Robotic Lunar Lander Concept

International Space Development Conference
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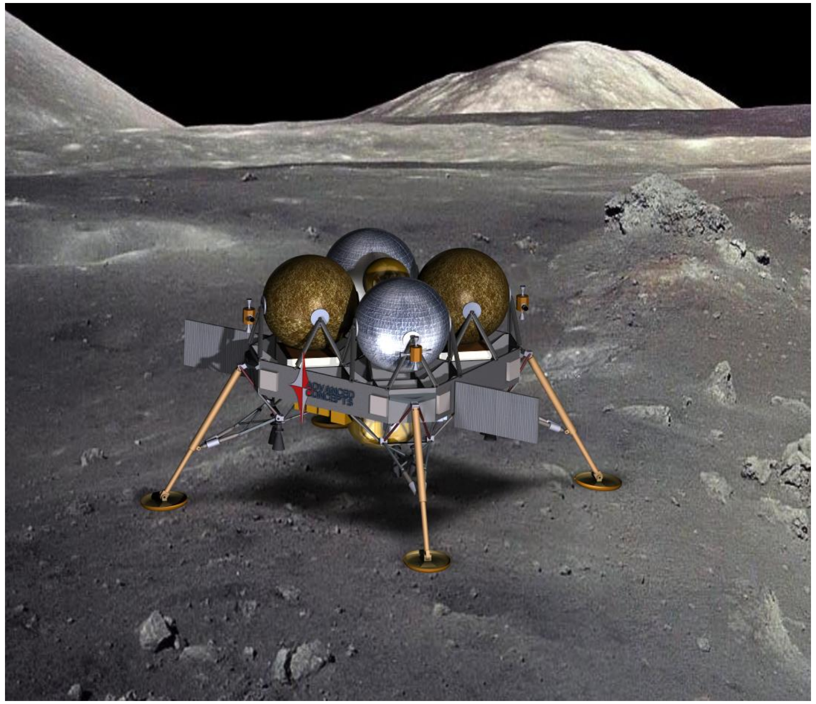


Background Information

- **Performed a short study of cryogenic lunar lander concepts in Summer of 2017**
  - Multi-center Lander Tech Office 2-phase effort to define a trade space and develop a concept to land cargo on the moon using cryo propellants
  - Purpose: Investigate viability of cryo propellant lander within the constraints of existing launch vehicle capabilities

- **Findings:**
  - For 500 kg payload, lander wet mass exceeded Atlas V 551 capability
  - Cryogenic propellants trade better as landed payload grows
  - Cryogenic propulsion systems can enable more ambitious missions if more capable launch vehicles are available

After the Study

- **Team identified several areas for improvement**
  - electric-Pump fed methane thrusters may save mass over a pressure-fed system and enables improved engine performance
  - Landing legs may enable reuse and provide more stable landing platform
  - Payload access to the surface is challenging as landers grow in physical size due to increased propellant loading and lower density propellants
  - Structural optimization and reconfiguration of concept can reduce overall lander mass

- **Team took on a new perspective on launch vehicle performance**
  - Newly emerging launch vehicles promise increased payload capacity
  - Fitting the methane lander in existing launch vehicles is challenging
  - Leveraging new launch vehicles allows for an increase over the previous 500 kg landed mass target

The team determined that next lander concept study would leverage work completed in September, 2017 with focused improvements and an eye towards emerging launch vehicles and large landed payloads

Objective Statement and Approach

- **Study Objective: Update concept based on previous findings and design a lunar robotic lander concept that could support the demonstration of active cryo-fluid management technologies for NASA and serve as a workhorse lunar surface cargo delivery vehicle**
  - The lander should support the following:
    - Short term goal: Demonstration of long-duration (longer than standard lunar mission) active cryogenic fluid management technologies
    - Long term goal: Landing 1000 kg of cargo on the lunar surface using LOX/CH_4 propellant with a lander concept that is operationally and economically appealing to a private landing services provider
    - Modular cryo system that the end user can modify as needed (i.e. removing long-duration CFM components)
- **Mission portfolio approach**
  - Identify of portfolio of missions that the lander should be capable of executing to varying levels of performance
  - Select 1 mission to set the baseline design
  - Determine what performance the lander can achieve in the other missions

Key Concept Ideas

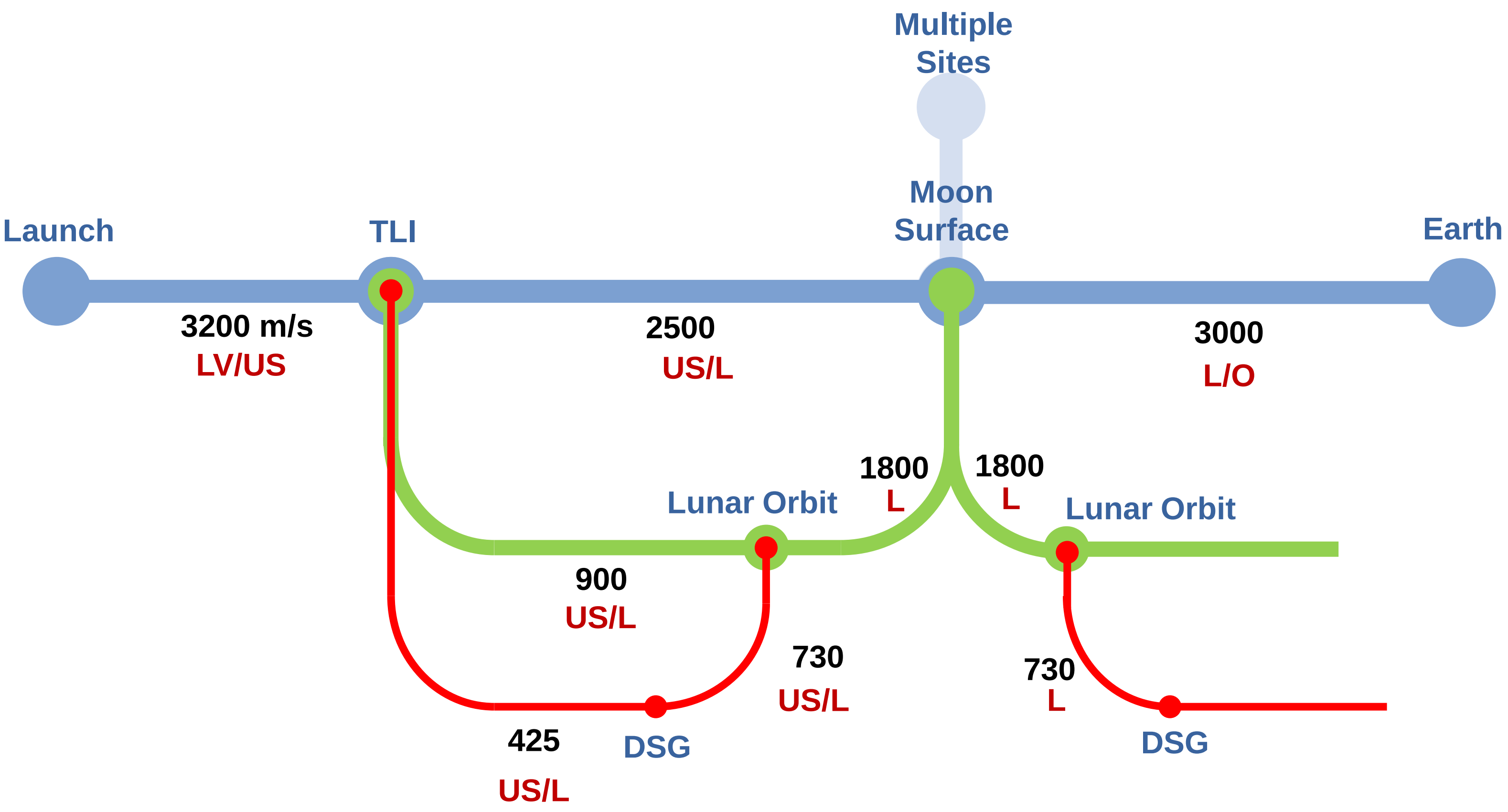
- ***Workhorse Lander*: Flexibility to support a range of lunar landing missions while filling a gap in payload delivery capability**

- ***Demonstration of Technology*: NASA uses the lander design to demonstrate feed-forward technologies in propulsion and cryogenic fluid management**

- ***Forward-Leaning in Specific Areas*: Lander concept relies on methane propulsion and associated CFM technologies, applying commercial and government technology development programs already underway, while employing high-TRL components in other areas to maintain affordability**

- ***Applications for the Future*: Applying advances in cryo propulsion, the lander lays the groundwork for more ambitious endeavors in the future, including human exploration beyond Low Earth Orbit.**

Mission Modes: ΔV Map



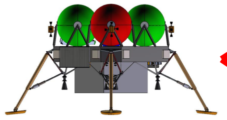
Potential Elements to Perform Maneuvers

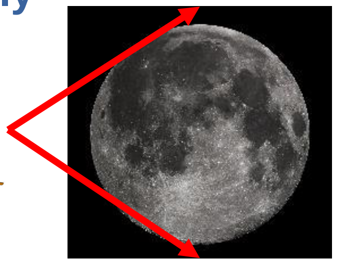
LV = Launch Vehicle
US = Upper Stage
L = Lander
O = Other

Potential Missions

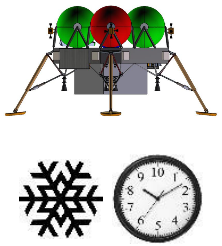
Landing Profile

Polar Only



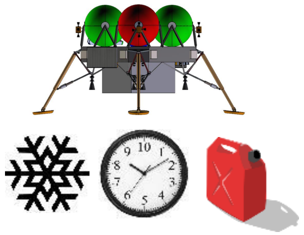


Global Access

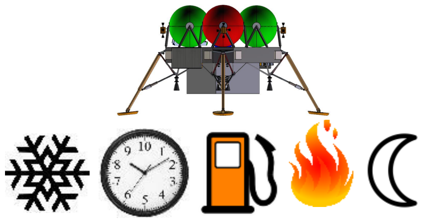


Surface Mission Profile

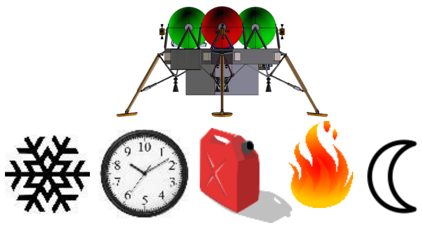
Crater Exploration



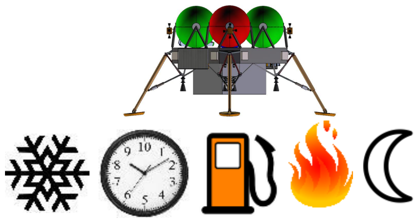
Return to Orbit



Surface Hopping



Reusable Lander



= Restart required

= Loiter time (up to 14 days) required

= Active CFM required

= Lunar Surface Day / Night survival considerations

= Additional DV margin required

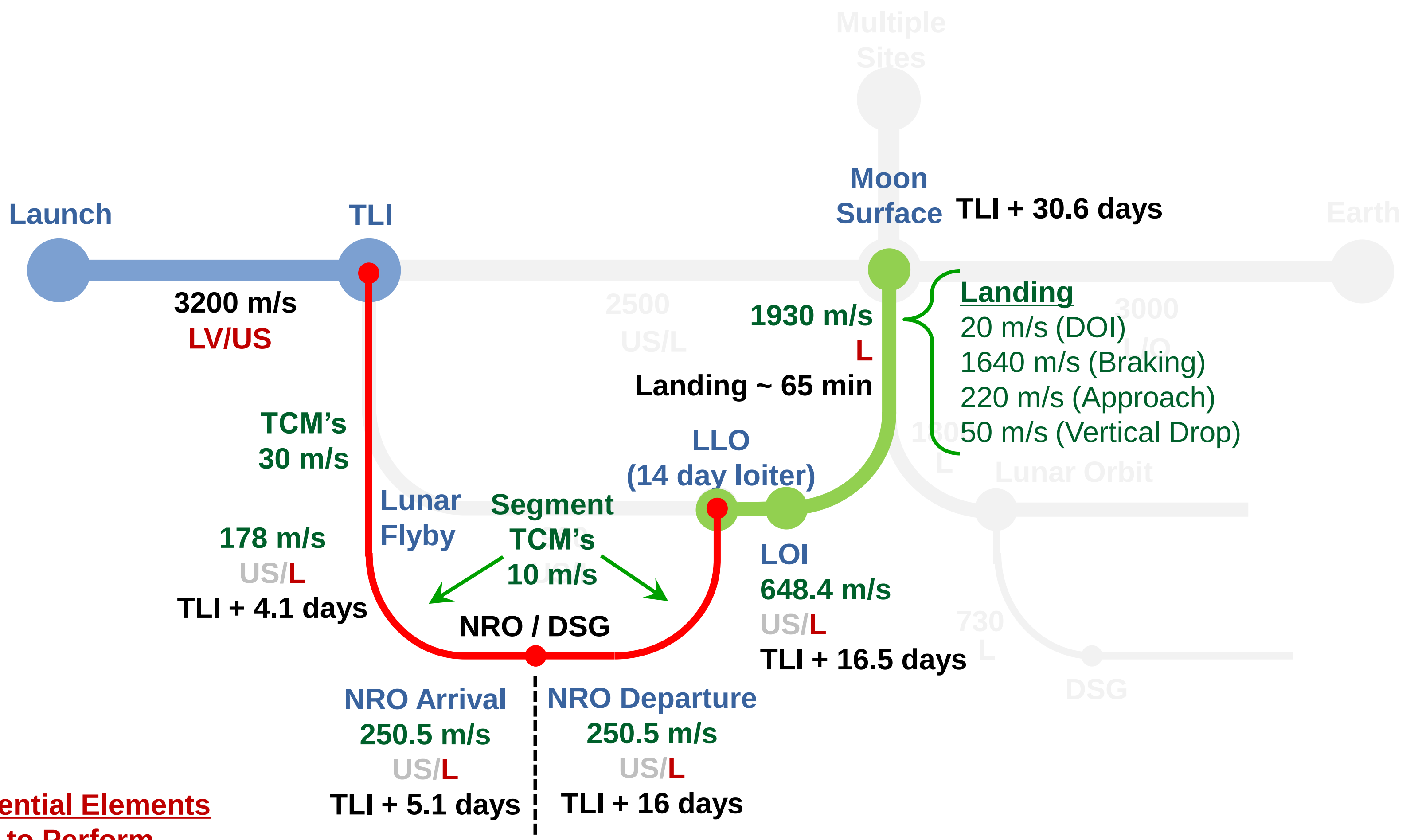
= Return DV required (By ISRU or in-space prop transfer), at least 1900-2500 m/s

Baseline Mission Description

- **Baseline mission was selected to serve as the sizing case for the lander concept**

- **Mission Profile:**
  - Deliver 1000 kg of payload to the lunar surface
  - Layover in near-rectilinear halo orbit (NRHO) for potential stay at the Deep Space Gateway facility
  - Transfer from NRHO to low lunar orbit (LLO) for phasing and precision landing navigation
  - Global lunar surface access can be achieved through a loiter period in LLO of up to 14 days

Mission Modes: ΔV Map



Potential Elements to Perform Maneuvers

LV = Launch Vehicle
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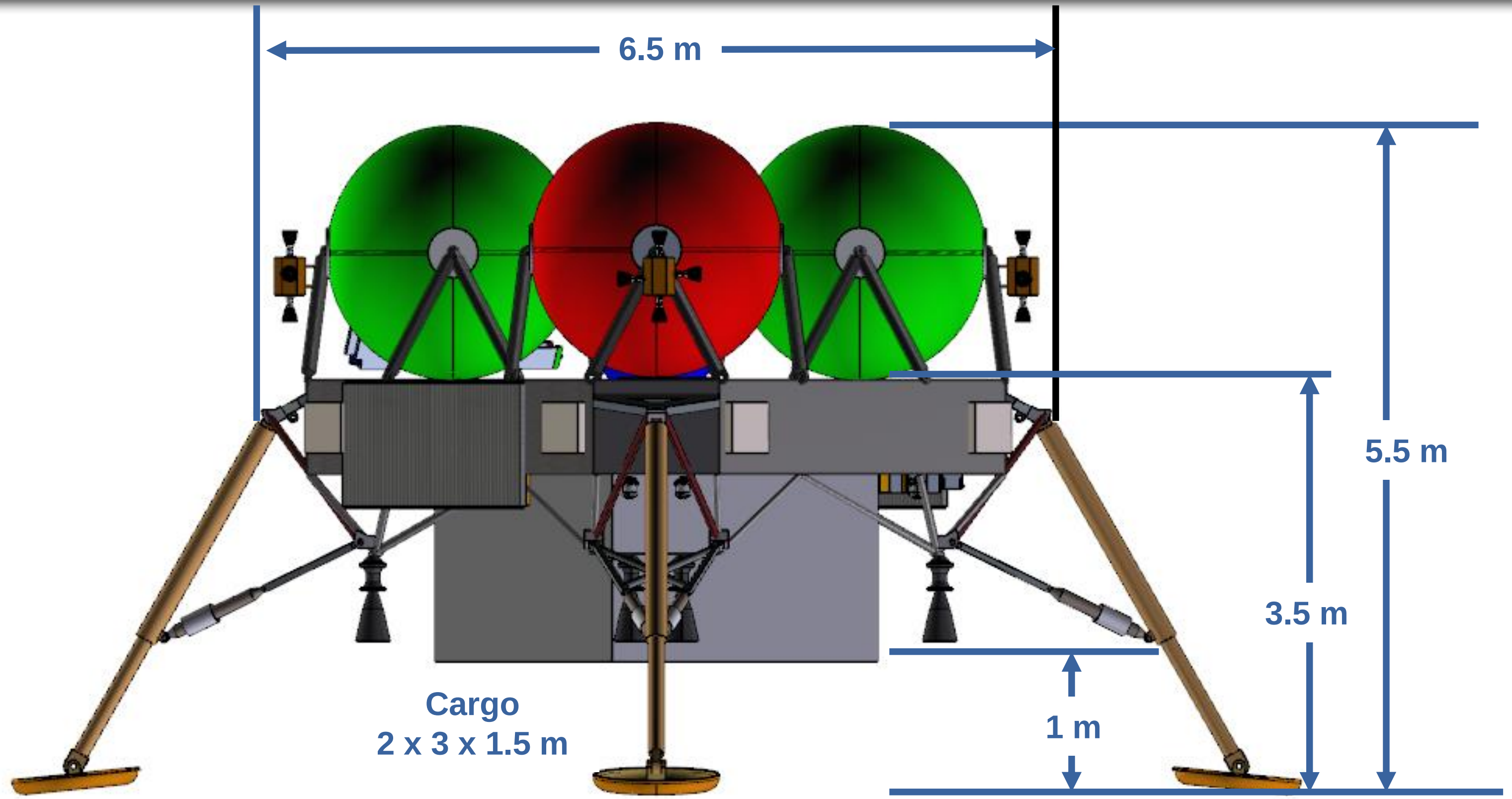
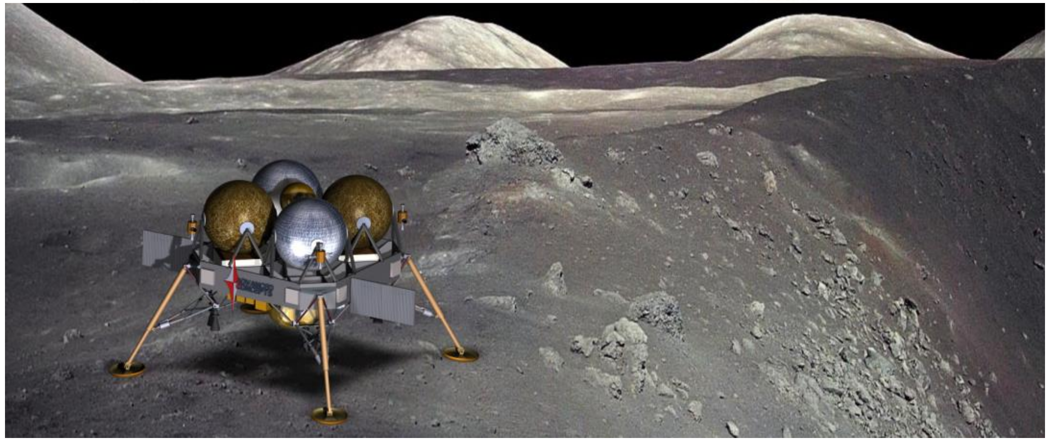
L = Lander
O = Other

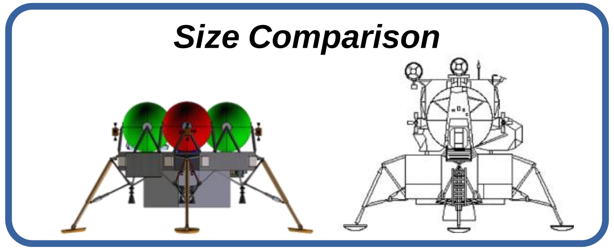
Notes:

* *All DVs except for landing are ideal/impulsive.*
* *Guestimate (placeholder) NRO loiter of 10.9 days*

Lander-Cargo







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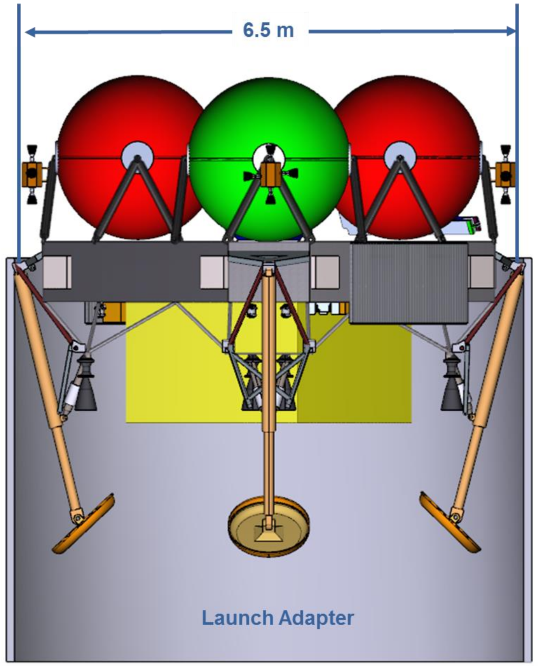
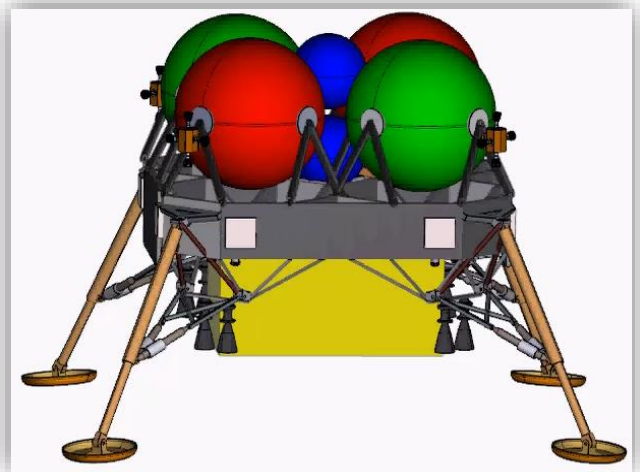
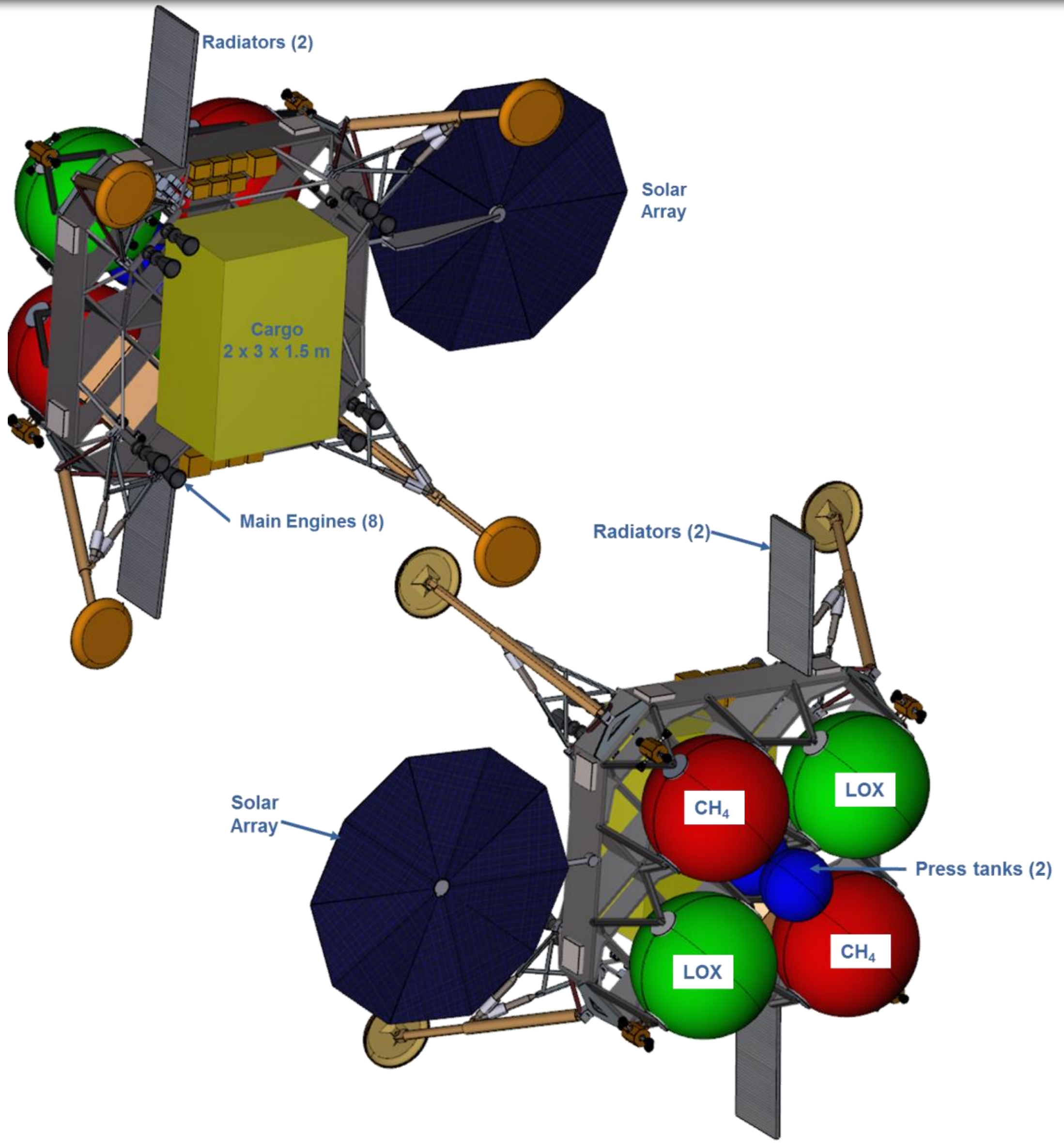
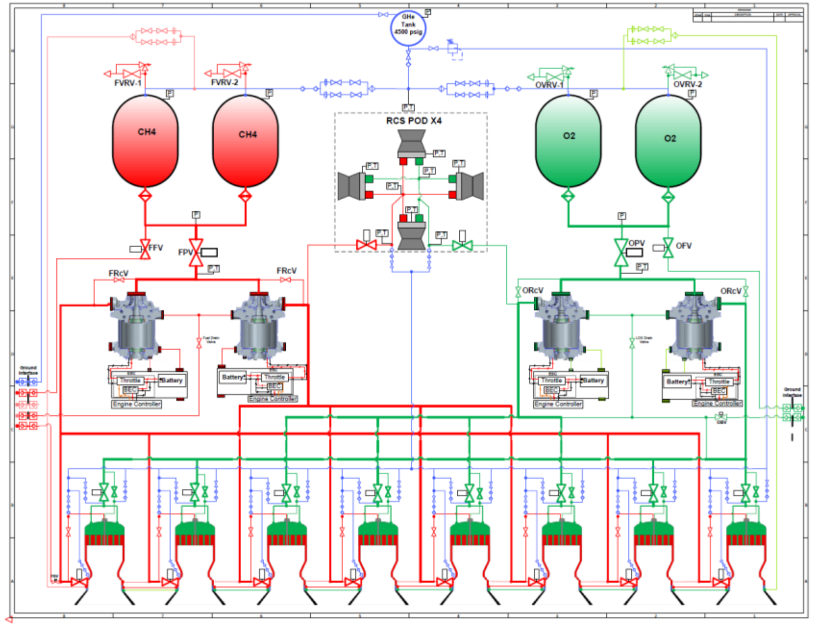






Concept Analysis

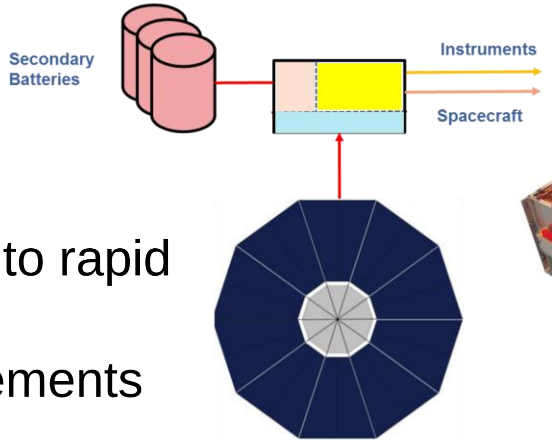


◆ CFM

- Baselined active cryo storage for longer-duration missions
- Removable parts for short-duration missions
- 2 cryocoolers required; 0.650 kW power req.

◆ Propulsion

- 8 x ePump-driven 1,400 lbf Lox/LCH4 main engines
- 16 x press-fed 30 lbf Lox/LCH4 RCS thrusters
- 67 kW required operational power to run ePumps



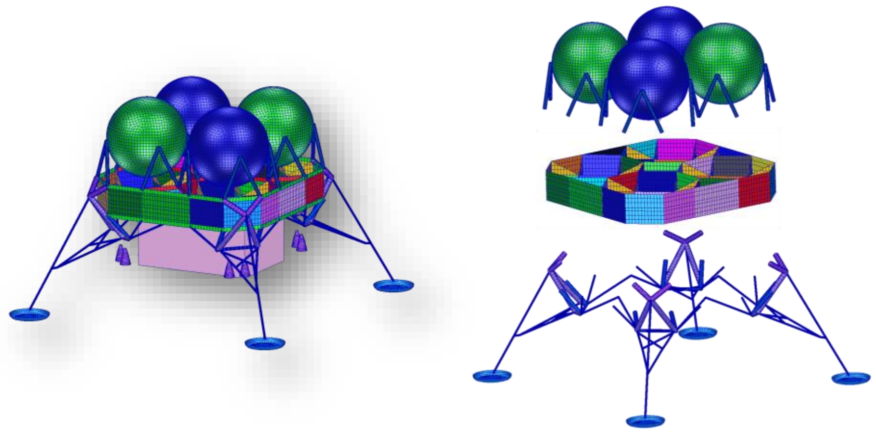
◆ Power:

- Single ultraFlex solar array for steady-state operations
- Batteries for propulsion system are significant challenge due to rapid discharge requirement to support electric pump operations
- Flight heritage battery solution heavy given discharge requirements

Concept Analysis

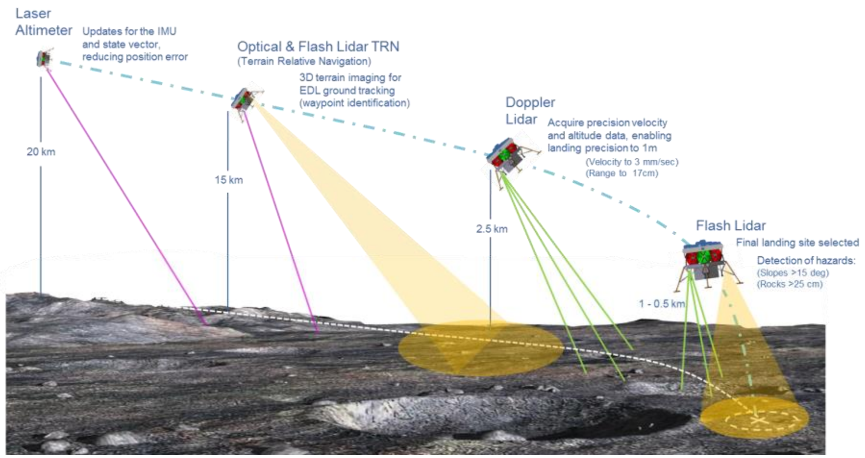
◆ Structures

- Full FEA performed for Earth Launch / Ascent, Propulsive Lunar Descent, and Lunar Landing
- Aluminum primary frame structure
- Composite tank support struts to minimize thermal conductivity



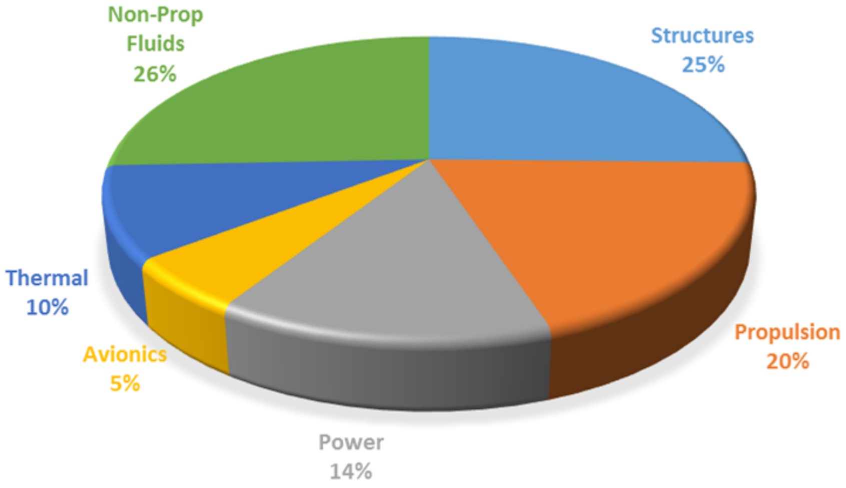
◆ Avionics

- 1-fault tolerant critical systems w/ component redundancy
- X-band comm to DSN
- Autonomous landing & hazard avoidance system based on LaRC/JPL work underway for lander project office
- Automated Rendezvous & Docking bolt-on avionics kit identified for return-to-orbit missions



Baseline Lander MEL

MEL - CFM Lunar Lander Demo		Basic Mass (kg)	Contingency (%)	Contingency (kg)	Predicted Mass (kg)
Mass Breakdown Structure					
1.0	Structures	1079.60	9.89%	106.74	1186.34
2.0	Propulsion	760.88	20.68%	157.33	918.21
3.0	Power	521.00	27.26%	142.00	663.00
4.0	Avionics	226.71	14.11%	31.99	258.70
5.0	Thermal	367.23	25.00%	91.81	459.04
Dry Mass		2955.42	17.93%	529.87	3485.29
6.0	Non-Prop Fluids	1201.91			1201.91
Inert Mass		4157.33			4687.20
7.0	Usable Propellant	9700.00			9700.00
Total Stage Gross Mass		13857.33			14387.20



Payload = 1000 kg

Total Launch Mass = 15387.2 kg

CFM Demo Mission Description

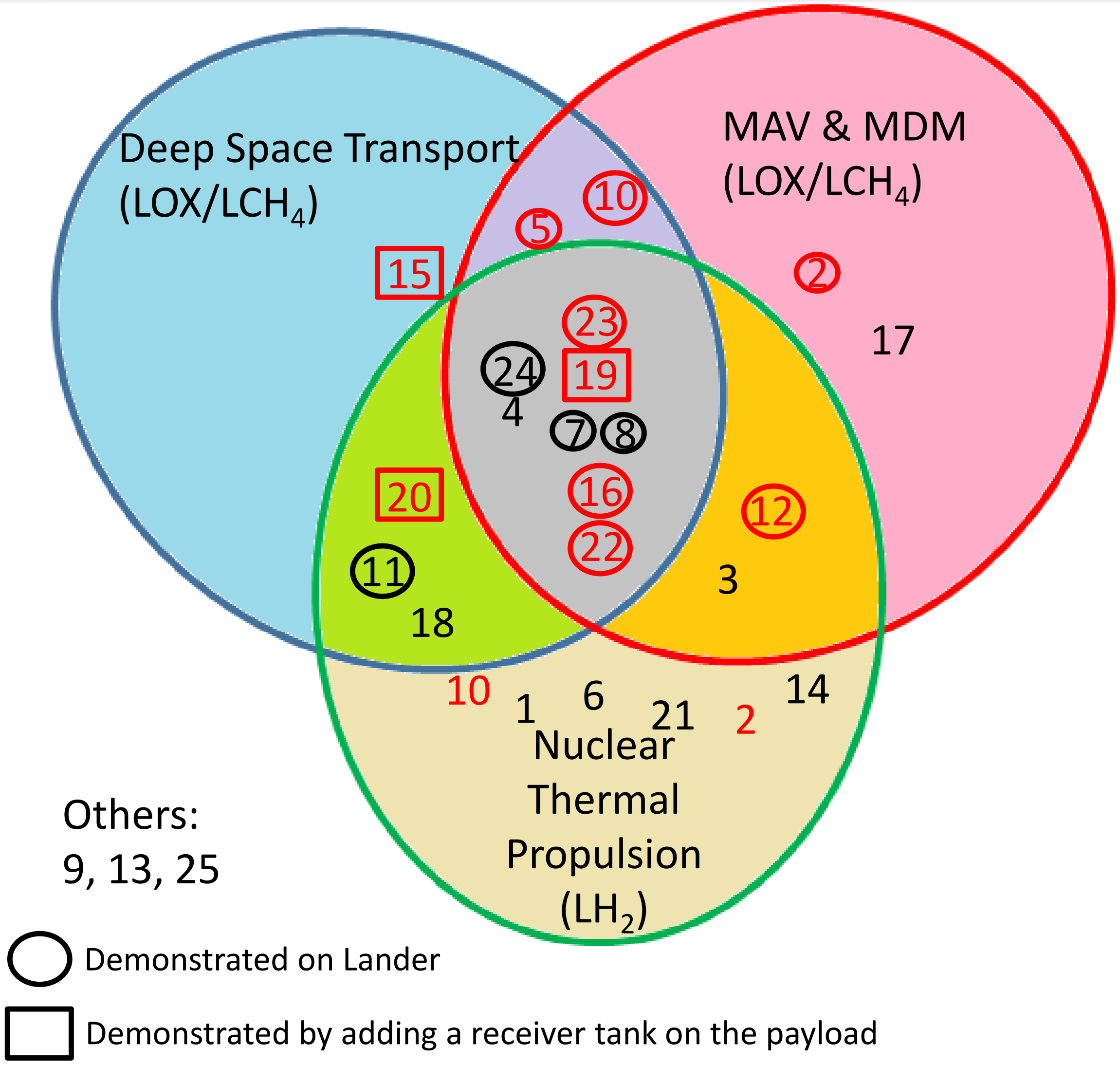
- **A potential first mission for the lander concept is a technology demonstration mission**
  - Demonstrate general mission operations
  - Demonstrate Lox/LCH4 landing propulsion
  - Demonstrate long-duration cryo-fluid management

- **Mission Profile:**
  - Lander payload is replaced with CFM demonstration payload for use prior to lunar landing
  - Follow same general mission profile as baseline lander mission
  - Extend stay in both NRHO and LLO to achieve various CFM technology demonstration goals
  - Lunar landing at the end of the mission demonstrates landing propulsion

Top Level CFM Demo Mission Requirements

- **Must fit within the lander design for the operational reference mission**
  - Propellant loads limited to lander design tank volumes
- **Must leverage CFM technologies already built into the operational lander design to the greatest extent possible**
  - Add CFM Demonstration payload to supplement demonstration goals
- **Must end with a lunar landing demonstration**
  - Nominal mission duration and operations are set however, if off nominal performance is revealed, the in-space portion of the mission will be cut short to ensure enough propellant is available to land on the moon
    - i.e. Demonstrate CFM for X days OR until propellant load = Y kg, whichever limit is reached first, then immediately initiate landing sequence

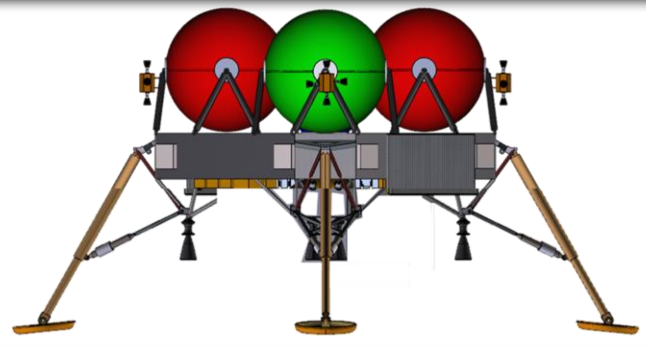
Cryogenic Fluid Management Across Multiple Propulsion Pieces



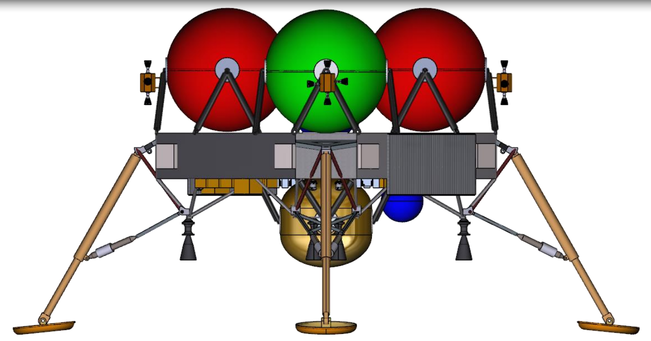
Red numbers indicate technologies that need to fly to reach TRL 6.
Does not capture effects of scale.
Fluid specific technologies may be shown in multiple locations.

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations (MAV & ISRU)	9
Liquid Acquisition Devices	10
Low Conductivity Structures	11
MPS Line Chilldown	12
Para to Ortho Cooling	13
Propellant Densification	14
Propellant Tank Chilldown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction	18
Termodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25

CFM Tech: Lander vs Demo Payload

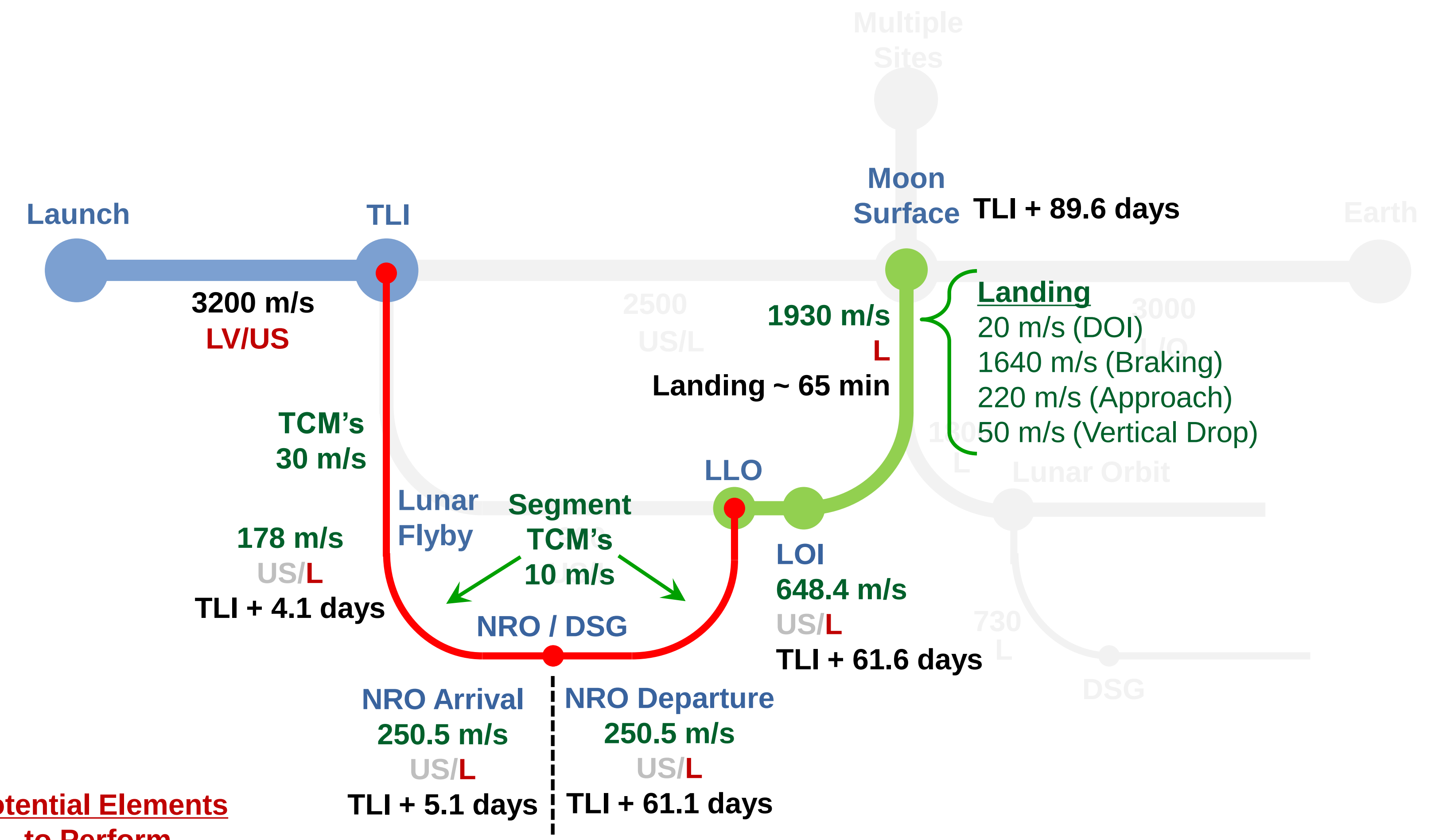


- Lander-Only Demo
- Captures ~80% of technologies to be demonstrated
- Reduces complexity and cost
- Requires addition of second set of avionics for instrumentation and data transmission



- Lander w/ Payload Demo
- Captures 100% of technologies to be demonstrated
- Adds methane tank, helium tank, fluids, and tank connections for transfer demo
- Requires addition of second set of avionics for instrumentation and data transmission

Mission Modes: ΔV Map



Potential Elements to Perform Maneuvers

LV = Launch Vehicle
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L = Lander
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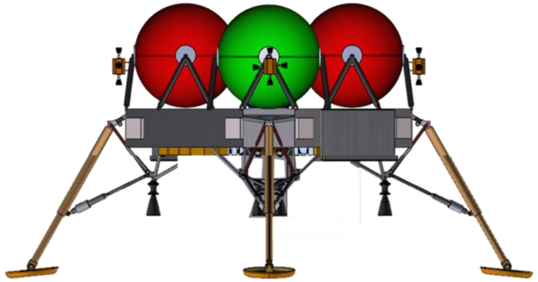
Notes:

** All DVs except for landing are ideal/impulsive.*

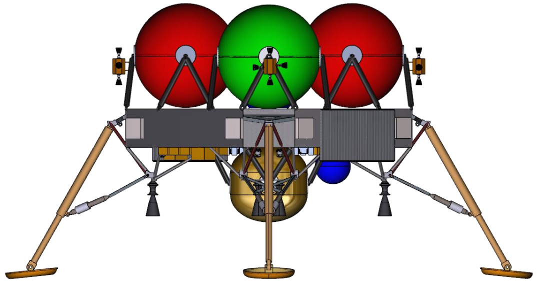
Lander-CFM Demo Options

Lander-Only Demo



MEL - CFM Lunar Lander Demo		Predicted Mass (kg)
Mass Breakdown Structure		
1.0	Structures	1216.59
2.0	Propulsion	918.21
3.0	Power	663.00
4.0	Avionics	409.92
5.0	Thermal	459.04
Dry Mass		3666.75
6.0	Non-Prop Fluids	1201.91
Inert Mass		4868.67
7.0	Usable Propellant	9700.00
Total Stage Gross Mass		14568.67
8.0	Payload	0.00
Total Stack Gross Mass		14568.67

Lander w/ Payload Demo



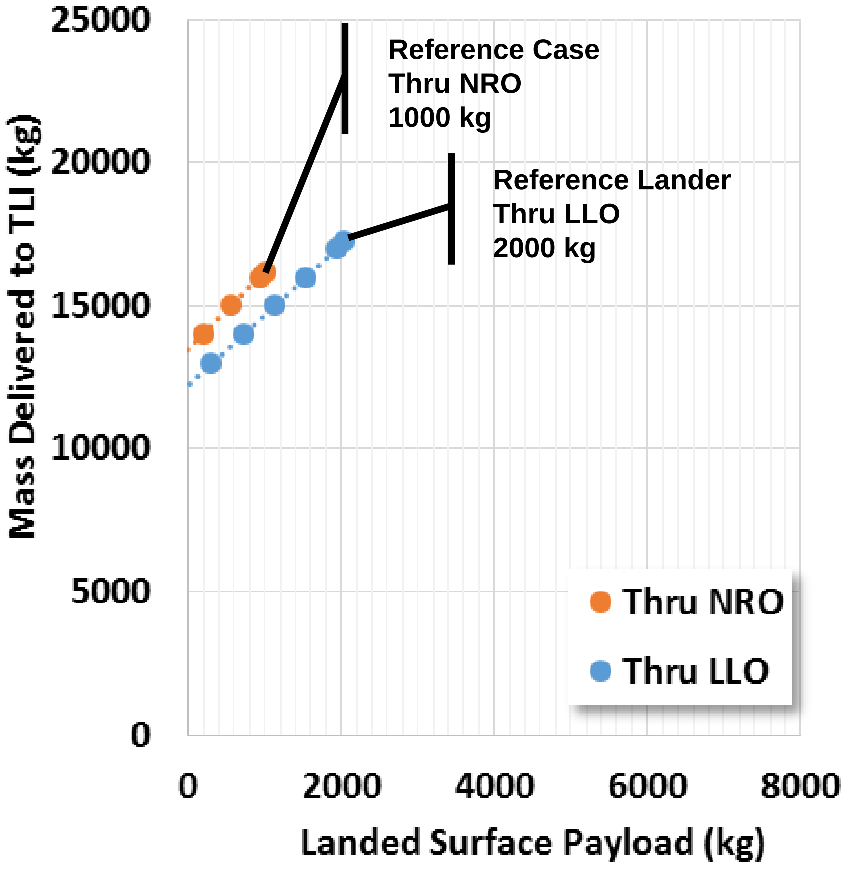
MEL - CFM Lunar Lander Demo		Predicted Mass (kg)
Mass Breakdown Structure		
1.0	Structures	1186.34
2.0	Propulsion	918.21
3.0	Power	663.00
4.0	Avionics	258.70
5.0	Thermal	459.04
Dry Mass		3485.29
6.0	Non-Prop Fluids	1201.91
Inert Mass		4687.20
7.0	Usable Propellant	9700.00
Total Stage Gross Mass		14387.20
8.0	Payload	1000.00
8.1	*Structures*	*67.76*
8.2	*Propulsion*	*135.22*
8.3	*Power*	*0.00*
8.4	*Avionics*	*177.64*
8.5	*Thermal*	*100.79*
8.6	*Non-Prop Fluids*	*16.34*
8.7	*Usable Propellant*	*502.25*
Total Stack Gross Mass		15387.20

Mission Portfolio

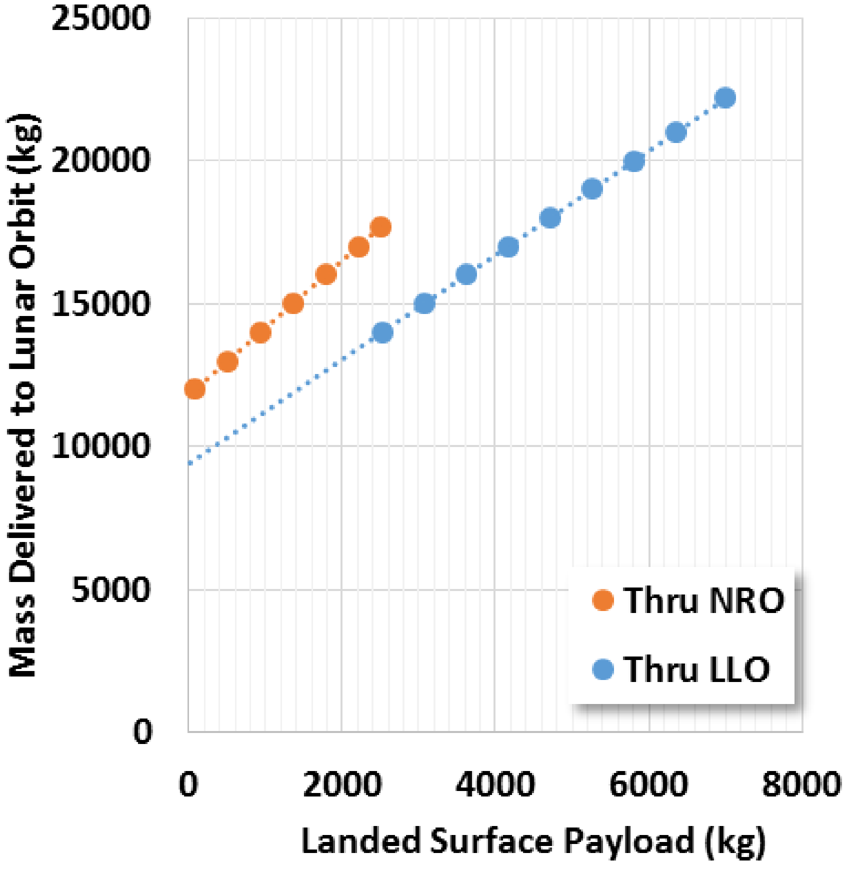
- **Various lunar mission profiles are assessed for delta-V budgets and timelines**
  - Lunar mission profile consists of launch profile, lunar arrival mode and landing profiles
  - Payload is then a fallout calculation from sizing propellant loads
- **Getting to the Surface**
  - Polar Access: Achievable anytime from a polar orbit
  - Global Access: Achievable from a polar orbit with a loiter of up to 14 days
- **Once on the Surface**
  - Crater Lander: Carry additional ΔV for landing
  - Hopper: Carry additional ΔV for traversing to secondary landing sites
  - Return from Surface: Perform ascent to carry payloads back to orbit
  - Reusable Lander: Refuel the lander for multiple landing missions

Lander Performance Example

Launch Vehicle Delivers Lander to TLI; Lander Performs Orbit Insertion

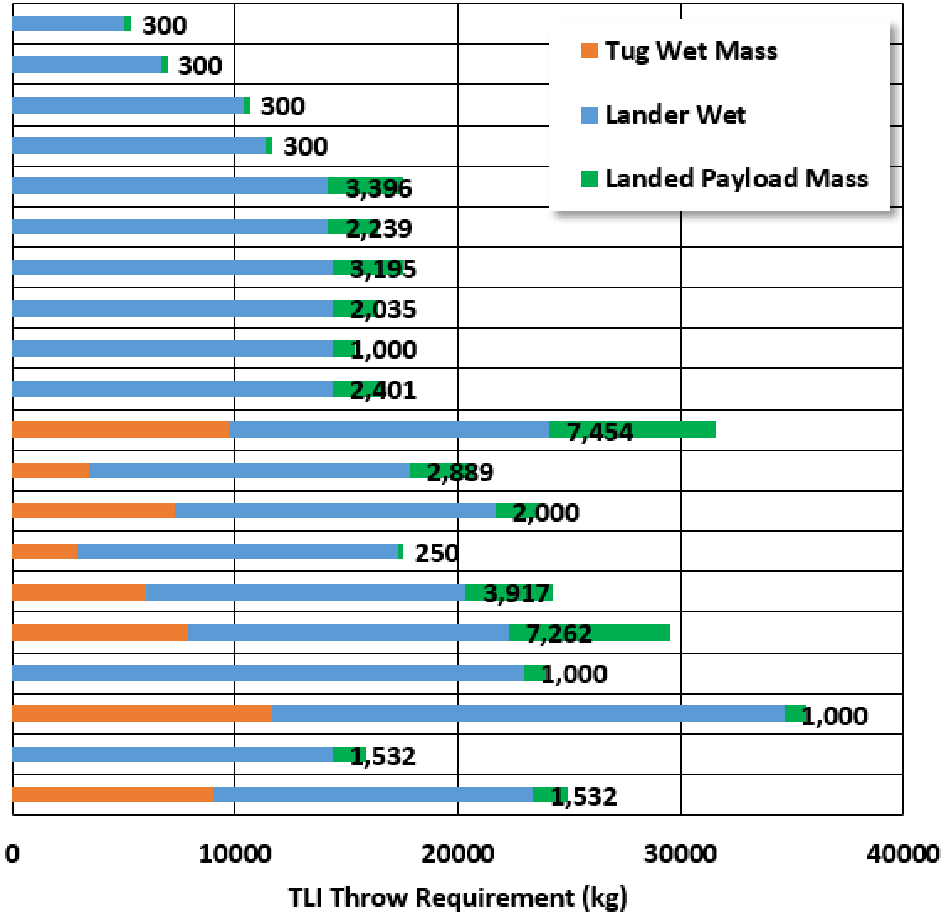


Launch Vehicle Delivers Lander to Lunar Orbit; Lander Performs Landing Only



Some Mission Performance Cases

Mission	Waypoint Delivery	Prop Storage	Waypoint
Disposable Small PL Delivery (300 kg) Scaled	Lander	Passive	Direct
			LLO
Disposable Small PL Delivery (300 kg)			Direct
			LLO
Disposable Max PL Delivery			Direct
			LLO
Disposable Max PL Delivery		Active	Direct
			LLO
			NRHO
			NRHO*
Disposable Max PL Delivery w/ Delivery Stage	Delivery Stage**		LLO
			NRHO
Hopping to 2nd Site 100 km Range	Delivery Stage**		LLO
			NRHO
Reusable Tug**, Disposable Lander	Lander		NRHO
			NRHO*
Reusable w/ Stretched Tanks			LLO
Reusable Stretched Tanks w/ Tug**			NRHO
Reusable w/ Surface Lox ISRU			LLO
Reusable w/ Surface Lox ISRU w/ Tug**			NRHO



Lander Prop	Tug Prop	Total Resupply	Tanker Wet	ISRU Prop
0	4783	4783	7854	0
0	6305	6305	9756	0
15174	0	15174	20843	0
15174	9349	24523	32529	0
6650	0	6650	10188	3026
6650	7215	13865	19206	3026

** Low Energy Arrival*

*** Tug transports lander from NRHO to LLO ;*

Delivery stage performs orbit insertion at waypoint from TLI

Summary & Findings

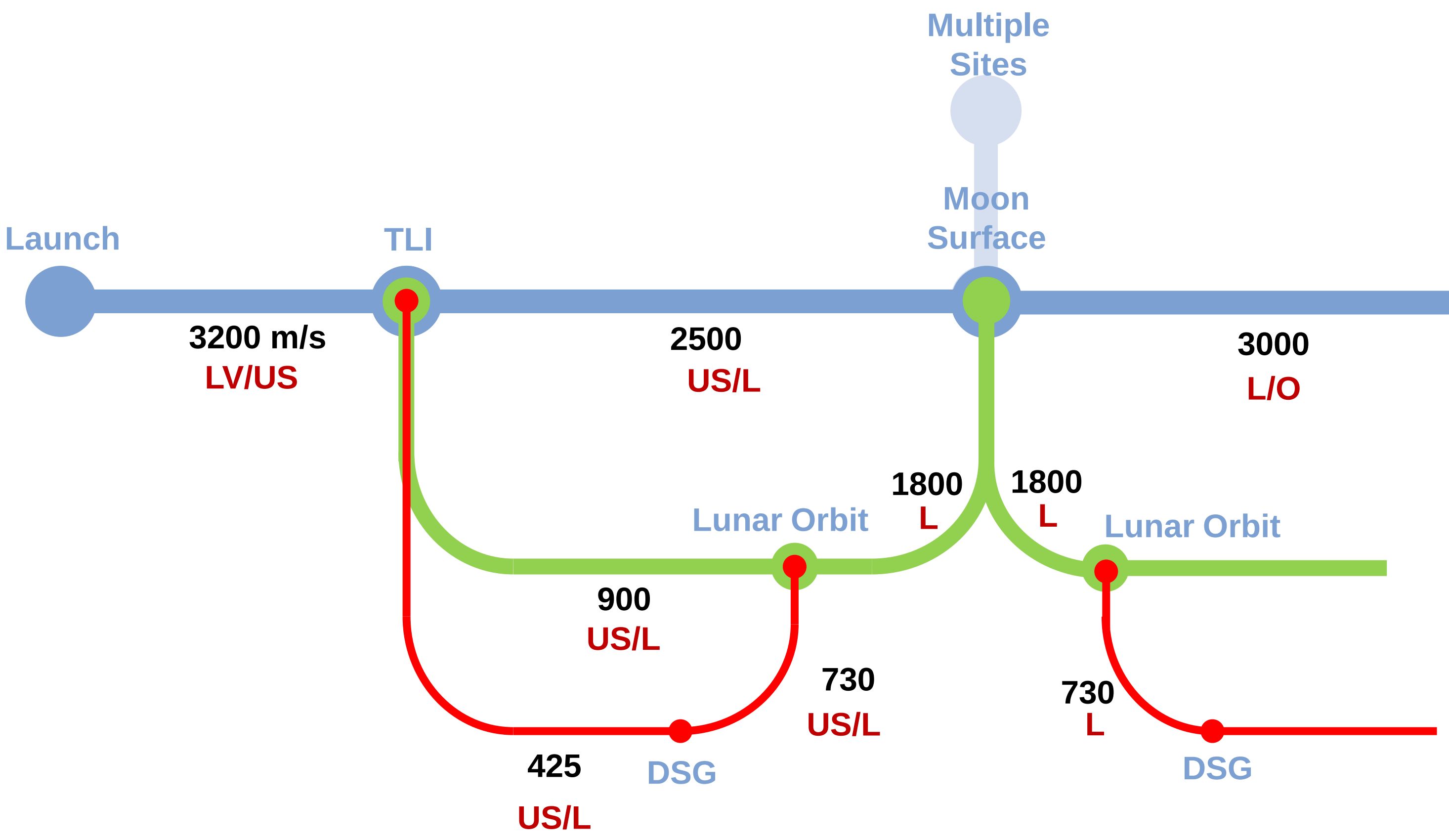
- **A viable lander concept has been developed that leverages cryogenic propulsion technologies**
  - Inclusion of cryo propulsion increases performance and generates flight data for future applications
- **Active cryo fluid management supports significant mission flexibility**
  - Longer duration missions (hopping, return, reuse) will require active CFM
  - More ambitious missions with higher ΔV budgets will benefit from the higher performance offered by LOX/LCH4 propulsion
- **Mission flexibility and performance make this an appealing concept for commercial partners**
  - System supports a viable CFM demonstration mission

Future Work

- **Structures and Configuration**
  - Examine load configurations with payloads on top of lander instead of “underslung” configuration
- **Propulsion**
  - Refine design of electric pump-driven MPS including power storage & distribution
- **Thermal**
  - Assess environmental heat loading for various loiter trades in LLO vs NRHO
- **Power**
  - Assess alternative battery concepts for reducing battery mass
  - Look at kits for alternative mission profiles w/ long-duration surface stays
- **Avionics**
  - Look at kits for various mission profiles featuring AR&D
- **CFM Demo Payload**
  - Trades on LLO vs NRHO testing periods
- **Analysis Plans**
  - Extended portfolio analysis
  - Mission Portfolio – Technology mapping exercise

BACK UP

Mission Modes



Potential Elements to Perform Maneuvers

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US = Upper Stage
L = Lander
O = Other

Varying mission modes by incorporating other mission elements can free up lander propellant for alternative uses. Can be applied to carry additional payload or enable mission profiles with additional ΔV.

Propellant Transfer & TVS Demonstration

w/ Demo Payload if Available

8 Week NRO Coast

- 4 Week Payload Active Cooling
- Transfer Demonstration

Transfer	Transfer To	Lander Tank Level	Payload Tank Level	Pressurization
0	Initial	86.30%	30%	N/A
1	Payload	73%	50%	Autogenous
2	Payload	43.3%	95%	Helium
3	Lander	56.5%	75%	Helium
4	Lander	73%	50%	Helium
5	Payload	56.5%	75%	Helium

- 4 Week Payload Passive Storage
  - Demonstrate Pressure Control
    - Payload Tank at 75% Liquid Level
    - Pump Based Mixing with Axial Jet or Spray Bar
    - Thermodynamic Vent System (TVS)
    - ~ 0.51 kg/day Propellant Loss

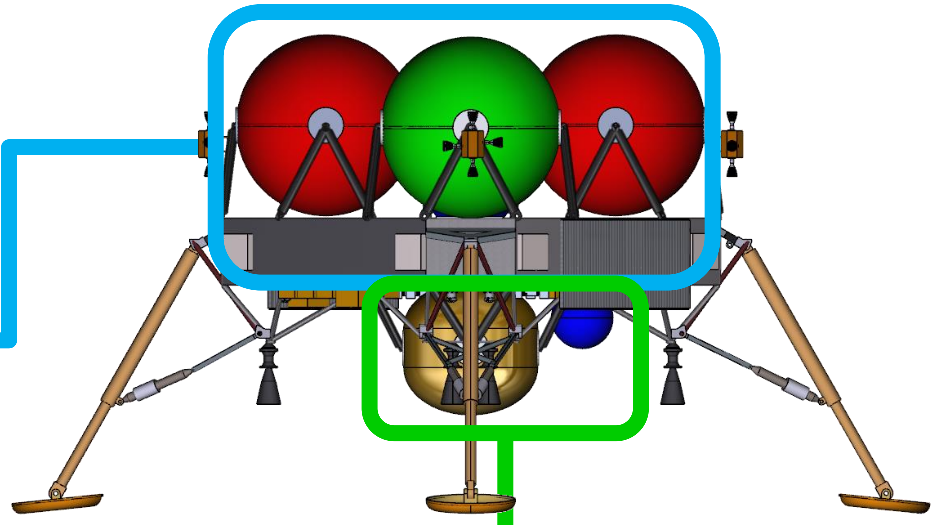
4 Week LLO Coast

- 4 Week Payload Active Cooling
- Transfer Demonstration

Transfer	Transfer To	Lander Tank Level	Payload Tank Level	Pressurization
	Initial	52.3%	74%	N/A
6	Payload	38.4%	95%	Autogenous
7	Payload	43.3%	95%	Helium
8	Lander	94.6%	10%	Helium
9	Lander	51.6%	75%	Helium
10	Lander	56.5%	Expulsion	Helium

- Expel propellant from Payload prior to DOI burn

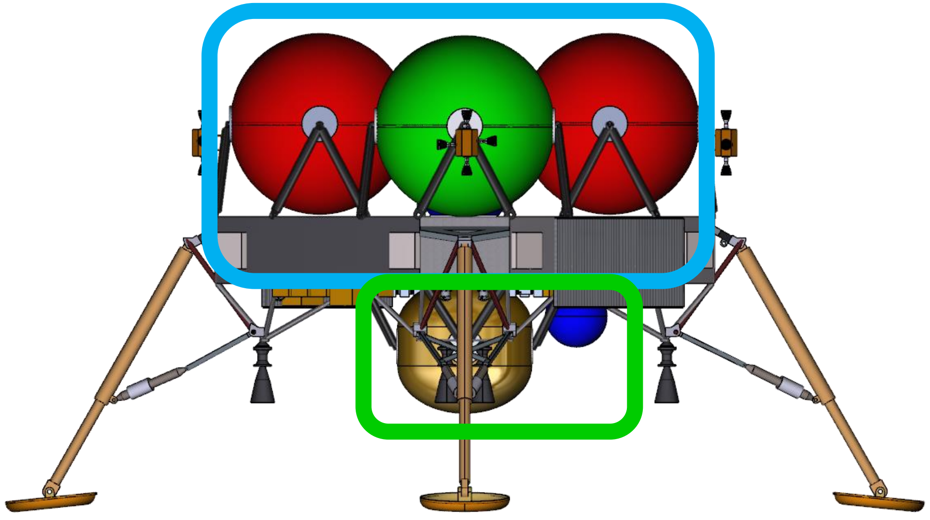
CFM Tech: Lander vs Demo Payload



LANDER CONCEPT:
- Two 1.84m Spherical LCH4 Tanks
- Two 1.84m Spherical LOX Tanks
- Long Duration Storage Required
- Actively Cooled

PAYLOAD CONCEPT:
- One 1.5m X 1.5m Cylindrical Tank with Elliptical Domes
- Working Fluid: Methane
- Utilizes Lander Cryocooler

CFM Tech: Lander vs Demo Payload



CFM Tech Required for Lander Concept:
- Autogenous Pressurization (#2)
- Helium Pressurization (#5)
- High Eff & Cap 90K Cryocooler (#7)
- High Vac MLI (#8)
- PMDs/LADs (#10)
- Low Conductivity Structures (#11)
- Pump Based Mixing (#16)
- Tube-On-Tank BAC (#22)
- Unsettled Mass Gauging (#23)
- Valves, Actuators, and Components (#24)

Test Objectives not Covered by Lander Concept:
- Propellant Tank Chilldown (#15)
- Thermodynamic Vent System (#19)
- Transfer Operations (#20)
- Effects of Scaling in micro-g
- Passive Storage

CFM Tech on Demo Payload:
- Helium Pressurization Capability (#5)
- High VAC MLI (#8)
- PMDs/LADs (#10)
- Low Conductivity Structures (#11)
- Pump Based Mixing (#16) with Axial Jet or Spray Bar
- Tube-On-Tank BAC (#22)
- Unsettled Mass Gauging (#23)
- Valves, Actuators, and Components (#24)
- Propellant Tank Chilldown (#15)
- Thermodynamic Vent System (#19)
- Transfer Operations (#20)
- Effects of Scaling in micro-g
- Passive Storage

CFM Tech Mapping

Technology	No	*Landing Missions* Global Access	*Landing Missions* CFM Demo	*Landing Missions* Polar Access	*Alternate Missions* Crater Lander	*Alternate Missions* Hopper	*Alternate Missions* Ascent	*Alternate Missions* Reuse
Advanced External Insulation	1					Yellow	Yellow	Yellow
Autogenous Pressurization	2	Green	Green D	Green	Green	Green	Green	Green
Automated Cryo-Couplers	3							Green
Cryogenic Thermal Coating	4	Yellow	Yellow D	Yellow	Yellow	Yellow	Yellow	Yellow
Helium Pressurization	5	Green	Green D	Green	Green	Green	Green	Green
High Capacity, High Efficiency Cryocoolers 20K	6							
High Capacity, High Efficiency Cryocoolers 90K	7	Green	Green D		Green	Green	Green	Green
High Vacuum Multilayer Insulation	8	Green	Green D	Green	Green	Yellow	Yellow	Yellow
Liquefaction Operations (MAV & ISRU)	9							
Liquid Acquisition Devices	10	Green	Green D	Green	Green	Green	Green	Green
Low Conductivity Structures	11	Green	Green D	Green	Green	Green	Green	Green
MPS Line Chilldown	12	Green	Green D	Green	Green	Green	Green	Green
Para to Ortho Cooling	13							
Propellant Densification	14							
Propellant Tank Chilldown	15							
Pump Based Mixing	16	Green	Green D	Green	Green	Green	Green	Green
Soft Vacuum Insulation	17							
Structural Heat Load Reduction	18							
Termodynamic Vent System	19		Blue D	Green				
Transfer Operations	20		Blue D					Green
Tube-On-Shield BAC	21							
Tube-On-Tank BAC	22	Green	Green D		Green	Green	Green	Green
Unsettled Liquid Mass Gauging	23	Green	Green D	Green	Green	Green	Green	Green
Valves, Actuators & Components	24	Green	Green D	Green	Green	Green	Green	Green
Vapor Cooling	25							

Green	***Required***
Yellow	***Potential Application***
Blue	***Unique to CFM Demo Payload***
D	***Demonstrated during CFM Demo Mission***

By baselining active CFM, we are able to future-proof the lander, enabling other fallout missions that would follow the first demo mission