Simplifying Complex Problems with Systems Engineering Tools: *A Lunar Architecture Analysis Case Study*

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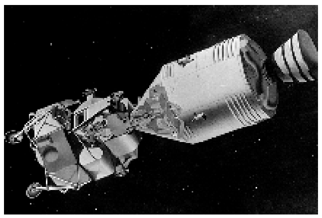
Space Systems Engineering Conference
November 10th, 2005
Paper # GT - SSEC.B.5

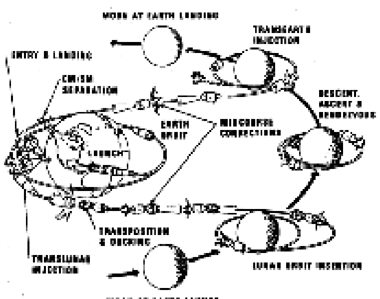
Introduction

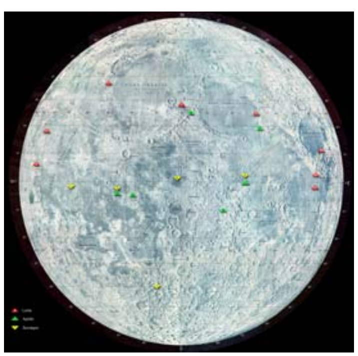
- **The systems engineering process is largely driven to the end goal of developing a product**
  - Space systems involved in human lunar exploration are still too immature to use the full, detailed systems engineering process

- **Simplified analyses of human lunar exploration systems and architectures are required to narrow the trade space**
  - Some systems engineering tools prove extremely useful for simplifying these complex analyses

Space Systems: Lunar Architecture Analyses







- **Space systems analysis problems are complex, especially when attempting to build a lasting human exploration campaign**
  - Multiple elements:
    - Propulsive elements of varying performance
    - Payload elements of varying mass & function
  - Multiple maneuvers:
    - Several burns of varying degrees of difficulty
    - Multiple burns may be completed by single stage
  - Multiple possible destinations:
    - Choice between various lunar orbits and other staging locations (i.e. Earth-Moon L1)
    - Choice of lunar landing sites

Systems Engineering Tools

- **N^2 Diagrams: Functional decomposition**
  - Aids in identifying dependencies between elements and element functions
    - Identify required element functions
    - Identify feed-forward and feed-back characteristics

- **Trade Trees: Trade & sensitivity analysis organization**
  - Aids in organizing analyses that investigate trades of characteristics and sensitivities to performance variations

- **Simplified Modeling: Mass fraction-based assessment**
  - Provide quick, zero-level analysis to assess large portions of a broad trade space in sufficient detail to isolate trend and sensitivity drivers

Space System Analysis Problem: *Lunar Exploration*

- **Understanding commonalities & dependencies**
  - Must understand the performance dependencies of certain mission elements on other mission elements
  - Helps to identify which elements may be mission performance drivers

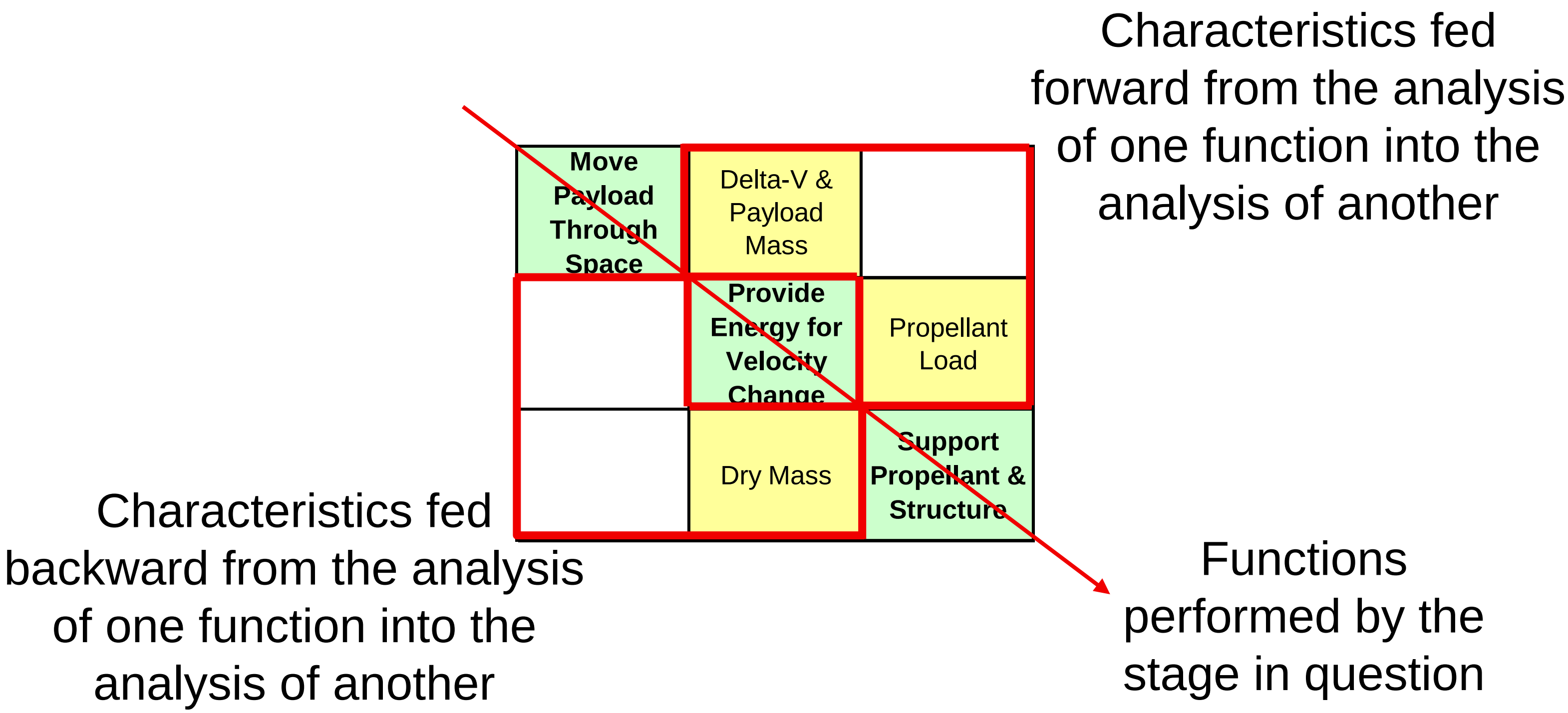
- **Discriminating between mission modes and methods**
  - Quick assessments of mission modes over a broad trade space of payload masses and stage propellant choices may help isolate promising mission modes (i.e. direct return or lunar orbit rendezvous)
  - Isolated trends may discriminate between parking orbit type or landing sites or combined stage functions

N^2 Diagram Example: Stage Calculations

Move Payload Through Space	Delta-V & Payload Mass	
	Provide Energy for Velocity Change	Propellant Load
	Dry Mass	**Support Propellant & Structure**

- **Stage must move a payload through space, providing energy from propellant to accommodate delta-v requirements**
- **Stage dry mass must accommodate propellant requirements and loads, sized based on propellant mass fraction**

N² Diagram Example: Stage Calculations



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Move Payload Through Space Delta-V & Payload Mass Tra In Provide Energy for Velocity Change Propellant Load Dry Mass Support Propellant & Structure	Total Stage Mass			Total Stage Mass	Total Stage Mass
Stage Dry Mass	**Orbit Alignment**			Total Stage Mass	Total Stage Mass
		Lunar Ascent	Total Stage Mass	Total Stage Mass	Total Stage Mass
			Lunar Descent	Total Stage Mass	Total Stage Mass
				Lunar Orbit Insertion	Total Stage Mass
					Trans-Lunar Injection

N² Diagram Examples: Specific Mission Architectures

Lunar Orbit Rendezvous

Trans-Earth Injection	Total Stage Mass			Total Stage Mass	Total Stage Mass
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Lunar Orbit Rendezvous: EDS for LOI

Trans-Earth Injection	Total Stage Mass			Total Stage Mass	Total Stage Mass
Stage Dry Mass	**Orbit Alignment**			Total Stage Mass	Total Stage Mass
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				Lunar Orbit Insertion	Total Stage Mass
				Stage Dry Mass	**Trans-Lunar Injection**

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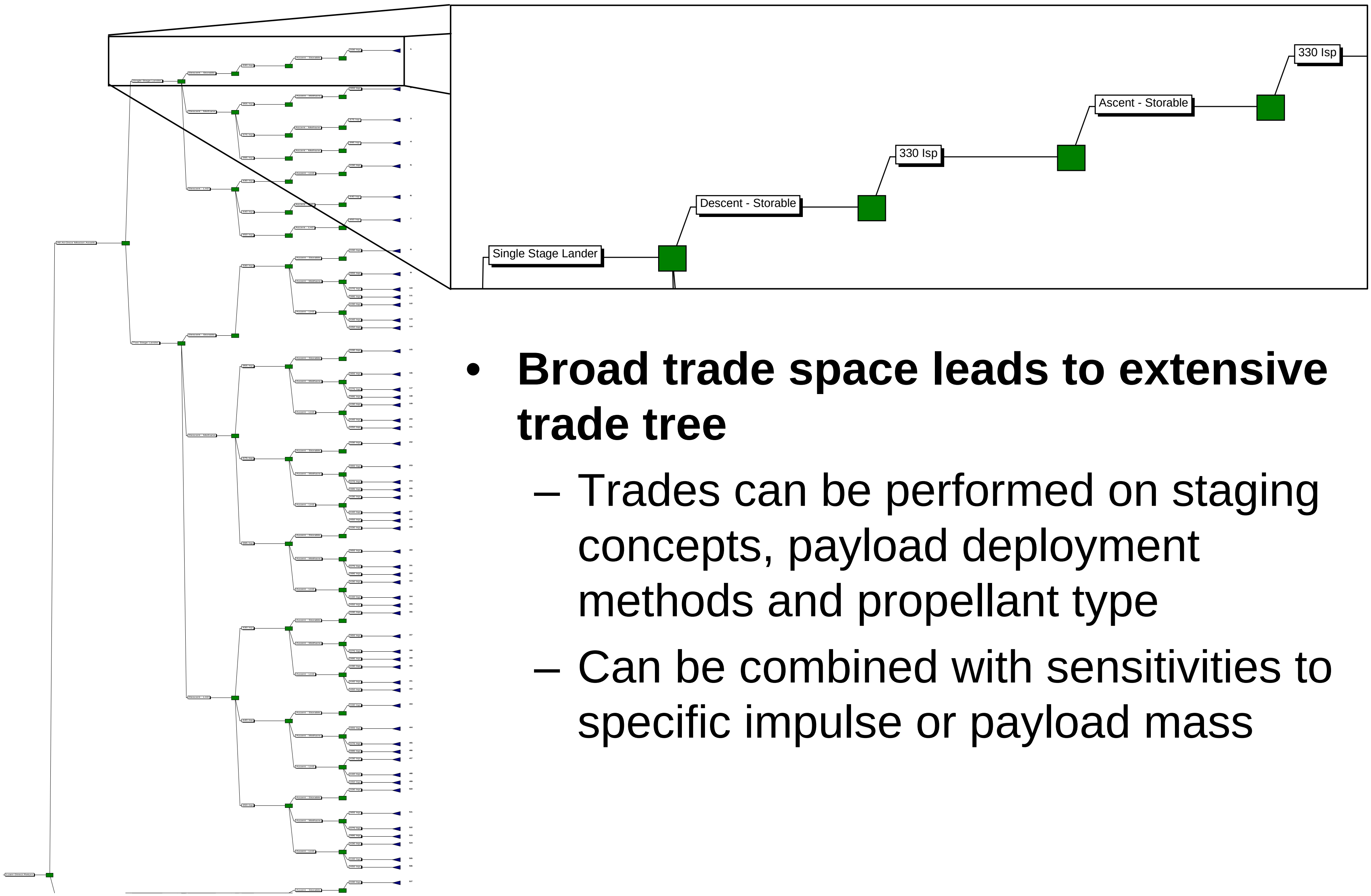
				Lunar Orbit Insertion	Total Stage Mass
				Stage Dry Mass	**Trans-Lunar Injection**

Lunar Direct Return: Single Stage Lander

Trans-Earth Injection		Total Stage Mass	Total Stage Mass	Total Stage Mass	Total Stage Mass
	Orbit Alignment				
Stage Dry Mass		**Lunar Ascent**	Total Stage Mass	Total Stage Mass	Total Stage Mass
Stage Dry Mass		Stage Dry Mass	**Lunar Descent**	Total Stage Mass	Total Stage Mass
				Lunar Orbit Insertion	Total Stage Mass
				Stage Dry Mass	**Trans-Lunar Injection**

Trade & Sensitivity Analysis: *The Trade Tree*



- **Broad trade space leads to extensive trade tree**
  - Trades can be performed on staging concepts, payload deployment methods and propellant type
  - Can be combined with sensitivities to specific impulse or payload mass

Trade & Sensitivity Analysis: *Trade Trees in Excel*

All-At-Once	Single Stage Lander	Descent Storable	330 ISP	Ascent Storable	330 ISP

All-At-Once	Single Stage Lander	Descent Storable	330 ISP	Ascent Storable	330 ISP
All-At-Once	Single Stage Lander	Descent Methane	355 ISP	Ascent Methane	355 ISP
All-At-Once	Single Stage Lander	Descent Methane	375 ISP	Ascent Methane	375 ISP
All-At-Once	Single Stage Lander	Descent Methane	395 ISP	Ascent Methane	395 ISP
All-At-Once	Single Stage Lander	Descent LH2	430 ISP	Ascent LH2	430 ISP
All-At-Once	Single Stage Lander	Descent LH2	440 ISP	Ascent LH2	440 ISP
All-At-Once	Single Stage Lander	Descent LH2	450 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent Storable	330 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent Methane	375 ISP
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All-At-Once	Two Stage Lander	Descent Methane	355 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Methane	375 ISP	Ascent Methane	375 ISP
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All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Methane	375 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent Methane	395 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent LH2	430 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent LH2	440 ISP
All-At-Once	Two Stage Lander	Descent Methane	395 ISP	Ascent LH2	450 ISP
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All-At-Once	Two Stage Lander	Descent LH2	430 ISP	Ascent LH2	450 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Storable	330 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Methane	355 ISP
All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent Methane	375 ISP
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All-At-Once	Two Stage Lander	Descent LH2	440 ISP	Ascent LH2	430 ISP
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All-At-Once	Two Stage Lander	Descent LH2	450 ISP	Ascent LH2	450 ISP

- **Adapting trade tree to Excel allows for use of trade tree with Excel models**
  - Basic modeling capability is established based on PMF and iterative calculations
  - VB code developed to call trade tree line items for individual case runs of specific trade tree branches

Sample Cases

- **Lunar Direct Return Specific Impulse Sensitivity**
  - Assumes mass for CEV, which is carried to the lunar surface and returned directly from the lunar surface to Earth
- **Lunar Orbit Rendezvous Parking Orbit Trade**
  - Separate stages for all burns with a transfer habitat, CEV and staged lunar lander and surface habitat
  - Trade between 100 km circular parking orbit and 100 x 5000 km elliptical parking orbit
- **Lunar Orbit Rendezvous Stage Propellant Trade**
  - Separate stages for all burns with a transfer habitat, CEV and staged lunar lander and surface habitat
  - Trade propellant options for each stage in all combinations

LDR Trades & Sensitivities

- **Assume:**
  - LOx/LH_2 EDS
  - 11 MT crew hab
- **Trade:**
  - Staged vs. Not Staged Lander
  - Descent & Ascent propellant
    - NTO / N_2H_4
    - LOx / CH_4
    - LOx / LH_2
  - Sensitivity to I_{sp} for each propellant
- **56 combos**

LDR Trade Tree

Staging	Descent Isp	Ascent Isp
No	330	330
No	355	355
No	375	375
No	395	395
No	430	430
No	440	440
No	450	450
Yes	330	330
Yes	330	355
Yes	330	375
Yes	330	395
Yes	330	430
Yes	330	440
Yes	330	450
Yes	355	330
Yes	355	355
Yes	355	375
Yes	355	395
Yes	355	430
Yes	355	440
Yes	355	450
Yes	375	330
Yes	375	355
Yes	375	375
Yes	375	395
Yes	375	430
Yes	375	440
Yes	375	450
Yes	395	330
Yes	395	355
Yes	395	375
Yes	395	395
Yes	395	430
Yes	395	440
Yes	395	450
Yes	430	330
Yes	430	355
Yes	430	375
Yes	430	395
Yes	430	430
Yes	430	440
Yes	430	450
Yes	440	330
Yes	440	355
Yes	440	375
Yes	440	395
Yes	440	430
Yes	440	440
Yes	440	450
Yes	450	330
Yes	450	355
Yes	450	375
Yes	450	395
Yes	450	430
Yes	450	440
Yes	450	450

LDR N^2 Diagram

Trans-Earth Injection		Total Stage Mass	Total Stage Mass	Total Stage Mass	Total Stage Mass
	Orbit Alignment				
Stage Dry Mass		**Lunar Ascent**	Total Stage Mass	Total Stage Mass	Total Stage Mass
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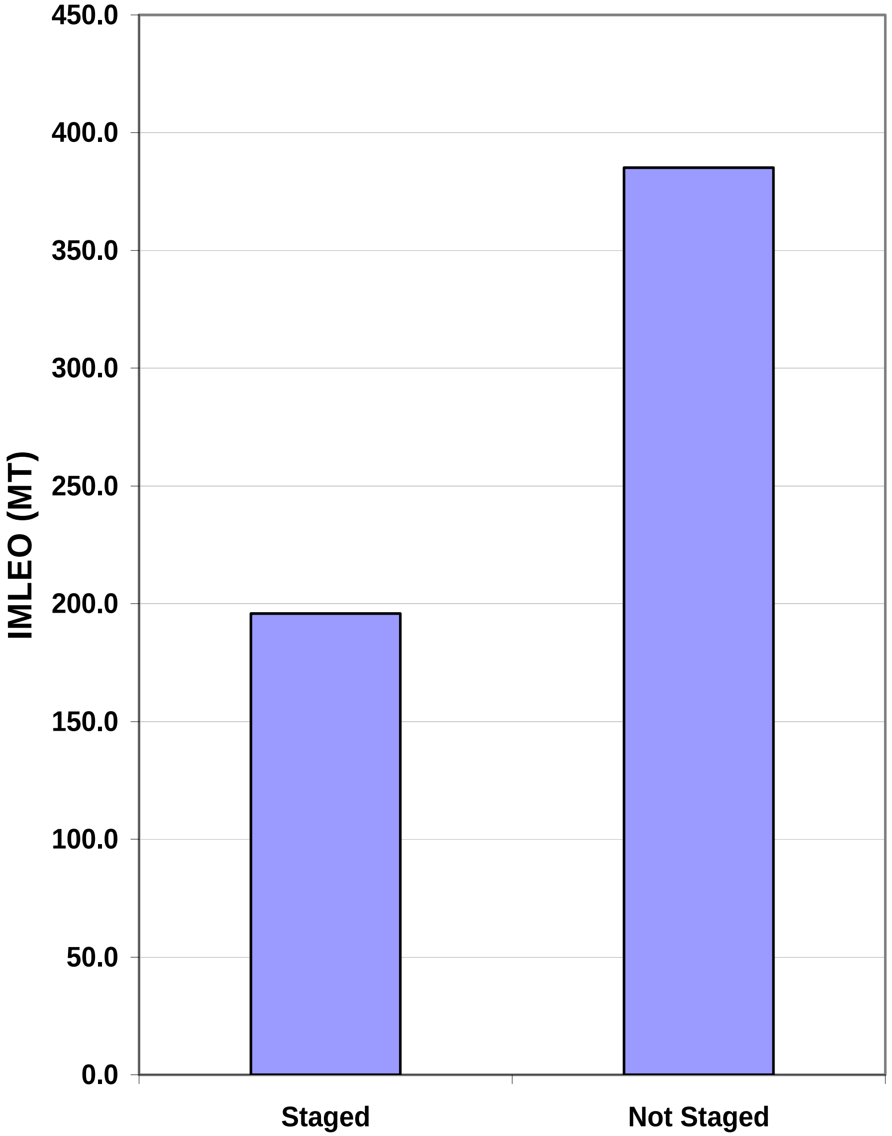
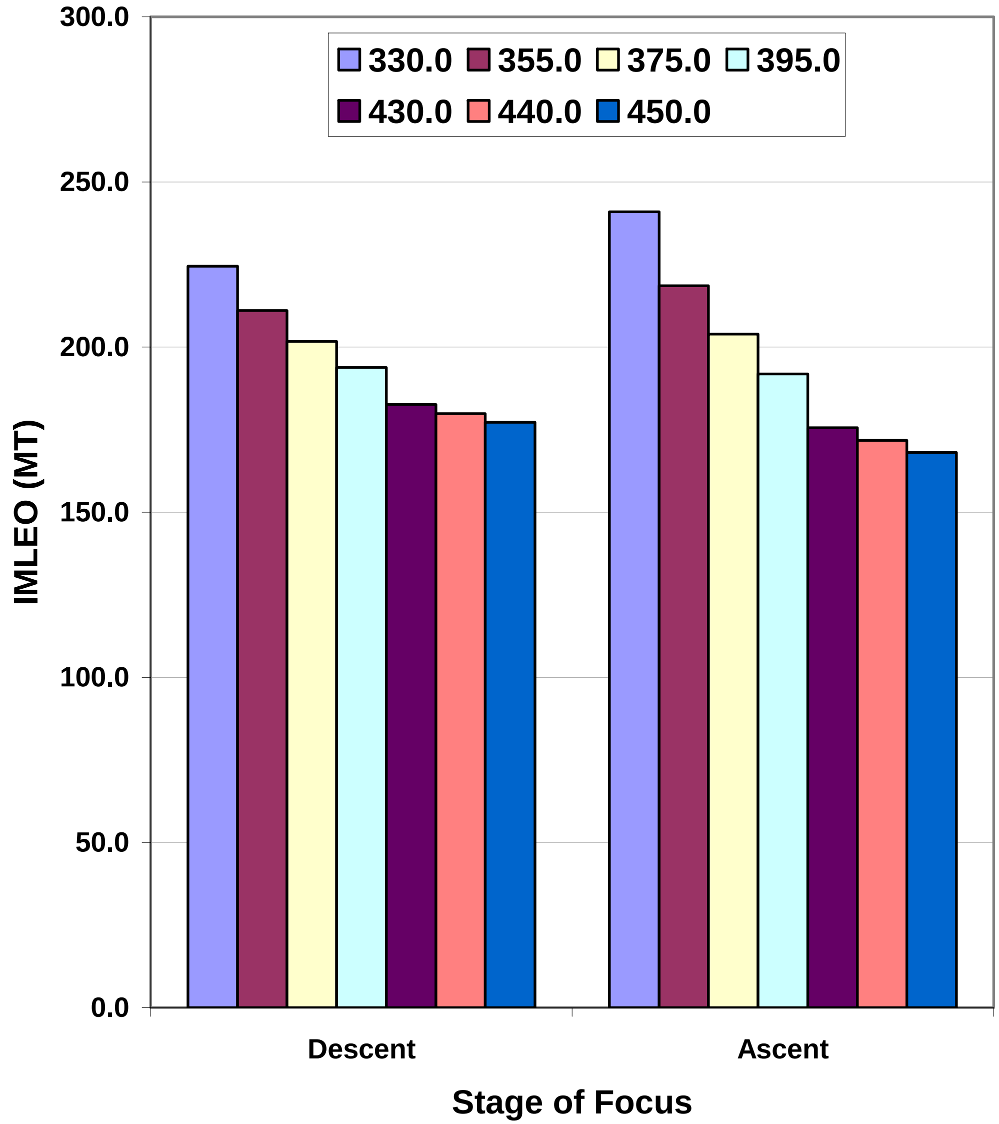
LDR Trades & Sensitivities: Results

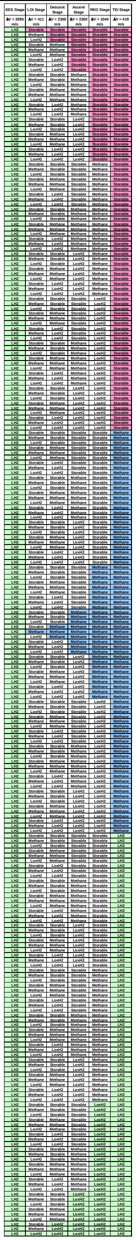


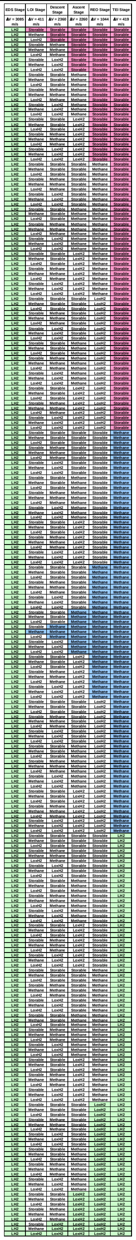


LOR Parking Orbit Trade

- **Assume:**
  - LOx/LH$_2$ EDS
  - 5 MT capsule
  - 4 MT trans hab
  - 5 MT surface hab
  - 2 MT ascent hab
- **Trade:**
  - 100 km circular vs. 100 x 5000 km elliptical orbit
  - Run for all propellant combinations
- **243 propellant combos for each orbit case**

LOR Trade Tree





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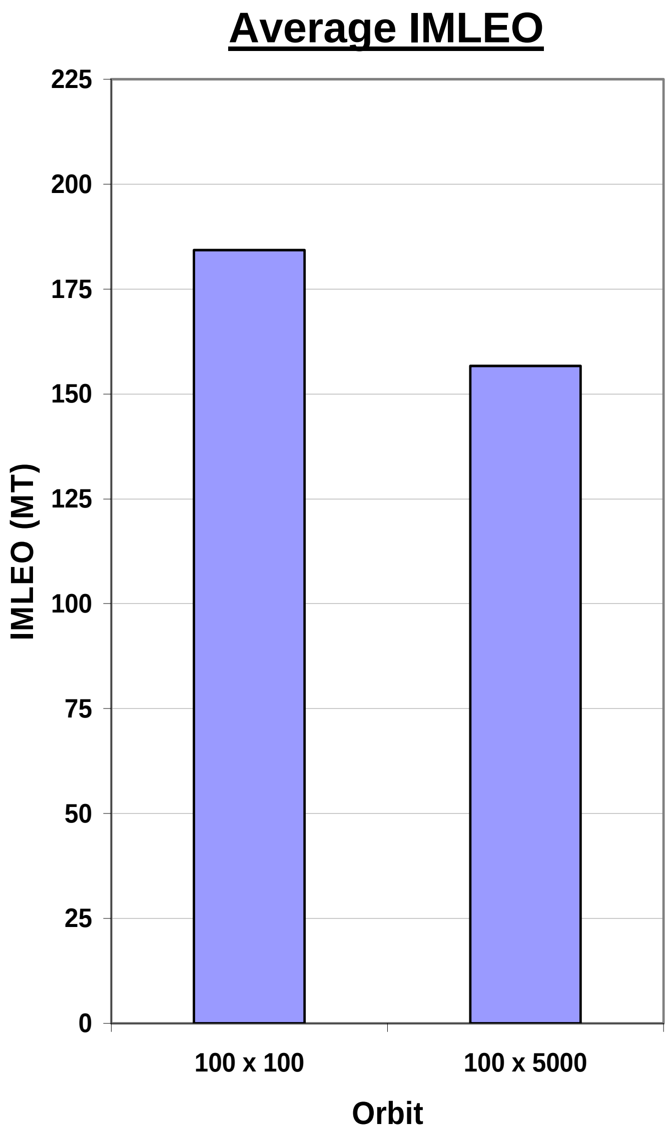

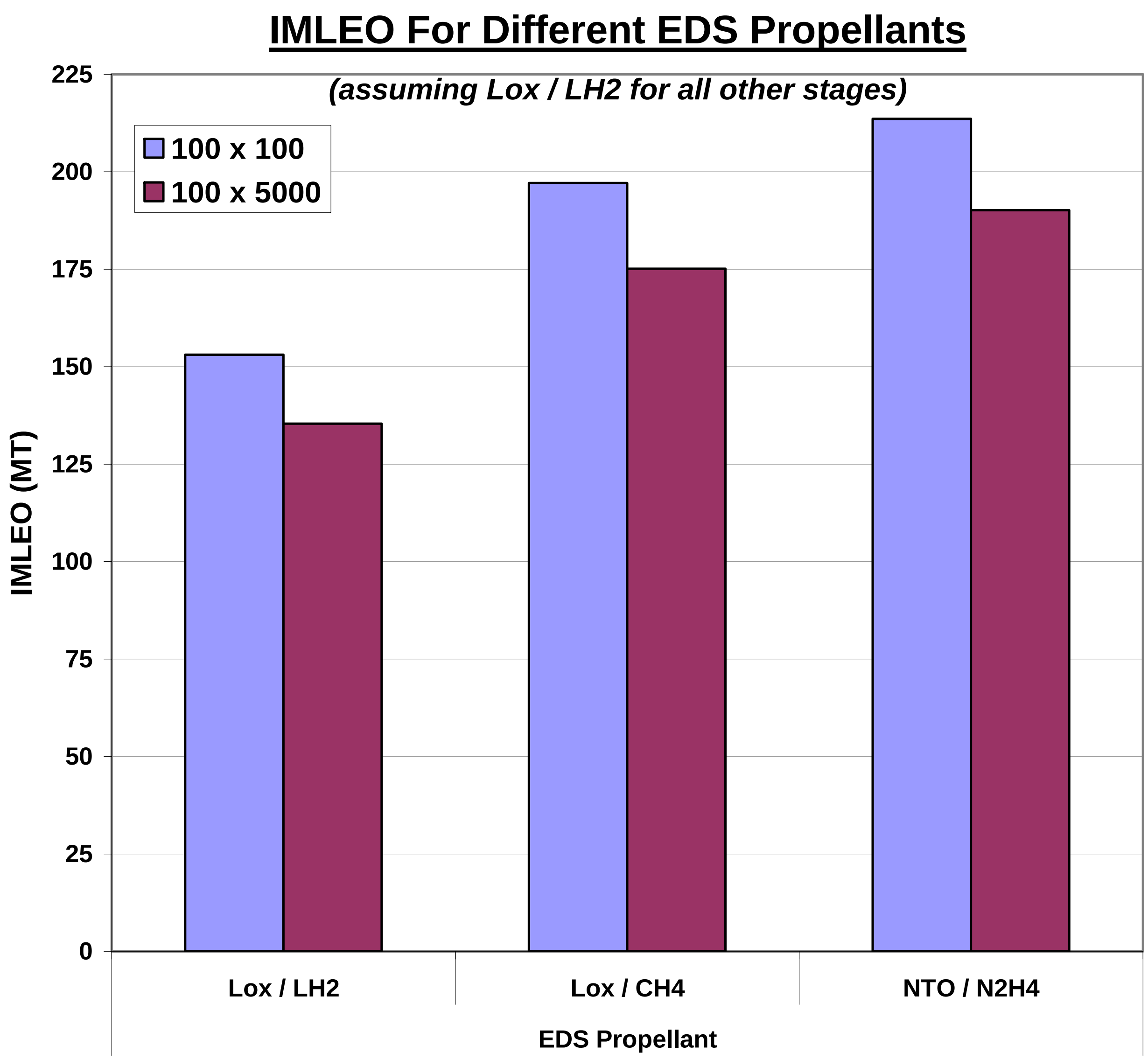

LOR Stage Propellant Trade

- **Assume:**
  - LOx/LH_2 EDS
  - 100 km circular parking orbit
  - 5 MT capsule
  - 4 MT trans hab
  - 5 MT surface hab
  - 2 MT ascent hab
- **Trade:**
  - Run for all propellant combinations
- **243 propellant combos**

LOR Trade Tree

EDS Stage	LOI Stage	Descent Stage	Ascent Stage	REO Stage	TEI Stage
ΔV = 3085 m/s	ΔV = 411 m/s	ΔV = 2360 m/s	ΔV = 2260 m/s	ΔV = 1044 m/s	ΔV = 419 m/s
LH2	Storable	Storable	Storable	Storable	Storable
LH2	Methane	Storable	Storable	Storable	Storable
LH2	LoxH2	Storable	Storable	Storable	Storable
LH2	Storable	Methane	Storable	Storable	Storable
LH2	Methane	Methane	Storable	Storable	Storable
LH2	LoxH2	Methane	Storable	Storable	Storable
LH2	Storable	LoxH2	Storable	Storable	Storable
LH2	Methane	LoxH2	Storable	Storable	Storable
LH2	LoxH2	LoxH2	Storable	Storable	Storable
LH2	Storable	Storable	Methane	Storable	Storable
LH2	Methane	Storable	Methane	Storable	Storable
LH2	LoxH2	Storable	Methane	Storable	Storable
LH2	Storable	Methane	Methane	Storable	Storable
LH2	Methane	Methane	Methane	Storable	Storable
LH2	LoxH2	Methane	Methane	Storable	Storable
LH2	Storable	LoxH2	Methane	Storable	Storable
LH2	Methane	LoxH2	Methane	Storable	Storable
LH2	LoxH2	LoxH2	Methane	Storable	Storable
LH2	Storable	Storable	LoxH2	Storable	Storable
LH2	Methane	Storable	LoxH2	Storable	Storable
LH2	LoxH2	Storable	LoxH2	Storable	Storable
LH2	Storable	Methane	LoxH2	Storable	Storable
LH2	Methane	Methane	LoxH2	Storable	Storable
LH2	LoxH2	Methane	LoxH2	Storable	Storable
LH2	Storable	LoxH2	LoxH2	Storable	Storable
LH2	Methane	LoxH2	LoxH2	Storable	Storable
LH2	LoxH2	LoxH2	LoxH2	Storable	Storable
LH2	Storable	Storable	Storable	Methane	Storable
LH2	Methane	Storable	Storable	Methane	Storable
LH2	LoxH2	Storable	Storable	Methane	Storable
LH2	Storable	Methane	Storable	Methane	Storable
LH2	Methane	Methane	Storable	Methane	Storable
LH2	LoxH2	Methane	Storable	Methane	Storable
LH2	Storable	LoxH2	Storable	Methane	Storable
LH2	Methane	LoxH2	Storable	Methane	Storable
LH2	LoxH2	LoxH2	Storable	Methane	Storable
LH2	Storable	Storable	Methane	Methane	Storable
LH2	Methane	Storable	Methane	Methane	Storable
LH2	LoxH2	Storable	Methane	Methane	Storable
LH2	Storable	Methane	Methane	Methane	Storable
LH2	Methane	Methane	Methane	Methane	Storable
LH2	LoxH2	Methane	Methane	Methane	Storable
LH2	Storable	LoxH2	Methane	Methane	Storable
LH2	Methane	LoxH2	Methane	Methane	Storable
LH2	LoxH2	LoxH2	Methane	Methane	Storable
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LH2	LoxH2	LoxH2	LoxH2	Methane	Storable
LH2	Storable	Storable	Storable	LoxH2	Storable
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LH2	Storable	LoxH2	Storable	LoxH2	Storable
LH2	Methane	LoxH2	Storable	LoxH2	Storable
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LH2	LoxH2	Methane	Methane	LoxH2	Storable
LH2	Storable	LoxH2	Methane	LoxH2	Storable
LH2	Methane	LoxH2	Methane	LoxH2	Storable
LH2	LoxH2	LoxH2	Methane	LoxH2	Storable
LH2	Storable	Storable	LoxH2	LoxH2	Storable
LH2	Methane	Storable	LoxH2	LoxH2	Storable
LH2	LoxH2	Storable	LoxH2	LoxH2	Storable
LH2	Storable	Methane	LoxH2	LoxH2	Storable
LH2	Methane	Methane	LoxH2	LoxH2	Storable
LH2	LoxH2	Methane	LoxH2	LoxH2	Storable
LH2	Storable	LoxH2	LoxH2	LoxH2	Storable
LH2	Methane	LoxH2	LoxH2	LoxH2	Storable
LH2	LoxH2	LoxH2	LoxH2	LoxH2	Storable
LH2	Storable	Storable	Storable	Storable	Methane
LH2	Methane	Storable	Storable	Storable	Methane
LH2	LoxH2	Storable	Storable	Storable	Methane
LH2	Storable	Methane	Storable	Storable	Methane
LH2	Methane	Methane	Storable	Storable	Methane
LH2	LoxH2	Methane	Storable	Storable	Methane
LH2	Storable	LoxH2	Storable	Storable	Methane
LH2	Methane	LoxH2	Storable	Storable	Methane
LH2	LoxH2	LoxH2	Storable	Storable	Methane
LH2	Storable	Storable	Methane	Storable	Methane
LH2	Methane	Storable	Methane	Storable	Methane
LH2	LoxH2	Storable	Methane	Storable	Methane
LH2	Storable	Methane	Methane	Storable	Methane
LH2	Methane	Methane	Methane	Storable	Methane
LH2	LoxH2	Methane	Methane	Storable	Methane
LH2	Storable	LoxH2	Methane	Storable	Methane
LH2	Methane	LoxH2	Methane	Storable	Methane
LH2	LoxH2	LoxH2	Methane	Storable	Methane
LH2	Storable	Storable	LoxH2	Storable	Methane
LH2	Methane	Storable	LoxH2	Storable	Methane
LH2	LoxH2	Storable	LoxH2	Storable	Methane
LH2	Storable	Methane	LoxH2	Storable	Methane
LH2	Methane	Methane	LoxH2	Storable	Methane
LH2	LoxH2	Methane	LoxH2	Storable	Methane
LH2	Storable	LoxH2	LoxH2	Storable	Methane
LH2	Methane	LoxH2	LoxH2	Storable	Methane
LH2	LoxH2	LoxH2	LoxH2	Storable	Methane
LH2	Storable	Storable	Storable	Methane	Methane
LH2	Methane	Storable	Storable	Methane	Methane
LH2	LoxH2	Storable	Storable	Methane	Methane
LH2	Storable	Methane	Storable	Methane	Methane
LH2	Methane	Methane	Storable	Methane	Methane
LH2	LoxH2	Methane	Storable	Methane	Methane
LH2	Storable	LoxH2	Storable	Methane	Methane
LH2	Methane	LoxH2	Storable	Methane	Methane
LH2	LoxH2	LoxH2	Storable	Methane	Methane
LH2	Storable	Storable	Methane	Methane	Methane
LH2	Methane	Storable	Methane	Methane	Methane
LH2	LoxH2	Storable	Methane	Methane	Methane
LH2	Storable	Methane	Methane	Methane	Methane
LH2	Methane	Methane	Methane	Methane	Methane
LH2	LoxH2	Methane	Methane	Methane	Methane
LH2	Storable	LoxH2	Methane	Methane	Methane
LH2	Methane	LoxH2	Methane	Methane	Methane
LH2	LoxH2	LoxH2	Methane	Methane	Methane
LH2	Storable	Storable	LoxH2	Methane	Methane
LH2	Methane	Storable	LoxH2	Methane	Methane
LH2	LoxH2	Storable	LoxH2	Methane	Methane
LH2	Storable	Methane	LoxH2	Methane	Methane
LH2	Methane	Methane	LoxH2	Methane	Methane
LH2	LoxH2	Methane	LoxH2	Methane	Methane
LH2	Storable	LoxH2	LoxH2	Methane	Methane
LH2	Methane	LoxH2	LoxH2	Methane	Methane
LH2	LoxH2	LoxH2	LoxH2	Methane	Methane
LH2	Storable	Storable	Storable	LoxH2	Methane
LH2	Methane	Storable	Storable	LoxH2	Methane
LH2	LoxH2	Storable	Storable	LoxH2	Methane
LH2	Storable	Methane	Storable	LoxH2	Methane
LH2	Methane	Methane	Storable	LoxH2	Methane
LH2	LoxH2	Methane	Storable	LoxH2	Methane
LH2	Storable	LoxH2	Storable	LoxH2	Methane
LH2	Methane	LoxH2	Storable	LoxH2	Methane
LH2	LoxH2	LoxH2	Storable	LoxH2	Methane
LH2	Storable	Storable	Methane	LoxH2	Methane
LH2	Methane	Storable	Methane	LoxH2	Methane
LH2	LoxH2	Storable	Methane	LoxH2	Methane
LH2	Storable	Methane	Methane	LoxH2	Methane
LH2	Methane	Methane	Methane	LoxH2	Methane
LH2	LoxH2	Methane	Methane	LoxH2	Methane
LH2	Storable	LoxH2	Methane	LoxH2	Methane
LH2	Methane	LoxH2	Methane	LoxH2	Methane
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LH2	LoxH2	Methane	Storable	Storable	LH2
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LH2	Storable	Methane	Storable	Methane	LH2
LH2	Methane	Methane	Storable	Methane	LH2
LH2	LoxH2	Methane	Storable	Methane	LH2
LH2	Storable	LoxH2	Storable	Methane	LH2
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LH2	LoxH2	LoxH2	Storable	Methane	LH2
LH2	Storable	Storable	Methane	Methane	LH2
LH2	Methane	Storable	Methane	Methane	LH2
LH2	LoxH2	Storable	Methane	Methane	LH2
LH2	Storable	Methane	Methane	Methane	LH2
LH2	Methane	Methane	Methane	Methane	LH2
LH2	LoxH2	Methane	Methane	Methane	LH2
LH2	Storable	LoxH2	Methane	Methane	LH2
LH2	Methane	LoxH2	Methane	Methane	LH2
LH2	LoxH2	LoxH2	Methane	Methane	LH2
LH2	Storable	Storable	LoxH2	Methane	LH2
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LH2	Storable	LoxH2	LoxH2	Methane	LH2
LH2	Methane	LoxH2	LoxH2	Methane	LH2
LH2	LoxH2	LoxH2	LoxH2	Methane	LH2
LH2	Storable	Storable	Storable	LoxH2	LH2
LH2	Methane	Storable	Storable	LoxH2	LH2
LH2	LoxH2	Storable	Storable	LoxH2	LH2
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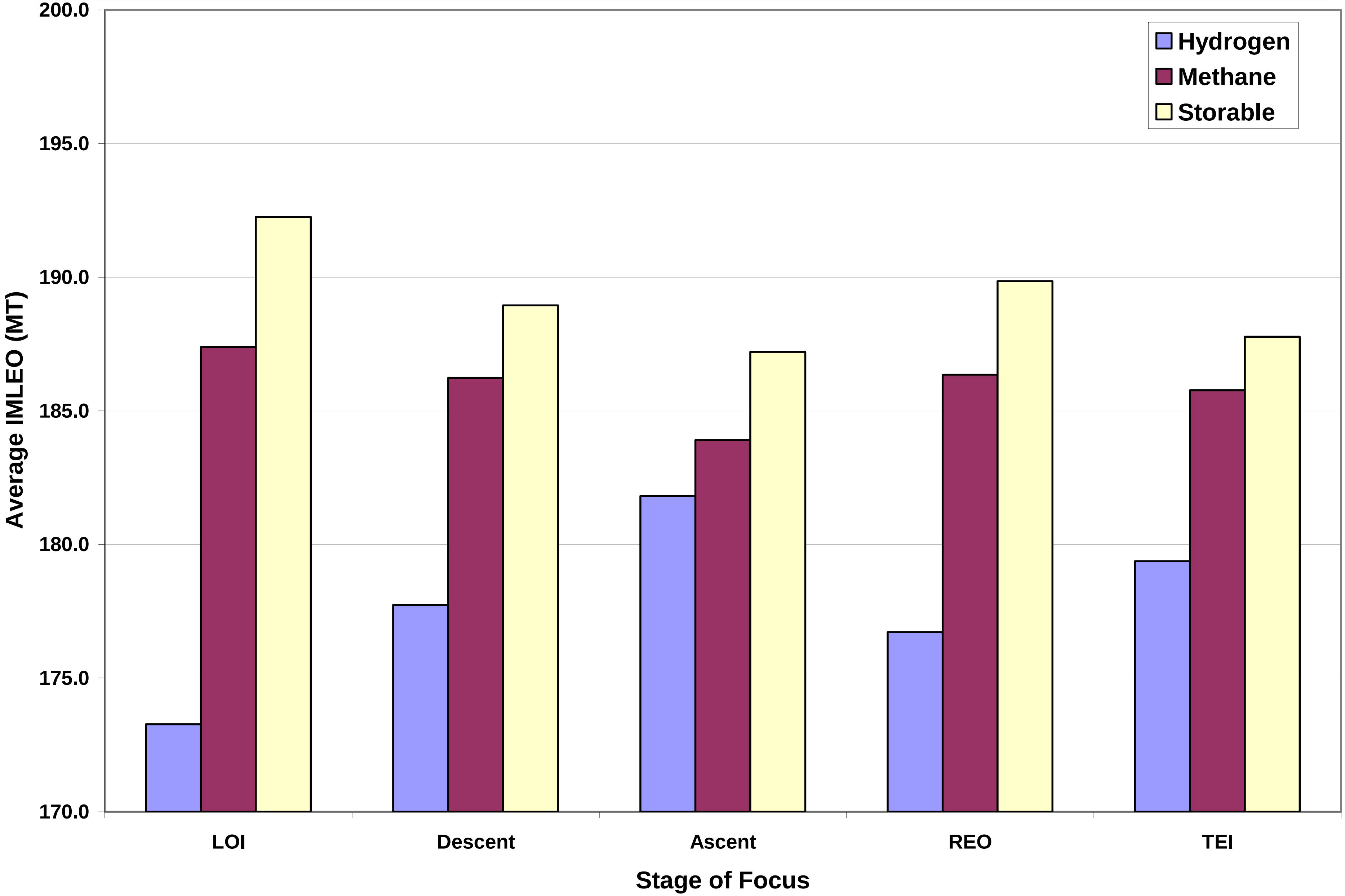
LH2	Storable	Methane	LoxH2	LoxH2	LH2
LH2	Methane	Methane	LoxH2	LoxH2	LH2
LH2	LoxH2	Methane	LoxH2	LoxH2	LH2
LH2	Storable	LoxH2	LoxH2	LoxH2	LH2
LH2	Methane	LoxH2	LoxH2	LoxH2	LH2
LH2	LoxH2	LoxH2	LoxH2	LoxH2	LH2

LOR N^2 Diagram

Trans-Earth Injection	Total Stage Mass			Total Stage Mass	Total Stage Mass
Stage Dry Mass	**Orbit Alignment**			Total Stage Mass	Total Stage Mass
		Lunar Ascent	Total Stage Mass	Total Stage Mass	Total Stage Mass
			Lunar Descent	Total Stage Mass	Total Stage Mass
				Lunar Orbit Insertion	Total Stage Mass
					Trans-Lunar Injection

LOR Stage Propellant Trade: Results



Sample Case Trade Results

- **Lunar Direct Return Specific Impulse Sensitivity**
  - A large span in IMLEO values across traded specific impulses leads to the conclusion that both the ascent and descent stages are significant mission performance drivers
  - As stage propellant performance increases, the mission is less sensitive to variations in the propellant I_{sp}
  - Staging the lander is preferable for the lunar direct missions

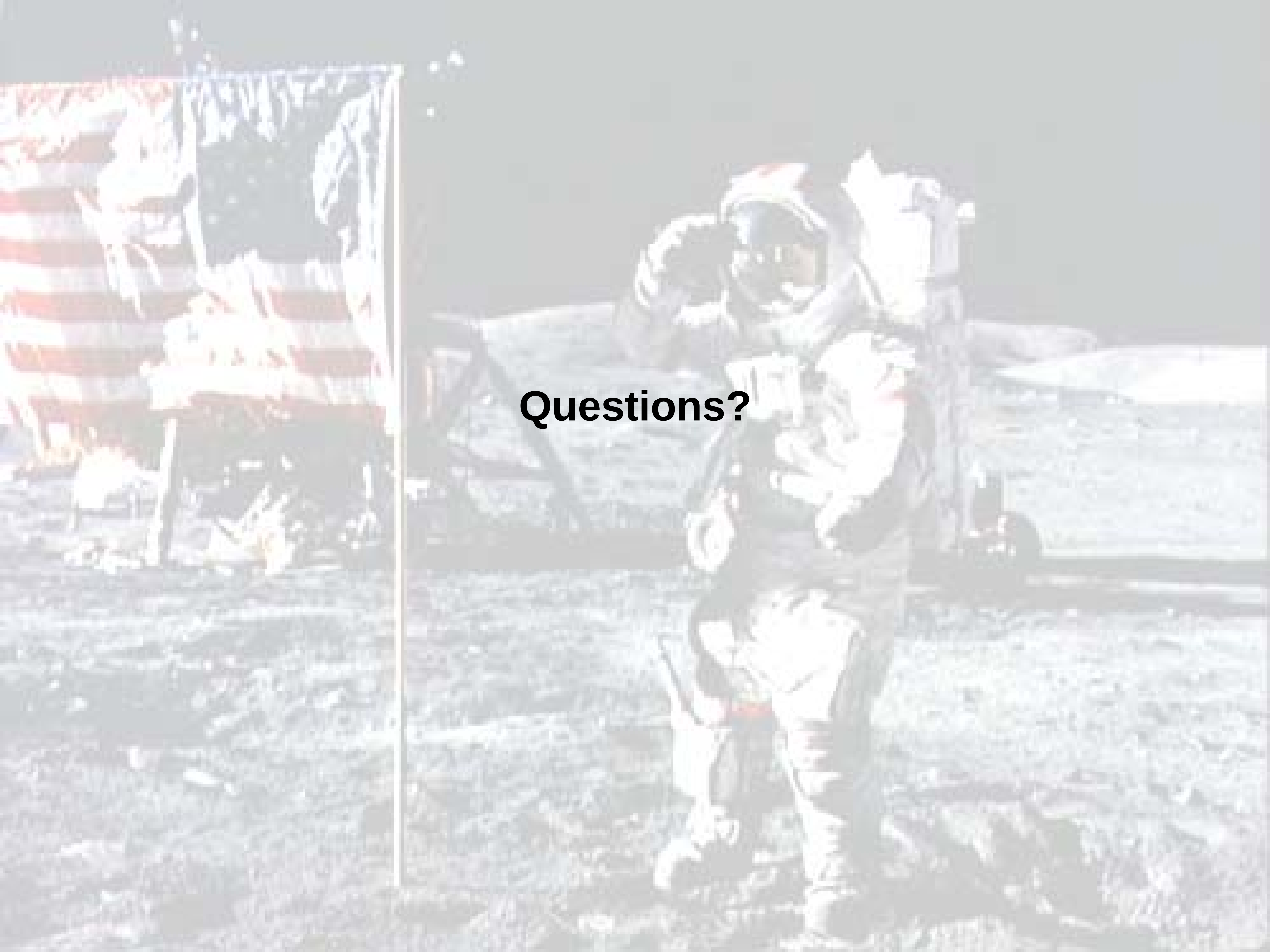
- **Lunar Orbit Rendezvous Parking Orbit Trade**
  - Elliptical parking orbits can provide IMLEO savings over circular parking orbits
  - As EDS propellant performance decreases, elliptical orbit staging savings increase but overall mission performance decreases

- **Lunar Orbit Rendezvous Stage Propellant Trade**
  - Selection of LOI and Descent propellants are the largest drivers of mission performance
  - These stages move large masses through large delta-v’s

Conclusions

- **Systems engineering tools can help simplify complex architecture analysis problems**
  - They aid in identifying functional dependencies among mission elements
  - They aid in organizing and quickly assessing broad trade spaces at a high level to isolate trade space trends

- **Using these tools for lunar exploration architecture analyses helps to identify trends and dependencies at a high level**
  - This allows engineers to direct the detailed analyses down those paths that show the most promise of delivering the best possible mission architecture


Questions?