3-D Printed Hybrid Propulsion Solutions for SmallSat Lunar Landing and Sample Return

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STP Project Summary

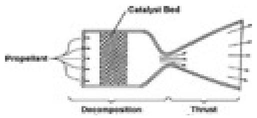
- **Primary Objective**: Hybrid rocket development with testing in a near vacuum to raise the TRL level.
- **Relevance and Impact:** Low cost, "green" propulsion allows repeatable access to lunar surface features, including "Skylights" into caverns suitable for human habitat development. Data collected from repeated low-cost scout-missions assists in vetting list of potential targets.
- **Technical Approach:** Design, build, and test 25-50 N system packages into 12-U size. On-demand ignition reliability to be demonstrated under both ambient and vacuum conditions. Long duration burn and capability to fire in pulsed or throttled mode demonstrated. Hardware in loop (HIL) simulations with hardware proposed. HIL tests track prescribed energy profiles necessary for lunar landing and sample return missions.
- **Key Technical Issues:**
  - On-Demand Motor Start/Restart,
  - Low Erosion Nozzle for Long Duration Burns
  - Engineered Hybrid Fuel Materials and High-Density Hybrid Oxidizer Development
  - Precision Deep Throttle
- **FOMs:** Successful PDR, CDR, Successful Integration and Test, QA campaign completed.
- **Starting TRL:** 4.5 **Planned Year 2 Ending TRL:** 6

Research Motivation: Why Develop "Green" Propellants?

- Electronics miniaturization has allowed technology supporting small and inexpensive, but highly-capable small spacecraft to grow enormously during the last decade.
- However, this technology development has mostly centered on spacecraft bus design and miniaturization of sensor components, leaving the propulsion component development obsolete by comparison.
- Only two operational alternatives for small spacecraft propulsion are currently available:
  - *Higher-performing systems based on hydrazine,*
  - *Low-performing systems based on cold-gas.*
- Monopropellant Hydrazine ($\mathbf{N_2H_4}$) is most ubiquitous of present-day monopropellants.
  - *Desirable for simplicity and compact form factor.*
  - *Hydrazine is highly toxic and dangerously unstable.*
  - *Acute exposure can be lethal, and it is a suspected carcinogen.*
  - *Use of hydrazine requires expensive precautions.*
- Emerging commercial spaceflight market will clearly support development of green alternatives to hydrazine.

Research Motivation (2)

- Hydrazine
  - Monopropellant/Hypergolic Applications
  - Good performance, very Reliable
  - Extremely Toxic, High Detonation Risk
  - Very Expensive for storage and servicing
  - NASA/USAF Actively seeking "greener" alternatives



European Space Agency Space Research and Technology Center (ESTEC)

Bombelli, V., "Economic Benefits for the Use of Non-toxic Monopropellants for Spacecraft Applications, AIAA- 2003-4783, *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Huntsville, AL, July 2003. https://arc.aiaa.org/doi/10.2514/6.2003-4783

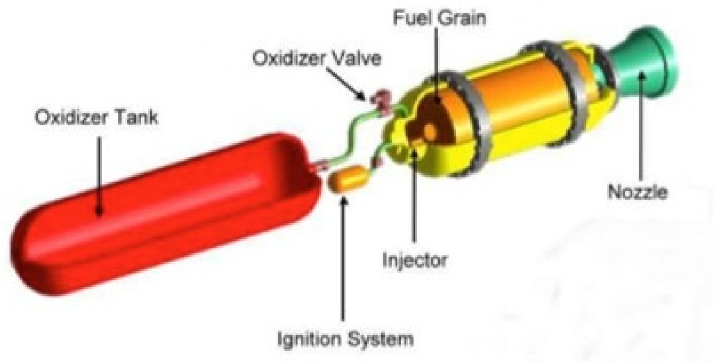
ESA technicians load hydrazine on the Herschel Space Observatory

Hydrazine

" ... with a growing regulatory burden, the infrastructure requirements associated with hydrazine transport, storage, servicing, and clean up procedures associated with accidental releases, are becoming increasingly cost prohibitive. In an era of shrinking operational budgets servicing payloads that require hydrazine as a propellant will operationally infeasible. ...."

Original Project Objectives

- **Build small spacecraft thruster system using non-toxic, non-explosive components and fabricate as many components as feasible using modern *Additive Manufacturing Techniques***



- **Investigate design option for multiple additively manufactured components including oxidizer delivery system fitting attachments, motor cap, motor casing, insulation, and fuel grain.**

- **Investigate potential for 2-3 orders of magnitude reduction in design and production costs**

Rapid Advance of Technologies to Flight → Enabling Turn-Key Propulsion Solution

Chemical Rocket Comparisons

Feature	Liquid, Bipropellant	Solid Propellant	Monopropellant Hydrazine	Hybrid Bipropellant
Safety	Potential for combustion instability, can explode, volatile propellants	Highly flammable significant explosion potential, DOT 1.1	Significant Explosion/Decompositon Hazard	**Inert propellants, low explosion and transport risk**
Toxicity	Ranges from non-toxic to highly toxic	Exhaust products highly toxic	Highly Toxic, Carcinogenic, Significant Vapor hazard	**Exhaust products non-toxic (CO_2, H_2O)**
Fabrication Costs	Extremely expensive	Expensive, mostly due to handling difficulties	Expensive, mostly due to handling difficulties, Noble metals for catalyst bed	**Inexpensive**
Complexity/ Reliability	Highly complex, moderate reliability	Simple-to-moderate complexity, high reliability	Simple Design, Highly Reliable	**Moderate complexity, high reliability**
Operation	Throttleable, restartable, high performance	No restart, throttle capability, moderate performance, Issues with starting under cold conditions	Requires Significant pre-Heat, Propellant environmental control, Throttleable and restartable	**Thottleable, Restartable, moderate to-High performance, Works well at cold temperatures**

3-D Printed Hybrid	Performance Characteristics to Existing Space Mono-Propellants§§§				
Propellant	**Hydrazine**	**LMP-103S**	**AF-M315E**	**Nytrox/ABS Hybrid**	**H_2O_2/ABS Hybrid**
Flame Temperature	600-750 ^oC	1600 ^oC	1900 ^oC	3000 ^oC****	2900 ^oC§§§§
I_{sp}, *s*	220-225	252 (theory), 235 (delivered)	266 (theory) 245 (delivered)	300 (theory) 294 (delivered)††††	324 (theory) 302 (delivered)*****
Specific Gravity	1.01	1.24	1.465	0.650 (87% N_2O)	1.392 (90% H_2O_2)
Density Impulse, *N-s/liter*	2270	3125 (theory) 2915 (delivered)	3900(theory) 3650 (delivered)	2800 (theory) 2600 (delivered)	4450 (theory) 4002 (delivered)
Preheat Temperature	315 ^oC, cold-start capable	300 ^oC	370 ^oC	N/A none-required	N/A none-required
Required Ignition Input Energy, *Joules*	N/A	12,000 J (10 Watts @ 1200 seconds)	27,000 J (15 Watts @ 1800 seconds	2-5 J (4-10 Watts for 500 msec)	2-8 J (8-16 Watts for 250-500 msec)
Propellant Freezing Temperature	1-2 ^oC	-7 ^oC	< 0 ^oC *(forms glass, no freezing point)*	-70 ^oC	-10 ^oC *(90% concentration)*
Cost	$	$$$	$$$$	$	$
Availability	Readily Available	Restricted Access	Limited Access	Very Widely Available‡‡‡‡	Very Widely Available†††††
NFPA 704 Hazard Class			  §§§§		

§§§ Data for hydrazine, LMP-103S and AFM315-E were taken from Ref. [7].

**** Due to the high pyrolysis energy of the ABS fuel, 3.1 MJ/kg, ABS Hybrid motors are self-ablative and do not get hot externally.

†††† Extrapolated to vacuum conditions based on ground test data.

‡‡‡‡ 80-90% N_2O solutions easily manufactured, as per procedure in this paper.

§§§§ *Based up the constituent components, Hydroxyl Ammonium Nitrate (HAN) and 2-Hydroxyethylhydrazine (HEHN)*

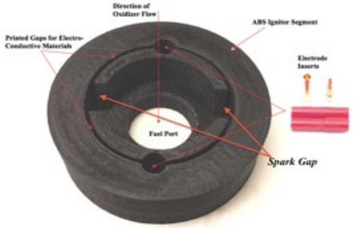
Why Additive Manufacturing for Hybrid Propulsion?

- **Conventional Aerospace Manufacturing**
  - o“One-off" or very low volume production runs.
  - o Maintenance of expensive manufacturing facilities and assembly lines
  - o Difficult to recover initial capital costs due to very low required production rates.

Mass-Produced FDM-Printed Fuel Grains

Scaling of FDM-Printed Fuel Grains

- **Additive Manufacturing Allows Reduced Development & Production Costs**
  - o Multiple small businesses currently thriving in additive manufacturing market
  - o Ideal for supporting low-to-moderate production rates
  - o Higher quality &consistency for low-volume components
  - o Almost no residual material waste using additive methods
  - o Vendors can produce identical pieces simultaneously
  - o ”Virtual assembly line.”

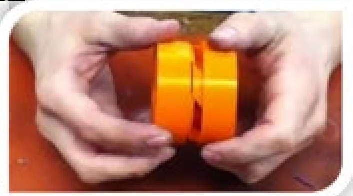


Sample ABS, FDP-Printed Fuel Grain

25-N Flight Weight Thruster System Testing at PRL

- **Ability to "order,” manufacture and deliver thruster system in days/weeks versus months/years will revolutionize space-launch market.**
  - o Multiple options available, significant design flexibility
  - o Ability to Specifically Engineer Plastic Alloys to Enhance Burn Properties
  - o Assure Structural Integrity, Provide for Self-Cooling Capability

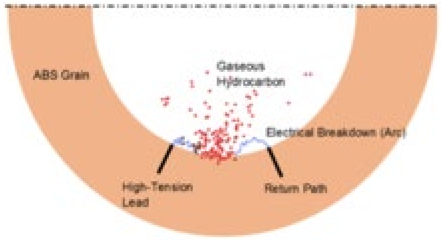
Connecting segments design stop secondary flow paths



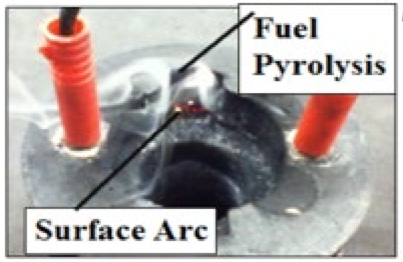
Assembly of fuel grain segments prototype - no build limits

Additive Manufacturing as Essential Enabler for ON-Demand Hybrid Rocket Ignition

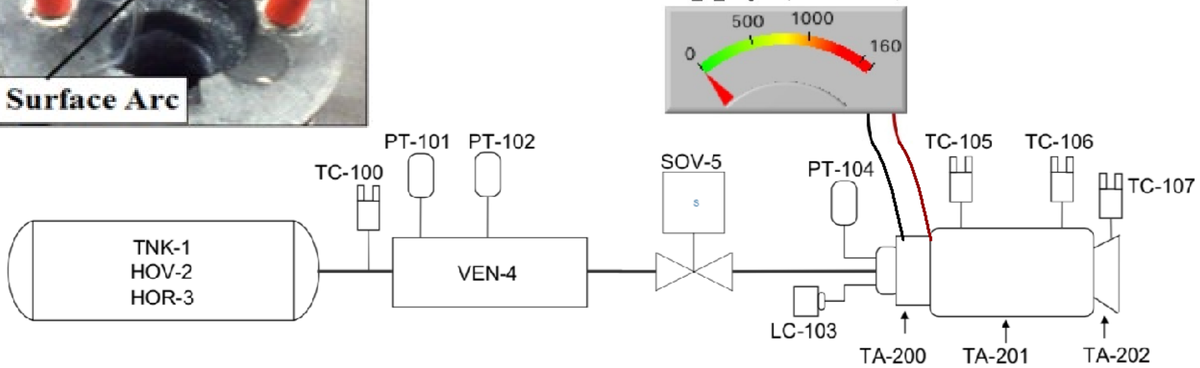
- ***Until recently, hybrid rocket systems never been seriously considered for in-space propulsion applications.***
- Hybrid rocket ignition has historically involved either 1-shot pyrotechnics which cannot support multiple restart cycles.
- During research investigating Acrylonitrile Butadiene Styrene (ABS) as a fuel for hybrid rockets, it was discovered that 3-D printed plastic possesses unique electrical breakdown characteristics.
- Application of a strong electric field induces a high-temperature arc along the surface of the ABS, concurrent with rapid production of hydrocarbon vapor.
- This behavior forms the basis of a novel "on-demand" ABS arc ignition system.



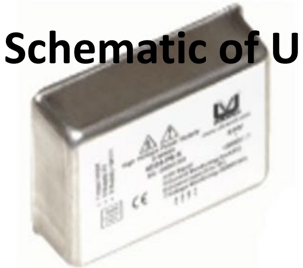
Arc Ignitor Joule-Heating Concept.



ligh-Voltge Digital Power Supply (HVPS)



Schematic of UltraVolt® HVPS Interface*



UltraVolt D-Series 1D15-P6

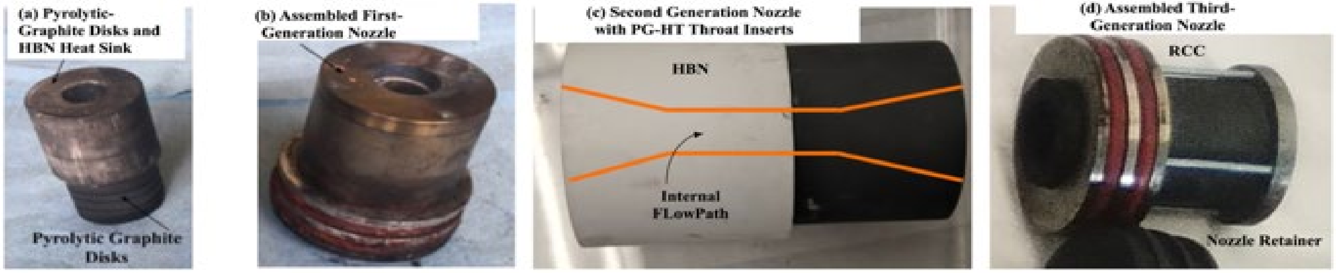
- Power Output – 0 to 1000V at 6mA
- Input Supply – 15Vdc

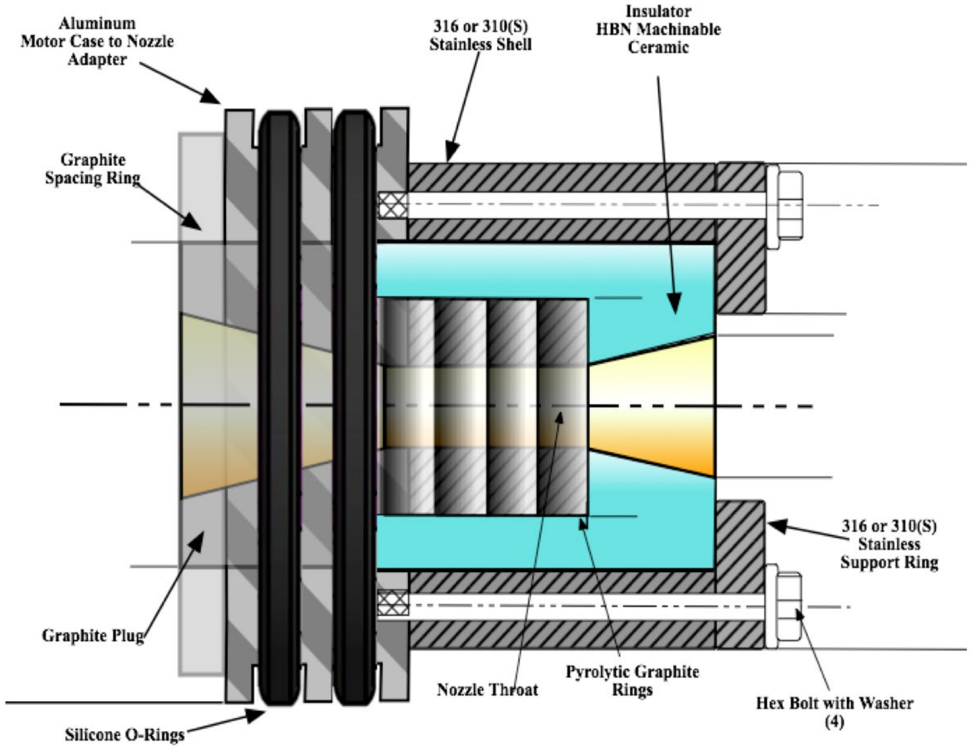
Ignition process is rapid, highly repeatable, and requires little power (<5W). ABS material insulates the motor resulting in low external case temperatures (<40C)

Low-Erosion Nozzle Assembly

- Operating environments of hybrid rocket systems are very different than occur for solid propulsion.
- Solid propellant systems generally operate at fixed equivalence ratio, set by propellant chemistry formulation, to run slightly fuel-rich.
- Slightly fuel-rich operation gives best c^* and eliminates highly-reactive and potentially erosive unburned oxygen in exhaust plume.
- Hybrid rockets, however, undergo a continual shift in Oxidizer-to-Fuel Ratio (*O/F*) as fuel port burns, opens up, and exposes more surface area.
- Large majority of hybrid system experience a positive *O/F* shift with motor burning leaner with time.
- This behavior exposes hybrid rockets to greater concentration of oxygen-rich exhaust by products than is experienced by solid rockets.
- Thus, throat erosion rate in a hybrid is generally 2 or 3 larger, as compared to similarly-sized solid propellant systems.
- The comparatively high-oxidizing environment of hybrid exhaust limits what materials can be effectively employed in nozzle construction
- Traditional C/C oxidizes quickly above 650°C and there are no viable oxidation resistant coatings
- Low-erosion refractory materials are a possibility but have a high mass

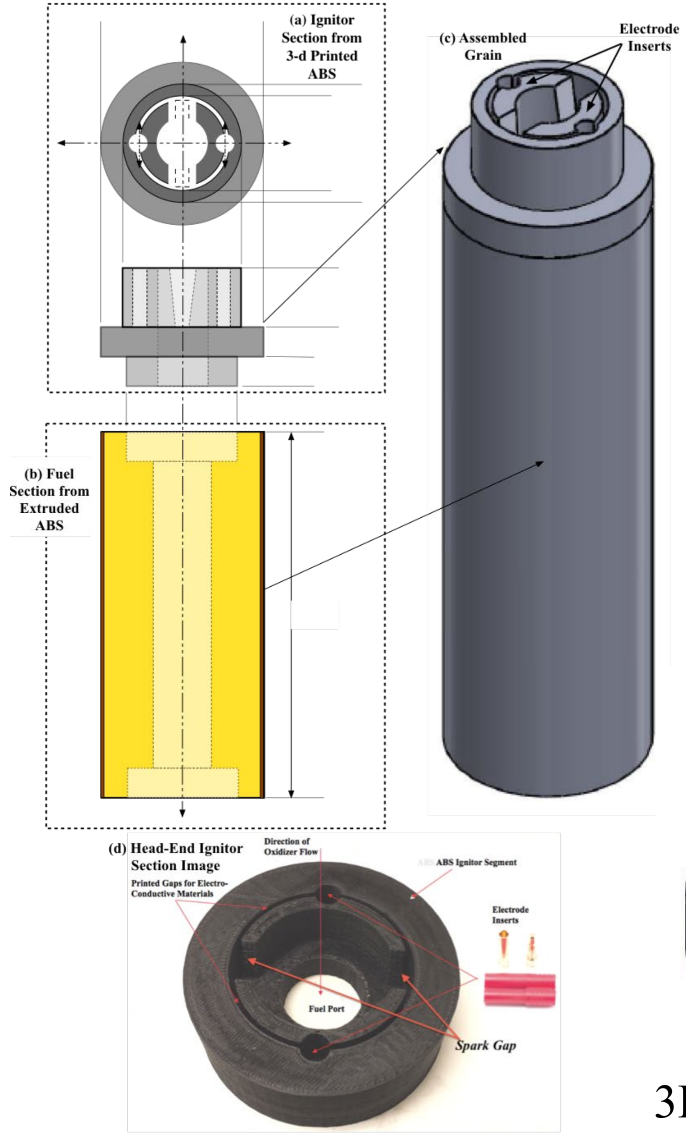
Three Generations of Light-Weight, Low Erosion Nozzle Configurations

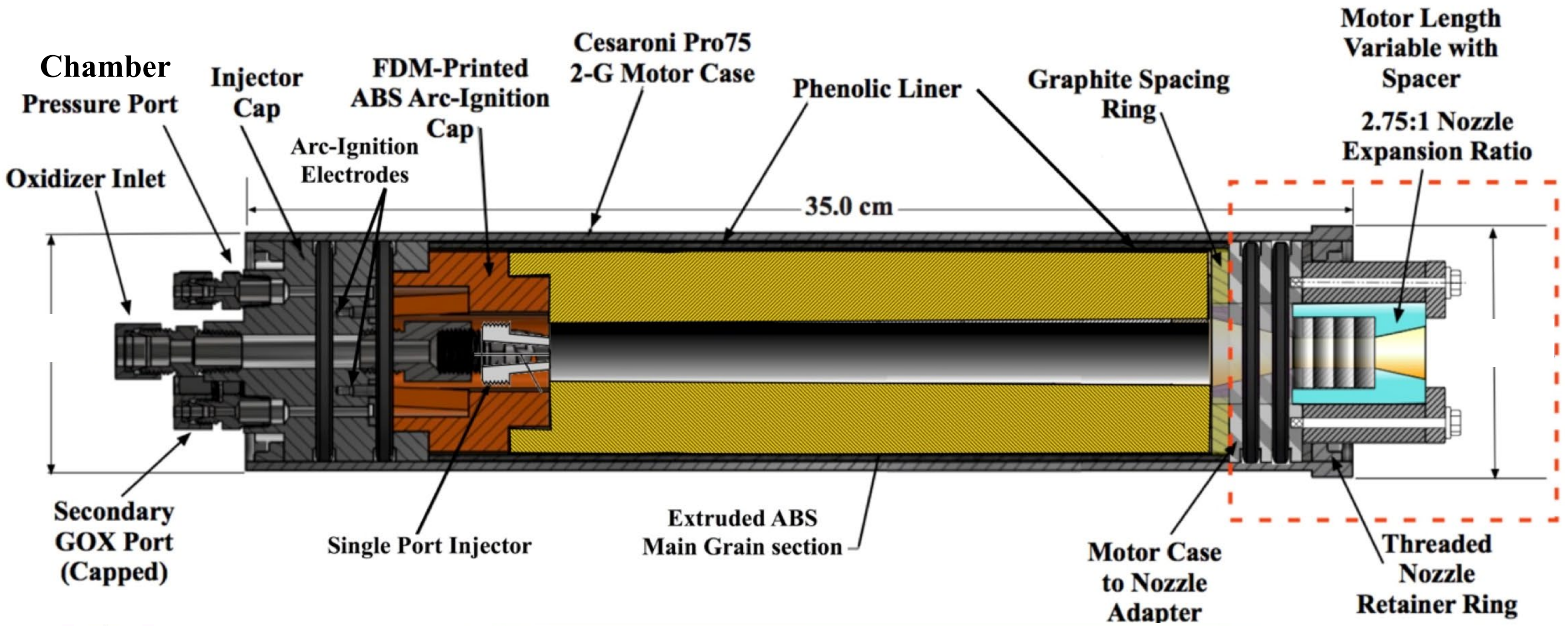


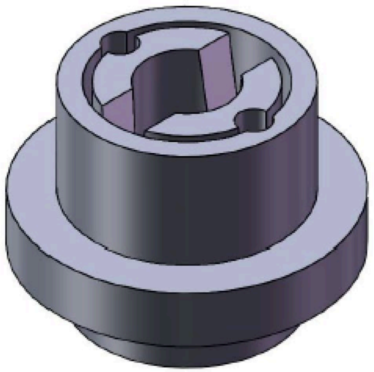


- **Gen-1**
  - Substrate-nucleated pyrolytic-graphite (*PG-SN*) throat inserts
  - PG-SN High Radial Thermal Conductivity > 400 W/m-K
  - Hexagonal Boron Nitride Heat Sink (99.5% pure)
  - HBN High Heat Capacity ~ 1500 J/kg-K
  - SS-316 Shell
- **Gen-2**
  - Annealed Continuously-nucleated pyrolytic-graphite (*PG-HT*) throat inserts
  - PG-HT Extremely High Radial Thermal Conductivity > 1600 W/m-K
  - Hexagonal Boron Nitride Heat Sink and Outer Shell (99.5% pure)
  - Rupture Modulus < 80 MPa
- **Gen-3**
  - Annealed Continuously-nucleated pyrolytic-graphite (*PG-HT*) throat inserts
  - Reinforced Carbon Fiber Composite (RCFC) Heat Sink and Outer Shell
  - RCC Moderate Heat Capacity, 700 J/kg-K
  - Rupture Modulus > 200 MPa

Low-Erosion Nozzle Test Hardware: Thrust Chamber Assembly and Motor Ignition System







3D-Printed ABS Ignitor Cap

Extruded ABS Fuel Segment

Nozzle Throat Erosion Testing Summary

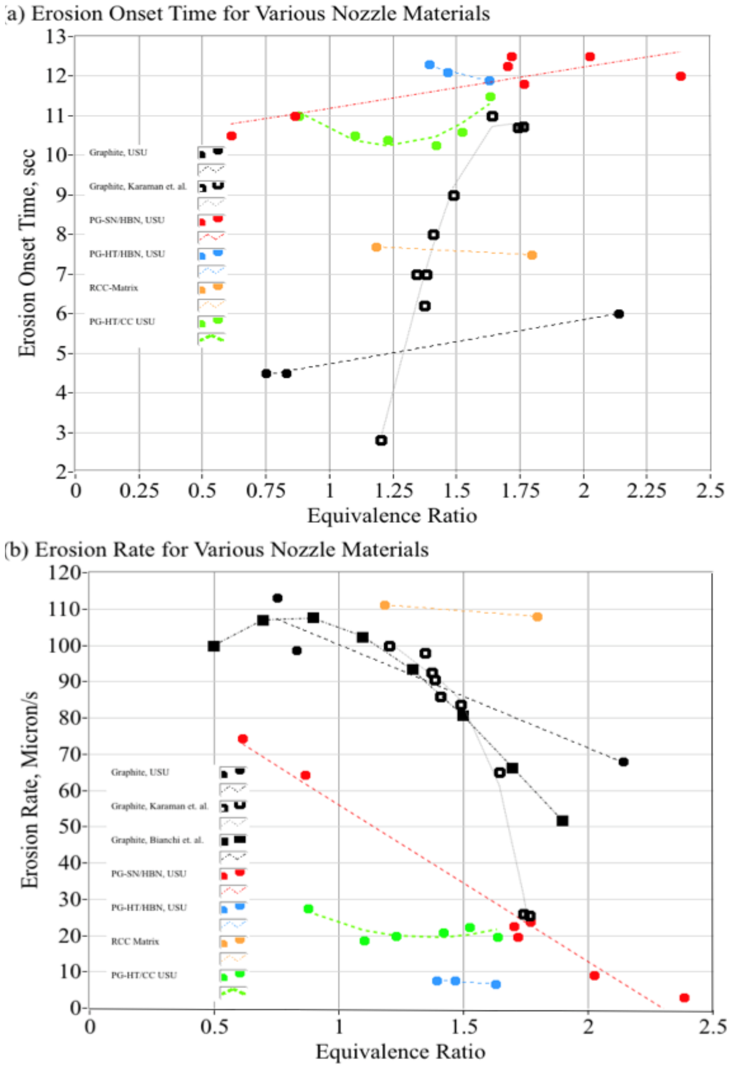
MARSHALL SPACE FLIGHT CENTER

COLLEGE of ENGINEERING UtahStateUniversity

Utah State Propulsion Research Laboratory

Summary of Long-Duration Hybrid Nozzle Testing Campaign.

Nozzle	Materials	No. Tests	Burn Durations	Test Description
Control 1	Monolithic Graphite	3	1 - 12 seconds 2 - 12 second 3 - 12 seconds	• Nozzle failed at 12 seconds for both burns. • High throat, nozzle exit erosion rates.
Control 2	Monolithic RCFC	2	1 - 12 seconds 2 - 20 seconds	• No in-test structural failures. • Survivable burn time > 20 sec. • High nozzle throat, exit erosion rates.
Generation 1	PG-SN Throat, HBN Heat-Sink, Stainless Steel Shell	7	1 - 5 seconds 2 - 10 seconds 3 - 15 seconds 4 - 15 seconds 5 - 15 seconds 6 - 20 seconds 7 - 30 seconds	• HBN heat-sink experience partial structural cracks after 20, 30 second burns. • Survivable burn time approximately 15 sec. • Moderate throat erosion rates. • Low nozzle exit erosion rates.
Generation 2	PG-HT Throat, HBN Heat-Sink (No Stainless Steel Shell)	3	1 - 10 seconds 2 - 15 seconds 3 - 15 seconds	• Thermal stress fracture of HBN-Shell for 2 of 3 tests. • Multiple HBN heat-sink fracture lines. • Survivable burn time approximately 10 sec. • Very low throat erosion rate. • Low nozzle exit erosion rate.
Generation 3	PG-HT Throat, RCFC Heat-Sink (No Stainless Steel Shell)	6	1 - 10 seconds 2 - 15 seconds 3 - 20 seconds 4 - 22 seconds 5 - 30 seconds 6 - 45 seconds	• Complete survivability for all burns. • Slightly higher throat erosion rate, as compared to Gen. II nozzle • Moderate nozzle Exit Erosion Rate. • RCFC-Composite support/heat-sink significantly more robust to thermal stresses, as compared to HBN. • Third-Generation nozzle PG-HT/RCFC is as to be a good compromise of between erosion-resistance vs material strength.

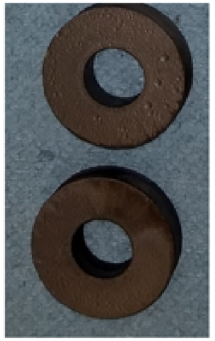


Comparing Erosion Onset Time and Rates of Erosion for the Baseline *Gr, RCC* Nozzles, & 1st, 2nd, 3rd Generation Low-Erosion Composite Nozzles.

PG-SN Throat

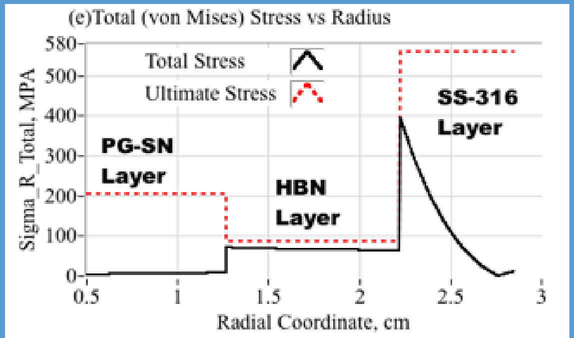
Post Burn Images

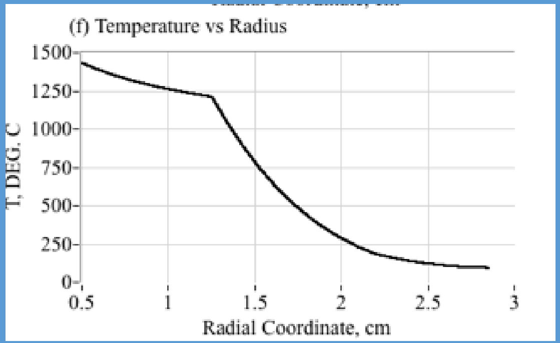
PG-HT Throat



Post-Burn Comparisons of PG-CH and PG-HT Nozzle Throat Inserts.

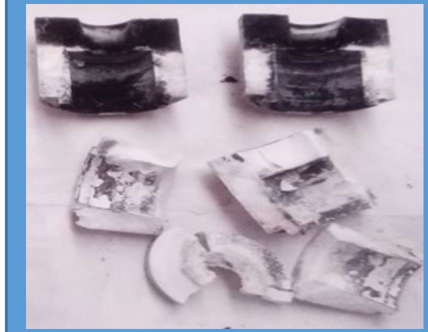
Nozzle Survivability Assessment

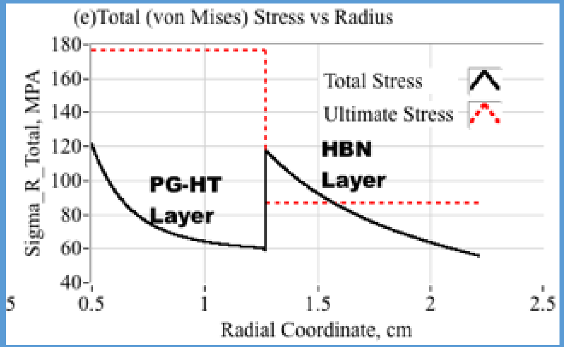


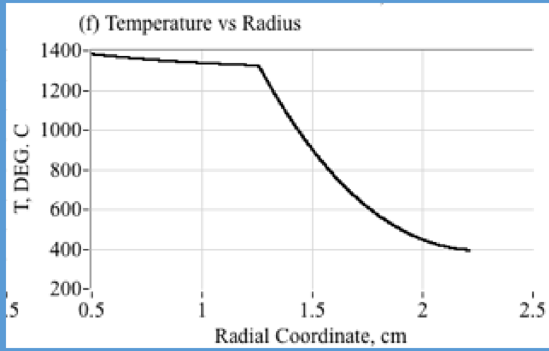


Thermally Induced Stress Failure of HBN Layer, Gen-1 Nozzle after 15-sec Burn

2-D Axisymmetric Thermal Stress Model Gen-1 Nozzle

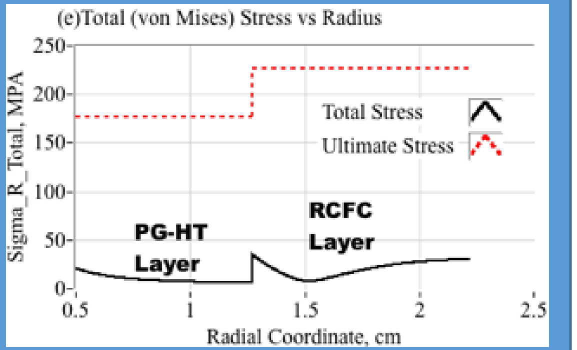


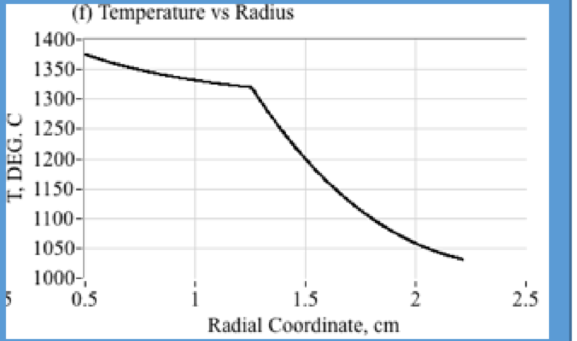




Thermally Induced Stress Failures of HBN Layer, Gen-2 Nozzle after 15-sec Burn

2-D Axisymmetric Thermal Stress Model Gen-2 Nozzle





2-D Axisymmetric Thermal Stress Model Gen-3 Nozzle

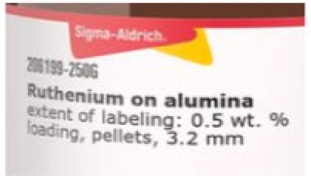
Low-Erosion Nozzle Development Summary Conclusion

- Three Generations of Low Erosion Nozzles for Hybrid Rockets were Investigated in this Development Campaign.
- Basic design features a high thermal conductivity PGr throat, surrounded by high heat capacity, heat sink.
- Gen-1, Gen-2 Composite PGr/HBN nozzle is highly effective and **shows a 5-fold decrease in erosion rates when compared to a graphite nozzle under similar burn conditions.**
- Unfortunately, because HBN has low thermal conductivity, large thermal gradients and uneven thermal expansion occurs. Associated thermal stresses resulted in nozzle failure for burns longer than 15 second.
- When HBN insulating layer replaced by RCFC (carbon/carbon), erosion rate is moderately higher, but nozzle survivability rate is significantly increased.
- Third-Generation PG-HT/RCFC nozzle is a good compromise of between erosion-resistance vs material strength/survivability.

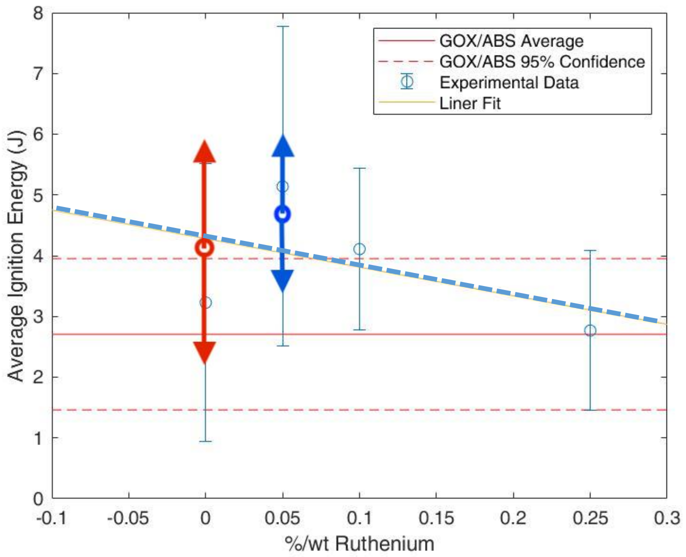
Engineered Hybrid Fuel Materials, High-Density Oxidizer Development

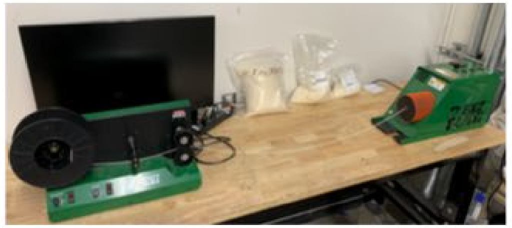
Background

- Gaseous Oxygen (GOX) is a safe and effective oxidizer for hybrid rockets, but due to low density is volumetrically inefficient at manageable pressures.
- Nitrous oxide (N_2O) is a significantly denser two-phase oxidizer, but is prone to uncontrolled decomposition events when exposed to contaminants and heat, i.e. during motor burn
- Nytrox is an 85/15% blend of N_2O and GOX that exhibits significantly safer operating properties while remaining nearly as dense as pure N_2O.
- Nytrox has unreliable ignition when used as a drop-in replacement in a GOX hybrid rocket system
- A solution with reliable ignition uses an additively manufactured fuel grain with custom-made ABS filament infused with ***ruthenium on alumina*** catalyst

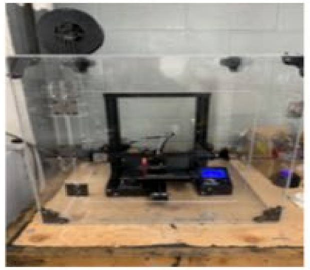


Catalyst-Infused Filament

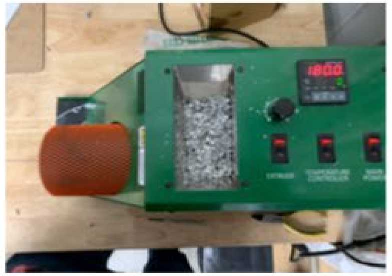




Filabot with Extruded Feedstock Filament



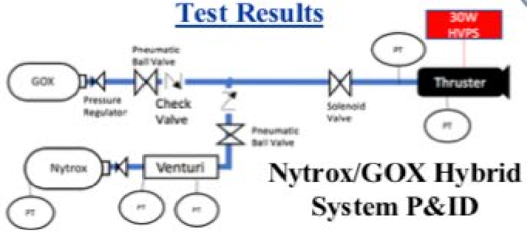
Catalyst-Infused Fuel Grain During Printing, Ender-3 FDM Printer



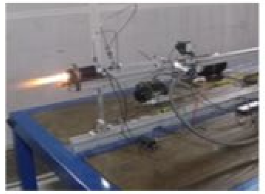
Shredded and Milled Catalyst-Infused ABS pieces in Filabot Hopper before Filament Extrusion

Plain ABS Fuel Grain, Ignition Slots, and Catalyst Insert with 2% Ru/Al_2O_3 Infusion

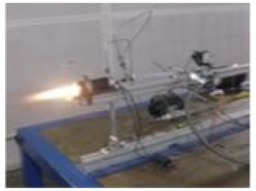
Test Results



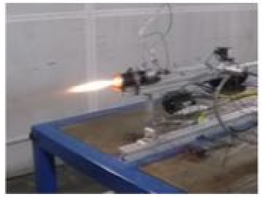
Nytrox/GOX Hybrid System P&ID



GOX/ABS Hot Fire

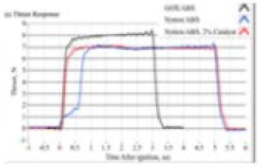


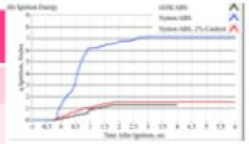
Nytrox/ABS Hot Fire

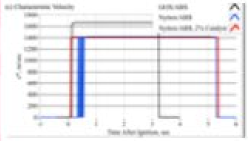


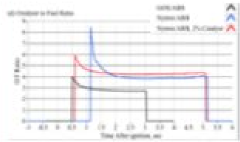
Nytrox/ABS/2% Ru/Al_2O_3 Hot Fire

Parameter	GOX/ ABS	Nytrox /ABS	[illegible]
Ignition Latency	0.42 sec	0.56 sec	1.041.79 1
Required Ignition Energy	1.20 Joules	1.43 Joules	7.05 Joules
C^*	1620 m/sec	1405 m/sec	1401 m/sec
I_{sp}	225 sec	192 sec	189 sec
O/F Ratio	2.367	3.722	3.677
Best Performance O/F Ratio	1.75	4.50	4.48
Equivalence Ratio	1.232	1.788	1.791
Best Performance Equivalence Ratio	1.667	1.479	1.470
Mean Specific Gravity of Propellants	0.397	0.720	0.726
Impulse Density, $\rho \cdot I_{sp}$	893.3 N-s/liter	1382.4 N-s/liter	1379.4 N-s/liter



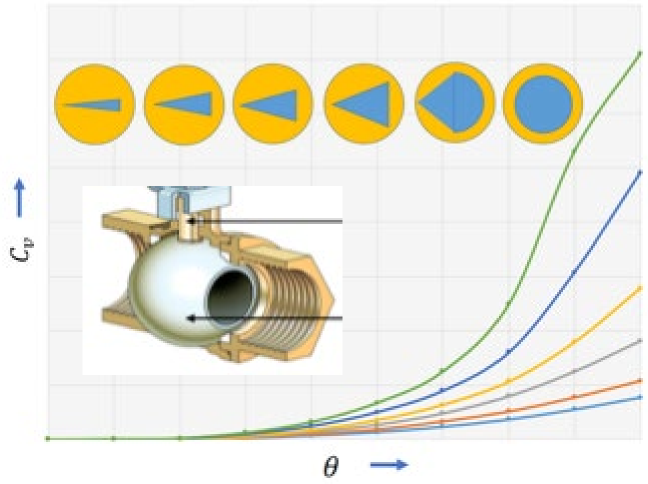




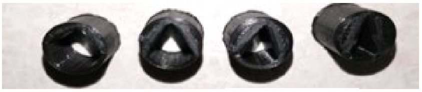


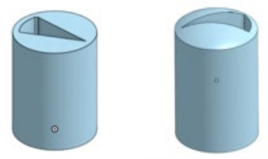
Throttling of Hybrid System

- Why Throttle Hybrid Rockets?
- Hybrid rockets offer the potential for "smart stages" launch vehicles, where propulsion operation is coupled with vehicle trajectory.
- When properly optimized hybrids have potential to significantly out-perform solid propellant systems, and may provide equivalent performance to bi-propellant liquid systems.
- Ability for hybrid systems to deeply throttle also offers potential for hybrid systems to perform both orbital insertion and on-orbit maneuvering functions.
- Precision-Throttle Necessary Requirement for Powered-Descent Lunar/Planetary Landings
  - Static "HOT-FIRE" testing using PRL's legacy 98 mm (4 inch) ABS/GOX hybrid motor
  - Stable Throttle to 80% Turndown
  - Open-Loop Throttle testing matrix completed During February 2022
  - 7 Total Throttle Tests

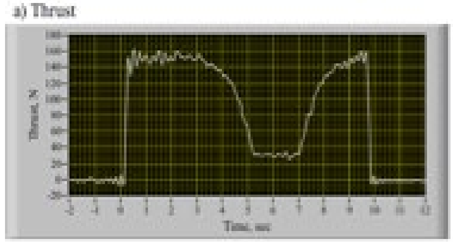


Ball-Throttle Valve V-Slot Port Configurations

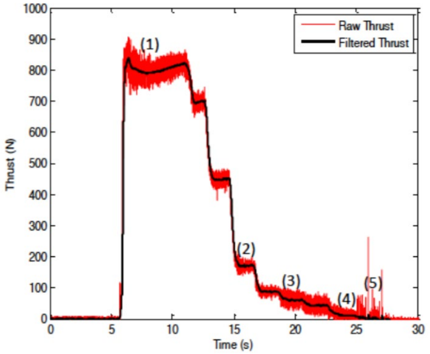




Cycled-Throttle Test



Deep Throttle Test



Deep Throttle Test

Questions?