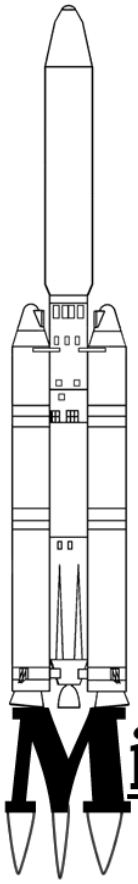
DEFENSE ENERGY SUPPORT CENTER



MissileFuels

Missile Fuels 101

Presented at DESC's Worldwide Energy Conference
September 28 - 29, 2004

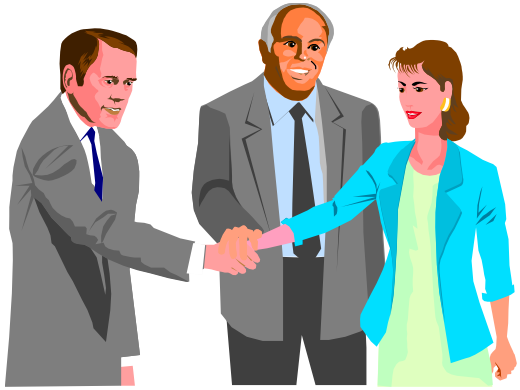
Sharon Murphy
Director
Missile Fuels Commodity Business Unit
Defense Energy Support Center

Missile Fuels CBU Mission Statement

To provide the Department of Defense, Federal Government customers, and commercial and academic space-related customers, with comprehensive logistics support for all missile fuels, chemicals and gases, cryogenic liquids and propellants in the most effective and economical manner possible.

Customer Support Profile

- **DoD's Integrated Materiel Manager for Missile Fuels products and services**
  - **DoD 4140.25M**
- **266 Customers**
  - **Includes commercial Space Launch Act**
- **213 Supply Points**
- **21 Controlled Storage Points containing DLA-owned product**
- **FY03 Sales: $69M**
- **Not BIG BUCKS but BIG Support to DoD Major Weapons/Space Programs**



Missile Fuels Customer Profile (FY 2003)

	#	%
• **DoD**		
Air Force	109	41%
Army	44	16%
Navy	10	4%
USMC	2	1%
Subtotal DoD	165	62%
• **Federal Civilian**		
NASA	16	5%
DOE	1	1%
Subtotal Federal Civilian	17	6%
• **Commercial**	84	32%
Total	266	100%

Product Line Overview

- **92 NSN's – 32 types of products/65 product classes**
- **Propellants**
  - **Hypergols**
  - **Liquids**
  - **Cryogenics**
- **Non-Propellant Cryogenics**
- **Gases**
- **Every product supports a DoD major weapon system or DoD space application in some way**

Chemicals and Gases

DEFENSE ENERGY SUPPORT CENTER

CHEMICALS AND GASES

- Ar - Argon
- D2 - Deuterium
- GF2- Fluorine
- He- Helium
- IPA - Isopropyl Alcohol
- IRFNA - Inhibited Red Fuming Nitric Acid
- JP 10 - Propellant
- Kr - Krypton
- Ne - Neon
- NF3 - Nitrogen Trifluoride
- PF1 - Priming Fluid
- RP1 – Rocket Propellant
- Xe - Xenon
- H2O2 - Hydrogen Peroxide

PROGRAMS/APPLICATIONS SUPPORTED:

- AIM - 9
- Stinger Missile
- Cruise Missile
- Shuttle
- Delta Launch
- MIRCL Laser
- MTHEL Program
- Super Conductor Magnets
- EXIMER Laser
- Aerostat
- National Aerospace Plane (NASP)
- High Altitude Simulation (SSME)

Missile Propellants and Cryogenic Fluids

HYPERGOLS

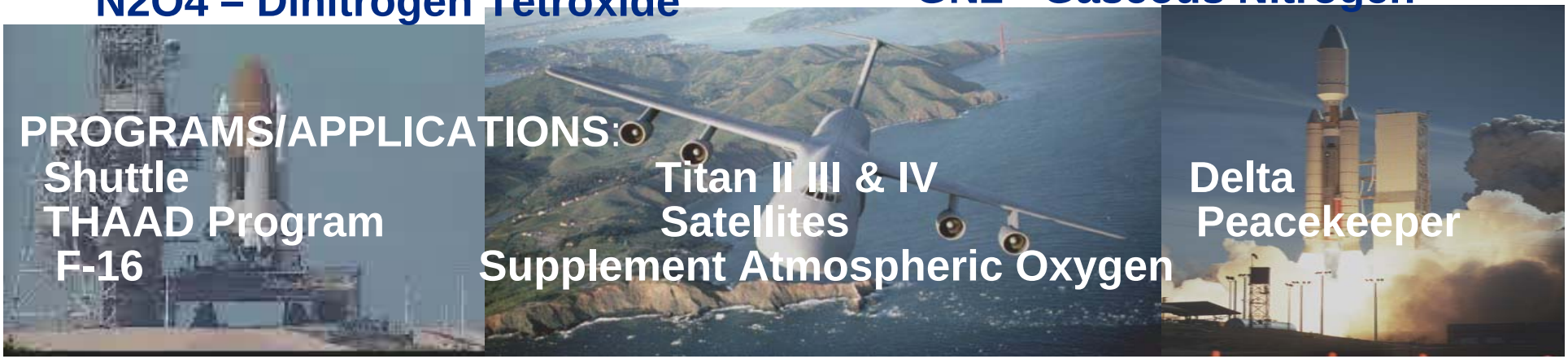
A-50 - Hydrazine / AH/UDMH MIX
AH - Hydrazine / Anhydrous
H-70 - Hydrazine / Water
MMH - Monomethylhydrazine
MPH – Monopropellant
HPH – High Purity Hydrazine
UDMH - Unsymmetrical-Dimethylhydrazine
N_2O_4 – Dinitrogen Tetroxide

CRYOGENIC FLUIDS

Liquid Air
LN2 - Liquid Nitrogen
LO2 - Liquid Oxygen
LH2 – Liquid Hydrogen

Gases

GH2 - Gaseous Hydrogen
GN2 - Gaseous Nitrogen



Contracting Snapshot

- 77 Active contracts
  - 95% Requirements-type contracts
  - Existing contracts are normally 3 year contracts w/two one year options
  - Moving toward multi year contracts – 3 to 5 year
  - Most are without Economic Price Adjustment
    - Re engineering this process
  - FOB Origin and Destination
- "Cradle to Grave" – Pre-award to contract closeout

Best Value Source Selection

- All Contracts
- Majority are Low Price Technically Acceptable
  - Technically Acceptable or Technically Unacceptable
  - Technical Capability and Past Performance
  - Technical Proposals limited to 5 pages
- Also utilize the Trade Off Process
  - Always used when Industrial Base of <u>One</u>
  - N204, Hydrazine, JP-10, RP-1
  - Non-Cost Factors
    - Technical Capability
    - Management and Mission Capability
    - Past Performance
    - Socio Economic (over $5M)
  - Plus Price Evaluation
    - Approx equal to Non Cost Factors
  - Tech Eval Team
    - MIC, MIP, BP, BQ and MK
    - Sometimes the customer

Integrated Materiel Manager

- **DoD's IMM for Missile Fuel Products and Services**

Benefit to Customer

- Aggregate requirements
  - Gov't program buying power
  - Specialty products
  - Production run management
- Innovative & specialized supply solutions
  - Hazardous material services
  - Controlled Storage Points
  - Responsive delivery modes (pipeline, bulk)
  - Strategic supply points - Commercial

Benefit to Customer

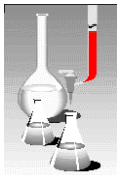
- Technical product management
  - Assure supplier base
  - Quality assurance
  - Responsive specification management
  - Expert “niche product” staff
  - Technical committee membership
- We do the specialized product logistics so customers don’t have to

Total Supply Chain Management

Safety

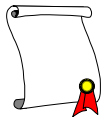
Finance

Quality



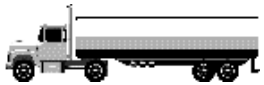
Chemist

Contracting



Inventory Management

Transportation



Benefit to Customer

- Customers can focus on their mission – don’t have to “sweat the small stuff”

Transportation

- Special handling
- Technical escort
- Container management
- Initiatives
- Special projects

Container Management

- Accountable Property Officer
  - Government owned and leased (9,000 pieces)
    - Built product/customer specific
      - ✓N2O4, hydrazine, nitric acid, argon; cannot get commercial off the shelf
      - ✓Pedigree maintained; track by serial number; ensure customer receives same container repeatedly; reduces risk of contamination
      - ✓Too costly for contractors/customers; longevity of government contracts uncertain for investment

3780 Helium

4213 Argon

330 Hydrazine

60 Dinitrogen Tetroxide

35 4BW Dinitrogen Tetroxide Cylinders

320 Hydrazine
95 Nitric Acid

8 Deuterium

6 Nitrogen Trifluoride

24 Helium

25 Helium Leased

8 Hydrazine Leased

8 Dinitrogen Tetroxide Leased

13 Hydrazine (9 for storage)

8 Dinitrogen Tetroxide

2 NASA

TN-1
1067
DINITROGEN TETROXIDE, LIQUIFIED
SOLUTION
INHALATION HAZARD
1067
2
OXIDIZER
CORROSIVE
NO SMOKING WITHIN 200 FT.

How To Order

- Identify support
  - Program supported
  - Product
  - Unit pack
  - Quantity
  - Delivery address and date
  - Order detail
- Identify the funding
  - Billing information
- Program POCs

Summary

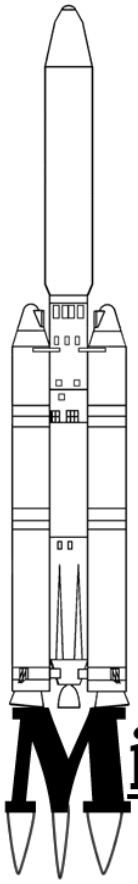
- Customer service is our #1 priority
- Experts in management of hazardous materials
- Well known in aerospace and fuels communities
- Proactive
- Economies of scale for best pricing

Points of Contact

Inventory Mgmt	Melanie Mueller	melanie.mueller@dla.mil
Transportation	Cathy Mokry	catherine.mokry@dla.mil
Packaging	Joe Bresnok	joseph.bresnok@dla.mil
Marketing	Charlene Smoot	charlene.smoot@dla.mil
Technical	Ken Grams	ken.grams@dla.mil
Quality	Rod Fischer	rodney.fischer@dla.mil

Web Site: www.desc.dla.mil

DEFENSE ENERGY SUPPORT CENTER



MissileFuels

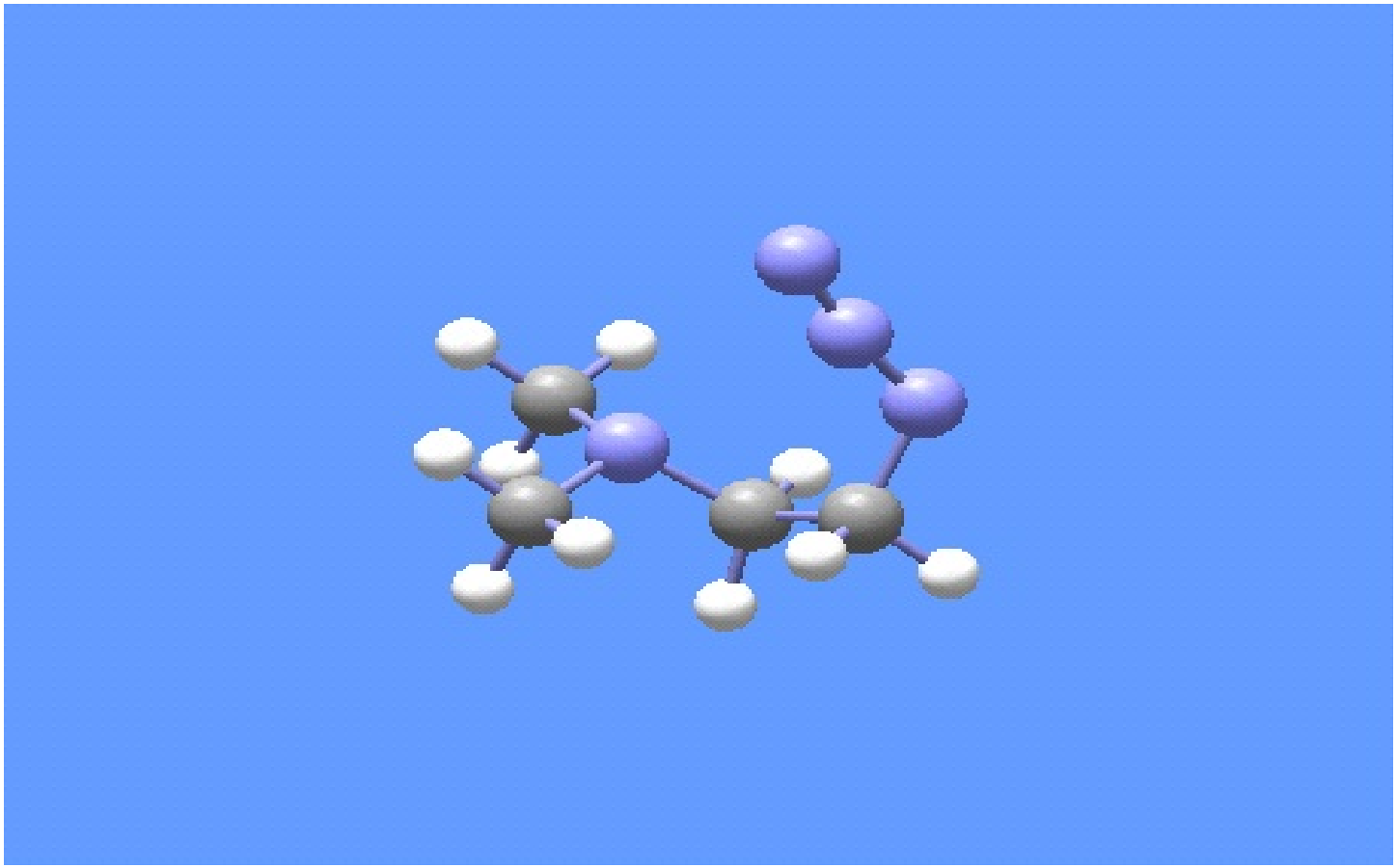
A Short History of Dimethylaminoethylazide (DMAZ)

Authored D.M. Thompson
Presented by Dr. W.M. Chew
U.S. Army Research, Development and Engineering Command
Aviation and Missile Research, Development and Engineering Center
AMSRD-AMR-RD-PS-R

In the Beginning

- DMAZ was conceived as a MMH replacement in 1994
- DMAZ was developed as an attempt to make an azide material that was also hypergolic
- DMAZ has also proved to be multifunctional in its applications
  - Hypergolic fuel with…
    - Inhibited Red Fuming Nitric Acid
    - Concentrated Hydrogen Peroxide
  - LOX/DMAZ Bipropellant
  - Monopropellant
  - Model Airplane Fuel Alternative

Dimethylaminoethylazide (DMAZ)



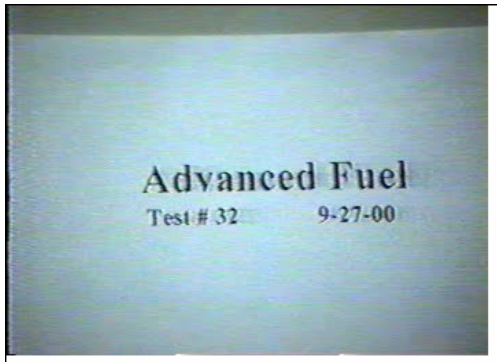
DMAZ vs. MMH

- Equivalent Performance (by mass or volume)
- Wider Temperature Range as a Liquid
  - Lower Freezing Point
  - Higher Boiling Point
- DMAZ is 6X lower in vapor pressure
  - Minimizes exposure in air
- DMAZ is 30X less toxic (based on LD-50 acute toxicity)

DMAZ and Inhibited Red Fuming Nitric Acid (IRFNA)

- IRFNA/DMAZ
  - 1600 psi chamber pressure
  - 99% C* Efficiency
  - Same L* as Titan

DMAZ and Gaseous Oxygen (GOX)



No Picture

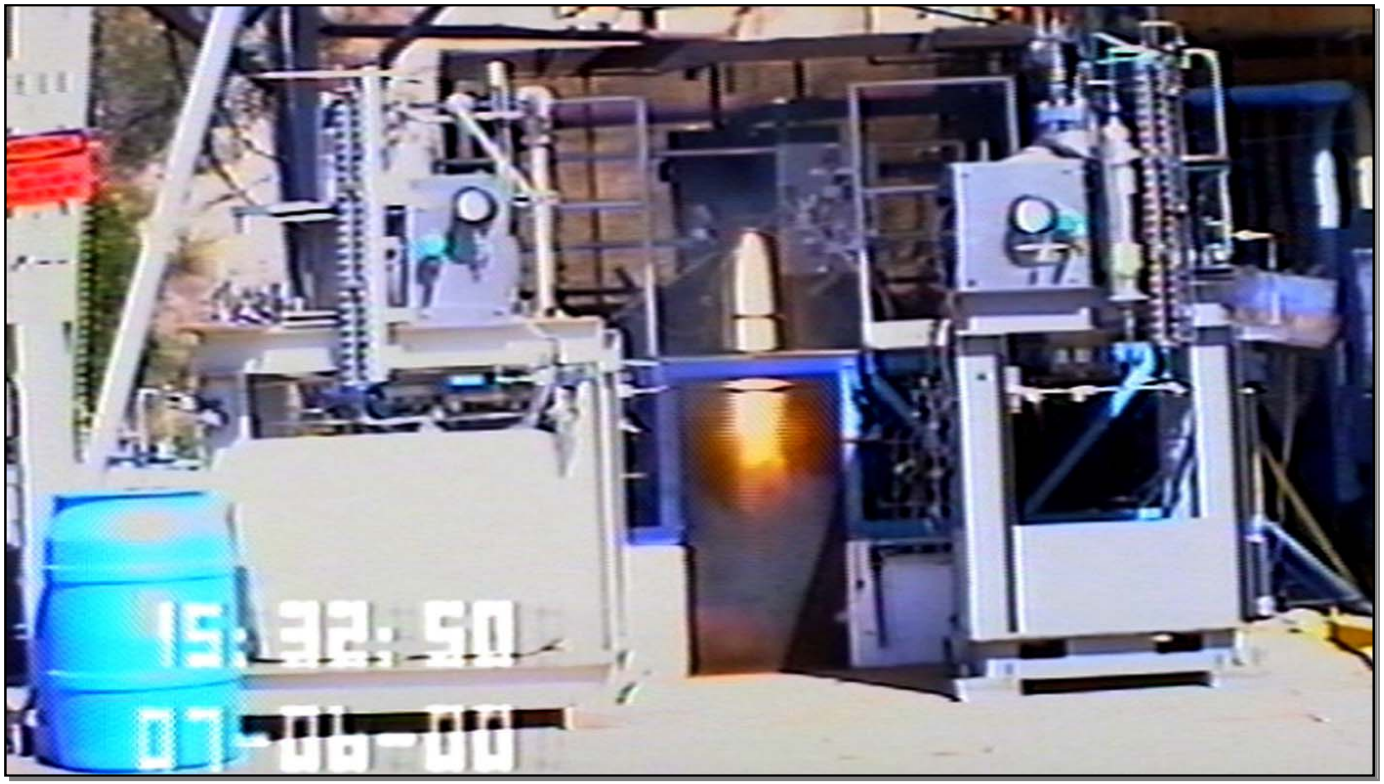
goxdmaz1

DMAZ and GOX

No Picture

goxdmaz2

DMAZ and Hydrogen Peroxide



DMAZ as a Monopropellant

- Hydrazine is state-of-the-art for monopropellant thrusters
  - Hydrazine is also carcinogenic
- DMAZ is also a monopropellant
  - Uses same catalyst as hydrazine
  - 15X less toxic than hydrazine
- Chamber pressure, 500-2500 psi
- Chamber Temperature, 650-800 Celsius
- Up to 24 seconds of operation

DMAZ as Monopropellant

atrgg05

Model Airplane Fuel

- Model Airplane Fuel is typically a mixture of nitromethane, ethanol and castor oil (castor oil is used to lube the piston)
- A hobbyist in southern California obtained a sample of DMAZ from 3M and was interested in using it in model airplanes. Darren Thompson suggested a formulation (80% DMAZ, 20% Castor Oil) that delivered 10% more rpm (11,000 vs. 10,000) than a 5% nitromethane formulation.

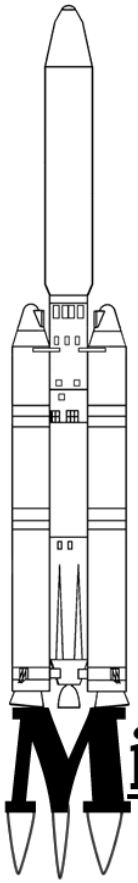
Transition to Industry

- 3M
  - Produced 100 lbs. in pilot plant scale production, June ’99
  - Produced more than 1000 lbs. in pilot plant scale production since
  - Very Strong Marketing Effort
  - POC Dr. Tony Manzara (651) 458-1392
- Mach I, Inc.
  - 3M Distributor
  - Providing evaluation samples of DMAZ upon request
  - POC Bernie Kozowski (610) 279-2340

Conclusion

- DMAZ is a multifunctional liquid propellant with potential applications in the defense and commercial industries

DEFENSE ENERGY SUPPORT CENTER



MissileFuels

ADVANTAGES OF GEL BIPROPULSION

William M. Chew

World Wide Energy Conference

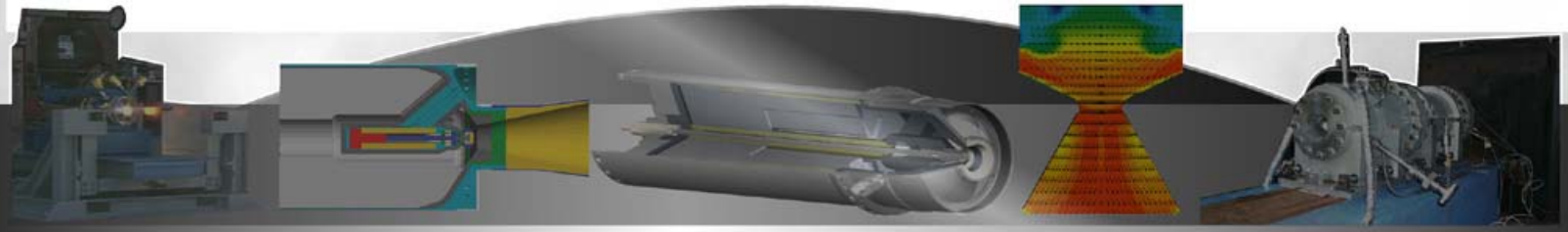
September 28, 2004

Propulsion & Structures Directorate
U.S. Army Aviation & Missile Command
Redstone Arsenal, AL

Army Transformation Goals

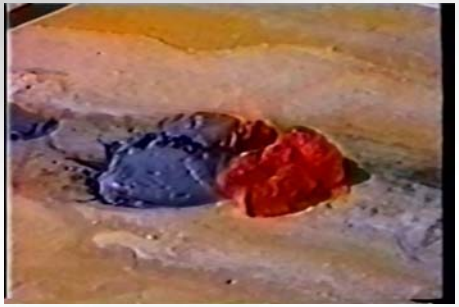
...A "Hands-On" Approach to Research & Development

- **Future weapons should be**:
  - Smaller
  - Lighter
  - More lethal
  - More reliable
  - Fuel efficient
  - More survivable
- **Survivability includes**:
  - Low observable plumes
  - Ballistic protection
  - Long range acquisition
  - Deep targeting
  - Early attack
  - First round kill at smaller caliber



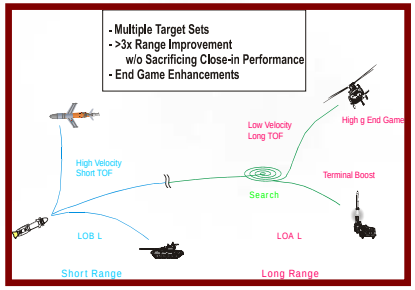
Advantages of Gel Propulsion

...A "Hands-On" Approach to Research & Development



Safety

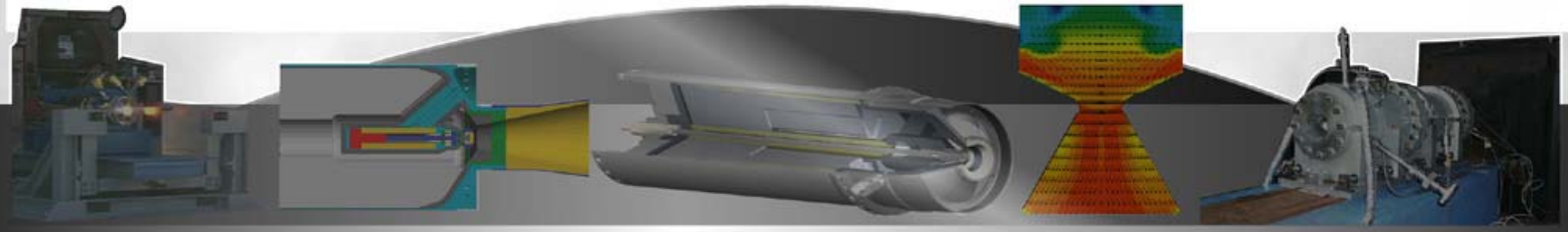
Logistics



Controllable Thrust

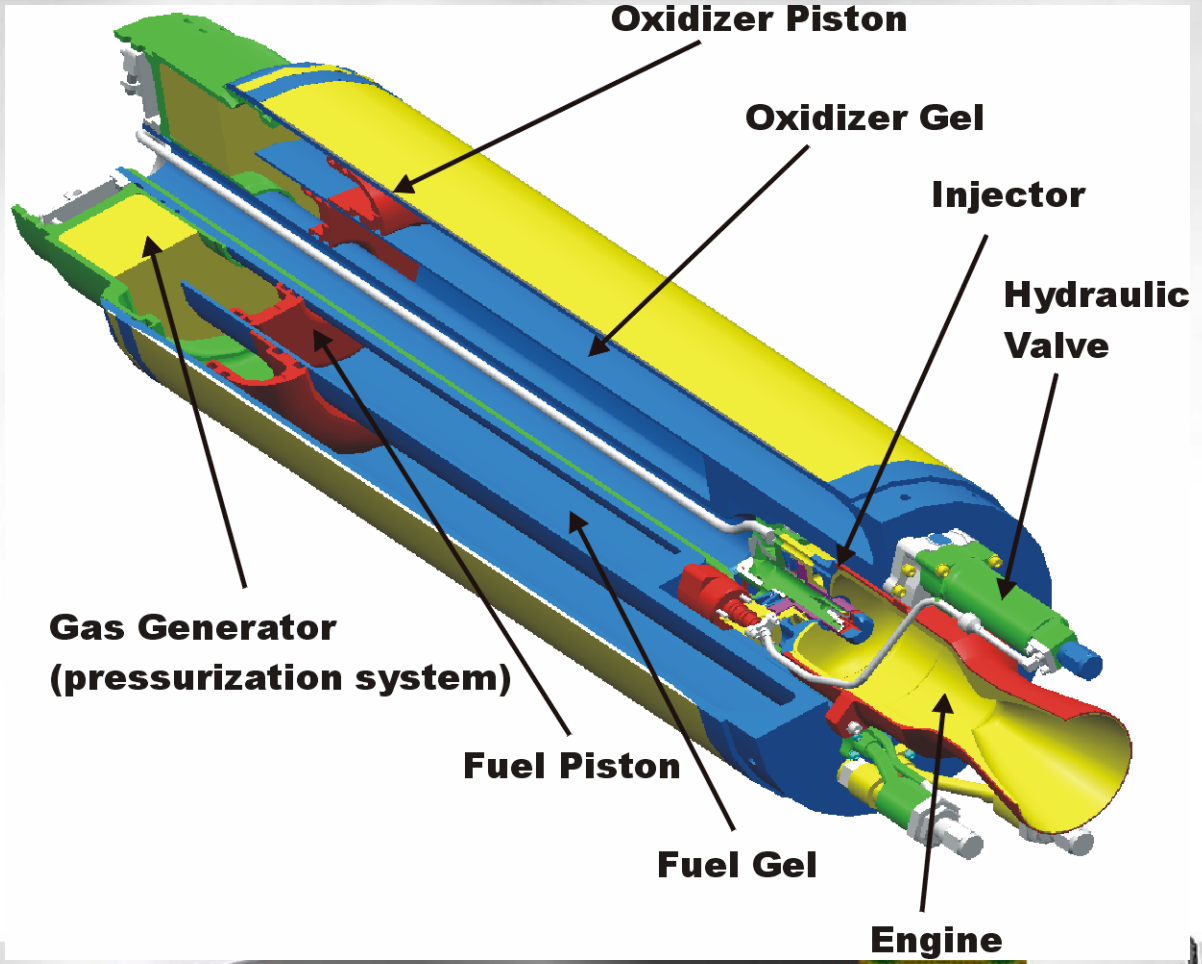
Mature

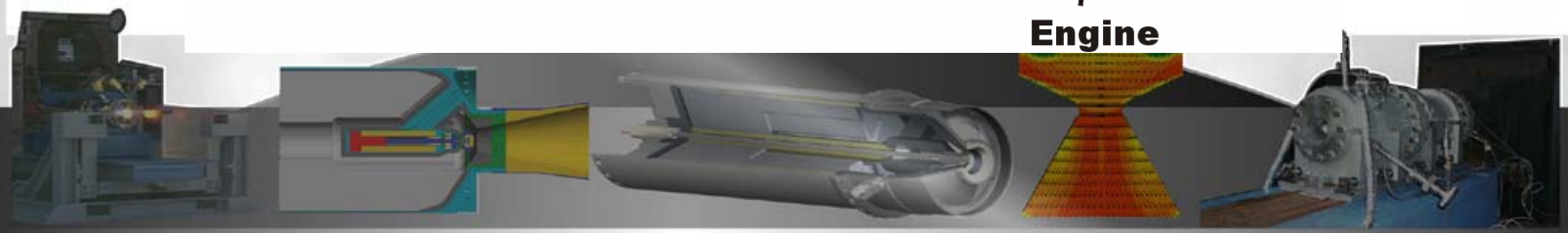
Performance



FMTI Schematic Diagram

...A "Hands-On" Approach to Research & Development

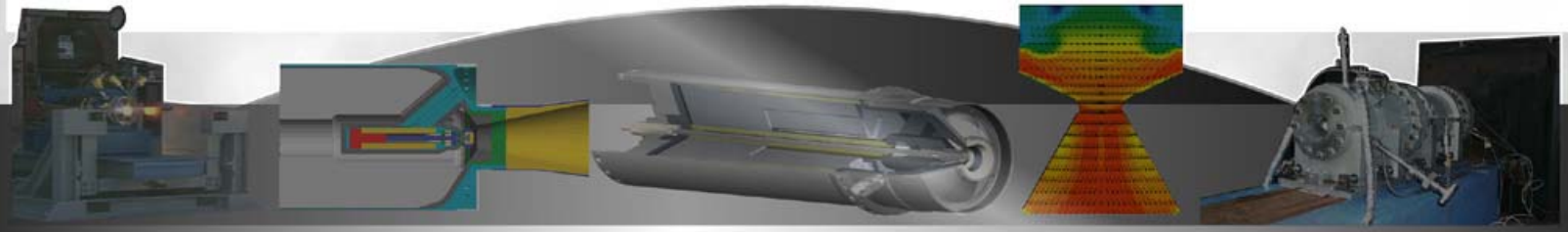




What Are Gelled Propellants?

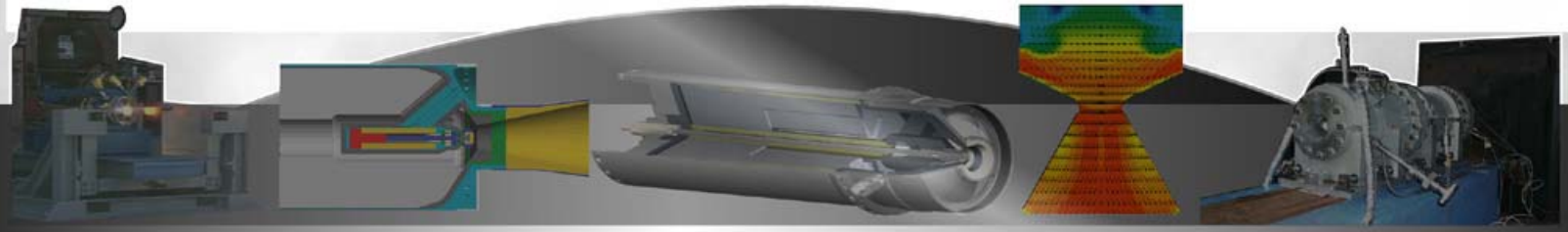
...A "Hands-On" Approach to Research & Development

- Gelled propellants are formed by adding a gellant to a liquid propellant.
- Gelled propellants are semi-solids.
  - Similar appearance to jelly
  - Won’t flow until a force is applied
  - Are shear thinning (viscosity decreases with increasing shear rate)



Gel Propellants

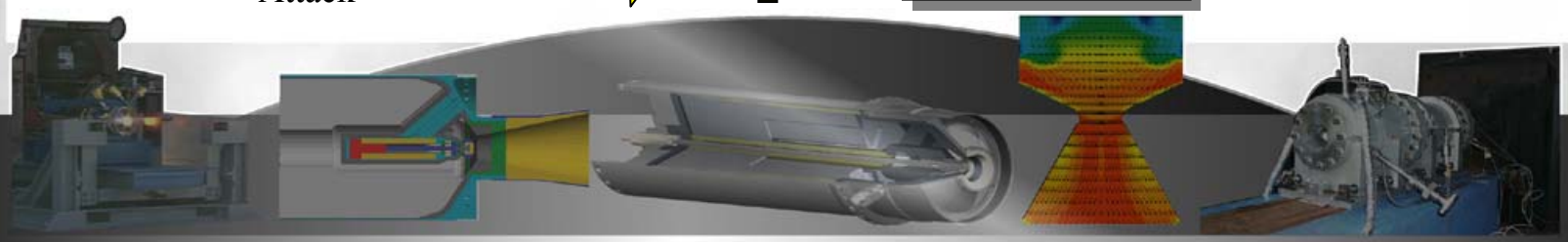
- **Advantages of gelling the liquid phase**
  - Gels are immobilized and will not spill if tank is ruptured, reducing the surface area of exposed propellant
    - Decreases the probability of exposure of hazardous material to personnel
    - Lowers the evaporation rate: longer safe response time
  - Gellation reduces vapor pressure
    - Neither fuel or oxidizer will reach Immediate Danger to Life or Health (IDLH) in an enclosed room.
    - Gives personnel time to don appropriate safety equipment for mitigation



Tests to Assess Insensitive Munitions (IM) Compatibility: MIL-STD-2105

...A "Hands-On" Approach to Research & Development

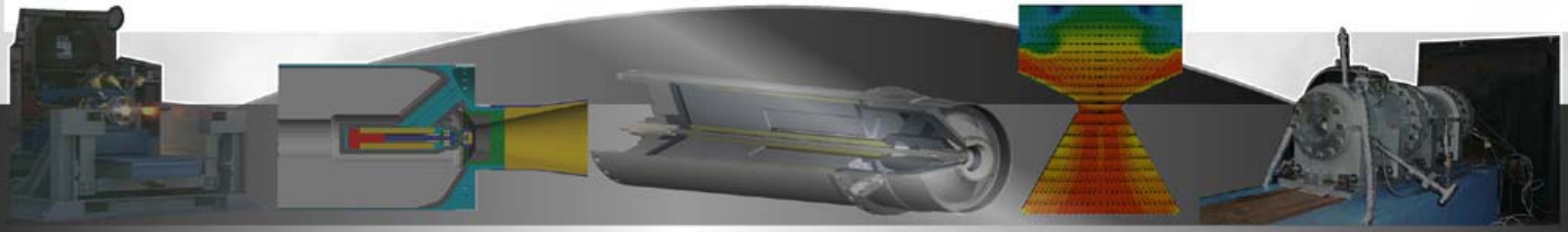
The Threats	The Tests
Shaped Charge Weapon Attack	Shaped Charge Jet Impact
Detonation in Magazine, Store, Aircraft or Vehicle	Sympathetic detonation
Magazine, Store, Aircraft or Vehicle Fuel Fire	Fast cook-off
Fire in Adjacent Magazine, Store, or Vehicle	Slow cook-off
Small Arms Attack	Bullet impact
Fragmenting Munitions Attack	Fragment impact



Gels Pass IM Tests

...A "Hands-On" Approach to Research & Development

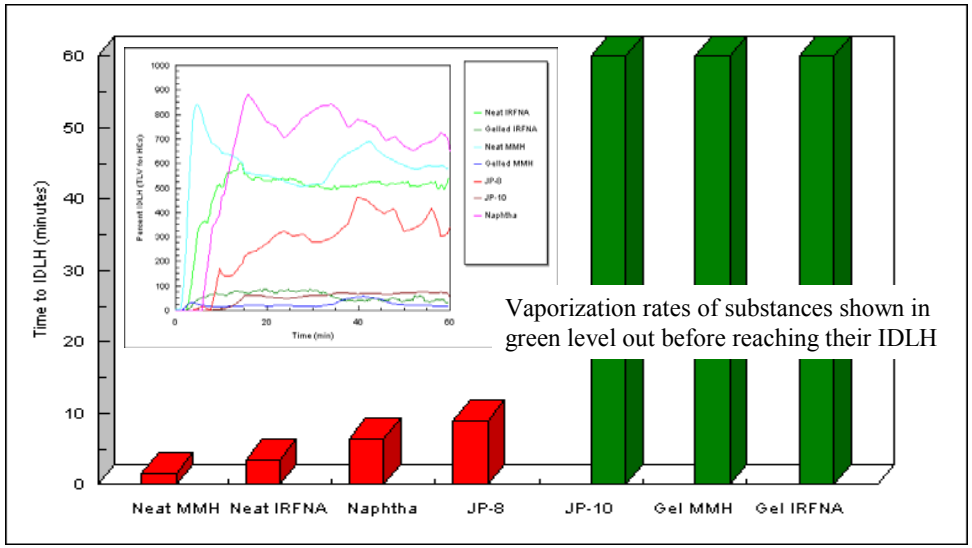
- Gels in tandem tank configuration have passed Bullet Impact, Fast Cook-off, Slow Cook-off, and Shaped Charge Jet Tests.
- By analogy, gel propulsion systems are expected to pass Fragment Impact (Bullet Impact) and Hot Spall (Shaped Charge Jet); Sympathetic Detonation should not be an issue with gels.
- Fuel and oxidizer gels are stored in separate tanks, therefore, are not as susceptible to IM threats as solid propellants with fuel and oxidizer in intimate contact.
- Gels are immobile, therefore will not flow out of ruptured tanks like liquid propellants.



Toxicity of Various Propellants as a % of their Individual IDLH* Level

TRW

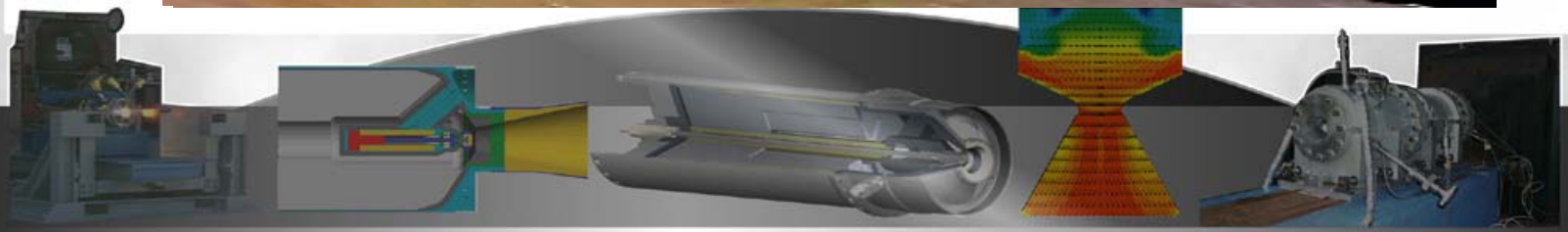
- Toxicity of gelled propellants is comparable to the toxicity of JP-10 which is already carried on board Navy ships and far less than Naptha, a currently approved shipboard cleanser used on Navy ships
  - Gelled Propellant spills can be neutralized with water and household chemicals
  - Storing gels in Army depots or vehicles will not impact missile life cycle cost
  - Naptha and JP-8 are known carcinogens, MMH is a suspected carcinogen



*Immediate Danger to Life and Health (IDLH)

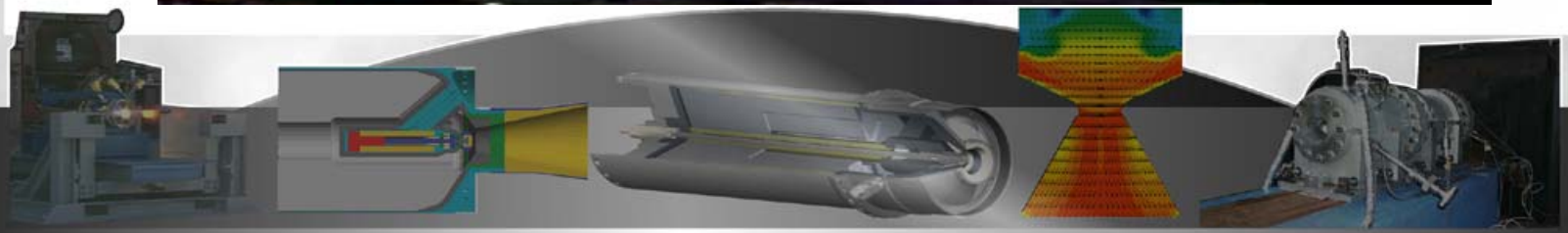
Gelled Propellants

...A "Hands-On" Approach to Research & Development



Cleans Up Easily With Water

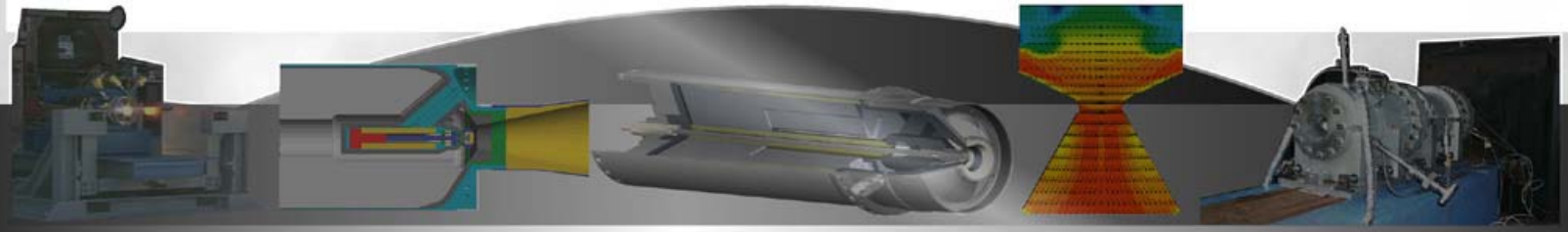
...A "Hands-On" Approach to Research & Development



Logistics Advantages

...A "Hands-On" Approach to Research & Development

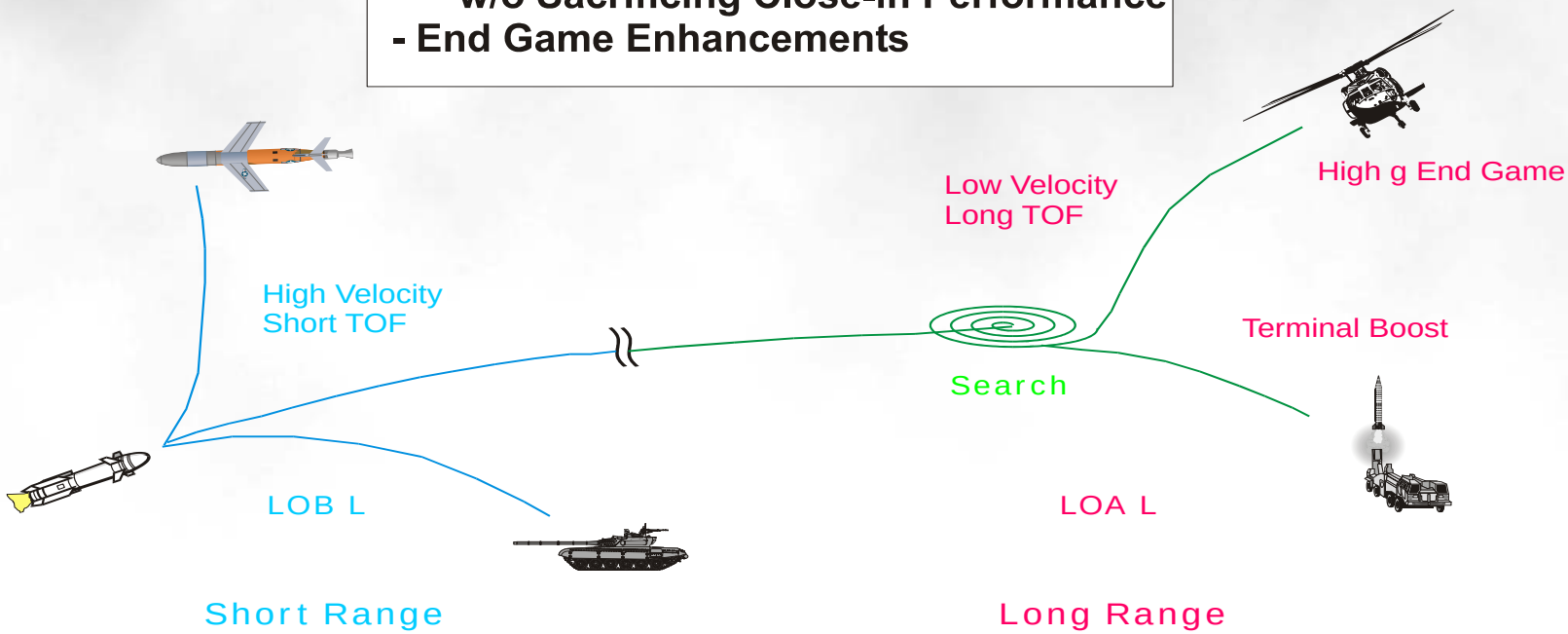
- **Multi-mission Capability Greatly Reduces System Lifetime Costs**
  - Lower training costs
  - Lower maintenance costs
  - Lower missile costs
- **Gel Propellants Are Easily Demilitarized**
- **Gel Propellants Have Long Shelf-life**
  - Low corrosion rates
  - 15 year-old gels have acceptable properties
  - Centrifuge tests suggest no settling
- **Storage and Transportation Procedures Being Adopted**
  - JANNAF's (Joint Army, Navy, NASA, and Air Force) Liquid Propulsion Subcommittee is developing recommended procedures
  - These will be sent to the DoD Explosive Safety Board for Adoption

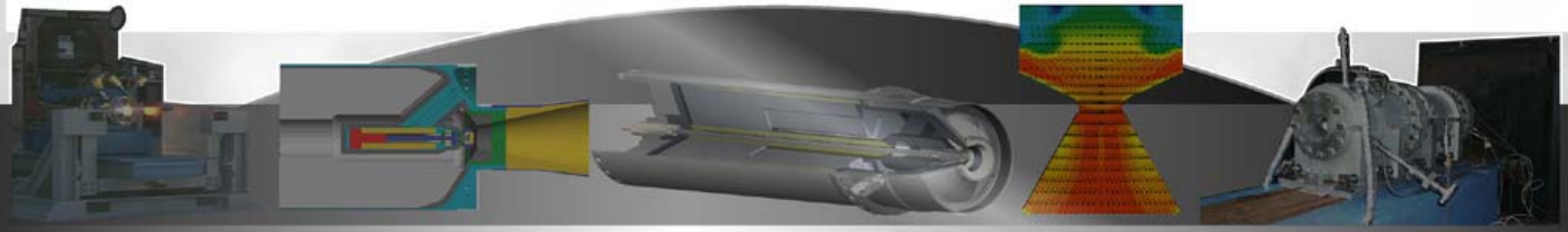


Applications of Controllable Thrust Propulsion

...A "Hands-On" Approach to Research & Development

- Multiple Target Sets
- >3x Range Improvement
  w/o Sacrificing Close-in Performance
- End Game Enhancements

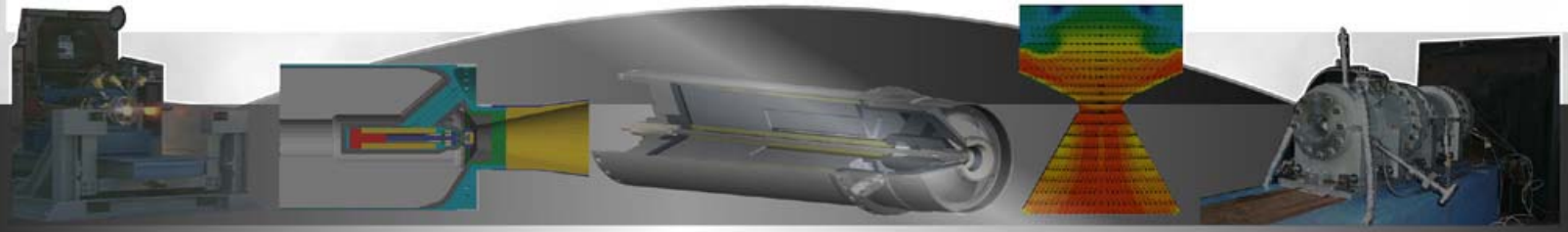




Gel Propulsion Provides High Performance

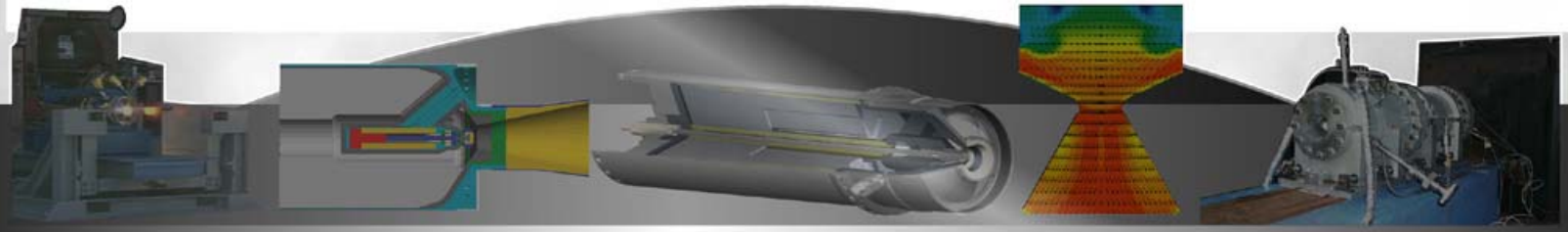
...A "Hands-On" Approach to Research & Development

- Gel Engine Tests Typically Have 260 lbf*s/lbm Specific Impulse
- Repeatable pulse widths of 2ms have been demonstrated
- Gel propulsion can provide high performance, minimum signature, and IM compliance in one system
- High-energy Solids Increase Performance
- Can Provide Controllable Thrust Using Pulse-width Modulation or Throttling
- Vortex Engine Provides High Combustion Efficiency at Low Cost



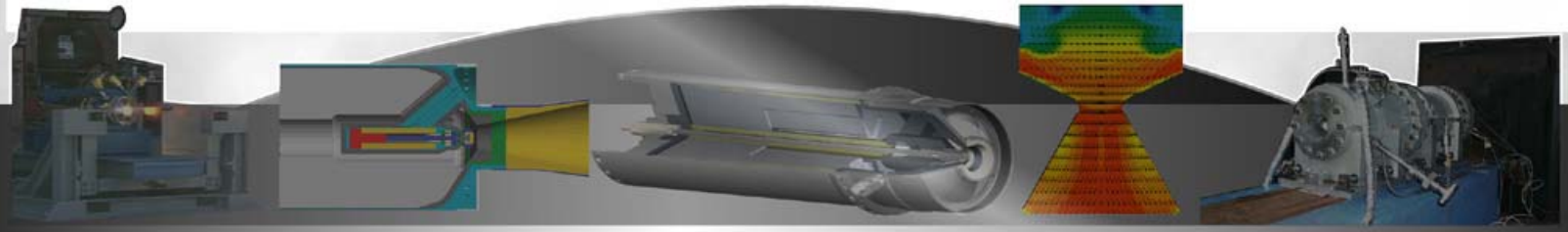
Gel Propulsion Have Been Demonstrate in Flight Tests

- Highly Successful FMTI Flight Tests in 1999 and 2000
  - Doubled the range of a deployed missile with the same shape, size, and using the same launcher
  - First flight test of gel propulsion
  - First flight test of tactical missile with thrust control
  - Demonstrated the ruggedness of gel propulsion systems



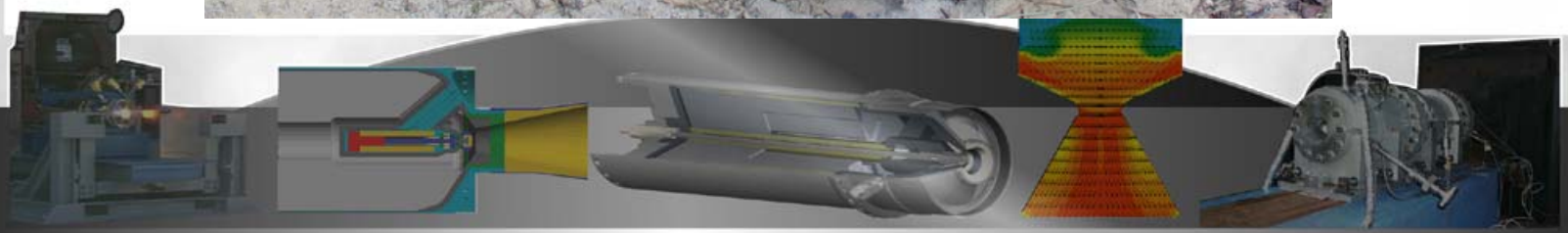
2000 FMTI Flight

...A "Hands-On" Approach to Research & Development



Survivable Propulsion System

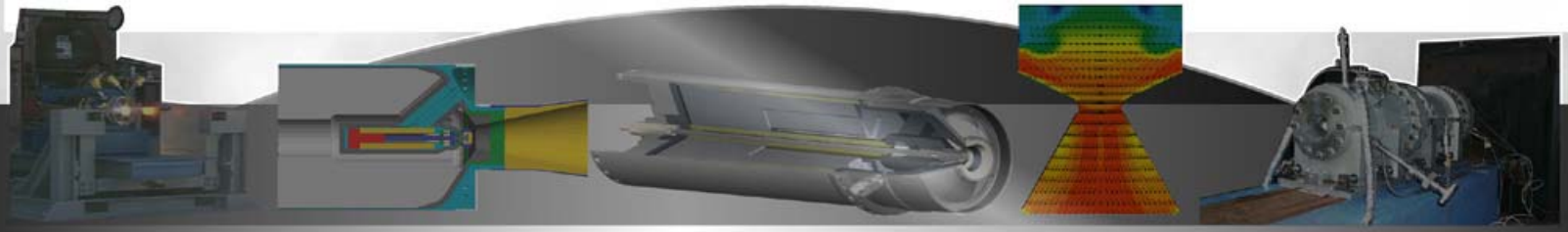
...A "Hands-On" Approach to Research & Development



Recent Progress

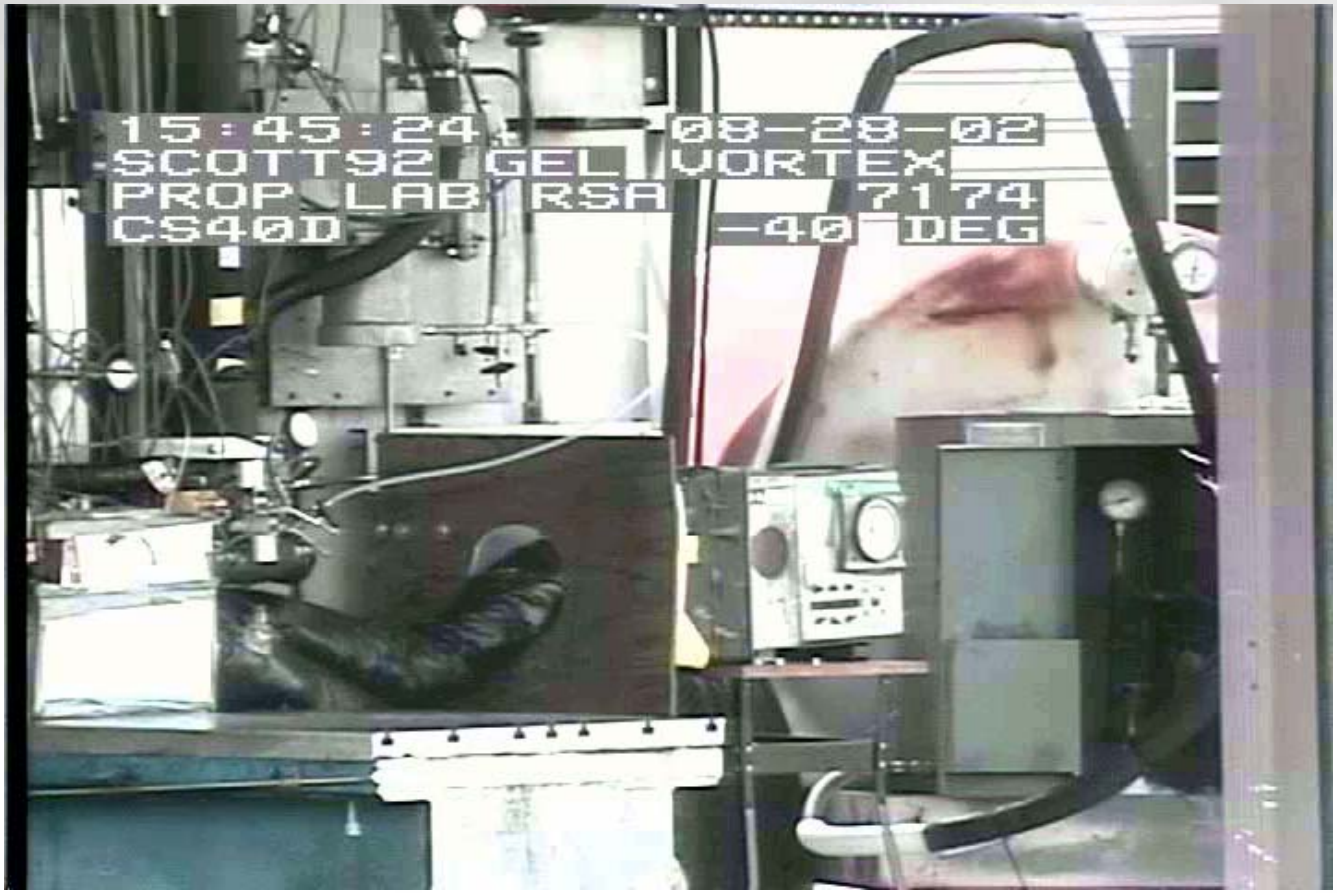
...A "Hands-On" Approach to Research & Development

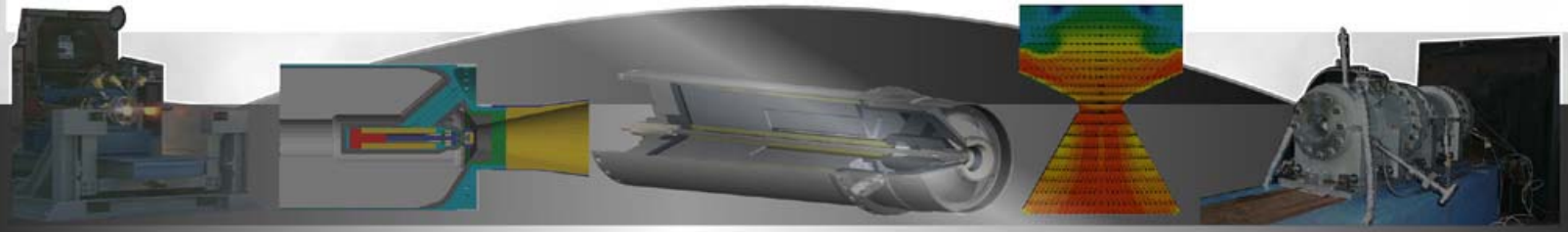
- Successful Engine Tests at -40°C
  - Face shut-off and vortex engines
  - Minimal O/F shift from ambient temperature
  - Small, expected drop in thrust
- Successful Constant Pressure Throttling
  - Vortex engine with passive spring controlled pintle
  - 12:1 turn-down ratio while maintaining Pc within 2%
- Successful Low Pressure, Low Thrust Engine Tests
  - Combustion chamber pressure lower than 100 psig
  - Thrust levels less than 100 Lbf
- Mixing and Combustion Models Being Experimentally Validated
- Gel Propellants in Tandem Tanks Passed Shaped Charge Jet IM Test



-40°C Engine Test

...A "Hands-On" Approach to Research & Development





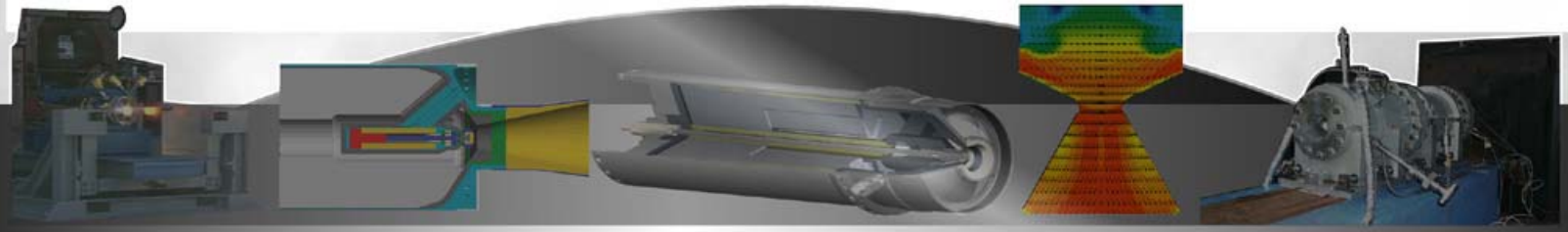
Pressure Controlled Throttling Engine

...A "Hands-On" Approach to Research & Development

Current Propellant Research

...A "Hands-On" Approach to Research & Development

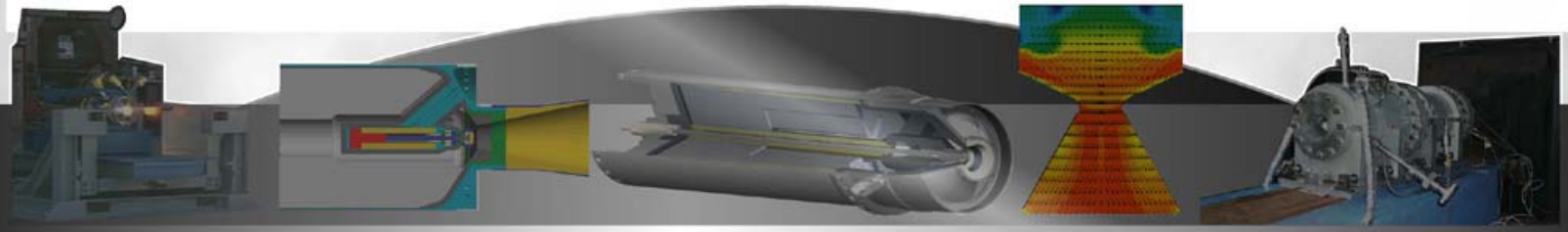
- Less toxic alternatives to MMH
- Advanced fuel gel formulations
- Rheological characterization
- Compatibility and shelf life
- Gel manufacture and quality control
- Reducing hazard classification for gelled propellants



Current Hardware Development

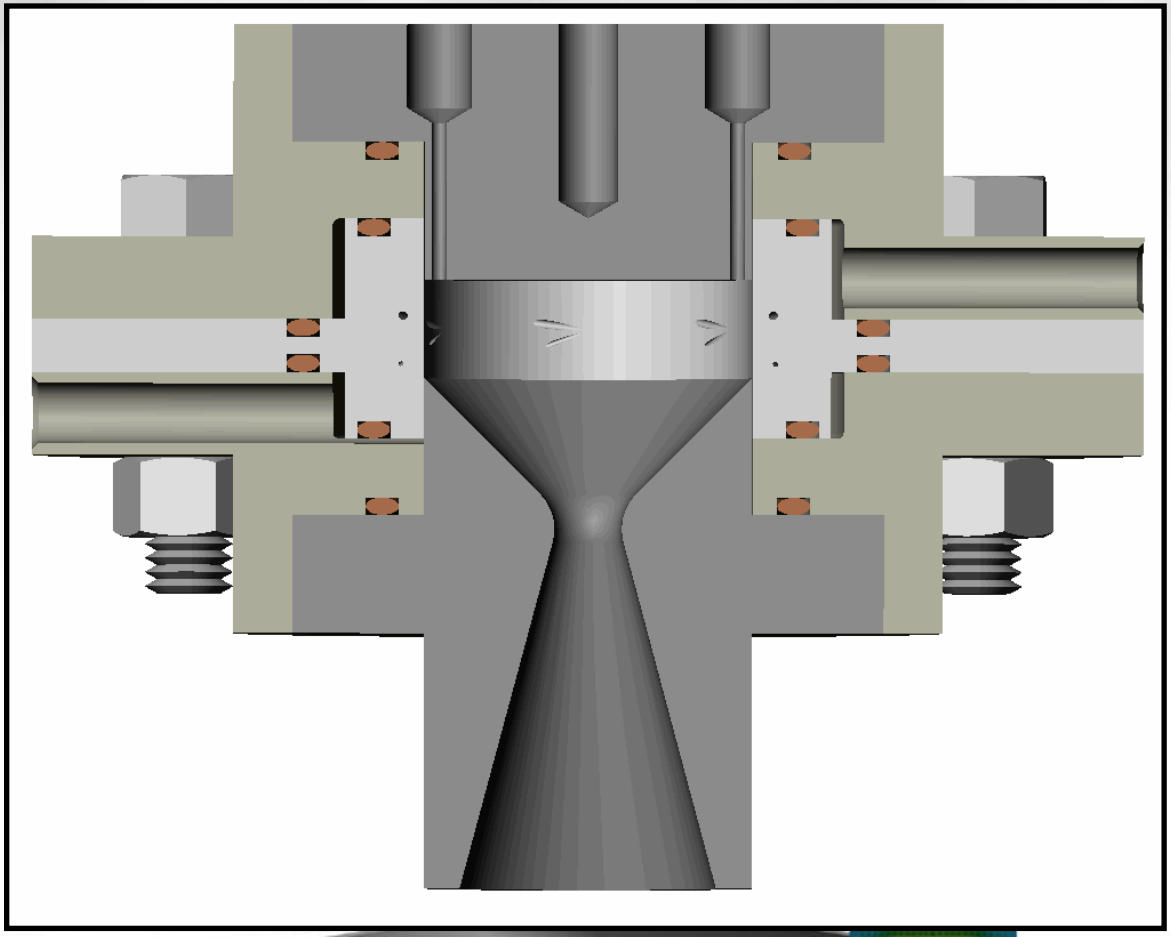
...A "Hands-On" Approach to Research & Development

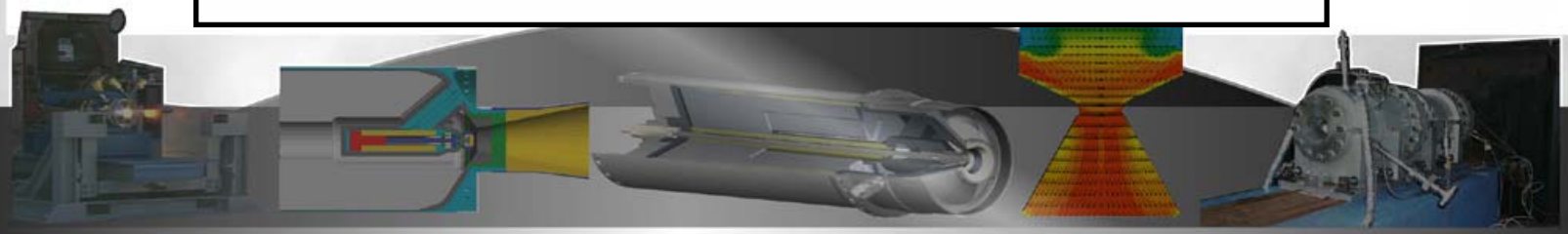
- Vortex Engine: small, inexpensive, efficient
- Advanced Tanks: coupled pistons for O/F control
- On-Demand Gas Generator: precise pressurization control, higher system efficiency
- Valves: gels don't require valves with high tolerances, minimal corrosion, and thousands of cycles



Vortex Engine

...A "Hands-On" Approach to Research & Development

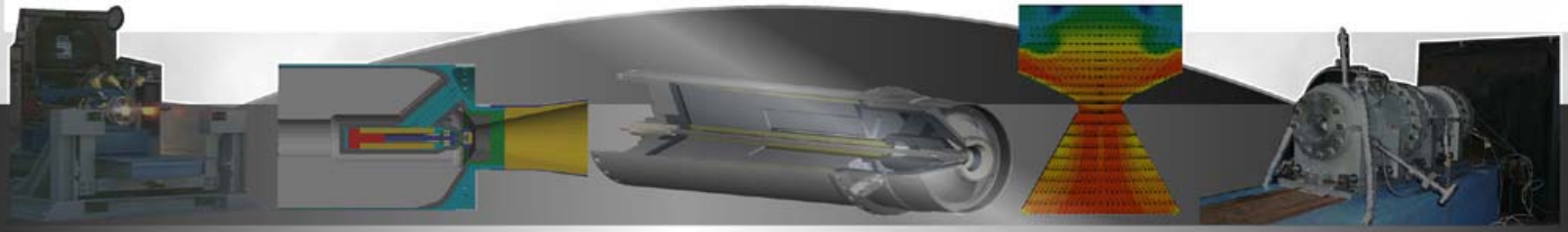




Leveraging with SBIR Programs

...A "Hands-On" Approach to Research & Development

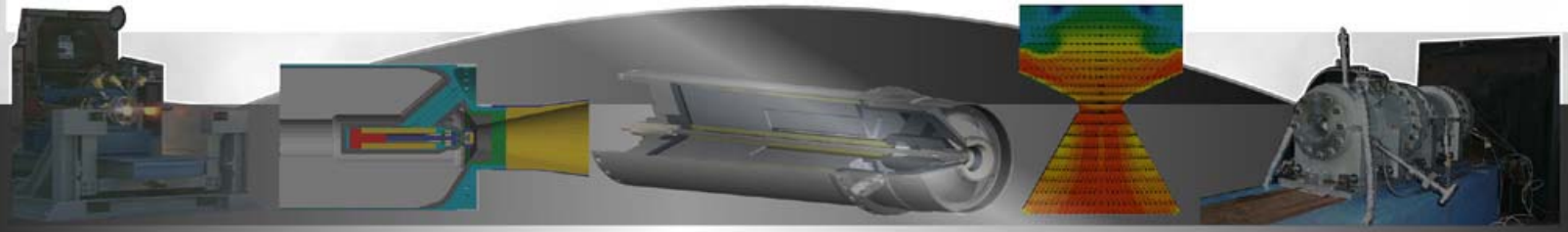
- Twenty Two Contracts for $14M
- Ten Topics
  - Pressure-controlled throttling engine
  - Gel mixers
  - Gas generator catalysts
  - Mixing and combustion modeling and experimental verification
  - Particulate fuel gellant
  - Time dependent, non-Newtonian rheometer
  - Gel propellant valve
  - Coupled piston gel tanks
  - Advanced fuel gel
  - Polymeric liner for propellant tanks



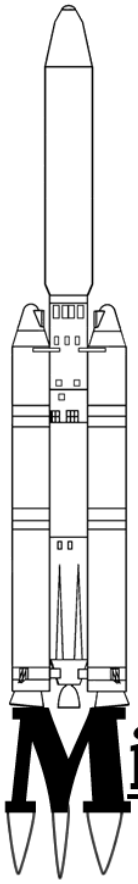
Conclusions

...A "Hands-On" Approach to Research & Development

- Gel propulsion is an exciting, revolutionary technology that provides greatly enhanced flexibility, range, and survivability.
- Gelled propellants are safe.
- Gel propulsion technology is mature - a TRL level of 6.



DEFENSE ENERGY SUPPORT CENTER



MissileFuels

Rocket Propellant Development Efforts at Purdue University

Professor Stephen (Steve) Heister

School of Aeronautics and Astronautics

Purdue University, West Lafayette, IN

World Wide Energy Conference

28 September, 2004

Outline

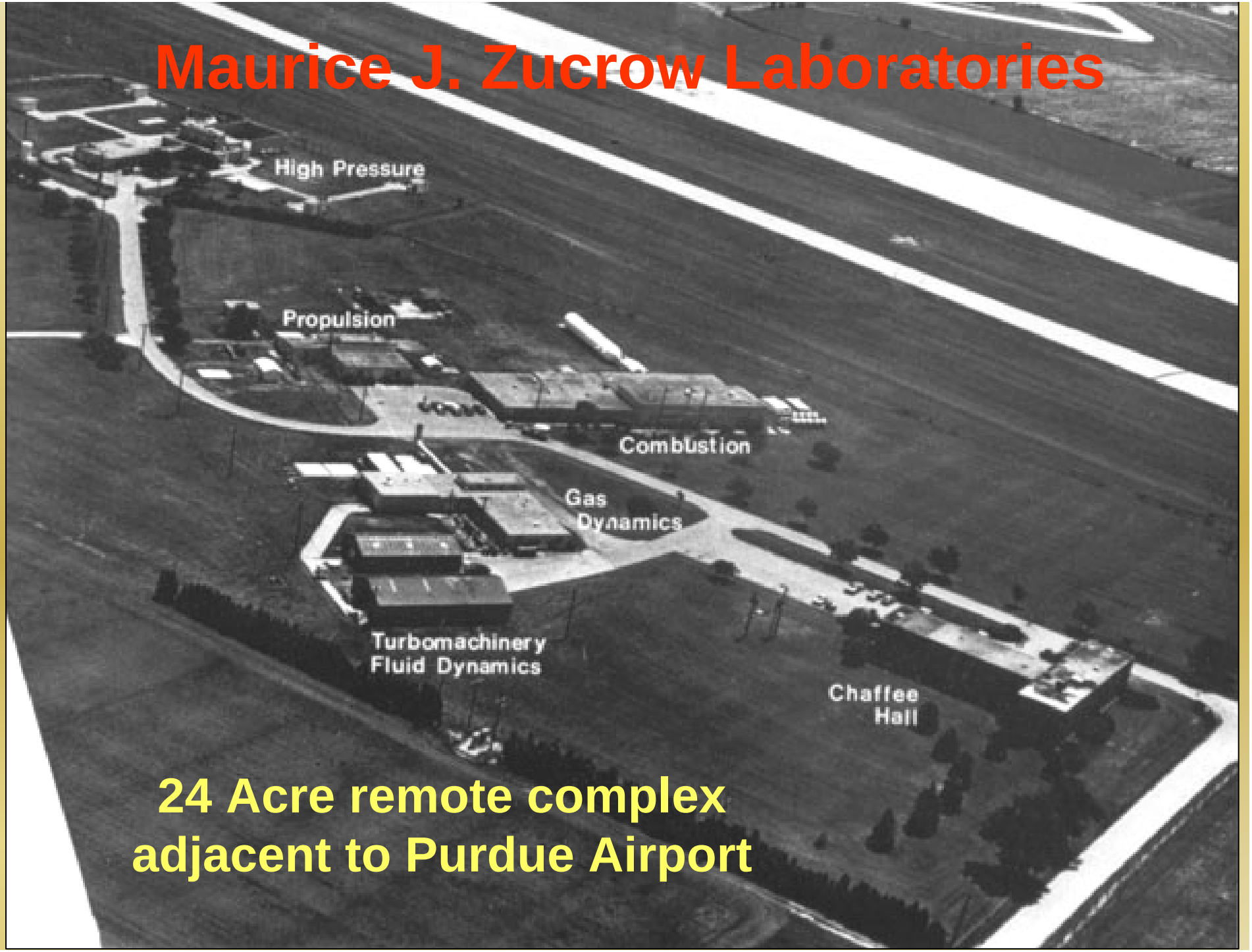
- Overview of Purdue Propulsion Facilities at Maurice Zucrow Labs
- DMAZ Combustion with 90% HP
- Non-toxic Hypergolic Fuels with 98% HP
  - -- Vacuum Ignition Testing of Boeing Fuel
  - -- Testing of Swift Enterprises Fuel
- AFRL Ionic Liquid Fuel Testing with 98% HP
- Droplet Decomposition Studies

Purdue Testing Facilities

- **Advanced Propellants & Combustion Lab** (APCL) – 600 sq. ft. of space at Maurice Zucrow Labs (MZL), includes two reinforced concrete test cells, associated control room and vacuum capability
- **MZL High Pressure Lab**

  – 6000 sq. ft. of space including two reinforced concrete test cells, instrumentation rooms, propellant tankage rooms, and remotely located control room

Maurice J. Zucrow Laboratories



24 Acre remote complex adjacent to Purdue Airport

Senior Personnel

Steve Heister

- Ph.D. UCLA, 1988
- Aerospace Corp. 1983-90, Manager, Propulsion Technology Section
- Lockheed 1981-82, Propulsion Installation Department
- TRW (sabbatical) 1997
- Phillips Lab (AFAL), 1991 Summer Faculty
- Author/co-author of over 100 technical papers in ballistics, design, atomization, cavitation

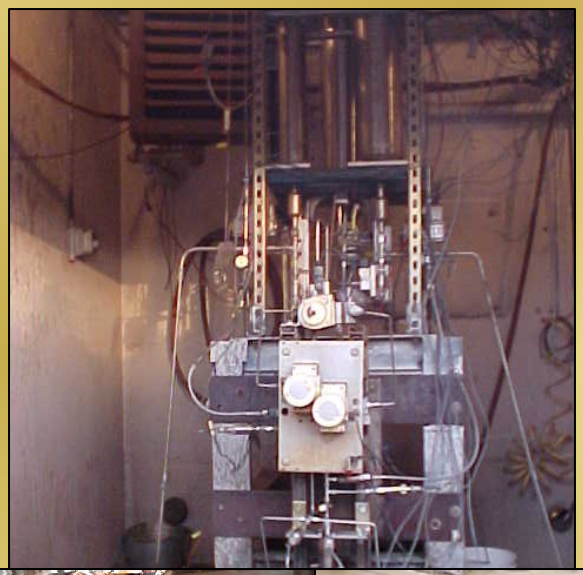
Bill Anderson

- Ph.D. Penn State, 1996
- Marshall Space Flight Center 2000-01, Engineer
- Orbital Sciences 1997-2000, Senior Principal Propulsion Engineer
- Penn State Propulsion Engineering Research Center 1990-97, Associate Director
- Aerojet 1988-90, Senior Engineer
- Garrett Turbine Engine Division 1986-88, Aerothermal Sciences Engineer
- Aerojet 1984-86, Thermal Sciences Engineer

Scott Meyer

- M.S. Purdue, 1992
- Beal Aerospace Technologies 1998-2001, Propulsion Engineer
- Sverdrup Technology (AEDC) 1993-97, Project Engineer, Propulsion integration wind tunnel testing
- US Rocket Works 1990-97, Co-developed and patented a hybrid rocket motor ignition device

Advanced Propellants and Combustion Lab



- Two cells w/ 1 Klbf thrust stands
- Propellant supply of 1800 psia
- 2 - 4 gallon peroxide tanks (90/98%)
- 1 & 4 gallon fuel tanks
- National Instruments hardware & LabView software
  - 32 channels pressure
  - 32 channels temperature

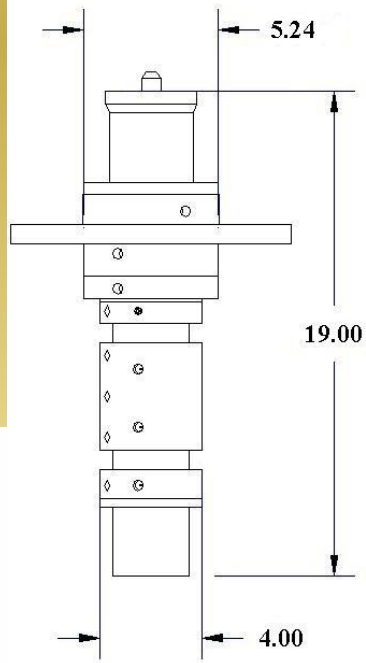
- All valves computer controlled
- Rapid test article installation
- Design/Build/Test course

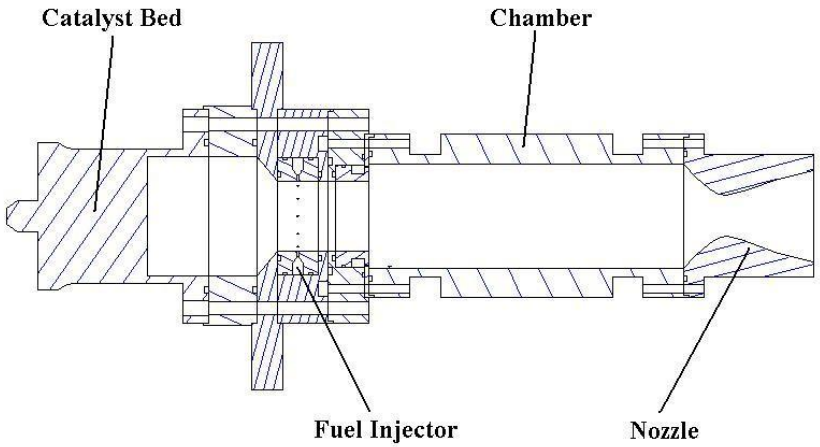
High Pressure Lab Overview

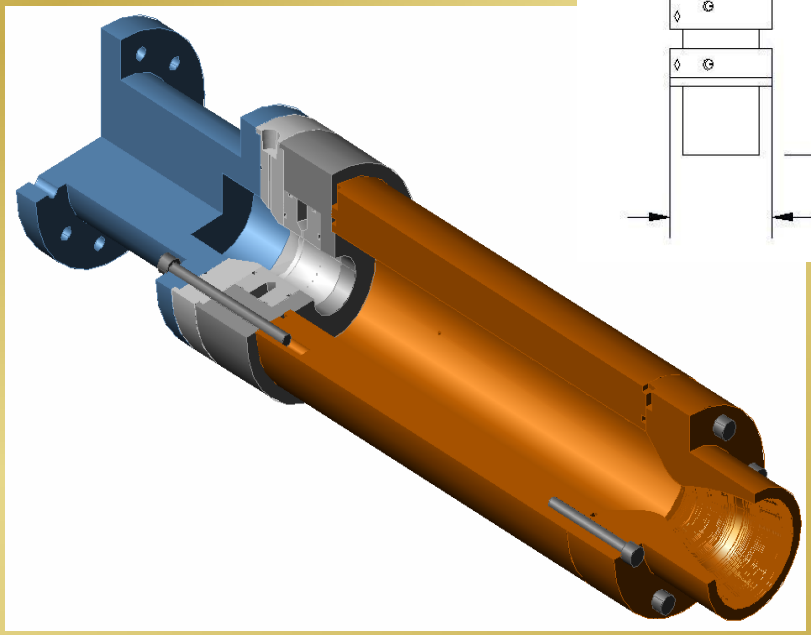
- Propellant flows
  - LOX – 15 lb/s
  - H2O2 – 30 lb/s
  - LHC – 20 lb/s
  - H2O – 90 lb/s
- 6K psi supply pressure
- Remote control of experiments using LABVIE
- Unique opportunity for real-scale experiments
- Student involvement is key
- Large NASA investment
  - Support and advice from SSC, MSFC, GRC, WSTF
  - Research

Staged-Bipropellant Dump Combustor

- Modular design to accommodate different fuel flows and contraction ratios



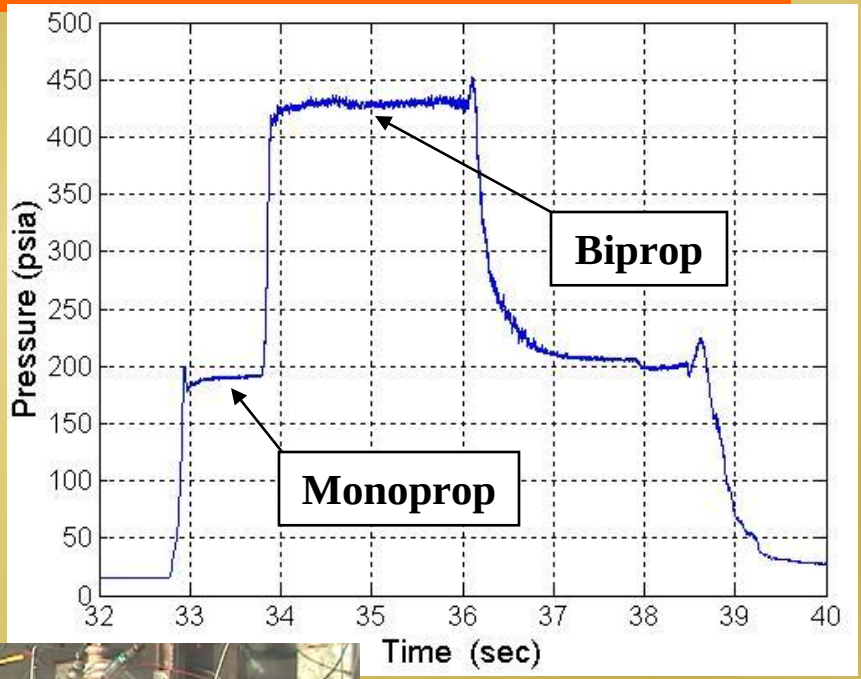


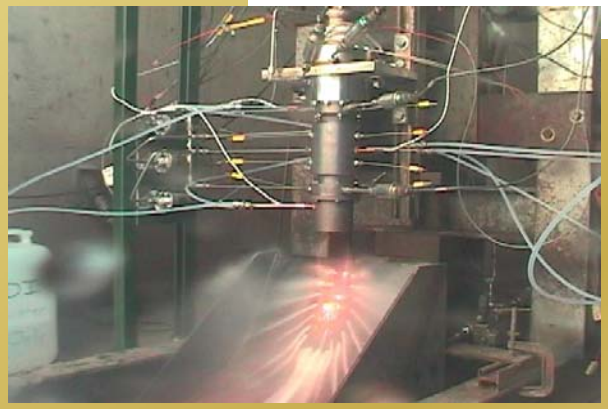


- Engines built for interface to 90% and 98% HP catbeds

DMAZ Combustion with HP

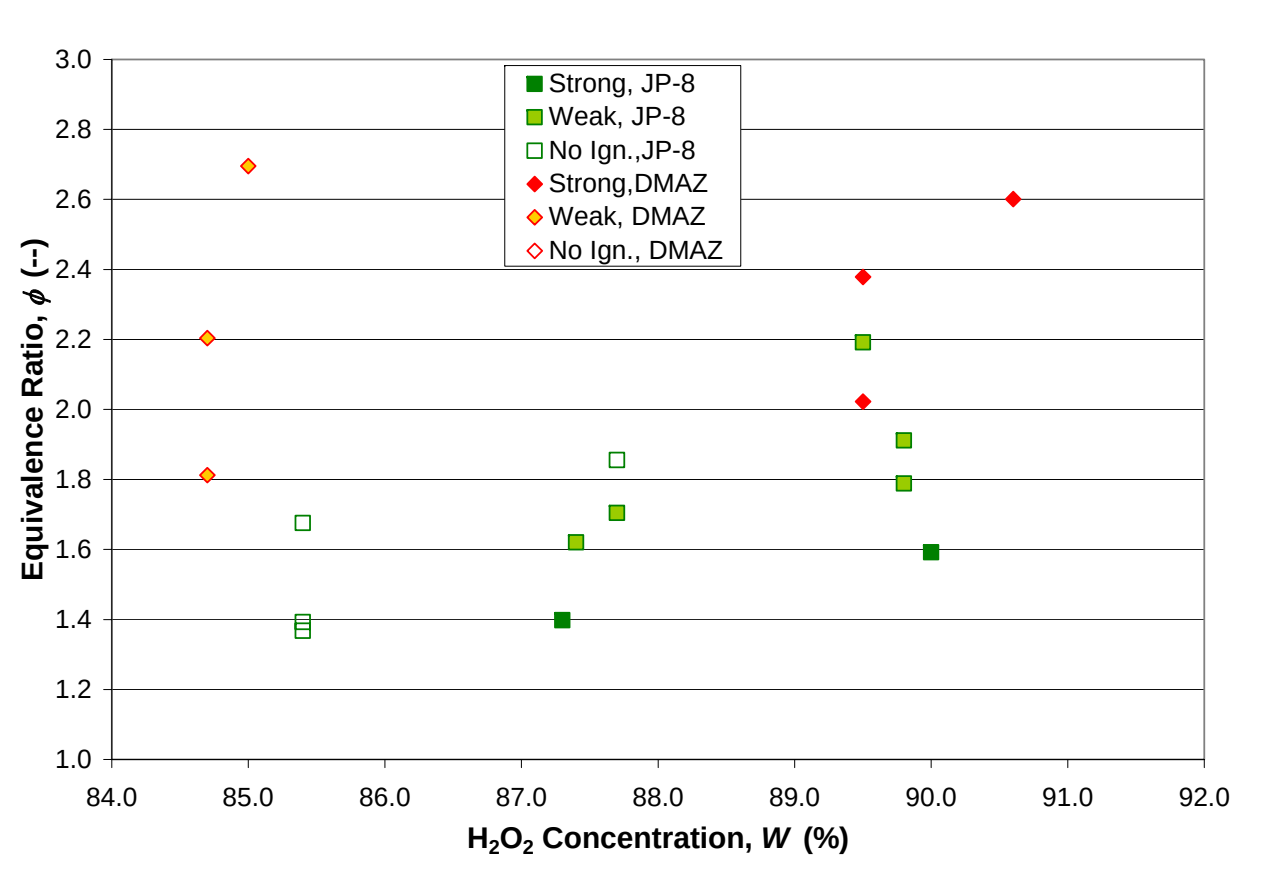
- Dimethyl-2 Azidoethylamine (DMAZ) developed by D. Thompson, AMCOM
- The chemical makeup is: (CH3)2NCH2CH2N3
- 90% H_2O_2 / DMAZ
  - 3 sec firing
    O/F = 3.65, $\dot{m}$ = 2.1 lb/s
- Pc = 430 psia
- C* efficiency ≈ 99 %





DMAZ Biprop Test Firing

Comparison of Autoignition Data



DMAZ fuel ignited under all tested conditions – much more ignitable than JP-8

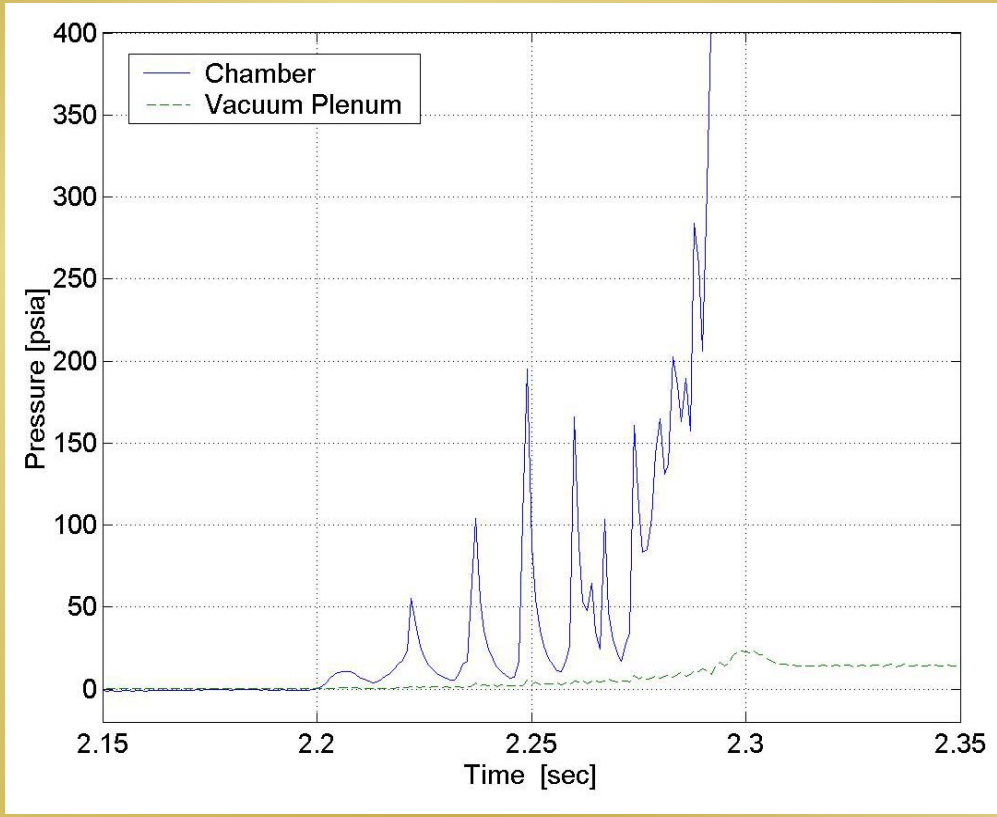
C* effcy ≈ 90-100 %

Vacuum Ignition of Hypergolic Fuels

- NASA/MSFC Project – Rocketdyne thruster design
- Small exhaust plenum attached/sealed with thruster nozzle
- Vacuum Release Plate
  - Held in place by vacuum
  - 600-in3 acrylic and metal plenum

Vacuum Ignition Verified for Rocketdyne Hypergolic Fuel

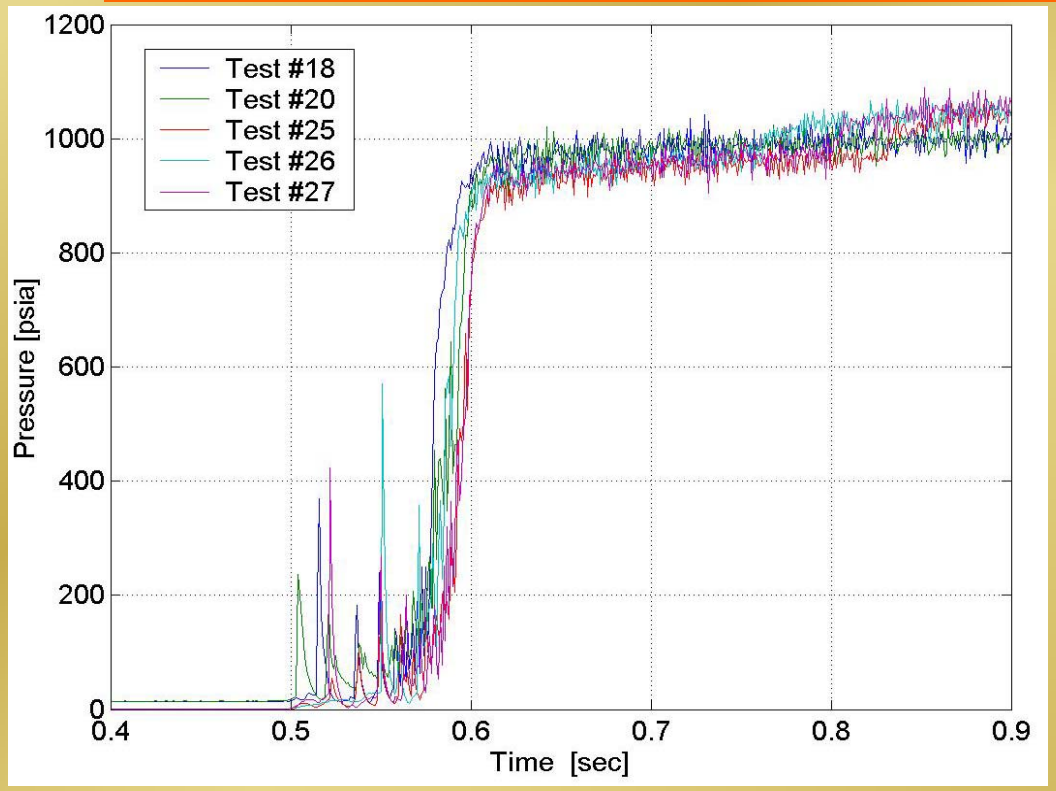
- Ignition occurring in vacuum
  - Combustor flow chokes before significant rise in plenum pressure
  - Video shows combustion exiting thruster, filling plenum, release plate detaching



Vacuum Ignition Tests

School of Aeronautics and Astronautics

Vacuum Ignition Tests



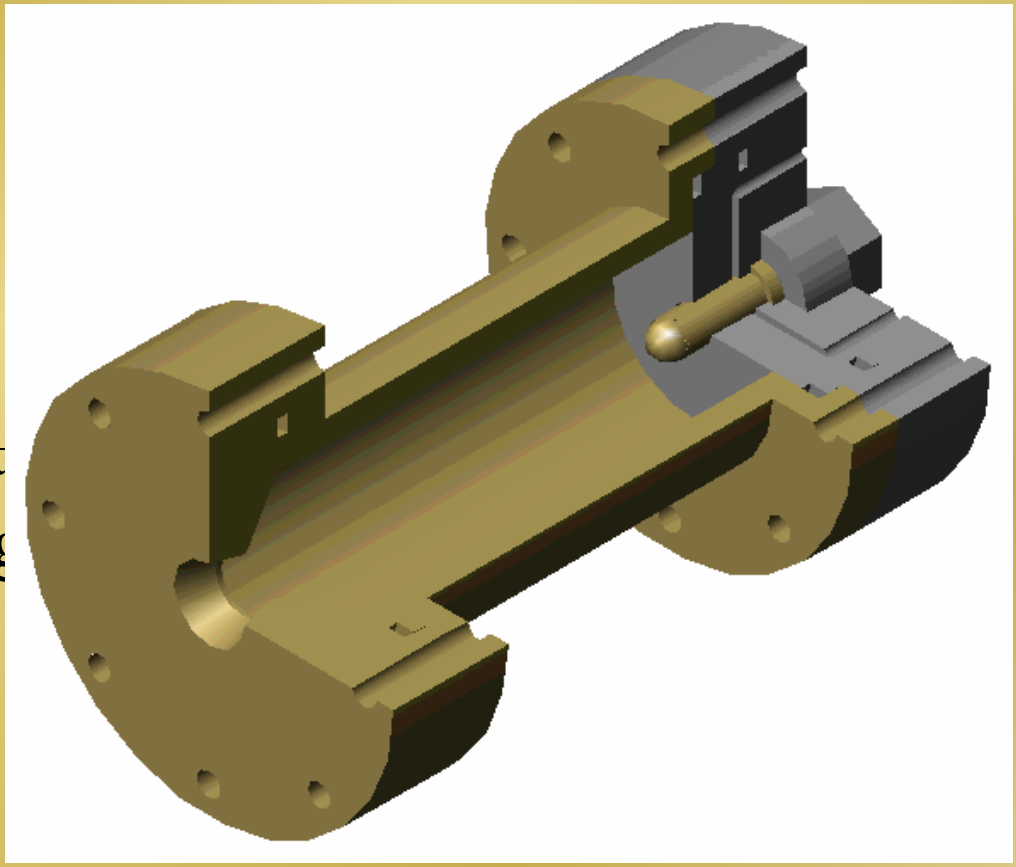
Hypergolic ignition not affected by vacuum environment

Comparing vacuum tests with atmospheric tests

- Same presence and magnitude of startup pressure oscillations
- Same startup transient time
- Same steady-state injector and chamber pressures

Pintle-Based Bipropellant Combustor

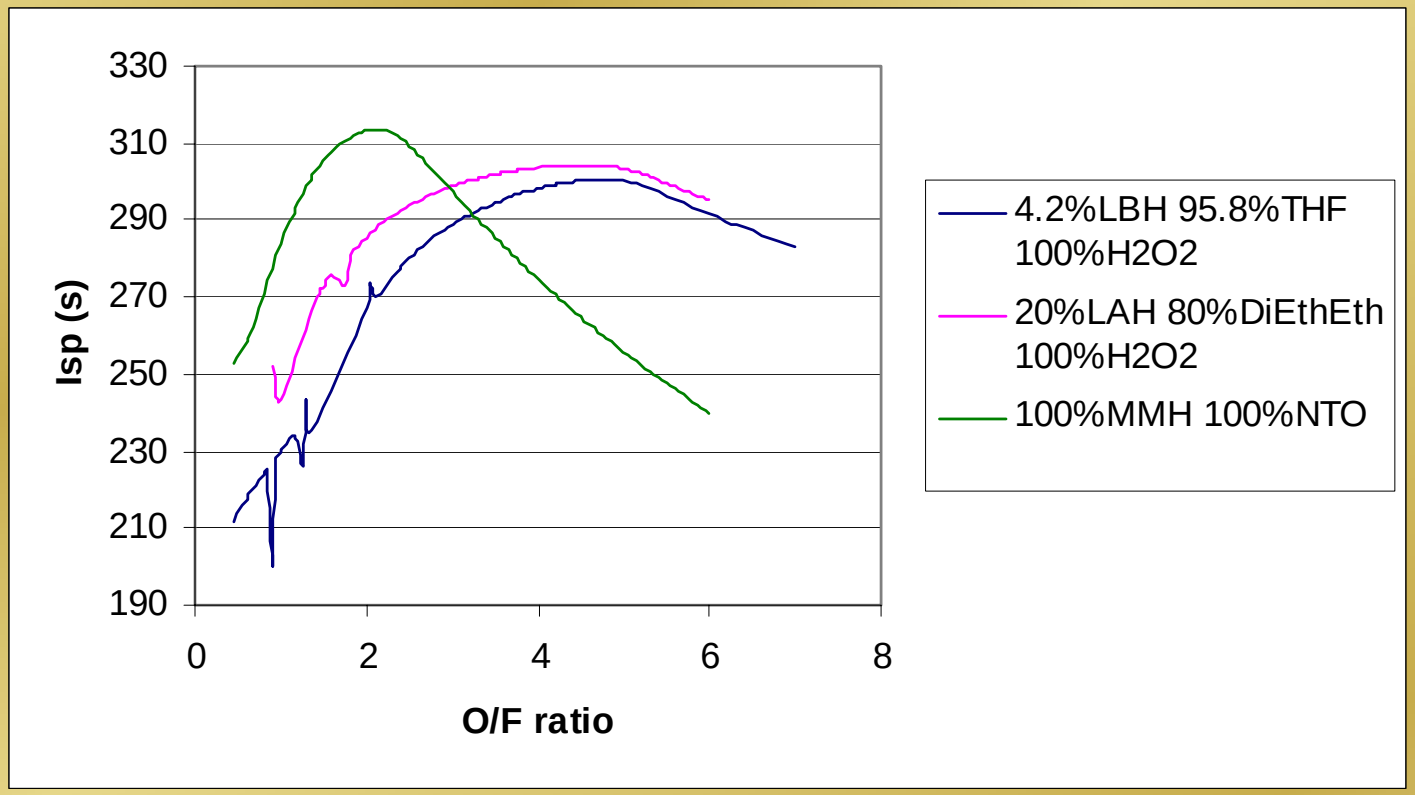
- 200-lb_f thrust (vac ideal)
- Stainless steel and copper construction
- Modular design
  - Vary engine parameters
  - Replace damaged/worn part
- Over 200 successful firing with several hypergolic fuels



Testing of Swift Enterprises Hypergolic Fuels

- Project funded by NASA MSFC & SMDC
- The following solutions were obtained and tested:
  - Fuel A: 4.2% by weight lithium borohydride (LBH) in tetrahydrofuran (THF)
  - Fuel B: 20% lithium aluminum hydride (LAH) in diethyl ether
- LAH Performance was poor due to oxide formation in plumbing system and injector

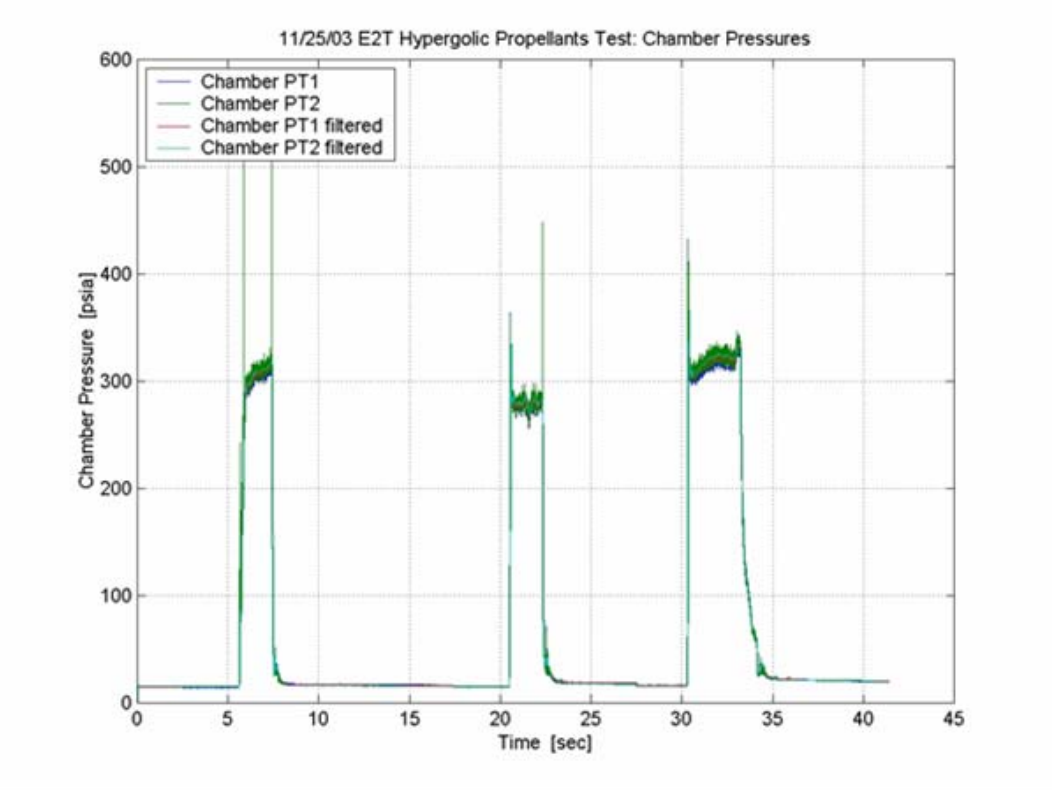
THEORETICAL Isp RESULTS



100% HP, Pc = 500 psi, Expansion ratio = 10

LBH/98% HP Firing

LBH Test Results



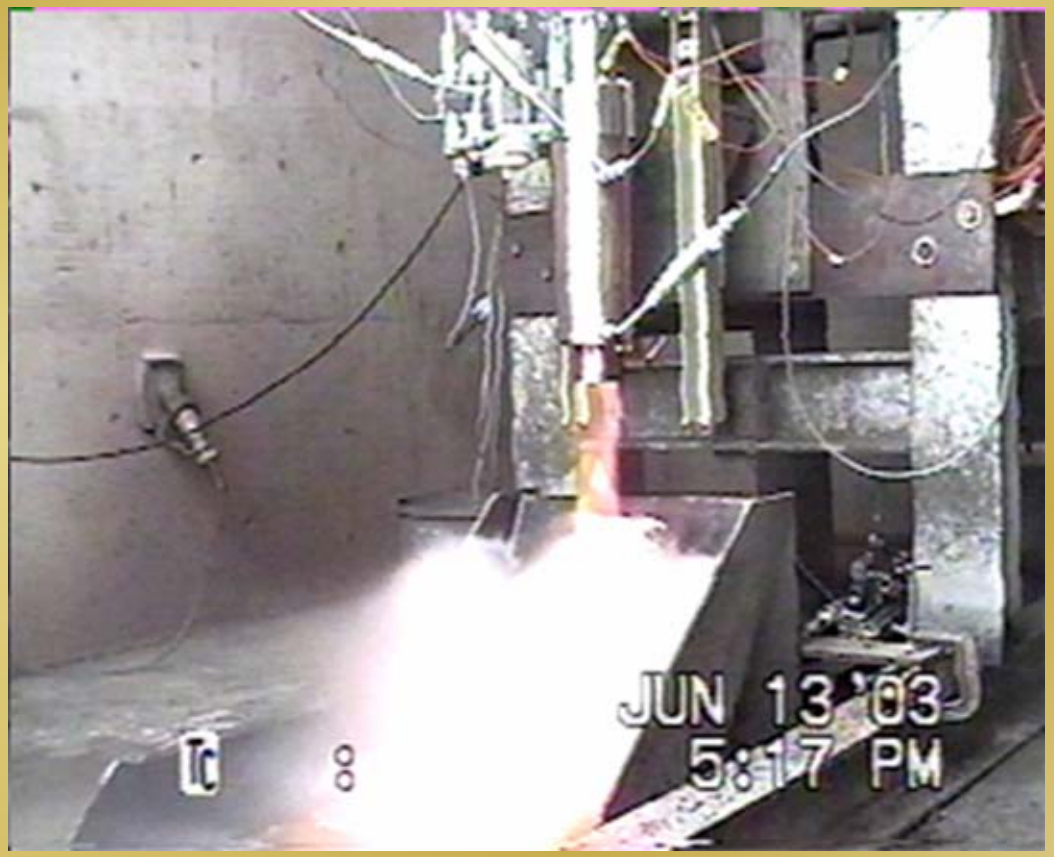
Rapid, reproducible ignition

Relatively low noise (2-3%)

Fuel flows were low due to check valve problems

AFRL Ionic Fuel Testing

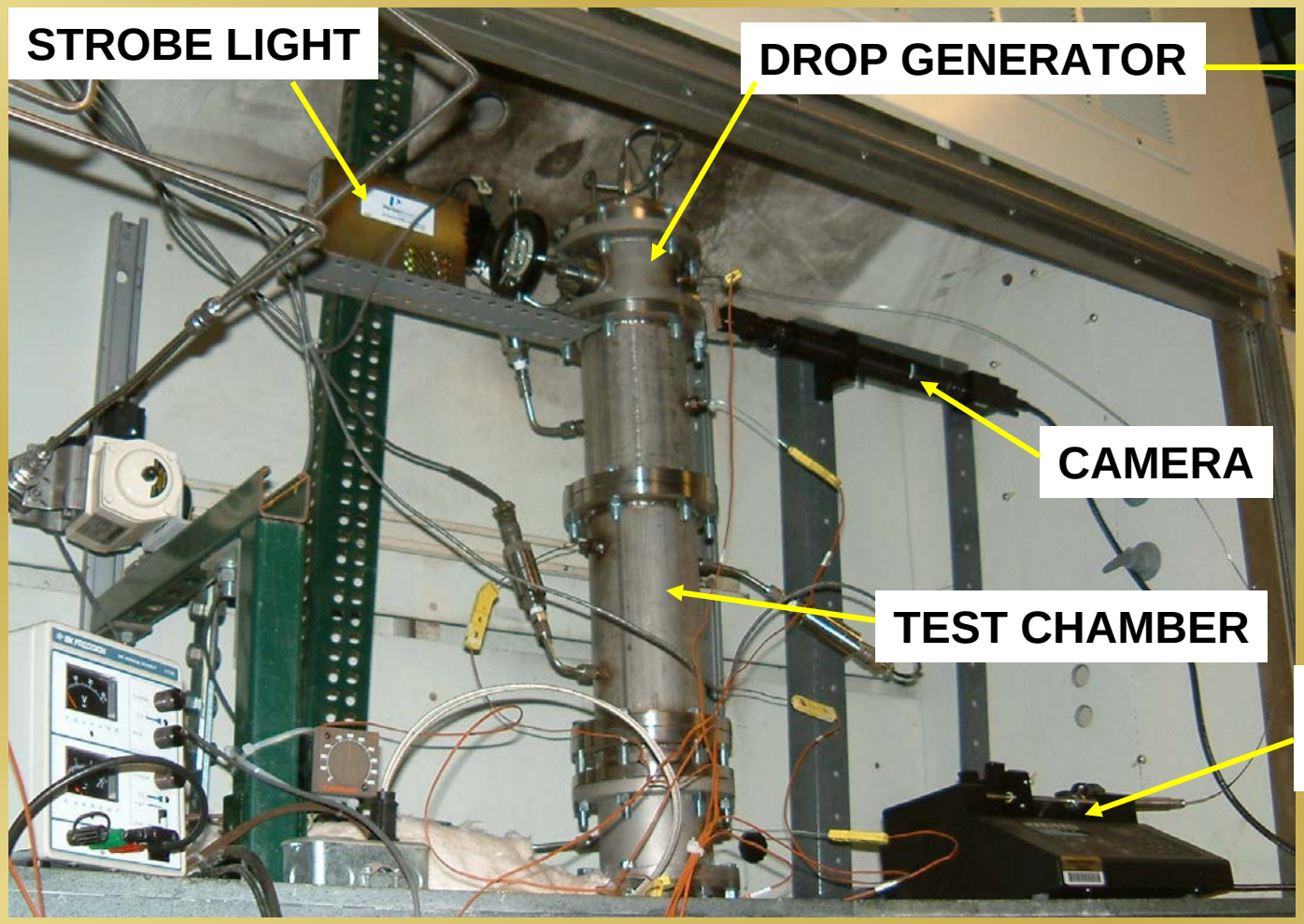
- Fuel under development at AFRL-Edwards AFB in group of Dr. Tom Hawkins
- Fuel tested using 98% HP in staged-biprop dump combustor
- Three test series conducted – both steady and pulsed performance evaluated

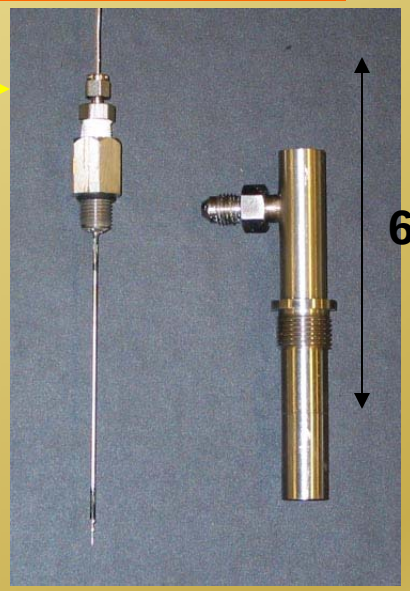


Droplet Thermal Decomposition Studies

- Inject drops into inert or decomposition products atmosphere to better approximate combustor dynamics
- Ensemble average diameter measurements at each discrete location to obtain droplet size history
- Measurements at pressures of up to 10 atm
- Investigate behavior of DMAZ, HP, HAN, AFM-315, ADN, etc.

Experimental Apparatus

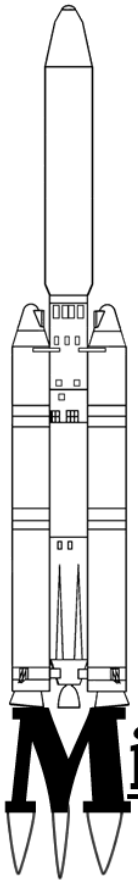




Conclusions

- New classes of lower toxicity propellants are showing promising combustion results
  - DMAZ combustion/ignition characteristics
  - Vacuum ignition verified in nontoxic storables
  - Encouraging results obtained for AFRL ionic liquid fuel and Swift Enterprises LBH-based hypergol

DEFENSE ENERGY SUPPORT CENTER



MissileFuels

Advanced Rocket Bipropellant Liquids and Gels

Current Vision, Status, and Challenges

Michael McPherson

Technical Principal – Propellants

Aerojet Missile and Space Propulsion

Sacramento, California

Prepared for the 2004 Worldwide Energy Conference
28 – 30 September 2004
Hyatt Regency Crystal City, Arlington, VA

Objectives

AEROJET

- To Review the Effort for Liquid BiPropellant Support, Industry Perspective
  - Current Programs,
  - Advanced Studies,
  - Green Propellants
- Outline the Development Steps for Advanced Propellants
- Provide a few Examples of Recent Studies with New Propellants
- Discuss the Challenges in Future Work

Overview – Propellant Categories

AEROJET

- **Type by Physical Properties:**
  - **(Earth) Storable**
    - **Stable Liquid at Room Temperatures (298K, ~77°F)**
  - **Space Storable**
    - **Generally, Liquid Phase in the Range –200 to 0°F (150-250K)**
  - **Cryogenic**
    - **Generally, Liquid Phase < -238°F (-150°C, 123K)**
- **Type, by Reactivity:**
  - **Hypergolic – React upon Contact**
  - **Igniter/Torch Lit (Non-Hypergolic)**
    - **Requires External Initiation Source**

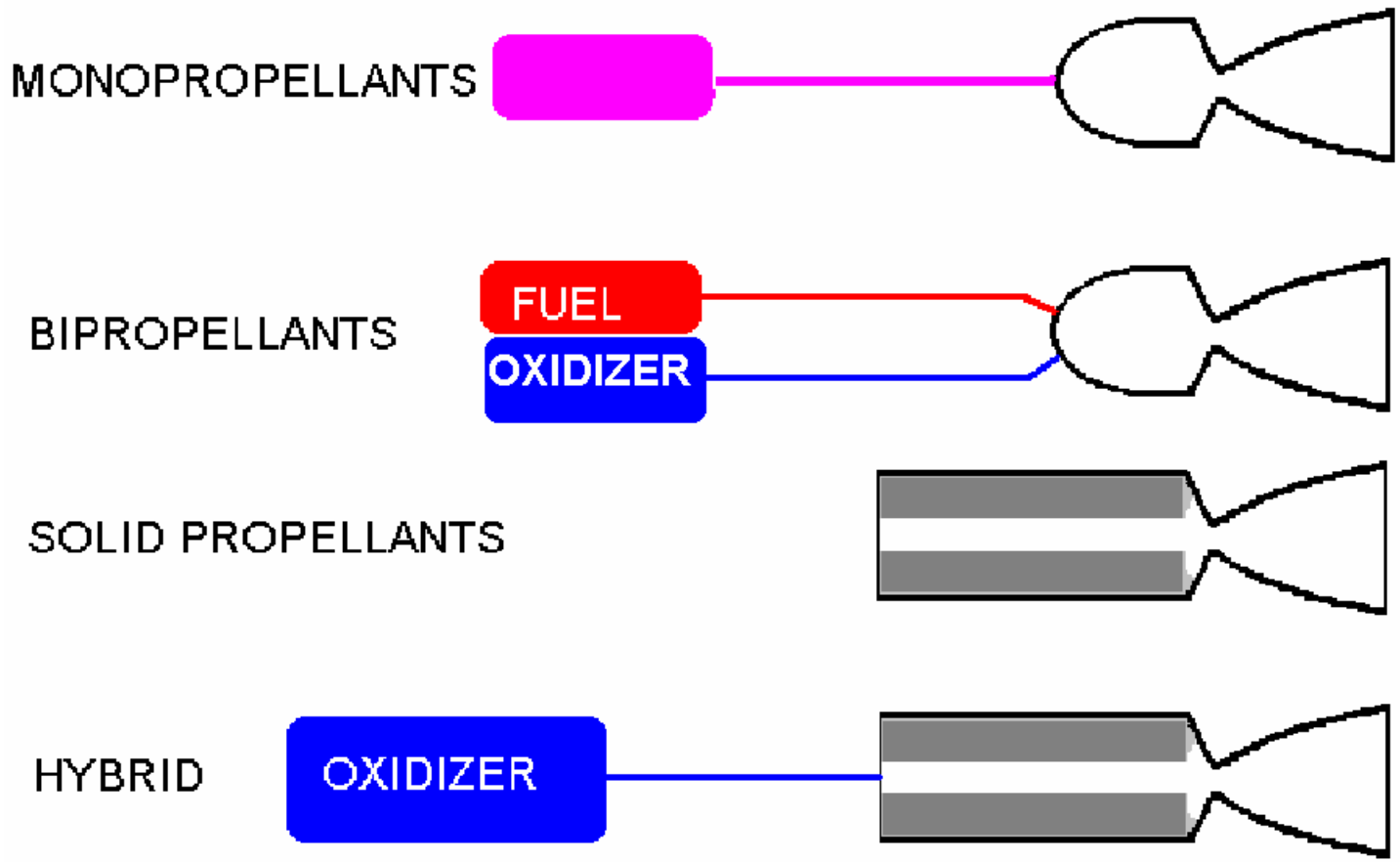
Development Roadmap for Rocket Fuels (and Oxidizers)

AEROJET

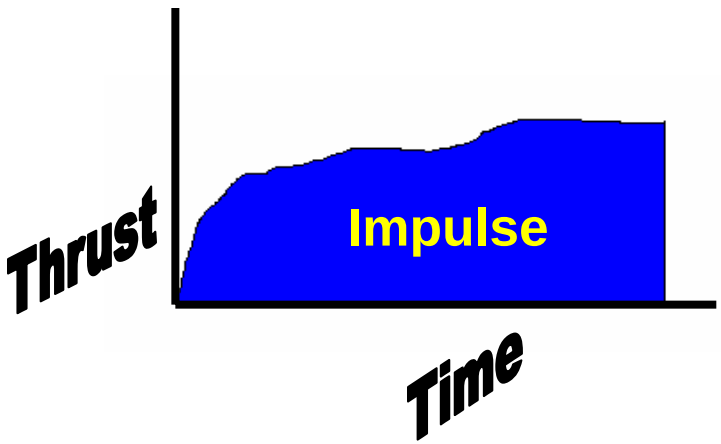
- Synthesis of Novel Compounds
- Thermochemical Calculations
- Physical Properties Definition
- Toxicity and Hazards Elucidation
- Storability and Compatibility Determination
- Subscale (Bench-level) Performance Evaluations
  - Reactivity (Ignition Delay), Heat Transfer, Droplet Formation
  - Verification of Combustion Energies and Reaction Products
  - Gas Solubilities, Flow Characteristics, Other Parameters
- Static Tests
  - Sea Level, then Firings at Simulated Altitude (Vacuum Chambers)
  - Flight Tests!

Cost vs Performance Drivers Establish Need!
(Mitigated by *Risk*)

Overview – Chemical Propulsion Systems



Propulsion Elements



- **Thrust (Force) divided by mass rate of flow (consumption of propellant) yields *effective exhaust velocity***
- **V_{eff} converted from mass flow to weight flow rate (via gravitational constant) yields *Specific Impulse,* which depends on chamber and exhaust pressure ratio, heat losses, divergence angle of the nozzle, and other factors**
- ***Isp* is the conventional measure of propellant performance, units of seconds**
- **Chemical Propulsion Isp ranges from 150 to 400 sec**

A Little Bit of Rocket Science…

AEROJET

…in the connection between exhaust velocity and thermochemical nature of the propellant:

$$v_e = \sqrt{\frac{2\gamma}{\gamma - 1} g_0 R \frac{T_c}{M} \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} \right]}$$

Where:

R = ideal gas constant

T_c = chamber temperature

g_0 = gravitational acceleration constant

M = average molecular wt. of the exhaust gas

γ = ratio of specific heats c_p/c_v

p_1 = pressure at the exit plane of the nozzle

p_2 = chamber pressure

Thermodynamic Toolbox

$$Isp \propto v_e \approx \sqrt{\frac{T_c}{M}}$$

High Temperature Combustion,
Low Molecular Weight of Combustion Species,
Optimize Propellant Performance

Calculated Theoretical Performance

	SPECIFIC IMPULSE, lb_f s/lb_m	DENSITY IMPULSE, lb_f s/cu. in.
IRFNA/DMAZ	287	13.8
IRFNA/MMH	284	13.36

Source: U.S. Army MICOM

New Multifunctional Fuels (DMAZ) Compare Favorably To Conventional IRFNA/MMH in Theoretical Performance

AlkylHydrazines – The Fuel that Flies

AEROJET

- **Hydrazine, Methylhydrazine, Unsymmetrical Dimethylhydrazine**
  - **Versatile, Understood, and Effective**
  - **Mono- or Bi-Propellant**
  - **Can be used as a Working Fluid for Electrothermal Thrusters**
  - **Hypergolic with Many Oxidizers**
  - **Favorable Thermodynamic Properties ($\Delta H_f°$=+50.434 kJ/mol)**
  - **Miscible with Ammonia, Water**
  - ***However*, Toxicity is a Significant Detractor, Cost Impact Not Well Captured**
- **Wide Industrial Experience Base outside Aerospace**
  - **As Hydrazine Hydrate, in Industrial Boilers for Corrosion Control**

Alkylhydrazines Are Very Difficult to Displace, based on Flight Experience

Versatility of Hydrazine Hard to Surpass

- BiPropellant
  - Heavy Lift, Space, Decades-Old Programs, with Nitric Acid-based Oxidizers
- Monopropellant
  - Catalytic Thrusters
  - Augmented Thrusters: Electrothermal, and ArcJet

Electrothermal Hydrazine Thruster

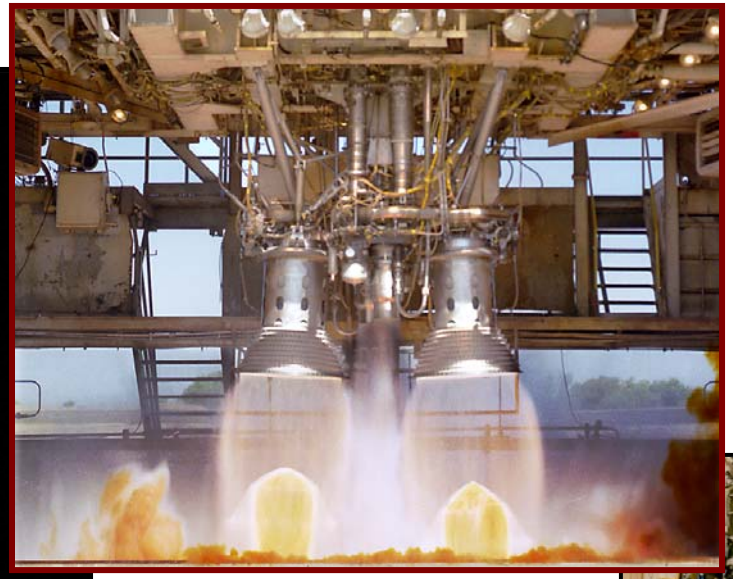
Hydrazine Arcjets and Power Processing Unit

- Gas Generant
  - Auxiliary Power Units
  - Emergency Power Units
  - Emergency Submarine DeBallasting

Go Titan!!!

AEROJET

Titan IV



1st Stage LR-87

2nd Stage LR-91

BiPropellant Conventions

AEROJET

- Common Practice Finds Oxidizers, then Fuels, Listed as BiPropellants, such as LOX/Kerosene, or NTO/Aerozine 50
  - BiPropellant Performance Properties Often Determined More by Oxidizer than Fuel
  - Since There's Fewer Oxidizers than Fuels, it's Just Easier to Group by Oxidizers
  - Most Efficient BiPropellant Performance Occurs, More Often, at More Oxidizer Mass than Fuel Mass
    - MR, or "Mix Ratio", Often >2 to 3
    - As Opposed to OFR, or "Oxidizer-to-Fuel Ratio", a Formulation Parameter in Solid Propellants
      - Optimums Closer to 1.1 to 1.5 for Highest Theoretical Performance

Common, and Not so Common, Oxidizers

AEROJET

- LOX, Liquid Oxygen, O_2
- NTO, (Di)Nitrogen Tetroxide, N_2O_4
- WFNA, White Fuming Nitric Acid, HNO3
- IRFNA, Inhibited Red Fuming Nitric Acid, $HNO_3/NO_2/HF$
- MON, Mixed Oxides of Nitrogen, N_2O_4/NO
- HTP, High Test Peroxide, say, 75-90+ wt% (Balance water), H_2O_2
- Nitrous Oxide, N_2O
- HAN, $[NH_3OH]^+ [NO_3]^-$, and related "ionic liquids"

Watch Out for These!

- Liquid Fluorine, LF_2, Interhalogens; i.e. ClF_3, ClF_5
- Ozone, O_3
- Fluorides of Nitrogen, Oxygen,

BiPropellant Fuels, Conventional & Emerging

AEROJET

- Liquid Hydrogen, Liquid Methane (Cryogenic Fuels)
- Earth-Storable Fuel Examples
  - Kerosene, RP-1
  - Ethanol
  - Ammonia
  - Hydrazine, Methylhydrazine, Unsymmetrical Dimethylhydrazine ("Alkylhydrazines")
- Personal Favorites: DMAZ, ECP Dimer…
  - Very Promising High Performance Reduced Toxicity Alternate Fuels

Alternative Hypergolic Fuels*

- **Hydrazine or MMH Replacement Potential**
  - **Aliphatic Amines, such as Triethylamine, $(C_2H_5)_3N$**
  - **Substituted Aliphatic Amines *(…what's a DMAZ?)***
  - **Energetic Groups:**
    - **Nitro**
    - **Nitratoester**
    - **Azido**
    - **Strained-Ring, Unsaturation *(…what's an ECP Dimer?)***
  - **Ethyleneimino Functionality**
    - **Aziridines, based on ring structure:** CH_2NHCH_2

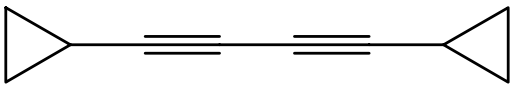
---

* ***With Nitric-Acid Based Oxidizers***

New BiPropellant Fuel Examples

AEROJET

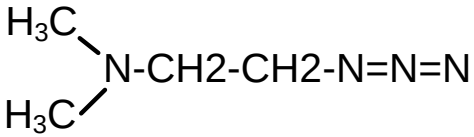
- **ECP Dimer**



1,4-dicyclopropyl-1,3-butadiyne

  - ***Improved Performance, Reduced Toxicity Aerozine 50 or MMH Replacement… ?***
  - ***Hypergolic with NTO, IRFNA, WFNA***
  - ***Miscible with Non-Polar Paraffinic Fuels***
    - ***Examples: JP-7, JP-8, RP-1***
  - ***Commercially Available (Organic Technologies)***

- **DMAZ**



dimethyl-2-azidoethylamine

  - ***Improved Performance, Reduced Toxicity MMH Replacement… ?***
  - ***Hypergolic with HTP*, Notably with Added Homogeneous Metal-Organic Catalysts***
    - ***Manganese- or Cobalt-based Soluble Catalysts***
    - ***Certain Others…***
  - ***Miscible with ECP Dimer, DMAZ is More Polar, yet mixes with RP-1 and JP's***
  - ***Commercially Available (3M, via MACH-1)***

---

* 98+ %w HTP, predominant interest. Hypergolicity affected, among other things, by water content

Theoretical Performance, Hypergols as Gels

AEROJET

AAMCOM Data (from DMAZ Gel Patent), Pc=2000psi						
	Isp, sec	***MR, O/F wt basis***	***Ratio****	***Density*Isp, lbf*s/(in^3)***	***MR, O/F wt basis***	***Ratio****
MMH	285	2.8	1	13.37	2.8	1
DMAZ	281	2.8	0.986	13.56	2.8	1.014
* normalized to MMH theoretical performance						

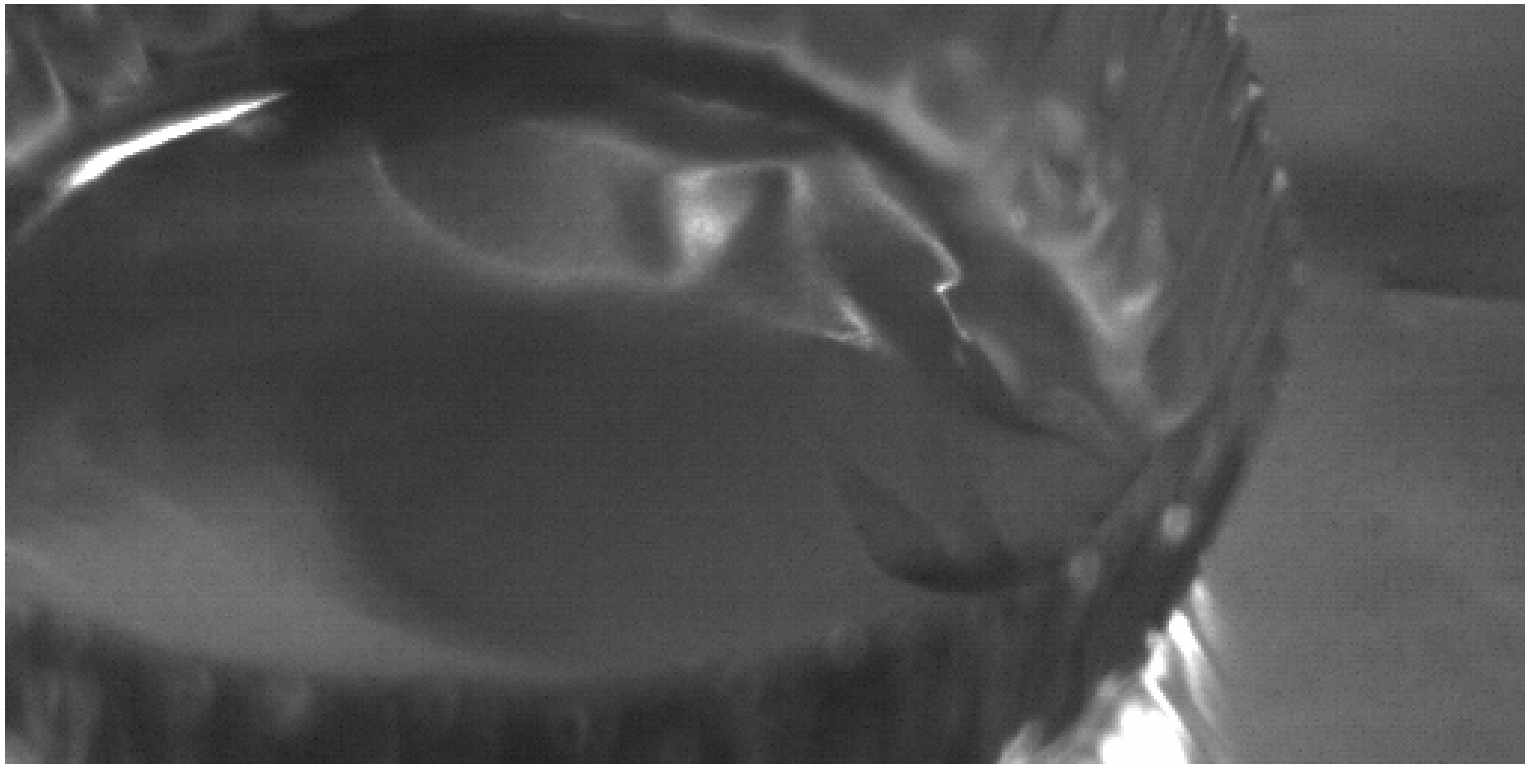
Lower Isp, Higher Impulse*Density, Shown for DMAZ Gel Fuels with Gelled IRFNA, as Compared to MMH/IRFNA Gel

Reaction Delay Testing

- High Speed Video

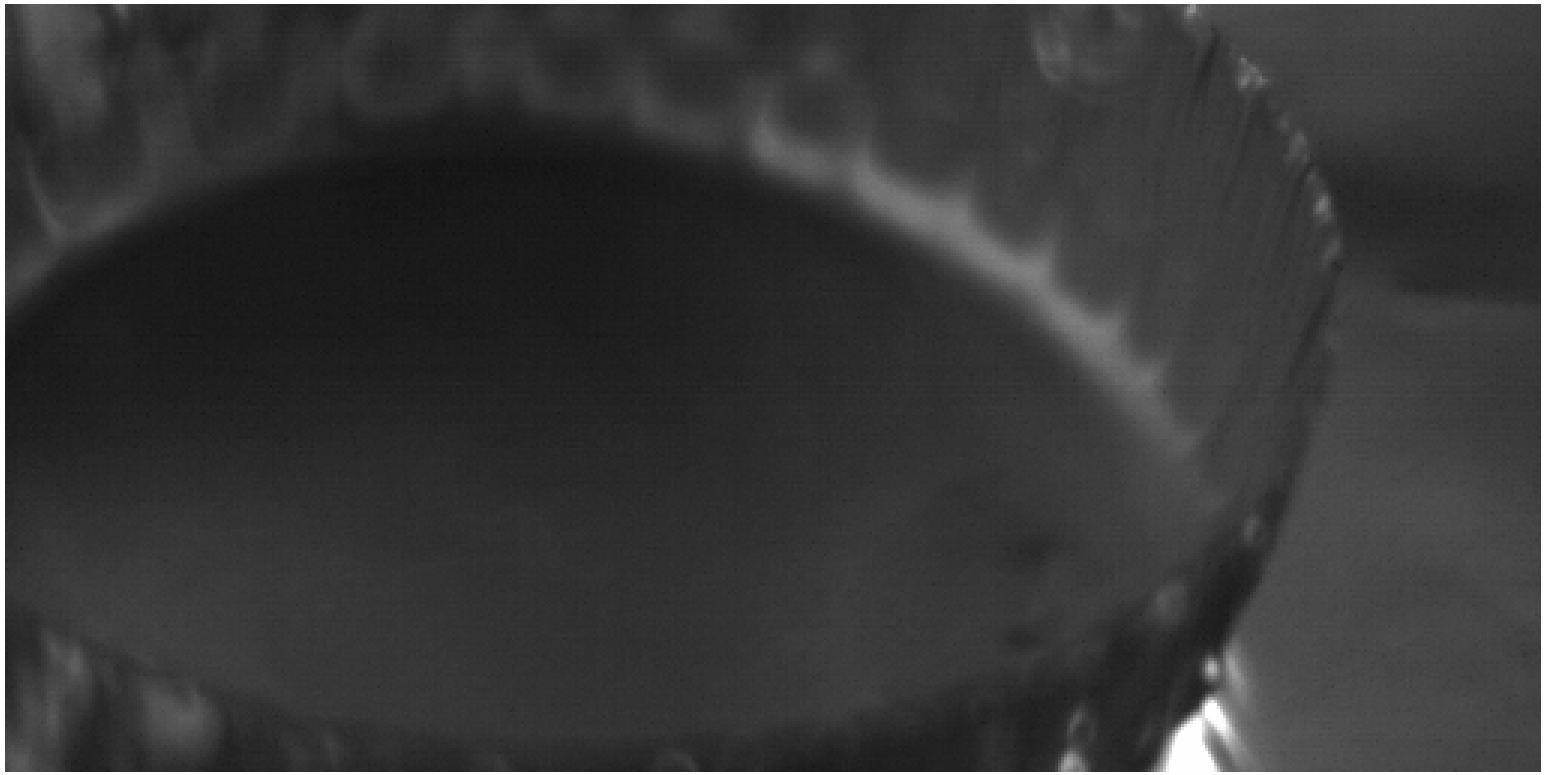
9 millisec delay; ECP Dimer into WFNA

Reaction Delay Videos (cont'd)



192 millisec delay; DMAZ onto WFNA

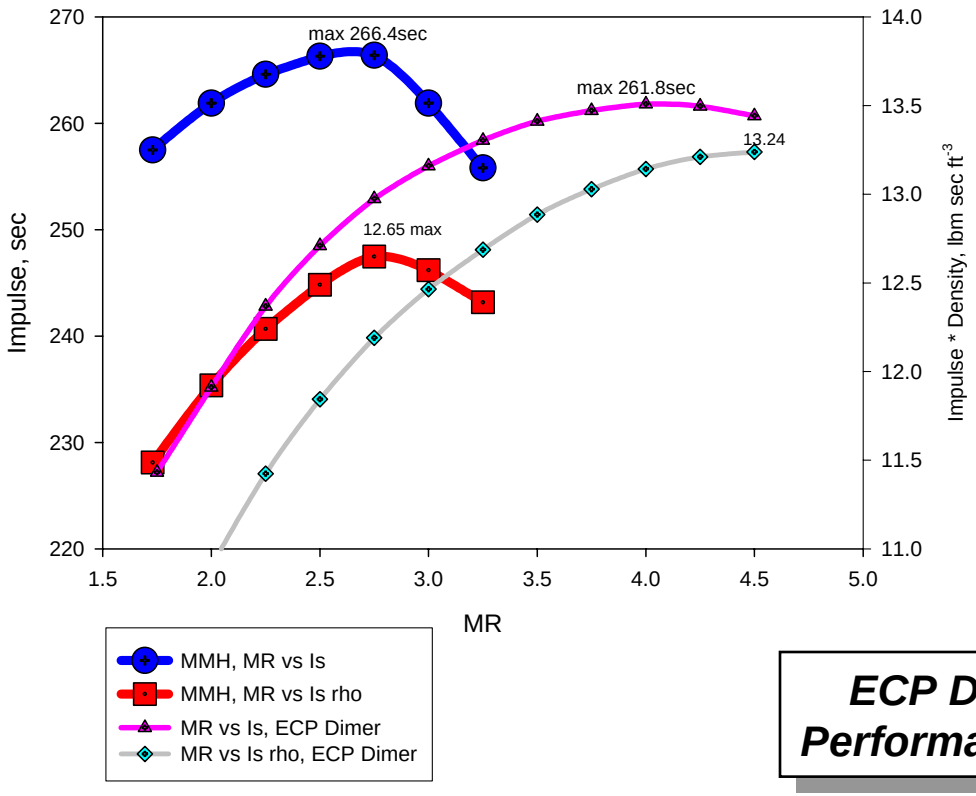
Reaction Delay Videos (cont'd)



MMH onto WFNA; 7millisec delay

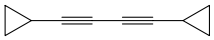
Theoretical Performance (Cont'd)

Theoretical Performance*,
Baseline Neat MMH Gel with Gelled IRFNA Type IIIB,
Compared to Fuel Gel Using ECP Dimer**



ECP Dimer Gels Closely Match Performance Levels with MMH Gels

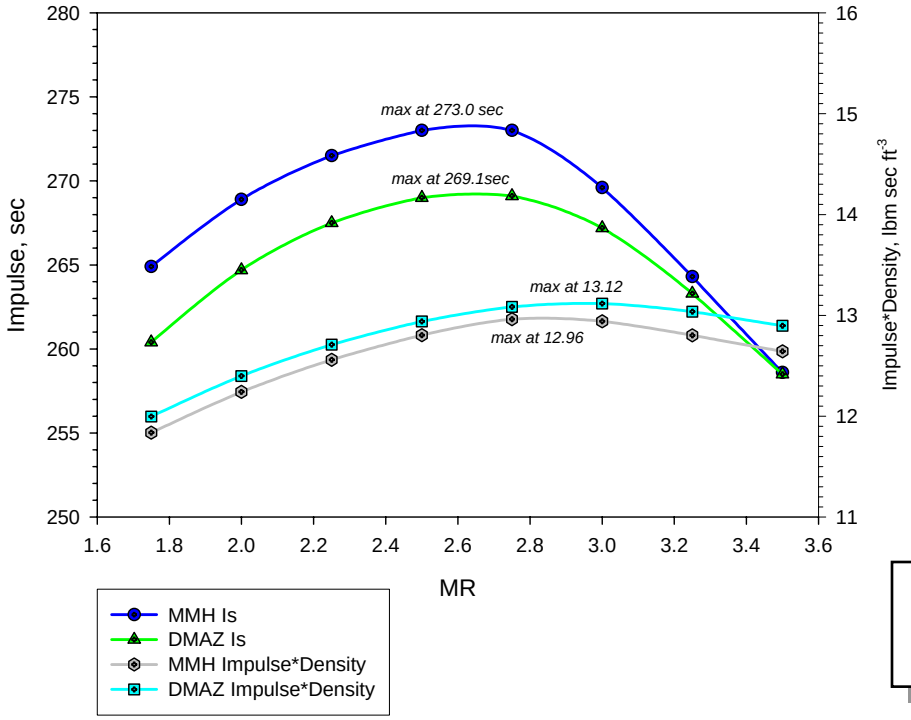
** Pc 1000psia, optimum expansion to 1atm, shifting equilibrium*

*** 1,4-dicyclopropyl-1,3-butadi-yne,* 

Theoretical Performance (Cont'd)

Theoretical Performance*,
Baseline Neat MMH Gel with Gelled IRFNA Type IIIB,
Compared to Fuel Gel Using DMAZ**

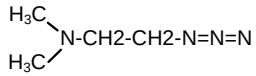
--Corrected Data, 9-16-03--



DMAZ Gels Closely Match Performance Levels with MMH Gels

* Pc 1000psia, optimum expansion to 1atm, shifting equilibrium

** dimethylaminoethylazide, CINCH, 2-(dimethylamino)ethylazide, 2-DAMEZ

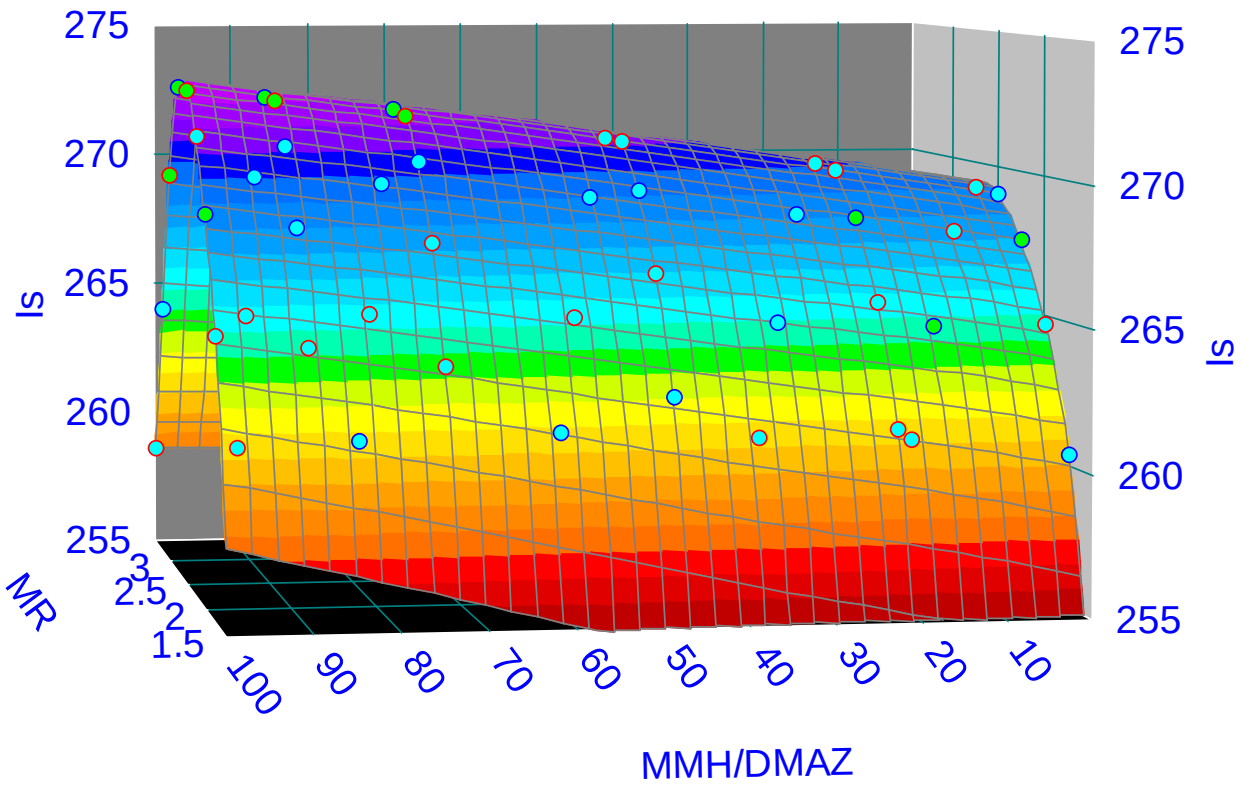


Theoretical Performance

3D Is MMH + DMAZ neat gel.xls --Corrected Data 9-16-03--

Rank 1 Eqn 404 Chebyshev X,Y Bivariate Polynomial Order 5

r^2=0.99968374 DF Adj r^2=0.9994283 FitStdErr=0.10385258 Fstat=4267.3296



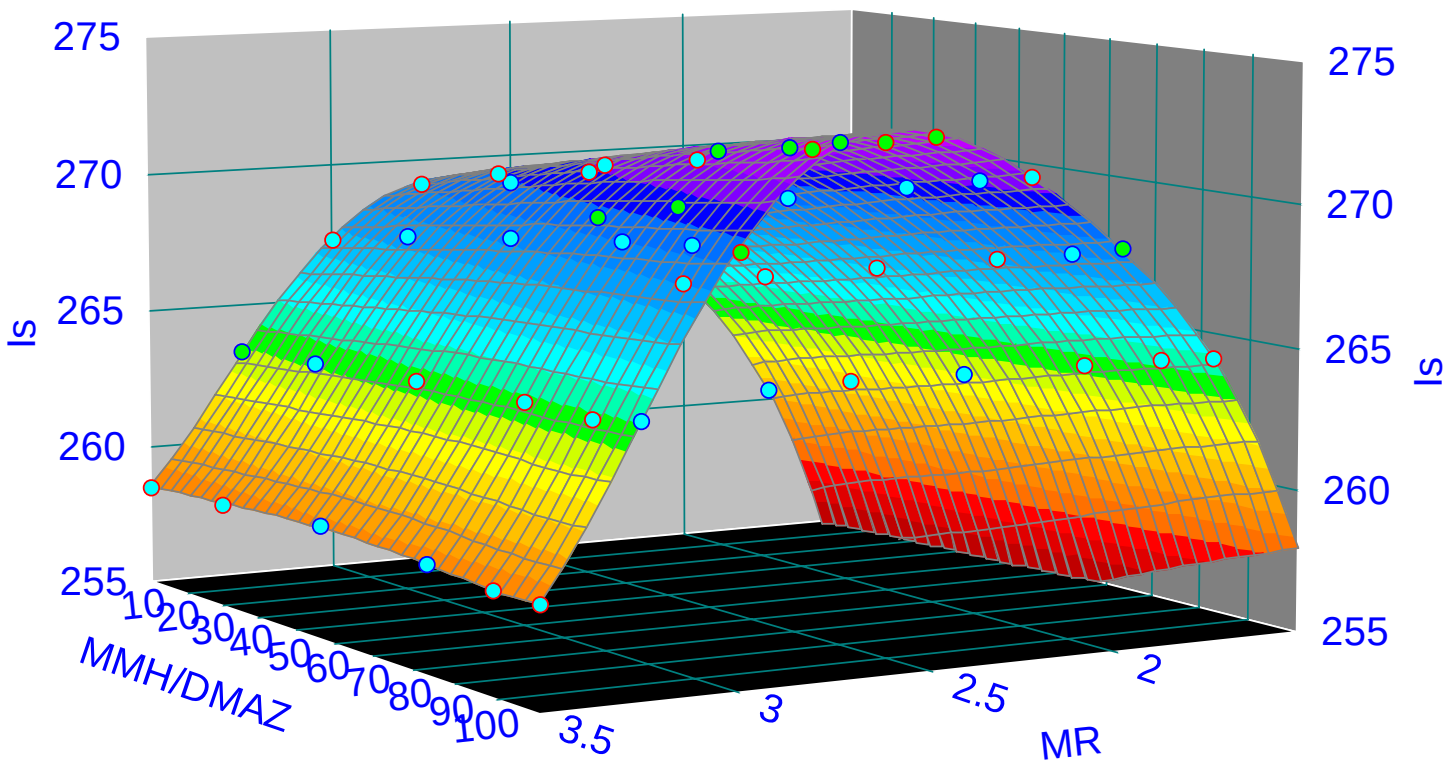
Theoretical Performance

AEROJET

3D Is MMH + DMAZ neat gel.xls --Corrected Data 9-16-03--

Rank 1 Eqn 404 Chebyshev X,Y Bivariate Polynomial Order 5

r^2=0.99968374 DF Adj r^2=0.9994283 FitStdErr=0.10385258 Fstat=4267.3296



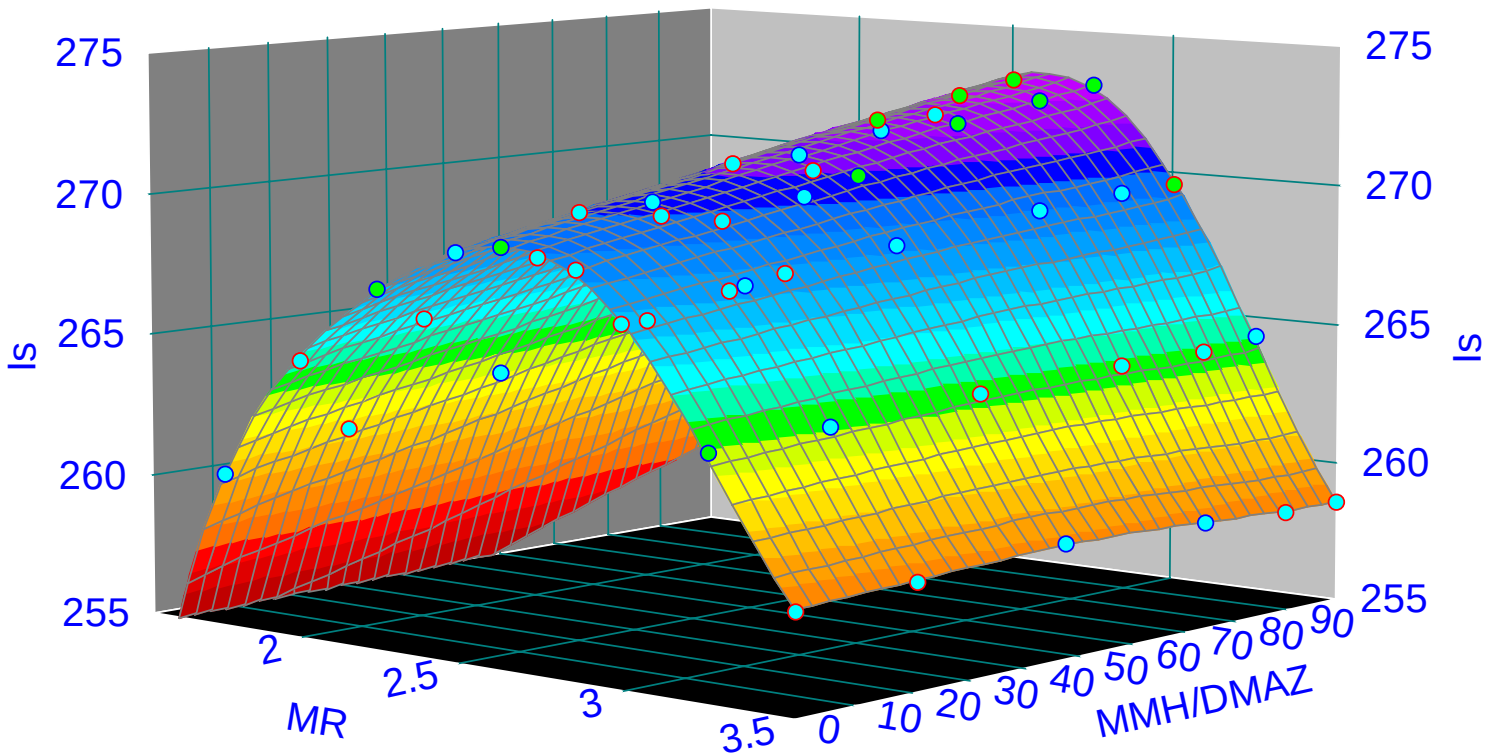
Theoretical Performance

AEROJET

3D Is MMH + DMAZ neat gel.xls --Corrected Data 9-16-03--

Rank 1 Eqn 404 Chebyshev X,Y Bivariate Polynomial Order 5

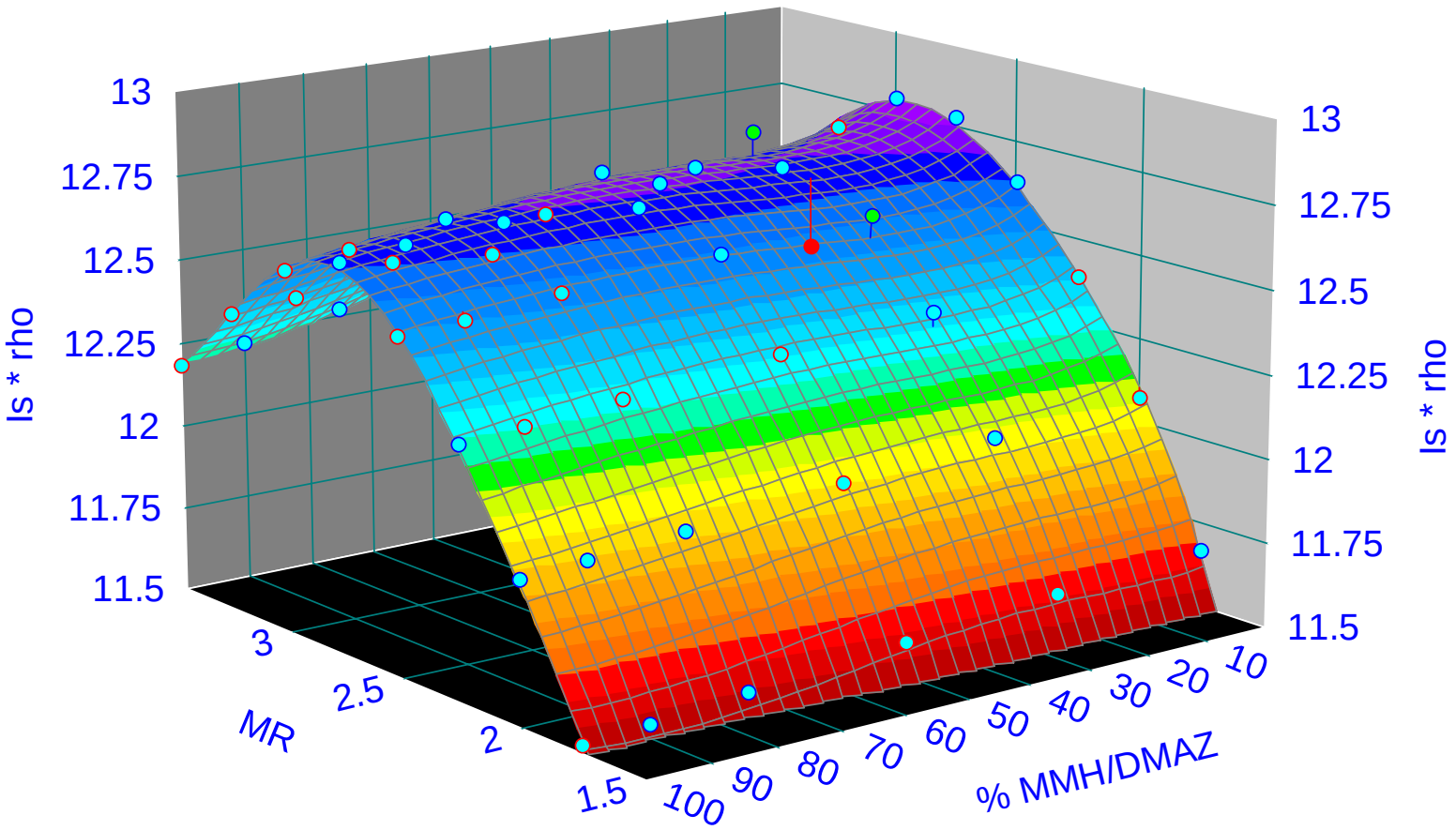
r^2=0.99968374 DF Adj r^2=0.9994283 FitStdErr=0.10385258 Fstat=4267.3296



Theoretical Performance

Rank 1 Eqn 404 Chebyshev X,Y Bivariate Polynomial Order 5

r^2=0.9895029 DF Adj r^2=0.98102447 FitStdErr=0.048857634 Fstat=127.25692

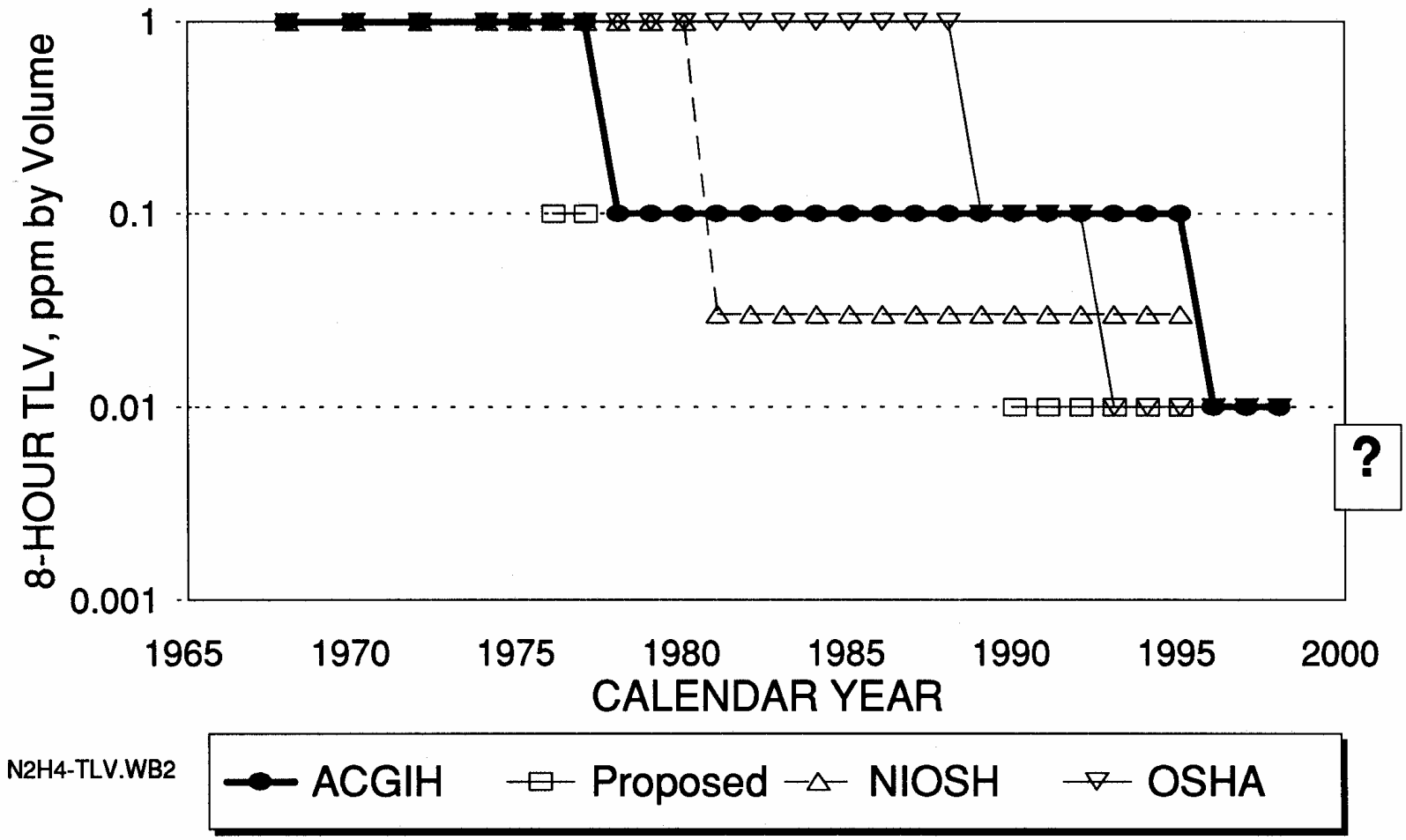


Toxicity

AEROJET

- Fully Contained Protective Gear Specified for Field Handling of Toxic Propellants
  - NASA, USAF, ESA use Self-Contained Atmospheric Protection Ensemble ("SCAPE") Suits for NTO and Alkylhydrazine Transfers
  - Industry (including Aerojet) Most Often Use Self-Contained Breathing Apparatus ("SCBA") or Supplied-Air Respirators together with Class B Chemical Splash Suits
- The ACGIH Exposure Maximum, for an 8-hr Shift is 10 parts per Billion, as Inhalation Exposure
  - Can this exposure level be competently detected?
  - Show me the Data!
- Toxicity of Oxidation Products (such as UDMH →NDMA)
  - These Residues are Known Carcinogens

Toxicity



Schmidt, Hydrazine, 2001

Toxicity

Field Site Storable Propellant Transfer

AEROJET

FUELING XMM AT KOUROU

Class A Chemical Protective Gear in Use (Kourou)

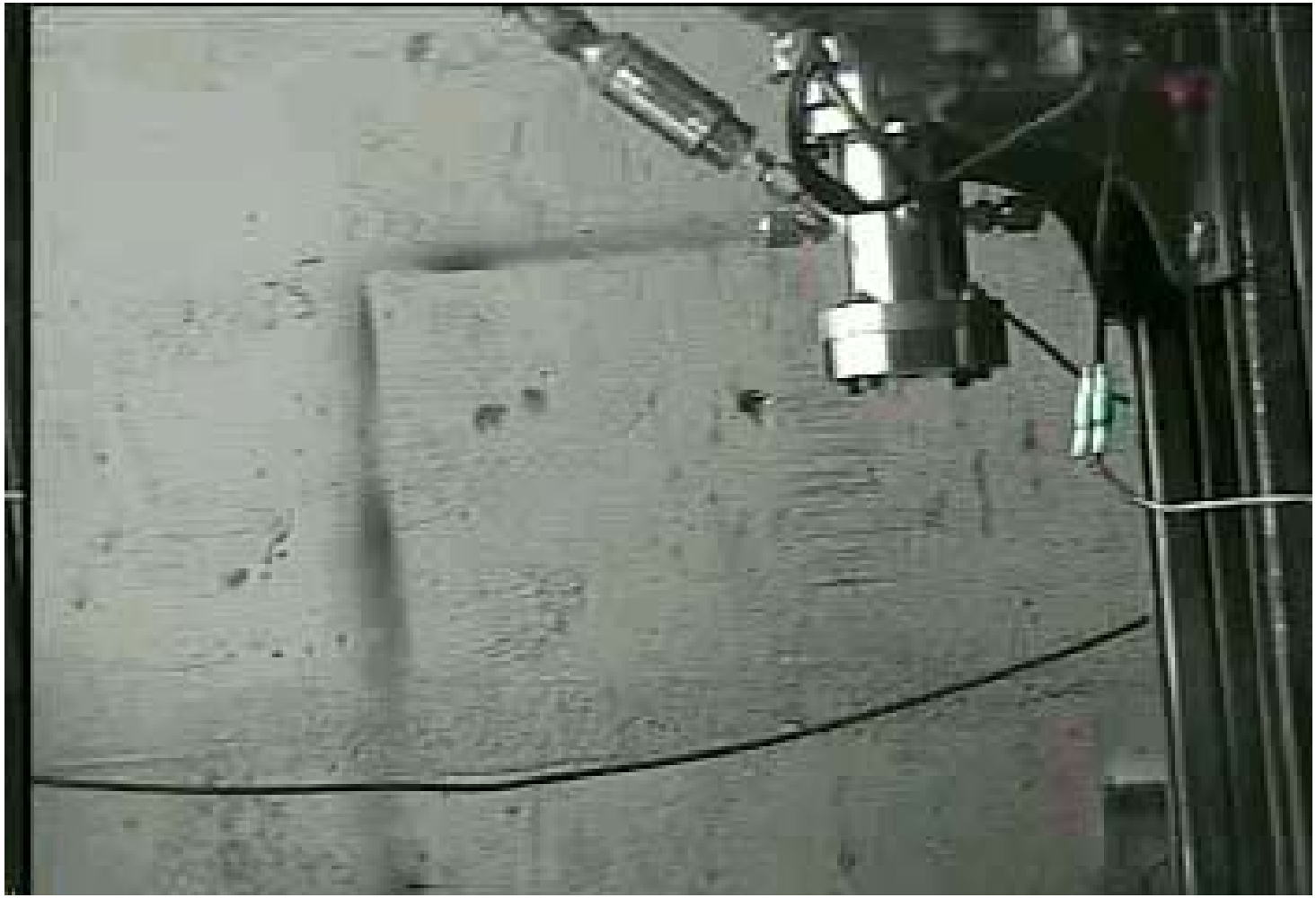
Fueling AMSAT at Kourou

Hazards and Other Detractors

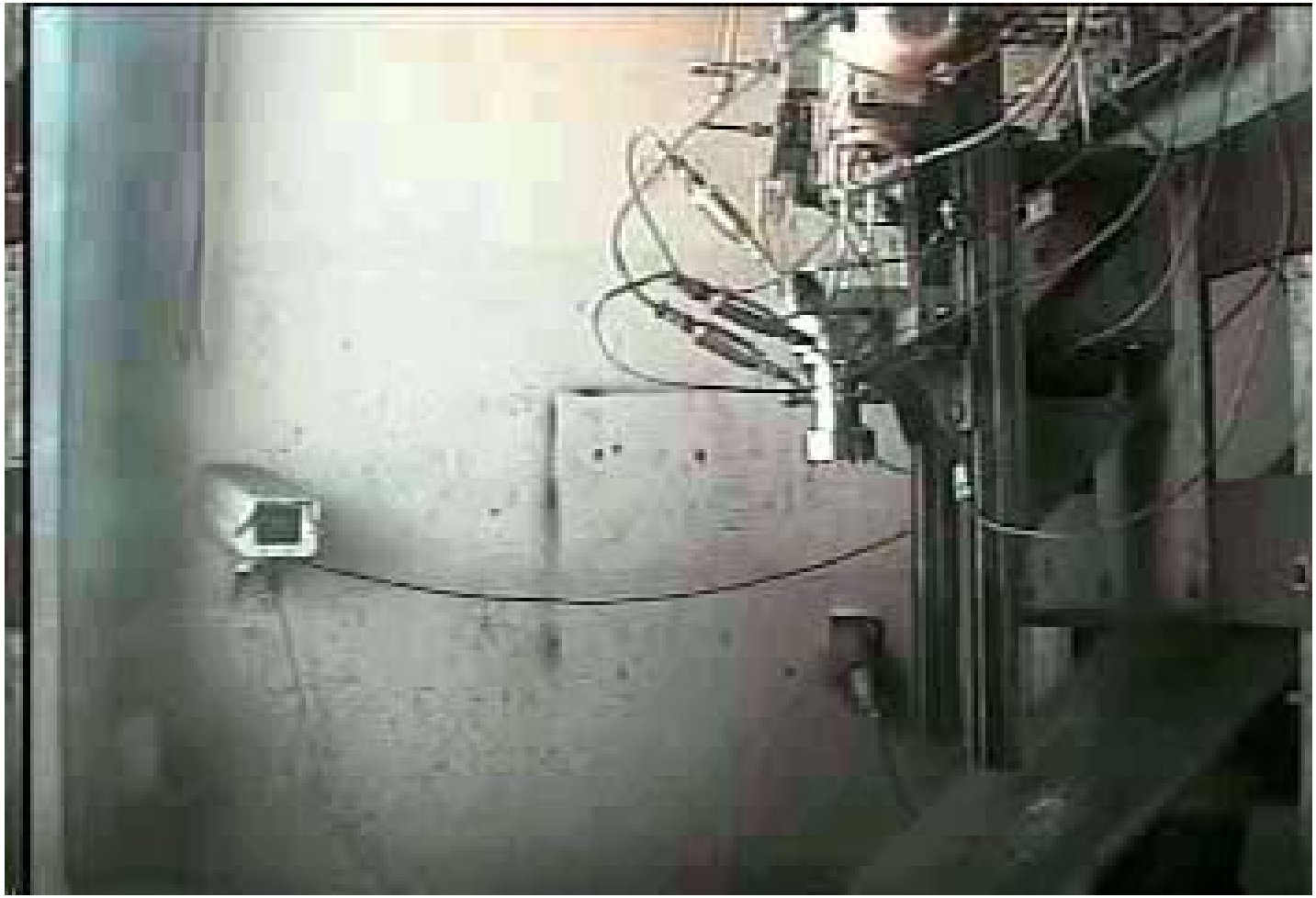
AEROJET

- Other Risks Include:
  - Flammability, Explosive Vapors
  - Compatibility, Compatibility, Compatibility
- Storability, Materials for Tanks & Lines, Seals, O-Rings, etc.
- Decomposition Rates
- Phase Changes (f.p., b.p., etc.)
- Reactivity (Related to Compatibility)
  - <u>Reaction Delay, as Hypergols</u>

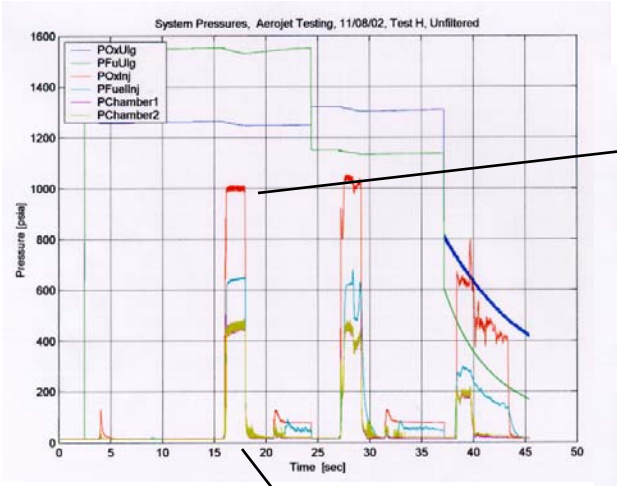
> 30 millisec Reaction Delay BiPropellant Test

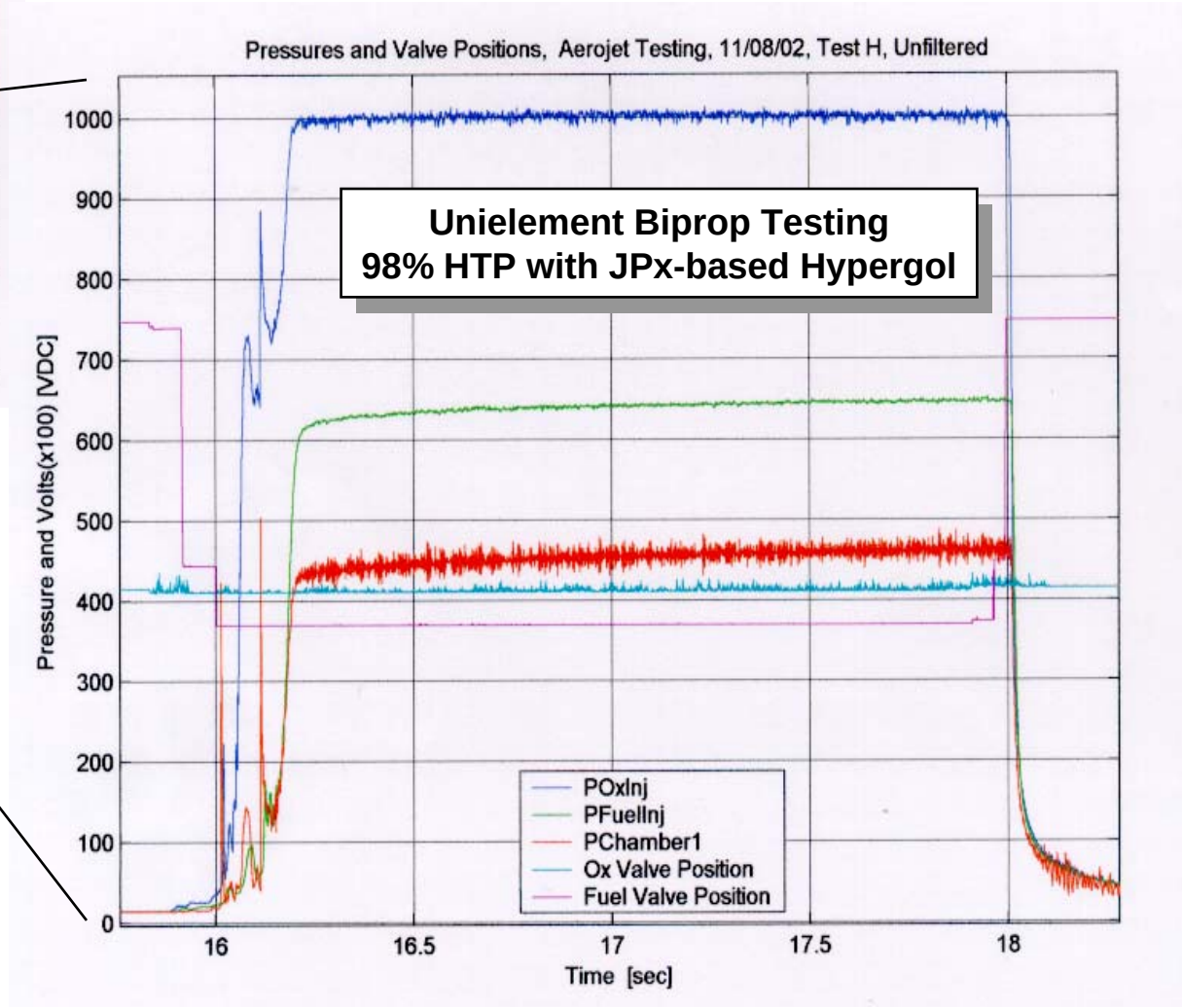


< 20 millisec Reaction Delay BiPropellant Test



Bipropellant Applications- H_2O_2/HC Hypergol Blend





Challenges – Not All-Inclusive…

AEROJET

- As We've Seen, New BiPropellant Reactivity is Major Parameter for Success
  - Measured via Drop-on-drop Methods, < 20 millisec Delay Translates to Acceptable Subscale Test Firings
  - Extensive Static Tests Still Required; Needs Facility Risk Management
- Fuel and Oxidizer Blends, or Gels, Can Provide Tailored Propellant Properties
  - Albeit at High Cost, Until Economies of Scale are Enabled
  - Within-Molecule Functional Groups, and their Orientation, May be Tailored in the Lab for Improvements in BiPropellant Performance
  - Blends of Complementary Liquid Fuels or Oxidizers May Prove to be a Preferred Approach
- Competition with the Alkylhydrazine Heritage Systems is Fierce; Risk Assessment Favors (Toxic) Storables at this Time, and for Foreseeable Future
  - Green Propellants, with Their Potential for Greatly Reduced Hazards and Associated Cost Savings, May Drive Development of These New BiPropellants

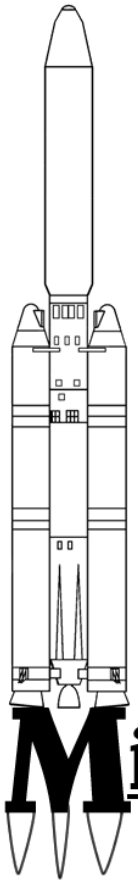
References, Acknowledgments

AEROJET

- Dr. Eckart W Schmidt, discussions, lectures and notes
  - A Real Rocket Scientist!
- Sutton, Biblarz, *Rocket Propulsion Elements,* 7th Ed., 2001

Dr. Eckart Schmidt (at left) with Mars Viking Lander University of Washington LFEM-STEP

DEFENSE ENERGY SUPPORT CENTER



MissileFuels

Weapon Systems and Civil Program Overview

Presented at the DESC's Worldwide Energy Conference
September 29, 2004

Melanie Mueller

Chief, Requirements Branch

Missile Fuels Commodity Business Unit

Defense Energy Support Center

Overview

- Our mission
- Programs we support and which products we use to support them
- Future changes
- Support Structure to keep up with new technology developments

Who We Are
Mission Statement

- DoD's Integrated Materiel Manager for Missile Fuels:
  The single agency for providing Department of Defense, Federal Government customers, and commercial and academic space-related customers, with comprehensive logistics support for all missile fuels, chemicals and gases, cryogenic liquids and propellants in the most effective and economical manner possible.

Missile Fuels Customer Profile

- DoD
  - Air Force
  - Army
  - Navy
  - USMC
- Federal Civilian
  - NASA
  - DOE
- Commercial
  - Research and Development
  - Commercial Space Launch

CBU Snapshot Product Line Overview

- Three categories of products
  - <u>Propellants – 3 types</u>
    - Hypergols
      - Hydrazine – 7 grades
      - N_20_4 – Oxidizer
    - Liquids
      - Priming Fluid (PF-1)
      - RP-1
      - Isopropyl Alcohol (IPA)
      - Hydrogen Peroxide (H_2O_2)
      - Inhibited Red Fuming Nitric Acid (IRFNA)
      - JP-10
    - Cryogenic
      - Liquid Oxygen (LOX)
      - Liquid Hydrogen (LH_2)

CBU Snapshot Product Line Overview Cont'd

- Non-Propellant Cryogenics
  - ✓ Liquid Nitrogen (LN)
  - ✓ Liquid Air
  - ✓ Liquid Argon
  - ✓ Liquid Helium
- Gases
  - ✓ Nitrogen
  - ✓ Argon
  - ✓ Helium
  - ✓ Hydrogen
  - ✓ Gaseous Deuterium (D_2)
  - ✓ Nitrogen Trifluoride (NF_3)
  - ✓ Fluorine
  - ✓ Xenon
  - ✓ Krypton
  - ✓ Neon

Major Programs Supported by the Missile Fuels CBU

- USAF Titan, Delta and Atlas
- F-16 Emergency Power Unit
- F-15/F-16 Air Intercept Missile, Avenger, Sidewinder
- All Cruise Missiles – Navy Tomahawk, Harpoon, & USAF's ALCM/ACM
- AIM9 and Stinger Missiles
- US Army 37C Drone and Lance Missiles
- Wind Tunnels
- DoD Laser Programs
- Space-Based Weapons (R&D)
- NASA Space Shuttle
- International Space Station

Additional Programs

- Evolved Expendable Launch Vehicle (EELV)
- Atlas
- Terminal High Altitude Area Defense THAAD
- Military and commercial satellites
- Peacekeeper
- Milstar
- Fleet Leader
- Sea Launch
- Global Star
- National Oceanic Atmospheric Administration NOAA

Atlas II

RP-1

LOX

N2O4

HPH

LN2

Delta II

RP-1

LOX

A-50

N2O4

LN2

Titan II

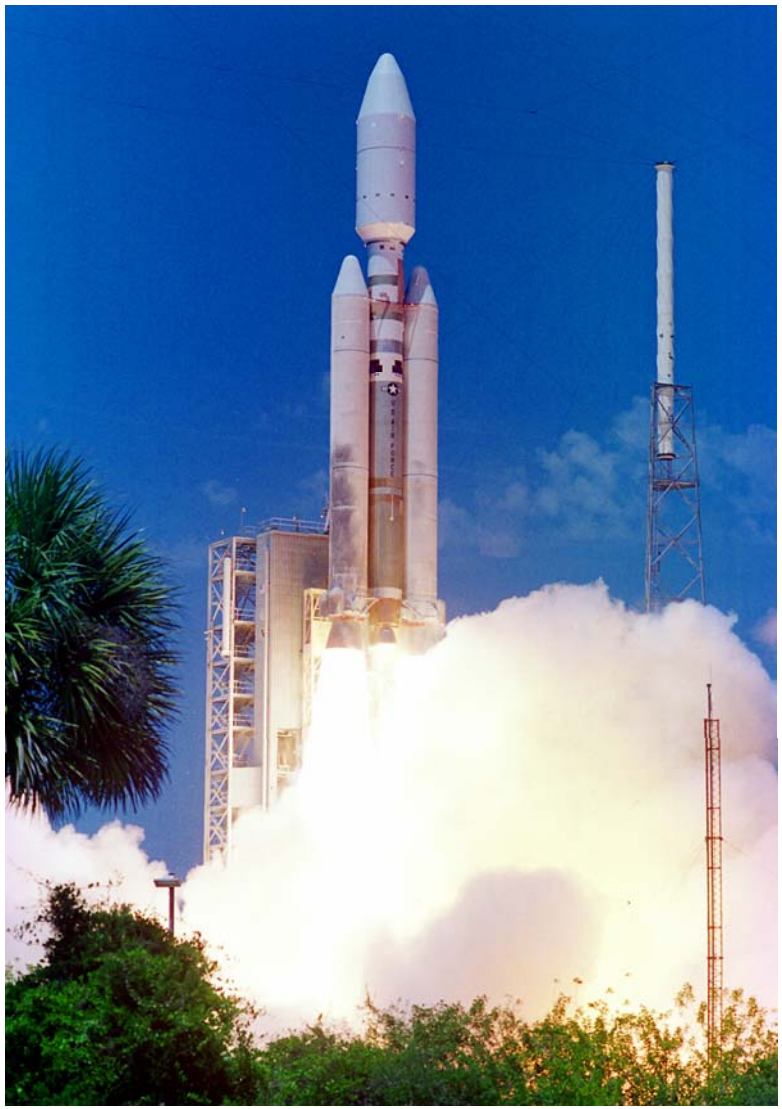
A-50

N2O4

Liq Helium (Bulk)

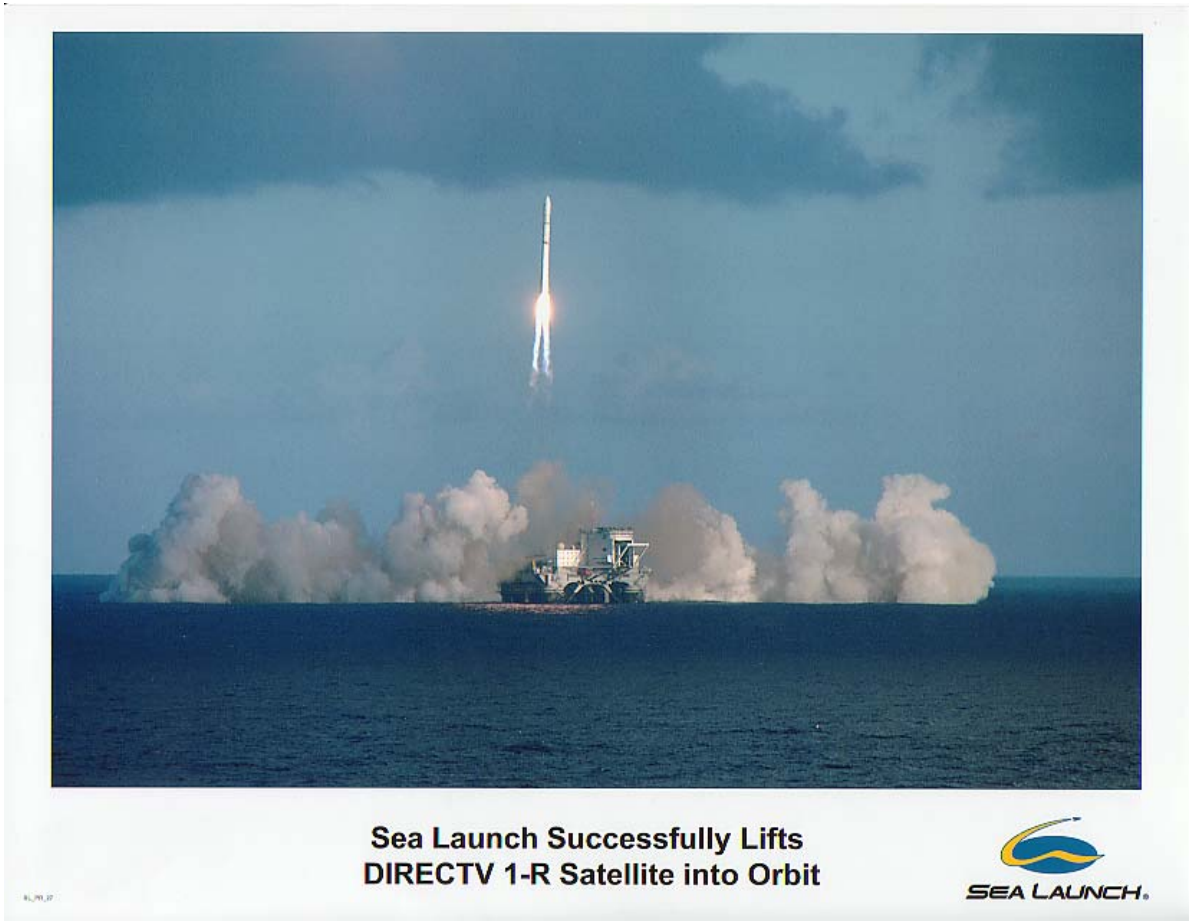
LN2

Titan IV



A-50
N2O4
Liq Hydrogen
LOX
Liq Helium
(Bulk)
LN2

Sea Launch Of DirectTv 1-R Satellite (MMH)



Space Shuttle

MMH

MPH

N2O4

F-16 (H-70)

Space Shuttle (IPA)

Mobile Tactical High Energy Laser

NF3

D2

H202

Airborne Laser (H2O2)

Lance Missile (Nitric Acid)

Air-Launched Cruise Missile (ALCM)
PF-1 and JP-10

Conventional Air-Launched Cruise Missile, CALCM (JP-10)

Harpoon

[redacted]

JP-10

Tomahawk

JP-10

Evolved Expendable Launch Vehicle (EELV) Atlas V

RP-1

LOX

GN2

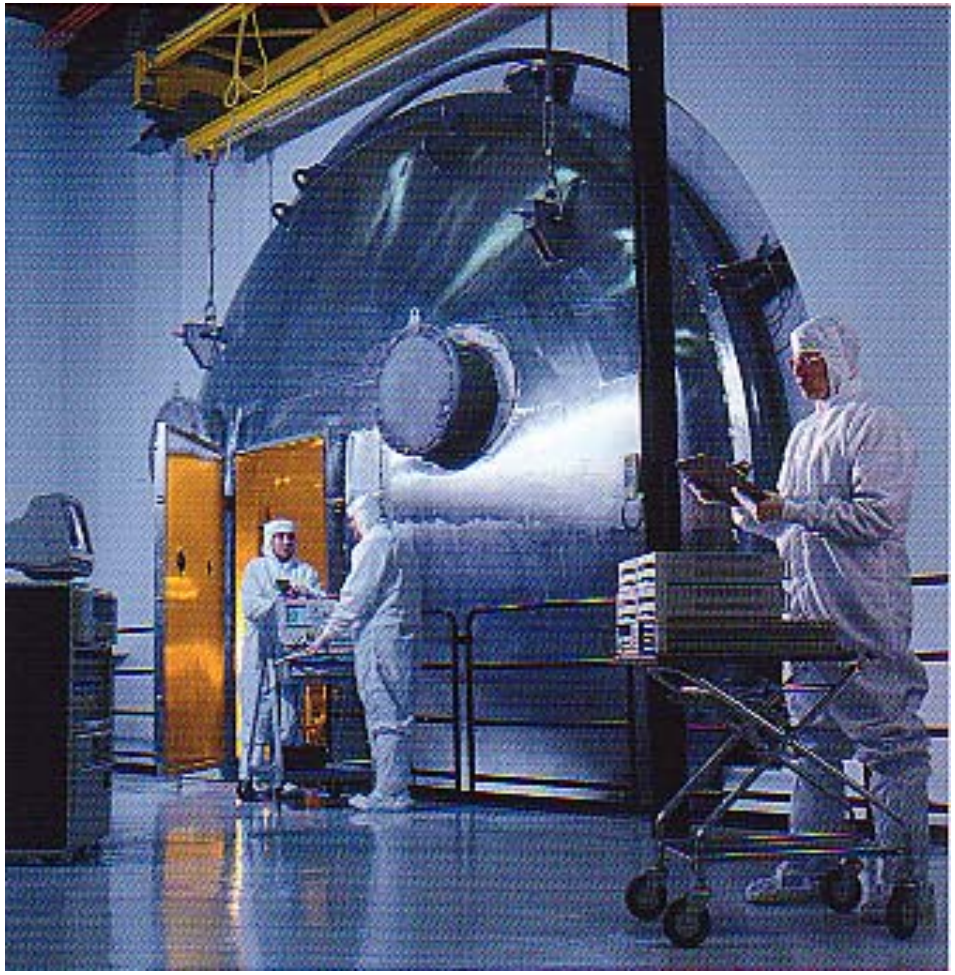
LN2

RS-68 Propulsion System (LH2)
For Boeing EELV Delta IV

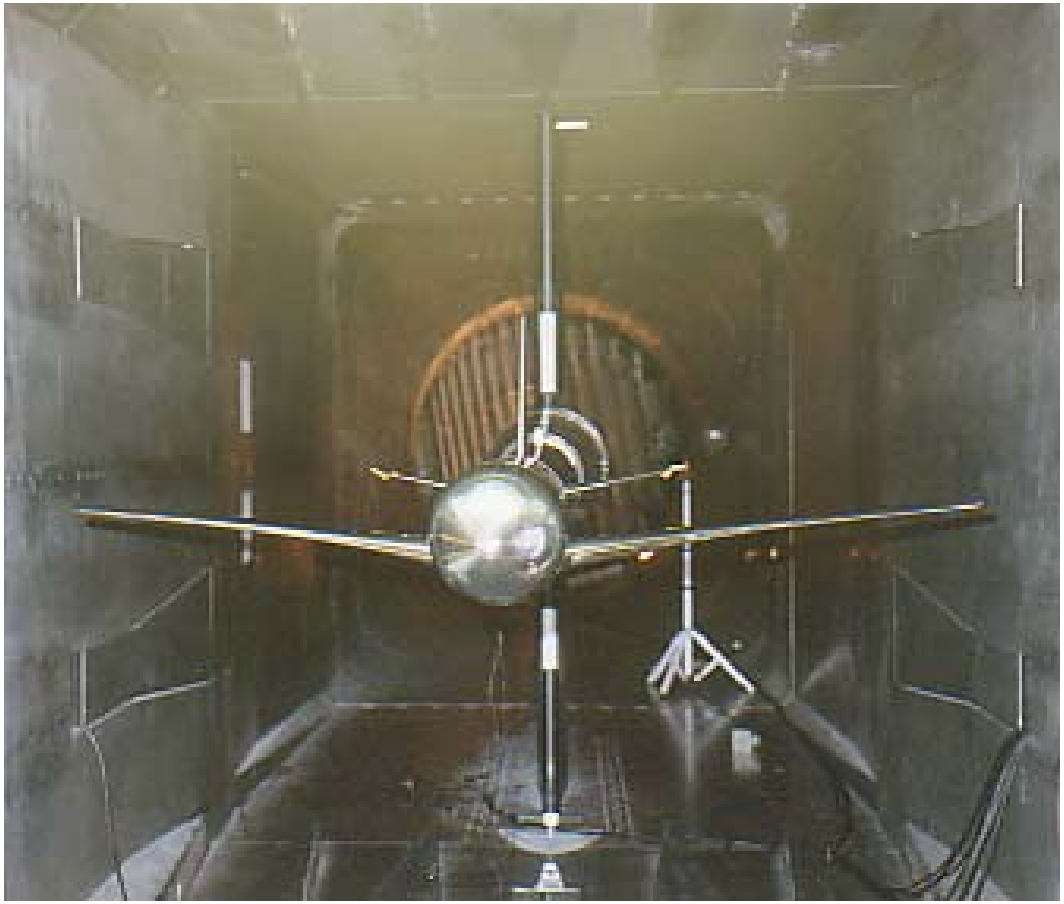
F-15 (LN2)

C-5 (LN2)

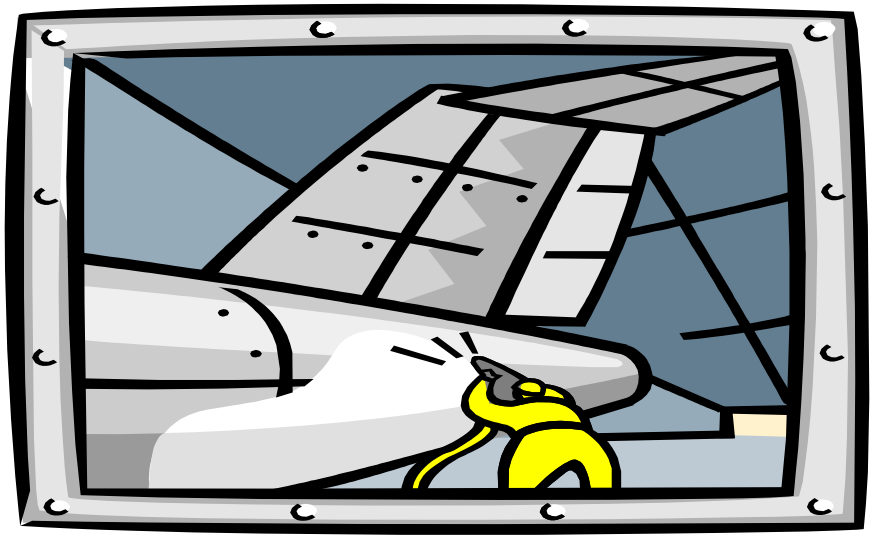
Space Based Infrared Systems Aerojet Test Facility in Azusa, Calif (LN2)



Windtunnel (Liquid Air)



Welding Technology and Flight Line (Liquid Argon)



Air Force Research Lab (Helium, Hypergols and RP-1)

AIM9 Sidewinder Missile (6000 PSI Argon)

Stinger
6000 PSI Argon

Avenger (6000 PSI ARGON)

Aerostat Deployment Demonstration
Gas Helium

[redacted]

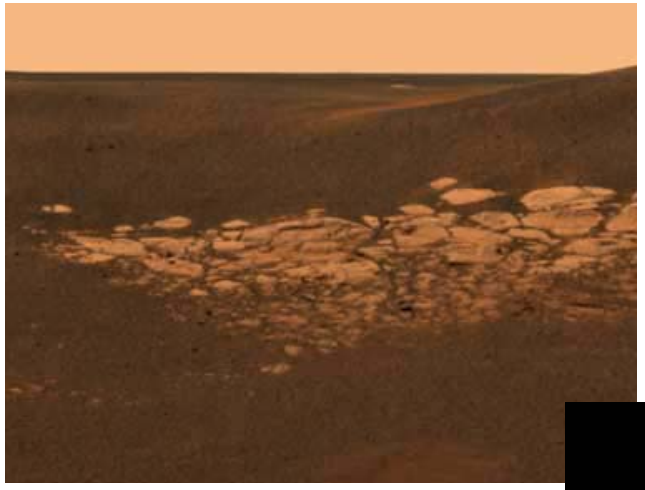
Tethered Aerostat Radar System (Bulk Helium)

Hypersonic (High Speed) Sled Testing (Bulk Helium)

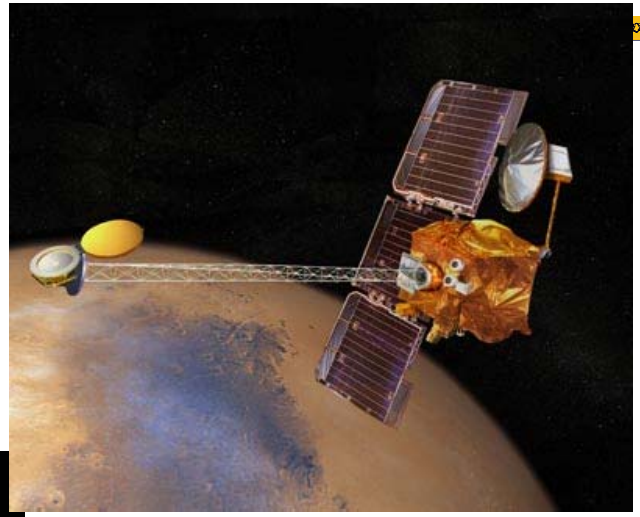
Space-Based Laser Integrated Flight Experiment (D2, GN2)

Hall Effect Thruster (Xenon)

Deep Space Communications

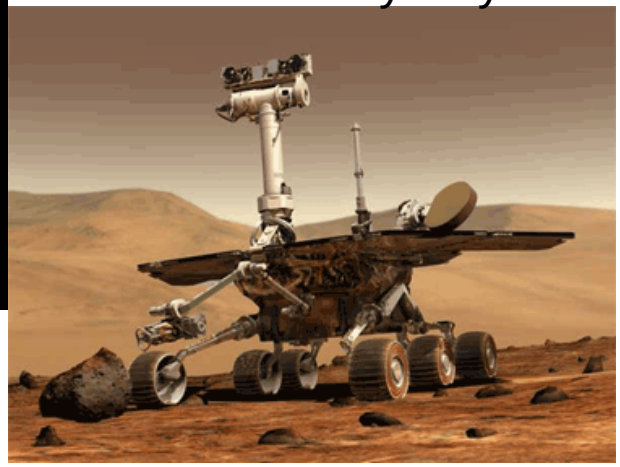


Outcropping on Mars picture taken by the Rover Opportunity



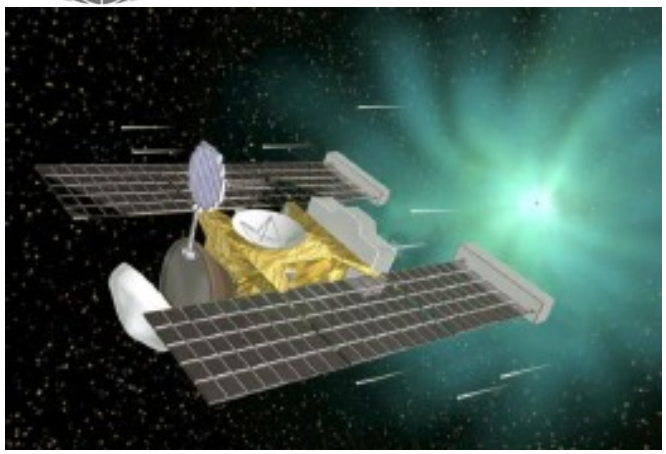
Mars 2001 Odyssey

Mars Global Surveyor

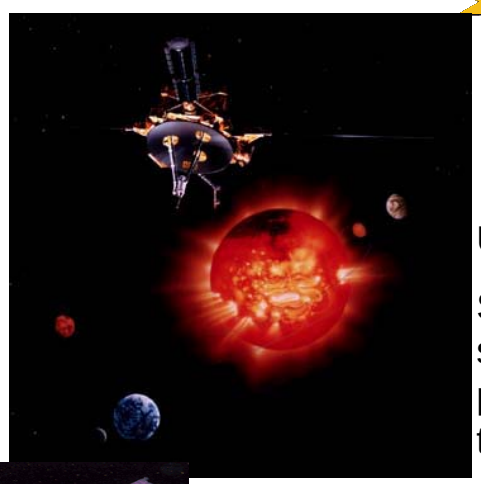


Rover on Mars

Deep Space Communications

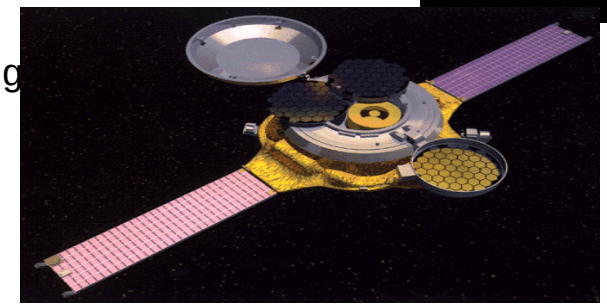


Stardust, sent to the Wild 2 Comet, bringing samples home in 2006

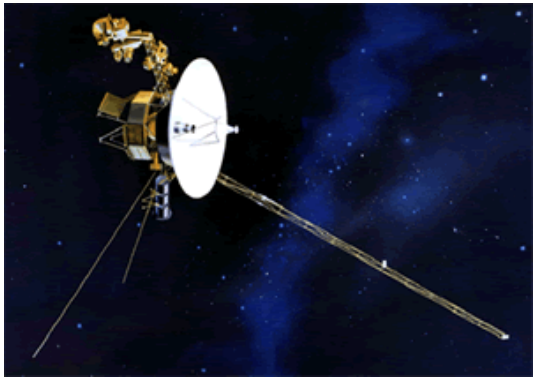


Ulysses

Sent to study the poles of the Sun



Genesis sent to bring home samples of the Solar Wind, returns to Earth September 8, 2004



Voyagers I and II, the farthest Man-made objects in Space

Spitzer InfraRed Space Telescope studying our Universe in the Infrared

Where We Are Going?

- Not stopping with EELV
- Command majority of propellant buys for DoD & commercial programs
- Capture full DoD market to obtain maximum benefit in pricing for gov't
- Capture additional FedCiv agency business
- Capture additional commercial space launch business

Support Strategy

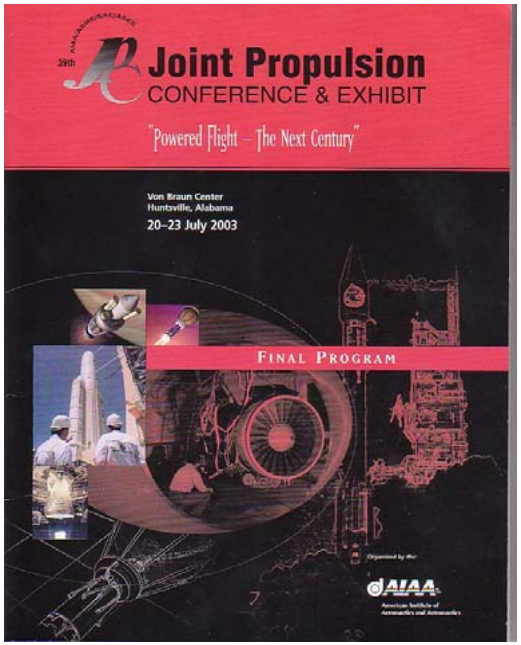
- On-going market evaluation
  - Main market for DoD; uncaptured cryogenic propellants and pressurants
- Partner with suppliers identifying new customers and target markets
- Approach target customers to consolidate requirements

Business Strategy

- Site Visits and presentations to:
  - DoD program offices
    - (i.e. Space Command, Missile Defense Agency)
  - FedCiv programs
    - (i.e. NASA, DOE. NOAA)
  - Commercial space industry
    - (i.e. Aerojet, Pratt & Whitney)
  - DESC regional offices
    - Eyes and ears for Missile Fuel leads

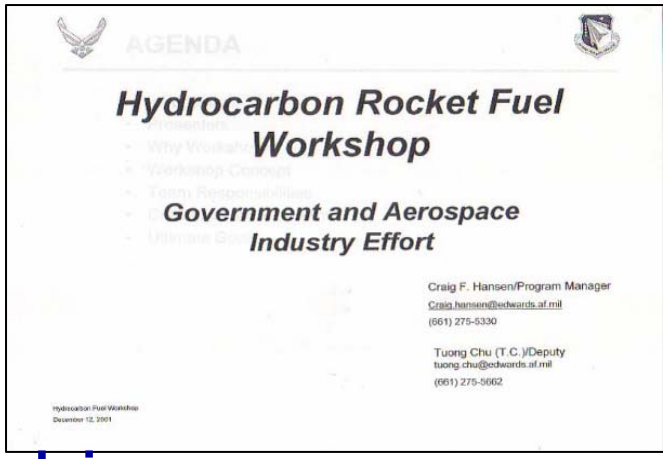
Additional Efforts

- Propulsion Conference Attendance (& presentations)
  - Joint Navy Army NASA Air Force (JANNAF) Propulsion Agency Conferences
  - Joint Propulsion Conference
  - National Space Symposium
  - Green Propellants Conference



Additional Efforts

- Workshop involvement
  - Hydrocarbon Rocket Fuel
  - Hydrogen Peroxide
  - New propellant development



- Propellant Committee membership
  - Liquid Propellants Committee on Standards
  - Tactical Missile Panel
  - Liquid Hydrocarbon (RP-1) Panel
  - Hydrogen Peroxide Panel

New Propellants Market Requirements

- Actively working with DoD and industry to support new developmental products that are:
  - Safer
  - Environmentally friendlier
  - Higher energy
  - Higher density

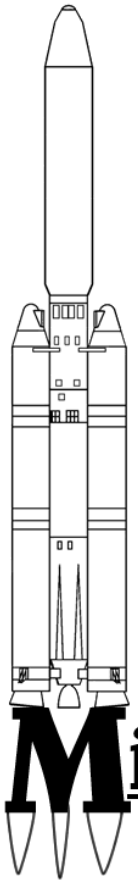
Summary

- Our mission
- Programs we support and which products we use to support them
- Future changes
- Support Structure to keep up with new technology developments

Salute To Titan

[redacted]

DEFENSE ENERGY SUPPORT CENTER



Missile Fuels