TFAWS INTERDISCIPLINARY SESSION

MOON BASE

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MOON BASE TRANSPORTATION – DELIVERIES TO THE LUNAR SURFACE

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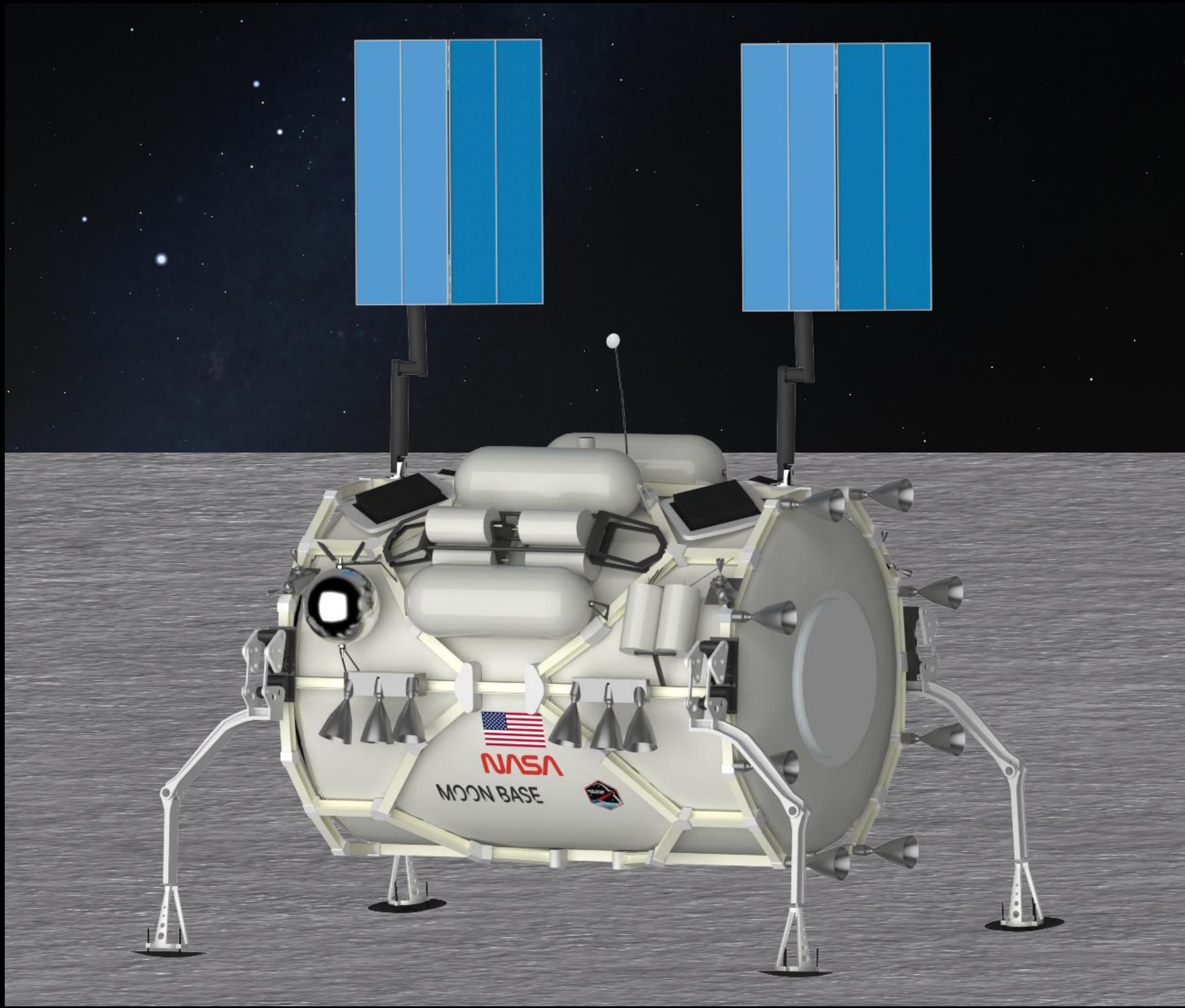
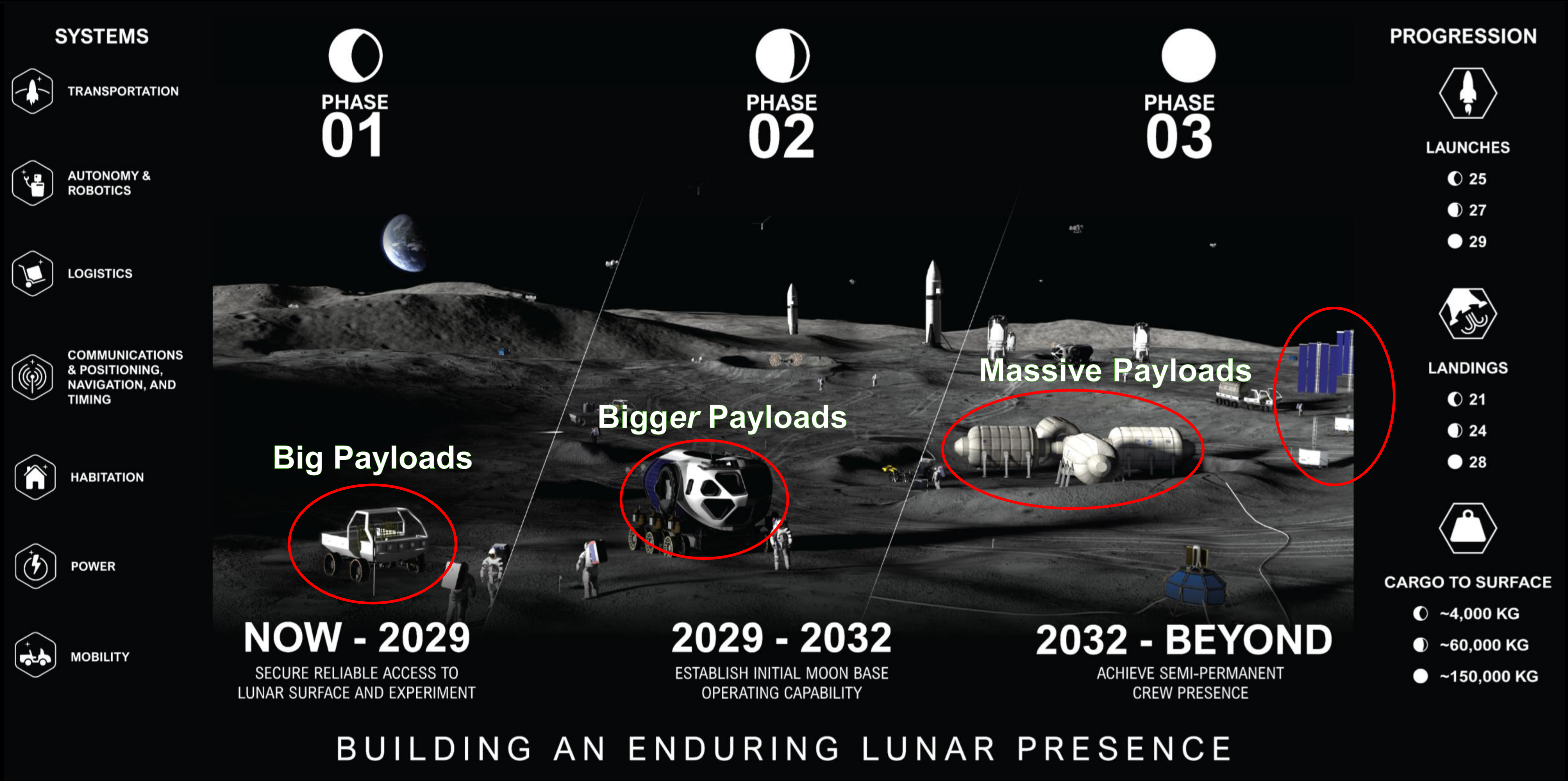
PRESENTATION OVERVIEW

- **Motivation & Objective**
- **Mission Overview**
- **Vehicle Architecture**
- **Key Elements of Mission Ops**
- **Conclusions**



MOTIVATION



SYSTEMS
TRANSPORTATION
AUTONOMY & ROBOTICS
LOGISTICS
COMMUNICATIONS & POSITIONING, NAVIGATION, AND TIMING
HABITATION
POWER
MOBILITY
PHASE 01
PHASE 02
PHASE 03
Big Payloads
Bigger Payloads
Massive Payloads
NOW - 2029
SECURE RELIABLE ACCESS TO LUNAR SURFACE AND EXPERIMENT
2029 - 2032
ESTABLISH INITIAL MOON BASE OPERATING CAPABILITY
2032 - BEYOND
ACHIEVE SEMI-PERMANENT CREW PRESENCE
PROGRESSION
LAUNCHES
25
27
29
LANDINGS
21
24
28
CARGO TO SURFACE
~4,000 KG
~60,000 KG
~150,000 KG
BUILDING AN ENDURING LUNAR PRESENCE

Develop an end-to-end mission concept to transport large payloads to the Lunar South Pole in support of Moon Base.

The transfer vehicle combines in space and landing capability with jettisonable prop storage stages.

MISSION OVERVIEW

SYSTEM DESIGN IS AN EXERCISE LEFT TO THE READER

MISSION PHASES

1. **Launch and Launch Vehicle Separation**
   - Integrated vehicle stack of Lunar Lander (LL) + Payload in LV payload fairing
2. **Trans Lunar Injection (TLI)**
   - Thrust to get out of Earth's gravity well
3. **Mid Course Corrections (MCC)**
   - Heading updates and pointing maneuvers
4. **Lunar Orbit Insertion (LOI)**
   - Entering the Moon's gravity well
5. **LOI Corrections**
6. **Lunar Descent and Touchdown (LDT)**
   - Pre-Landing Navigation
     - High altitude tracking
     - Low altitude tracking
   - Vertical Descent
     - Final site selection
     - *Hands off the controls & see what happens*

Launch Config Dependent dV (does LV supply?)

~Fixed dV (Lander must achieve)

Risk Tolerance Dependent dV

Figure Almost to Scale

GROUND RULES AND ASSUMPTIONS

Assumptions

- Launch/lunar phasing is optimal for mission
- Comms & ground tracking is sufficient/accommodating
- Space qualified (rad hard) hardware readily procurable
- Launch Vehicle (LV) with capability exists
- Launch loads and stack configurations are within dynamic envelope of fairing
    - Adapters are sufficiently stiff
- Landing site conditions are conducive to landing
    - More detail for vehicle needed to select max slope & surface feature sizes
    - No other assets in landing site (so far)

Ground Rules

- Slow roll in transit for thermal regulation and arrays point
- Sufficient lighting for TerRain based Nav (TRN) to work
- No insurmountable thruster limitations for landing and in space trajectory control
    - Selecting based on accelerations & life
- Sufficient electrical power to have no concern of eclipse/shadow in space

Make This Big!

Make This Feasible

- $m = m_{payload} + m_{vehicle} + \overbrace{m_{Propellant} + m_{Pressurant}}$

???

"LANDER" DESIGN REQUIREMENTS

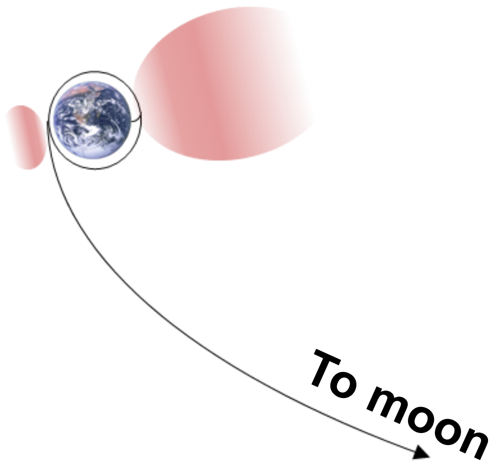
1. **Navigate in space & touchdown at desired location**
2. **Survive radiation/thermal environment(s)**
3. **Any jettisoned elements need separation analysis**
4. **Pyrotechnics (cutters/valves/*etc.*) need specific analysis**
5. **Adequate acceleration for Hohmann transfers/descent/touchdown**
6. **Not impose excessive loads into the payload (launch/landing/*etc.*)**
7. **Comm/instrumentation for the payload**

Desirable: **avoid (Rendezvous, Proximity Operations, and Docking) RPOD & prop transfer**

TRANSPORTATION FROM THE EARTH

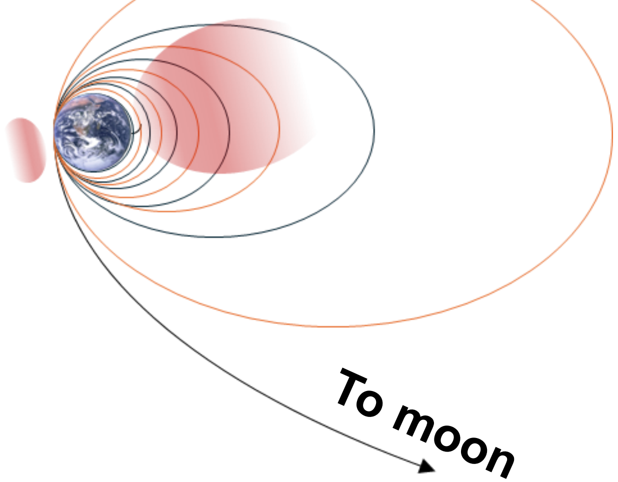
MOON BASE

Fast - Apollo



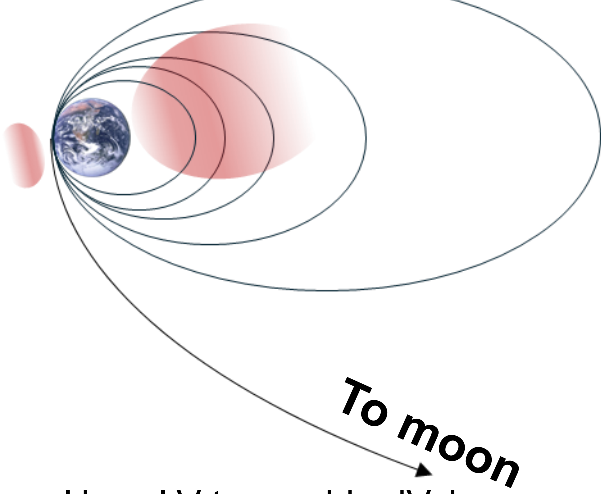
- Avoids Van Allen Belts
- ~5 day mission to the moon
- Facilitates cryo prop sys

LEO - Hohmann



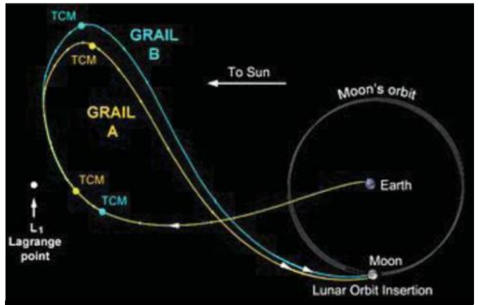
- Trade # of burns for time/thrust
- 300/600 m/s per burn for 10/5 burns
- ~10/15 days for 5/10 orbits

EO - Hohmann



- Uses LV to provide dV, burn on first half orbit, then correction
- ~300 m/s per burn for 5 burns
- ~9 days

Ballistic Lunar Transfer

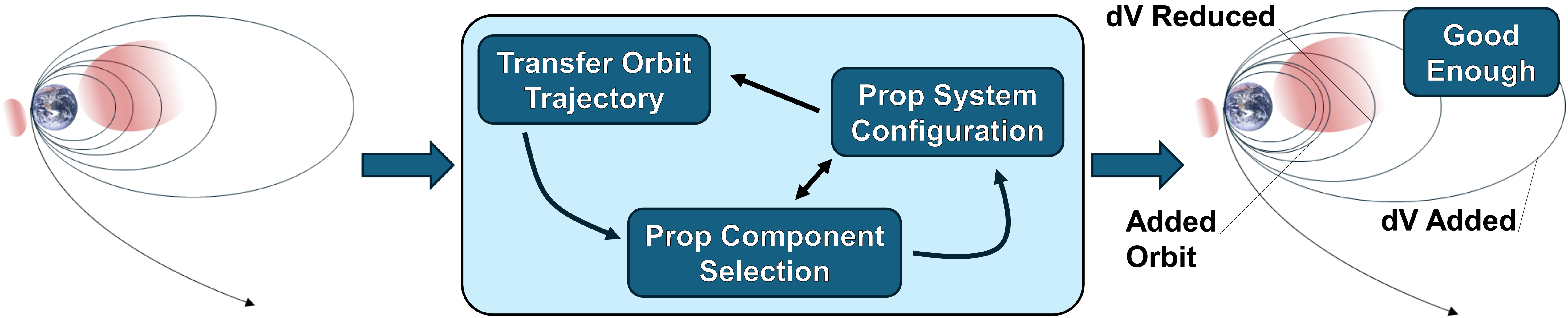


Dichmann *et Al. GSFC 2013*

- Minimizes prop needs
- *Trade space to calculate dV, extended mission time – Good or bad*

Step	Apollo	10 Burn LEO Hohmann	5 Burn LEO Hohmann	EO Hohmann
1 – Launch *to*	*Earth Parking Orbit*	*200 km Circular*	*200 km Circular*	*200 x 10,000 km Elliptical*
2 – TLI	3.2 km/s	3.15 km/s	3.25 km/s	1.4 km/s
3 – MCC	0.05 km/s	0.05 km/s	0.08 km/s	0.08 km/s
4 – LOI	0.89 km/s	0.89 km/s	0.89 km/s	0.89 km/s
5 – LOI Corrections			**0.05 km/s**	
6 – LDT	2.45 km/s	2.25 km/s	2.25 km/s	2.25 km/s
Total dV [km/s]	**6.59**	**6.39**	**6.52**	**4.67**

PROP SYS & TRAJECTORY CODEVELOPMENT



- In space transit requires prop use, major dV burns & RCS use
  - For big transfers, optimize mass use
  - Primary prop tanks can be sized to be "for dV burns"
  - When the burn is complete, jettison the excess mass
    - Use pyro valves/cutters to safe systems prior
- Overall goals of
  - Making the mission more viable (success probability increase)
  - Reducing propellant consumption (cost reduction)
  - Increasing payload mass (cost reduction)

Pointing Losses

$$dV = ISP \cdot g_0 \cdot \cos(\theta) \cdot \ln\left({m_o}/{m_f}\right)$$

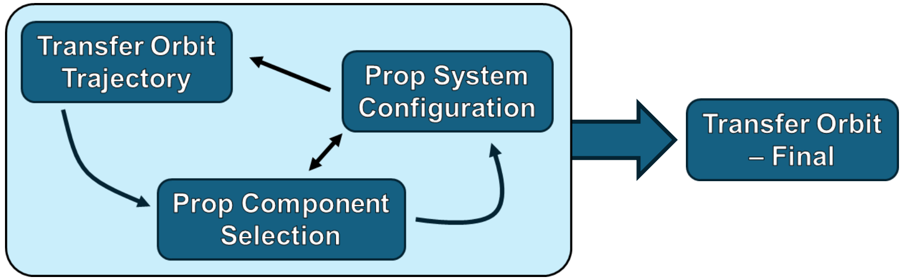
$$dV = ISP \cdot g_0 \cdot \sum_k \cos(\theta_k) \cdot \ln\left({m_{o_k}}/{m_{f_k}}\right)$$

Per Stage Counting Index

BURN SCHEDULE & MISSION DESIGN

- **1.4 km/s equally across 5 burns ~ 285 m/s each**
- **Burn to 98.5% of tank capacity ~ 92,000 in³**
- **Assume 2 Prop tanks + 6 pressurant + structure per element**

36 Pressurant tanks for 6 stages



- **Burn 1 dV = 285 m/s, Jettison 285 m/s**
- **Burn 2 dV = 25 m/s, 308 m/s**
- **Burn 3 dV = 296 m/s, Jettison 604 m/s**
- **Burn 4 dV = 100 m/s, 704 m/s**
- **Burn 5 dV = 258 m/s, Jettison 962 m/s**
- **Burn 6 dV = 425 m/s, Jettison 1387 m/s**

$$m_{payload} + m_{vehicle} = 11,000\ kg$$

$$m_{payload} + m_{vehicle} = 10,700\ kg$$

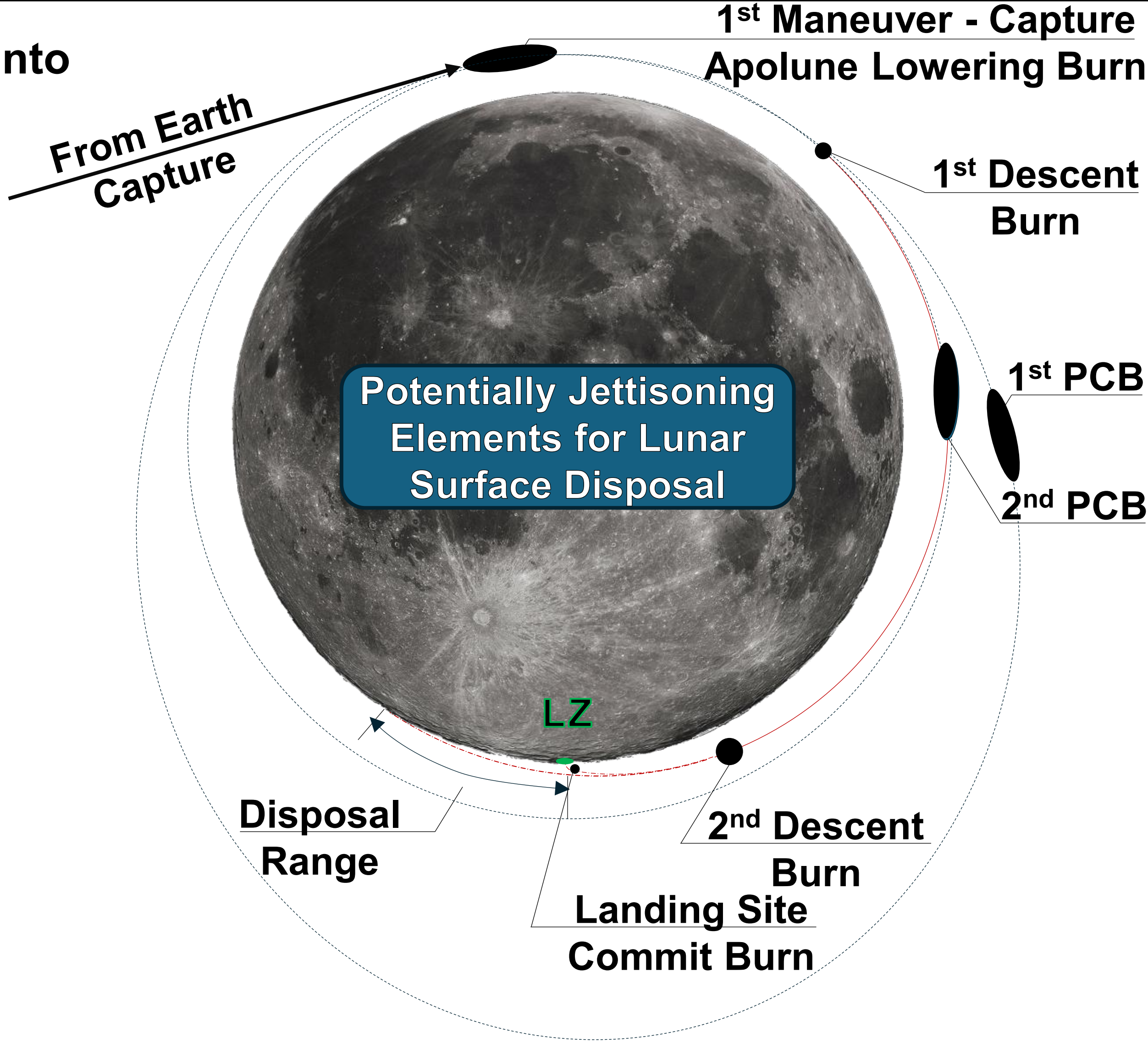
$$m_{payload} + m_{vehicle} = 10,400\ kg$$

$$m_{payload} + m_{vehicle} = 10,100\ kg$$

It is accepted the pressurant tank # is obnoxious

LUNAR TOUCHDOWN CONOPS

- 1st Maneuver – Capture, retrograde burn, puts Stack into polar elliptical lunar orbit 200 x 1400 km
  - Capture somewhere in lunar north
  - Hold for 24 hours ~ 8 orbits for nav updating
  - Within 8 orbits, Plane Correction Burn (PCB)
- Commit to retrograde circularization burn
  - ~Same location as 1st maneuver
  - Lower to 200 km circular
  - Hold for 24 hours ~ 11 orbits for nav updating
  - Any high altitude GNC should be switched on
- 2nd Plane Change Burn
  - "Final" landing trajectory selection
- On subsequent rev, 1st Descent Burn
  - Puts stack onto terminal path
- 2nd Descent burn, reduces horizontal velocity
  - At 50 km altitude, start optical TRN
- Landing Site Commit Burn

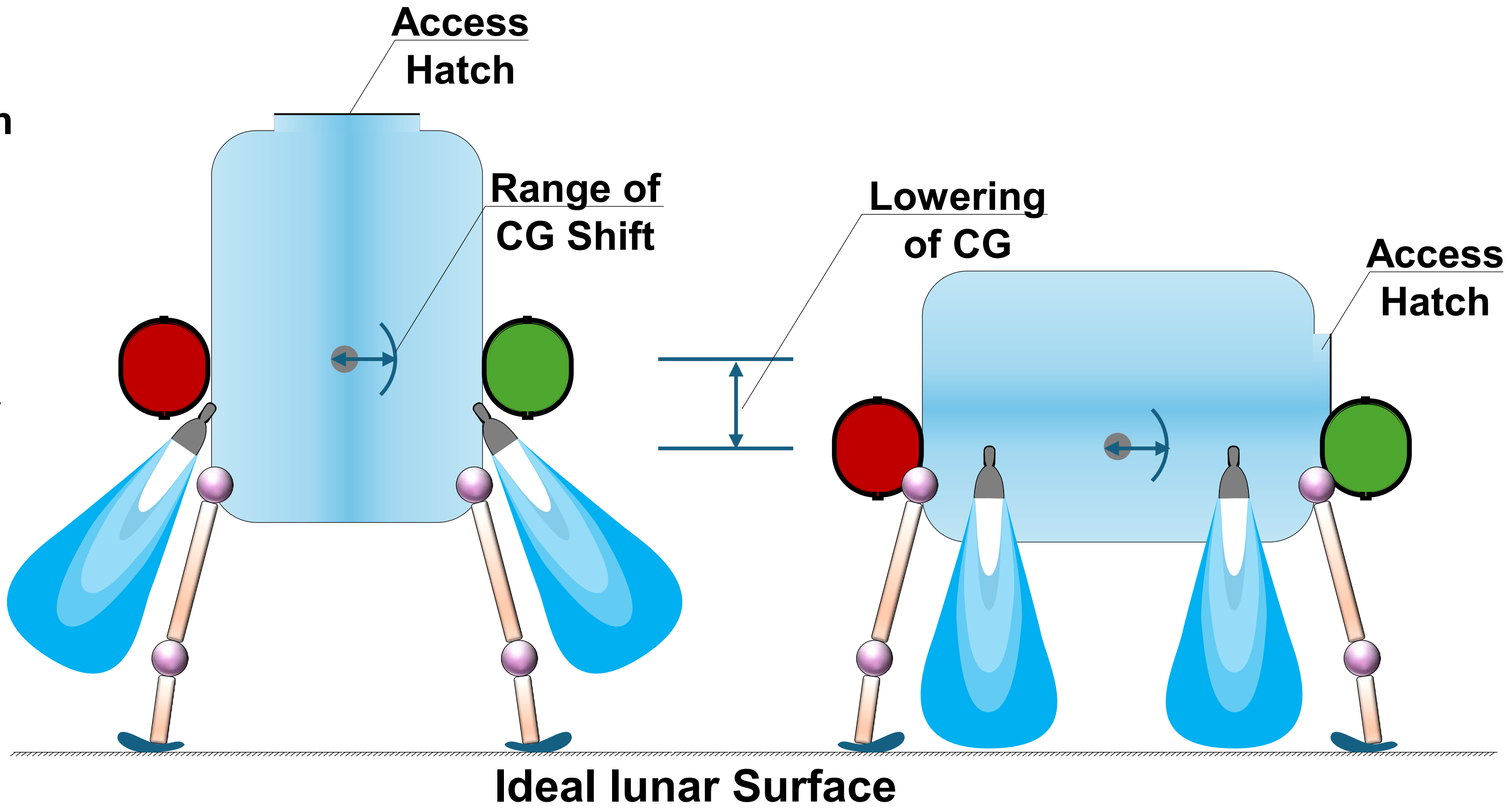


THRUSTER TRADE SPACE

- ~ 2.4 km/s dV Needed for in space maneuvers
  - TLI + MCC + LDT
- Assume 300s ISP for MMH/NTO thrusters
- >20,000 kg of prop needed
- Thrusters must provide sufficient acceleration to complete transfer
  - Small thrusters would need more orbits & create burn time constraints
  - Big thrusters increase mass & create LV packing constraints
- *Optimal* thrusters enable redundancy and better attitude control
  - Thruster sets should be positioned to push through the mass center
- 900 lb_f (4.00 kN) class thrusters x8 ~ 0.9 m/s^2
- 200 lb_f (0.89 kN) class thrusters x8 ~ 0.2 m/s^2
- Similar considerations needed for landing
  - How much to arrest vertical velocity?
  - How much needed for attitude/lateral control?

LANDING CONFIGURATION

- **Payload is ~5.5m ø x 6.6m**
- **Landing of Vertical vs Horizontal Payload**
- ***We are part of Moon Base***
  - **Current concepts show elements with long axis horizontal on the surface**
- **Advantages of Horizontal**
  - **Reduced height of access hatch**
  - **Lowered CG**
  - **Less off axis thrust (higher efficiency for descent)**
  - **Wider footprint on longitudinal axis**
  - **Easier launch packing config**
- **Prop use will shift cg laterally**
  - $\rho_{MMH} \approx 885$ kg/m^3, $\rho_{MON3} \approx 1440$ kg/m^3
  - **Fed at near equal volumetric flowrate**



- **Thruster config 4x3, 12 total – 8 used for vertical**
  - **Some off axis θ_j for thrusters**

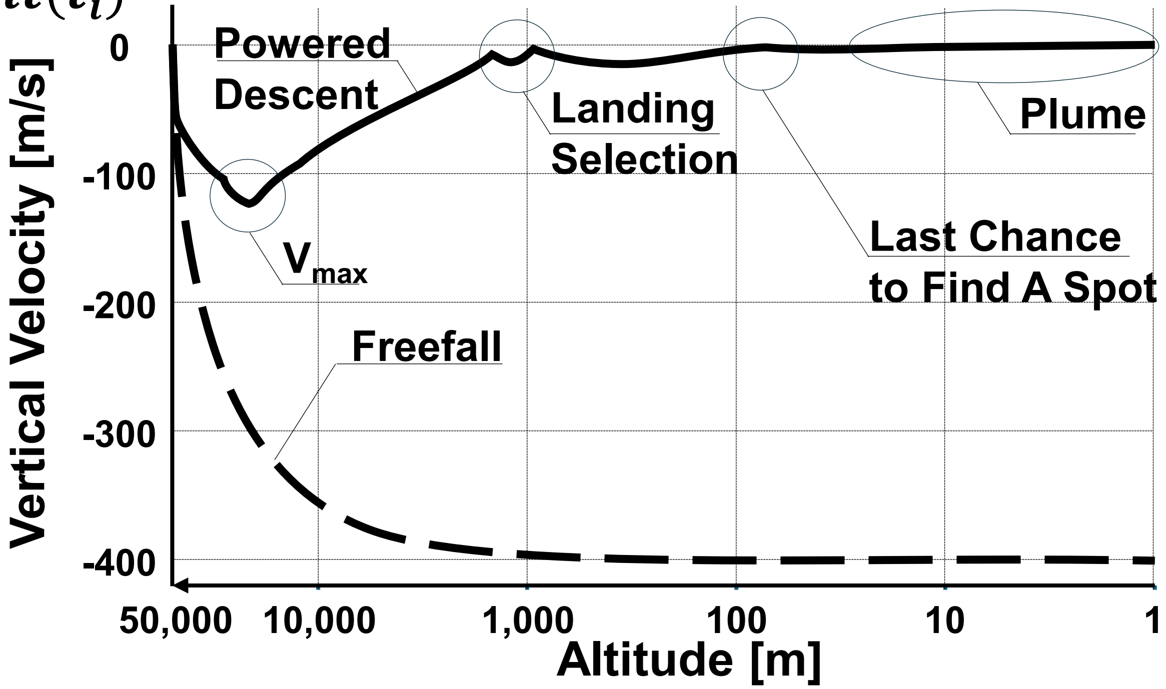
$$g(t_i) = \frac{G \cdot M_L}{(R_L + Alt(t_i))^2}$$

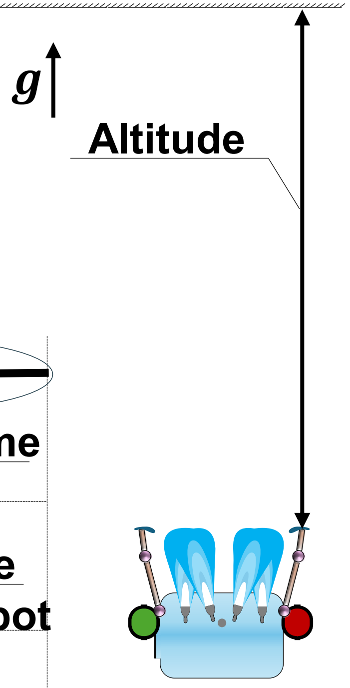
$$\dot{m}_j = \frac{F_{thrust_j}}{g_0 \cdot ISP}$$

Mass Flow Rate

- $a_{net_i} \approx -g(t_i) + \frac{\sum\left[F_{thrust_j} \cdot \cos(\theta_j)\right]}{m_i - \Delta t \cdot \sum \dot{m}_j}$
- $\Delta V_{net_i} \approx a_{net_i} \cdot \Delta t, \quad V_{net}(t_{i+1}) \cong \Delta V_{net_i} + V_{net}(t_i)$
- $\Delta Alt \approx \Delta V_{net} \cdot \Delta t, \quad Alt(t_{i+1}) \cong \Delta Alt + Alt(t_i)$
- **Assumes 1 Dof**
  - **Variable 2 body gravity**
  - **Additional prop remaining for**
    - **Rotation & lateral displacement**
    - **Additional thrusters may be needed to control cg shift**
- **Velocity change reversal after V_{max}**
- **Two "hovering" periods occur**
  - **~1000 m & ~80m**
  - **Optical/Radar navigation, negligible plume**

Ideal lunar Surface
South Pole



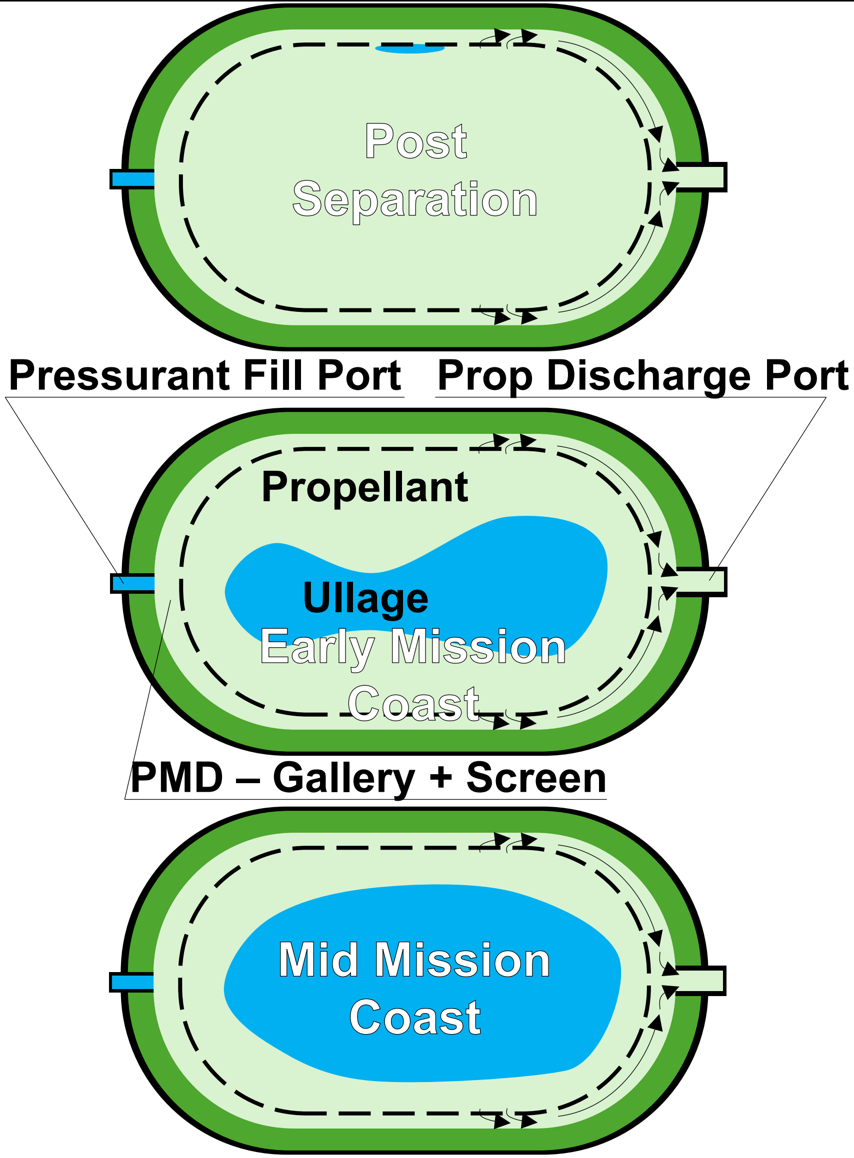


PROP HARDWARE LIMITATIONS

SETTLING PROPELLANT IS AN EXERCISE LEFT TO THE READER

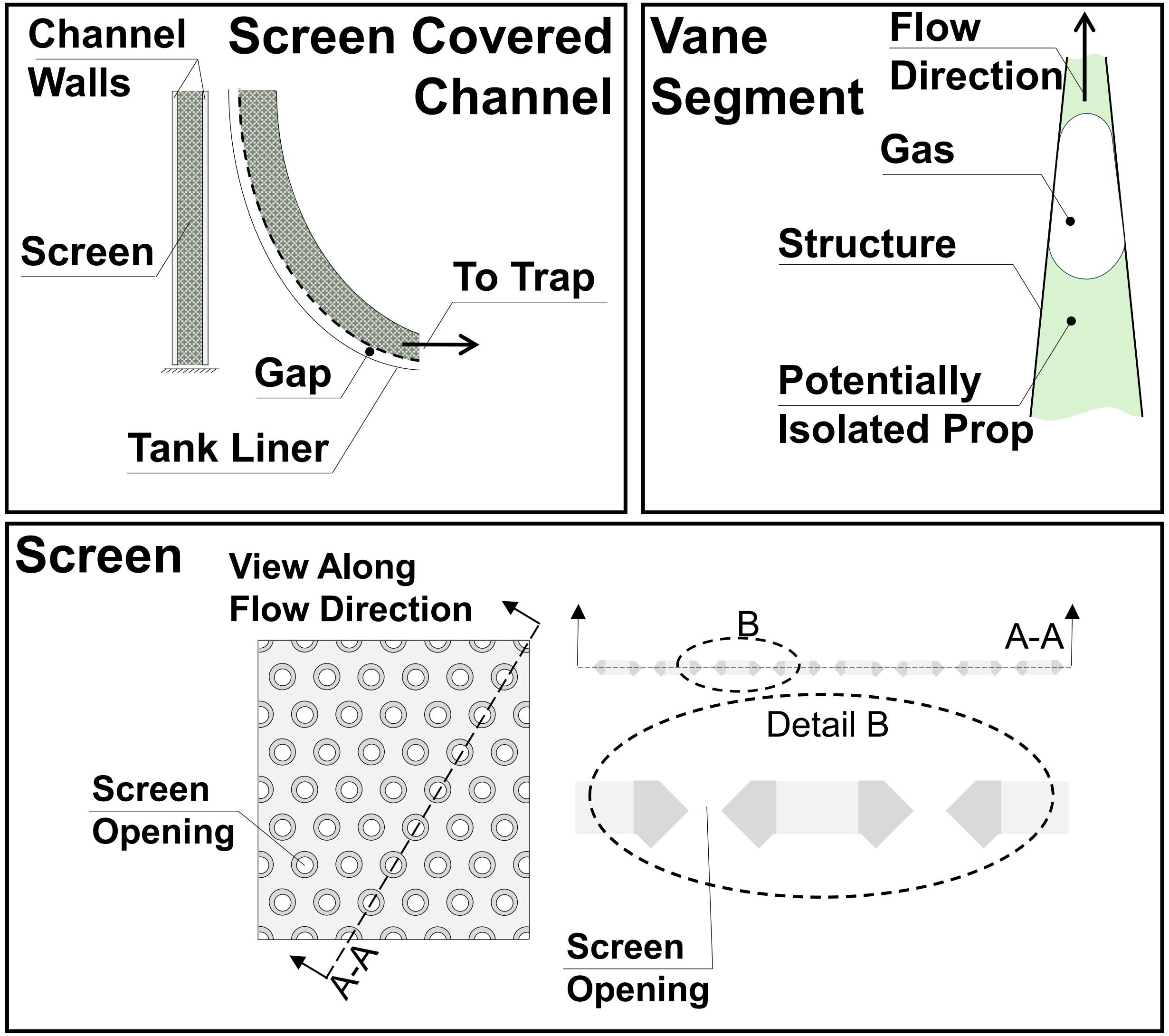
PROP TANK SELECTION (STOREABLES)

- **Prop acquisition is handled by the tank, diaphragm or propellant management devices (PMDs)**
  - **Whole trade space to explore**
- **Thin wall structures, metal or COPV designs**
  - **Tank Volume, Fixed Maximum Expected Operating Pressure (MEOP), Fill Fraction (FF) on Launch are all controlled by tank**
- **Propellant tanks are developed and qualled, then manufactured**
  - **PMD's are designed for *in space - sans* gravity**
  - **Delta Qual is needed to verify performance requirements**
- ***Saturday Morning Science* Dr. Don Pettit (~47 min)**
  - **Experiments on the ISS for surface tension – Youtube**



PROPELLANT MANAGEMENT DEVICES PMDS

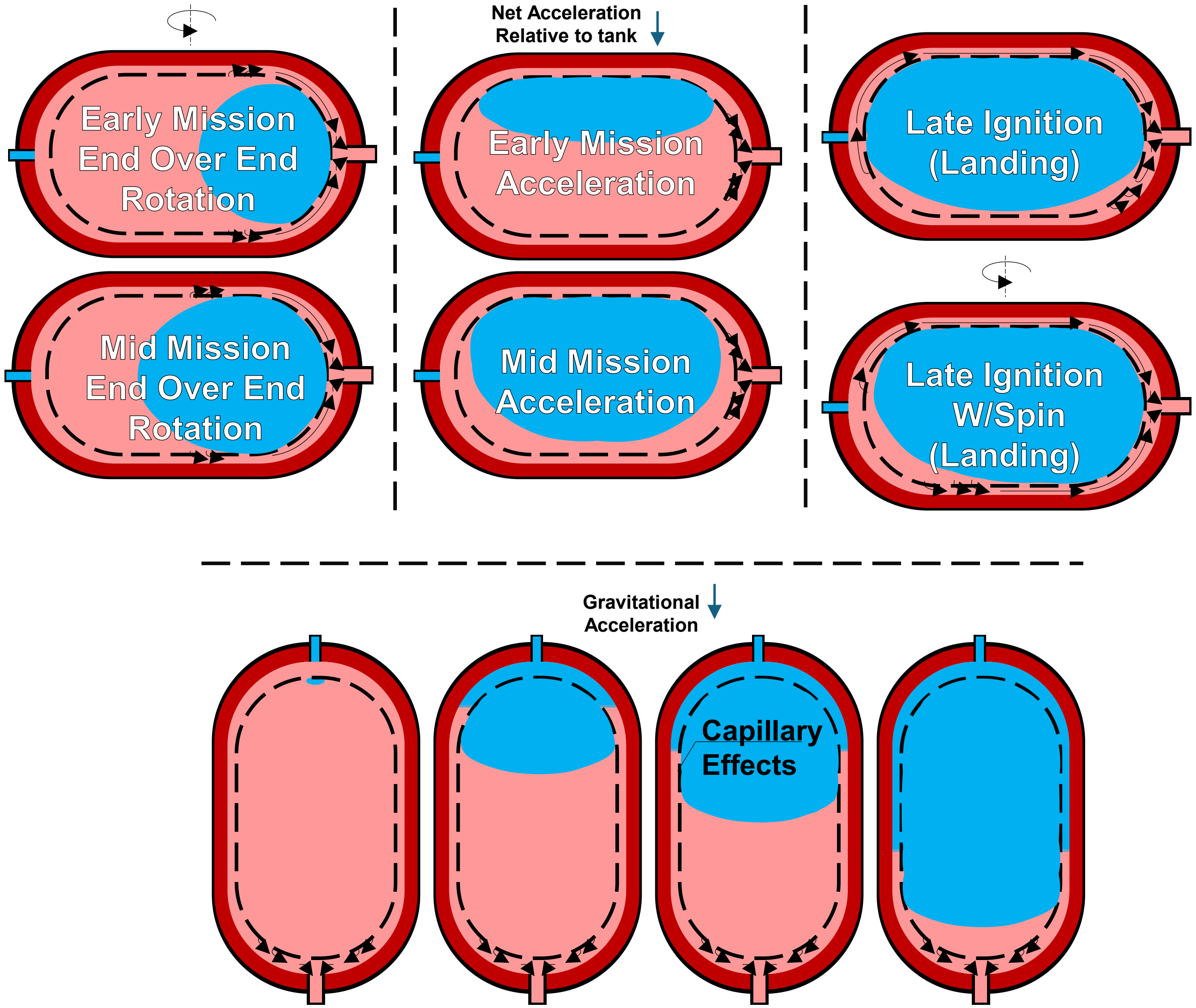
- PMDs ensure ullage (gas) free prop delivered
- PMDs control
  - Minimum Ignition characteristics, GNC flight restrictions, and more
- Geometry/manufacturing determines characteristics
  - Screens, Gallery, Traps, Vanes, Sponges, Channels, Troughs, Pickup assemblies
- NTO/MON3 has more stringent design limitations
  - Higher viscosity & freezing point
- Detail beyond scope of this work
  - D.E Jaekle Jr: AIAA-91-2172, AIAA-93-1970, AIAA-95-2531, AIAA-97-2811



PROPELLANT MOVEMENT

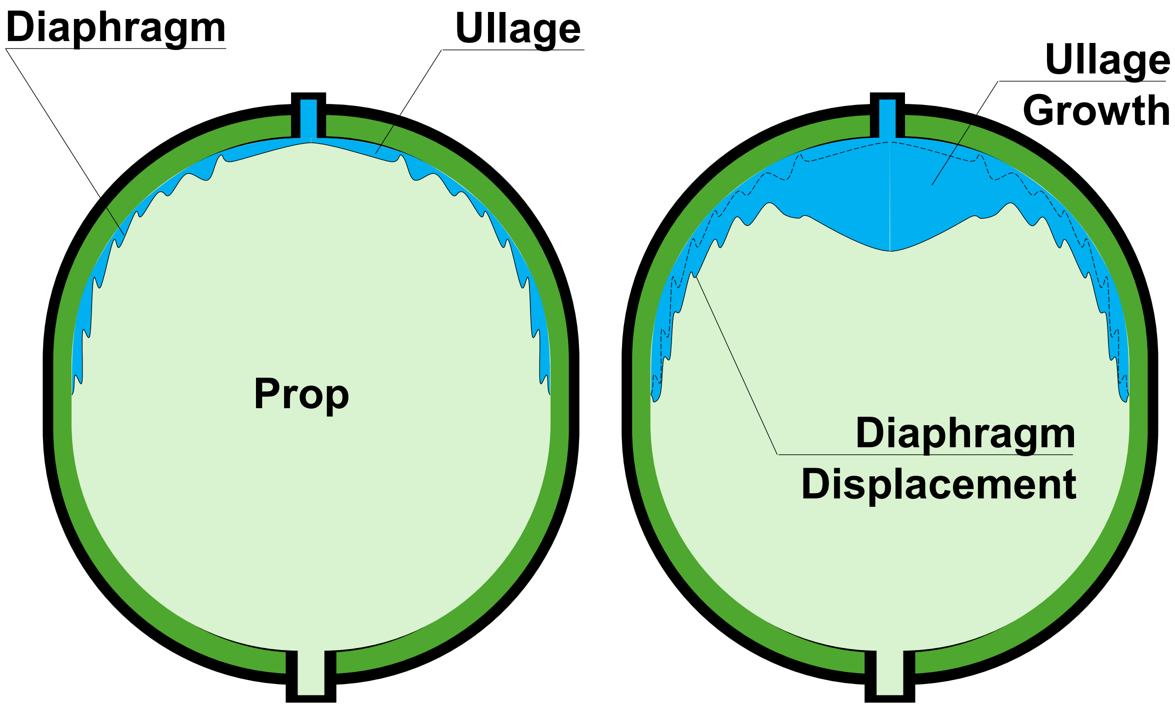
MOON BASE

- **PMDs must account for linear & rotational movement of prop in flight**
  - ***Small* tank settling thrust pulse to move ullage - then fire thrusters full bore**
- **Tank orientation for landing determines ability to provide prop for thrusters**
- **Descent & Landing is a huge undertaking**
  - **12 – 900 lb_f thrusters @ 300s isp 50% duty cycle ~ 55 gal per minute (GPM) of each commodity**
  - **~ 8 minutes for those ~92,000 in^3 tanks**



DIAPHRAGMS FOR LANDING

- **Diaphragm - membrane to separate ullage & prop**
  - **Moves as prop is consumed**
- **Cons**
  - **Heavy + Single use**
  - **Require extensive testing to get shape right**
- **Advantages**
  - **Easy to track both commodities**
  - **Omnidirectional acceleration compliance**
  - **Useful for high discharge rates**

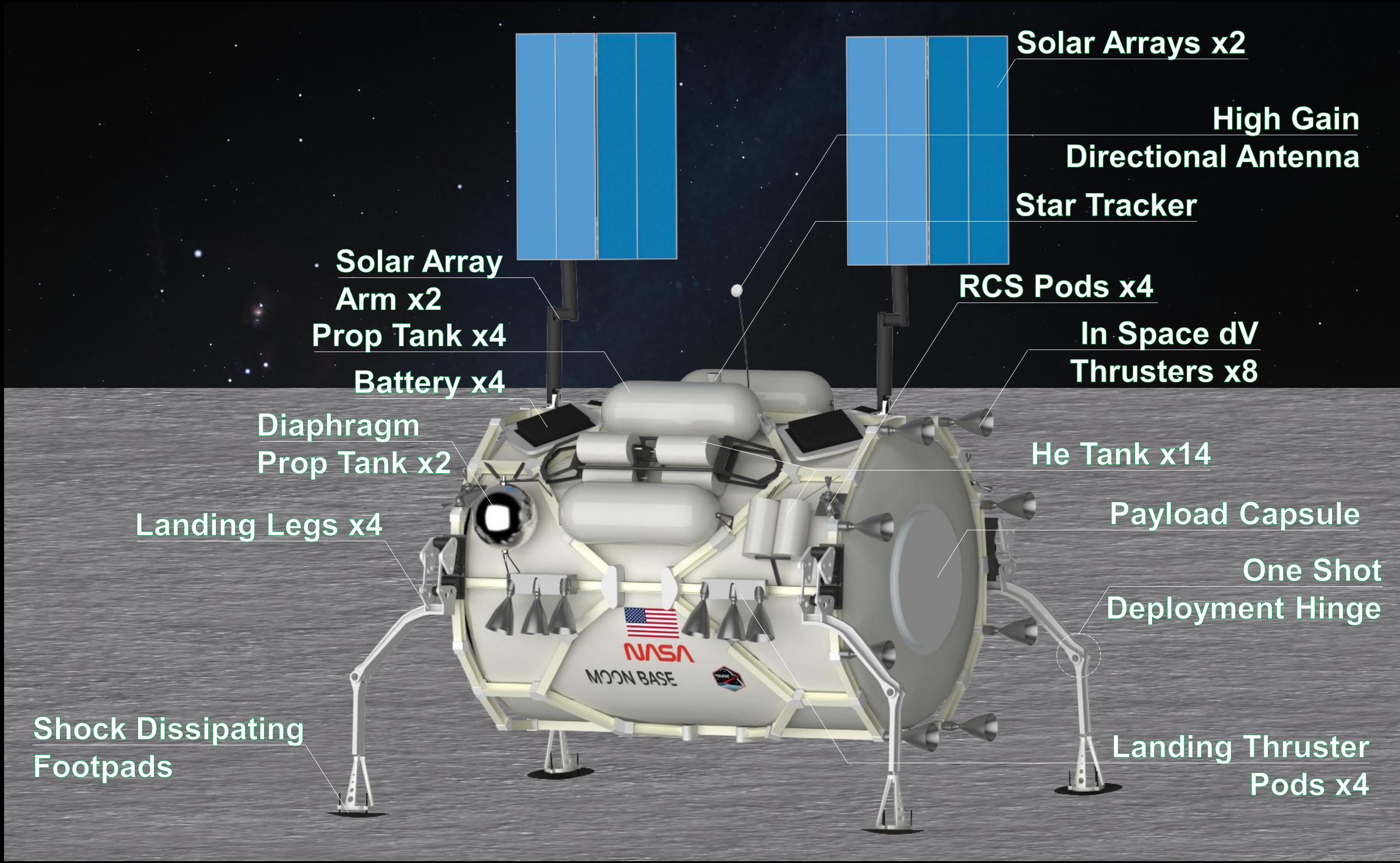


FLIGHT HARDWARE SYSTEMS

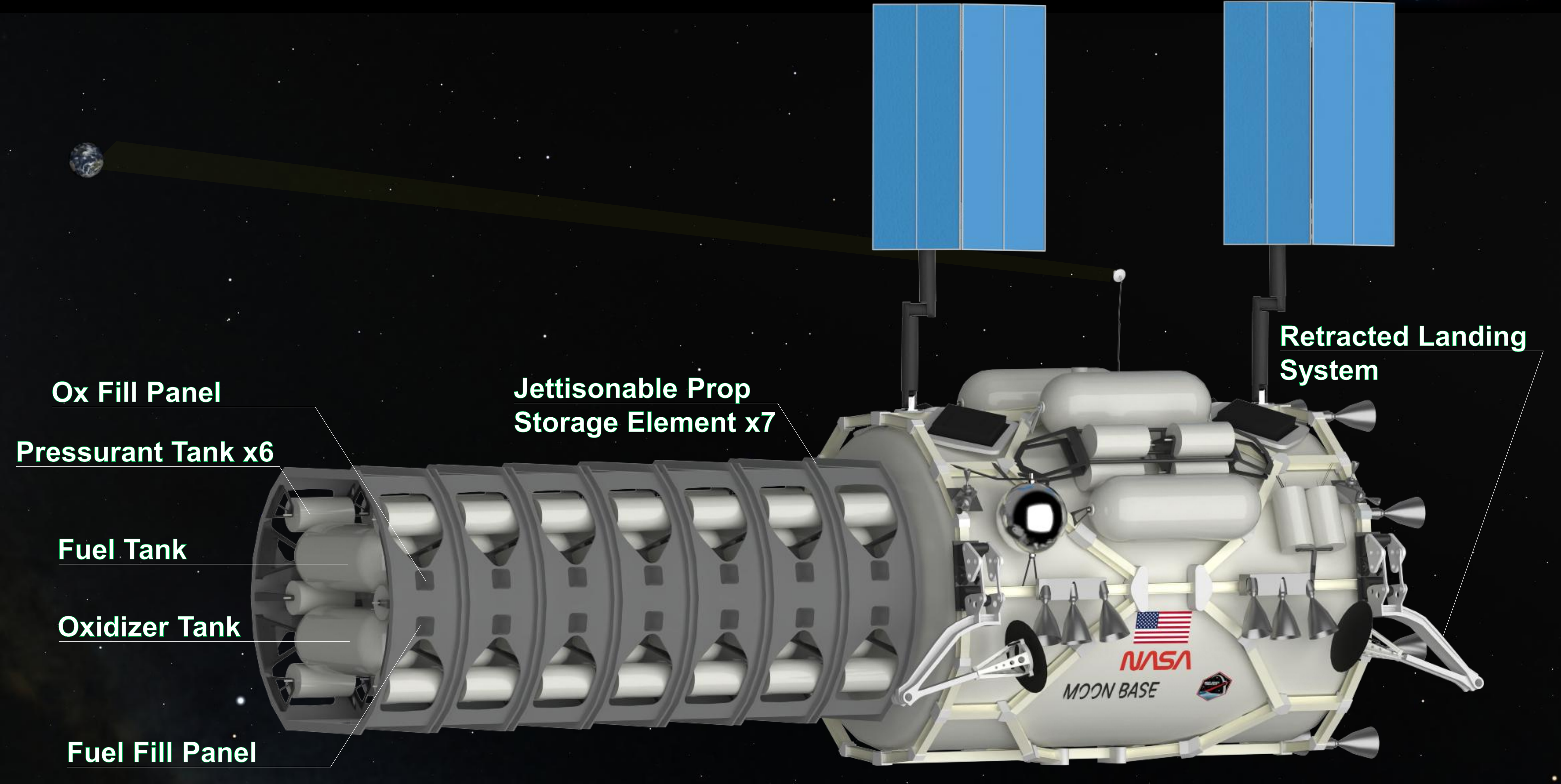
ALSO, AN EXERCISE LEFT TO THE READER

THE LANDER

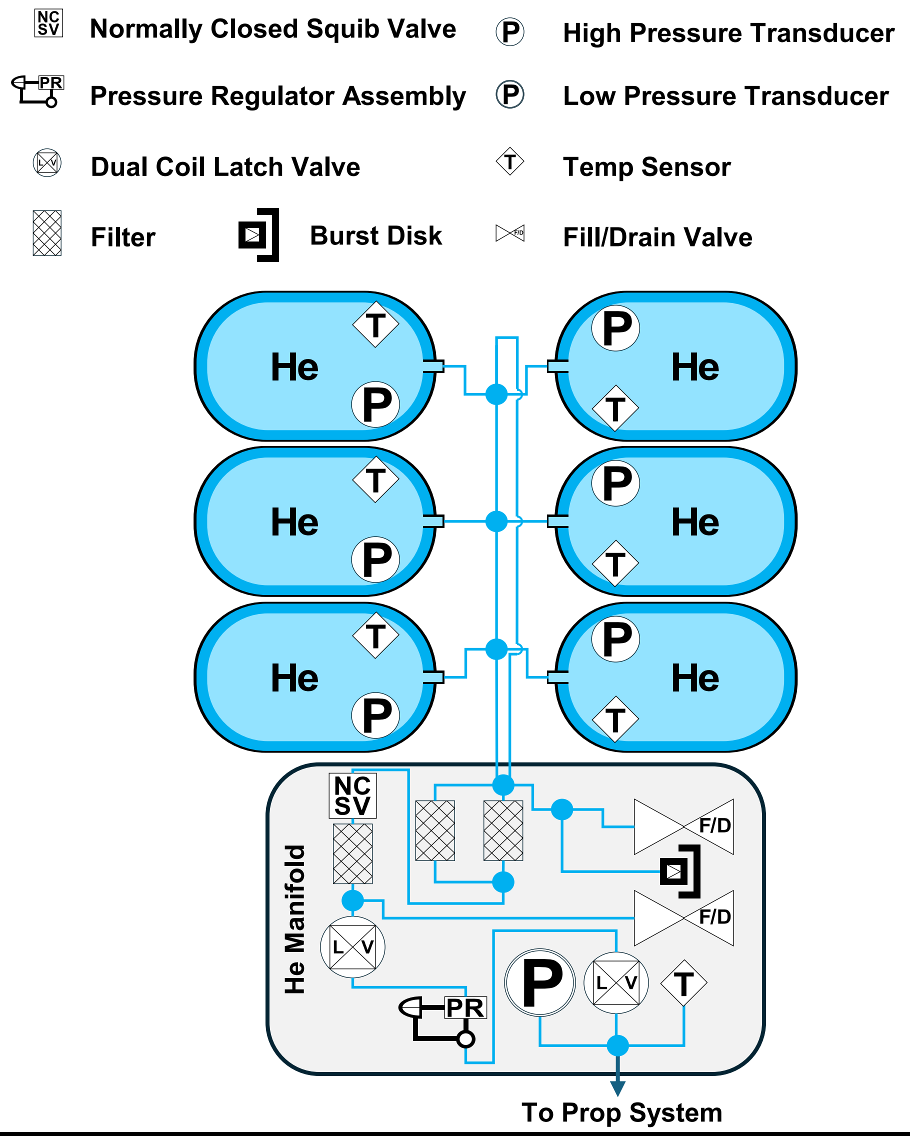
- **Not Shown**
  - Flight computers
  - Radios
  - Ground tracking instruments
  - Heaters
  - Blankets
  - Tubes & wires
  - Prop manifolds
  - Radiators
  - Actuator drivers
  - Thruster heat shields



THE IN SPACE FLIGHT VEHICLE



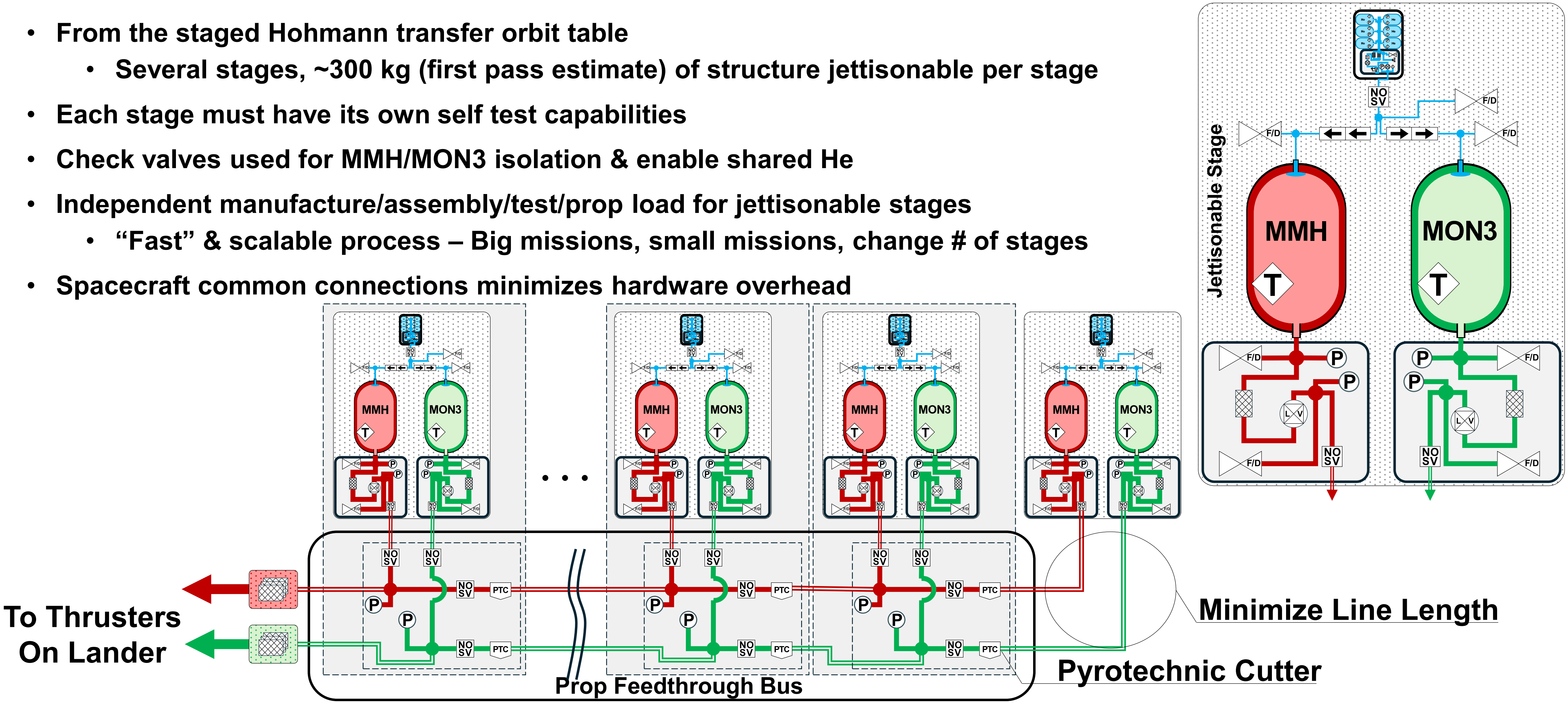
- **He/Prop budgets Interdepdent ~5,000/92,500 in^3 tanks**
- **Iterate on number of tanks to what makes sense ~6**
  - **Pressure regulators must have upstream pressure at "empty" state, prop tanks must be full**
  - **Compressibility effects of high pressure He**
  - **Acoustic resonance/data frames/eclipses/*etc.***
    - **double line from tank asy to control resonance**
- **Trade analysis to determine redundancy requirements on duplicity of elements (Valves/Regulators/*etc.*)**



COMMODITY STORAGE AND DELIVERY

M O O N BASE

- From the staged Hohmann transfer orbit table
  - Several stages, ~300 kg (first pass estimate) of structure jettisonable per stage
- Each stage must have its own self test capabilities
- Check valves used for MMH/MON3 isolation & enable shared He
- Independent manufacture/assembly/test/prop load for jettisonable stages
  - “Fast” & scalable process – Big missions, small missions, change # of stages
- Spacecraft common connections minimizes hardware overhead



CONCLUSIONS

- A mission solution was presented to take a large payload from the Earth to the Lunar Surface in support of Moon Base
  - Launch vehicle target orbits were shown
  - Transfer orbit ConOps
  - Landing Descent and Touchdown (LDT) ConOps was presented

- TLI achieved through jettisonable prop stages
  - Optimization of TLI burn schedule & vehicle configuration

The authors would like to thank the entirety of the DSL and LENS workforce for their contribution to this effort.

QUESTIONS?

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