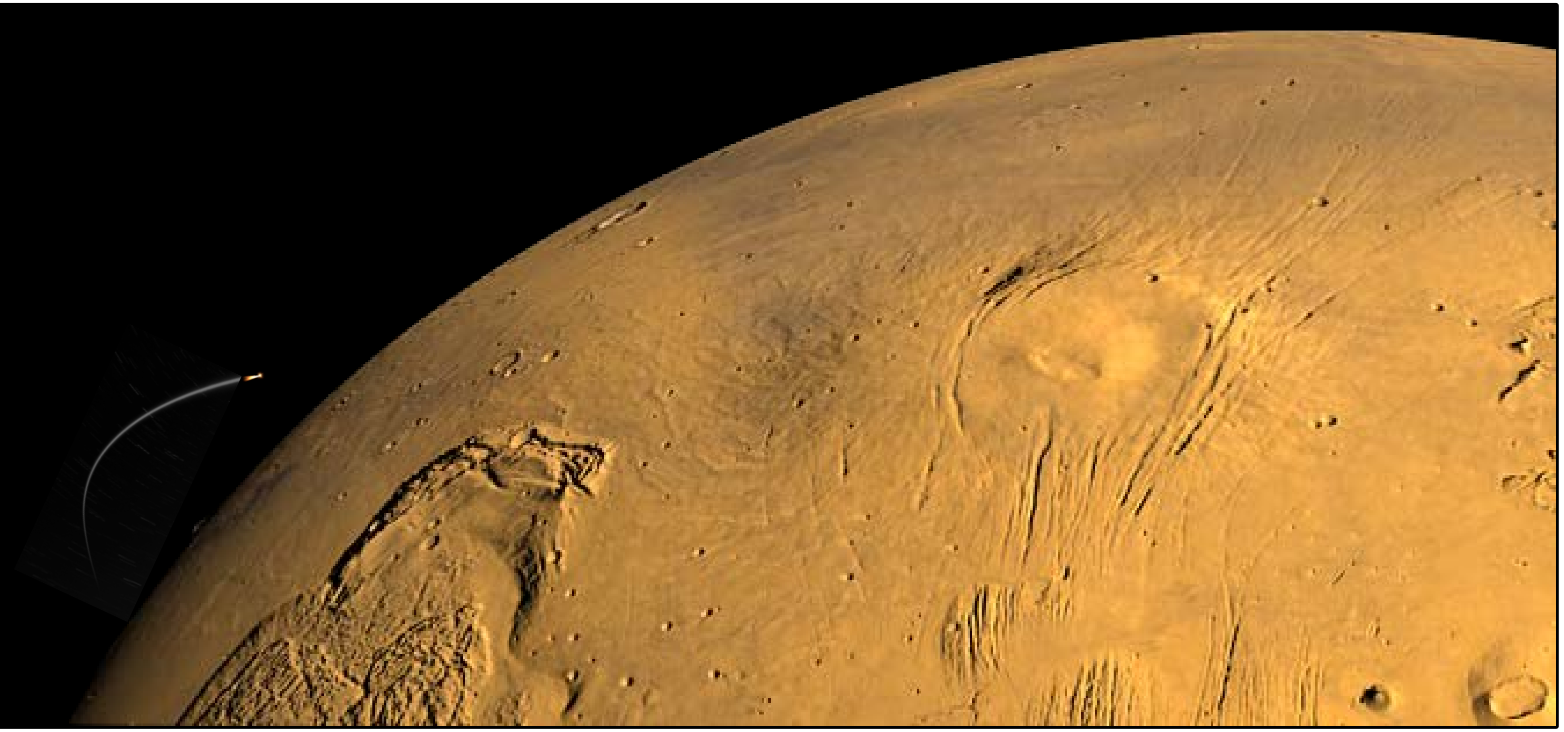
Mars Ascent Vehicle



Jet Propulsion Laboratory
California Institute of Technology

MARSHALL SPACE FLIGHT CENTER

A Single Stage to Orbit Design for a Hybrid Mars Ascent

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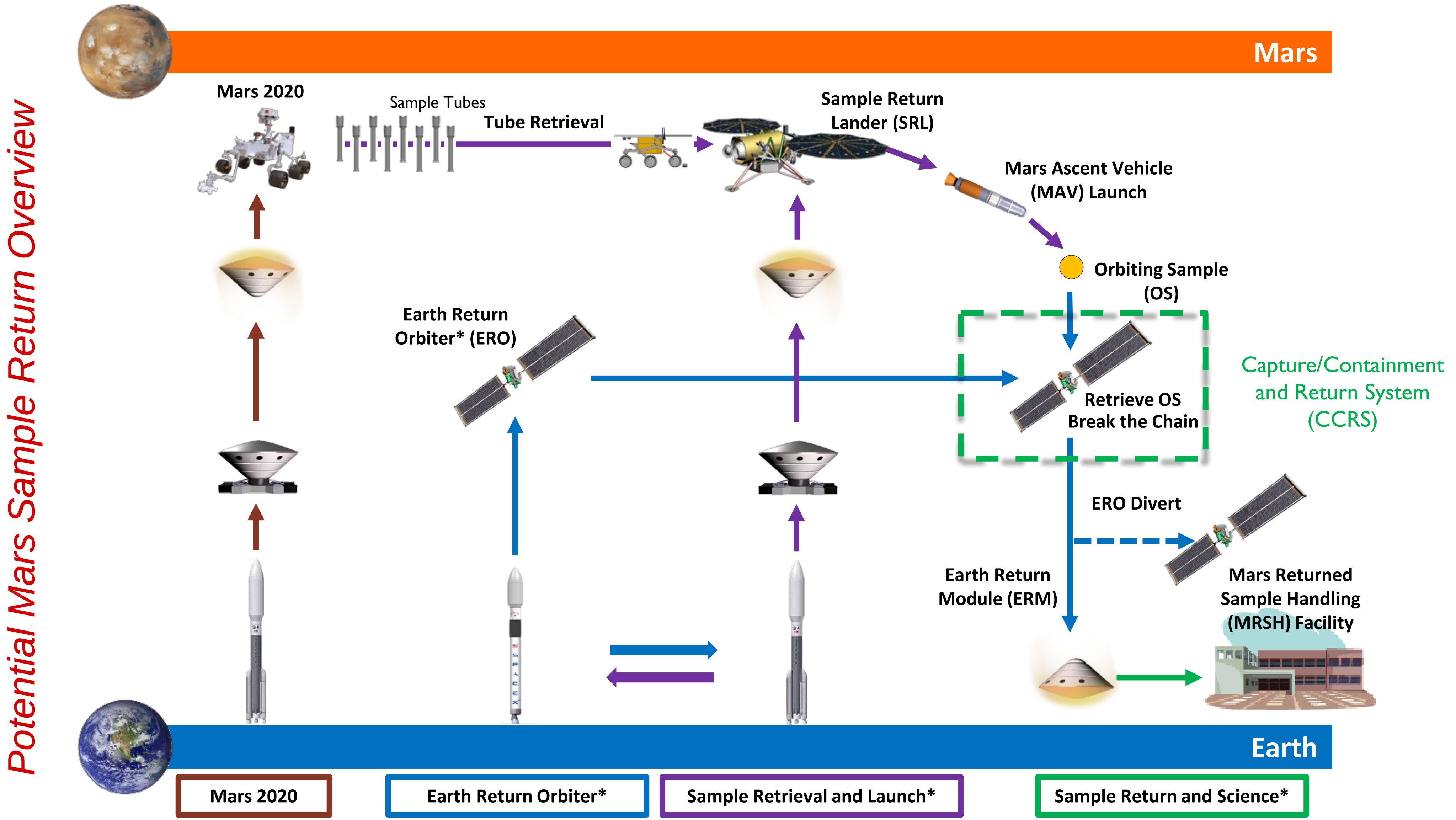
Ashley Karp, Barry Nakazono/JPL
Greg Zilliac/ARC

MAV Big Picture



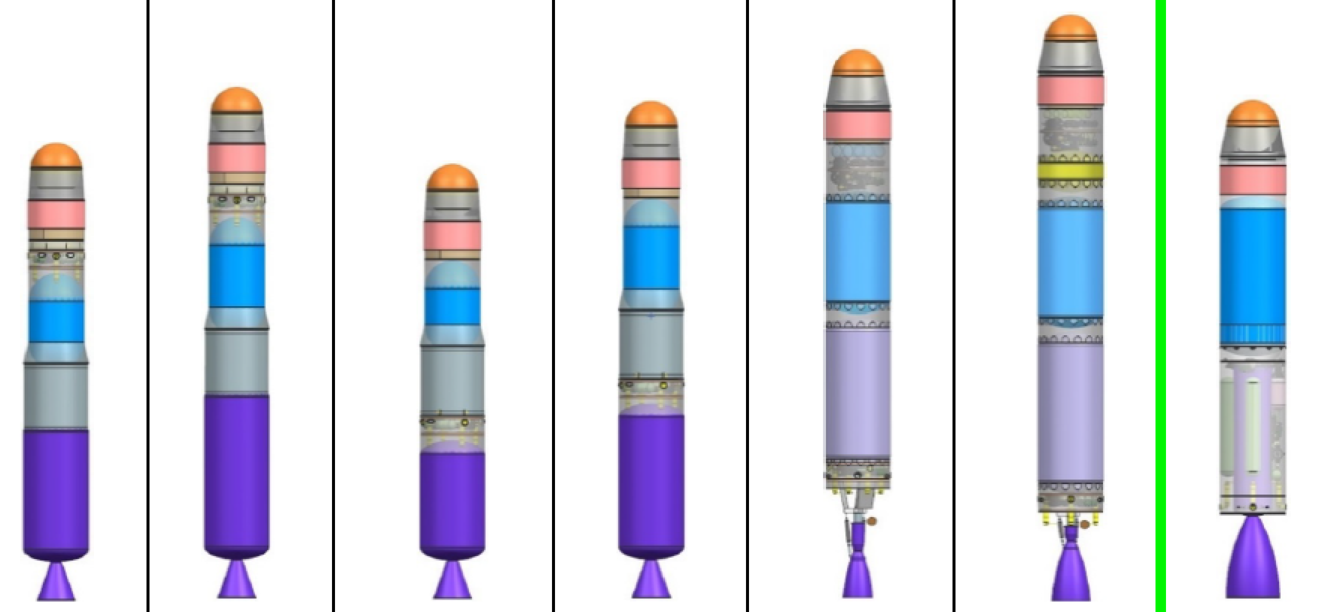
*Concepts under study

Intro

- Single Stage to Orbit (SSTO) hybrid propulsion system is being studied as an option for a conceptual Mars Ascent Vehicle (MAV).
- Benefits of the hybrid option include its predicted low temperature behavior, high performance and ability to restart (enabling the SSTO).
  - However, the hybrid technology remained at a relatively low Technology Readiness Level (TRL).

Mars Ascent Vehicle FY 2015 Study

Mars Ascent Vehicle

	Case 1a	Case 1b	Case 2a	Case 2b	Case 5	Case 6	Case 7
	Solid-Solid G-G	Fixed Solid-Solid G-G	Solid-Solid G-U	Fixed Solid-Solid G-U	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid
							
Payload/ OS	14 kg, 30 cm OS taken as reference						
GLOM	318.8	341.5	274.1	297.1	255.0	269.8	219.1
Length	2.64 m	2.96 m	2.51 m	2.87 m	3.21 m	3.39 m	2.89 m
AFT	-58 C	-58 C	-58 C	-58 C	-90/-44 C	-90/-44 C	-90/-66 C

(Temp limit if frozen/temp limit if not frozen)

In an attempt to increase the TRL, a technology development program has been underway for the past four years.

Pre-Decisional: For planning and discussion purposes only.

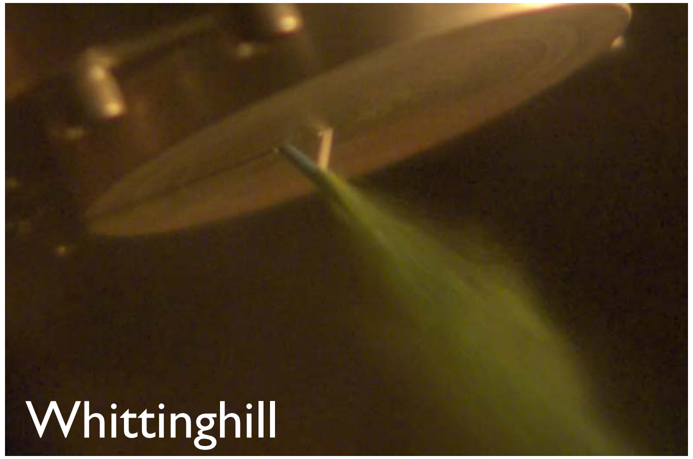
MAV Studies

- MAV 2015 Study concluded that for a certain set of requirements, hybrids had advantages. However TRL was low and plan made to develop the technology to be ready to compete for > 2030 launch.

- In 2018, launch window moved up to 2026, shortening technology development time for the Hybrid MAV propulsion.

Hybrid Testing – Hypergolic Ignition

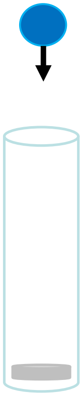
Liquid



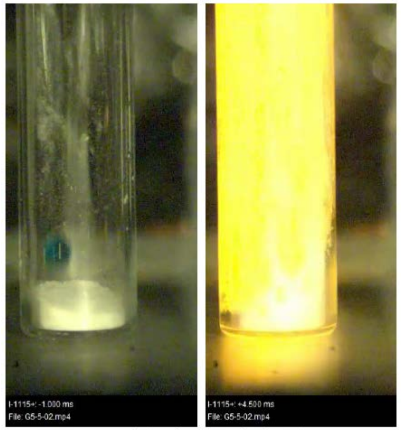
TEA/TEB and MON-25

Solid

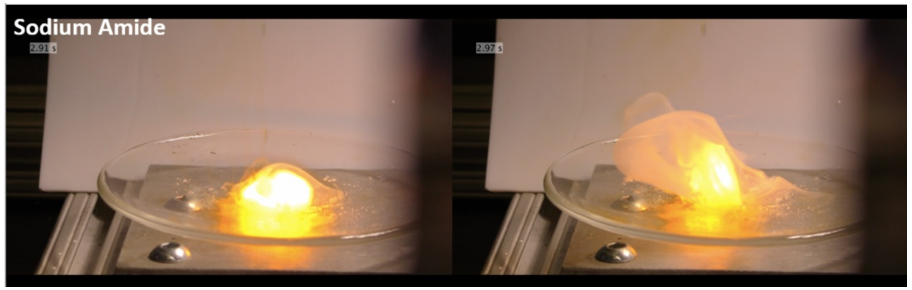
MON



Additive

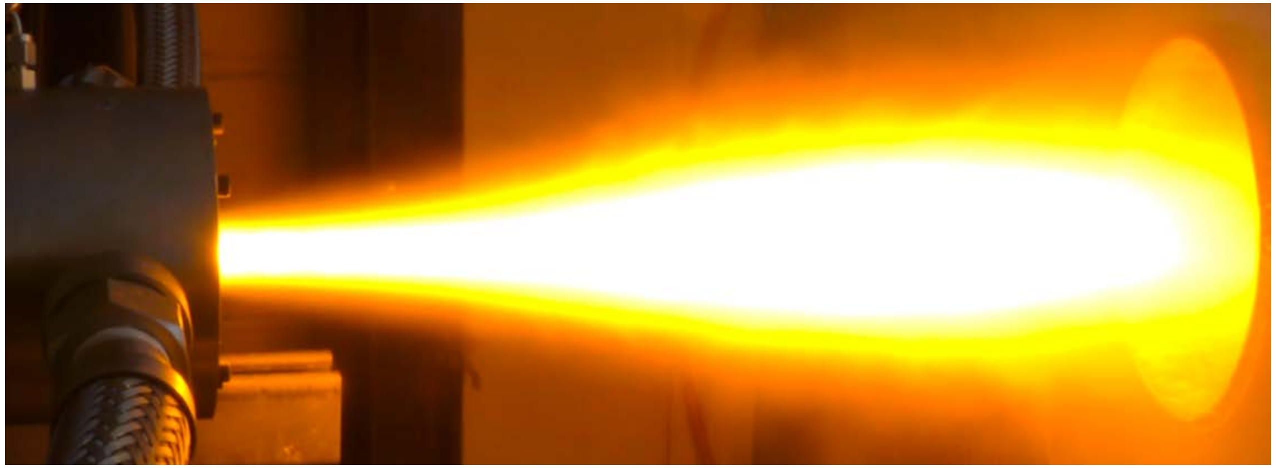


(a) sodium amide (G5-5)



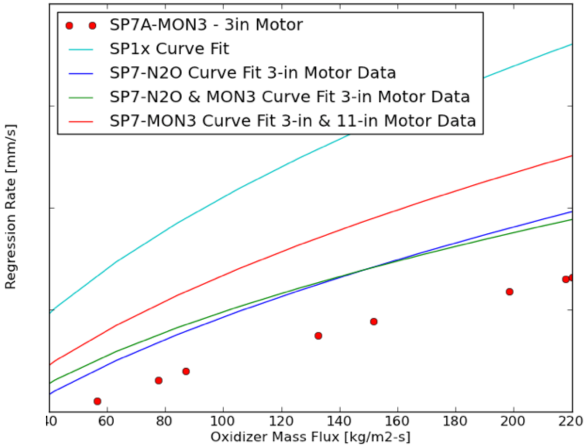
Droplet Ignition Testing at Purdue and Penn State

Subscale Motor Testing at Purdue (moving to Vacuum)

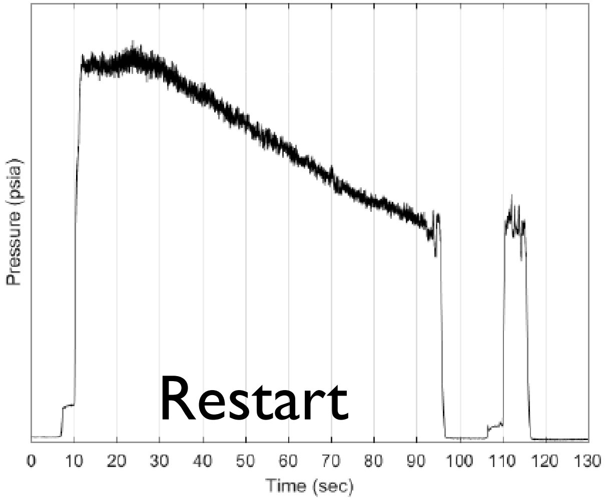


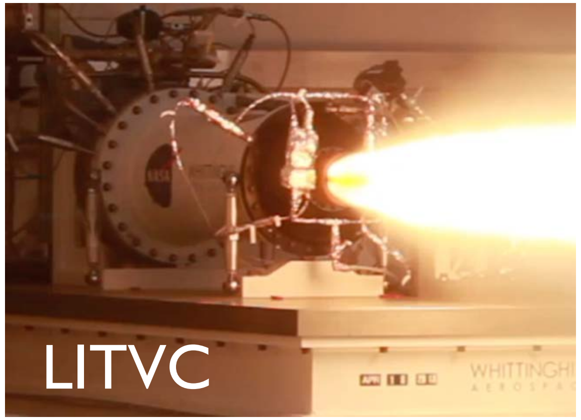
Hybrid Testing – Regression & Motor

Space Propulsion Group



Whittinghill Aerospace



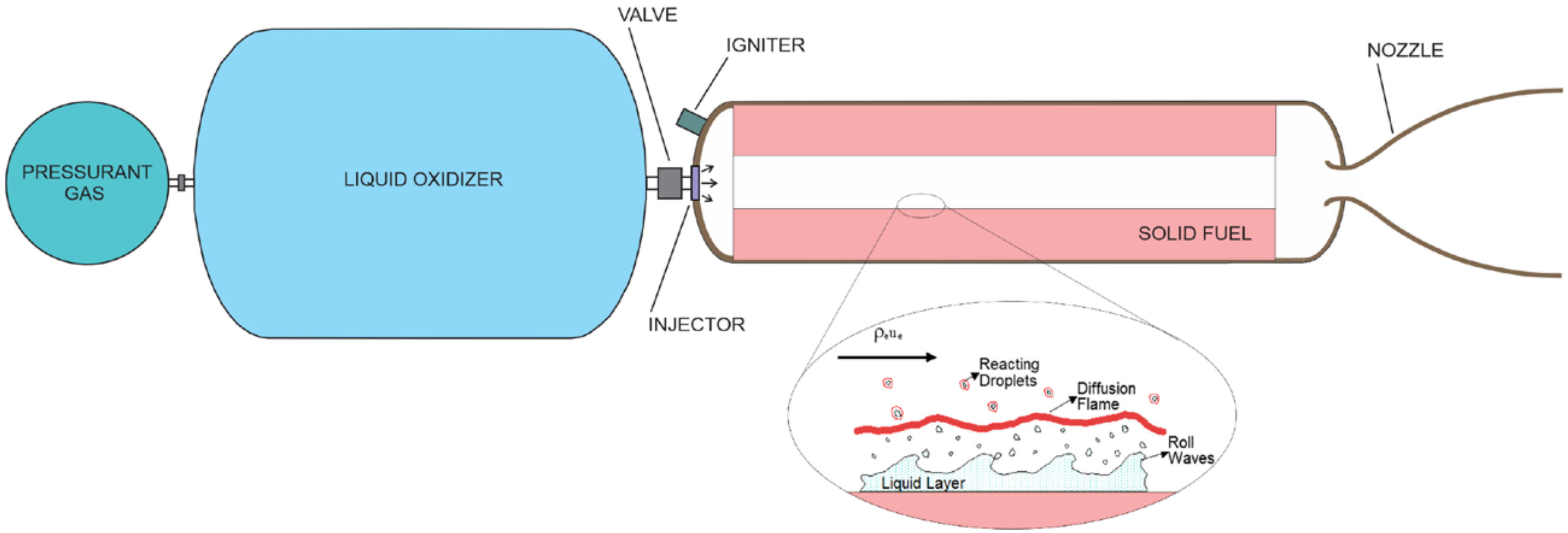


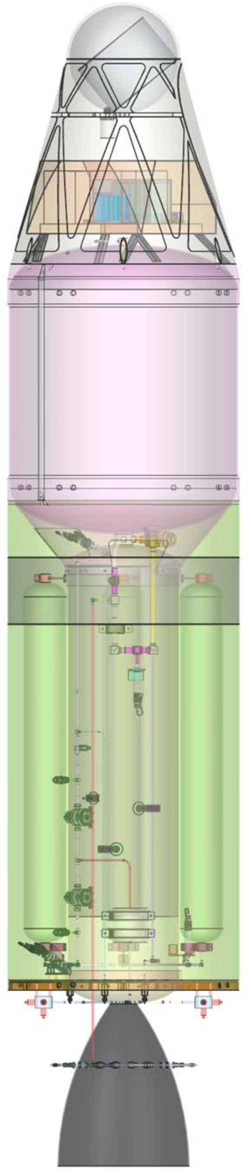
Preliminary Architecture Assessment

- The results of the technology development program have been incorporated into an updated design for a Hybrid Mars Ascent Vehicle. The goal was to show a hybrid propulsion design that closes under the guidelines currently envisioned for a potential Mars Sample Return campaign.
- The study is called a Preliminary Architecture Assessment, which has been done for both a Hybrid and Solid MAV design, with designs of the major subsystems required.
  - A down select between the Solid and Hybrid propulsion MAVs is scheduled for late 2019.
  - Solid MAV is AIAA-2019-4149 ‘A Design for a Two stage Solid MAV’, Wednesday at 10.

Hybrid Motor Overview

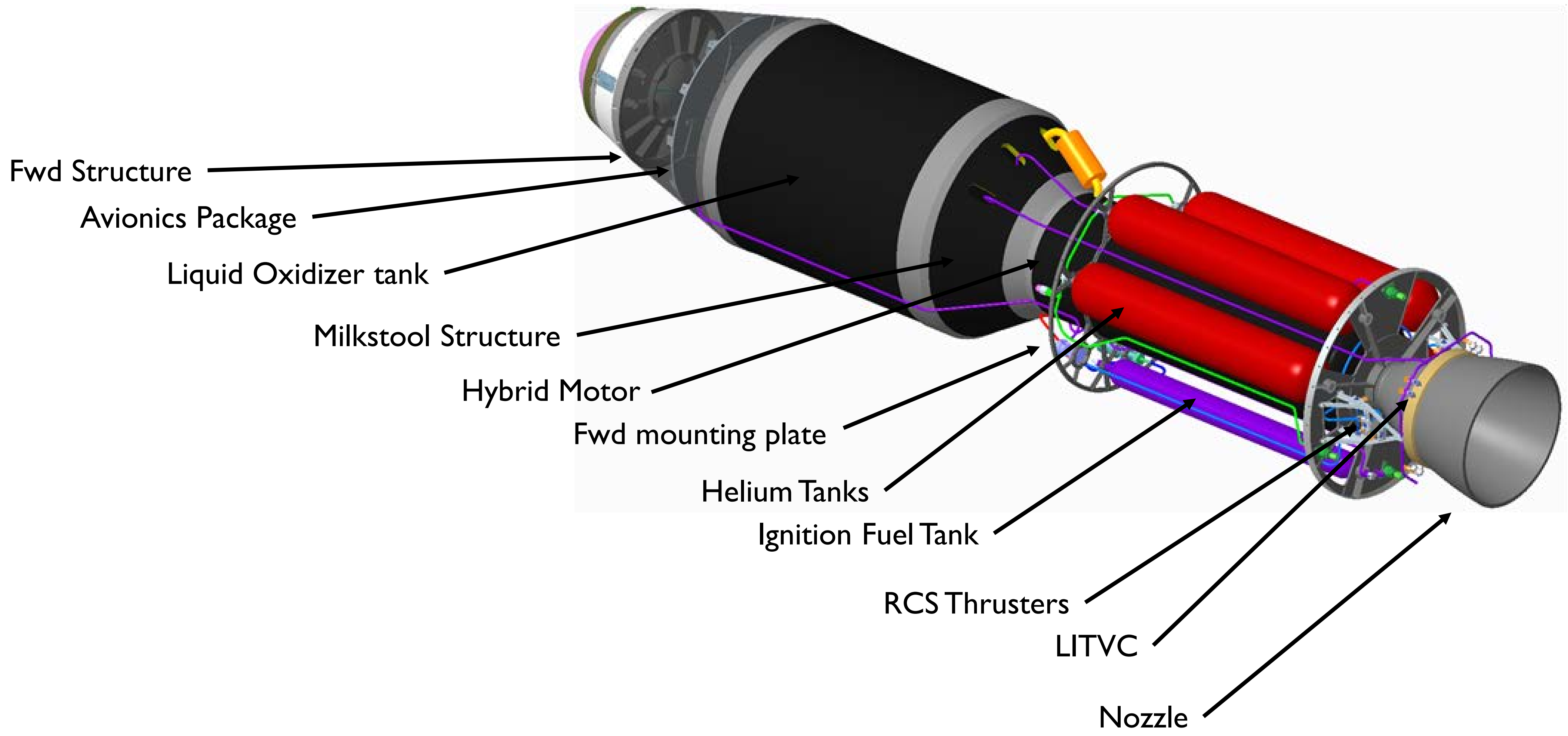
- Hybrid motor is based off of the 2016 Point of Departure Review
  - Updated for system level design changes and to incorporate results of recent analyses and testing.
- The fuel is a wax based, liquefying hybrid fuel, developed for this application. (SP7 and the reduced regression SP7A)
  - Burn rate is dependent on oxidizer mass flux (very weak dependency on pressure and temperature)
  - Shear force from oxidizer creates instability (roll waves and droplets) in the fuel liquid layer, essentially acting as fuel injection system and increases burn rate over conventional hybrid fuels.





2016 PODR

Overview and Schematic



Driving Requirements

Property	Value
GLOM target	400 kg
MPA	14 kg (20 samples)
Max Vehicle Length	2.80 m
Max Vehicle Diameter	0.57 m
Operational Temperature	-20C +/- 2C
Non-Operational temp	-40C to +40 C
Prop System qual temp (wetted)	Non-op +10/-10C
Quasi Static Load	Lateral 15g
Minimum Orbit Altitude	300 km
Eccentricity	0.006
Target Orbital Insertion Inclination angle	25 degrees
Max Angle of Attack	4 degrees
Launch Angle	30-60 degrees

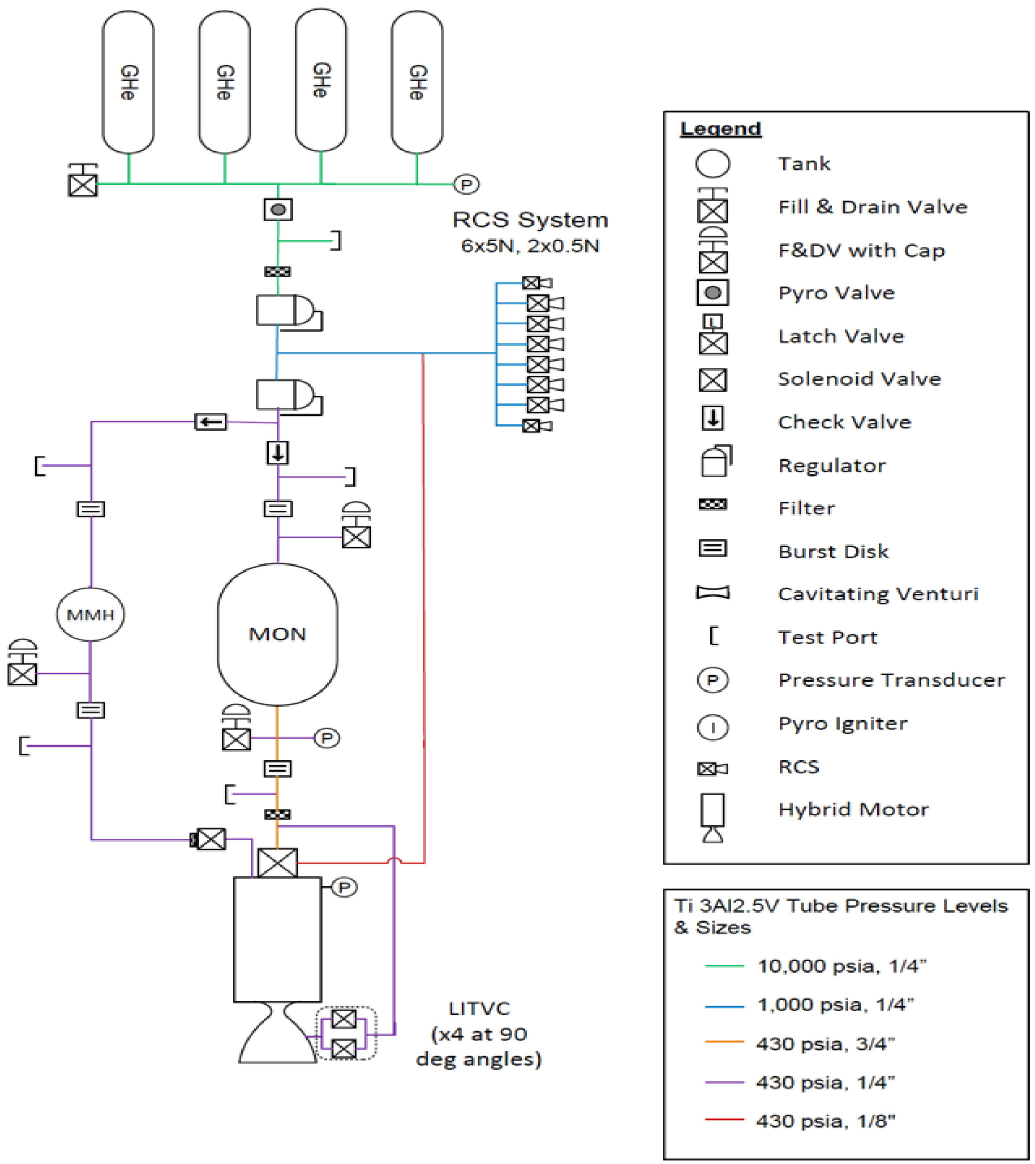
- Payload, length, diameter, GLOM, and semi-major axis (relates to eccentricity) are significant driving requirements and were defined by JPL
- MAV Allowable Flight temperatures drove the selection of the propellants.
  - Fuel can handle temperature extremes.
  - MON-25 has -55 C freezing point.

Length = 2.8 m

GLOM = ~401 kg

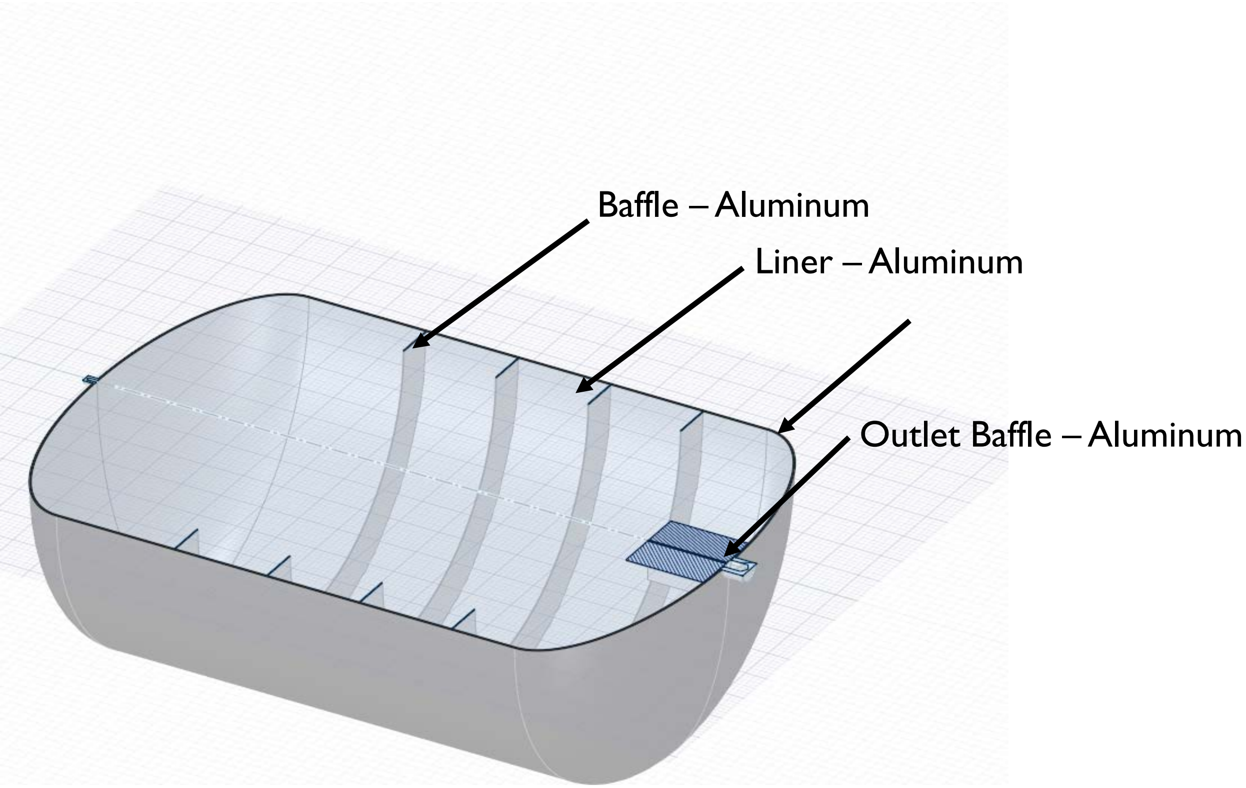
Schematic

- Components:
  - Main motor: 7 fluid handling components (not including filters and fill & drain)
  - RCS: 8 cold gas thrusters
  - LITVC: 8 valves, operate in pairs at 90° intervals
- Meets range safety requirements for catastrophic hazards.
  - Priming analysis suggests need to replace burst disc down stream of MON tank with pyrovalve.



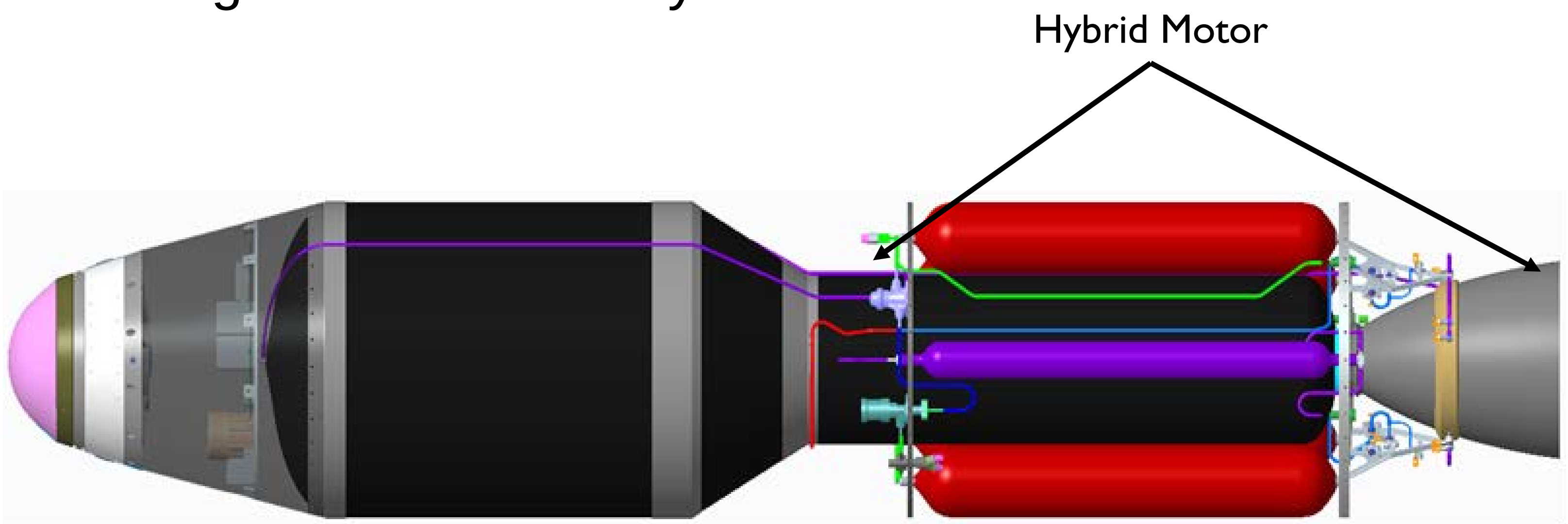
Oxidizer Tank

- COPV w/aluminum liner
- Baffles included in design (assuming slosh challenges vehicle control authority)
  - Slosh requirements not generated during PAA, opportunity to reduce conservative number, pending analysis
  - Integral baffle design could cause tank deformation on pressurization and composite gap.
    - Redesign with internal can design, to remedy



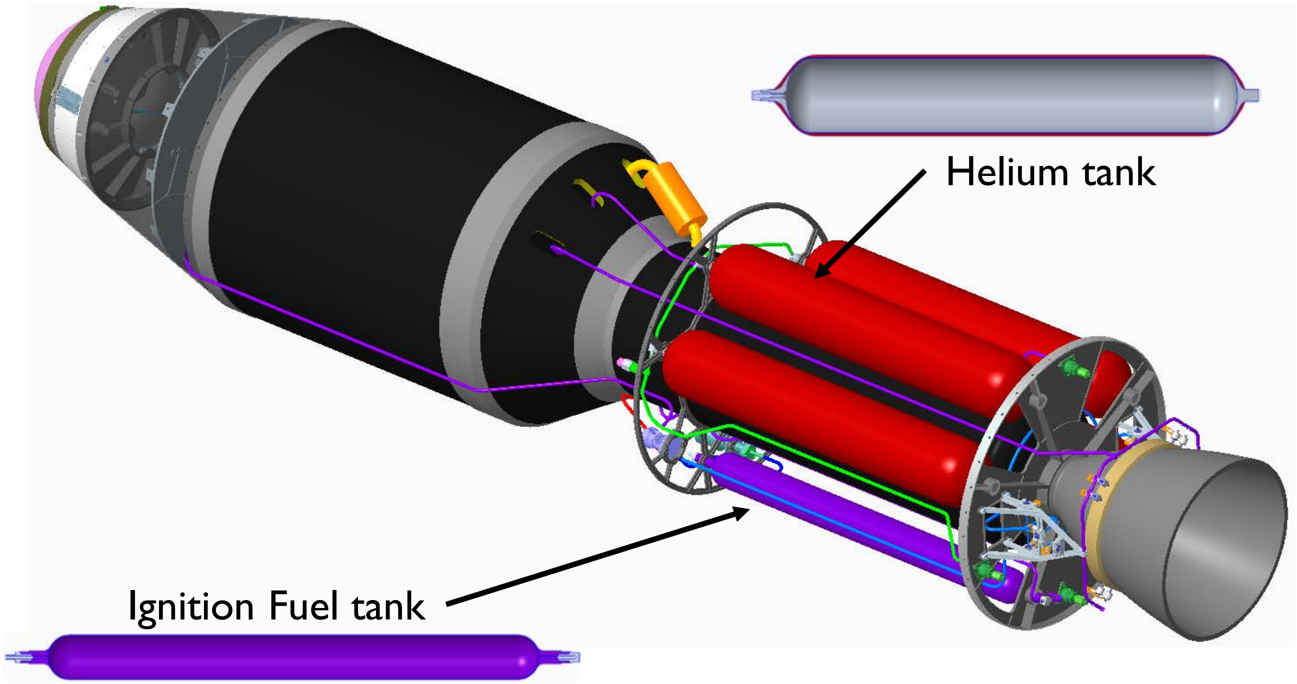
Hybrid Motor

- COPV with titanium liner
  - Load titanium parts, weld together
- SP7A has high CTE, needs to be assembled into case at low temperature to ensure fuel in compression at -20C operation temperature.
- MON-25 and MMH are both injected
  - Ignition and stability



Pressurant and Ignition fluid tanks

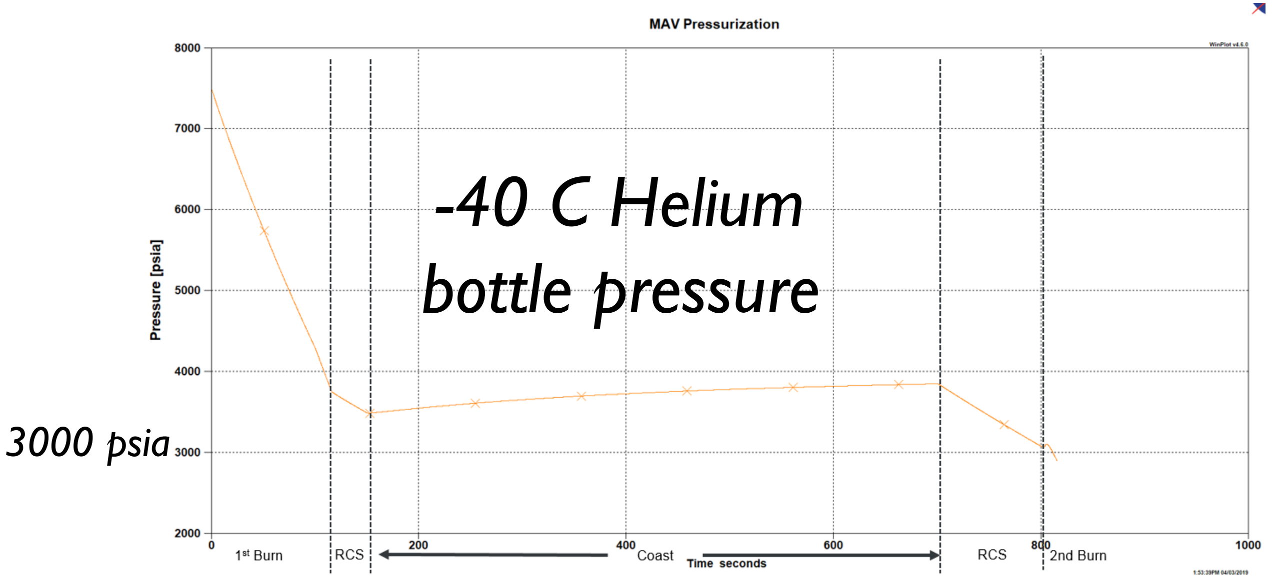
- Regulated blow down pressurization system fed by Helium tanks.
  - 4 Helium tanks, opportunity to reduce to 3 if they are preferentially heated
  - Helium used for RCS fluid

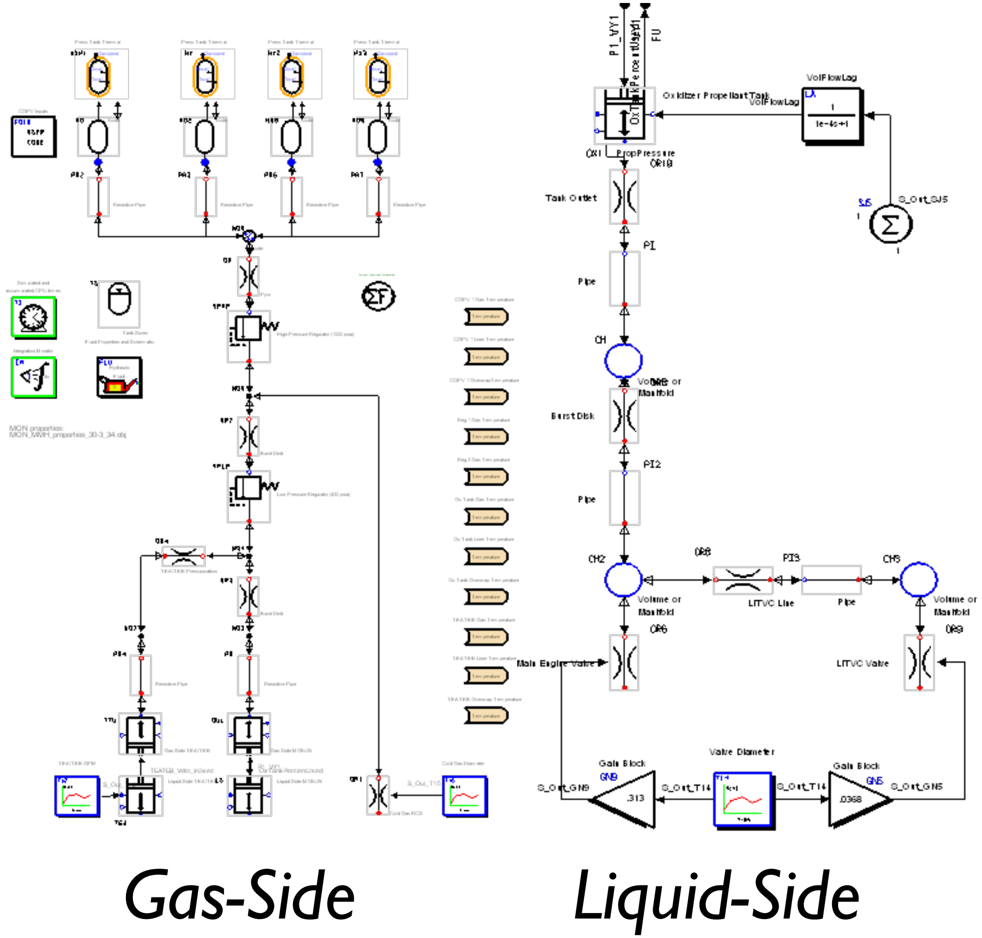


- Monomethyl Hydrazine injected for ignition and sustained stability
  - Heat injected in the head end helps with combustion stability.
  - MMH not yet tested in hybrids, however shown hypergolic with MON-25 at -40C in biprop thrusters. (current tests use TEA/TEB with GOx)

Design and Analysis Results – Feed System Analysis

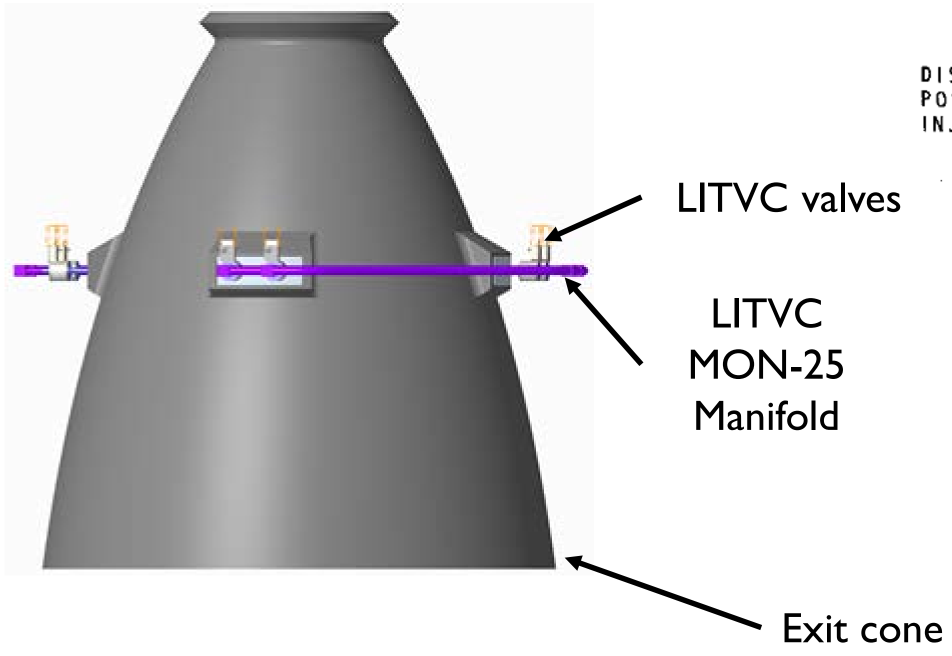
- Easy5 modeling of the feed system.
  - Filters and check valves not included.
- System capable at -40C, over sized, but cold @ regs.
  - Potential for mass reduction
- Additional analysis done with preheated Helium, lower initial pressure and different number of tanks.

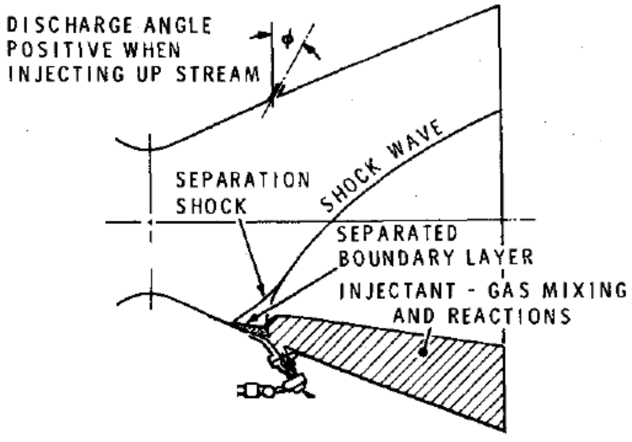




Liquid Injection Thrust Vector Control (LITVC)

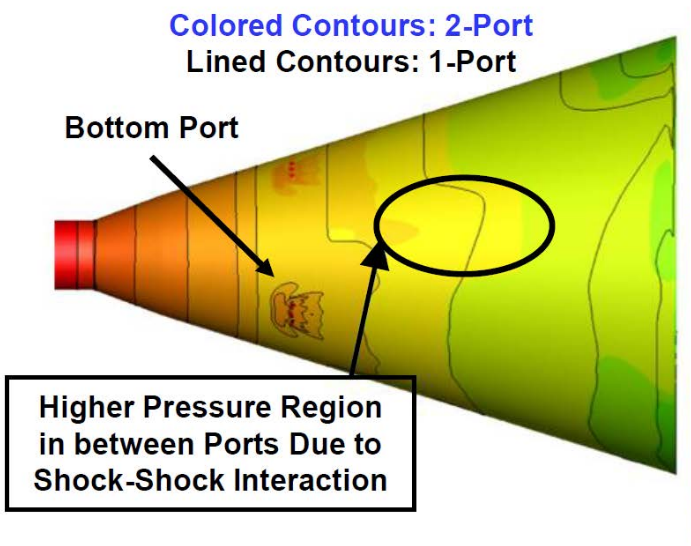
- LITVC deflects flow at the injection points and relies on RCS to roll LITVC in the correct direction
- Nozzle is a fixed design and has to survive two burns
- Heritage: LITVC previously flown on the strap-on Titan Solid Boosters
- Testing conducted on short (Earth expansion) nozzles at WASP and SPG
  - Measured side thrust during testing at WASP





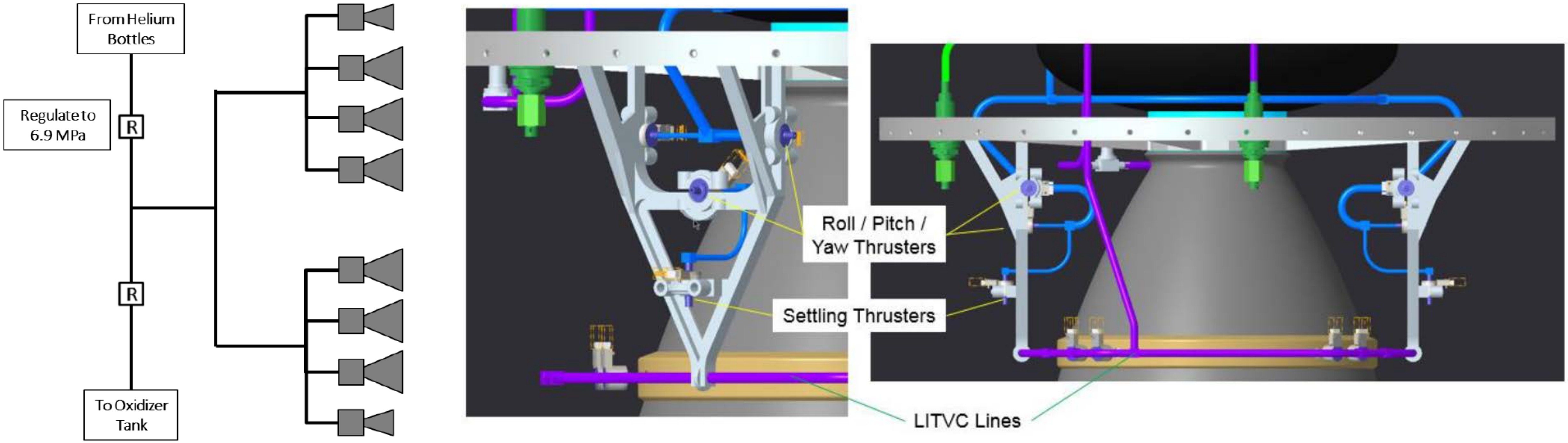
LITVC system and thrust deflection effects

Multi-Port Firing – Surface Pressure



RCS Configuration

- Regulated helium Cold gas
  - High TRL Components
  - Helium already used as oxidizer pressurant
  - Does not add much mass/complexity to use He for RCS as well

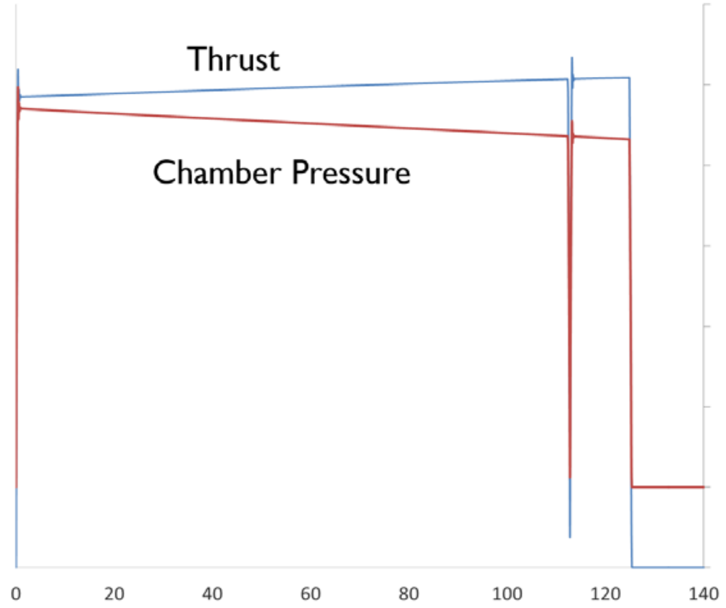


Two Dimensional Kinetics (TDK) Nozzle Analysis

- Hybrid motor performance had been calculated using NASA's One Dimensional Equilibrium: Chemical Equilibrium Analysis (CEA) software with an assumed nozzle efficiency
  - CEA finds the best case rocket performance
- TDK analysis calculates nozzle boundary layer flow, two-phase flow losses and the amount that the combustion gases can react while they're in the nozzle
- TDK analysis was run to give an optimal nozzle contour.
- It indicated that the (textbook) nozzle efficiency assumption was too high and that the best nozzle performance was actually at a lower mixture ratio
- Result: 4% decrease in Isp due to over estimating nozzle performance.
- Still assessing implications and options, but changes were made to the motor design
  - Increased fuel in motor case to decrease the O/F
  - Benefit: lower O/F, which should reduce nozzle erosion
  - Challenge: lower Isp. To make up the Isp difference, may require higher propellant mass, longer nozzle, higher chamber pressure or some combination thereof.

Design and Analysis Results – Ballistics Analysis

- Design conditions
  - SP7A MON-25 at -20C, regression rate from test data
  - Chamber Pressure =250 psi, Area Ratio=40
  - O/F shift over burn time included
  - 0.5 mil/s nozzle erosion
  - 95% c* efficiency
- Results:
  - Total Impulse=8.6584 kNs, Delta V=3878.97 m/sec
  - Chamber pressure drop due to nozzle erosion
  - Thrust increase due to injector delta P increase and MON-25 increase



Comparison	Pre-TDK	Post TDK
Code Run	CEA 1-D Equilibrium	2-D Kinetics
Specific Impulse (Isp)		~4% lower
Nozzle Efficiency		~4% lower
O/F	4.1	3.7 (~5 kg more fuel)
DV	3878. m/s	3882.8 m/s
Stabilizing fluid	TEA/TEB	MMH

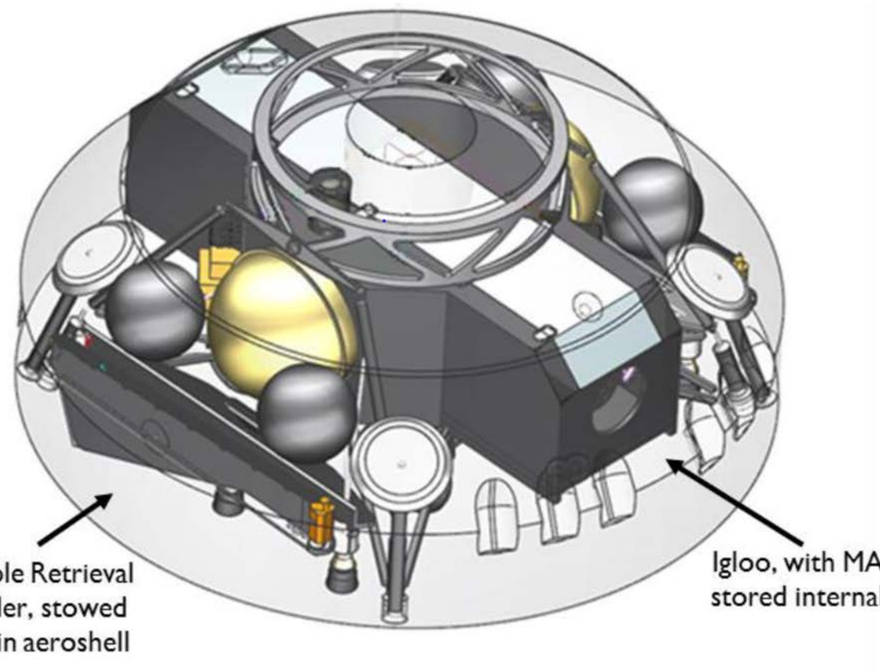
Future Development and Qualification

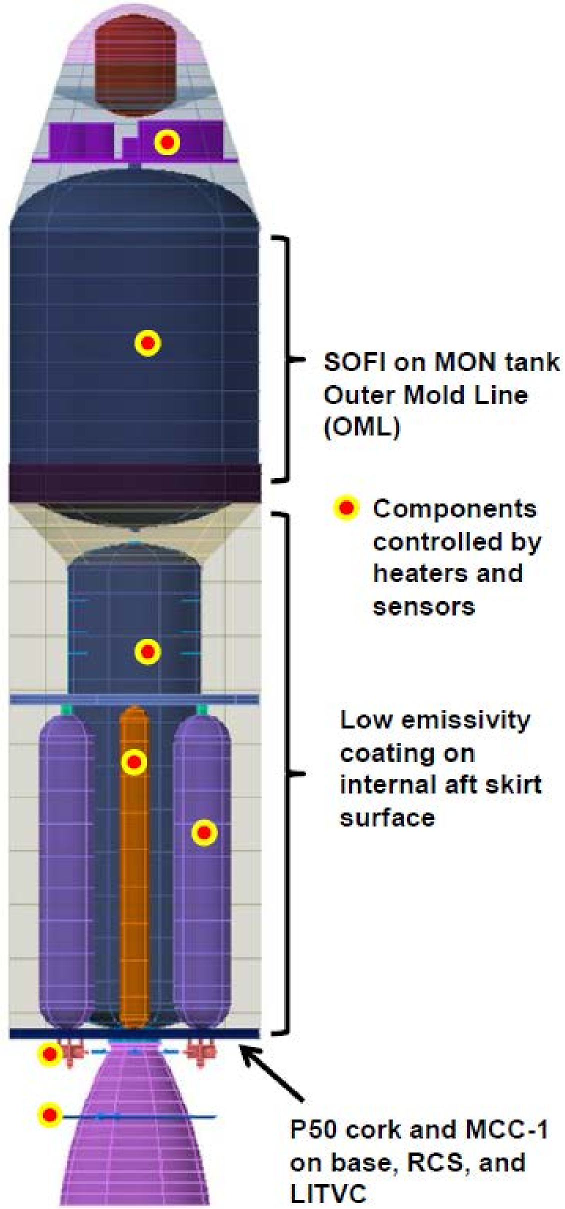
- Development requires 8 more motor tests (9 to include the descoped vacuum test this year.)
- Six motor qualification, plus one system test planned after development.

Hybrid Motors																			
Motor	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Development	1	2	3	4	5	6	7	8											
Motor Qualification									1	2	3	4	5	6					
System Qualification															1				
Flight Test																1			
Dynamic Test Model																	1		
Flight Deliverable																		1	2
Flight Liquid System	Development Motors will test outstanding risks/opportunities at a rate of ≈ 4 motors/year. - Design changes - Vacuum ignition - Ignition testing - Flight case - Removing cavitating venturi - Optimizing residual fuel - LITVC testing - Hypergolic ignition - Reducing throat erosion - Thermal cycling full motor - Planetary Protection														X	X		X	X
Planetary Protection									X	X	X	X	X	X	X	X		X	X
Thermal Cycling									X	X	X	X	X	X	X	X			
Shock and Vibe										X	X	X	X	X	X	X			
Altitude Start									X	X	X	X	X	X	X	X			
Operating Temperature									NOM	NOM	HIGH	LOW	LOW	HIGH	NOM	NOM			
1st Ignition Flow Rate									NOM	NOM	LOW	HIGH	LOW	HIGH	NOM	NOM			
Oxidizer Flow Rate									NOM	NOM	HIGH	LOW	HIGH	LOW	NOM	NOM			
Fuel Utilization									NOM	NOM	LOW	HIGH	HIGH	LOW	NOM	NOM			
Coast Time									NOM	NOM	HIGH	LOW	HIGH	LOW	NOM	NOM			
2nd Burn Altitude Start									X	X	X	X	X	X	X	X			
2nd Ignition Flow Rate									NOM	NOM	HIGH	LOW	LOW	HIGH	NOM	NOM			
2nd Burn Oxidizer Flow Rate									NOM	NOM	LOW	HIGH	LOW	HIGH	NOM	NOM			
LITVC Function									X	X	X	X	X	X	X	X			

Thermal System

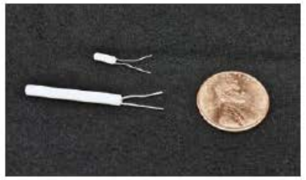
- High Technology Readiness Level (TRL) Thermal control system components are used to maintain Mars Assent Vehicle (MAV) operating and non-operating temperatures for all stages of flight.





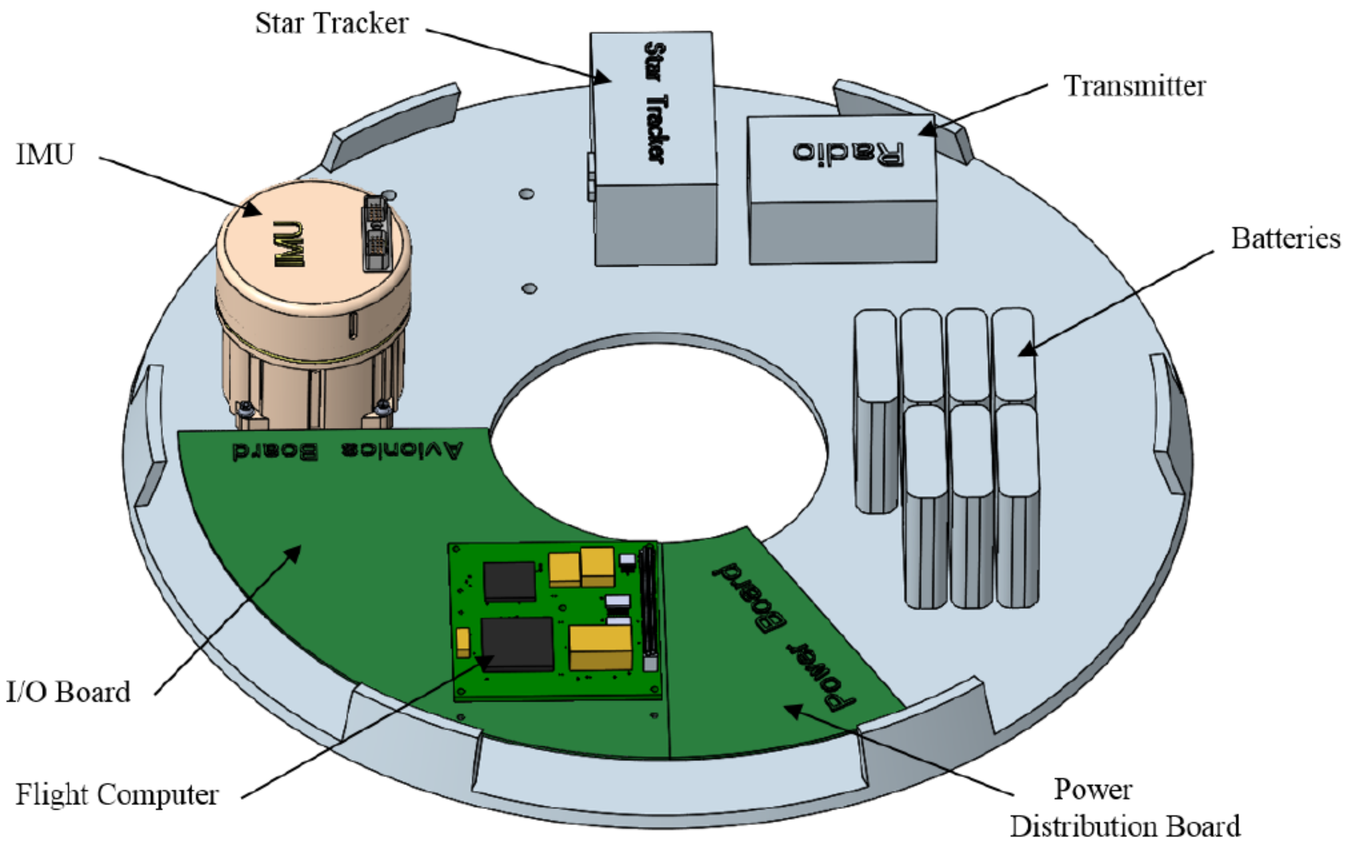

Line Heaters


Single Element Polyimide patch/strip Heaters


PRT Sensors

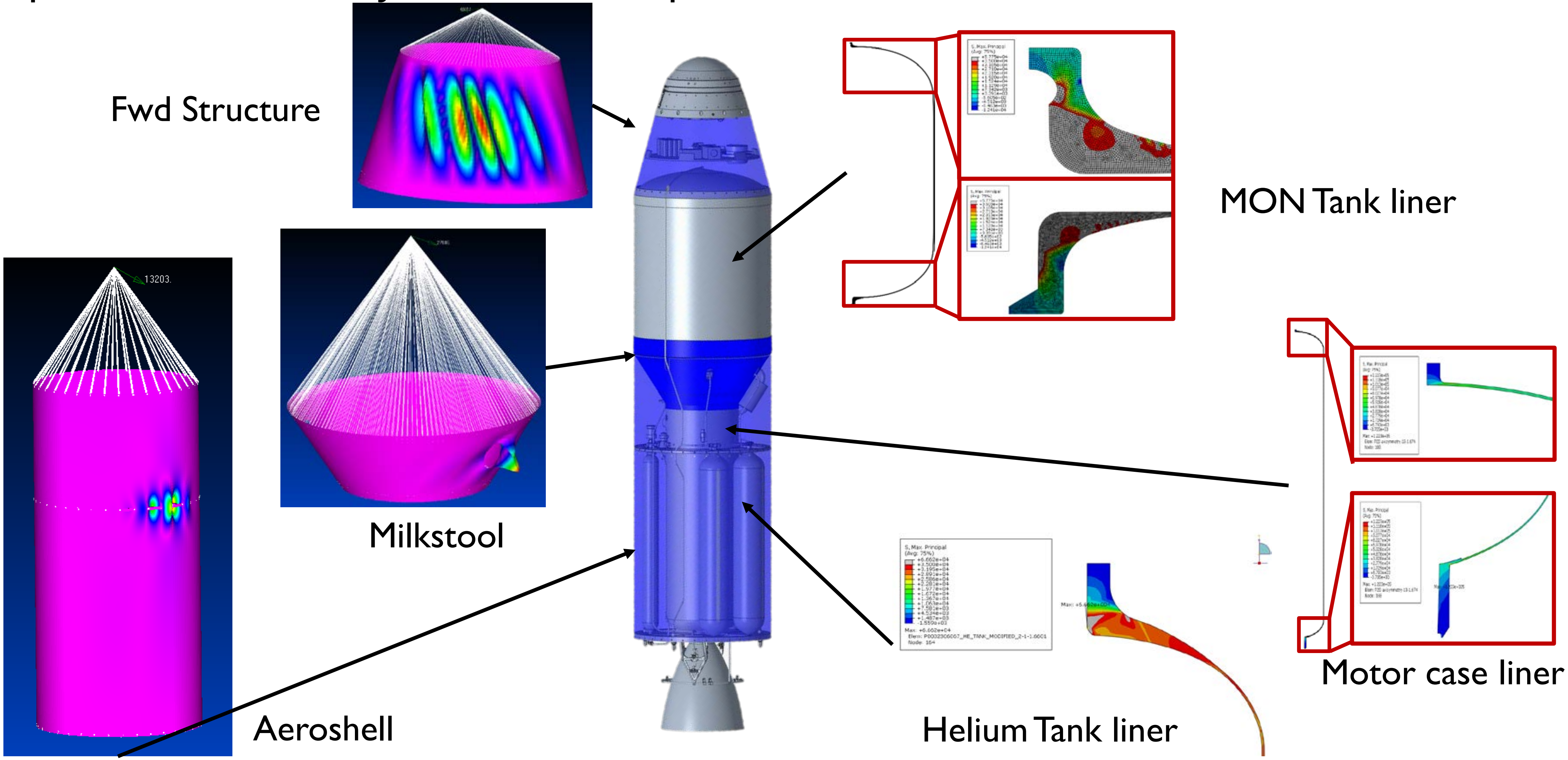
Avionics

- Main functions
  - Maintain communications
  - Positioning
  - Power during flight
- Characteristics
  - High TRL components when possible
  - Custom plate design
  - Umbilical connector located near avionics bay
- Technology Development
  - Antenna design



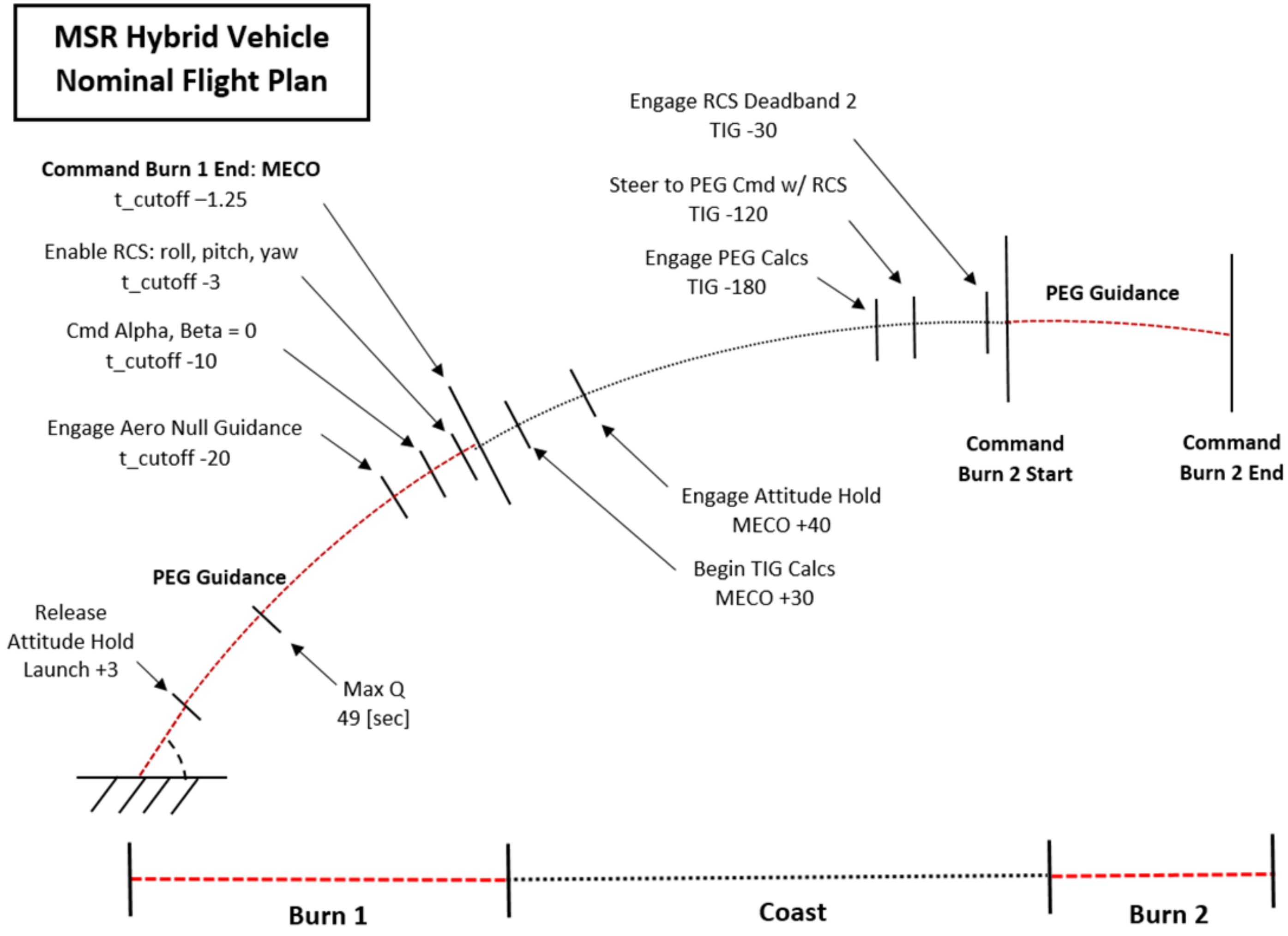
Structures Assessment

- Multiple structural Analyses were completed



GN&C Analysis

- Takeaways
  - Nominal 6DOF trajectory closes with vehicle data and models provided for analysis
  - Orbit tolerances met in all cases
  - Control authority/stability issues with Hybrid MAV vehicle in some dispersed runs at end of MECO
  - Orbit performance is impacted by lofting and aero angle nulling before MECO
  - Analysis updated the size of the RCS thrusters.
  - Analysis indicated only 4 LITVC valves required.



Hybrid MAV PAA Summary

- Design predicted to close from a propulsion point of view (GLOM~400 kg, dV=~3900 m/s, fits in the lander)
- More development work to be done
  - No obvious show stoppers
  - Testing to demonstrate that the total impulse can be delivered
  - Some analyses need to be finalized to reduce mass
- Engine shutoff is an important capability
  - Additional capability in the RCS system for fine tuning of orbit
- Motor design is flexible and can be modified as vehicle matures
- Preliminary thermal, structural, and CFD analysis results have been incorporated

PAA PEER Review Results

- In July 2019, a PAA Peer Review of the Hybrid and Solid concepts was conducted.
  - Both Hybrid and Solid MAVs can meet weight and length requirements.
  - Solids have a generally higher Technology Readiness Level.
  - Solids have a slight mass advantage.
  - Hybrid MAV had a better orbital accuracy with some of the Solid MAV cases not meeting the orbital accuracy requirements
- Peer Review Recommendation was to investigate further the Solid and Hybrid MAV trajectory assumptions to see if Solid MAV can meet the orbital requirements with all of the dispersions.
  - Peer Review Board recommended that if the Solid MAV can be shown to meet the orbital requirements better, to drop the Hybrid MAV and down select to the Solid MAV.

Future Work

- Upcoming full duration burn of Motor C at Whittinghill Aerospace
  - Objectives include: full duration burn (for fuel residuals) with a restart, vacuum first ignition and rapid ignition.
- Solid hypergolic testing at Purdue University will continue in a vacuum chamber
- Continued CFD modeling, subscale burnrate testing and fuel characterization at Space Propulsion Group

- Down select between Solid and Hybrid MAV concepts expected in December of 2019

Questions?