A Hybrid Propulsion Solution for the Mars Ascent Vehicle

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Mars Sample Return Mission Architecture
CHEMICAL ROCKETS
All modern launch systems use conventional solid and/or liquid rocket propulsion systems.

- **Liquid Main Engines**: High performance and throttle-able but complex, expensive, explosion hazard.
- **Solid Rocket Booster**: Mechanically simple but cannot throttle, expensive, explosion hazard, environmental hazard.
Hybrid Rocket System

Gas Pressurization

Liquid Oxidizer

Control Valve

Igniter

Injector

Motor with fuel grain

Nozzle

port
On August 17, 1933, the first rocket launch of the Soviet Union was a hybrid that used gelled gasoline and liquid oxygen.

*Soviet rocket pioneer M.K. Tikhonravov and the GIRD-9.*
Why hybrids ??

The Challenger disaster - January 28, 1986

Titan 34D-9 SRM failure - April 18, 1986

In the middle of all this was Dave Altman, now almost 100, of Menlo Park. A member of the Rogers commission, a founder of CSD and one of the inventors of segmented solid boosters, he firmly believed and still believes that solids should be replaced by safer, cheaper, throttleable hybrids.
Some history of hybrids- (1960 - 1985)

- 1960's: Extensive research at various companies.
  - Chemical Systems Division of UTC
    - Modeling (Altman, Marxman, Ordahl, Wooldridge, Muzzy etc…)
    - Motor testing (up to 40,000 lb thrust level)
  - LPC: Lockheed Propulsion Company, SRI: Stanford Research Institute, ONERA (France)

- 1964-1984: Flight System Development
  - Target drone programs by Chemical Systems Division of UTC
    - Sandpiper, HAST, Firebolt
  - LEX Sounding Rocket (ONERA, France)
  - FLGMOTOR Sounding Rocket (Sweden)

- 1973-1982: Indian Institute of Science 100 kgf motor
  - Swirl injection, hypergolic solid fuels with RFNA
  - 96% c* efficiency

CSD’s Li/LiH/PBAN-F\textsubscript{2}/O\textsubscript{2} Hybrid Measured Isp=480 sec

Firebolt Target Drone
Recent History - (1981 - Present)

• 1981-1985: Starstruck Co. launched the Dolphin sounding rocket (35 klb thrust)
• 1985-1995: AMROC continuation of Starstruck
  – Tested 10, 33, 75 klb thrust subscale motors.
  – Developed and tested the H-1800, a 250 klb LO$_2$/HTPB motor.
• 1990’s: NASA Hybrid Propulsion Development Program (HPDP)
  – Successfully launched a small sounding rocket.
  – Developed and tested 250 klb thrust LO$_2$/HTPB motors.
• 2002: Lockheed developed and flight tested a 24 inch LO$_2$/HTPB hybrid sounding rocket (HYSR). (60 klb thrust)
• 2003: Scaled Composites and SpaceDev developed N$_2$O/HTPB hybrid for the sub-orbital vehicle SpaceShipOne. (20 klb thrust)
• 2013: April 29 First powered flight of Space Ship Two
• 2019: February 22 Virgin Galactic flight of VSS Unity with its first passenger.
Paraffin vs Polymeric Fuels
In a hybrid rocket, the fuel surface regression rate is determined by the mass flux in the port.

\[ \dot{r} \cong aG^n \]

\[ G = \frac{\dot{m}_{\text{port}}}{\pi r^2} = \frac{\dot{m}_{\text{ox}} + \dot{m}_{\text{fuel}}}{\pi r^2} \]

Constants \( a \) and \( n \) are empirical values for a given choice of fuel and oxidizer. Typically \( 0.4 < n < 0.7 \).

In a solid rocket the propellant surface regression rate is determined by the chamber pressure.

\[ \dot{r} = aP^n \]

The constant \( a \), depends on propellant temperature, while \( n < 1 \) is required to prevent explosion.
Just to be clear, hybrid motor combustion is governed by two coupled first order semi-empirical PDEs

**Fuel surface regression rate equation**

\[
\frac{\partial r (x, t)}{\partial t} = \frac{a}{x^m} \left( \frac{m_{port}}{\pi r^2} \right)^n
\]

\[m_{port} = \dot{m}_{ox} + \dot{m}_f\]

**Port mass flow growth rate equation**

\[
\frac{\partial m_{port} (x, t)}{\partial x} = \rho_f (2\pi r) \frac{a}{x^m} \left( \frac{m_{port}}{\pi r^2} \right)^n
\]
Classical Hybrids

The hybrid design concept has been known for more than 85 years.

Small hybrid rocket motors built to military specifications were used in target drone programs between 1968 and 1983 (Sandpiper, Hast, Firebolt). Soon Space Ship Two will begin to take tourists to the edge of space.

Yet, despite this experience, the hybrid has never been developed to power large launch systems capable of taking a payload to orbit. Why?
Multiport designs

CSD (1967) 13 ports

AMROC (1994) 15 ports

Lockheed Martin (2006) 43 ports
Solid Cryogenic Hybrids - Air Force (AFRL) Tests

- Solid propellant is a frozen material

- Motivation:
  - Performance Benefit: More flexibility on propellant selection (e.g. H₂ & O₂).

- AFRL at Edwards AFB
  - Solid Pentane @ 77 K.

- 3-5 fold increase in the regression rate for pentane.


The Air Force shared their experimental data with us.
In his PhD research, Arif Karabeyoglu was able to model the high mass transfer rates observed by the AFRL researchers and showed that:

1) Pentane forms a thin melt layer on the fuel surface.
2) The layer is linearly unstable under the shear by the gas flow in the port and strong blowing from the fuel surface.
3) Using results from the Nuclear Safety literature, Arif was able to include nonlinear growth and droplet entrainment in classical hybrid theory.

Conclusion - Total mass transfer is increased by a factor of 3 to 4.
Thin film instability plus nonlinear growth and wave breaking leads to entrainment of droplets along the port

\[ \rho_s \dot{r} = \rho_l V_l \]

Liquid blowing Reynolds number

\[ \frac{\rho_l U_l h}{\mu_l} = 0.1 - 1.0 \]

Film Reynolds number

\[ \frac{\rho_l V_l h}{\mu_l} = 100 - 300 \]


Viscosity of the melt layer increases with alkane molecular weight.

Viscosity of the melt layer decreases with melt layer temperature.
Entrainment for $C_nH_{2n+2}$ Series

Carbon numbers between 25 and 45 are predicted to burn rapidly

<table>
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<th>Carbon Numbers</th>
<th>Methane (Tested)</th>
<th>Pentane (Tested)</th>
<th>Paraffin Waxes</th>
<th>PE Waxes</th>
<th>HDPE Polymer (Tested)</th>
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<td>5</td>
<td>25</td>
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<td>Mw (g/mol)</td>
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Cryogenic
Non-cryogenic
Gas
Liquid
Solid
Polymer

Entrainment Boundary
Liquid layer hybrid combustion theory predicts

\[ \dot{r}_{\text{wax}} \approx \dot{r}_{\text{pentane}} \approx 3 - 5 \times \dot{r}_{\text{classical}} \]

Diagram depicts an 83% fuel loading design
NASA Ames Hybrid Combustion Facility
Test Motor Configuration
Regression rate data for paraffin-based fuel

Paraffin-based fuel: 70°C Melt Point, Fully Refined Wax (C_{32}H_{66}) + 2% Stearic Acid (C_{18}H_{36}O_{2}) by weight

Three fold improvement is confirmed.
Theoretical Isp Performance with LOX

$I_{sp\, vac}$
sec

Chamber Pressure: 500 psi
Nozzle Area Ratio: 70

Slightly better Isp performance compared to HTPB
Over 1000 tests to date at several scales using single port design

- **Thrust class - 50 lbs**
  - Oxidizer - GOx
  - Grain dia. - 2.375 inches
  - Nozzle type - simple conv.
  - Number of tests - 300

- **Thrust class - 5000 lbs**
  - Oxidizer - LOx
  - Grain dia. - 8.4 inches
  - Nozzle type - 2:1 conv.-div.
  - Number of tests - 50

- **Thrust class - 6000 lbs**
  - Oxidizer - LOx
  - Grain dia. - 5.25 inches
  - Nozzle type - 5:1 conv.-div.
  - Number of tests - 15

- **Thrust class - 2500 lbs**
  - Oxidizer - GOx
  - Grain dia. - 7.5 inches
  - Nozzle type - simple conv.
  - Number of tests - 40

- **Thrust class - 2000 lbs**
  - Oxidizer - MON3
  - Grain dia. - 11 inches
  - Nozzle type - 3:1 conv.-div.
  - Number of tests - 12

- **Thrust class - 900 lbs**
  - Oxidizer - N2O
  - Grain dia. - 10 inches
  - Nozzle type - 5:1 conv.-div.
  - Number of tests - 5

- **Thrust class - 15000 lbs**
  - Oxidizer - N2O
  - Grain dia. - 12 inches
  - Nozzle type - 5:1 conv.-div.
  - Number of tests - 25

- **Thrust class - 3000 lbs**
  - Oxidizer - LOx
  - Grain dia. - 8.4 inches
  - Nozzle type - 5:1 conv.-div.
  - Number of tests - 5

- **Thrust class - 3000 lbs**
  - Oxidizer - LOx
  - Grain dia. - 8.4 inches
  - Nozzle type - 2:1 conv.-div.
  - Number of tests - 50
FLAME VISUALIZATION
Oxygen compatible combustion visualization tunnel
Ashley Karp, Beth Jens

The experimental challenge – directly visualize oxygen-fuel combustion at 3000K up to 2 MPa

- Material - Brass
- Chamber pressure: atmospheric up to 17.24 bar
- Windows: 3.81 cm Polycarbonate, later Quartz
- Ignition: Nichrome wire, currently diode laser
Combined schlieren and OH* results - Blackened Paraffin 71 psi

Elevated pressure blackened paraffin tests – 170 psi
Visuals of several fuels

(a) Test 36- PE Wax. t = 2.60 s, P = 518.4 kPa (75.2 psi)

(b) Test 34- BP. t = 3.35 s. P = 1318.8 kPa (191.3 psi)

(c) Test 16- PMMA. t = 3.49 s. P = 412.6 kPa (59.8 psi)

(d) Test 37- Chocolate. t = 3.06 s. P = 428.1 kPa (62.1 psi)

(e) Test 15- HTPB. t = 2.89 s. P = 460.2 kPa (66.8 psi)

(f) Test 24- HTPB. t = 4.16 s. P = 1045.6 kPa (151.6 psi)
Entrainment visualization at elevated pressure

(a) Test 7: $G_{ox} = 20.5 \text{ kg/m}^2\text{s. } t = 3.05 \text{ s, } P = 276 \text{ kPa (40 psi)}$

(b) Test 7: $G_{ox} = 20.5 \text{ kg/m}^2\text{s. } t = 3.09 \text{ s, } P = 276 \text{ kPa (40 psi)}$

(c) Test 8: $G_{ox} = 36.6 \text{ kg/m}^2\text{s. } t = 3.15 \text{ s, } P = 483 \text{ kPa (70 psi)}$

(d) Test 8: $G_{ox} = 36.6 \text{ kg/m}^2\text{s. } t = 3.17 \text{ s, } P = 490 \text{ kPa (71 psi)}$

(e) Test 9: $G_{ox} = 20.4 \text{ kg/m}^2\text{s. } t = 3.29 \text{ s, } P = 814 \text{ kPa (118 psi)}$

(f) Test 9: $G_{ox} = 20.4 \text{ kg/m}^2\text{s. } t = 3.38 \text{ s, } P = 745 \text{ kPa (108 psi)}$

(g) Test 10: $G_{ox} = 36.3 \text{ kg/m}^2\text{s. } t = 3.46 \text{ s, } P = 1131 \text{ kPa (164 psi)}$

(h) Test 10: $G_{ox} = 36.3 \text{ kg/m}^2\text{s. } t = 3.49 \text{ s, } P = 1145 \text{ kPa (166 psi)}$
PEREGRINE
The largest motor we have built to date is a 15,000 lb class motor for the Peregrine sounding rocket project led by Greg Zilliac of NASA Ames. 90-95% C* efficiency
MARS SAMPLE RETURN
Mars Sample Return Mission Architecture
Mars Ascent Vehicle 2015 Case Study

- JPL/MSFC/LaRC carried out trade study in FY15 of MAV implementation options
  - Solid-Solid two-stage
  - Liquid bi-prop SSTO
  - Hybrid SSTO

- Based on propulsion performance and thermal accommodation, Hybrid SSTO option selected as current focus
The Mars 2020 rover will drill rock samples and place them in individual tubes.

The samples would be left on the surface of Mars for later pick up by a second rover.

The second rover would place the samples in the payload bay of the MAV which would then launch to Mars orbit.
Mars 2020 landing site was chosen November 2018

Jezero crater - 18° above the Mars equator

Curiosity rover – Temperature and Pressure at Gale crater on Mars (Aug 2012 to Feb 2013)

Gale crater - 5° below the Mars equator
Fuel temperature predictions during the Martian year including EDL

- EDL
- Winter
- Spring
- Summer
Critical Challenge: Mars Temperature

- Diurnal/seasonal extreme minima and maxima at Gale crater (-127°C to 20°C)
  - Paraffin is primarily crystalline with a weak glass transition below -108°C.
  - MON25 freezing point is -58°C.

MON25
N2O4 – 75% by mass
NO – 25% by mass
Freezing point -58°C
A wide temperature range fuel designated SP7 was developed in 2015 by Space Propulsion Group, Inc.

Thermal cycling representative of 200 Mars sols at Mars pressure was carried out at NASA Marshall Space Flight Center. Both aluminized and non-aluminized samples were studied.

Figure 11. Test configuration for long term temperature cycling of eight SP7 fuel samples. Each fuel sample is instrumented with a thermocouple at the inner and outer diameters.

The EDL cycle and the 50 winter cycles have been completed. The samples were removed from the test chamber for inspection following the completion of the 50 winter cycles. Small cracks were observed on a couple of samples; no large radial cracks were observed. Some small cracks were visible in the circumferential direction as expected. Further testing will determine if these cracks are an issue if they propagate into larger cracks or if they can be prevented. All eight samples successfully survived the EDL and winter cycles and will continue testing with the 100 spring/fall cycles.
Full scale MAV motor at test – Butte Montana 2018

Testing of SP7/MON3 carried out by Space Propulsion Group of Butte Montana and Whittinghill Aerospace of Mojave CA

Figure 6. Non-Dimensional Chamber Pressure for 3-in MON-3/SP7 Test

Figure 11. Non-Dimensional Chamber Pressure for Test MAV_11_19

3 inch motor

96% C* efficiency

11 inch motor

MON3 has a relatively low vapor pressure.

At larger scales poor atomization, evaporation and mixing leads to flame-holding instability.
The Mars Ascent Vehicle Growth

Figure 1. Hybrid MAV Case 7.3. The result for the hybrid propulsion system for the FY2015 study.

Figure 2. Pressure Fed Hybrid Mars Ascent Vehicle Concept

Figure 9. Comparison of historical sample tube size to present M2020 derived size and resulting OS size and mass.
Thanks for all the help!

Recent PhD grads

Jonah Zimmerman
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Ashley Karp
NASA - JPL

Tim Szwarc
NASA - JPL

Beth Jens
NASA - JPL

Yaniv Scherson
Anaergia

Javier Stober
MIT

David Murakami
NASA Ames

Pavan Narsai
Lockheed Martin

Ashley Micks
Ford Motor Co

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Anna Thomas
Stanford AA

David Dyrda
Stanford AA

Matt Subramaniam
Stanford AA
QUESTIONS
Mars Environment used for MAV Thermal Analysis

a. Winter

b. Spring

c. Summer
Thin film instability plus nonlinear growth and wave breaking leads to entrainment of droplets along the port.

\[ \rho_s \dot{r} = \rho_l V_l \]

\[ V_l \]

\[ h \approx 50 - 100 \mu M \]

**Film Reynolds number**

\[ \frac{\rho_l U_l h}{\mu_l} = 100 - 300 \]

**Liquid blowing Reynolds number**

\[ \frac{\rho_l V_l h}{\mu_l} = 0.1 - 1.0 \]


