Top Level Objectives

Architecture Solutions:

- **Direct To Planet**
  Launch Crew, Equipment, Supplies, And Propellant To Planet Surface. Minimal Pre-positioning. Mission Is Essentially Self-Contained
- **LEO Staging**
  Multiple Launches To Assemble Crew, Equipment, Supplies, And Propellant At LEO For Transport To Planet Surface.
- **Space Gateway**
  Multiple Launches To Preposition Equipment, Supplies, And Propellant At Space Node. Crew Transport With Re-supply At Nodes.
- **LEO And Space Gateway**
  Multiple Launches To Assemble At LEO. Preposition Equipment, Supplies, And Propellant At Space Node. Crew Re-supplied.



Conclusions:

- **Direct To Planet Architectures Speed Exploration At Sacrifice To Other Objectives**
- **LEO Gateway Is Advantageous For Any Lunar Campaign**
- **Gateways Maximize Opportunities For Science Due To Frequent Access To Space And Planet**
- **Space Economy Aided By Nodal Architectures Due To Largest Number Of Required Elements**

Down Selection To Gateway Architecture Provides Best Opportunity To Address All Top Level Objectives

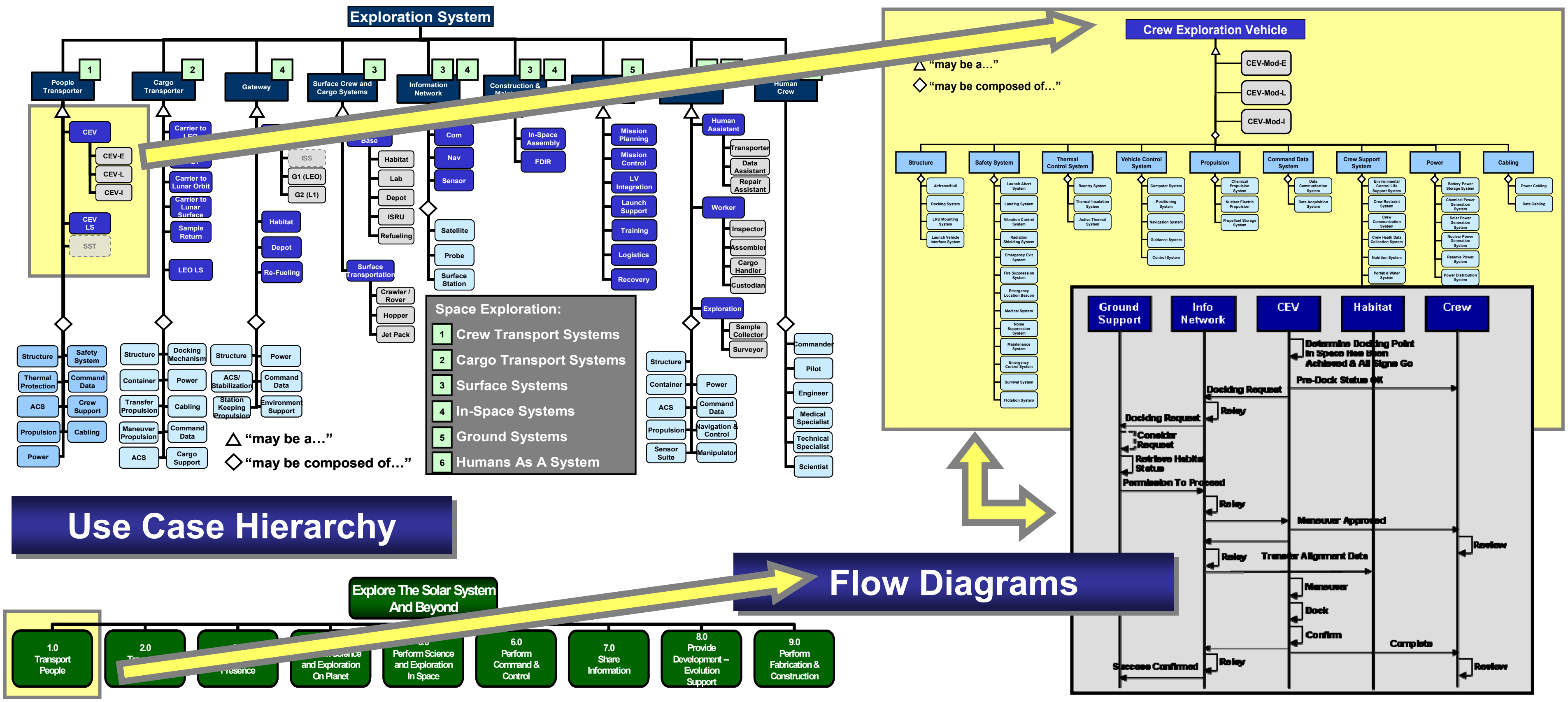
3.0 Architecture Overview And Definition

Bruce Peters

Architecture Element Decomposition

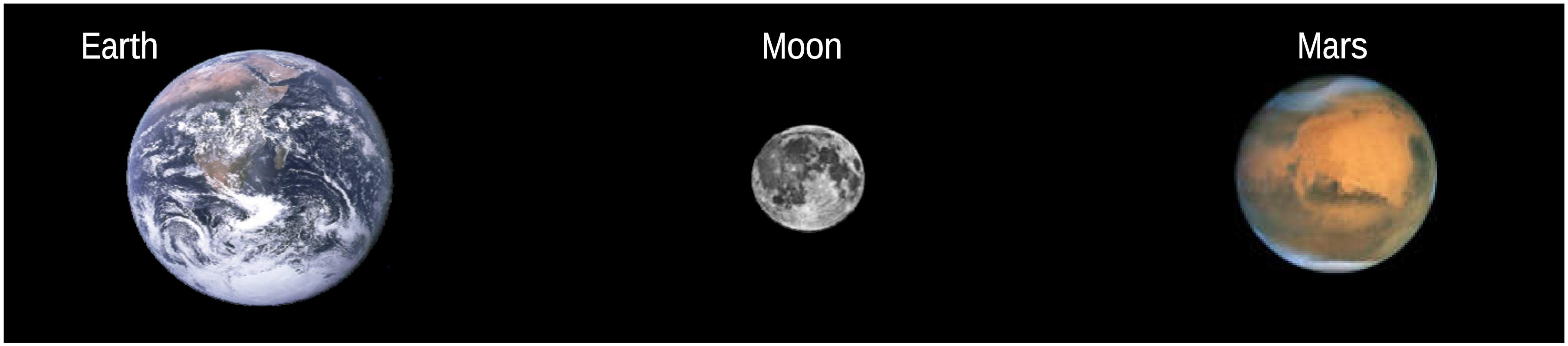
Integrated Products Define Behavior In Terms Of Elements and Interactions And Interfaces

Element Decomposition



Lower Level Element Decomposition Supports Detailed Use Case Development and Functional Allocation To Define Architecture Elements And CONOPS

Functional Commonality



High Degree of Commonality Between Landing on the Earth Moon and Mars

- Transport and Sustain Crew
- Engines for Deorbit
- Heat Shield
- Atmosphere – Use Parachutes
- Engines for Soft Landing
- Land on Land – Preferred
- Land on Water - Emergency
- Safely Land Crew

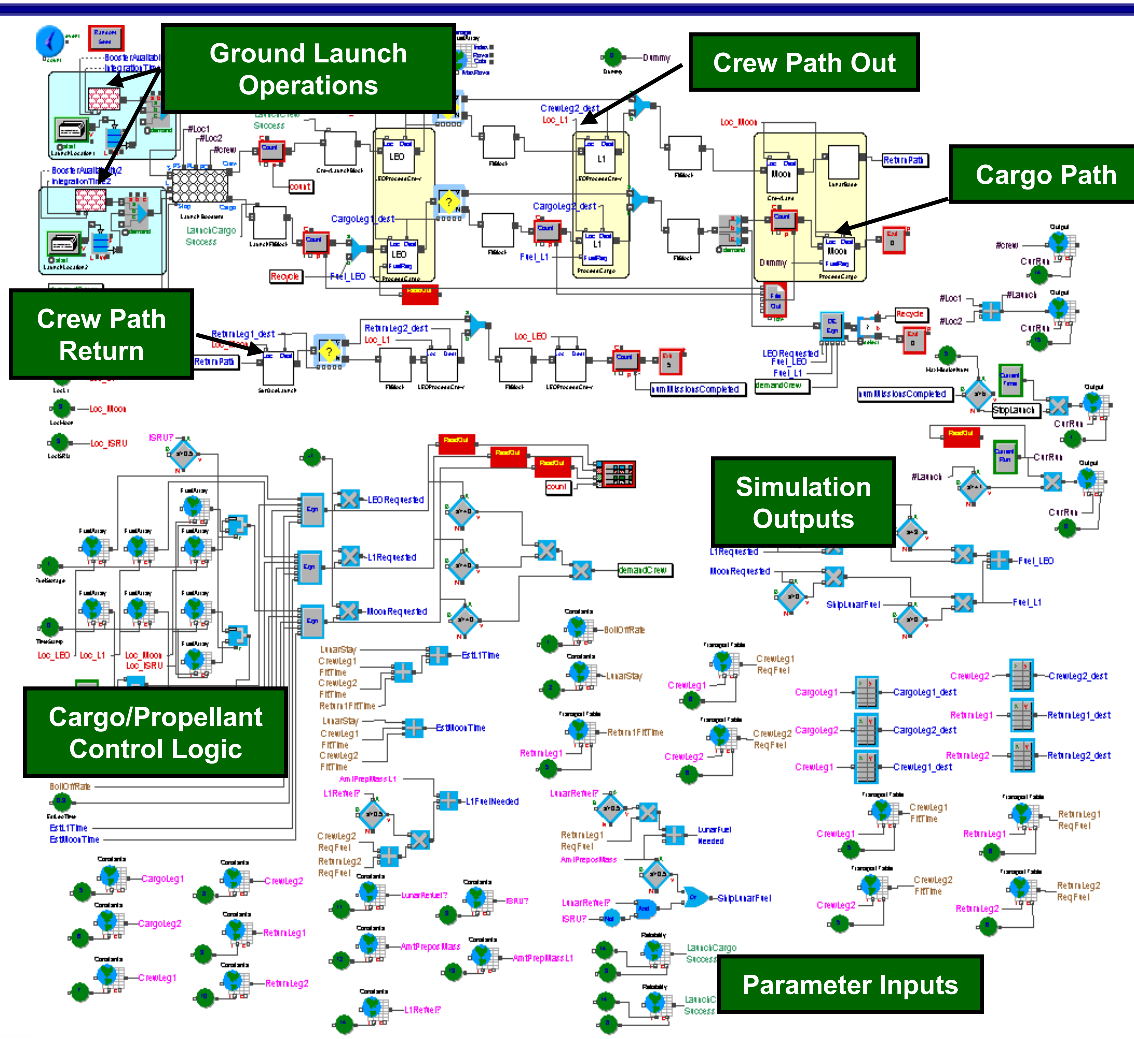
- Transport and Sustain Crew
- Engines for Deorbit
- ~~Heat Shield~~
- ~~Atmosphere – Use Parachutes~~
- Engines for Soft Landing
- Land on Land
- ~~Land on Water~~
- Safely Land Crew

- Transport and Sustain Crew
- Engines for Deorbit
- Heat Shield
- Atmosphere – Use Parachutes
- Engines for Soft Landing
- Land on Land
- ~~Land on Water~~
- Safely Land Crew

Design A Modular CEV to Land on the Earth, Moon, and Mars

Transportation Model

- **Simulates Movement of Mass Through the Transportation System**
  - EXTEND
  - Incorporates Timing
  - Interfaces With Excel
- **Crew Launch When All Pre-positioned Supplies and Cargo Are In Place**
- **Cargo/Mass Flows Toward Lunar Surface**
  - Desired Mass Halts Flow
- **Parameter Inputs Based on Physical Mechanics**
- **Outputs Launch and Propellant Requirements**



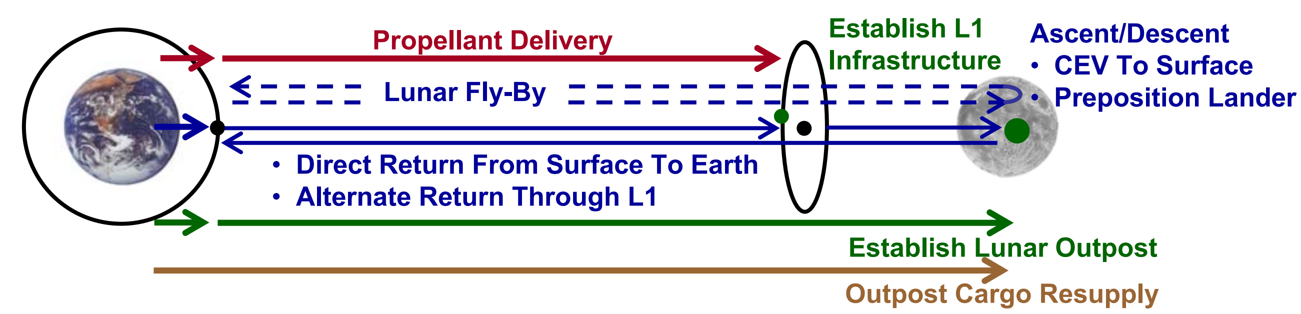
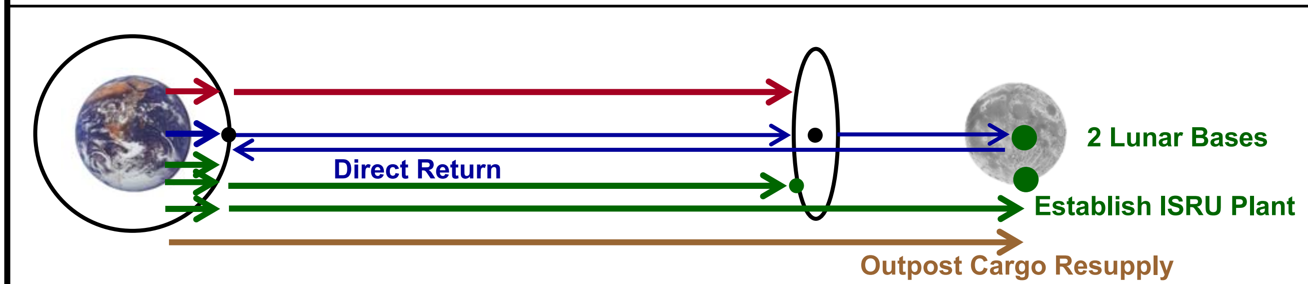
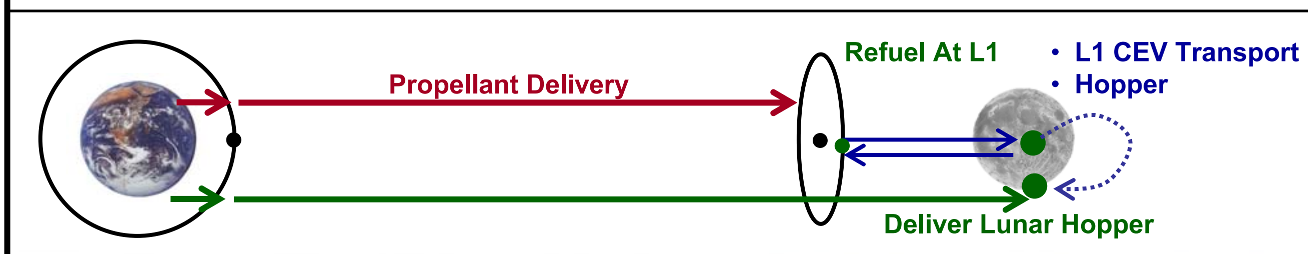
Discrete Event Simulation Of Architecture Is Used To Perform Trades And Analyses To Evaluate Architecture Elements, CONOPS, And Determine Sensitivities

Ground Rules And Assumptions

- Emphasize Gateway Architecture Concepts
- Architecture Concepts Must Foster In Situ Resource Utilization (ISRU)
- LEO Specified At 407 km Altitude, Circular Orbit
- Calculated ΔV and Flight Time From Orbital Mechanics and References To Determine Minimum Acceptable Transport Duration with Acceptable Energy
- For This Analyses, L1 Position Fixed, Relative To Earth And Moon
- Off Earth Robotic Assembly, Set-up, and Operation For All Infrastructure
- Chemical Propulsion (LOX, Hydrogen) $I_{sp} = 440$
- Only Hydrogen Fuel Subject To Boil-off at a Rate of 0.1% per Day
- Robotic Reconnaissance Missions Select Near Lunar Equator And South Pole Locations For Probable Extended Presence And Continued Exploration
- Assume One Crewed Mission Per Year Over 5-year Campaign In Spiral-2

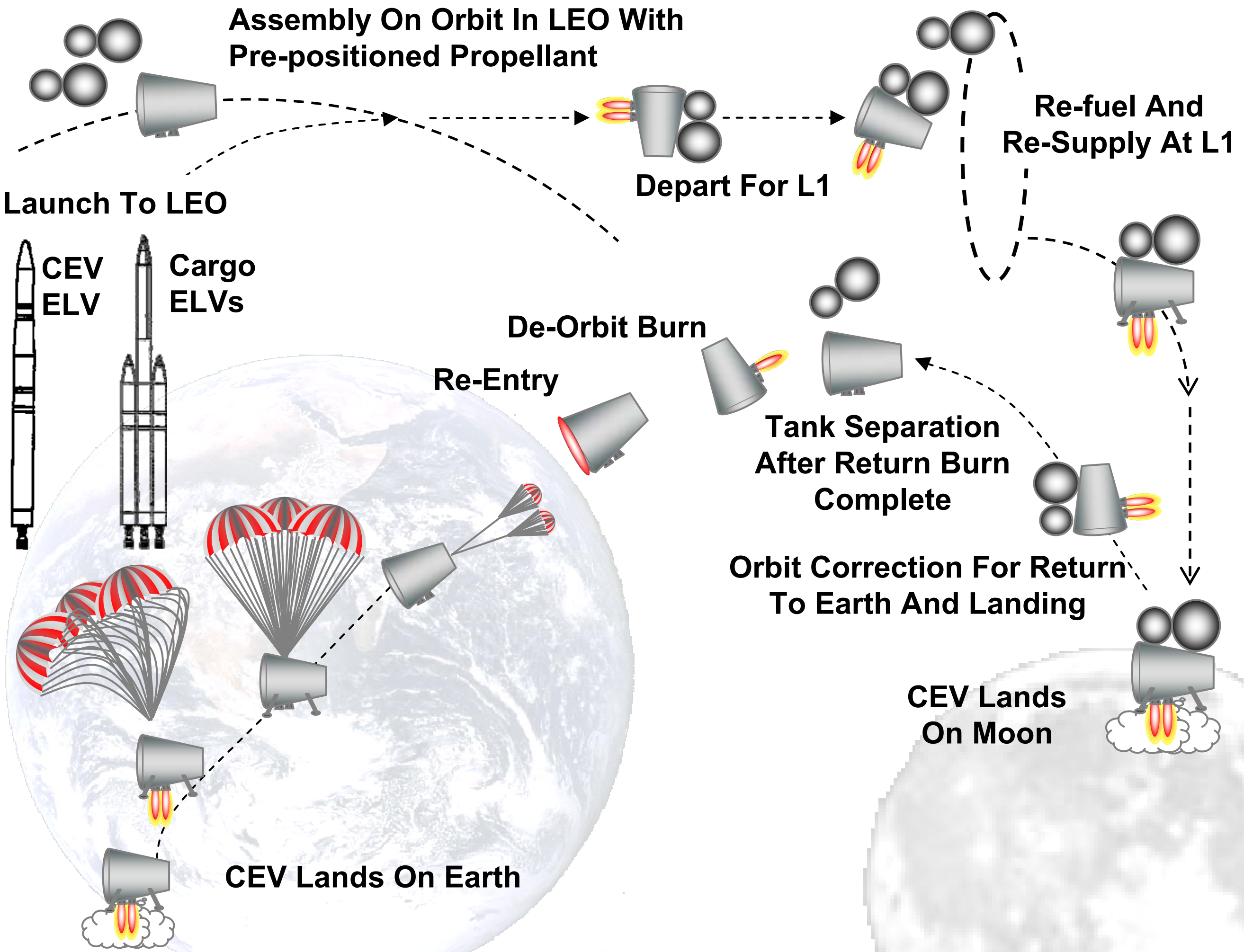
Architecture Concepts Provide A Point Of Departure For Further Studies

Lunar Mission Definition

Launch To LEO Orbit: Orbital Assembly & Refueling / L1 Gateway: Refueling & Safe Haven / Lunar Surface: Crew Habitat & Safe Haven	SPIRAL	
	2	• Lunar Fly-By • 3-7 Day Lunar Stay (No Habitat) • 14 Day Lunar Stay (With Habitat At South Pole Or Equator) • One Mission Per Year, 5-yr Campaign
	3	• 30-90 Day Expanded Presence On Lunar Surface (South Pole And Equator) Through Night • Begin ISRU Processing • Require One Crewed Mission Per Year
	**Added Mission**	• Human Exploration Of Multiple Lunar Surface Locations (Use Hopper And L1 Excursions)

The Full Gateway Architecture Is Evolvable, Flexible And Provides Added Capability

CEV CONOPS



- Re-Supply at L1 On Transport To Moon
- Re-Supply Mission On Lunar Surface (For Extended Stays Beyond 7 Days)
- CEV Delivers Crew To And From Lunar Surface
- Re-Fuel Capability At L1 Using Pre-positioned Propellant Transported From Earth
- Direct Return To Earth From Lunar Surface (No Rendezvous At L1 Or LLO Required)
- Extended Lunar Stays Meets Up With Pre-positioned Habitat And Supplies

Architecture Supports The CEV In LEO, L1, and The Lunar Surface

Architecture Efficiency Index

$$EI = \underbrace{\left(\frac{\text{Element Launches}}{\text{Total Launches}}\right)}_{\text{Launch Efficiency}} \underbrace{\left(\frac{\text{CEV Prop. Consumed}}{\text{Total Prop. Consumed}}\right)}_{\text{Propellant Efficiency}} \underbrace{\left(1 - \frac{\text{Total Launches}}{\text{Launch Capacity}}\right)}_{\text{Launch Capacity Margin}}$$

Launch Efficiency
- Launches Of Architecture Elements Compared To Launching Supplies And Prop.
- More Infrastructure And Supporting Launches Is Costly

Propellant Efficiency
- Prop. Used To Move Crew vs Total Prop. Consumed
- Cost Of Using Prop. To Move Prop.
- Major Architecture Driver
- Low Efficiency Propulsion Technologies Are Costly

Launch Margin
- Excess Capacity Within Launch Systems To Recover From Failure
- Rewarded For High Sustainable Launch Rates

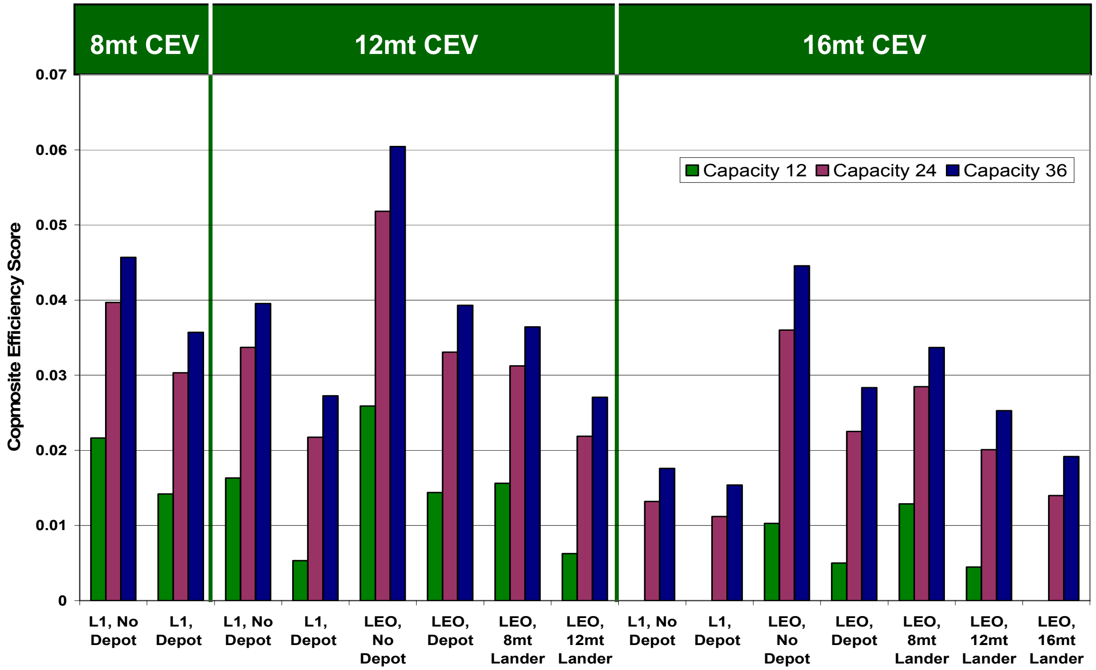
CEV Includes Crew, Internal Consumables, and Dry Mass

TRADE STUDIES:

- 20MT ELV vs 80MT Lift To LEO
- CEV Sizing (8 mt vs 16 mt)
- Direct Return To Earth
- Lunar Propellant Depot
- Launch Capacity/Frequency

EI Measures Interaction Between CEV Mass, Infrastructure, and Launch Rates

Architecture Efficiency Composite Score



Approach To Composite Score:

- Adds Influence Of Objectives To The Efficiency Index To Determine Effectiveness Of Viable Architectures Of Responding To Program Objectives

- **Only Evaluate Viable Spiral-2 Architectures**
- **Current Estimated Launch Capacity Of 12 Launches Per Year Is Sufficient To Achieve All Architectures**
- **L1 With Small CEV Benefits Architecture**
- **Lunar Depot Does Not Strongly Benefit Any Architecture**

Conclusions:

- **L1 Permits A Smaller CEV**
- **Second Launch Service Increases Performance (Two Boosters, Two Launch Pads)**
- **LEO Assembly Only Architectures Competitive Through Spiral-2**

Influence Of Objectives Impacts The Selection Of Architecture

Architecture Sustainability Index

$$SI = \left(\overbrace{1 - \left(\frac{\text{Total Launches}}{\text{Launch Capacity}}\right)}^{\text{Impact Of Loosing A Launch}}{}^{\overbrace{\frac{\text{Total Launches}}{\text{Launch Losses}}}^{\text{Losses Reflect System Reliability}}} \right) \times \overbrace{\left(\frac{\text{Total Launches}}{\text{Launch Capacity}}\right)}^{\text{Launch Capacity Margin To Recover}}$$

Impact Of Loosing A Launch
- Launches Required To Support The Mission Compared To The Total Launch Capacity
- Excessive Unused Launch Infrastructure Can Be Costly
- Margin Is Desired For System Robustness To Overcome Programmatic Changes

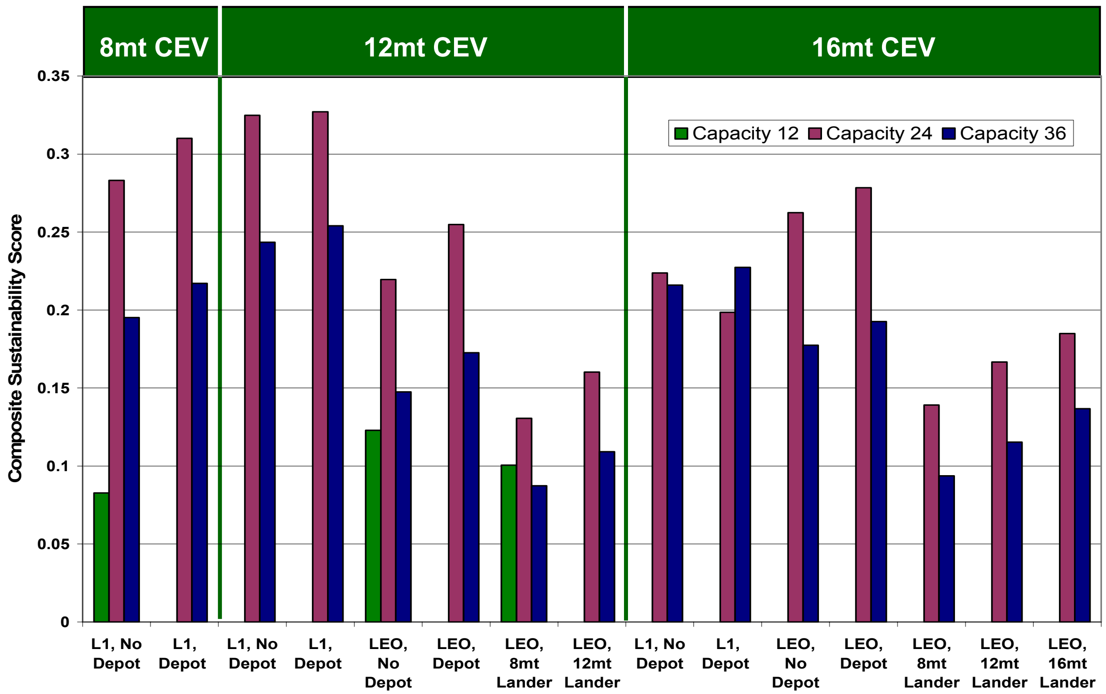
System Reliability
- Launch Incurred Losses Will Require Additional Launches To Successfully Execute Mission Goals
- Losses Of Smaller Cargo ELVs Have Less Impact On Mission Success

Launch Capacity Margin
- Excess Capacity Within Launch Systems To Recover From Failure
- Rewarded For Flexibility (Mitigate Schedule Delays And Technical Issues) And Versatility To Carryout Future New Missions

— TRADE STUDIES:
- 20MT ELV vs 80MT Lift To LEO
- CEV Sizing (8 mt, 12 mt, 16 mt)
- Direct Return To Earth
- SoS Reliability And Systems Reliability
- Launch Capacity/Frequency
- Launch Site, Integration Facilities

SI Measures Interaction Between Launch Infrastructure, Reliability, And Mission Success

Architecture Sustainability Composite Score



- **Only Evaluate Viable Spiral-2 Architectures**
- **Current Estimated Launch Capacity Of 12 Launches Per Year Is Sufficient To Sustain Some Architectures**
- **L1 With 8 Or 12 mt CEV Has Greater Flexibility And Sustainability Than LEO Only**

Approach To Composite Score:

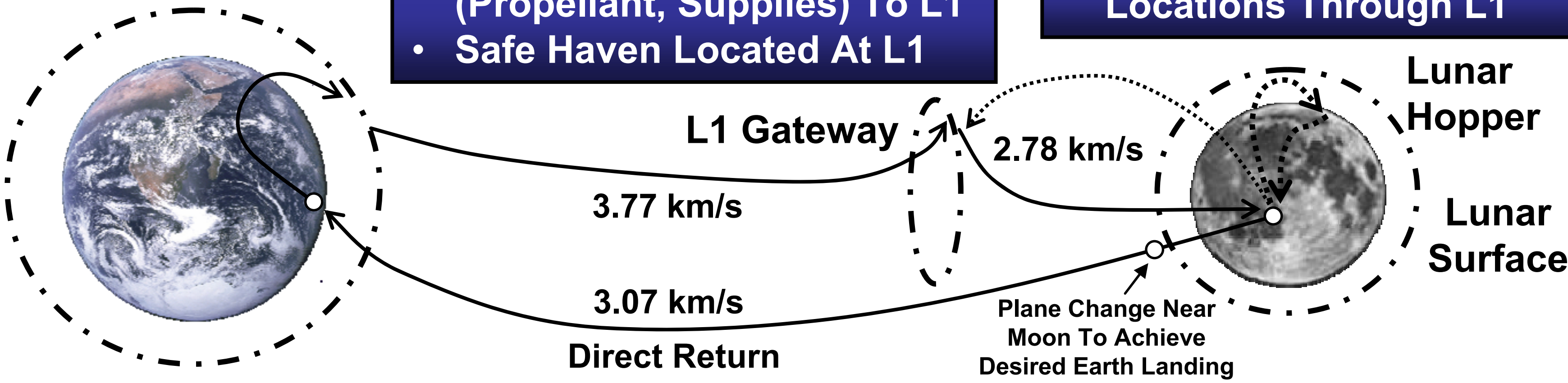
- Adds Influence Of Objectives To The Sustainability Index To Determine Effectiveness Of Viable Architectures Of Responding To Program Objectives

Conclusions:

- **No Benefit For Investment In Further Launch Capability Beyond 24/yr**
- **L1 Enhances Sustainability**

Influence Of Objectives Demonstrates Greater Sustainability Of L1 Architectures

Results - Gateway



- Pre-position Of Cargo (Propellant, Supplies) To L1
- Safe Haven Located At L1

- Explore Multiple Surface Locations Through L1

- Hopper Extends Lunar Access & Capability

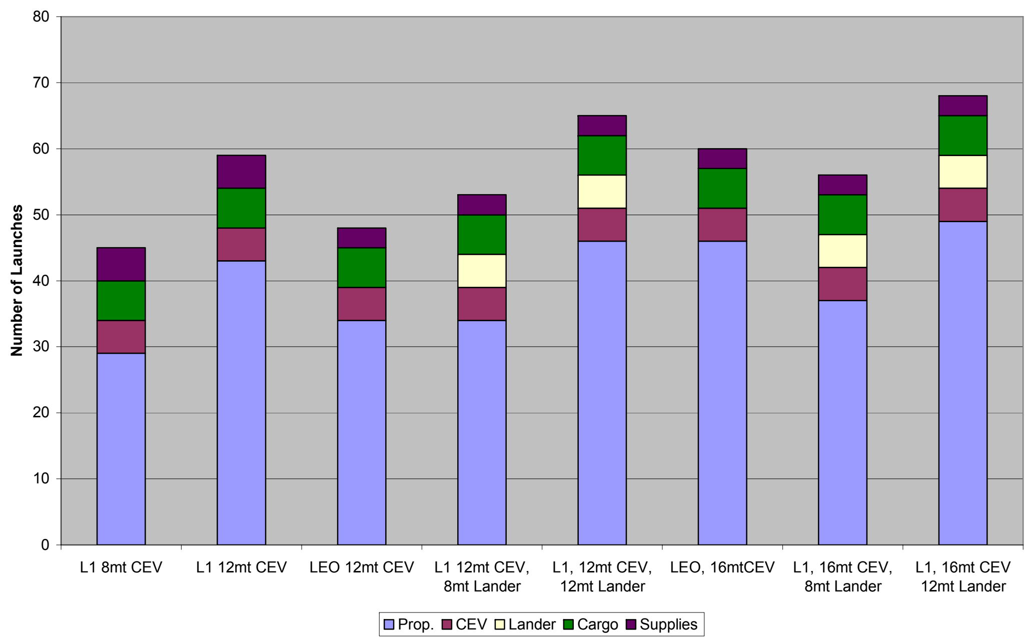
- Multiple ELV Launches Of Cargo To LEO
- Assemble CEV-Mod-L For Lunar Exploration
- Single Launch Of CEV-Mod-E For Crew To LEO
  - IVHMS On Booster
  - Launch Abort System

- Direct Return Without Need To Rendezvous At L1 Or LLO
  - Increased Safety In Emergency
  - Less Engine Firings

- Pre-position Of Supplies And Infrastructure To Lunar Surface
- Safe Haven On Lunar Surface

Gateway At L1 Provides Flexibility, Safety, Shorter Transport Modes

Results – Total Launches To LEO



- **Smallest CEV Through L1 (Less Launches To LEO) Achieved If CEV Lands On Moon**
- **L1 And LEO Only Architecture Competitive**
- **Possibility To Utilize International And Commercial Launch Capability To Supply Propellant To LEO**

Spiral-3

- Assume Lunar Infrastructure Established In Spiral-2
- 20 mt EELV For Cargo Launch
- Two Launch Pads
- EELV With IVHMS For CEV Launch
- 1 Mission Per Year For 5 Years

CEV Sizing

- 8 Or 12 mt CEV Through L1 With Landing On Moon (Supported By CEV Concept Development)
- 12 Or 16 mt CEV From LEO With Landing On The Moon (Supported By CEV Concept Development)
- 8 Or 12 mt Non-reusable Lunar Lander

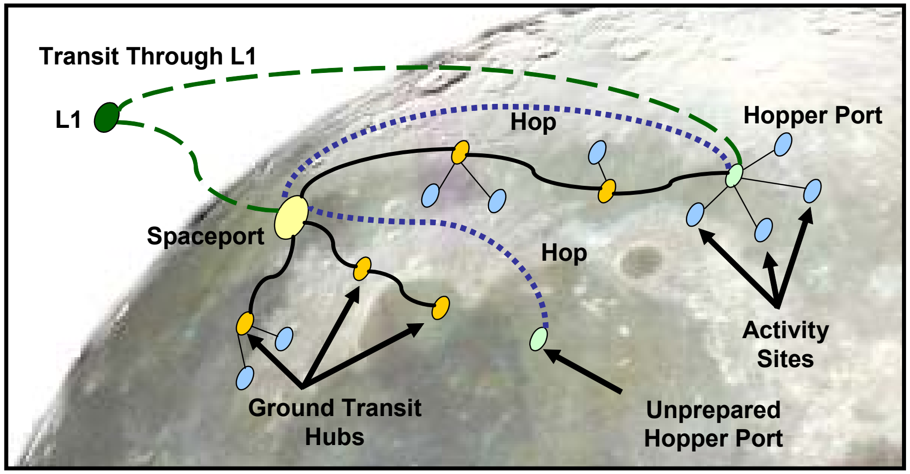
L1 Architecture Analysis Indicates Advantage To CEV That Lands On The Moon

Results - CEV

- **Smaller/Lightweight CEV-Mod-L Provides Greater Architecture Flexibility**
  - Lower CEV-Mod-L Mass Requires Less Pre-position Of Propellant
  - CEV-Mod-L Functional Analysis Leads To 8 mt Minimum Realistic Mass
  - Maximum CEV-Mod-L Of 16 mt Mass For Direct To Lunar Surface
  - CEV-Mod-L Mass Growth Impacts Architecture Effectiveness
- **CEV-Mod-L Permits Landing On Moon and Mars**
  - Similar Functionality Indicated Between Lunar And Earth Landing
  - Only One Crewed Vehicle Development Program Required
- **Direct Return To Earth From Lunar Surface**
  - Capability For Abort, Emergency, And Reduced Propellant Pre-positioning
  - Direct Return Provides Option To L1 Or Lunar Hop At No Added Cost
- **Cross Range Capability Desired For Safe Landing On Land**

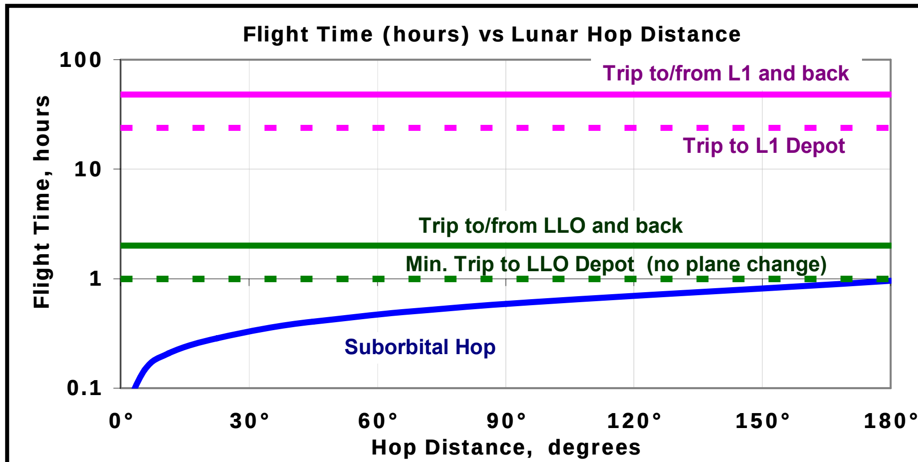
8 mt CEV Goal Provides Greatest Flexibility With L1 Architecture

Results – Lunar Base Location



- Spaceports Will Be Limited Due To Development And Installation Costs
- Ground Transports Have Limited Range
- Hopper Extends Access To Remote Activity Sites
- Hopper Adds Lunar Survey Capability

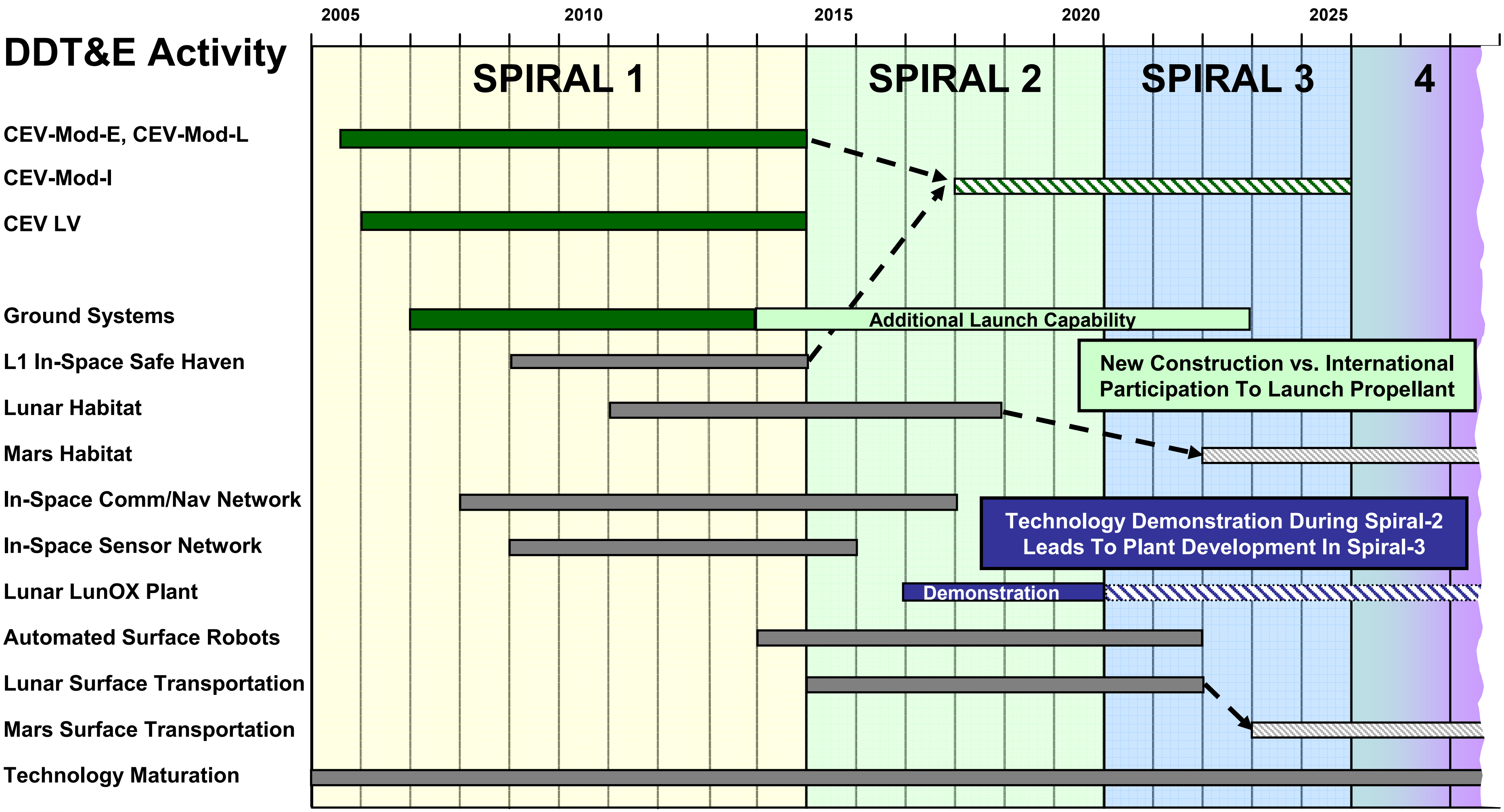
- L1 With Re-supply Capability Permits Access To Any Remote Lunar Location
- CEV Or Lander Permits Access To Lunar Surface And Can Be Used As A Hopper
- L1 Permits Easier Access To Different Sites Not Always Achieved From LLO



Suborbital Hopper Travel Time Much Less Than L1 Trip; Even Much Less Than LLO Depot, When Rendezvous And Refuel Times Are Factored In

Combination Of L1 And Lunar Hopper Provides Greatest Flexibility For Human Exploration Of Multiple Lunar Sites

Top-Level Development Schedule



CONOPS Supports NASA Objectives And Minimizes Concurrent Development Programs

Alternatives Still To Be Evaluated

- Alternative Launch Sites, LVs, And International Participation
- Expand The Analysis Of HLVs And SDVs
- In Space Propulsion Technologies
- Lunar Base Options For Spiral-3
- Investigate Lunar Surface Power Options
- Safe Haven Capabilities
- Expand The Analysis Of Mission And System Reliabilities
- Expand The Analysis Of Mission Success And Contingencies
- Continue ISRU Investigations
- Lunar Cargo Lander Study

Refinement Of CONOPS , Gateway Architecture, And Elements Will Continue

4.0 System And Element Requirements

Functional Allocations

- **Functional**
  - CEV-Mod-L Must Permit Refueling Or Propellant Tank Replacement If Gateway Architectures Are To Be Viable
  - CEV-Mod-L Maximum Nominal Transit Time Is 4 Days
  - CEV-Mod-L Must Have Sufficient Propellant On Moon To Permit Emergency Return Direct To Earth (Which Is More Than Necessary For Trip To L1)
  - CEV-Mod-L Lunar Landing Capability Desired But Not Required In L1 Architecture (Minimize Need For Two Concurrent Crewed Vehicle Development Programs)
  - Safe Haven Located At L1 And Lunar Surface
  - Resupply Of CEV-Mod-L Required To Support Lunar Stay Beyond 4-Days
  - Ability To Resupply Crew Within 15 Days
  - CEV Must Be Capable Of Automated Flight Control
  - CEV Should Support CONUS Landing

Functional Requirements Support NASA Objectives And Maximize Flexibility

Performance Requirements

- **Performance**
  - 8 mt CEV Mass Goal (TBR) Greatly Benefits Gateway Architecture
  - CEV-MOD-L Must Have Provisions And Operational Systems With Margin For 8 Days For Four Crew For Safety Concerns
  - CEV Contains Minimum 3.07 km/s (TBR) For Direct Return From Lunar Surface To Earth (CEV Team Further Refining Value)
  - CEV Must Have Sufficient Cross Range Capability To Support Land Landing
- **Interface**
  - CEV And Cargo Must Interface To Both Atlas-V, Delta-IV Heavy (20 mt Lift To LEO)
  - Common Docking And Transfer Interface On All Elements
  - Common Propellant Transfer And Refueling

Performance Requirements Supports NASA Objectives

Drivers And Sensitivities

- **CEV Mass Strongly Influences Propellant Required**
  - Impact Number Of Launches To LEO
  - Potential Impact To Launch Integration Facilities
  - Mitigation Approach Could Involve International Launch Assets For Re-fueling
- **Radiation Shielding Of CEV Is Severe Penalty**
  - Utilize Solar Weather Prediction To Minimize Risk
  - Transport Segment Limited To 4-Days
  - Safe Havens Available With Sufficient Shielding At L1 And Moon
- **Launch Of Propellant Mass To LEO Dominates All Architectures**
- **CONUS Landing Stresses CEV For Direct Return**
  - Cross Range Capabilities Increased
  - Orbital Plane Change Near Moon Can Add Substantial ΔV

CEV Mass, Launches To LEO And CONUS Landing Drive CEV And Architecture

Drivers And Sensitivities

- **LV Capabilities And Lift Mass To LEO**
- **CEV Crew Size**
- **Propellant Mass Required To Move Propellant In Space**
  - Alternative Technologies May Mitigate Sensitivity
- **Reliability Of Storage And Transfer Of Cryo Propellant In Space**
  - Technologies Under Development Need To Be Demonstrated In Spiral-2
- **ISRU Propellant Or LunOX Production Effectiveness For Future Spiral-3 Missions**
- **Abort Scenarios For Crew Safety Determine Size And Mass Of L1 Infrastructure**
  - Safe Haven Shielding And Supplies For 4 crew For Maximum 15 Days
  - Pre-positioning Of Propellant For CEV Transit

CEV And Architecture Sensitive To Availability And Location Of Re-fueling

Initial Feedback on ESMD Level 1 Requirements (1 of 2)

TOPIC	REQUIREMENTS	IMPLICATION	RECOMMENDATION
Lunar Landing	CEV0450G, CEV0460G, CEV0490G, CEV0500G, CEV0600G, CEV0612G, CEV0630G	Requires two separate vehicle developments – CEV and LSAM; Requires LLO rendezvous for return to Earth	Do not preclude CEV as lunar lander; avoids risk of failed LLO rendezvous; allows direct return to Earth from Lunar surface
Lunar Orbit Rendezvous	CTS0100G, CEV0450G, CEV0460G, CEV0485C, CEV0490G, CEV0500G, CEV0600G, CEV0612G, CEV0630G	Requires uncrewed automated CEV in LLO; Requires additional capacity for LSAM and CEV rendezvous maneuvers and fuel; Source of risk to crew survival	Do not require Lunar orbit rendezvous to transfer crew; Allow CEV to carry crew from Earth surface to lunar surface and back to Earth surface
Launch Site and Ground Support	CTS0020H, CVS0020H	Only Eastern Range can support Exploration missions	Allow additional launch site for redundancy, launch rate, and launch opportunities for Spiral 3 and beyond
Passive Re-Entry	Applicable Document: NPR 8705.2	NPR 8705 requires passive reentry capability for CEV for crew safety; strongly drives CEV design and mold line	Do not preclude active stability concepts if contractor can demonstrate viability and benefits

Written Feedback Will Be Consolidated and Submitted on 3 December as Requested

Initial Feedback on ESMD Level 1 Requirements (2 of 2)

TOPIC	REQUIREMENTS	IMPLICATION	RECOMMENDATION
CEV Launch Abort	CVS0080H, CVS0390C	Requires highly reliable, automated abort / escape capability for CEV LS; Represents "Significant Improvement" in crew survival over existing systems	CEV RFP should include abort / escape capability explicitly; Acquisition and DDT&E approaches should ensure the integration of CEV and LV into a complete Launch System including the balancing of LV reliability with abort/escape requirements; Have CEV LV available for integration and testing with CEV from 2011 thru 2014
CEV LV Reliability	CVS0140C, CVS0390C	Requires high reliability for LV with additional improvement required for Spiral 2 and again for Spiral 3	
Crew Rescue	CTS0405G, CTS0120G, CEV0410G	Rescue anytime and anywhere is challenging and may not be feasible; Requirements suggest second CEV launched with every crew as remotely controlled backup CEV for escape/rescue	Do not preclude backup CEV with launch on demand capability as rescue vehicle
Extensibility to Mars	No CONOPS or Requirements for Spirals 4 and 5	Mission needs for Spirals 4 and 5 are not factored into CONOPS and architecture	Consider at a minimum Spiral 4 and its needs for transportation and staging in requirements analysis and definition; include extensibility to Mars in proposal evaluation criteria

Written Feedback Will Be Consolidated and Submitted on 3 December as Requested

5.0 Trade Studies And Analysis For Super System And CEV

Key Architecture Trades

Name		Description	Results	Status
1a	**Architecture FOMs – Programmatic Objectives**	The set of objectives prepared for the proposal and the weighting factors for evaluating or ranking the architectures must be investigated to identify sensitivities. That analysis must also incorporate the possible programmatic concerns in an attempt to determine the robustness of the architectures to changes in program direction and scope.	• **Gateway Architecture Has Highest Composite Score Against Program Objectives.**	**Completed**
1b	**Architecture FOMs – Efficiency Index**	The development of a novel efficiency index based on transportation systems is needed to quantitatively measure the performance of the architectures with respect to mass of architecture elements, propellant usage, launch capacity, and launch frequency.	• **Efficiency Index Shows L1 Has Competitive Performance Through Spiral-3.**	**Completed**
2a	**Gateway Location**	Excursions on the location of the gateways will be investigated. As identified by early studies of the objectives and evaluation criteria, the location of the gateways is an important part in the performance of the architecture. A LEO gateway has obvious advantages but the location of a gateway at L1 or LLO will be investigated.	• **L1 And LLO Offer Comparable Performance.** • **L1 Has Flexible Access To Lunar Surface.**	**Completed**
2b	**Gateway Location – L1 Orbital Characteristics**	A study is needed to determine the nature of the Earth-Moon Lagrange Point (L1) orbit. Issues of orbital geometry, fuel usage, rendezvous maneuvering and period must be addressed.	• **L1 Orbit Analysis Shows Stable Orbit Achievable**	**Completed**
3	**Launch Vehicle To LEO**	Utilization of a LEO gateway is going to be dependent on how most of the payloads are lifted into LEO. This indicates that the advantages and disadvantages of existing ELVs and future heavy Lift vehicles (HLVs) must be evaluated both independently and when used in consort with other LVs. Initial modeling and simulation indicates that multiple acceptable solutions are achievable with proportional blending of ELVs and HLVs within the architecture but that the choices have major implications to life cycle costs and scheduling.	• **ELVs Support The Architecture And Require Modification Rather Than Development.** • **HLVs Minimize Launches Required But Require Vehicle Development.**	**First Analysis Completed. Further Analysis Is Underway**

Key Architecture Trades

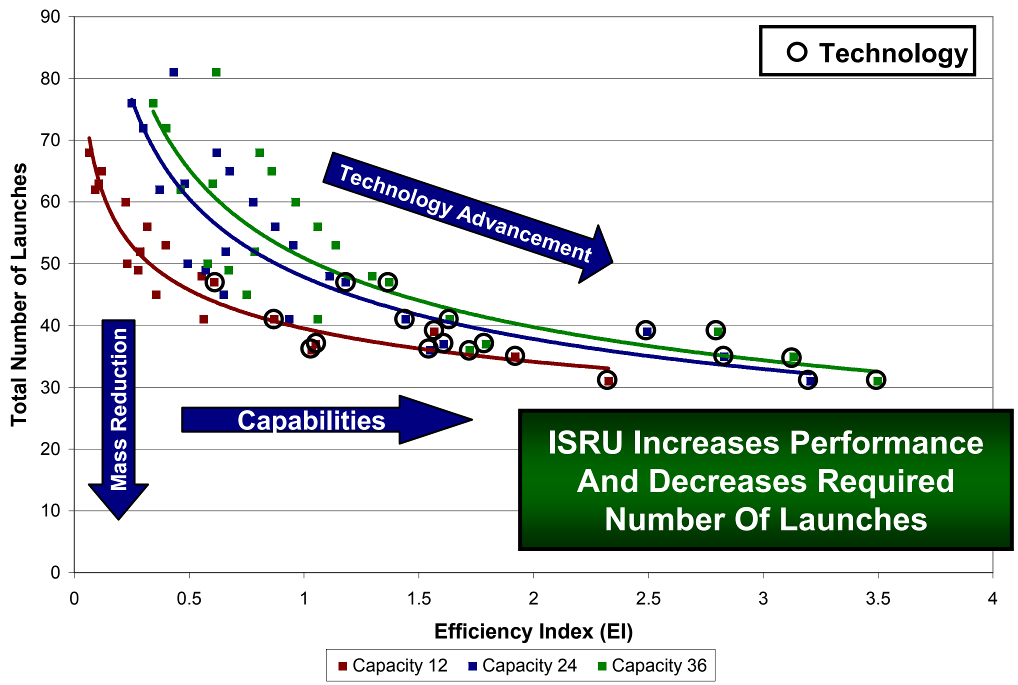
Name		Description	Results	Status
4a	**Lunar Gateways – Locations and Distribution**	Behavior modeling of lunar exploration missions will be highly dependent on the location of lunar landing sites and the impact on the architecture to be able to reach and support them. Therefore, trades are needed to look at locations near the equator, poles, and latitudes between. A central location with excursions from it compared to multiple and maybe independent locations on the moon need to be examined.	• **Both Polar And Equatorial Locations Preferred For Science And ISRU.** • **L1 Permits Access To Both.** • **Lunar Hopper Provides Added Capability.**	**Underway**
4b	**Lunar Gateways – Mission Duration**	The length of lunar exploration will be related to the goals and desires of the USA and the need to test critical systems prior to crewed operations extend to Mars. Schedule and achievements must be flexible to account for testing of critical systems to reduce risk while not placing undue delays on further exploration of Mars.	• **Extended Lunar Stay Needed To Fully Test Infrastructure.** • **Multiple Early Missions Desirable To Refine CONOPS And Equipment.**	**Underway**
4c	**Lunar Gateways - Power**	The power requirements for a prolonged stay on the lunar surface will greatly impact selection of power supply technologies. Lunar night will be a strong driver for sustainable power.	• Alternative Technologies Are Being Traded	**Started**
4d	**Lunar Gateways - ISRU**	The potential for in situ resource utilization (ISRU) for the generation of Lunar oxygen (LunOX) from lunar rock for use as the oxidizer in propellant would substantially decrease the logistics of transporting propellant. The infrastructure, power required, and technical maturity need to be evaluated in order to determine if the approach can be economical.	• **ISRU Reduces Required Propellant Mass That Must Be Launched From Earth To Support The Architecture**	**Underway**

Key Architecture Trades

Name		Description	Results	Status
5a	**Nuclear Power**	Trade studies are needed to define nuclear options for power and propulsion. The savings in launches of fuel for power generation must be compared to the number of launches required to establish and operate a nuclear facility on the lunar surface or in space.	• The payback in reduced launches possible with nuclear power must be determined.	**Started**
5b	**Nuclear Propulsion**	Long term missions indicate the need to have alternative propulsion but the impacts to launches and CONOPS must be explored to determine the benefits vs. the cost as expressed in launches to LEO.	• Nuclear propulsion benefits must be compared to alternatives.	**Started**
6	**Robotic Options**	Robotic options will be explored through trade studies and through the behavior modeling including allocation of functionality to robots or humans. The use of robots as precursors to human exploration will drive the communications/data handling and autonomous operation of the robots and place requirements on the architecture.	• The ability of astronauts and scientists to have a tele-presence along with the level of autonomous operation will drive the robotic missions	**Started**
7	**Mars Mission**	The inability to easily resupply or rescue a Mars mission indicates that greater redundancy and flexibility will be required in comparison to the planned lunar missions.	• Novel and affordable approaches must be considered to achieve mission success and maintain crew safety	**Started**

6.0 Technology Requirements

Technology Benefits



Conclusions:
- **LEO Architecture Inherently More Efficient than an L1 Architecture**
- **Selected Technologies (e.g. ISRU) Offer Substantial Performance Gains**

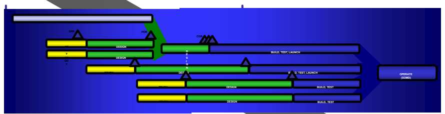
Maximum Efficiency Curve
- Efficiency Curve Is Defined By Capabilities, Architecture, And Technology
- ISRU Provides Large Increase In Efficiency By Minimizing Launches To LEO
- Small CEV In A LEO Architecture Has Large Efficiency Benefits Compared To A Large CEV

Impact To Architecture
- Technology Improvements Can Have Large Effect On Architecture Efficiency
- A Combination Of Launch Capabilities, Architecture And Technology Improvement Avenues Can Be Traded To Find Maximum Efficiency At Minimum Risk

Architecture Analysis Has Identified Technology Investments

Development of Spiral 1 and Spiral 2 Critical Technologies

2005 2010 2015 2020 2025 TBD



- Crewed Access to Low Earth Orbit
- Robotic Exploration, Lunar

Spiral-1

- Crewed Exploration, Lunar Extended Duration
- Robotic Exploration, Mars

Spiral-2

- Crewed Exploration, Lunar Long Duration
- Robotic Exploration, Mars

Spiral-3

- Other Potential Capabilities

- Crewed Exploration, Mars Surface

Critical Technologies	Planned
IVHMS and Launch Abort Subsystem	Spiral 1
Thermal Protection System (TPS)	Spiral 1
Automated Rendezvous and Docking	Spiral 2
In-Space Refueling (Cryo)	Spiral 2
Power Generation	Spiral 3
Propulsion	
Electric	Spiral 3
ISRU - LunOX	Spiral 3
Nuclear	Spiral 4
Closed-Loop ECLSS	Spiral 4
Artificial Gravity	Spiral 4
Autonomous Robotics	Spiral 4

Planned Technology Development

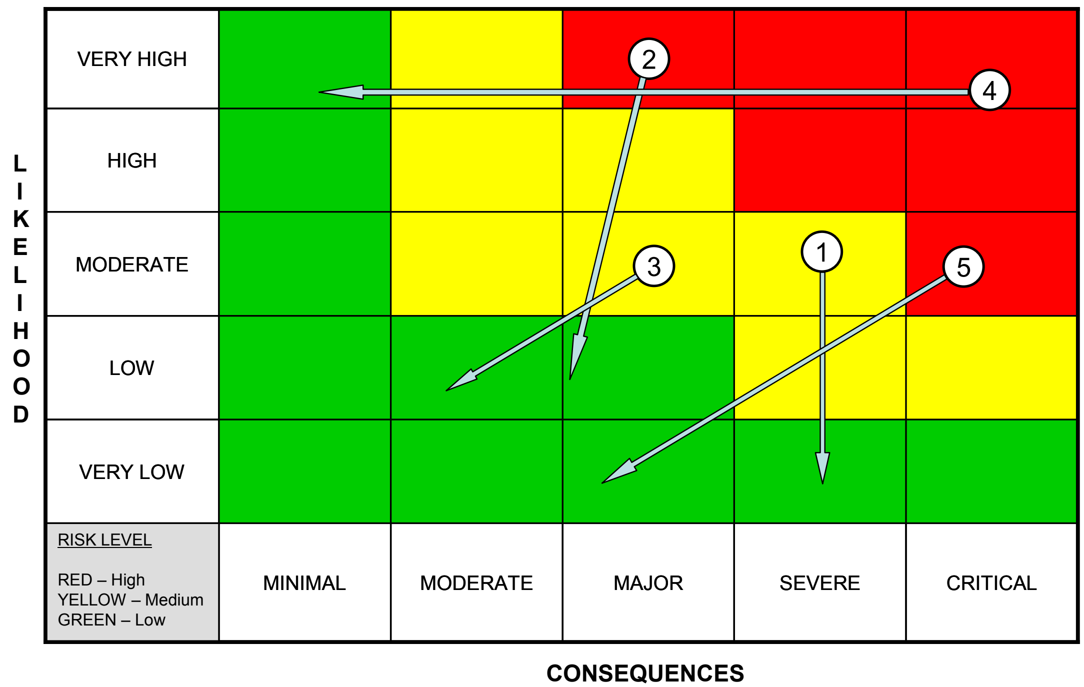
Critical Technologies Included in CEV and SoS Development Plans

7.0 Exploration Programmatic And Technical Risk Assessment

Top-Level, Long-Term Architecture Risks

DESCRIPTION

(1) Not Achieving Human Flight Safety Ratings for a System Using Existing United States Launch Vehicles
(2) Failure of a Space Docking Attempt
(3) Strained Relations with Countries That Can Provide Man Rated Launch Vehicles
(4) Long Term Space Exposure Causing Damage To Infrastructure
(5) Failure of Maintenance and Logistics Supply Train



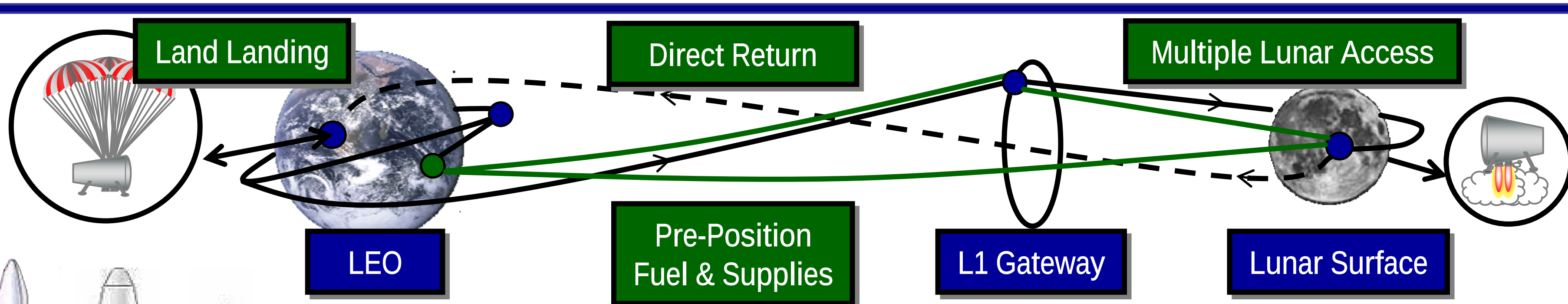
MITIGATION

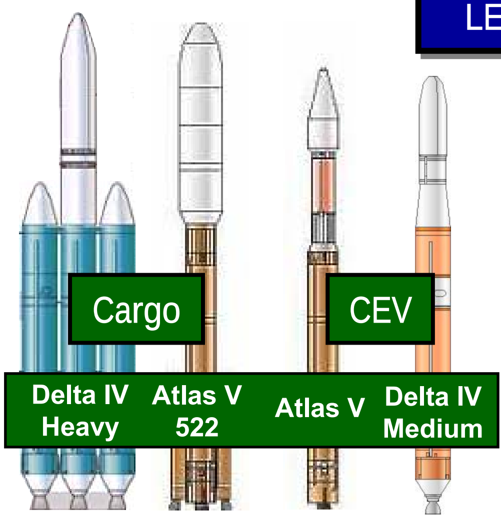
(1) Establish Human Flight Ratings of Multiple Launch Systems Using Different Launch Vehicles to Obtain a Primary Launch System and Multiple Backup Launch Systems
(2) Implement into the Architecture Robust Standard Interfaces and a Recover and Reattempt Docking Capability. Provide Early Testing and Integration. Establish Straightforward Safety Docking Procedures.
(3) Use Foreign Man Rated Launch Vehicles as Backup Systems.
(4) Design the Architecture with Multiple Crossover Functions and Duplicate Systems. Provide On-Board Repair Capability/Access to Subsystems to Facilitate Emergency Repairs and Execution of Standard Maintenance Procedures. Provide Redundant Communication Channels to Maintain Open Communication to Ground Support Personnel.
(5) Provide Frequent Robotic Supply Runs to All Gateways. Integrate Logistic Paths to Reduce Long Distance Resupply. Provide an Excess of Supplies to the Supply Depot. Frequently Ship Supplies from the Supply Depot to Keep Supplies Distributed.

Architecture Risks Are Identified And Mitigation Strategy Developed

8.0 Summary

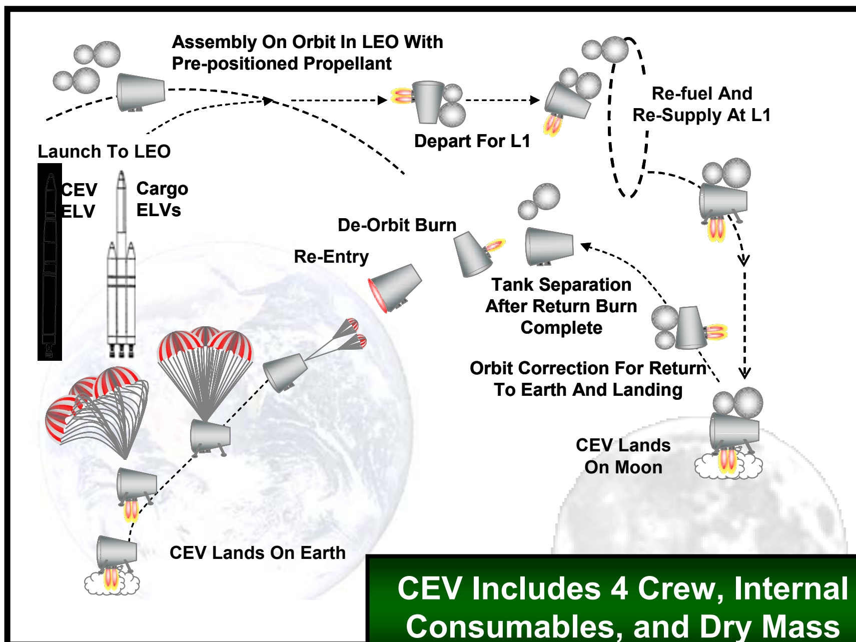
Gateway Architecture





CEV: EELVs With IVHMS And Launch Abort

Cargo: 20 mt EELV To LEO Orbit, 24 Launch/Year



CEV Includes 4 Crew, Internal Consumables, and Dry Mass

Architecture Elements

- CEV
- Human Rated Launch System
- EELV Cargo Launch System
- In Space Cargo Transport
- Safe Haven
- Lunar Habitat
- Cargo Lander
- Lunar Hopper

Through Spiral 3: Gateway Architecture Using ELVs And 8 mt CEV Supports All Missions

Summary – CA1

Exploration Objectives	• Discussed Objectives, Updates • Relations to Architecture
Architecture Overview/Definition	• Gateway Architecture Refinement • Use of Transportation Model for CEV Operations • Evaluation Using Novel FOMs
System and Element Requirements	• Functional Allocations, Drivers, Sensitivities • Feedback on ESMD Requirements
Trade Studies and Analysis	• Highlighted Key Architecture SoS Trades • Documented in Mid-Term Report
Technology Requirements	• Identified Technology Investments • Mapped Technology Needs to Spiral Timelines
Programmatic and Technical Risk Assessment	• Defined Long-Term Architecture Risks and Mitigation Approaches

Back Up

Inputs – Assess National Goals

References:

- **The Presidential Directive**
  - Implement A Sustained And Affordable Human And Robotic Program
  - Extend Human Presence Across The Solar System
  - Develop The Innovative Technologies, Knowledge, And Infrastructures To Explore
  - Promote International And Commercial Participation In Exploration
- **NASA Level 0 Requirements**

Guidelines:

- **Columbia Accident Investigation Board Final Report**
- **Aldridge Commission Report**

National Concerns

Programmatic Challenges

President, Congress, NASA, Industry

We Identified Three Top-level, Strategic Objectives For The Vision For Space Exploration

Science

- **Establish a robust, sustainable program of exploration**

Economic

- **Enable a self-sustaining market-based space economy**

Security

- **Foster U.S. national defense and economic security**

Three Strategic Objectives Drive The Major Objectives That Support Scientific, Economic And Security Concerns Of NASA And The Nation

Programmatic Challenges

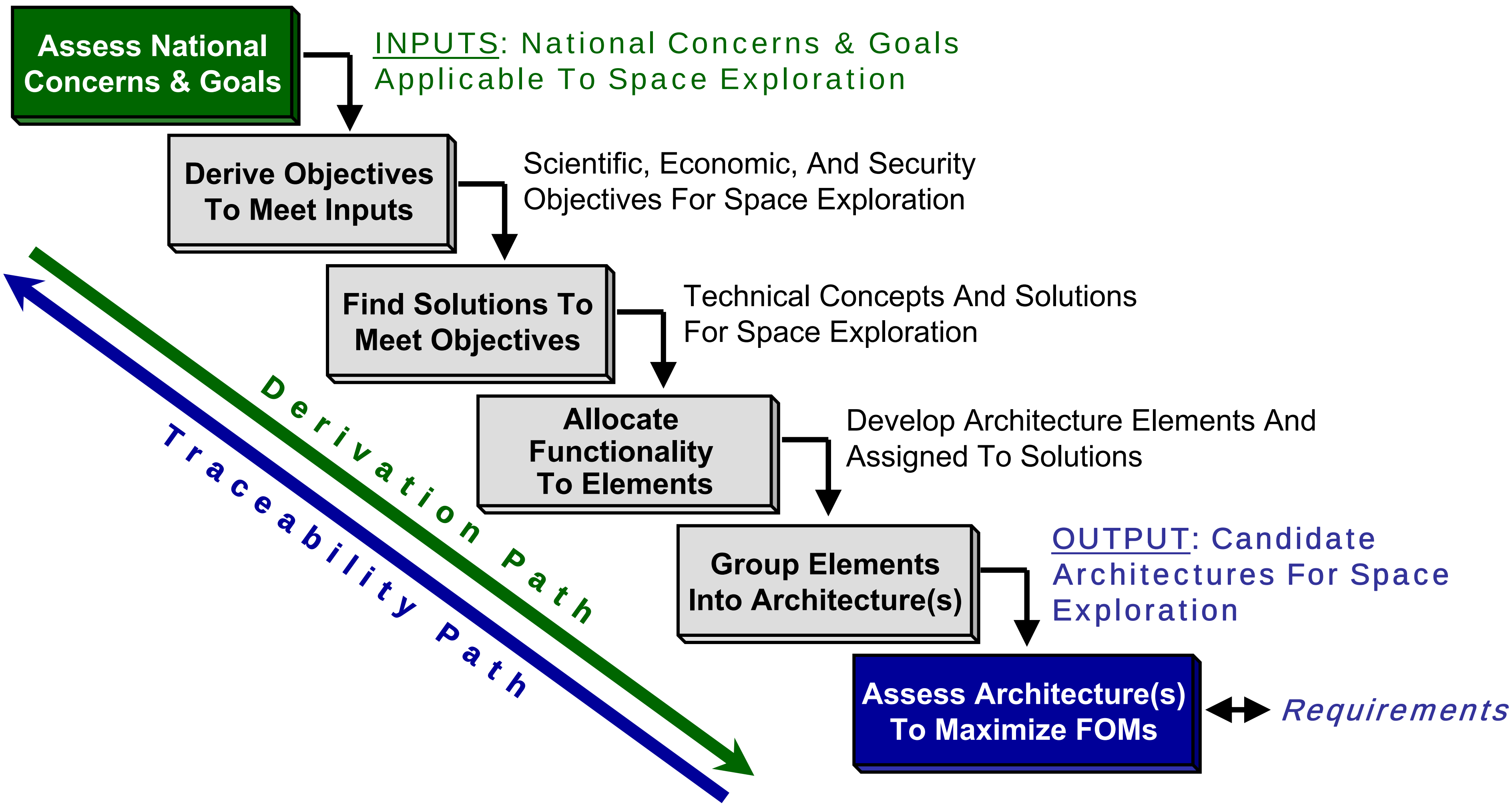
Our Team Examined Experiences From NASA, DoD, And Commercial Projects In Formulating Our Preliminary Architecture

These Experiences Motivate Choices Of Specific Architecture Elements And Approaches To Support The Decades Long Campaign

Historical Challenges	Architectural Features Motivated to Respond to Difficulties
Program Funding Fluctuations	• Incremental Approach To Development. • Spiral Development And Use/Qualification Of Commercial Components To Achieve Capability
Program Redirection – Political Changes	Develop An Adaptable Architecture Composed Of Overlapping Functionality To Allow System Flexibility And Evolution
Instability Of International Partnerships	Segment Missions Based On Critical US Economic And Security Requirements And Non-critical Items To International Participation
Volatile Science Objectives	Standard Equipment Interfaces And Payload Accommodations, Use Of Science Peer Review Process Modeled On Hubble Space Telescope
Public Program Support Diminishing With Time	Provide Inspiration Through Regular Significant Events, Establish Broad Contractual Base, Broad Involvement And Extensive Education
Lack Of Predictable Access To Exploration Data / Results	Distributed Nodes, Vehicles, And Sensors Paired With High Bandwidth Data Paths To Provide Abundant Amounts Of Data

Our Architecture And Approach Will Mitigate Many Of The Challenges Experienced By Large And Complex Projects Taking Place Over Many Years

Generate Architectures



Our Architecture Development Process Is Designed To Accommodate Changes At All Steps And Traces The Impacts Of The Changes Through The Architecture Model

Exploration Objectives

Strategic Objectives	Exploration Objective	Science	Economic	Security	NASA Level-0 Req Link
Establish Robust, Sustainable Program Of Exploration	Provide maximum probability of Total Program Success	√	√		1
	Provide maximum probability of Mission Success	√	√	√	1
	Provide for safety of human space explorers	√	√	√	1.5, 3.3
	Provide for flexibility in and aborts during mission execution	√	√	√	1.1
	Provide means to be anywhere on lunar surface	√	√	√	1.1, 1.7, 2
	Provide many opportunities for robotic science/exploration	√	√		1.2, 1.4, 1.6
	Provide many opportunities for human science/exploration	√	√		1.3, 1.5
	Provide maximum benefit/return-to-cost ratios	√	√		1
	Provide opportunities to inspire/train next generation	√	√	√	6
	Provide opportunities to improve foreign relations	√	√	√	3.2, 4
	Provide means to test hardware bound for Mars & beyond	√	√		1.3, 1.5, 3.2
Enable Self-Sustaining Market-Based Space Economy	Ensure broad/expanding industrial base for space		√	√	2, 4, 5
	Provide demand for steady supply of hardware, parts		√	√	2, 4, 5
	Maximize compatibility of space hardware/processes		√		3.2, 4
	Provide opportunities to excite the general public		√		6
Foster U.S. National Defense And Economic Security	Provide means to approach launch on demand	√	√	√	2, 5
	Provide assured access to space	√	√	√	1.7, 2, 3.1, 5
	Provide means to protect U.S. space assets		√	√	Not In Level-0
	Ensure protection of U.S. intellectual property		√	√	Not In Level-0
	Ensure U.S. leadership in space technology		√	√	6
	Ensure U.S. lead in robotics/UAV technologies		√	√	1.2, 1.4, 1.6

All Of Our Objectives Are Linked To NASA Level-0 Requirements

Ranking Of Program Goals

H	0.8	High influence or interest
M	0.5	Med. influence or interest
L	0.2	Low influence or interest

Score = Sum(**Influence** x **Interest**)

What Stakeholders Want

STAKEHOLDERS	NASA	Congress/Taxpayer	Dept. of Defense	State Department	General Public	School System	International Partners	Science Community	Space Contractors	Space Entrepreneurs	Space Activists	United Nations	Score	RANK
LEVEL OF INFLUENCE ON PROGRAM	H	H	H	M	M	M	M	M	M	L	L	L	**Score**	**RANK**
Regular PR --"Wow factor"	H	H	L	L	H	H	L	M	H	H	H	L	3.45	1
National Pride/International Prestige	H	H	H	M	H	L	H	L	L	L	L	L	3.39	2
Economic/Intellectual Security	L	H	M	H	M	H	M	H	M	M	L	L	3.33	3
Return on Investment thru Commercialization	M	H	L	L	H	L	H	M	H	H	H	L	3.21	4
Return on Investment thru Jobs	M	H	L	L	H	L	H	M	H	H	L	L	3.09	5
Accessible science	H	L	M	L	M	M	M	H	M	L	L	L	2.82	6
Regular Work -- Big projects	H	M	L	L	L	L	H	M	H	L	L	L	2.67	7
National Security (militarily)	L	H	H	M	M	L	L	L	L	L	L	L	2.46	8
Superiority	L	H	H	M	M	L	L	L	L	L	L	L	2.46	9
Direct Space Experimentation	M	L	M	L	L	H	L	H	L	M	M	L	2.40	10
Constant Data for Theoretical Evaluation	M	M	L	L	L	H	L	H	L	M	M	L	2.40	11
Stay in School by having neat stuff available	H	L	L	L	M	H	L	M	L	L	L	L	2.28	12
Regular Return on Investment	M	H	L	L	H	L	L	L	L	L	L	L	2.22	13
Math & Science Majors	M	L	L	L	L	M	L	H	H	L	L	L	2.19	14
Fast return -- short term risk for recognition	L	L	L	L	L	L	H	M	L	H	L	L	1.77	15
Benefits Sharing	L	L	L	M	L	L	H	L	L	L	L	H	1.77	16
Private/Direct Access or Experience	L	L	L	L	M	L	L	M	L	M	H	L	1.68	17
International Balance	L	L	L	H	L	L	L	L	L	L	L	H	1.62	18
Raise Standard of World Living	L	L	L	M	L	L	M	L	L	L	L	H	1.62	19
Space Colonization	L	L	L	L	L	L	L	L	L	M	H	L	1.38	20

Objective Factors

1.0 - 0.7 (Ranks 1–5)

0.7 – 0.5 (Ranks 6–14)

0.5 – 0.3 (Ranks 15–20)

Addressing Key Objectives Is Used To Assign Objective Weighting Factors

Summary Of Objectives

- **Construct Set of Objectives That Demonstrate Both Technical And Political Realities**
- **NASA FOMs – Efficiently Relate to Technical Requirements**
- **Schafer Objectives – Qualitatively Rank Stakeholders Interests in Overall Architecture Operation**
  - **Foster Use of Robots:** Promote the Development and Operation of Robotics To Perform Tasks Difficult For Humans
  - **Increase Commercial Opportunities:** Promote the Partnership with Private Enterprise, Increase Potential For Space Economies
  - **Increase Flexibility To Changing Goals**
  - **Foster More International Opportunities:** Promote International Cooperation Though Launch Services and/or Joint Ventures
  - **Utilize Progressive Development**
  - **Regular Scheduled Milestones:** Promote Regular Opportunities For Public Buy-in
  - **Minimize Life Cycle Costs:** Promote Flat Annual Costs
  - **Minimize Reliance on Optimization:** Promote Modularization and Reuse Across Applications
  - **Minimize Reliance on New Technology:** Promote Use of COTS and Existing Technology to Minimize Development Cost and Time

	Objectives	Weighting Factor
NASA FOMs	**Safety**	0.7
	Reliability	0.3
	Sustainability	0.7
	Affordability	0.5
	Extensibility	1.0
	Evolvability	1.0
	Foster Use of Robots	0.7
	Increase Commercial Opportunities	0.5
	Increase Flexibility To Changing Goals	1.0
	Foster More International Opportunities	0.5
	Utilize Progressive Development	0.7
	Regular Scheduled Milestones	0.7
	Minimize Life Cycle Costs	0.8
	Minimize Reliance on Optimization	0.5
	Minimize Reliance on New Technology	0.3

Architecture Composite Score

Objectives		Objective Factor	Architecture Score
NASA FOMs	**Safety**	0.7	
	Reliability	0.3	
	Sustainability	0.7	
	Affordability	0.5	
	Extensibility	1.0	
	Evolvability	1.0	
Foster Use of Robots		0.7	
Increase Commercial Opportunities		0.5	
Increase Flexibility To Changing Goals		1.0	
Foster More International Opportunities		0.5	
Utilize Progressive Development		0.7	
Regular Scheduled Milestones		0.7	
Minimize Life Cycle Costs		0.8	
Minimize Reliance on Optimization		0.5	
Minimize Reliance on New Technology		0.3	

Program Objectives:
- Objective Factors Reflect Relative Importance Of Objective
- Each Viable Architecture Is Evaluated With Regards To Every Objective

Architecture Score:
- The Architecture Score Is A Performance Evaluation

Composite Score:
- Combine Objective Factor With Architecture Score To Determine Composite Score

Composite Score = Objective × Performance

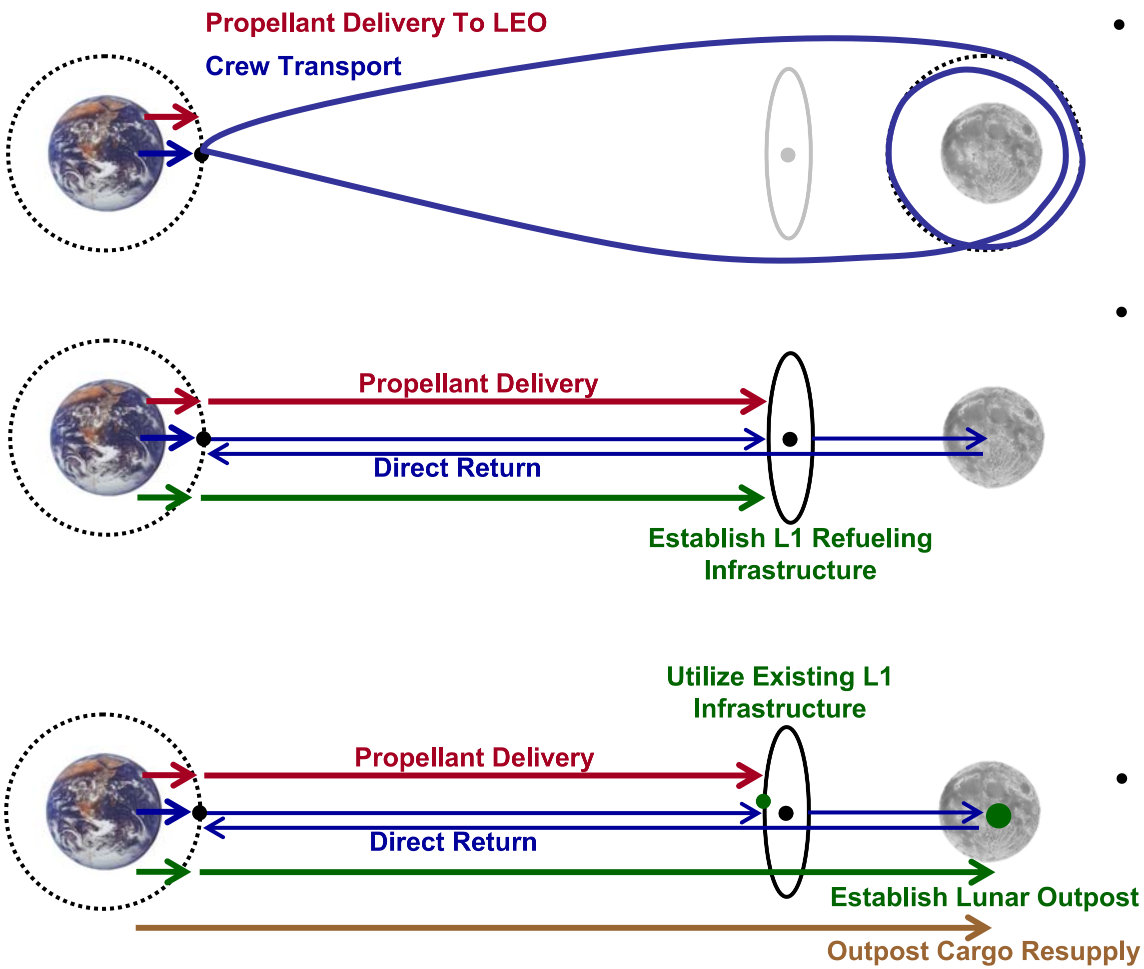
Composite Score Reflects Performance And Program Objectives

Mission Definition

		Reference Missions	Architecture CONOPS	CEV CONOPS
Spiral-1 2008-2014	1A	Robotic Orbiter to Moon	• Minimal Architecture Needed Prior To Lunar Exploration In Spiral 2 • Selected Architecture Concepts For Spiral 2 Will Bound The Design Space • Technology Demonstrations	• Design CEV For Stressing Spiral 2 And Utilize Design In Spiral-1 • Selected CEV Concepts Bound The Design Space
	1B	CEV Mod-E Flight Test Demo		
	1C	Robotic Lander on Moon		
	1D	CEV-Mod-E w/ Crew		
	1E	CEV Mod-L Demo w/o Crew		
	1F	CEV Mod-L Demo w/ Crew		
Spiral 2 2015-2020	2A	CEV-Mod-L to Lunar Orbit	• Staging In LEO, Direct To Lunar Surface • Staging In LEO, Through L1 To Lunar Surface – Direct Return To Earth • ISRU Propellant Production	*19 Concepts Identified For Evaluation In Architecture Model*
	2B	Short Crewed Mission to Lunar Surface		
	2C	Initial Extended Crewed Mission to Lunar Surface		
	2D	Extended Crewed Mission to Lunar Surface		
	2E	Robotic Orbiter to Mars		
	2F	Robotic Lander to Mars		
	3A	Long Duration Lunar Testbed for Mars	• Extend And Expand Lunar Architecture For Spiral 3	• Utilize CEV-MOD-L • Develop CEV-MOD-I
	3B	Lunar Testbed for CEV-Mod-I		
	4	Mars Flyby and Test of Martian Lander		
	5	Initial Human Mission to Mars Surface		

The Architecture, CEV, And Reference Missions Are Included In The Transportation Model

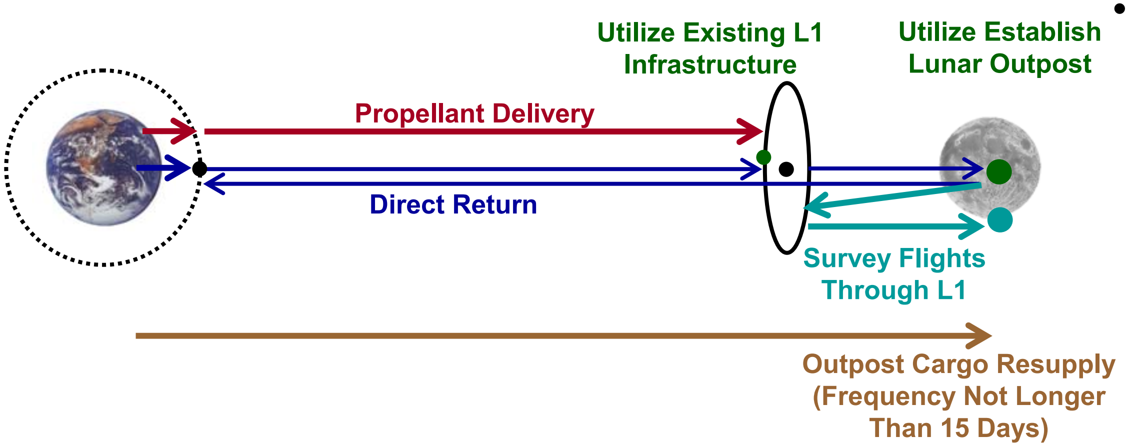
CONOPS – Spiral 2



- Lunar Fly-By
  - Launch CEV To LEO
  - Assemble/Refuel In LEO
  - CEV To Lunar Orbit
  - 8-Day Trip
- Lunar Landing – Short Stay
  - Preposition Propellant At L1
  - Launch CEV To LEO
  - Assemble/Refuel In LEO
  - Refuel At L1
  - Land On Lunar Surface, 3-4 Days Stay, No Habitat Or Prepositioned Supplies
  - Direct Return To Earth
- Lunar Landing - Extended Stay
  - Short Stay CONOPS With Additions
  - 7-14 Days Stay, Preposition Habitat And Supplies

CONOPS Supports NASA Objectives With Minimal Development And Prepositioning

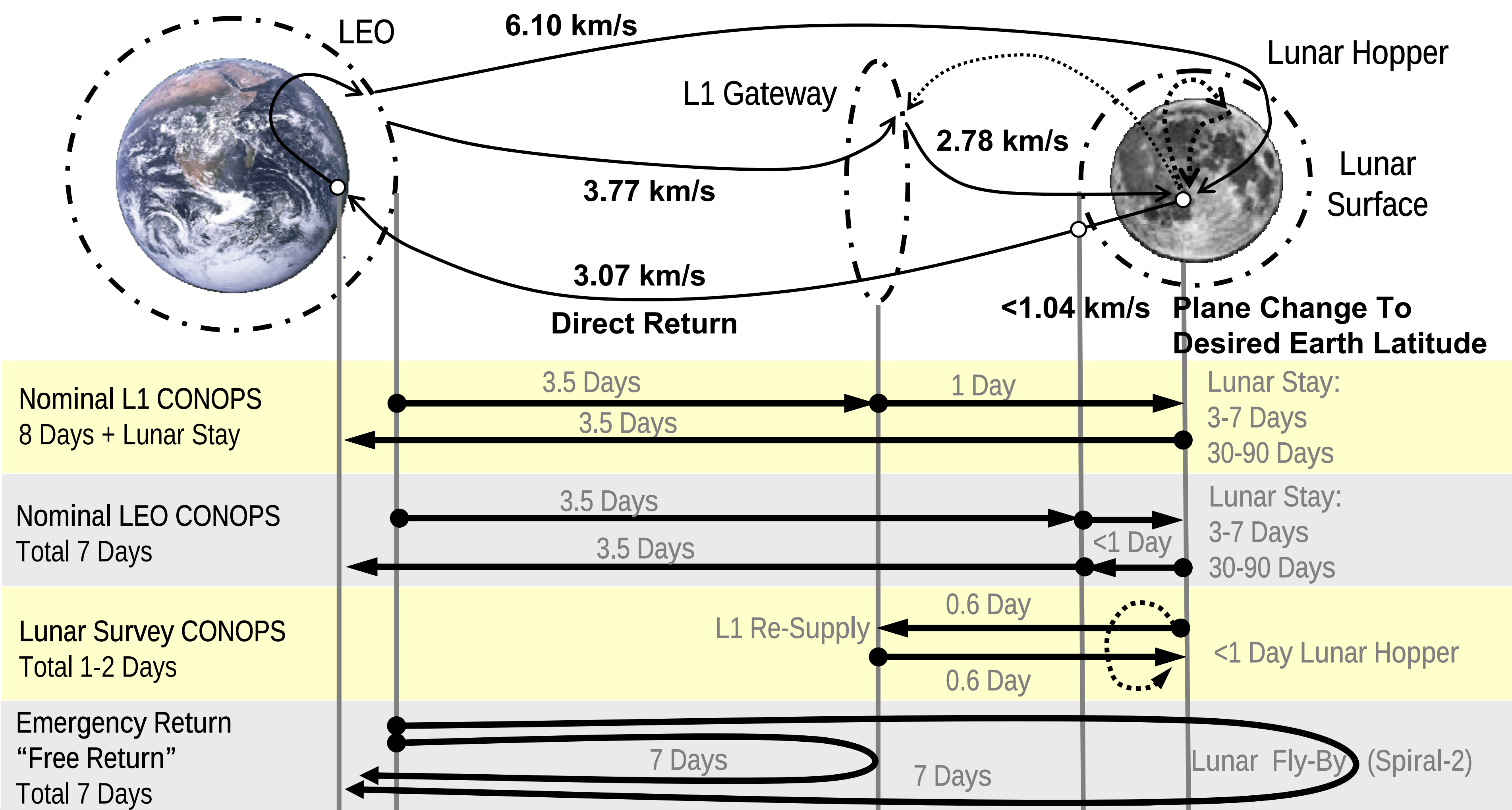
CONOPS – Spiral 3



- **Lunar Landing – Sustained Presence**
  - Preposition Propellant At L1
  - Launch CEV To LEO
  - Assemble/Refuel In LEO
  - Refuel At L1
  - Land On Lunar Surface, 30-90 Days Stay
  - Preposition Habitat And Supplies
  - Resupply Missions From Earth To Lunar Surface
  - Crewed Lunar Survey: Add Lunar Hopper Or CEV To Multiple Lunar Sites Through L1
  - Direct Return To Earth
- **Lunar Testbed For CEV-MOD-I**
  - Launch CEV-MOD-I To LEO
  - Assemble/Refuel In LEO
  - CEV-Mod-I To L1
  - 8-Day Trip

Additional CONOPS Supports Prolonged And Sustainable Presence On Moon

Transport Mode Timelines



Eight Days of Supplies And Minimum 3.07 km/s Within CEV Required for Safety

Transportation Model – Inputs

- **Launch Vehicle**
  - Booster Sizes Of 20mt And 80mt
  - Derived Launch Capabilities From Booster Availability And Integration Requirement Inputs.
  - 7 To 12 Launches Consistent With Existing Launch Support And Vehicles (Delta IV Heavy And Atlas V-551)
  - 24 Launches Must Use Both Delta And Atlas, Two Assembly Facilities And Two Launch Pads
  - Additional Launches Requires New Facilities
- **Transportation Parameters**
  - ΔV And Transported Mass Determine Propellant Requirements And Flight Times Between Nodes
- **Other Parameters**
  - Reliability Of Activities At Each Node Such As Launch, Docking, Engine Restart Failure, Etc.
  - Cryogenic Propellant Boil Off Rate
  - Support Structure Masses (E.G. Habitat, Power Plant, Safe Haven)

Transport Table

CEV Mass 12 **mt** **Fuel Mass Penalty** 0.3 **LanderMass** 8

Action	ID	CargoDeltaV	FltTime(days)	CargoMass	FuelNeeded	CEVDeltaV	FltTime	CEVFuelNeeded
LEO2L1	0	3.77	3.575052535	8	14.5309517	3.77	3.575052535	21.79642761
LEO2Moon	1	6.1	4.519280199	4	16.1983838	6.1	4.519280199	48.5951515
LEO2Mars	2	10.2	179.7127568	20	26.0379931	10.2	179.7127568	33.98723785
L12Moon	3	2.77	0.55343636	6	7.02799658	2.77	0.55343636	14.05599316
L12Mars	4	10.2	179.2280323	8	10.4151973	8	223.9836043	23.0404785
Mars2L1	5	10.2	179.2280323	8	10.4151973	8	223.9836043	23.0404785
Mars2LEO	6	10.2	179.7127568	20	26.0379931	10.2	179.7127568	33.98723785
Mars2Earth	7	7.2	180			7.2	180	19.68992262
Moon2L1	8	2.77	0.55343636	6	7.02799658	2.77	0.55343636	14.05599316
Moon2LEO	9					4	3.5	8.951811838
Moon2Earth	10	3.07	3.5			3.07	3.5	16.19272592
L12LEO	11	3.	[illegible]	[illegible]	09517	[illegible]	[illegible]	[illegible]
L12Earth	12	0.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dummy	13	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
EarthLaunch	14	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
MoonMoon	15	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
LEO2m2LEO	16	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
L12m2L1	17	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
LEO2m2E	18	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]
L12m2E	19	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]

Parameters

1	BoilOffRate	0.000167
2	LunarStay	14
3	ISRU	0
4	ISRU Rate	0.1
5	Cargo Leg1 ID	0
6	Cargo Leg2 ID	3
7	Crew Leg1 ID	0
8	Crew Leg2 ID	17
9	Crew Return1 ID	8
10	Crew Return2 ID	12
11	Refuel on Moon?	0
12	AmountPrepMass	0
13	AmtPrepMassL1	0
14	L1Refueling?	0.000

20mt	Pad1	Pad2
Number of Integration Facilities	2	2
Time Required for Integeration (days)	60	30
Number of Main Boosters Required per Vehicle	3	1
Number of GEMs Required per Vehicle	0	5
Pad Keepout Times (days)	10	1

Reliabilities

	Cargo	Crew	Comment
Launch	0.975	0.99	
Assembly LEO	0.85 -- 0.99	---	Ranges bound unknown reliability
Docking	---	0.99	System wide
Refueling	0.85 -- 0.99	0.99	Ranges bound unknown reliability
Crew Transfer	---	0.99	Only for use with Lander
Engine Failure	0.95 -- 0.99	0.99	Cargo based on upper stage reliability
Ion Engine Failure	0.93 -- 0.97	---	Rolls errors together for initial cut
Lunar Landing	0.95	0.99	
Earth Landing	---	0.99115	Shuttle based value
HLV	0.975	---	Based on 100% success for Delta IV and Atlas V

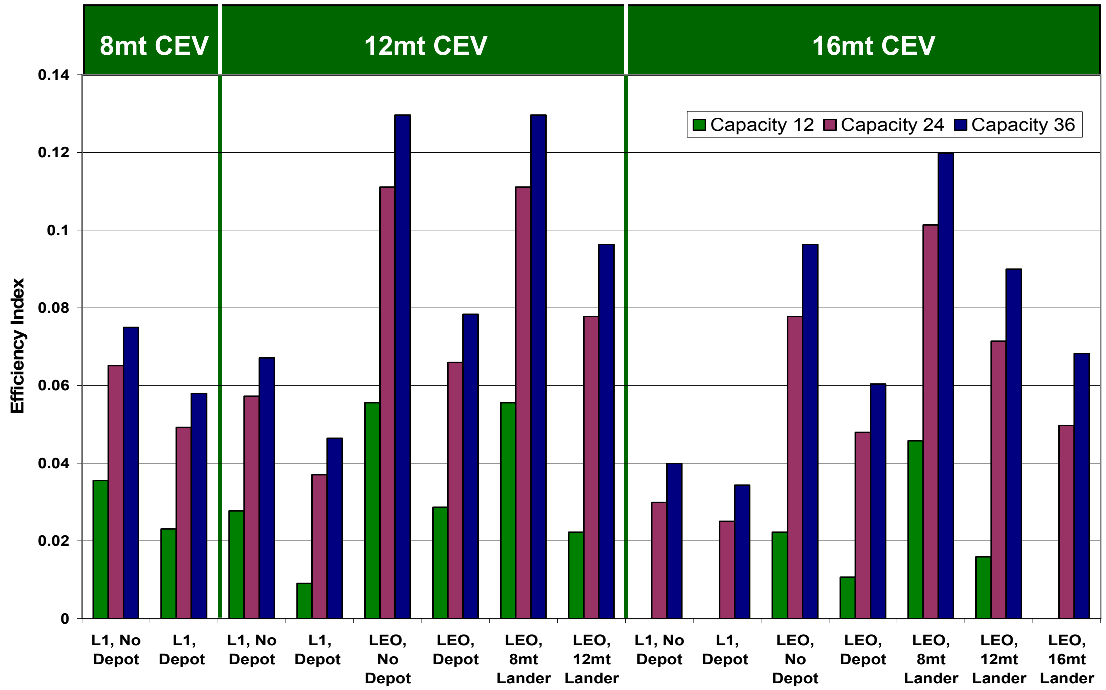
Transportation Requirements Calculated From Physical Principals

Transportation Model – Outputs

- **Time to Complete Objectives**
- **Total Launch Requirements**
  - Number of Crew Launches
  - Number of Cargo Launches
- **Total Amount of Mass Launched**
- **Total Amount of Mass Used at Each Node**
  - Almost Entirely Propellant
  - Divided into Mass Used for CEV and Mass Used for Other (e.g. Support or Propellant Transportation)
- **Total Number of Cargo Shipments Between Nodes**
- **Mass Collected At Each Node**
- **Total Number of Reliability Errors**
  - Indexed by type and location
  - Separate Crew and Cargo Reliability Error Responses

Discrete Event Simulation Of Architecture Is Used To Perform Trades And Analyses To Evaluate Architecture Elements, CONOPS, And Determine Sensitivities

Architecture Efficiency Index



CEV Mass Based On Detailed CEV Design Development

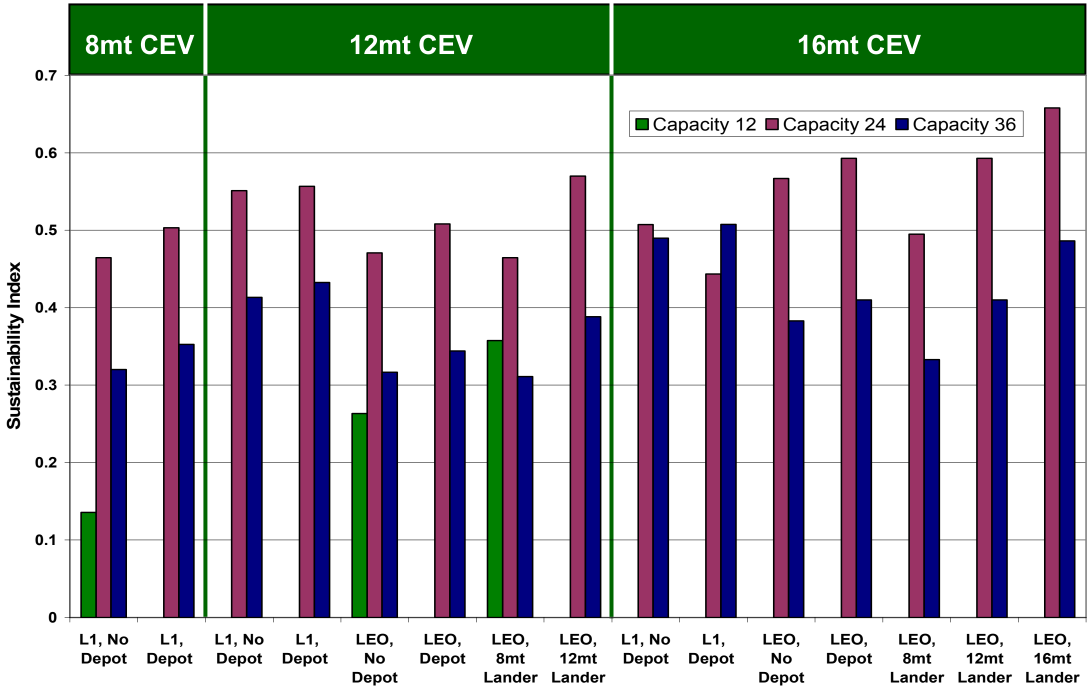
ISRU Requires Further Technology Development And Demonstration To Verify Performance Which Will Not Be Available By Spiral-2

Approach:
- Trade Between CEV Mass, Infrastructure, And Number Of Launches
- 16 mt Upper Limit For CEV Integration With Existing And Near-Term Launch Vehicles
- 8 mt CEV Mass Goal Permits Greatest Flexibility

Conclusions:
- **Only Evaluate Viable/Feasible Architectures**
- **Substantial EI Increase For 24 Launches Per Year – Warrants Investment**
- **Multiple Architectures Expected To Have High Performance**

EI Integrates Multiple Factors To Evaluate Architecture Performance

Architecture Sustainability Index



- Only Evaluate Viable Spiral-2 Architectures
- Current Estimated Launch Capacity Of 12 Launches Per Year Is Sufficient To Sustain Only Some Architectures

Approach To Sustainability Index:

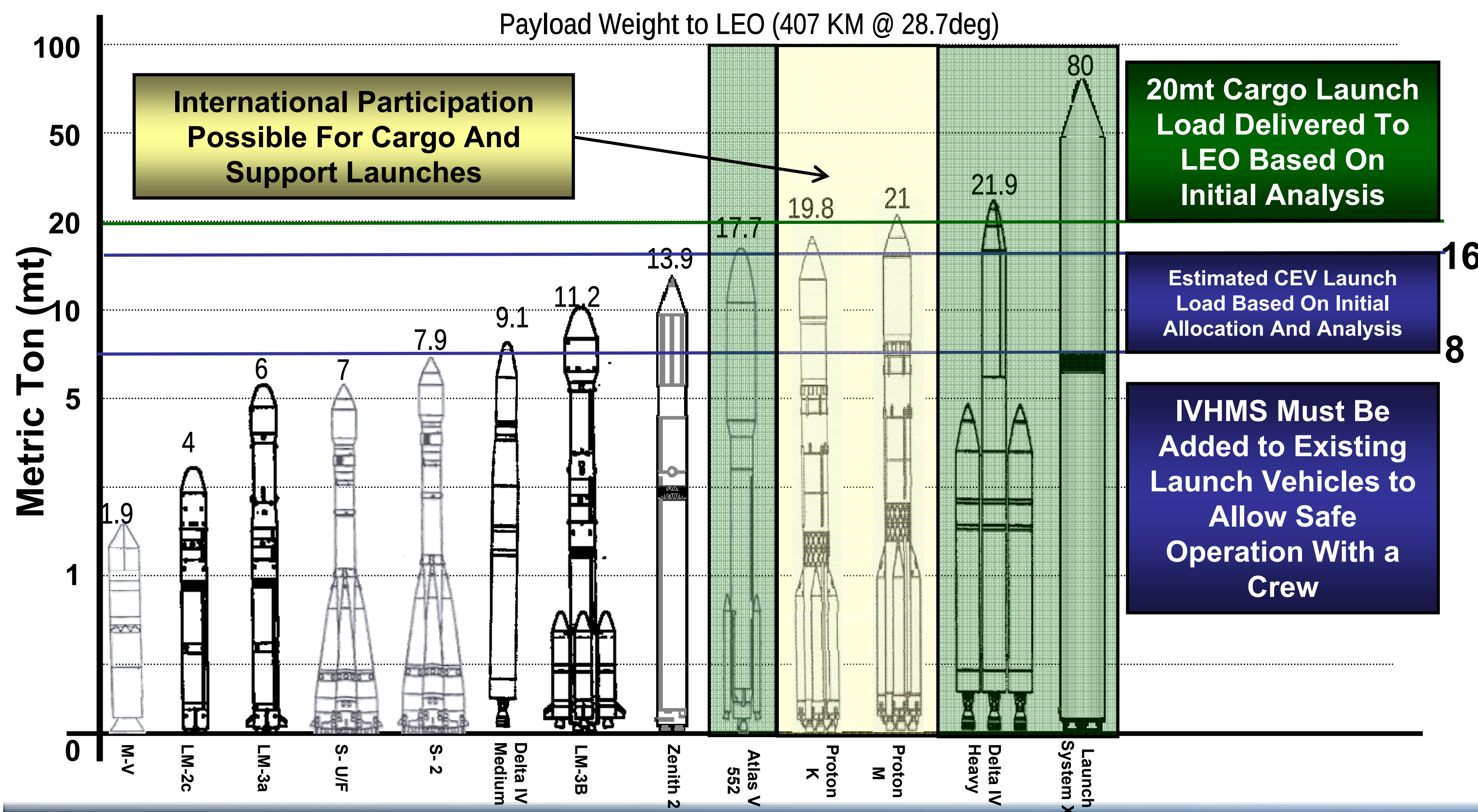
- Adds Influence Of Sustainability And Supportability (Includes Maintenance)
- Increases In Systems Reliability And Crew Safety Are Rewarded As Increasing Probability Of Mission Success

Conclusions:

- No Benefit For Investment In Further Launch Capability Beyond 24/yr
- L1 Enhances Sustainability Given CEV Size

SI Rewards Mission Success Through The Use Of Existing Capacity To Recover From Potential Failures

CEV Launch System Comparison



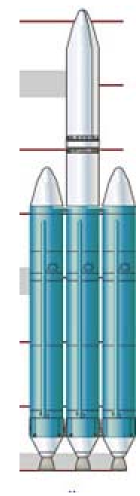
Delta IV Heavy And Atlas V Existing ELVs Provide Sufficient Capability For Cargo And CEV

Launch System Trades

- **Existing Systems**
  - Lift Capacity And Fairing Dimension Show Adapting ELVs Is Preferred
  - Current U.S. Assembly, Integration And Launch Facilities Support 12-24 Launches Per Year
- **Human Rating Implementation Options**
  - Additional Launch Abort System Cost And Risk Required For All Approaches
- **Launch Capacity**
  - Additional Launch Facilities and Production Facilities For HLV Would Require Significant Development Activity
- **International Participation**
  - Cargo Capacity To LEO Could Be Obtained From Existing Foreign Sources

Delta IV Heavy

- **3 Main Boosters – 21,892 kg to LEO**
- **40 Delta IV Booster Cores Per Year**
- **Parts Shipped Via The *Delta IV Mariner***
- **Two Horizontal Integration Facilities at CCAFS & VAFB**
- **Facilities Support Launch Of 24 Delta IV Heavy per Year**
- **Limited to 12 Launches per Year Due to Booster Production**



Atlas V

- **The 551 Variant – 20,050 kg to LEO**
- **One Vertical Integration Facility At CCAFB**
- **60 Day Integration For Atlas V 551**
- **Atlas V Constructed on Pad At VAFB**

Cargo And CEV Can Be Designed to Launch on Multiple Existing ELVs

Results - Launch System

- **Separate Cargo And Human Flight**
- **Baseline Existing Systems**
  - 20 t Lift Capacity For Cargo
  - CEV Fits Existing Fairing Dimension
  - Utilize Existing Launch And Integration Facilities
- **Modification Of Existing LV – No Development Required**
  - Common ELVs Suitable For Cargo And CEV
  - Minimize Need For Development Of HLV
  - Minimize Investment In Development Program

Integrated Vehicle Health Monitoring System (IVHMS) Must Be Added to ELVs to Allow Safe Operation With a Crew

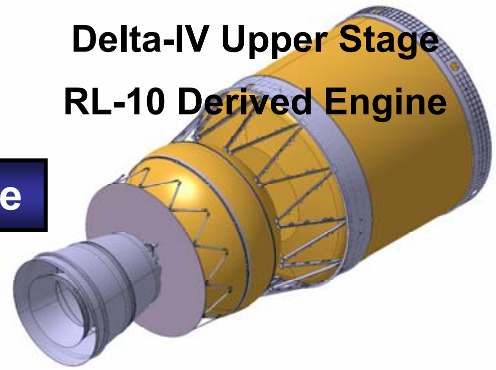
Baseline LV
- **Delta IV Heavy And Atlas V**
- **International Participation Is Possible**

20 t Lift Capability ELVs Available For Cargo, Modified ELVs With IVHMS For CEV

In Space Propulsion Comparison

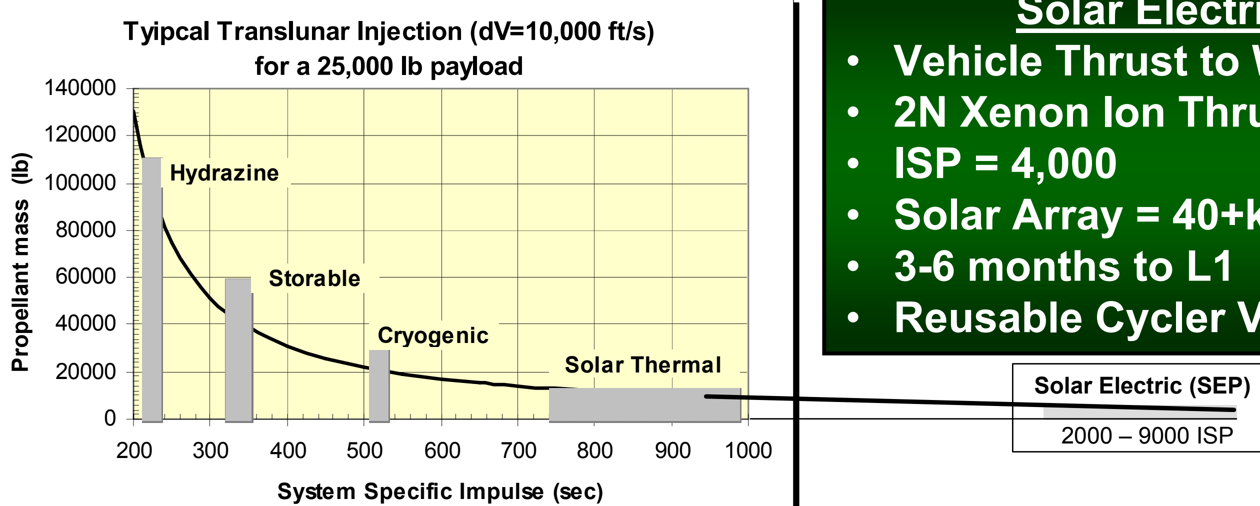
Point Of Departure

Delta-IV Upper Stage
RL-10 Derived Engine



Chemical Propulsion

- Vehicle Mass Ratio = ~2.5
- Vehicle Thrust = 460,000 lb
- 3 days to L1
- Vehicle Dry Mass = 10,000 lb
- Expendable/Non Reusable
- Controlled Disposal (Lunar Surface)



Solar Electric Propulsion

- Vehicle Thrust to Weight Ratio ~0.0001
- 2N Xenon Ion Thrusters
- ISP = 4,000
- Solar Array = 40+kWe
- 3-6 months to L1
- Reusable Cycler Vehicle

Chemical Propulsion Using RL-10 Derived Engine Provides

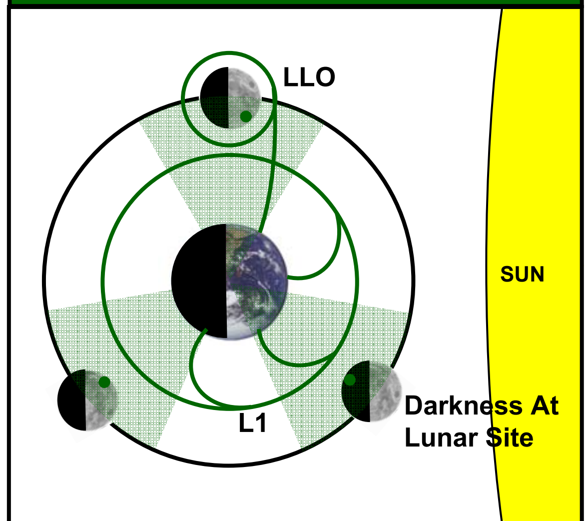
L1 vs LLO Study – Location Of Gateway

Purpose:
- Evaluate Access To Lunar Surface From L1 And Low Lunar Orbit (LLO) To Evaluate Architecture Impacts
- Quantify Lunar Ascent/Descent Constraints

Operational Advantages Of Lunar Gateway:
- Leaving Portion Of CEV Mass At Gateway Decreases Lunar Descent/Ascent Mass – Uses Less Fuel
- LLO Demonstrated In Apollo Program
- LLO Permits Optimization To Reduce Fuel Consumption
- Gateway Provides Option For Prepositioning Of Lunar Supplies
- Gateway Provides Option For Separate Lunar Lander

Equatorial Sites From Equatorial Orbit	Mid Latitude Sites From Inclined Orbit	Polar Sites From Polar Orbit
Only Equatorial Sites Available Every ~2 Hrs	Opportunity Every ~28 Days	Opportunity Every ~2 Hrs For Polar Sites ~14 Days Other Sites

Opportunities For Lunar Injection From LEO Into LLO No More Than Every 5 Days. Lighting Conditions On Lunar Site Will Vary



Continuous Opportunities For L1 Transfer From LEO. Lighting Conditions On Lunar Site Will Vary

L1 And LLO Support Gateway Architecture

L1 vs LLO Study – Location Of Gateway

Lunar Landing Site Location	From LEO To Moon		Opportunities For Ascent/Descent To Moon	
	Thru L1	Thru LLO	From L1	From LLO
Equator	Continuous Access	No More Than 5 Days Access	Continuous Access	Every ~2 hrs (From Equat. Orbit)
Middle Latitudes				Every ~14 days (From Polar Orbit)
Polar				Every ~2 hrs (From Polar Orbit)
ΔV (km/sec)	3.77	4.10	2.77	2.07

Results For LLO:

- Inclination (Equator, Inclined, Polar) Must Be Selected Upon Departure From LEO To Minimize ΔV
- Prohibitive ΔV To Alter Orbit
- LLO Selected Will Limit Access To Some Lunar Locations
- CEV Must Contain Greater Contingency Resources (Heavier) Due To Potential Limitations To Accessing LLO From Surface

Results For L1:

- Permits Continuous Access To Any Lunar Location In 24-48 Hours Transit Time

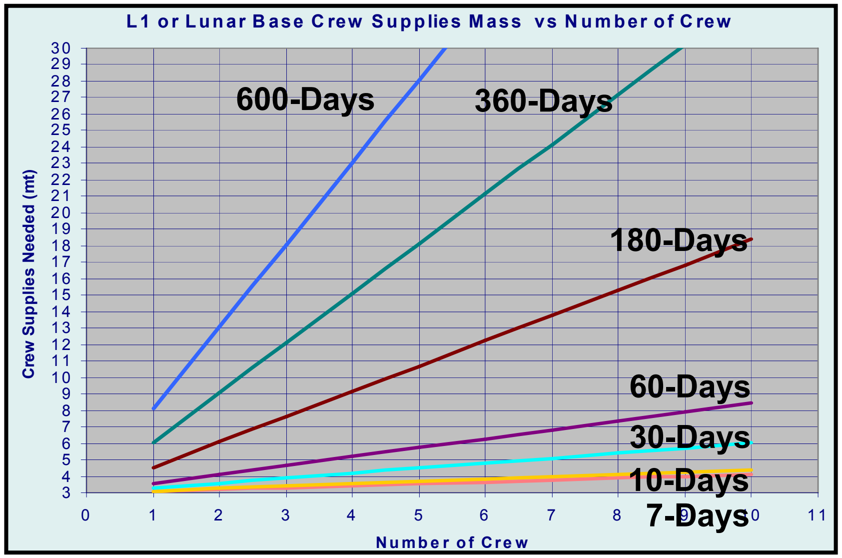
Conclusion:

- Greater Flexibility From L1 Permits Continuous Access To Lunar Surface
- L1 Permits Resupply And Emergency Support From Single Location

L1 Advantageous Over LLO Because Of Access To Lunar Surface For Spiral 3

Lunar Base Requirements

	Mass (mt)
• **Supplies, Science, and Spares**	
– Supplies (water, clothes, O2, N2, etc)	5-9
– Science (estimate 1MT a year)	0.5
– Spares (estimate 1/6 of total)	2
– Total supplies, science, spares	7.5-1.5
– Accommodations (30%)	2.3-3.5
– Total w/ Accommodations	10-15
• **EVA supplies**	
– 9 EMUs per crew rotation	1
– Consumables (35kg per EMU per EVA)	6
– EVA supplies accommodations (30%)	2
– Total EVA supplies w/ accommodations	9



Lunar Base Infrastructure:
- Cargo Module
- Lunar Habitat
- Rover
- Power Plant
- In-Situ Processing Plant

Propulsion Subsystem	
Structure	7.91
Resource Module Structure	
Cargo & Accommodations, Structure	
Miscellaneous Items	0.27
Avionics	0.66
Telemetry, Tracking, and Control (TT&C)	
Power Subsystem	3.50
Thermal Control	3.25
Payload Interfaces & Control	
Crew Systems	1.72
Consumeables	1.69
Total Mass	19.00

Propulsion Subsystem	
Structure	2.30
Resource Module Structure	0.50
Cargo & Accommodations, Structure	0.58
Miscellaneous Items	0.26
Avionics	0.20
Telemetry, Tracking, and Control (TT&C)	
Power Subsystem	0.97
Thermal Control	0.75
Payload Interfaces & Control	0.60
Cargo	12.84
Consumeables/Prop	
Total Mass	19.00

Lunar Surface Infrastructure Sizing For Spiral 3 Fits Within EELV

Lunar Gateway Assessment -- Preliminary

Figure of Merit / Measure of Perf.	One Base -- Polar	One Base -- Equatorial	Two Bases -- Polar	Two: Polar & Equatorial	None -- Station in LLO	None -- Station at L1	None -- Station in LEO
Normalized Pugh Vote (-2 to +2)	0.4	0.5	0.7	1.1	-1.0	-0.2	-0.2
Deployability	2	1	-1	0	-2	-2	-1
Evolvability	0	0	1	2	0	0	1
Operability	0	1	-1	0	-2	-1	-2
Applicability to Mars Exploration	1	0	1	1	1	1	-2
Robustness	0	0	2	2	-2	-2	-1
Safety & Survivability	0	1	1	2	-1	-1	1
Accessability from Earth to Base	-1	0	0	0	-1	1	2
Accessability from Base to Sites	0	0	1	1	-1	0	-2
Security	0	0	1	1	-1	-1	-1
Maintainability	2	2	1	1	-2	-1	0
Sustainability	0	0	-1	-1	0	0	1
Supportability	1	1	0	0	0	1	-1
Connectivity	0	0	1	1	-1	1	2
Commercialization Potential	1	1	2	2	-2	0	-1
International Involvement	1	1	2	2	-1	1	0
Adaptability	0	0	1	2	-1	0	1
Performance (Useful Work vs. Effort)	0	0	1	2	-1	-1	-1

LUNAR BASE OPTION

- L1 With Re-supply Capability Permits Access To Any Remote Lunar Location
- CEV Or Lander Permits Access To Lunar Surface
- Flight Is Faster Than Ground Transportation

Polar And Equatorial Lunar Bases Yield Maximum Benefits

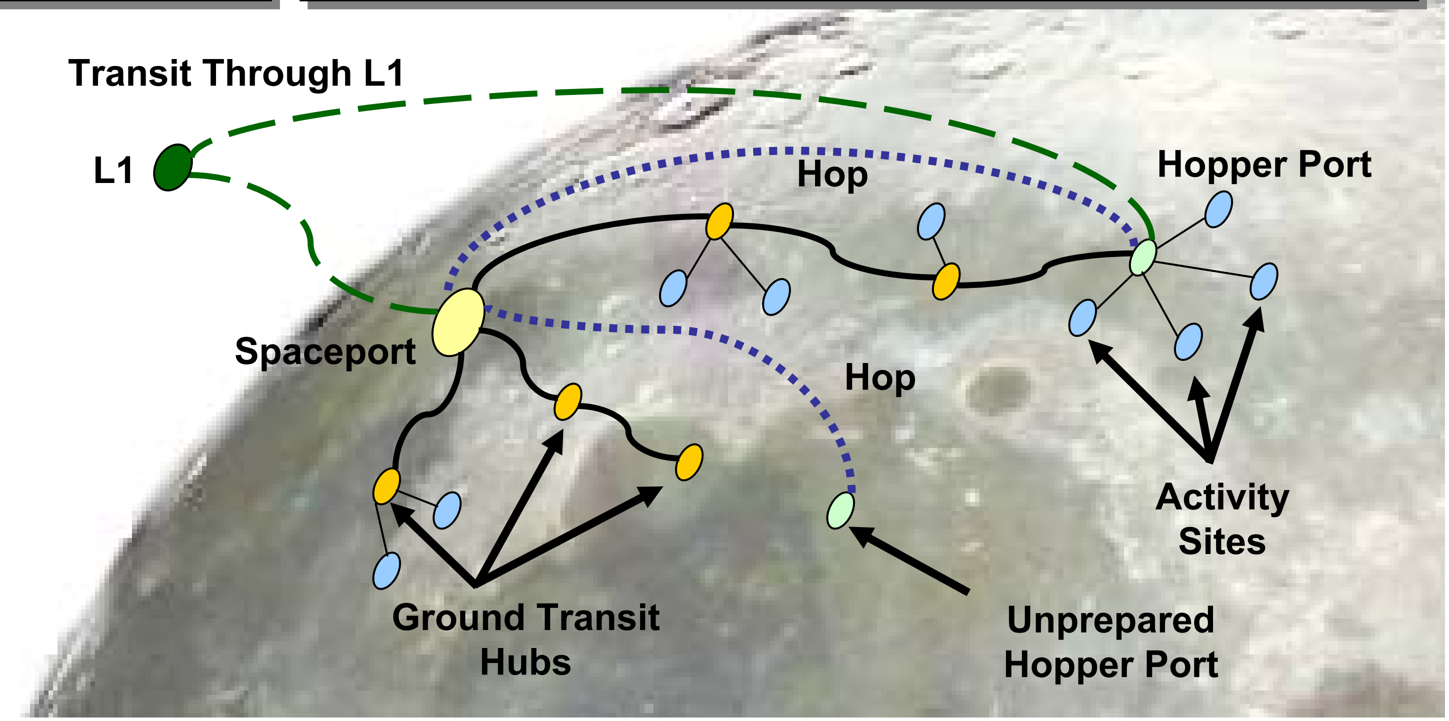
Lunar Basing and Evolvability

- L1 With Re-supply Capability Permits Access To Any Remote Lunar Location
- CEV Or Lander Permits Access To Lunar Surface

- Spaceports Will Be Limited Due To Development And Installation Costs
- Ground Transports Have Limited Range
- Hopper Extends Access To Remote Activity Sites
- Hopper Permits Manned Lunar Survey

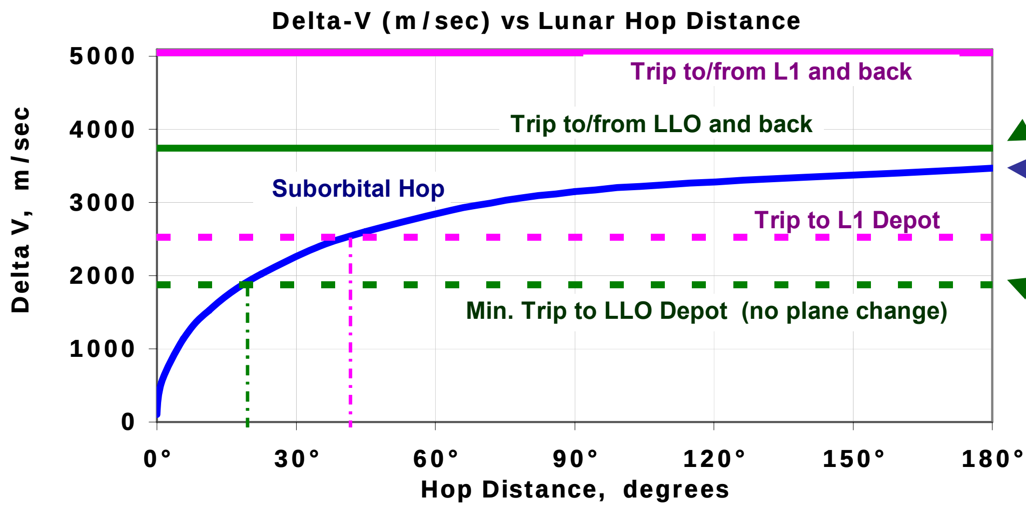
Node Types
- Spaceport hub
- Ground Transit hub
- Excursion Activity site

Node Functions
- Spaceport
- Hopperport
- Ground Transit
- Supply Node
- Safe Haven
- Maintenance
- Rest Stop
- Exploration Site
- Mining / Insitu
- Utility Sites
- Medical Capability



Exploration And Travel On Moon And Mars Surface Will Require Establishment Of Surface Transport Nodes To Cover Significant Distances

Initial Lunar Hopper Assessment



LLO basing good if no propellant resupply at destination (assumption for Hopper)

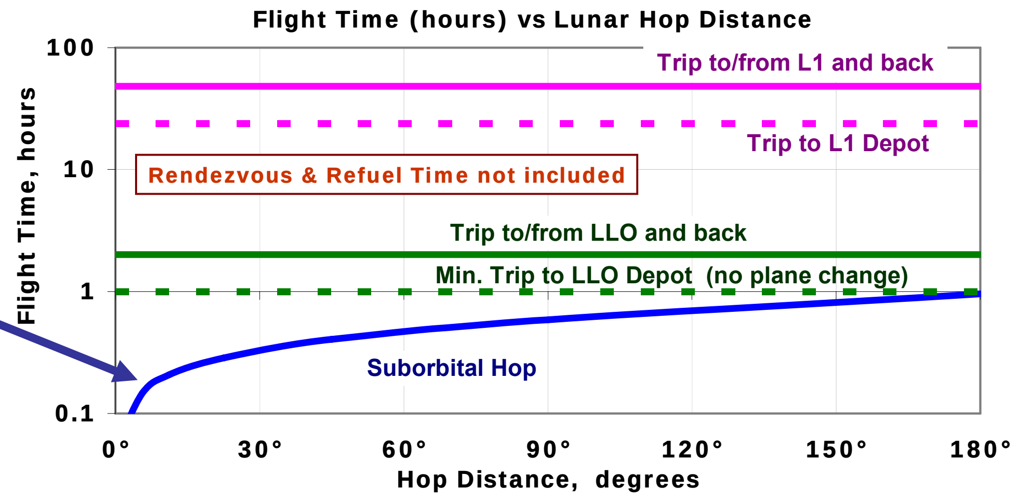
Suborbital Hopper requires less propellant than LLO/L1; unless vehicle stops to refuel on-orbit

LLO Depot yields smallest hopper; can refuel on-orbit – but cannot land if fails

Need many LLO Depots to have one in same orbit plane as path to destination

Suborbital Hopper Travel Time Much Less Than L1 Trip; Even Much Less Than LLO Depot, When Rendezvous And Refuel Times Are Factored In

- **Assumptions for 2-burn cases:**
  - Delta-V = liftoff + deceleration + landing
  - Liftoff & landing are short term high thrust burns
  - Landing Delta-V cost is 100 m/s
  - Flight time includes ballistic time, plus 2-gee thrusting time, 2-gee decel time, and landing time
- **Poles to Equator:**
  - 3150 m/s required to go ¼ circumference of moon



Significant ΔV Only Required For Hops Of Greater Than 90º Around Moon
Transit Times For Hopping Less Than One Hour Versus 2-3 Days For L1 Round Trip

CEV And LS Sizing Study

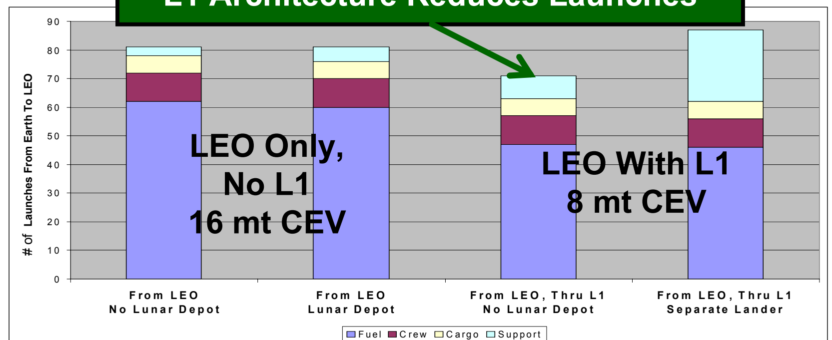
CEV Size:

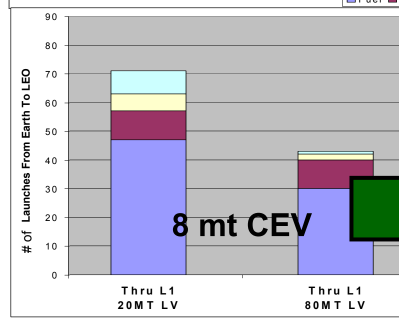
- Model Spiral 2 Missions
- Determine Number Of Required Launches For Architecture Concepts With And Without L1
- Independent CEV Model Indicates 8 mt CEV Is Feasible If Refueling Is Available From Architecture Nodes

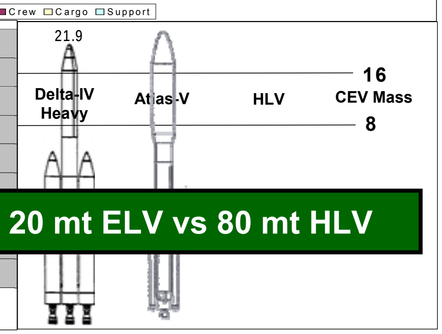
LV Size:

- Model Spiral 2 Missions
- Assume ELV With 20 mt And A New HLV With 80 mt Lift Capability To LEO
- HLV Reduces Launches In Proportion To Greater Lift Capacity – No Clear Benefit
- HLV Requires Full Development And Higher Cost Prior To 2014

L1 Architecture Reduces Launches







20 mt ELV vs 80 mt HLV

Conclusions:

- **80 mt HLV Is Not A Necessity For Launching Of Fuel**
- **L1 Architecture With ELV Supports 8 mt CEV Design Goal**

L1 With ELVs More Flexible And Extensible To Future Spiral 3 Missions

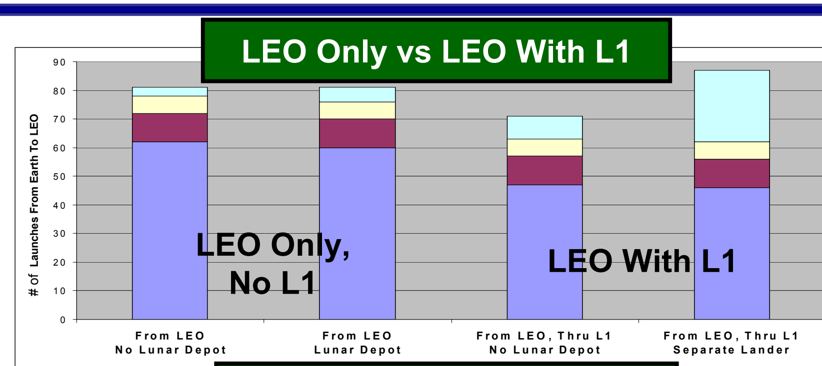
L1 Study

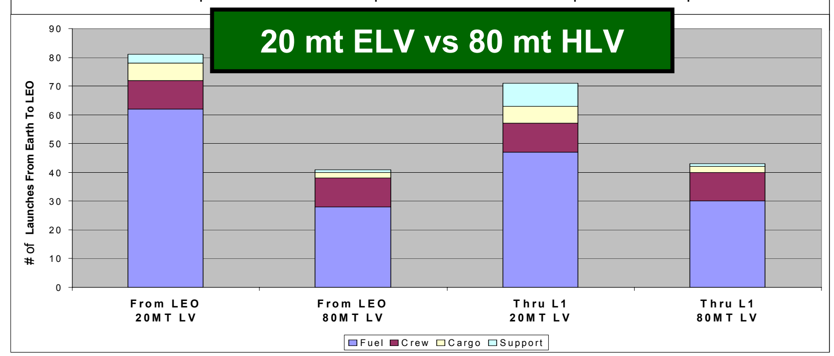
Purpose:
- Quantify The Advantages Of L1 In The Gateway Architecture

LEO
- Longer Transportation Segment Requires Larger CEV To Carry Additional Payload
- Mission Is Relatively Self Contained

L1
- Potentially Smaller CEV (Shorter Transport Segments, Shorter Flight Durations) Permitted To Refuel At L1

Approach
- Model the Architecture Concepts With And Without L1 To Compare Number Of Required Launches
- Assume EELV With 20 mt And A New HLV With 80 mt Lift Capability To LEO To Determine If Concept Benefits From HLV





Conclusions:
- **80 mt HLV Is Not A Necessity For Launching Of Fuel**
- **L1 Architecture Performance Comparable Or Better Than LEO Direct**

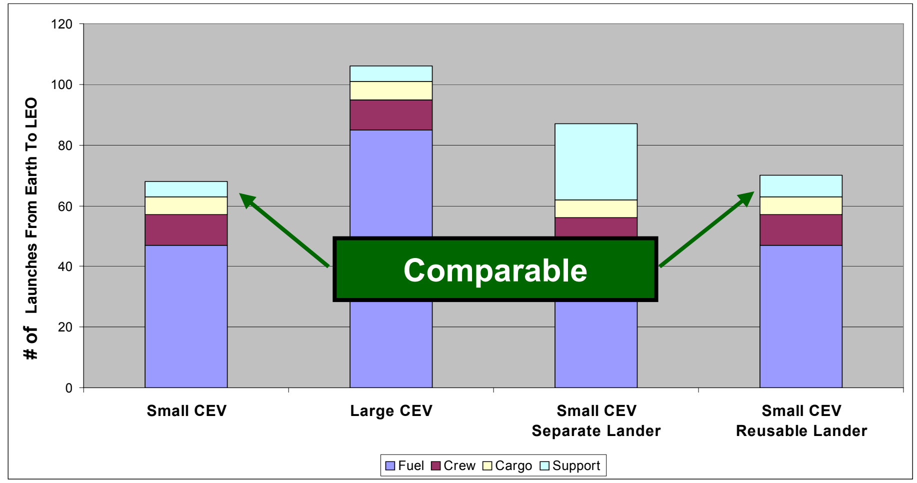
L1 More Flexible And Extensible To Future Spiral 3 Missions

CEV Size Sensitivity Study

Purpose:
- Determine The Relative Size Of The CEV To Support The Architecture
- Determine Sensitivities Of The Architectures To CEV Size
- Verify CEV Concepts Fit Architecture

Assumptions:
- Mass Is Limited To Launch On ELV

CEV Sizes
- Small (~8 mt) With Capability To Land On Planet. Sized For Shorter Transport Segments Of L1 Architecture
- Large (~16 mt) With Capability To Land On Planet. Sized For Longer Duration And LEO Architecture
- Small CEV With Separate Lunar Lander (~8 mt Each). Optimized Independently For Transport And For Lunar Landing. Need To Preposition Lander At L1



Conclusions:
- **Small Highly Capable CEV That Lands On Moon Significantly Reduces Fuel Supply Launches**
- **CEV With Reusable Lander Is Functionally Comparable To Small CEV That Lands On Moon**
- **Functionally Separating Lunar Lander From CEV Eases Design Process But Requires Crew Transfer**

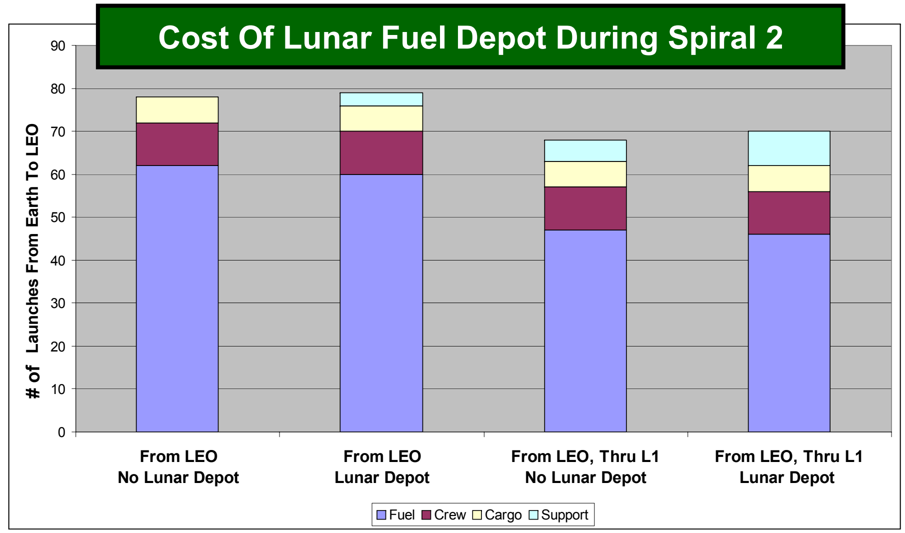
Small CEV Size (~8 mt) Provides Greatest Flexibility And Capability

Lunar Fuel Depot Study

Purpose:
- Determine Advantage Of Lunar Fuel Depot
- When Is Cost In Launches Recovered

Advantages Of Lunar Depot:
- Lunar Re-Fueling Supports Decreased CEV And Lunar Lander Size By Reducing Fuel Tank Size And Storage
- Ability To Re-Fuel On Lunar Surface Extends Architecture Capability For Spiral 3
- Re-Fueling From L1 Is As Fuel Efficient As Fuel Storage On The Moon During Spiral 2

Alternatives:
- Single Fuel Supply Depot At L1 Could Support Any Lunar Location
- Fuel Expended In Landing Fuel On Moon Equals Fuel Savings From Smaller CEV



Conclusions:
- **No Significant Architectural Advantage To Lunar Fuel Depot During Spiral 2**
- **Lunar Fuel Depot Permits Smaller CEV And Smaller Lunar Lander**

Lunar Depot Has Negligible Benefit On Architectures During Spiral 2

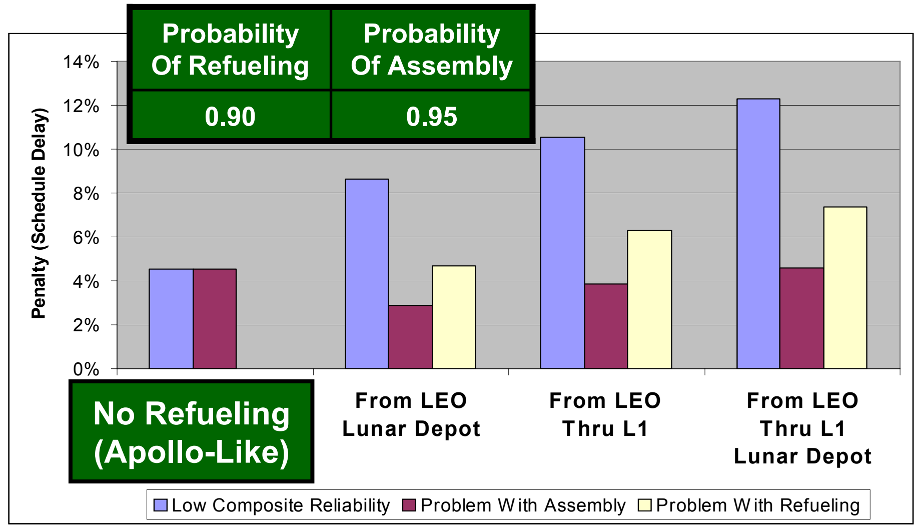
Refueling And Assembly Study

Purpose:
- Evaluate Sensitivity Of Gateway Architectures To Re-Fueling And Assembly

Assumptions:
- Assume 20 mt Booster To Maximize Number Of Assemblies And Re-Fuelings

Approach
- Include Reliabilities For Fueling And Assembly Similar To Failures
- Determine Additional Launches Required Due To Failures

Impact To Architecture
- L1 Architecture Very Sensitive Because Of More Refueling And Assembly Occurrences
- Direct From LEO Has No Refueling And Only Limited Assembly Due To Small Booster
- HLV Reduces Direct From LEO Assembly
- Schedule Delay In L1 Architecture Can Be Recovered Through Added Launches



Conclusions:
- **Refueling Reliability Of Cryo Propellants Is A Technology Issue That Needs To Be Demonstrated**
- **Assembly Reliability Is A Process Issue That Has Been Demonstrated But Can Be Improved**
- **Gateway Architectures Are Reliant On Re-Fueling Or Fuel Tank Exchange**

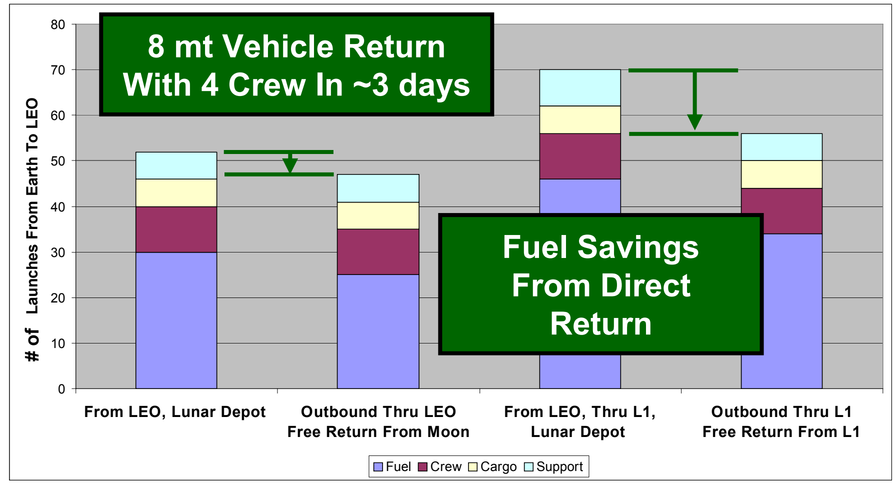
Architecture Can Utilizes Excess Launch Capacity To Mitigate Schedule Delays Due To Reliability

Direct Return To Earth Study

Purpose:
- Quantify Fuel Savings Benefit Of Direct Return From Lunar Surface To Earth
- Direct Return Increases Crew Safety

Assumptions:
- Direct Return From Moon To Earth = 3.07 km/s
- Ascent To L1 And Direct Return From L1 To Earth = 3.29 km/s
  - Moon To L1 = 2.52 km/s
  - Direct Return From L1 = 0.77 km/s

Mission Safety:
- Direct Return Requires CEV To Contain Minimum Fuel To Achieve Safe Return
- Direct Return From Moon To Earth Is Sufficient ΔV For Ascent From Moon To L1 For Resupply
- Direct Return Minimizes Risk To Astronauts
- Direct Return Reduces Fuel Requirements



Conclusions:
- **Direct Return Is Required**
  - **From Moon To Earth Saves ~0.5 Fuel Launches Per Mission**
  - **From L1 To Earth Saves ~1.5 Fuel Launches Per Mission**
- **ΔV For Direct Return From Moon To Earth Could Be Used For Ascent From Moon To L1 For Resupply And Refueling**

Direct Return Reduces Launches For Refueling

Lunar Direct Reentry

Purpose/Background

- **Determine Reentry Trajectories For LEO To Determine Flight And Landing Characteristics.**

General Approach

- 2 Thrust Motors Capable Of 65000 N Each
- 440 Sec Isp For Deorbit Burn
- 365 Sec Isp For Landing
- Apollo Aerodynamic Data As A Function Of Mach Number And Angle-of-attack
- 8076.59 kg Mass
- 19.635 m2 Reference Area (5 Meter Diameter)

Deorbit

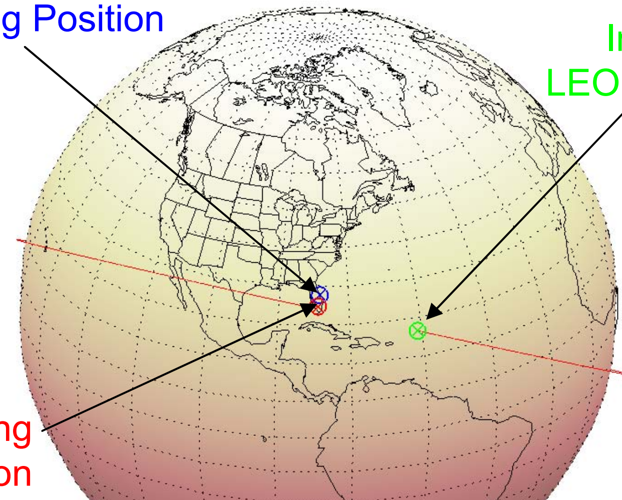
- Thruster Firing Begins At Time = 2070 Sec
- Fire Thruster To Reduce Orbital Speed By 100 m/s
- Throttle Set To 0.5, Corresponds To 32500 N Thrust Level Per Motor

Parachute

- 0.8 Axial Force Coefficient
- Drogue Deployed When Altitude < 6096 m, 2 sec To Unfurl
- Mains Deployed When Altitude < 4000 m, 15 sec to unfurl
- 1 Drogue Chute With 19.635 m^2 Reference Area (5 Meter Diameter)
- 3 Main Chutes With 962.113 m^2 Reference Area Each
- Drogue Chute “Cut” When Mains Deployed

Desired Landing Position

Initial LEO Position



Landing Position

- **CONUS Landing Stresses CEV And Departure From Lunar Surface**
- **Cross Range Capability Required For CEV**

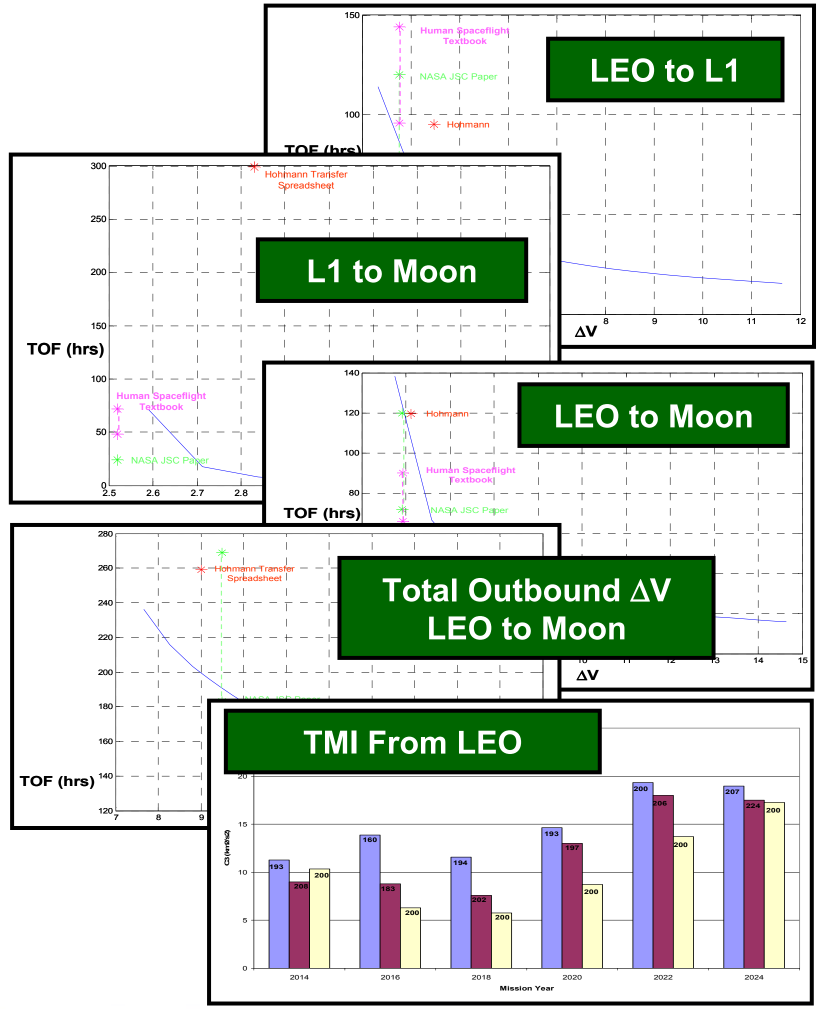
Landing

- Thrust Level And Isp As Specified in Approach
- Begin Thruster Firing When Altimeter Reading < 3 m
- Throttle Setting Varied Between 0.3 And 1.0 As A Linear Function Of Altimeter Rate

Detailed Simulations Underway For Analysis of Design Performance During LEO Re-Entry

Transport Modes

Trajectories	Δ V (km/s)	Time-of-Flight (hrs)
Earth to LEO	10.82 km/s (Hohmann) 9.7 km/s (University Source)	0.74 hrs. (Hohmann)
Earth to L1	12.01 km/s (Hohmann) 12.9 km/s (University Source)	95.12 hrs. (Hohmann)
Earth to Moon	13.64 km/s (Hohmann) 15.2 km/s (University Source)	119.41 hrs. (Hohmann)
LEO to L1	4.48 km/s (Hohmann) 3.77 km/s (Human Sp-flight)	95.3 hrs. (Hohmann) 96-144 hrs. (Human Sp-flight) 3-5 days (NASA JSC)
LEO to Moon Surface	6.12 km/s (Hohmann) 5.93 km/s (Human Sp-flight) 5.91 km/s (NASA JSC)	119.6 hrs. (Hohmann) 66-90 hrs. (Human Sp-flight) 3-5 days (NASA JSC)
L1 to Moon Surface	2.83 km/s (Hohmann) 2.52 km/s (Human Sp-flight, NASA JSC)	298.77 hrs. (Hohmann) 48-72 hrs. (Human Sp-flight) 1 day (NASA JSC)
LEO to Mars	9.00 km/s (Hohmann) 10.2 km/s (3.8 w/Aero-braking) (University Source) 9.5 km/s (3.71 w/Aero-braking) (NASA JSC)	258.94 days (Hohmann) 183 - 269 days (NASA JSC)
L1 to Mars	9.2 km/s (Hohmann)	259.3 days (Hohmann)
Moon to Mars	8.7 km/s (Hohmann)	259.3 days (Hohmann)



Delta-V vs Time-of-Flight Curves Are Provided to the Transportation Model

Solar Weather Prediction Study

- **Characterize Solar Weather Prediction For 4-Days By K-factors**
  - K-factor Values Selected: 1.00, 0.75, 0.50, 0.25
- **Historical Data Reflects 5 Significant Solar Weather Incidents (Their Strength And Orientation Would Affect Lunar Missions) In 40 Years**
  - 0.0003425 Probability Of Impact On Any Given Day (12 % Chance Per Year)
  - Accept 18 Hour Solar Event Arrival Time At Fastest Speeds
- **Assume Maximum Travel Away From Safe Haven Is 4-Days. Mission Departs, No Return For 4-Days**
  - Assume Mission Vulnerable During Entire Mission
  - Launch Only When Predicted Probability Of Solar Event Is Less Than Safety Threshold For All Four Mission Days (Reject Solar Event)
  - Set Safety Thresholds (Probability Of Solar Event That Causes Launch Postponement) Over Range Of 4.5 Standard Deviations
- **Simulate One Million Missions (To Account For Rarity Of Solar Events) For Each Of 19 Safety Thresholds**

Determine If Required CEV Shielding Can Be Reduced To Save CEV Mass And Still Permit Crew To Survive A Solar Event Through Solar Weather Prediction

Conclusions:

- **Maximum Predicted Mission Exposure Of 0.00110 Closely Agrees With Theoretical Value (0.0003425 Per Day Multiplied By 3.25 Days)**
- **Can Reduce Mission Risk To 0.069% But At Cost Of Postponing 73% Of Scheduled Launches (Missed Opportunities To Fly)**
- **Can Reduce Mission Risk To Nearly Zero At Cost Of 99.98% Postponed Launches**

Solar Weather Prediction Has Limited Ability To Effectively Decrease Radiation Shielding Unless The Number Of Flights Is Few And Schedule Is Not A Concern

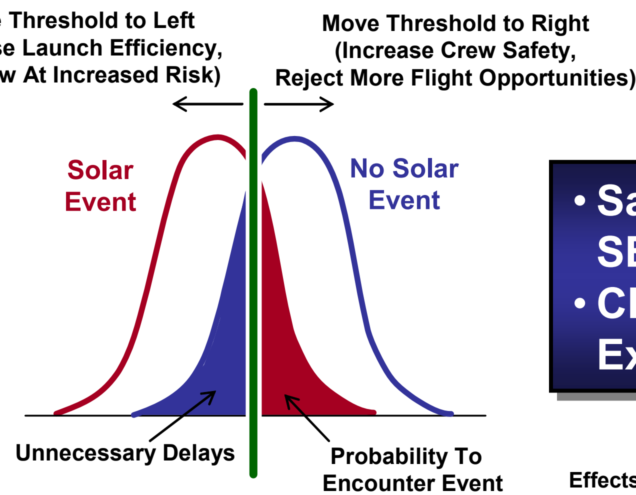
Solar Weather Prediction Study

Purpose/Background

- **Radiation Shield Will Be A Significant Amount Of Mass In The CEV Or Attached To the CEV**

Approach

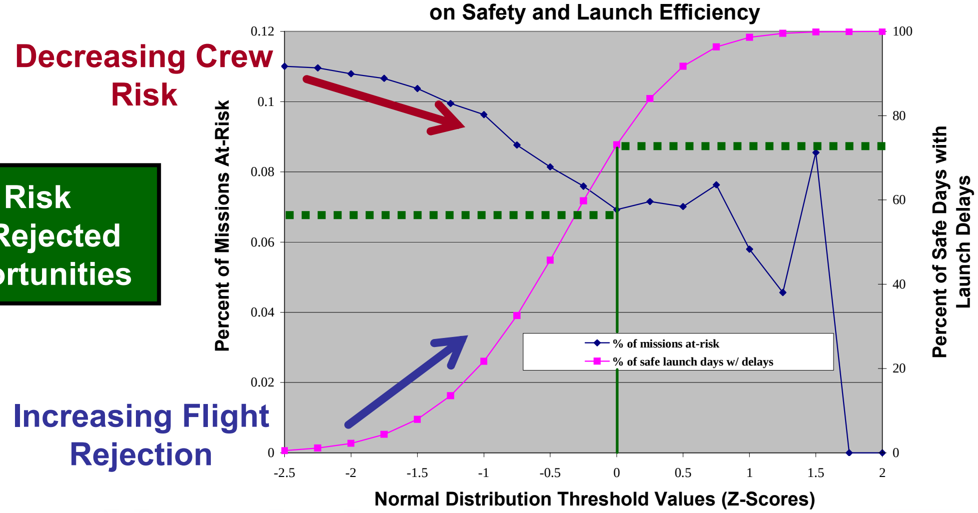
- **Determine Radiation Environment And Acceptable Crew Dosages**
  - Shielding From Galactic Cosmic Rays (GCRS) Not Critical For Short Lunar Transits
  - **Shielding From Solar Event Particles (SEPs) Needed Anywhere Beyond The Earth's Magnetosphere**
  - 30-day Exposure Limit Of 25 cSv Used For Lunar Transit



- **Safe Haven Requires SEP Shield**
- **CEV Can Rely On Short Exposure Risk**

0.069% Risk With 73% Rejected Flight Opportunities

Effects of Solar Weather Prediction on Safety and Launch Efficiency



Solar Weather Prediction In Short 4-Day Flights Decreases CEV Shielding Mass But May Limit Flight Opportunities

ISRU - Generating Lunar Propellant

ISRU Reduces Propellant Or Oxidizer Transport To Reduce Required Launches

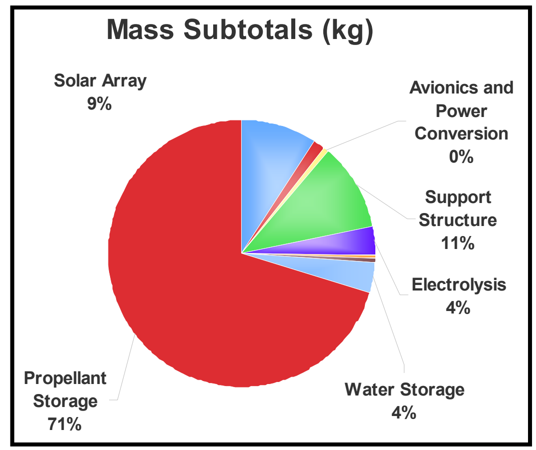
- **Level 0 Water To Propellant (LOX/LH_2) Model Created**
- **Model Assumes:**
  - Tracking Solar Power
  - Equatorial Heat Rejection
  - Parabolic Shaped Radiator Shades
  - Brayton Cycle Refrigerator

Production kg/year	Dry Mass kg	Wet Mass kg	Total Power kW	H2 tank kg
250	417	730	0	67
2000	1634	4134	4	533
4000	3025	8025	7	1067
8000	5807	15807	15	2133
16000	11370	31370	29	4267
40000	28060	78060	74	10667
100000	69785	194785	184	26667
200000	139327	389327	368	53333

Production vs. Facility Mass (Propellant From Lunar H2O)

Recommend Early Testing And Development Of LunOX ISRU During Spiral-2 In Order To Support Spiral-3 And Mars Activities

System	Dry Mass Subtotal (kg)	Percent Total Mass (kg)
Solar Array	12910	9.3
Radiators	1825	1.3
Avionics and Power Conversion	667	0.5
Support Structure	14928	10.7
Electrolysis	5074	3.6
Propellant Drying	288	0.2
Hydrogen Liquification	564	0.4
Oxygen Liquification	294	0.2
Water Storage	5000	3.6
Propellant Storage	97778	70.2
TOTAL	139327	100.0



ISRU Could Create Sufficient LunOX To Supply Oxidizer For Spiral-3

ISRU - Generating Lunar Propellant

- **Other models in work:**
  - Regolith to water
  - Regolith acquisition
  - Ice acquisition
  - Regolith to LOX
  - Energy Efficiency (Power In vs. Propellant Out)
- **Explore Pilot Plant Development And Demonstration During Spiral-2**
- **Explore Transport Of Lunar Propellant To L1 To Support Mars And Future Missions**

ISRU Power Supplied From Solar

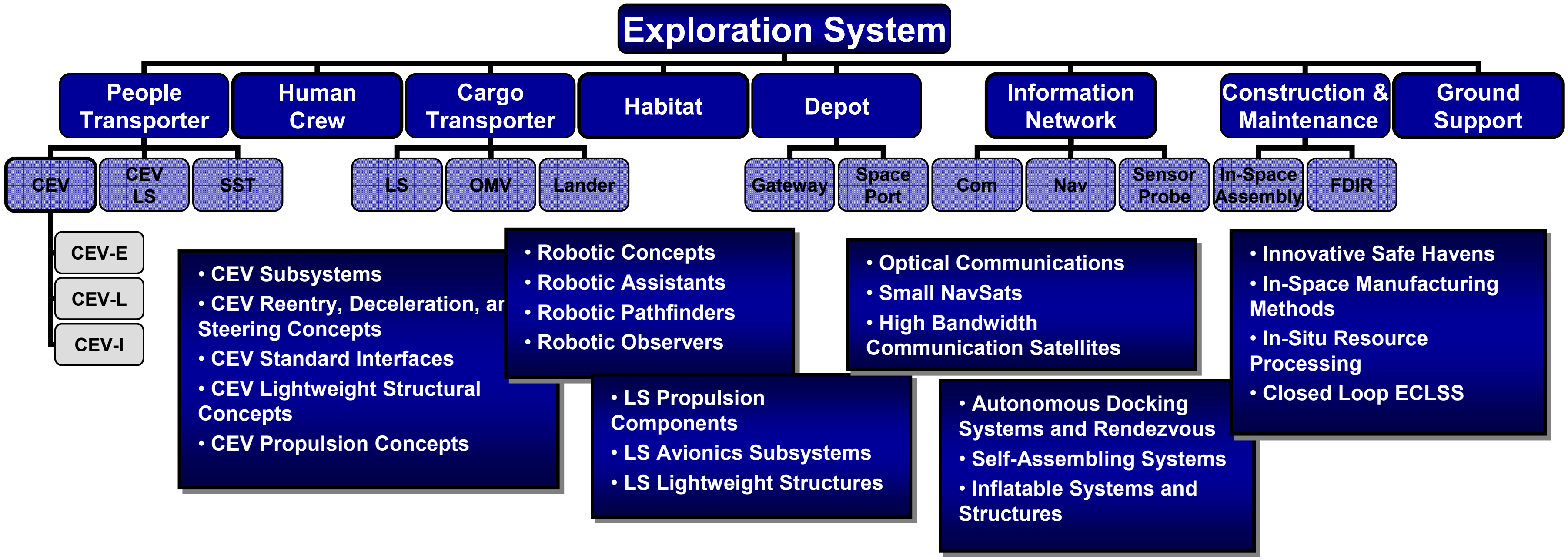
FOMs versus Solar Power Operating Time		Mass FOM (prop per year/dry mass)	Power FOM (prop per year/kW)	Dry Mass (kg)
		1.44	0.54	139327
Solar Insolation Percentage	10%	0.85	0.11	235216
	20%	1.14	0.22	175285
	30%	1.29	0.33	155308
	40%	1.38	0.43	145320
	50%	1.44	0.54	139327
	60%	1.48	0.65	135332
	70%	1.51	0.76	132478
	80%	1.53	0.87	130337
	90%	1.55	0.98	128673
	100%	1.57	1.09	127341

Source	Base Metal	Energy Required	O2 Mass Per Metal Mass
Al203	Al	28KWh/kg	0.9
Fe203	Fe	7KWh/kg	0.43
Fe304	Fe	5KWh/kg	0.38
Si02	Si	25KWh/kg	1.13
Ti02	Ti	15KWh/kg	0.69

LunOX From Regolith

Multiple ISRU Concepts Available
Demonstrate Capability During Spiral-2 In Order To Establish Pilot Plant In Spiral-3

Technology Evaluation



- **Identify and Investigate Critical Technologies for CEV and Architecture**
  - Review and Assess Candidates from H&RT SoS Technology Program
- **Identify Gaps in Technology for Spiral 1**
  - Support H&RT BAA 2nd Round in early 2005
- **Develop Technology Development Plan for Critical Technologies**

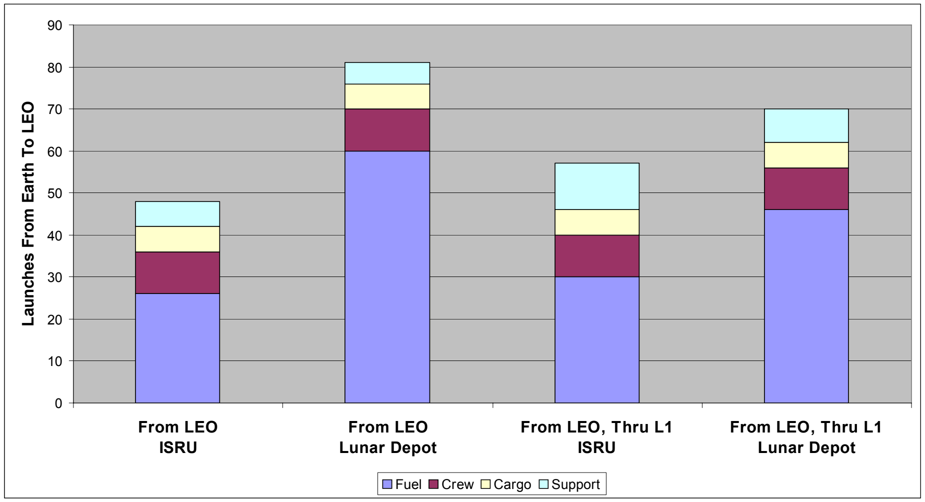
Technology Development

Critical Technologies	Planned
• IVHMS and Launch Abort Subsystem	• Spiral 1
• Automated Rendezvous and Docking	• Spiral 2
• In-Space Refueling (Cryo)	• Spiral 2
• Power Generation	• Spiral 3
• Propulsion	• Later Spirals
– Electric	– Spiral 3
– ISRU - LunOX	– Spiral 3
– Nuclear	– Spiral 4
• Closed-Loop ECLSS	• Spiral 4
• Artificial Gravity	• Spiral 4
• Autonomous Robotics	• Spiral 4

- **Ensure Spiral 1 and 2 Needs are Addressed with Technology Infusion BAA (Early 2005)**
- **Continue Research and Technology Development Approach**
  - ESR&T
  - HSR&T
  - Prometheus
  - IPP/SBIR/STTR
  - DART
- **Continue to Identify Critical Technologies and Fund Development**
- **Continue to Identify High-Payoff Technologies and Fund Research and Development**

Emphasis on Spirals 1 and 2 But Development of All Critical Technologies is Needed

Results - ISRU Technology



Potential ISRU LunOX Production

Production kg/year	Dry Mass kg	Wet Mass kg	Total Power kW	H2 tank kg
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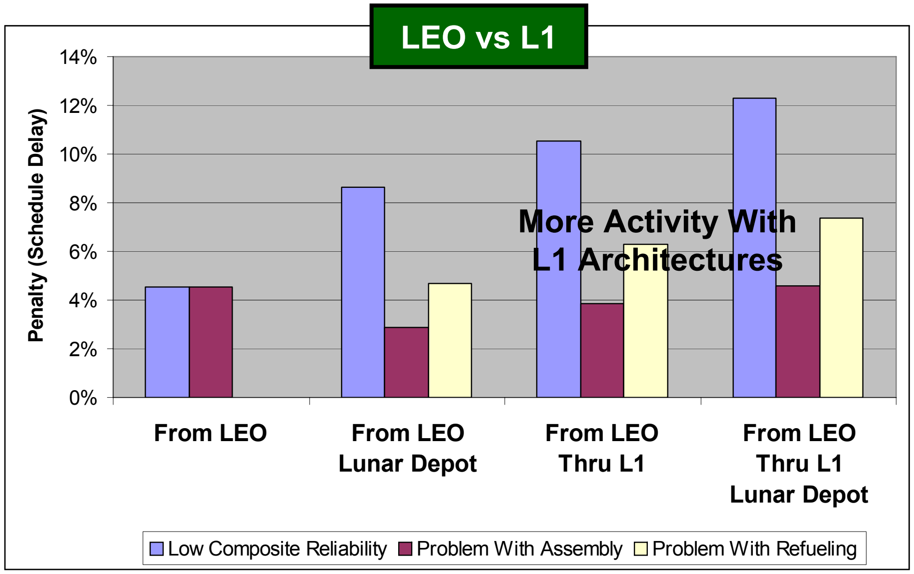
40000	28060	78060	74	10667
100000	69785	194785	184	26667
200000	139327	389327	368	53333

- **In-Situ Resource Utilization (ISRU)**
  - Assume Lunar Oxygen (LunOX) Production For Oxidizer in Propellant
  - Carry Hydrogen Fuel
  - Deliver LunOX Plant To Lunar Surface
  - Assume Robotic Operation
- **Impact To Architecture**
  - LEO Architecture Benefits More Because Of Increased Propellant Consumption (and Therefore Production)
  - Requires Initial Launches To Establish
  - May Require Manned Presence
- **Continued Study**
  - Added Benefit If LunOX Can Be Delivered To L1 For Spiral 3
  - Alternative LunOX And Propellant Production Technologies

ISRU Greatly Decreases Propellant Mass Requirements

Refueling And Assembly Study



Conclusions:

- **Refueling Reliability Of Cryo Propellants Is A Technology Issue That Needs To Be Demonstrated**
- **Assembly Reliability Is A Process Issue That Has Been Demonstrated But Can Be Improved**

- **Add Reliabilities To Transportation Model**
- **Sensitivity To Refueling And Assembly**
  - Assume 20 mt Booster
- **Impact To Architecture**
  - L1 Architecture Has Inherently More Refueling Occurrences, And Therefore Increased Sensitivity
  - Schedule Delay In L1 Architecture Can Be Recovered Through Adding Launches (Assuming Launch Capacity Exists)
  - L1 Architecture Can Recover From Refueling Sensitivity By Using Replacement Fuel Tanks Instead Of Refueling

L1 Architecture Launch Flexibility Can Overcome Potential Refueling And Assembly Risk Through Added Launches Of Propellant

Thermal Protection System Trade Study

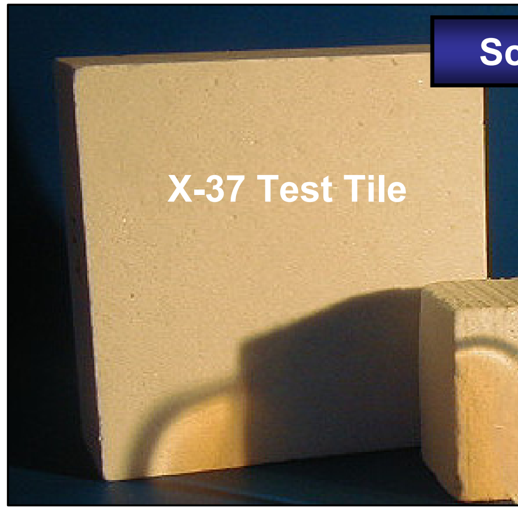
Purpose/Background

- **A Silicon-carbide Nano-cellular Based TPS Similar To What Was Tested Under The X-37 Program**

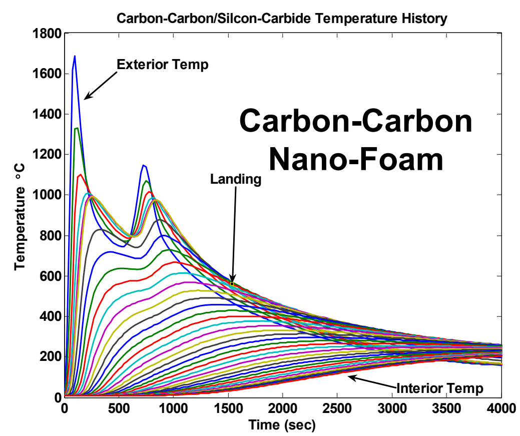
Approach

- **Analyze TPS Performance Using A Direct-return Trajectory From The Moon. The NASA Code MINIVER Was Used To Predict TPS Performance Of Each System.**
- **The Metric Used In This Trade Is The TPS Mass Per Unit Area Needed To Keep The Maximum CEV-E Structural Temperature Below 200º C.**
- **An Apollo Style Aero-ballistic Lifting-body Reentry Was Used.**

Schafer Nano-Cellular Foam



- **Carbon-carbon/Nano-foam Design Using 2.5 cm Of Carbon-carbon On Top Of 10 cm of Silicon-carbide Nano-foam Produced Same Temperature On Structure**
- **Mass Per Unit Area Of 47 kg/m^2**
- **Carbon-carbon/Nano-foam Design Represents A TPS Mass Reduction Of 50%**



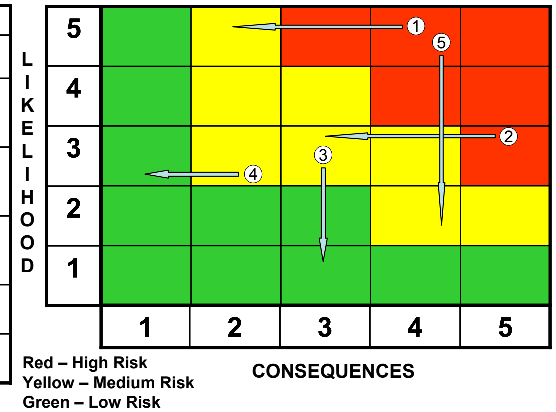
Reduction in Heat Shield Mass Will Reduce Propellant Requirements

Standard DoD-based Risk Process

- **Experienced With DoD Approach for Risk Identification, Assessment, Prioritization, Mitigation**
- **Identify and Describe Technical Risks for Architecture and CEV**
  - Identify New Candidate Risks
    - Standard Format for Description
    - Available to Whole Schafer/Boeing Team
  - Document in Monthly Report
- **Risk Assessment Panel Investigates Each Candidate Risk**
  - Representatives from SE&I, Architecture, and CEV Areas (Primary and Alternate)
  - Meet at least Monthly and As Needed
  - Review Candidate Risks and Assess Severity and Probability of Occurrence
  - Describe in Standard (Proposed) Risk Assessment Chart Format
  - Define Risk Mitigation Plans
    - Identify Risk Mitigation Approaches for Each Risk
    - Monthly Update and Refine Risk Mitigation Approaches
  - Obtain Concurrence from PM, Architecture Lead, and CEV Lead

Likelihood of the Event Occurring		
Level	Probability	… or the current process …
5	Very High	cannot prevent this event, no alternative or processes are available.
4	High	cannot prevent this event, but a different approach or process might.
3	Moderate	may prevent this event, but additional actions will be required.
2	Low	is usually sufficient to prevent this type of event.
1	Very Low	is sufficient to prevent this event.

Adapted From NASA ISS Risk Management and INCOSE



Consequence if the event occurs					
Level →	1 - Minimal	2 - Moderate	3 - Major	4 - Severe	5 - Critical
Technical	Minimal or No Impact	Moderate Rework, Same Approach Retained	Moderate Rework, Workarounds Available	Major Rework, But Workarounds Available	Unacceptable, No Alternatives Exist
Schedule	Minimal or No Impact	Additional Activities Required. Able to Meet Need Dates	Major Milestone Slip < 1Month	Major Milestone Slip >1 Month or Program Critical Path Impacted	Cannot Achieve Major Program Milestone
Cost	Minimal Impact < 5% Impact to Budget	Moderate Impact >5% to 10% Impact to Budget	Major Impact >10% to 20% Impact to Budget	Severe Impact >20% to 30% Impact to Budget	Critical Impact >30% Impact to Budget

Proven Risk Process Adopted From DoD SoS Development Programs