MAV

Mars Ascent Vehicle

Hybrid Rocket Propulsion for a Low Temperature Mars Ascent Vehicle

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MSFC

Marshall Space Flight Center

JPL

Jet Propulsion Laboratory
California Institute of Technology

AFESB

Vehicle Systems • Aerosciences • Flight Dynamics

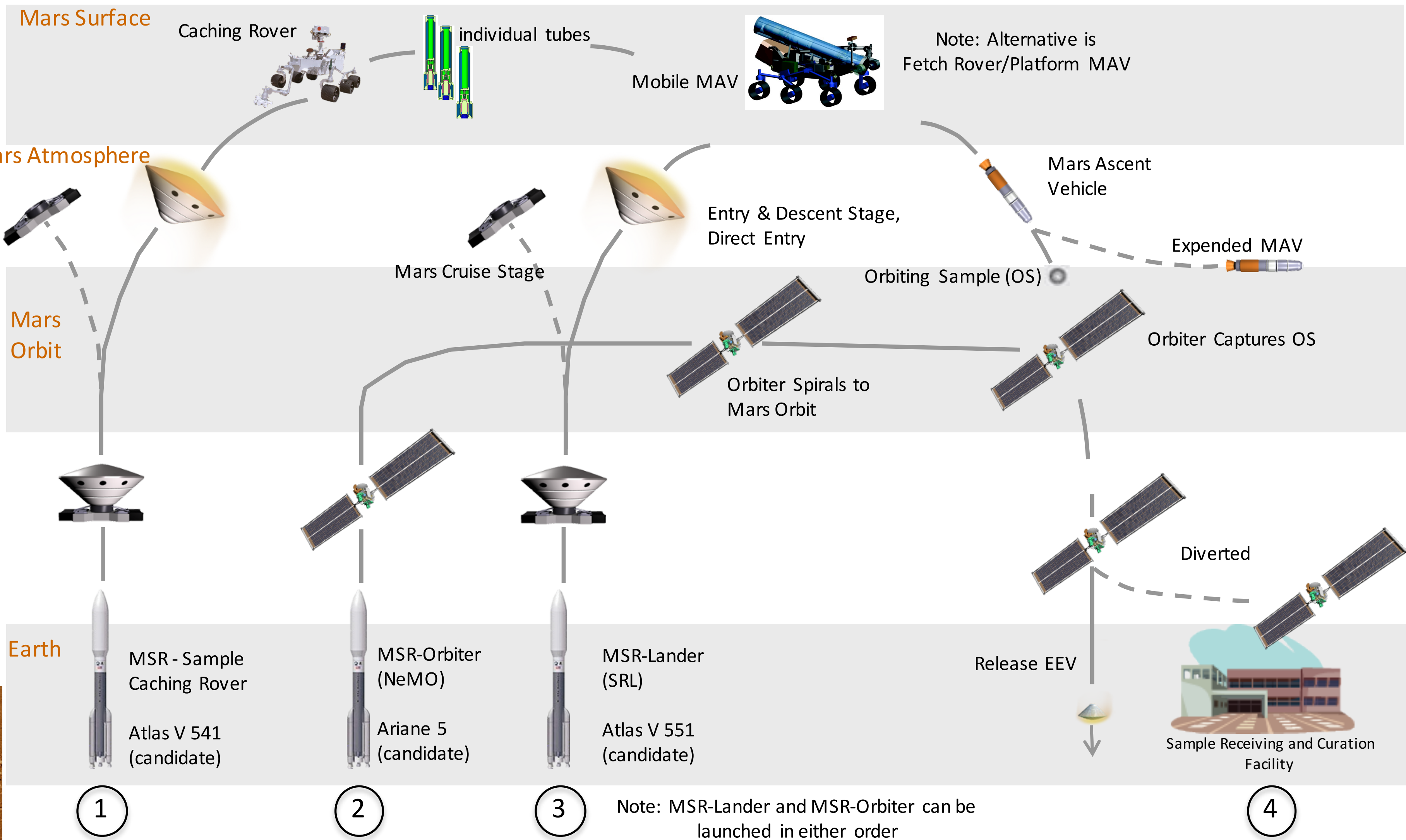
LaRC

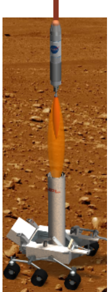
Agenda

- Introduction
- Design
- Technology Development
- Challenges
- Future Work
- Summary

MSR Reference Architecture

Mars Ascent Vehicle

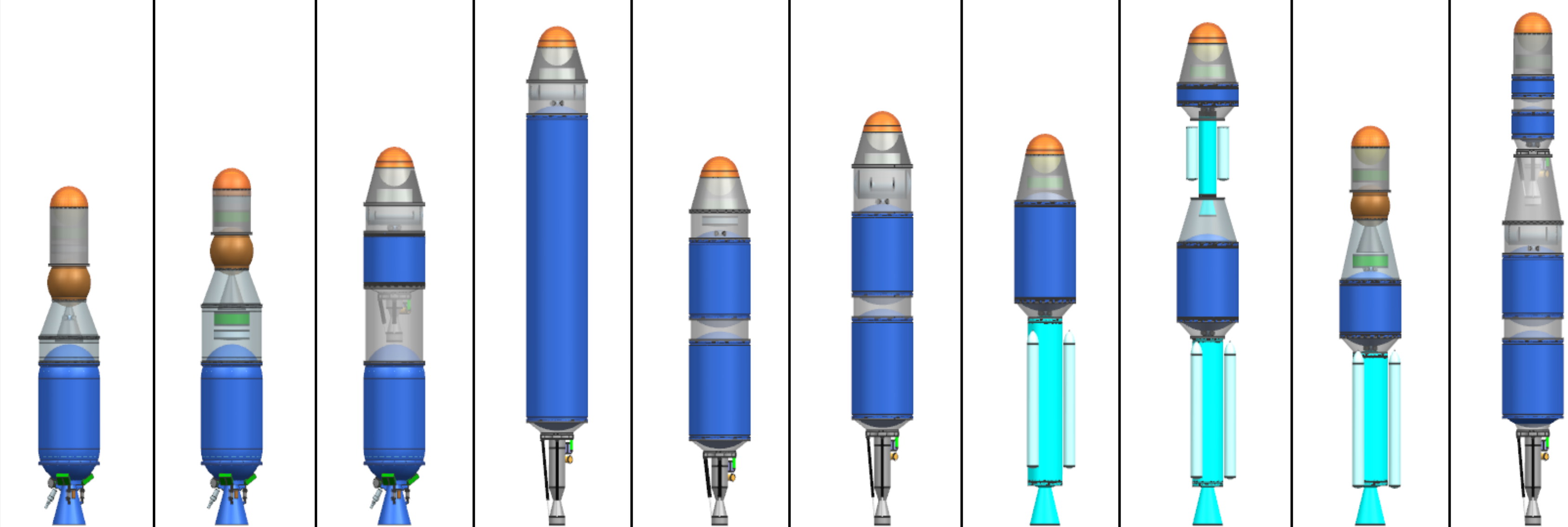




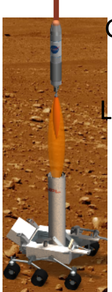
FY 14 Comparison of Systems

Mars Ascent Vehicle

6.65kg Payload, 20cm Reference OS



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
	Solid-Solid G-G	Solid-Solid G-U	Solid-Liquid G-G	SSTO Monoprop	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid	Hyb-Hyb G-G	Hyb-Solid G-G	BiProp-BiProp G-G
Score	0.60	0.54	0.32	0.52	0.79	0.76	0.76	0.621	0.52	0.57
GLOM	176	158	237	276	182	187	166	173	157	190
Length	1.88 m	1.98 m	2.09 m	2.76 m	2.04m	2.29 m	2.16 m	2.78 m	2.21 m	2.84 m
AFT	-40 C	-40 C	+17 C	+8 C	-37 C	-37 C	-72 C	-72 C	-40 C	-37 C

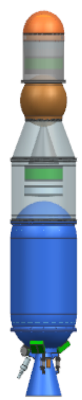


Pre-Decisional: For planning and discussion purposes only.

FY 14 Comparison of Systems

Mars Ascent Vehicle

6.65kg Payload, 20cm Reference OS

	Case 1	Case 2	Case 5	Case 6	Case 7
	Solid-Solid G-G	Solid-Solid G-U	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid
					
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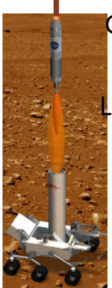
AFT	-40 C	-40 C	-37 C	-37 C	-72 C

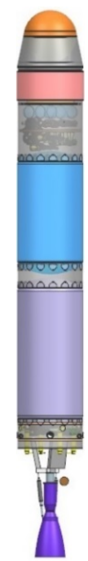


Pre-Decisional: For planning and discussion purposes only.

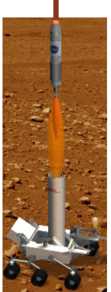
Mars Ascent Vehicle FY 2015 Study

Mars Ascent Vehicle

14 kg Payload, 30 cm Reference OS

	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)



Pre-Decisional: For planning and discussion purposes only.

Mars Ascent Vehicle FY 2015 Study

Mars Ascent Vehicle

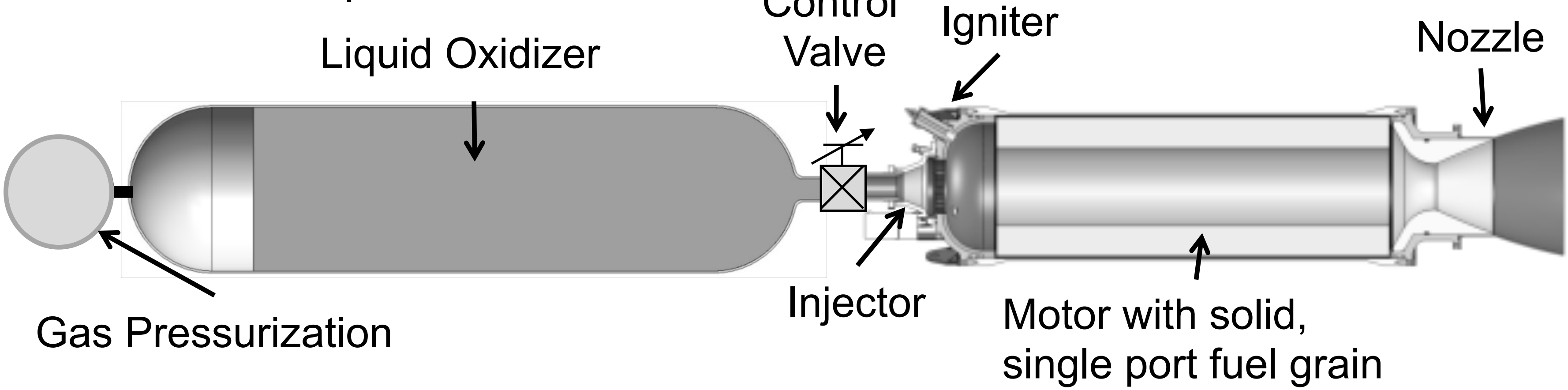
14 kg Payload, 30 cm Reference OS

	Case 7
	SSTO Hybrid 
Payload/OS	
GLOM	219.1
Length	2.89 m
AFT	-90/-72 C

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

What is a hybrid rocket?

- Hybrid rockets typically utilize solid fuel and liquid oxidizer.
  - MAV is interested in this option because of its high performance, minimum need for thermal control and capability for multiple starts.

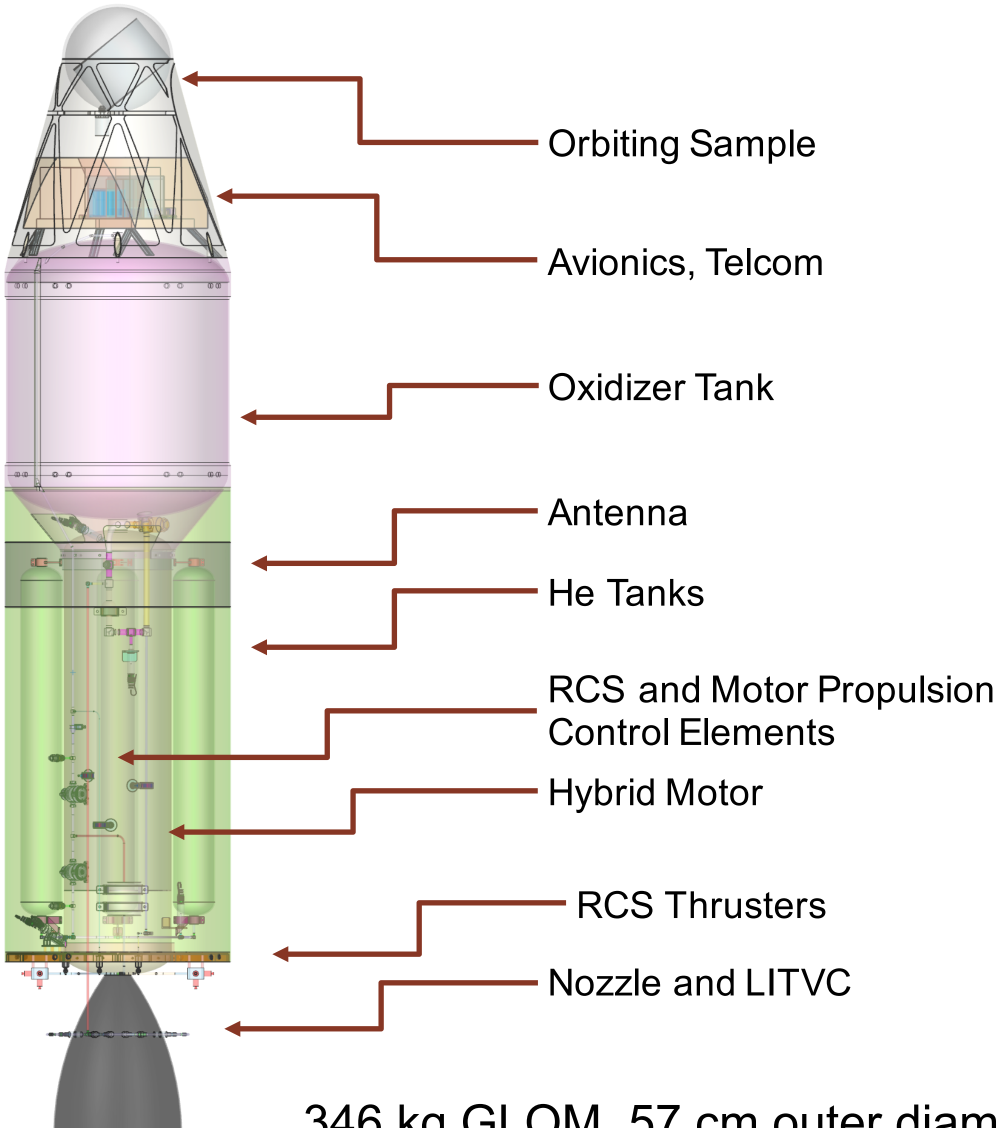


Fuel regression rate → $$\dot{r} = aG_{ox}^{n}$$ ← Empirically derived constants based on propellant combination

↑ Oxidizer Mass Flux (mass flow rate of oxidizer divided by the port cross sectional area)

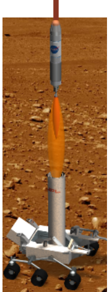
Baseline Concept Overview

Mars Ascent Vehicle



- The current design uses a hybrid propulsion system with ***MON30 (70% N_2O_4+ 30% NO)*** oxidizer and ***SP7, wax-based***, fuel.
- The propellant combination allows for storage temps as low as ***-72 C***, reducing power requirements for an SRL host lander on the surface of Mars.

346 kg GLOM, 57 cm outer diameter, 2.9 m long



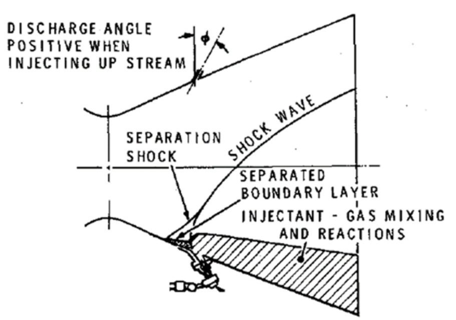
Areas of Technology Development

Mars Ascent Vehicle

New Hybrid Propellant Combination

Hypergolic Ignition

Thrust Vector Control



LITVC system and thrust deflection effects

While the hybrid option showed the most promise, it is also the lowest TRL.

Pre-Decisional: For planning and discussion purposes only.

New Propellant Combination

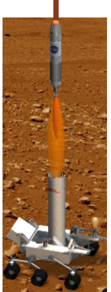
- Hybrid MAV Propellant Desires:
  - Low temperature capability for fuel and oxidizer to minimize thermal control in route to and on the surface of Mars
  - Operation at low temperature (-20 C)
  - High performance
- Selected propellant combination: SP7/MON
  - SP7 is a wax-based fuel with very good low temperature capabilities, developed by Space Propulsion Group.
  - Mixed Oxides of Nitrogen (N_2O_4 with NO)
    - MON3 is a good, room temperature surrogate for MON30 proposed for flight.

SP7 Wax-based Fuel

+

Mixed Oxides of Nitrogen

MON3 = $0.97\ N_2O_4 + 0.03\ NO$

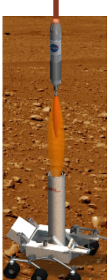


Hotfire Testing: SPG

- Developed a new wax-based fuel (SP7) specifically for the cold, highly variable Mars environment.
- Completed hotfire testing with N_2O in 2015
- Hotfire testing confirmed predicted regression rate with MON3 in 2016
  - Testing to date covers a little more than half of the actual oxidizer mass flux range
  - Full scale (11”) testing to begin in spring 2017

$$\dot{r} = aG_{ox}^{n}$$

SPG
Advancing Propulsion & Energy



Hotfire Testing: Parabilis

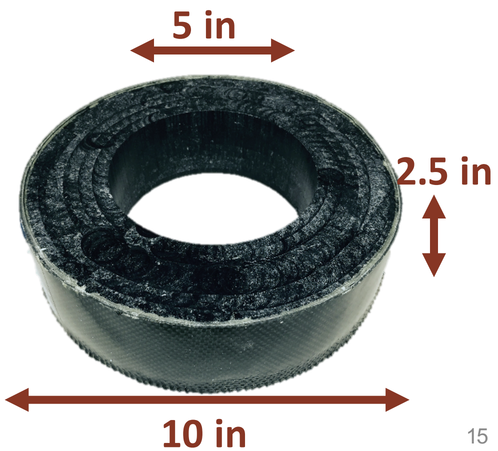
- Full scale (~10") motor testing attempted at Parabilis.
  - Several short burns were achieved; however injector issues persisted and time ran out before a stable burn was achieved.

Hotfire Testing: Whittinghill

- Whittinghill Aerospace was brought on in 2017 to hotfire test full scale motors.
  - Substantial experience with hybrid motors and LITVC
  - Experience with MON bipropellant engines.

Thermal Cycling of Fuel Core Samples

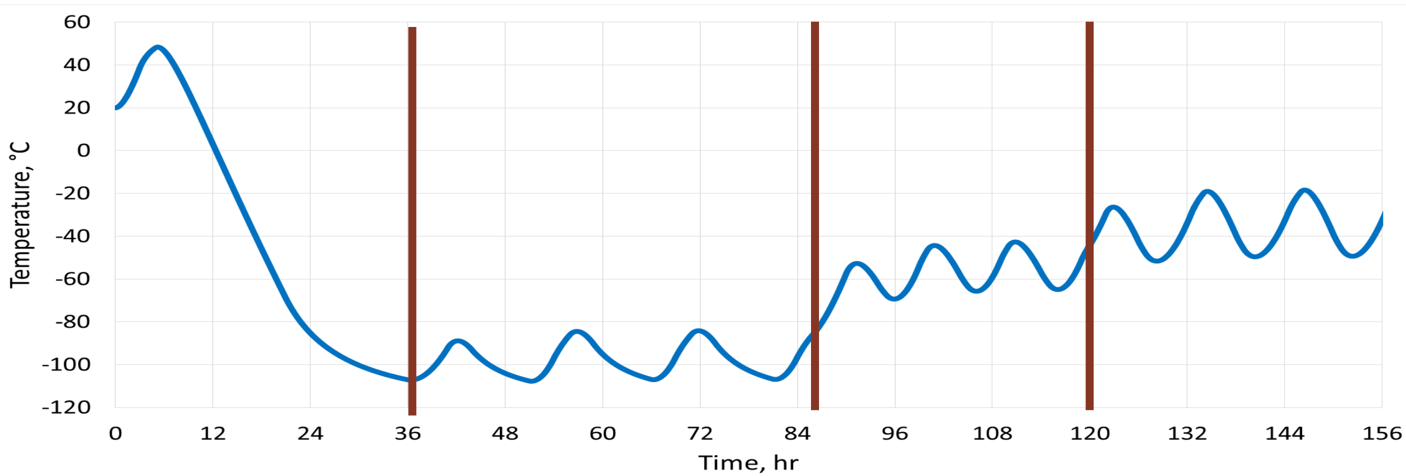
- Preliminary thermal testing completed at JPL to establish thermal rate limit using 2 samples.
- Completed 201 cycles at MSFC: 1 EDL cycle, 50 winter cycles, 100 spring cycles, and 50 summer cycles
  - 100 day test plan
  - 8 samples: four neat SP7, four aluminized SP7
- Gradient limits in ERD came out of thermal test failures
- Issues:
  - 2.5 inch thick samples, have not completed full length tests
  - b/a of tested samples was 2 instead of 3.
  - Some debonding was observed between the case and the fuel, but no radial cracking under Mars- like conditions.



Thermal Cycling of Fuel Core Samples

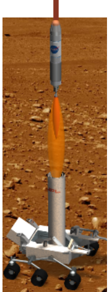
MSFC Results: Some debonding (case/core), no radial cracking

EDL Winter Spring Summer



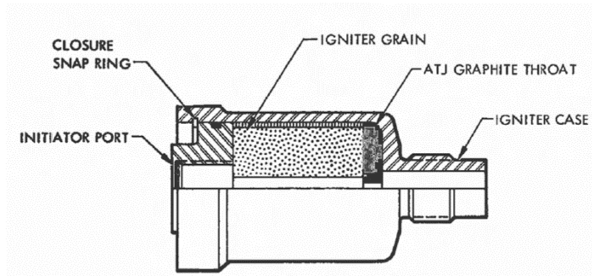
Average Test Results [Test Objectives]	EDL	Winter	Spring	Summer
Max Temperature, °C	40.3 [50]	-82.7 [-90]	-41.9 [-44]	-24.0 [-22]
Min Temperature, °C	-99.3 [-105]	-102.8 [-105]	-56.7 [-64]	-41.8 [-45]
Max Gradient, °C	12.5 [7.0-17.5*]	7.4 [0.9-17.5*]	6.2 [1.8-17.5*]	7.0 [2.3-17.5*]
Max Ramp Rate, °C/hr	7.6 [7.3-10.8]	7.5 [0.8-10.8]	5.9 [1.6-10.8]	6.0 [2.0-10.8]

* Max gradient and ramp rate objectives include the range from the predicted gradient to the highest successfully tested gradient or ramp rate.

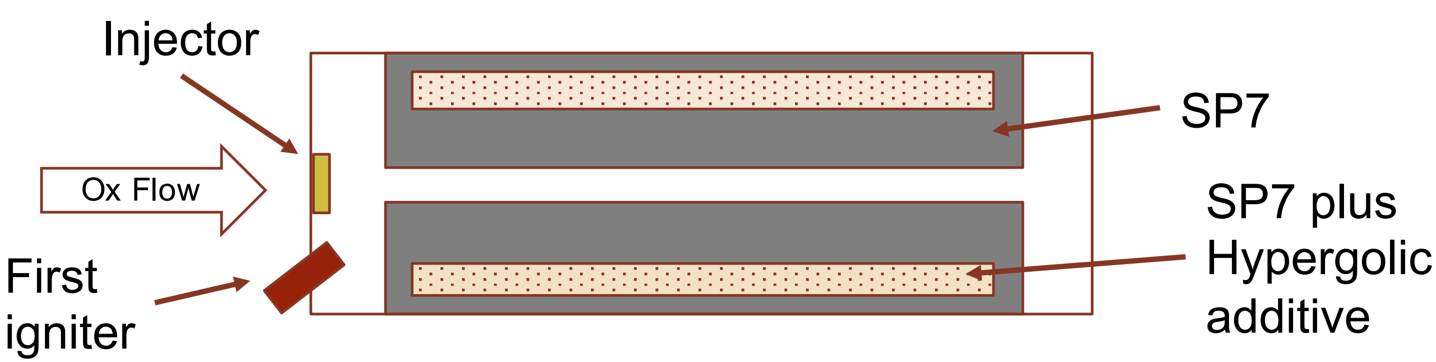


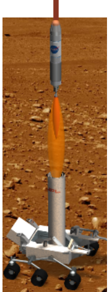
Ignitors

- First burn ignition utilizes a standard pyro ignitor with redundant NSI's and fired by the lander PIU.



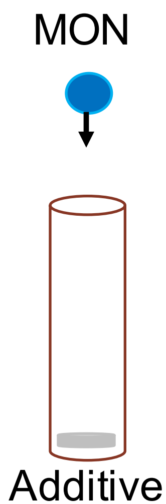
- Second burn: hypergolic additive in the SP7
  - *Hypergolic, Def: (of a rocket propellant) igniting spontaneously on mixing with another substance.*
  - A SP7 protective layer over the additive layer is envisioned for ground handling/stability





MON Drop Testing and Pellet Testing

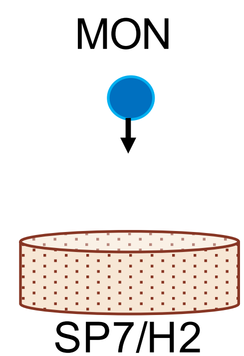
- Penn State and Purdue identified two top candidates with NTO/MON3
  - Purdue is continuing testing with MON-25

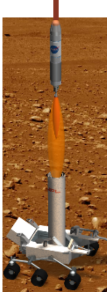


H1

H2

- Purdue then mixed H2 with SP7.
  - Hypergolic behavior exhibited with high loading and exposed reactants on surface (representative of second burn).

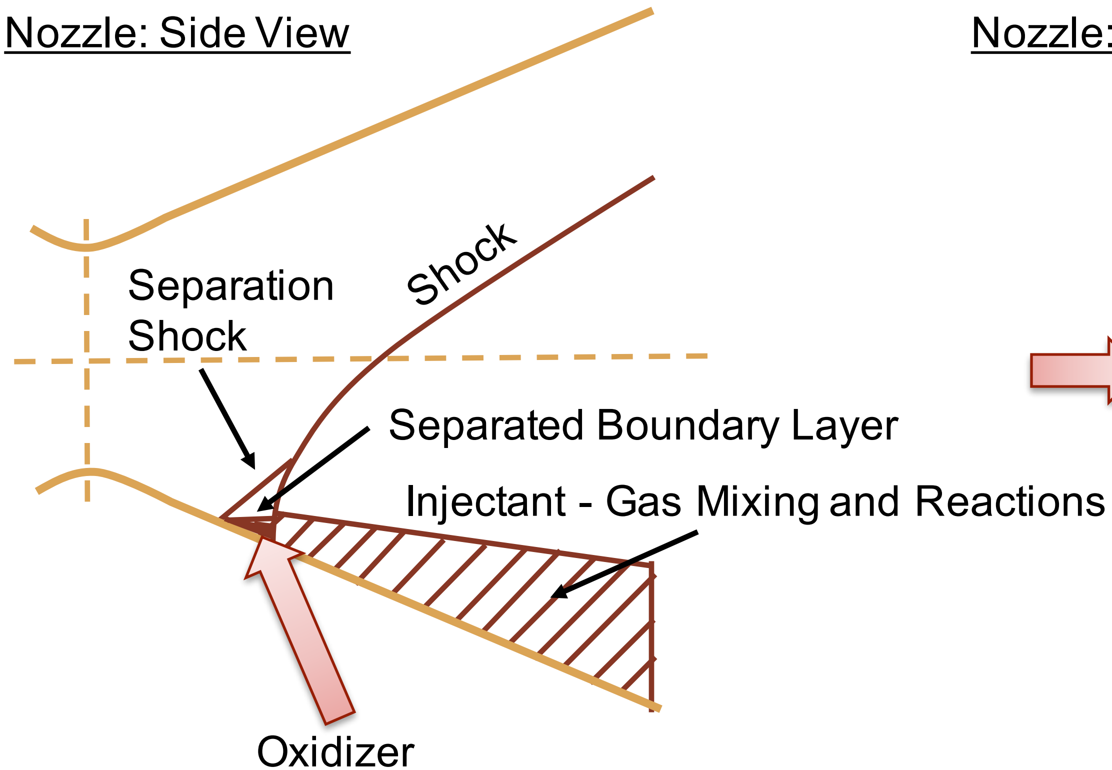




LITVC

- LITVC Performance is influenced by location of injection point and discharge angle.

Nozzle: Side View



Nozzle: Aft View

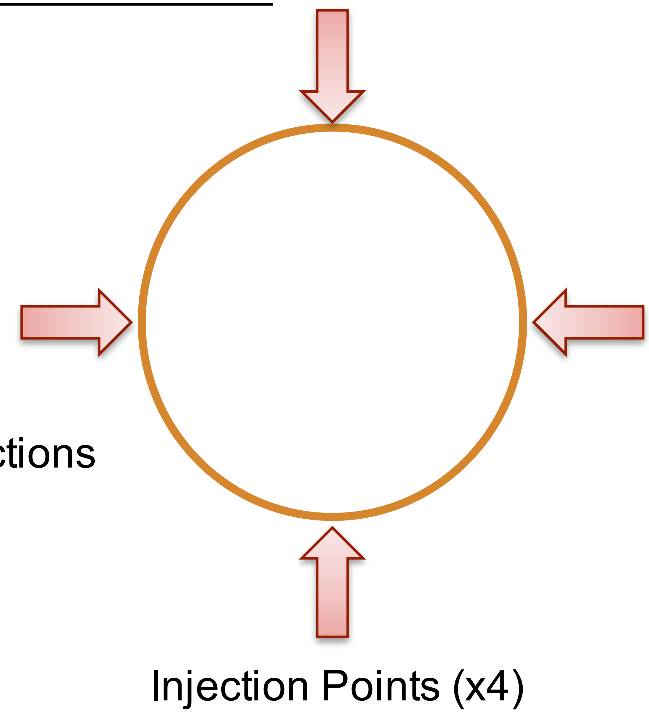


Image adapted from Zeamer, JSC Vol 14 No 6 June 1977 Liquid Injection Thrust Vector Control

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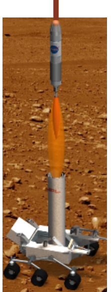
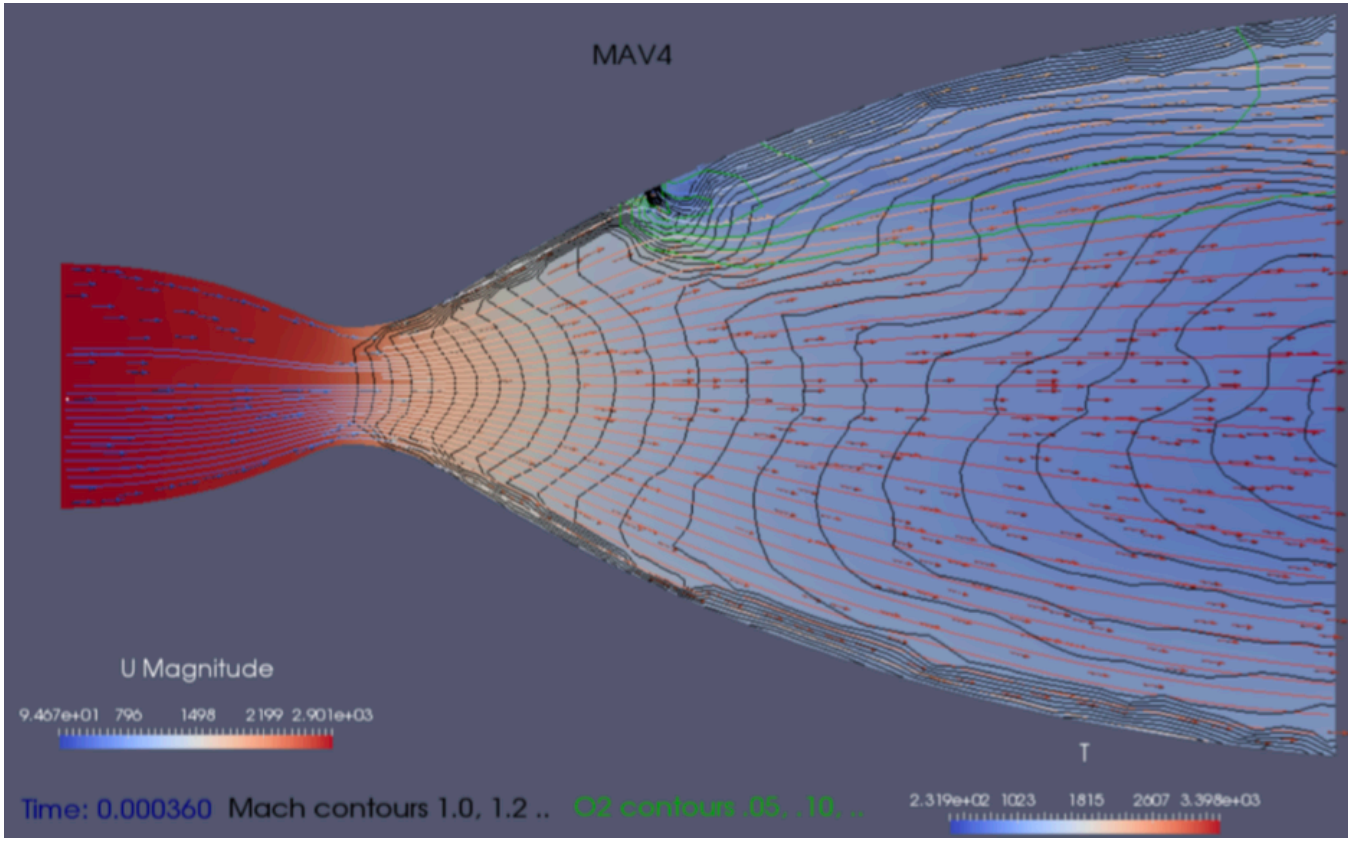


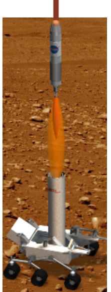
LITVC - Whittinghill

- The MON30 relationship was determined based on LITVC tests in different sizes and with different oxidizers. One set of tests with NTO was used to anchor the data.



Key Challenges

- There are many challenges to developing a new propulsion system for a potential flagship mission.
  - Comparatively low TRL of propulsion system
  - Multiple ignitions
  - Operation in the Mars environment
  - Optimal packaging / configuration
  - Ignition/Restart
  - Nozzle survivability, TVC and erosion

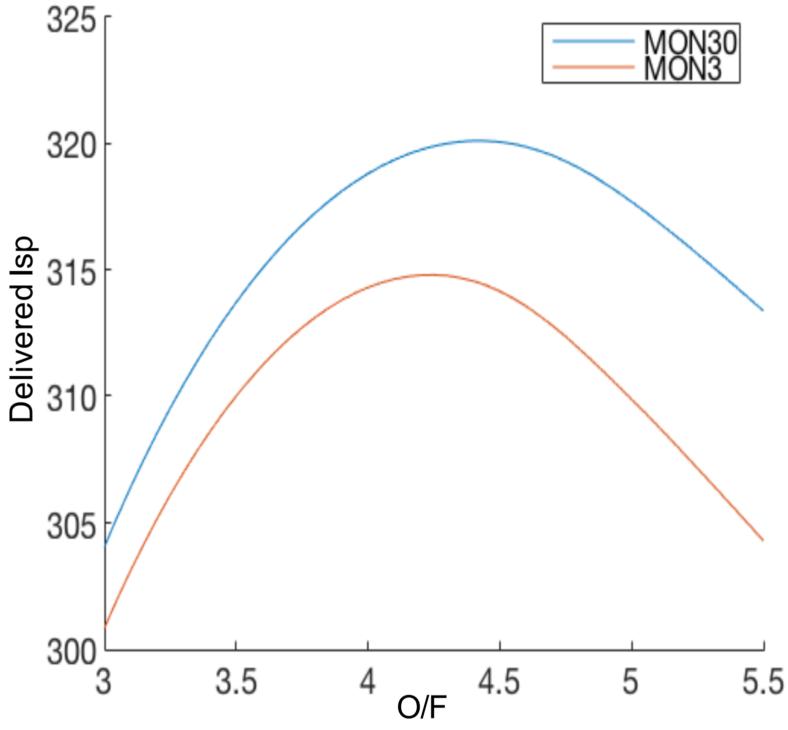


Research is being completed in all of these areas to mitigate the challenges.

Key Challenges

- Current hotfire testing with MON3 instead of MON30

	Changes when moving from MON30 to MON 3
GLOM	0.58%
Thrust	0.44%
Isp	-0.35%
Useable Prop	0.73%
Average O/F	-5.56%
Fuel Core OD	-0.70%
Fuel Core L/D	4.83%
Motor Length	2.66%
Motor Mass	1.35%
Loaded Ox	-0.09%
Loaded Fuel	4.63%
Ox Tank Length	-1.52%
Loaded He	-1.26%

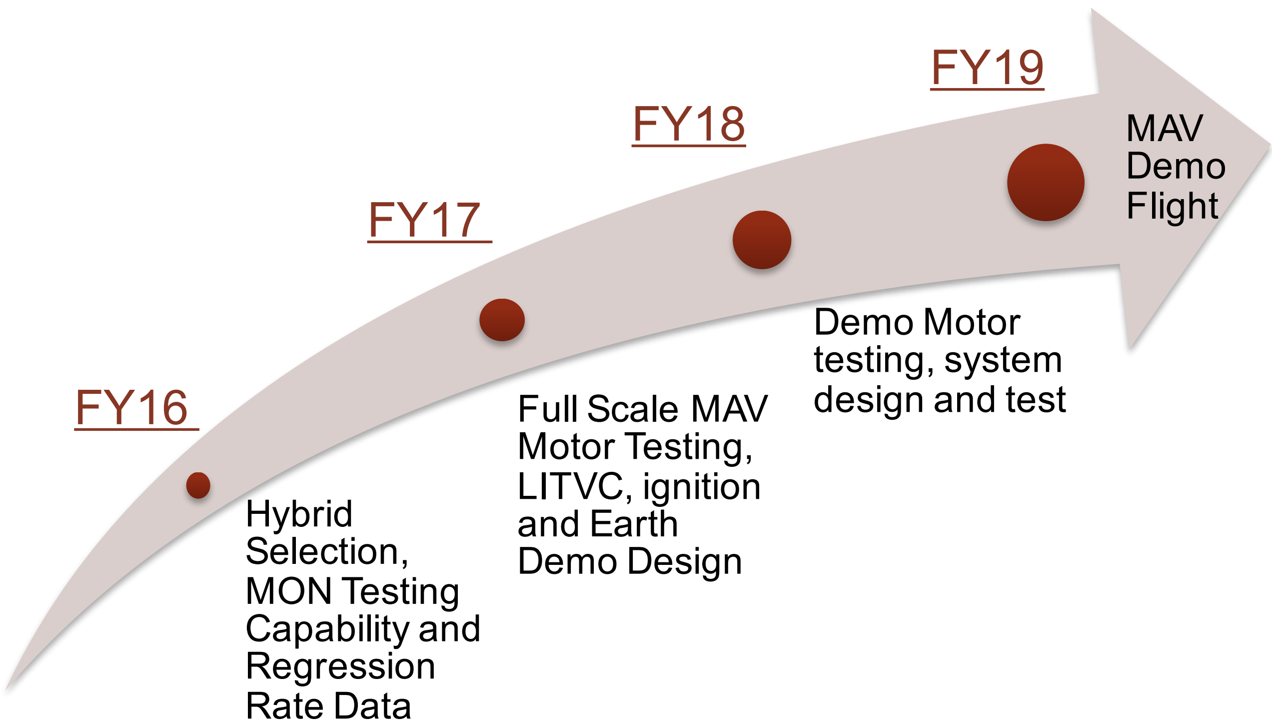


Future Work

- Completely characterize newly developed fuel (SP7)
- Complete study on CTE mismatch of insulator/case and fuel grain
- Ignition testing
- Nozzle and TVC testing

Path Forward – Proposed Demo Launch

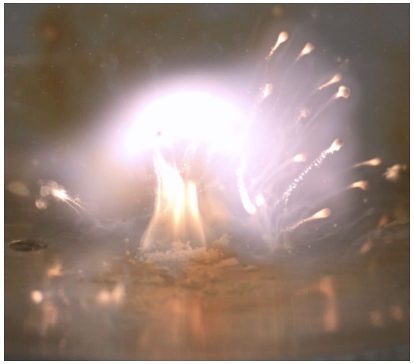
- Technology development to culminate with Earth-based demonstration flight

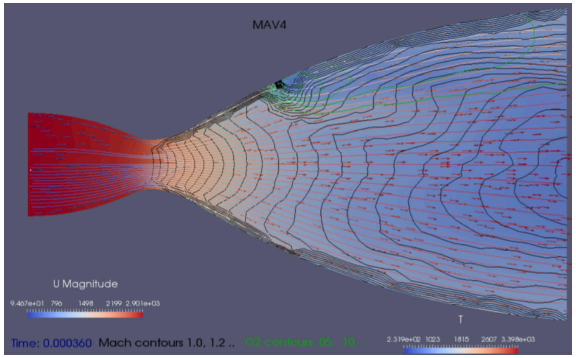


Summary

Mars Ascent Vehicle

- A wax-based fuel/MON30 hybrid propulsion system is capable of meeting the requirements of a Mars Ascent Vehicle.
- Substantial technology investment is ongoing to develop hybrid propulsion technology for this application (currently TRL 3)
- Full scale testing in FY17 will raise the TRL to 4.
- Major Accomplishments in FY16:



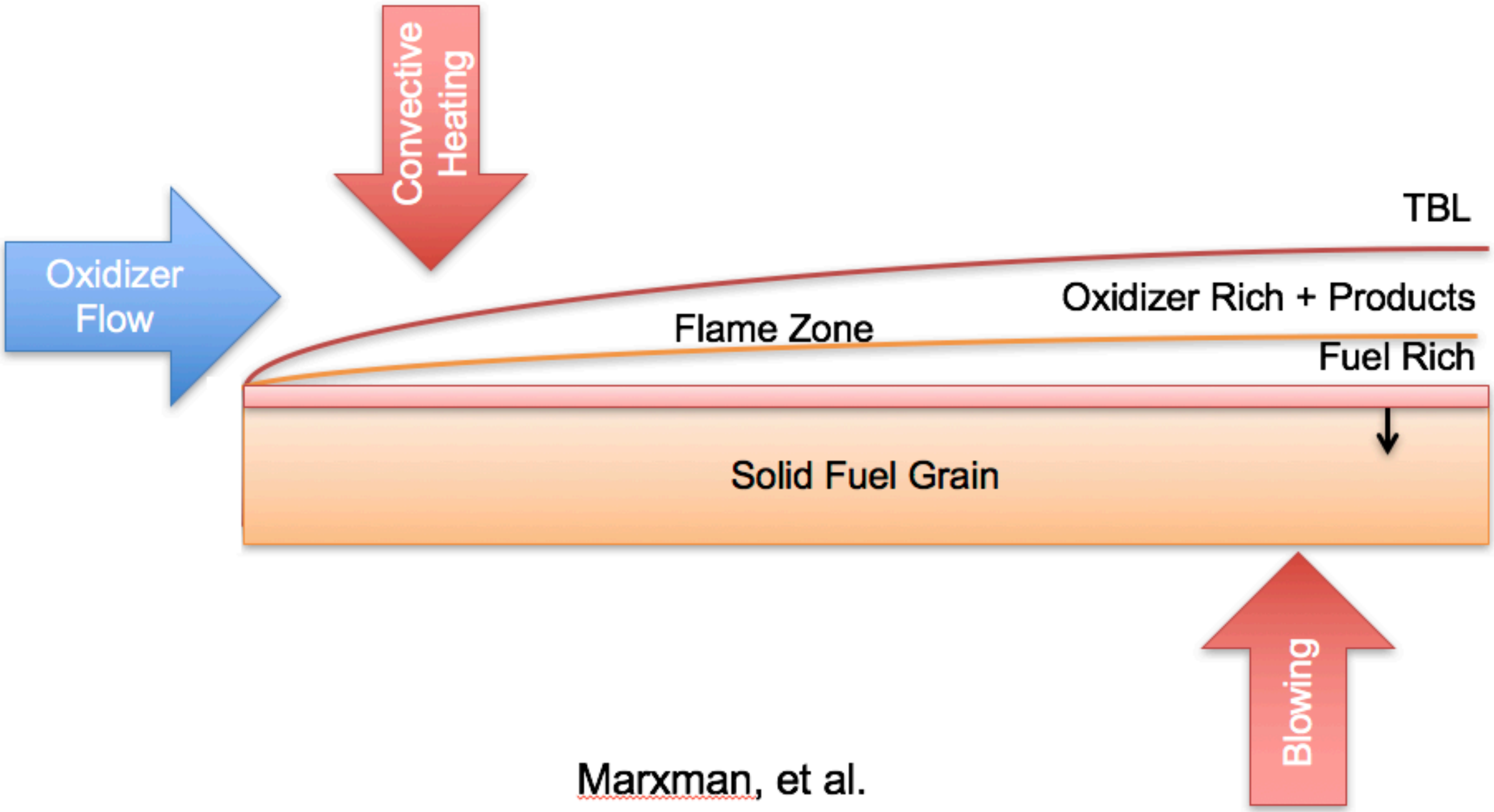


While several technological challenges remain, significant development and risk mitigation has already been accomplished in this short time period.

Questions?

Mars Ascent Vehicle

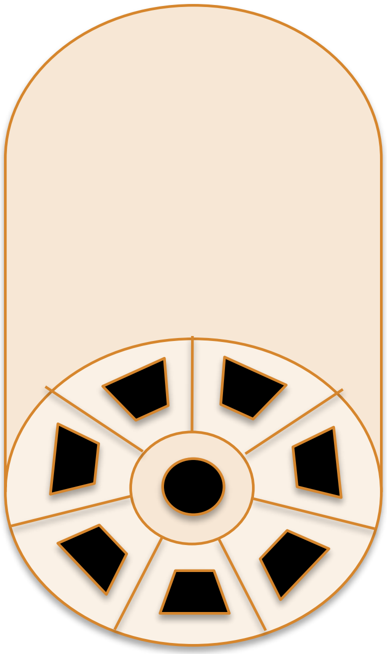
Classical Hybrid Combustion

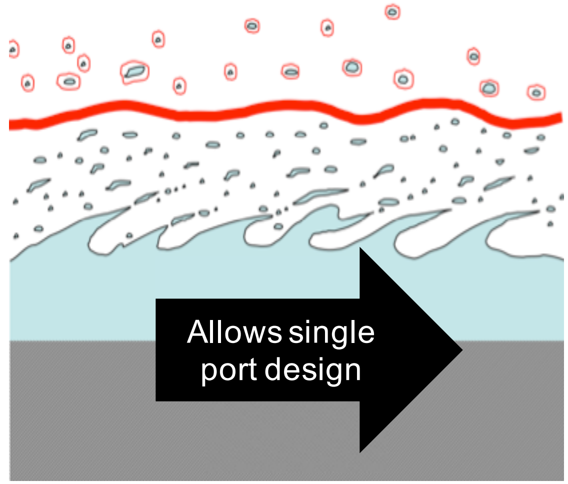


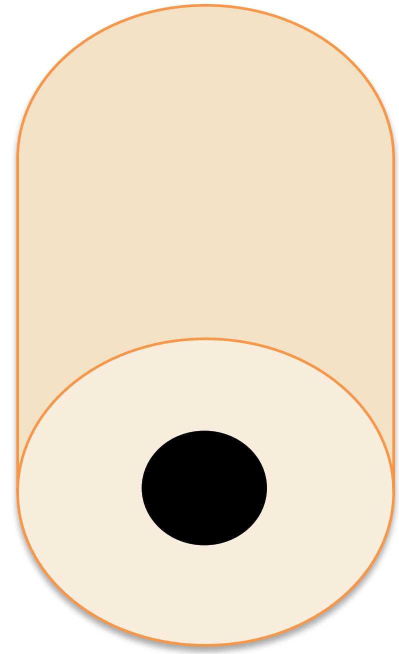
Marxman, et al.

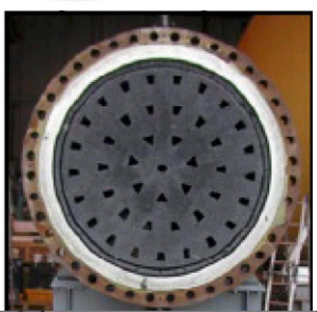
Evolution of Hybrid Rockets

Mars Ascent Vehicle

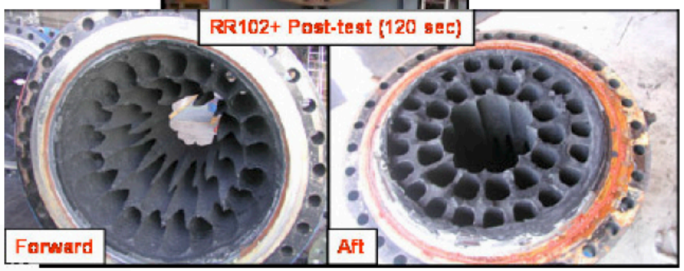








Lockheed Martin 2006 Multiport Test Source: Karabeyoglu, 2012



Peregrine Motor Test, NASA Ames, Source: Aerospace America 2011.