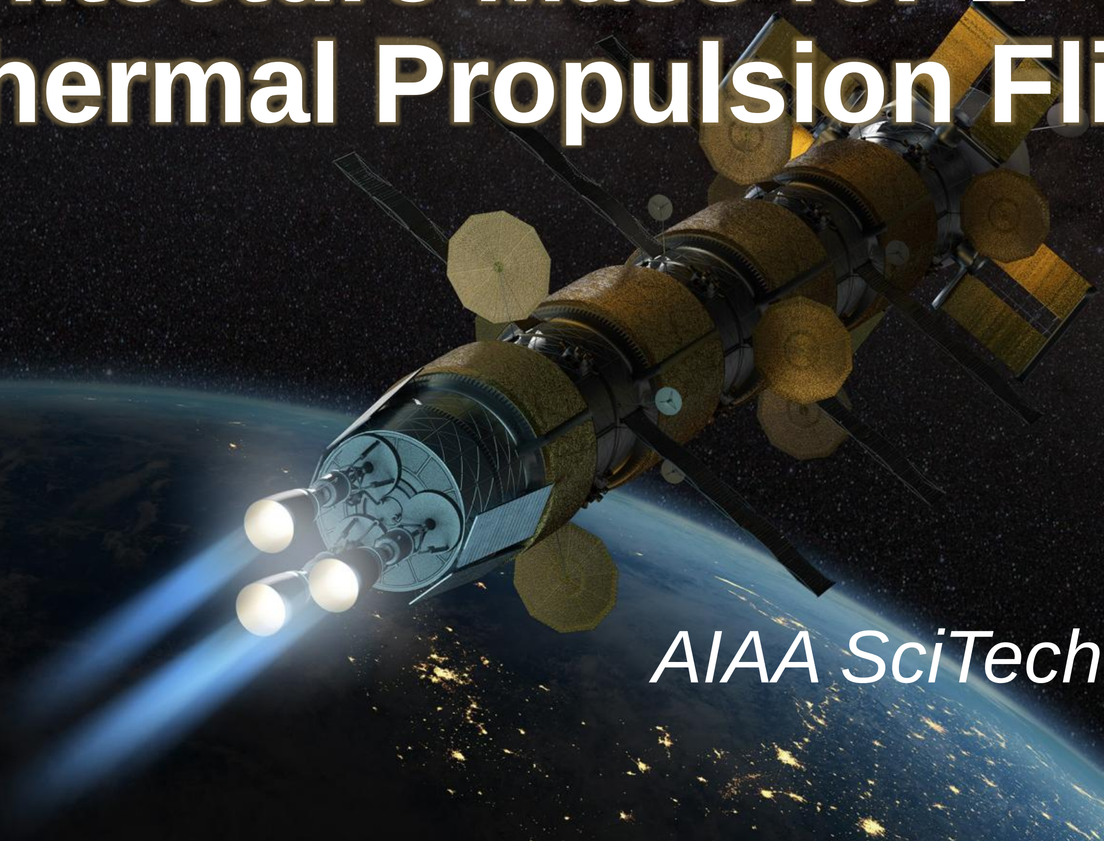
Effect of Engine Thrust and Isp Tradeoffs and Alternate Propellants on ΔV Budget and Architecture Mass for 1st Generation Nuclear Thermal Propulsion Flight Test Systems



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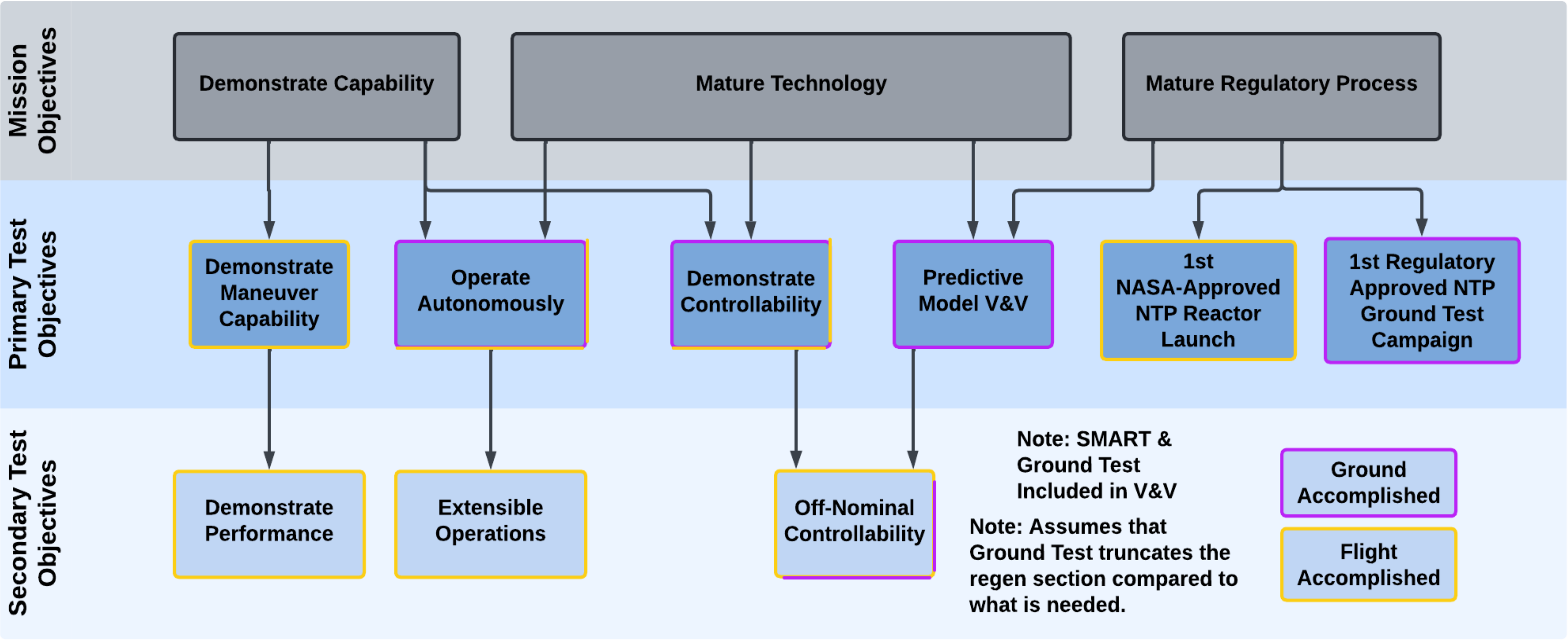
Gen-1 Flight Test System Design Space Exploration

- Review Gen-1 Flight Test requirements and objectives
- Review the types of NTP propellant options and associated engine cycles
- Establish launch vehicle options
- Simulate different vehicle configurations using different launch vehicles using AMA's in-house NTP system architecture model
- Analyze results and locate possible trends and knees
- Discuss conclusions and impacts

This work considers ONLY single launch architectures, future work will consider multi-launch architectures.

Test Objectives (Gen-1 NTP Mission)

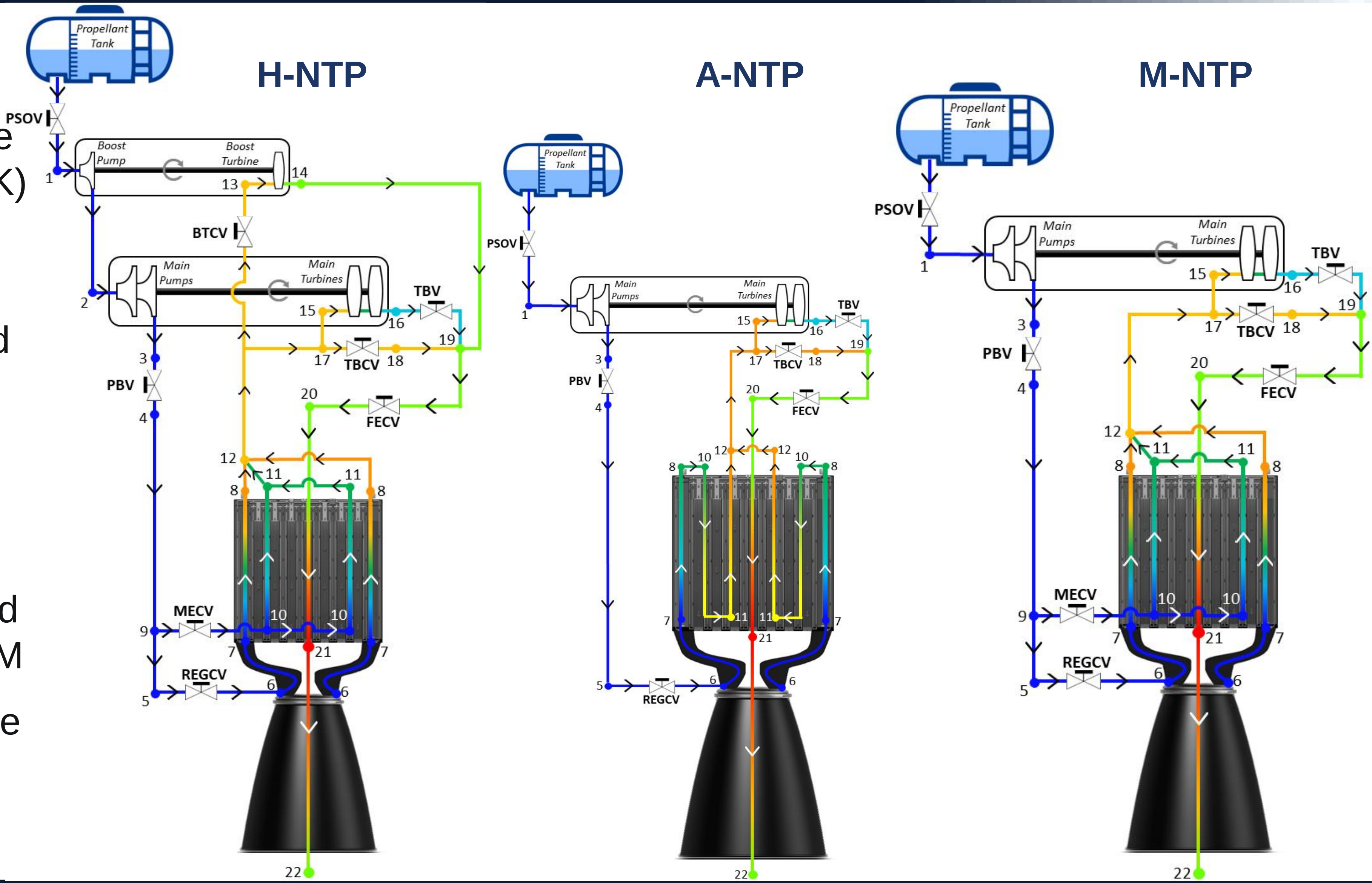
Leveraging DRACO and development testing, Gen-1 has more ambitious test objectives



Propellant Options for NTP Systems

Hydrogen (H-NTP), Ammonia (A-NTP), and Methane (M-NTP)

- Orbit dwell time is likely to occur prior to full burn test
- Hydrogen will require 2-stage CFM systems (90 K and 20 K)
- Liquid hydrogen is about a tenth the density of liquid ammonia and a sixth of liquid methane
- Hydrogen vehicles will likely be volume limited
- Methane will require a 100 K single stage CFM system and ammonia will not require CFM
- All three variants can produce the same thrust using the same reactor class with minimum modifications



Considered Launch Vehicle Options

Only Commercial Launch Vehicles are Considered

- Launch Vehicles arranged in the order of capability from lowest to highest
- Falcon 9, Falcon Heavy, and Vulcan have similar capabilities
- Starship has largest fairing and highest mass to orbit capability

Parameter	Falcon 9 Recoverable	Falcon Heavy Recoverable	Vulcan	New Glenn	Starship
Payload to 1000km circular orbit (kg)	16800.0	18000.0	18450.0	31550.0	109240.0
Fairing diameter (m)	5.2	5.2	5.4	7.0	9.0
Fairing length (m)	18.6	18.6	21.3	19.6	18.0
Payload diameter (m)	4.6	4.6	4.8	6.4	8.0
Payload length (m)	16.5	16.5	18.6	18.5	17.2
Volume (m^3)	240.0	240.0	280.0	487.0	650.0

Gen-1 Trade Study Matrix

- This mission considers 0 kg of payload.
- Each case assumes 100 m/s of RCS before the burn(s) is/are performed.
- Cryogenic fluid management is assumed to be used where applicable.
- This matrix attempts to explore various propellant options, engine architectures, and mission scopes with the goal of fitting everything on a singe commercial vehicle launch.

Thrust-Engine Mass	Propellant-Isp	Launch Vehicles	# Burns (equally distributed ΔV)
10klbf-3000kg	H-750	Starship	1 (limit to 1 km/s)
12.5klbf-3400kg	H-825	New Glenn	2 (max LV ΔV)
15klbf-3400kg	H-900	Falcon 9 Recoverable	4 (max LV ΔV)
25klbf-3400kg (ammonia)	A-375	Falcon Heavy Recoverable	1 (limit to 2.5 km/s)
25klbf-5000kg	A-450	Vulcan	
	M-350		
	M-494		

Master Equipment List (MEL) Components

The MEL loads user specified parameters for various components which include the following:

- Battery
  - Considering Ni-CD, Ni-H2, and Li-ion
- Bus Structure
  - Extends beyond propellant tank to house components for the stage
- Communications/Command & Data-Handling Systems/Guidance, Navigation, & Control
  - Imports a dataset of individual components (mass, power, mass growth allowance
- Cryogenic Fluid Management
  - Considers 3 modes: Active (both 90 K and 20 K CFM modules), Reduced Boil-Off (only 90 K module), and Passive (only tank insulation layers)
- Engine
  - Uses quasi-steady state data set and imposes temporal derivatives to simulate transient engine operation
- Docking and Thrust Structures
  - Truss structures that are composed of connecting beams
- Main Propellant Tank
  - Configured for mono- and bi-propellants
- Power Management and Distribution
  - Dependent on peak power draw
- Radiator and Mechanisms
  - Considers both radiator panels and extension/gimbal mechanisms
- Reaction Control System (RCS)
  - Considers oxidizer and fuel tanks along with a helium tank scaled by the size of the RCS.
- Solar Arrays
  - Considers both solar panels and extension/gimbal mechanisms

Vehicle Architecture Model Physics

- Transient analysis uses first principles instead of the Ideal Rocket Equation
  - $mass_{i+1} = mass_i - \dot{m}dt$
  - $\Delta V_{i+1} = \Delta V_i + \left(\frac{Thrust}{mass_i - \frac{\dot{m}dt}{2}} - g\right) dt$
- Allows for engine transients to be incorporated with varying $\dot{m}$ and $Thrust$.
- Analysis is iterative with a starting guess propellant mass and corresponding tank mass to the resulting propellant volume.
- ΔV is calculated until the required value is reached.
- The last burn exhausts all the m_{prop}.
- m_{prop} is modified, and another iteration commences
- Convergence occurs when the required ΔV matches within a tolerance the produced ΔV from the guessed m_{prop}.

Basic Code Workflow

Reference Vehicle Class
`vehicle.subcomponent.value`

Mission Structure
ΔV, payload mass drop off, and stage jettison schedules

`While` $abs(\Delta V_{des} - \Delta V_{result}) > tol$

`While` $m_{prop} > 0$

Physics-Based Calculator

$$m_{prop_{i+1}} = m_{prop_i} - \dot{m}dt$$

$$\Delta V_{i+1} = \Delta V_i + \left(\frac{Thrust}{mass_i - \frac{\dot{m}dt}{2}} - g\right) dt$$

+

Engine Transient Evaluator
Quasi-steady state engine performance splines
Temporal derivatives serve as limits

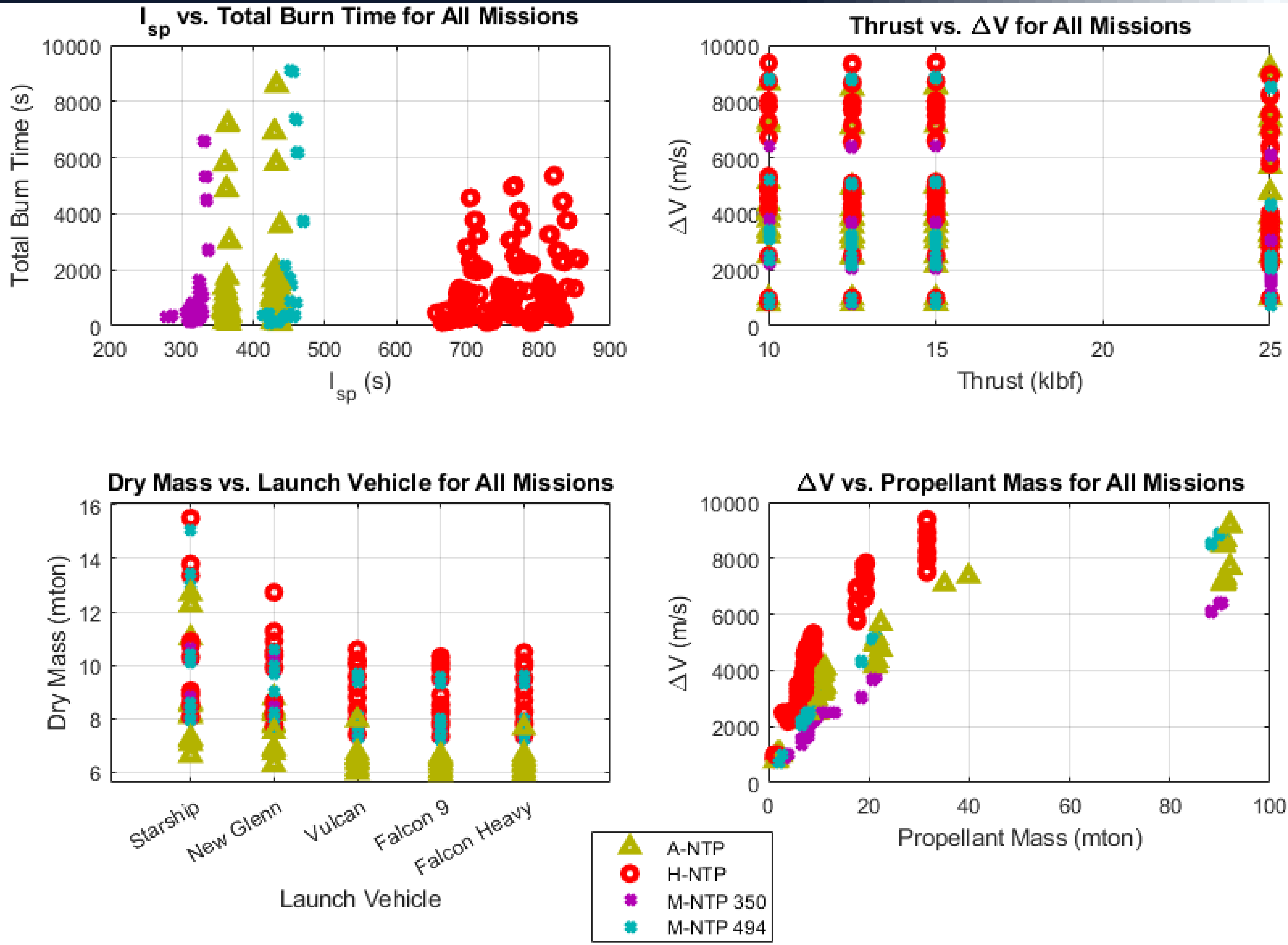
Adjust Propellant Volume ∀

$$\forall = \forall \left(\frac{\Delta V_{des}}{\Delta V_{result}}\right)^2$$

Reevaluate the MEL and RCS propellant masses

Gen-1 General Mission Results

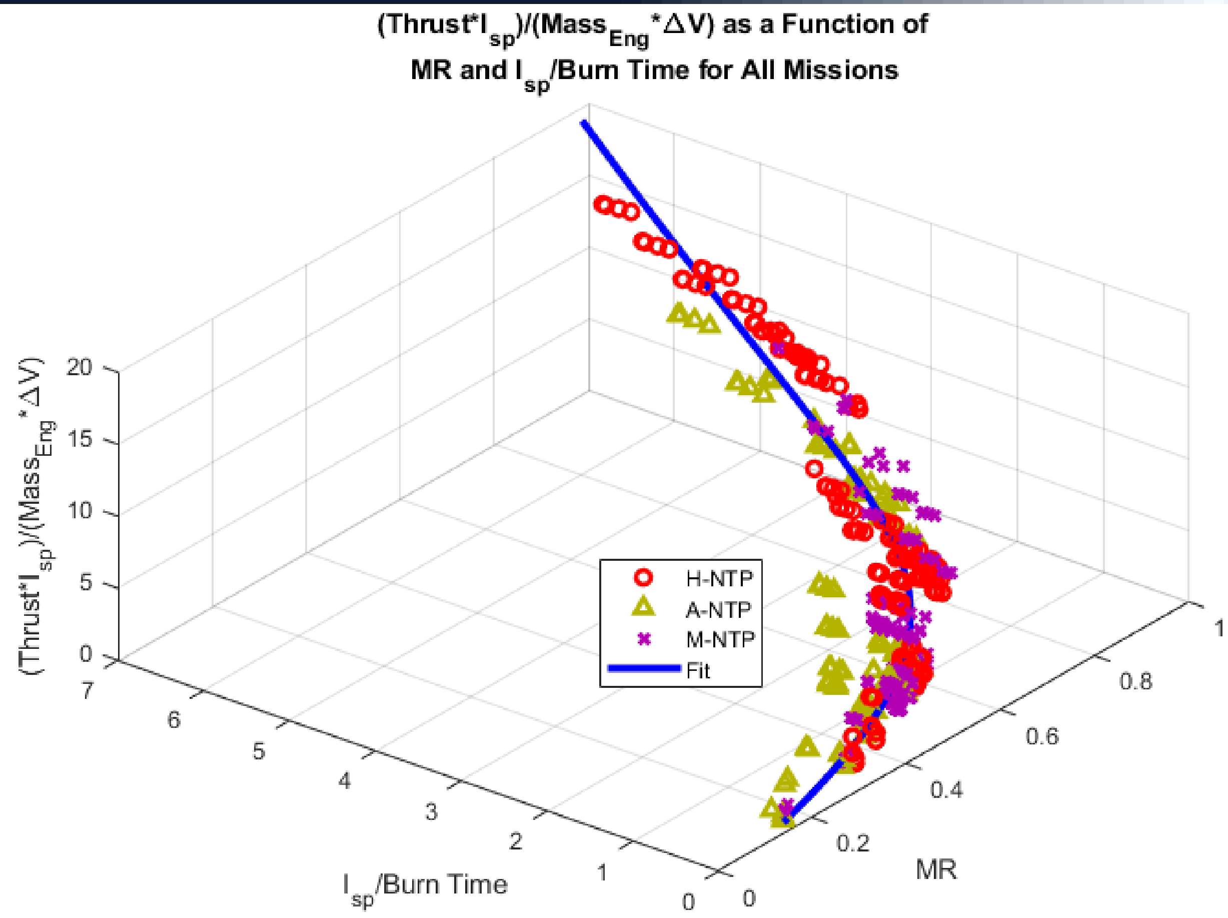
- H-NTP can provide the highest ΔV.
- M-NTP can provide the highest burn time
- A-NTP can provide the lowest dry mass
  - Therefore, A-NTP can provide lowest cost.
  - No need for cryocooler development
- H-NTP can accomplish the 1 km/s mission with 1.25 mton propellant mass



Dimensionless Parameter Results

Three considered dimensionless parameters:

- **Mass Ratio MR**: inert mass to total initial mass ratio
- **Time ratio $\frac{I_{sp}}{t_{burn}}$**: Specific impulse to burn time ratio – the ratio of the time it takes for the engine to produce 1 N of thrust using 1 kg of propellant to the total time that the engine produces thrust.
- **Dimensionless engine parameter $\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V}$**: Similar to Reynold's number – the ratio of engine impulse to the change in momentum supplied.



$$MR = f\left(\frac{I_{sp}}{t_{burn}}\right) = \frac{51{,}883\frac{I_{sp}}{t_{burn}} + 5{,}193}{\left(\frac{I_{sp}}{t_{burn}}\right)^2 + 52{,}180\frac{I_{sp}}{t_{burn}} + 44{,}345}$$

$$\frac{I_{sp}}{t_{burn}} = g\left(\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V}\right) = 0.3644\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V} - 0.2519 \rightarrow t_{burn} = \frac{I_{sp}}{g\left(\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V}\right)}$$

$$MR = h\left(\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V}\right) = \frac{294{,}634\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V} - 185{,}749}{\left(\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V}\right)^2 + 312{,}850\frac{F_{Eng} I_{sp}}{m_{Eng}\Delta V} + 295{,}292}$$

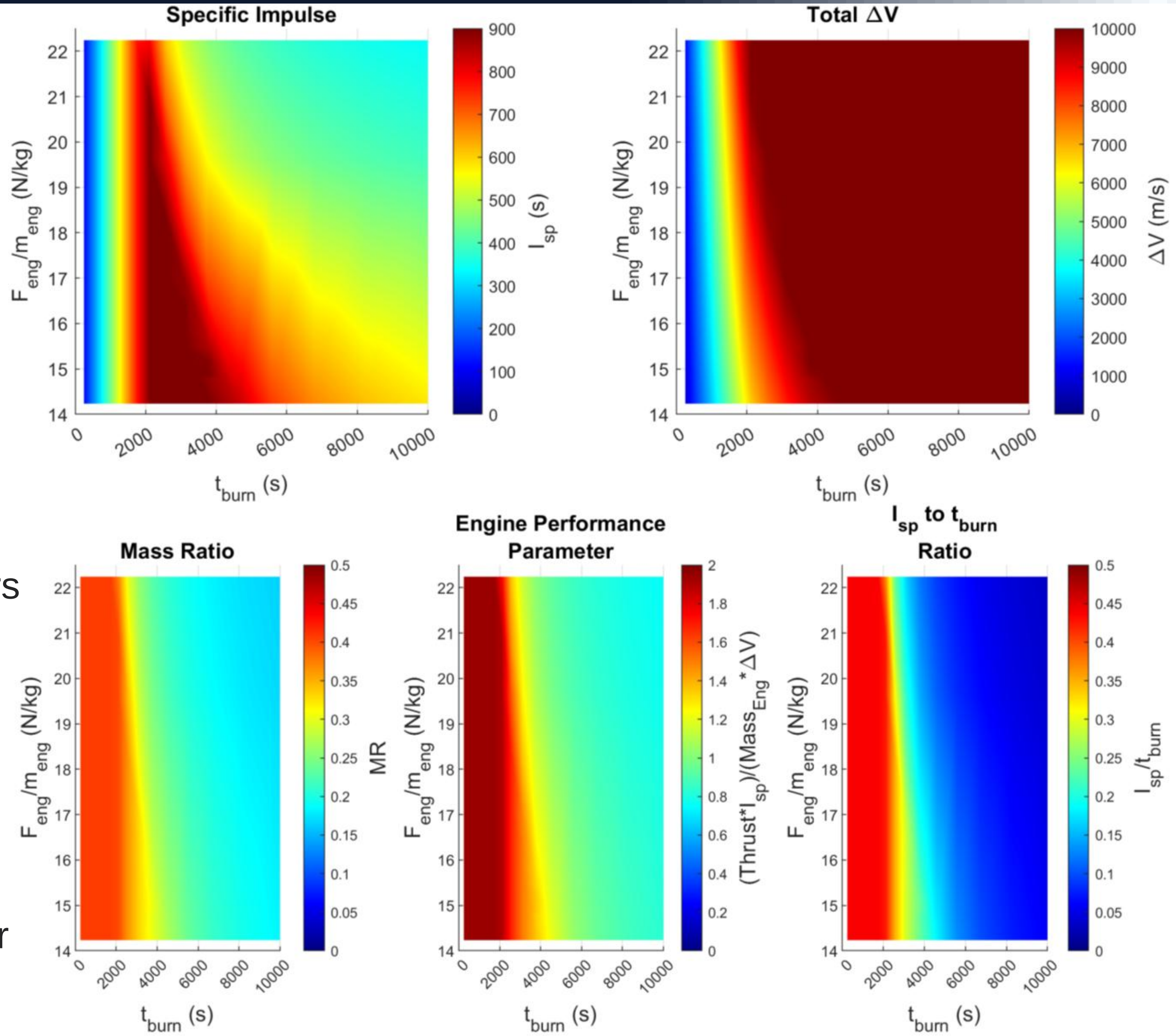
Using Dimensionless Parameters

- The MR and t_{burn} can be predicted by engine parameters (F_{Eng}, m_{Eng}, and I_{sp}) and desired ΔV
- Number of burns or launch vehicle do not have a significant effect.
- The dimensionless equations can be used to answer questions such as:
  - "**Which propellant should be used?**" given F_{Eng}, m_{Eng}, and t_{burn}.
  - "**How much test time is possible to obtain?**" given F_{Eng}, m_{Eng}, and I_{sp}.
  - Note that MR and ΔV remain as floating parameters in both cases

Parameter	Definition	Units
F_{Eng}	Engine thrust class	N
I_{sp}	Specific impulse	s
m_{Eng}	Engine mass	kg
ΔV	Change in velocity	m
t_{burn}	Burn time	s
MR	Inert mass to initial wetted mass ratio	-

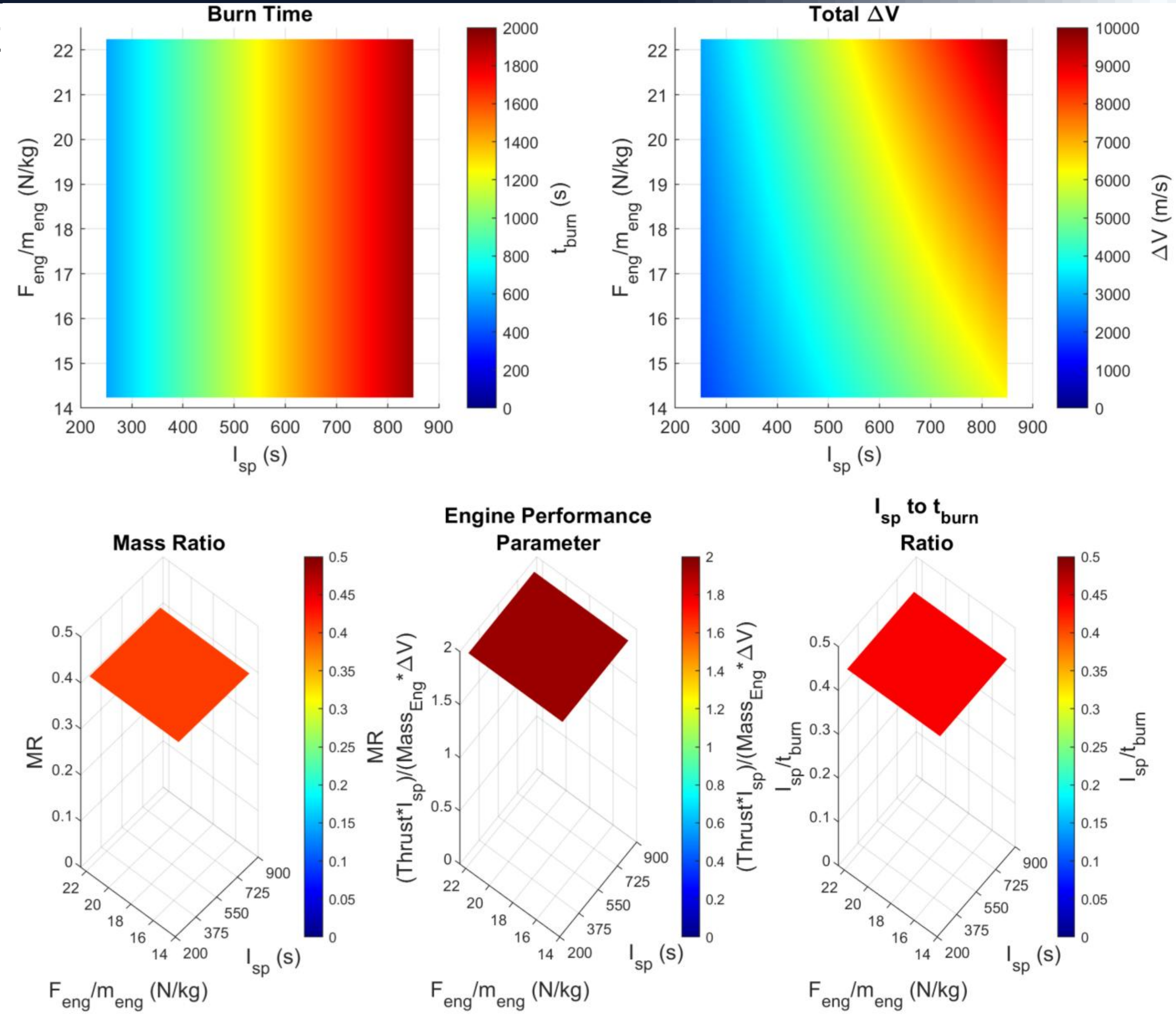
Which propellant should be used?

- Given $\frac{F_{Eng}}{m_{Eng}}$ and t_{burn}, want to determine the propellant
- Solution space is plotted which shows I_{sp}, ΔV, MR, $\frac{F_{Eng} I_{sp}}{m_{Eng} \Delta V}$, and $\frac{I_{sp}}{t_{burn}}$ as functions of $\frac{F_{Eng}}{m_{Eng}}$ and t_{burn}.
- Three regions are shown:
  - Up to 2000 second t_{burn}: lower t_{burn} require propellants with lower I_{sp} independent of $\frac{F_{Eng}}{m_{Eng}}$. I_{sp} increases linearly with t_{burn}. Dimensionless parameters are constant.
  - 2000 to 4000 second t_{burn}: require propellants with highest I_{sp}. Lower $\frac{F_{Eng}}{m_{Eng}}$ result in lower ΔV. Dimensionless parameters decrease with increasing t_{burn}.
  - Above 4000 second t_{burn}: ΔV is maximized regardless of propellant, higher $\frac{F_{Eng}}{m_{Eng}}$ require propellants with lower I_{sp}. Dimensionless parameters minimize.



What burn time is possible?

- Given F_{Eng}, m_{Eng}, and I_{sp} (or propellant), want to determine the possible t_{burn}
- Solution space is plotted which shows t_{burn}, ΔV, MR, $\frac{F_{Eng} I_{sp}}{m_{Eng} \Delta V}$, and $\frac{I_{sp}}{t_{burn}}$ as functions of $\frac{F_{Eng}}{m_{Eng}}$ and I_{sp}.
    - t_{burn} linearly increases with I_{sp}
    - All dimensionless parameters are constant
    - Higher $\frac{F_{Eng}}{m_{Eng}}$ values yield higher ΔV
    - t_{burn} maxes out at 2000 seconds
- This solution space is a subset of the previous solution space
- This will provide the MINIMUM t_{burn} achievable and higher values are possible
- If t_{burn} is lower than desired, then the problem is changed to that of selecting the propellant.



Conclusions and Future Work

- Conclusions:
  - This work used AMA's in-house vehicle architecture model with an integrated MEL
  - NTP engine transients were considered
  - A matrix of 700 cases was evaluated for Gen-1 single launch flight tests
  - Among the cases:
    - A-NTP had the lowest dry mass
    - H-NTP had the lowest total mass
    - M-NTP had the highest burn time
    - Engines with the lower thrust showed higher burn times
  - Higher burn times will result in more available test data
  - Dimensionless parameters and curve fits were developed to represent the datapoints
  - Methodology of using the curve fits was presented to help guide the design

- Future Work:
  - Consider multi-launch mission architectures
  - Refine dimensionless parameters and curve fits

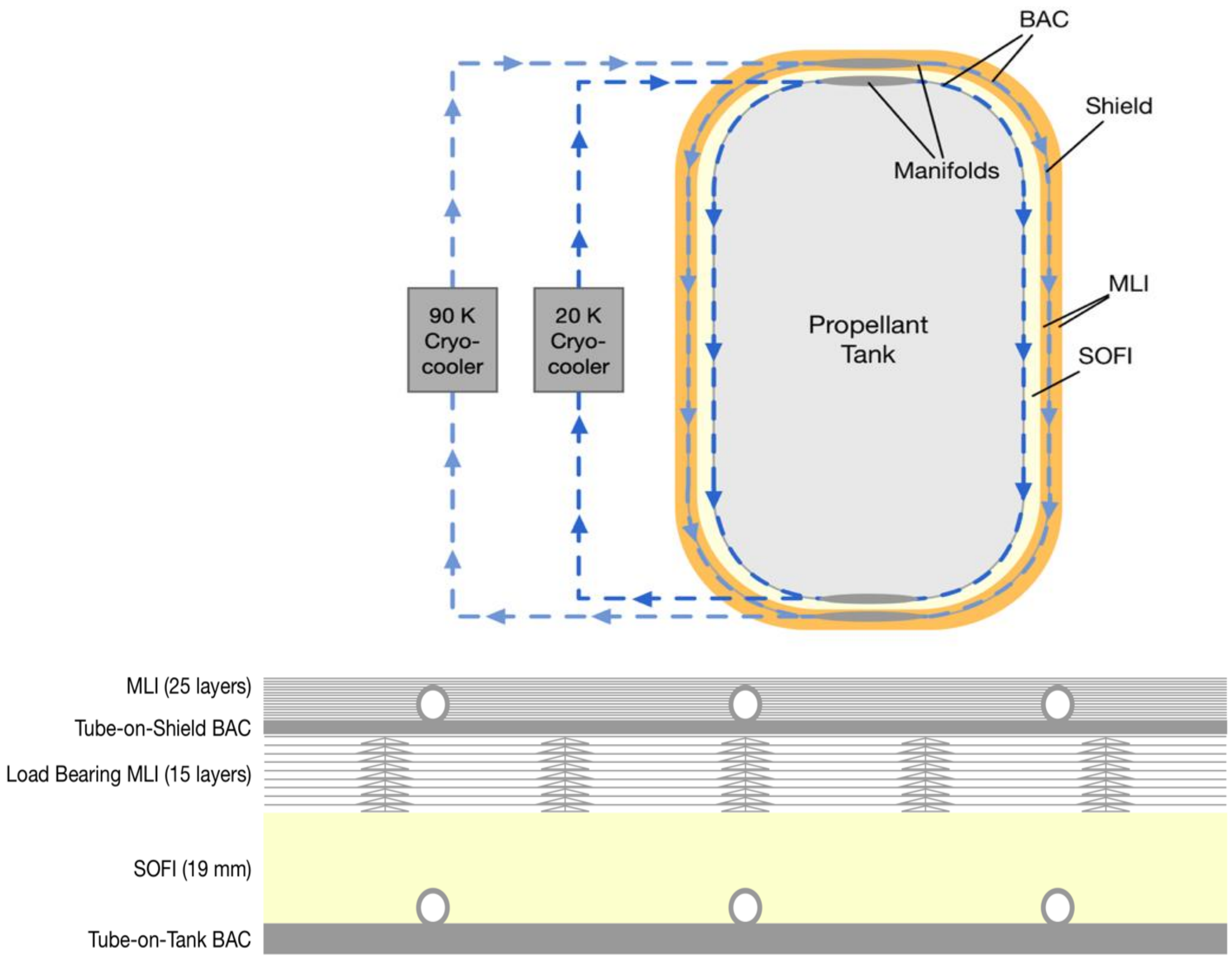
Questions???

ANALYTICAL MECHANICS ASSOCIATES

Back Up Slides

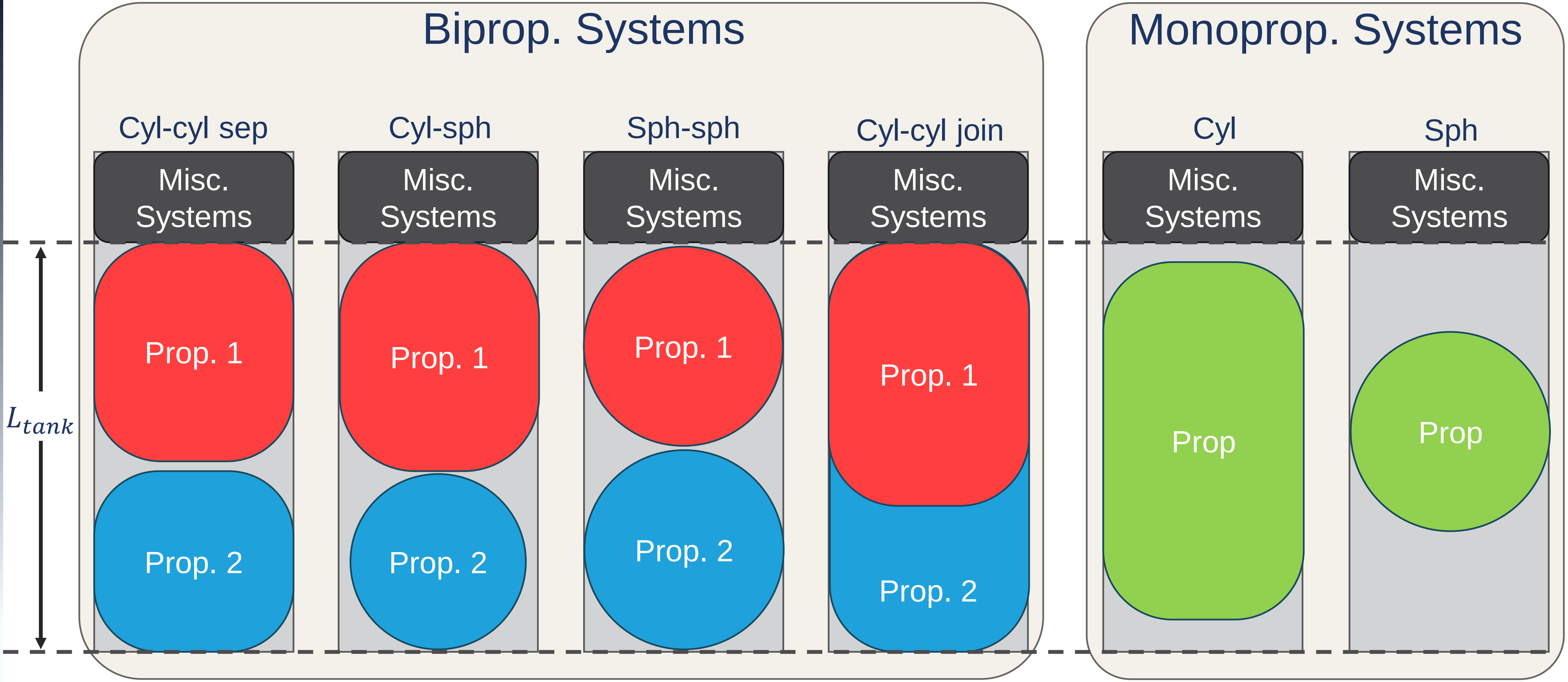
Descriptions of the CFM System

- Multilayer Insulation (MLI) is used to passively reduce the radiative heat load
- Spray-on Foam Insulation (SOFI) passively limits heat rate from the shield to the tank
- 20 K class cryocooler is required to maintain LH2 propellant as a liquid
- 2-zone cryocooling intercepts heat at an intermediate temperature and lifts heat at the tank wall
  - The 90K class cryocooler is much more efficient than the 20K class cryocooler
  - Based on work done at GRC & MSFC
- Technologies must be demonstrated in space
  - SOFI & Load-bearing MLI
  - Cryocoolers & Broad Area Cooling



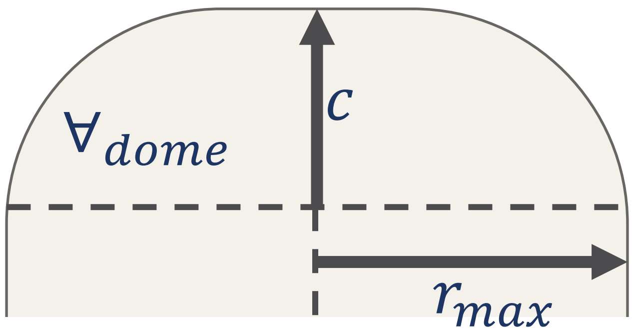
2-Zone Cryocooler and CFM Layout (Plachta, 2018)

Tank Configurations



Tank Algorithms

- Two imposed constraints:
  - Mixture ratio: $\phi = \frac{m_2}{m_1} = \frac{\rho_2 \forall_2}{\rho_1 \forall_1}$
  - Total tank limit: $L_{tot} = L_{misc} + L_{tank} \rightarrow L_{tank} = L_1 + L_2$



- Cyl-cyl sep:
  - $L_1 = \frac{\pi r_{max}^2 L_{tank} + 2\forall_{dome}\left(1 - \phi\frac{\rho_1}{\rho_2}\right)}{\pi r_{max}^2\left(1 + \phi\frac{\rho_1}{\rho_2}\right)}$
- Cyl-cyl join:
  - $L_2 = \phi\frac{\rho_1}{\rho_2}\frac{1}{\pi r_{max}^2\left(1 + \phi\frac{\rho_1}{\rho_2}\right)}(2\forall_{dome} + \pi r_{max}^2 L_{tank} - 2\pi r_{max}^2 c)$
- Cyl-sph:
  - $4\pi r_{sph}^3 + 6\phi\frac{\rho_1}{\rho_2} r_{max}^2 r_{sph} - 3\phi\frac{\rho_1}{\rho_2}(2\forall_{dome} + \pi r_{max}^2 L_{tank} - 2\pi r_{max}^2 c) = 0$
    - solve for r_{sph} through `fminbnd`
  - $L_{cyl} = L_{tank} - 2c - 2r_{sph}$

Tank Algorithms (Sph-sph)

- Mixture ratio: $\phi = \frac{m_2}{m_1} = \frac{\rho_2 \forall_2}{\rho_1 \forall_1}$
- Total tank limit: $L_{tot} = L_{misc} + L_{tank} \rightarrow L_{tank} = 2r_1 + 2r_2 + L_{res}$
- If $\rho_1 < \rho_2$:
  - $r_1 = r_{max}$
  - $r_2 = \sqrt[3]{\phi \frac{\rho_1}{\rho_2} r_{max}^3}$
- Else if $\rho_2 < \rho_1$:
  - $r_2 = r_{max}$
  - $r_1 = \sqrt[3]{\frac{\rho_2}{\phi \rho_1} r_{max}^3}$
- If $2r_1 + 2r_2 > L_{tank}$ or $L_{res} < 0$
  - $\phi \frac{\rho_1}{\rho_2} \left[-\left(\frac{\rho_2}{\phi \rho_1} + 1 \right) r_2^3 + \frac{3}{2} L_{tank} r_2^2 - \frac{3}{4} L_{tank}^2 r_2 + \frac{1}{8} L_{tank}^3 \right] = 0$
    - solve for r_2 through `fminbnd`
  - $r_1 = \frac{1}{2} L_{tank} - r_2$