Advanced Chemical Propulsion

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"ST Day 2000: Reducing Risk for the Next Generations"
Revolutionary Rockets

Advanced Fuels and High Energy Density Materials

- Strained Ring Hydrocarbons (Bai/TD40)
- Azide Fuel (US Army - Bai/TD40)
- Solid Hydrogen
- Recombination Energy Fuels (Palaszewski /GRC)
  - Penta Nitrogen (Palaszewski /GRC)
  - Poly-Oxygen (Palaszewski /GRC)
  - Metallized and Gelled Fuels (Palaszewski /GRC)
  - Powdered Aluminum Combustion (Litchford/TD15)

Launch Assist

- Cannons, Balloons, Aerial Refueling, Catapults, etc (Nolen/ED31, Jones/TD40)

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion
♦ Identify and develop advanced chemical propellants
  • Hydrocarbons for LEO propulsion
  • Monopropellants or Cryogenic propellants for upper stages

♦ Improve access to space capability
  • Smaller vehicle
  • Larger payload
  • Low cost

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Advanced Fuels Development Objective & Goal
 Revolutionary Rockets

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Criteria for Fuel Selection

- Predicts Better Performance (Isp) Over LOX/RP-1 System
- Most Desirable Physical Properties
  - Lower Vapor Pressure Compared to RP-1
  - Higher Density ($\geq$ RP-1 = 0.801 g/mL)
  - Freezing Point ($\leq$ -10 °C; RP-1 = -41.4 °C)
  - Boiling Point $\geq$ B. P. of RP-1
- Thermally Stable
- Compatible with the Current System

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Strained Ring Hydrocarbons
Performance Screening Test
- Small Scale Combustion Test
  - ~50 pounds Thrust Hot Fire Tests (limited by amount of fuels)
  - C* Efficiency
  - Isp
  - Material Comparability test
  - Initial Aging Studies

Initial Screening - 10 Grams
- Computational Chemistry
- Synthesis Routes
- Preliminary Characterization
  - Chemical, Physical, Hazard Properties
- Toxicity if Known?
- Synthesis Cost Evaluation

Development and Characterization
- Synthesis Scale-Up - 10 Pounds
  - Additional Characterization
    - Chemical, Physical, Hazard Properties
  - Formulation
  - Initial Aging Studies
  - Initial Compatibility
  - Initial Thermal Studies
  - Initial Toxicity Studies

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Strained Ring Hydrocarbons
Structural Requirement for High Energy Contents

- The energy contents can be increased by adding unsaturation in the molecule
  \[-(\text{CH}_2)-\text{CH}_2=\text{CH}_2\text{HC}=\text{CH}\]
- $\Delta H_f/C \sim -5 \sim 6.25 \sim 27.1$ Kcal/mole

Fuels

1,5-Hexadiyne
\[\Delta H_f = 91.8 \text{ Kcal/mole}
= 1.18 \text{ Kcal/g}
I_{sp} = 311.8 \text{ Sec}\]

1,7-Octadiyne
\[\Delta H_f = 79.9 \text{ Kcal/mole}
= 0.75 \text{ Kcal/g}
I_{sp} = 308.2 \text{ Sec}\]

Quadricyclane
\[\Delta H_f = 72.2 \text{ Kcal/mole}
= 0.78 \text{ Kcal/g}
I_{sp} = 307 \text{ Sec}\]

C8H10
C7H8

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Strained Ring Hydrocarbons
SUMMARY:

- With cooperation with Air Force Research Laboratory and Army, the performances of advanced hydrocarbon fuels will be compared with a base fuel (RP-1).

- The fuels are: Quadricyclane, bi-cyclo-propylidine, AFRL-1, 1,7 Octadiyne, AFRL-1 and Dimethyl amino ethyl azide (DMAZ). The theoretical performance of these fuels indicates that all of these fuels have higher ISP than RP-1.

Principle Investigator:
- S. Don Bai - NASA/MSFC TD40, 256-544-9036
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Strained Ring Hydrocarbon Fuel Testing
## Project Team Members
- **Project Manager**: John Cole, TD-15
- **System Engineer**: Scott Jackson, TD-15
- **MSFC PI**: S. Don Bai, TD-40
- **NASA/GRC**
- **AFRL**

## MSFC Test Team Members
- **Test Requester**: S. Don Bai, TD-40
- **Test Project Engineer**: Paul Dumbacher, TD-71
- **Test Instrument Engineer**: Smith/Wiley, TD-72
- **Test Control Engineer**: Gregory/Trieu, TD-73
- **Material Testing**: James Perkins, ED-36
- **Safety**: Rosalyn Patrick, QS-10

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**Strained Ring Hydrocarbon Fuel Testing**
Test Requirements

- Measure the performance parameters
  - Chamber Pressure
  - Fuel & Oxidizer Flow Rate
    - Venturi upstream and downstream conditions.
  - Thrust
- Characteristic exhaust velocity (C*)
  - Comparing relative performance of different chemical propellants.
- Specific Impulse (Isp)
  - Integrated thrust per mass over the time.

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Strained Ring Hydrocarbon Fuel Testing
Theoretical Comparison

Theoretical Isp

Estimated Performances

Theoretical C*

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Strained Ring Hydrocarbon Fuel Testing
Test Engine & Rig - Combustor

- Designed & Fabricated by G. G. Industries (Scot Claflin) for MSFC.
  - Overall Design
    - Propellants: LOX/kerosene - Modified for GOX/RP-1
    - Fuel flow rate: 0.08 lb/sec  Mixture Ratio: 2.0
    - Theoretical $c^*$: 5890 ft/sec  $c^*$ efficiency: 90%
    - Thrust coefficient, Cf: 1.35  Thrust: 52 lbs.

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Strained Ring Hydrocarbon Fuel Testing
Test Rig

- Originally Designed & Fabricated by Mason-Holodyne.
- Extensive Modification by STD Technology Evaluation Department.
  - Flexibility
  - Serviceable parts
  - Incorporation of MSFC expertise of testing
  - LOX system to GOX system
  - Instrumentation

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Strained Ring Hydrocarbon Fuel Testing
Test Rig - Schematic Diagram

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Strained Ring Hydrocarbon Fuel Testing
Test Matrix

- A successful test must go full duration, reach set point conditions for the chamber pressure, flow rate, etc., and involves the accurate measurements fuel and oxidizer flow rates, temperatures, chamber pressure, thrust and cooling water flow rate. Fuel will be switched from RP-1 tank to advanced fuel tank after ~12 seconds of ignition for Test 3 to Test 12. The cooling water flow rate is 0.65 #/sec. The cleaning of advanced fuel tank with Pentane is required after each different type of fuel in the test series. The test matrix is listed below.

<table>
<thead>
<tr>
<th>Run</th>
<th>Chamber</th>
<th>GOX</th>
<th>Tank 1-</th>
<th>Tank2</th>
<th>Tank 2</th>
<th>Test Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>RP-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pc (psi)</td>
<td>(#/sec)</td>
<td>(#/sec)</td>
<td>(#/sec)</td>
<td>(#/sec)</td>
<td>(sec)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>RP-1</td>
<td>0.08</td>
<td>Tbd system check out</td>
</tr>
<tr>
<td>2</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>RP-1</td>
<td>0.08</td>
<td>Tbd Ignition check out</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>RP-1</td>
<td>0.08</td>
<td>Tbd Switching check out</td>
</tr>
<tr>
<td>4</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>RP-1</td>
<td>0.08</td>
<td>~20 Base Line Data</td>
</tr>
<tr>
<td>5</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>NF#1</td>
<td>0.08</td>
<td>~20 AF#1: Quadracycline</td>
</tr>
<tr>
<td>6</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>NF#1</td>
<td>0.08</td>
<td>~20 Repeat</td>
</tr>
<tr>
<td>7</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>RP-1</td>
<td>0.08</td>
<td>~20 AF#2 BCP</td>
</tr>
<tr>
<td>8</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>NF#2</td>
<td>0.08</td>
<td>~20 Repeat</td>
</tr>
<tr>
<td>9</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>NF#2</td>
<td>0.08</td>
<td>~20 AF #3 1,7 Octadiyne</td>
</tr>
<tr>
<td>10</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>RP-1</td>
<td>0.08</td>
<td>~20 Repeat</td>
</tr>
<tr>
<td>11</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>NF#3</td>
<td>0.08</td>
<td>~20 AF#4 Azide</td>
</tr>
<tr>
<td>12</td>
<td>175</td>
<td>0.16</td>
<td>0.08</td>
<td>NF#3</td>
<td>0.08</td>
<td>~20 Repeat</td>
</tr>
</tbody>
</table>

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Strained Ring Hydrocarbon Fuel Testing
• Pre-testing Activities
  • Valve Impact Tests at AFRL
  • Short Term Aging Study
  • Material Comparability Tests
  • Dynamic Load Test of Thrust Measurement System

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Strained Ring Hydrocarbon Fuel Testing
♦ Objectives:
  • To test the detonation nature of the control valve while actuating it with the following advance HEDM fuels; Bicyclopropylidene, Cyclopropylacetylene 1,7-Octadiyne.

♦ Conclusions/Recommendation:
  • Based on the results from this test, the HEDM fuels; Bicyclopropylidene, Cyclopropylacetylene, and 1,7-Octadiyne should not have any reactions with different Marotta valves used on the NASA/Marshall.

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Valve Impact Tests at AFRL
Handling of Fuels require personal protective equipment

<table>
<thead>
<tr>
<th></th>
<th>Quadracyclane Lot #1001</th>
<th>Bicyclopropyldiene (aged)</th>
<th>1,7 Octadiyne 99%</th>
<th>Dimethyl-2-Azido Ethylamine</th>
<th>AFRL-1</th>
<th>RP-1 Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumel Ribbon</td>
<td>Strong Odor</td>
<td>Very Strong Odor</td>
<td>Some Odor</td>
<td>Not a very strong odor</td>
<td>Very strong odor</td>
<td>Some Odor</td>
</tr>
<tr>
<td></td>
<td>No visible reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible reaction</td>
<td>No visible reaction</td>
</tr>
<tr>
<td>Chromel Ribbon</td>
<td>Strong Odor</td>
<td>Very Strong Odor</td>
<td>Some Odor</td>
<td>Not a very strong odor</td>
<td>Very strong odor</td>
<td>Some Odor</td>
</tr>
<tr>
<td></td>
<td>No visible reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible reaction</td>
<td>No visible reaction</td>
</tr>
<tr>
<td>Magnesium Oxide Core</td>
<td>Strong Odor</td>
<td>Very Strong Odor</td>
<td>Some Odor</td>
<td>Not a very strong odor</td>
<td>Some Odor</td>
<td>No visible reaction</td>
</tr>
<tr>
<td></td>
<td>No visible reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible reaction</td>
<td>No visible reaction</td>
</tr>
<tr>
<td>Krytox 240AC</td>
<td>Strong Odor</td>
<td>Very Strong Odor</td>
<td>Some Odor</td>
<td>Not a very strong odor</td>
<td>Some Odor</td>
<td>No visible reaction</td>
</tr>
<tr>
<td></td>
<td>No visible reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible reaction</td>
<td>No visible reaction</td>
</tr>
<tr>
<td>Sauerisen Cement</td>
<td>Strong Odor</td>
<td>Very Strong Odor</td>
<td>Some Odor</td>
<td>Not a very strong odor</td>
<td>Very strong odor</td>
<td>Some Odor</td>
</tr>
<tr>
<td></td>
<td>No visible reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible reaction</td>
<td>No visible reaction</td>
</tr>
<tr>
<td>E Constantan</td>
<td>Strong Odor</td>
<td>Very Strong Odor</td>
<td>Some Odor</td>
<td>Not a very strong odor</td>
<td>Very strong odor</td>
<td>Some Odor</td>
</tr>
<tr>
<td></td>
<td>No visible reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible Reaction</td>
<td>No visible reaction</td>
<td>No visible reaction</td>
</tr>
</tbody>
</table>

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Short Term Aging Study
Material Comparability Tests
Specific Gravity Ratio: Quadricyclone / RP-1 = 1.17
Cstar efficiency (~1.8%) & Isp (~5 sec) are better than RP-1

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Test Results: Quadricyclone
Test 23: RP-1 vs 1,7 Octadiyne

Preliminary Test Result: 1,7 Octadiyne
Test 25: RP-1 vs AFRL-1

Preliminary Test Result: AFRL-1
Adv. Hydrocarbon Fuels

<table>
<thead>
<tr>
<th>Mixture Ratio</th>
<th>RP-1</th>
<th>Quadricyclane</th>
<th>1,7 Octadiyne</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.9 2.04</td>
<td>1.94 2.15</td>
<td>2.1</td>
</tr>
<tr>
<td>Cstar(Theory)</td>
<td>5887(100%)</td>
<td>6017(100%)</td>
<td>6000(100%)</td>
</tr>
<tr>
<td>Cstar(Experiment)</td>
<td>5348(90.8%)</td>
<td>5456(90.7%)</td>
<td>5503(91.7%)</td>
</tr>
<tr>
<td>Isp(Theory)</td>
<td>273.1(100%)</td>
<td>279.4(100%)</td>
<td>278.5(100%)</td>
</tr>
<tr>
<td>Isp(Experiment)</td>
<td>186.7(68.4%)</td>
<td>194.5(69.6%)</td>
<td>193.3(69.4%)</td>
</tr>
</tbody>
</table>

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Preliminary Test Result
BCP
* DMAZ
* AFRL-
* LM-1
* RG-1

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Fuels To Be Tested
Future R&D with AFRL

- Additional Compatibility Studies
  - Screening with More Materials
    - Polymers, Elastomers, Metals,

- Decomposition Studies
  - Gas Phase
  - Liquid Phase

- Additional Toxicity
  - Long Term Studies + 90 Day

- Environmental Studies

- Ignition / Combustion Studies
  - Gas Phase
  - Liquid Phase
  - WSR
  - Ignition Delay
  - Combustion Gases

- Refined Synthesis Cost Estimate
  - Number of Steps in Reaction
  - Cost of Materials
  - Heat Transfer - Heat or Cooling Issues
  - Waste Disposal

- System Analysis
  - Studies with Existing Systems

- Logistics
  - Transportation Costs
  - Storage Costs
  - Handling Costs
  - Disposal Costs

- Medium Scale Combustor - 1000 Pounds
  - (NASA/DOD/Industry)
  - Flame Temperature
  - Flow Rates - Pressure - Volume
  - Isp - Delivered
  - XXXXX......

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Strained Ring Hydrocarbons: Joint Project with AFRL
 Revolutionary Rockets

 Advanced Fuels and High Energy Density Materials
  • Strained Ring Hydrocarbons (Bai/TD40)
  • Azide Fuel (US Army - Bai/TD40)
  • Solid Hydrogen
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Agenda
Azide Fuel (DMAZ)

DOD/US Army/AF - NASA Project
Initiated for an alternate fuel to Hydrazine
NASA/White Sands Test Facility funded
NASA/MSFC will test as a bipropellant fuel

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"ST Day 2000: Reducing Risk for the Next Generations"
NASA Glenn Research Center Tasks

♦ Create highest specific impulse atomic rocket propellants with atomic boron, carbon, or hydrogen in solid hydrogen particles

♦ Mass and Energy Balance for Solid Hydrogen and Atomic Propellants: Complete solid hydrogen freezing experiments with improved mass flow rate measurements and estimates of energy for hydrogen freezing
  - the quality (temperature, pressure, and state) and flow rate of the hydrogen delivered to the liquid helium dewar would be quantified,
  - the temperature profile in the liquid helium dewar would be more accurately known, and
  - the quality (temperature and pressure) and composition of the LH\textsubscript{e} dewar vent gases would be determined

♦ Plan for completion of project in 4th quarter of FY 2001, with AIAA paper documenting the test series results

♦ Contact - Bryan Palaszewski, NASA GRC, (216) 977-7493

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Atomic Propellants
♦ Revolutionary Rockets

♦ Advanced Fuels and High Energy Density Materials
  • Strained Ring Hydrocarbons (Bai/TD40)
  • Azide Fuel (US Army - Bai/TD40)
  • Solid Hydrogen
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♦ Launch Assist
  • Cannons, Balloons, Aerial Refueling, Catapults, etc (Nolen/ED31, Jones/TD40)

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion
Vision

- Atomic propellant offer large potential increases in rocket specific impulse (Isp)
- Isp increases of hundreds of seconds over O2/H2 are theoretically possible
- Isp increases can reduce vehicle gross liftoff weight (GLOW) up to 80%
- A long history of research has opened new possibilities to harness atomic fuels
- Cryogenic storage temperatures of 4 K or lower are required

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Atomic Propellants: Why Atomic Propellants?
Specific Impulse (Isp) Map for Atomic Hydrogen

Atomic hydrogen engine performance

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Atomic Propellants
 Revolutionary Rockets

- **PDRE Development Project (Ryan/TD51)**
  - Pulse Detonation Engine / Pulse Detonation Rocket Engine
    - PDRE Bench Unit (Litchford/TD15)
    - Revolutionary Concept (REVCON) PDE (Hueter/TD15)
    - PDE Performance Code Development (Seymour/TD53)
  - Advanced Ejector (Blevins/TD40)
  - Air Augmented Aerospike CFD Analyses (Garcia/TD64)
  - Deeply Cooled Air Rocket Engine (Bai/TD40)
  - Liquid Air Combustion Engine (LACE) (Bai/TD40)
  - Multiple Reaction HE Explosive (Bonometti/TD40)

 Advanced Fuels and High Energy Density Materials

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Agenda
• Pulse Detonation Engine / Pulse Detonation Rocket Engine

- PDE Concept
- NASA MSFC PDRE Activities
- Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

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Revolutionary Rockets
Detonation process is self pressurizing
- High peak temperatures and pressures occur at microsecond time scales
- High cycle rates and multiple combustors produce even thrust


Pulse Detonation Propulsion Uses “Fill and Fire” Operations
Preliminary ASI tests are successfully demonstrating PDRE performance at 1 atm test condition.

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion
PDRE Potential Based on Higher Thermodynamic Efficiency and a Self Pressurizing Process
**PDRE Critical Technologies**

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Revolutionary Rockets

_Pulse Detonation Engine / Pulse Detonation Rocket Engine_

PDE Concept

NASA MSFC PDRE Activities

ASTP PDRE Development Projects

POC  NASA/MSFC  Hueter/Richard M Ryan
      256-544-4172

ASTP PDRE Research projects

In-House PDR Testing

POC  NASA/MSFC  Cole/Ron Litchford
      256-544-1740

Analysis

POC  NASA/MSFC  Cole/Dave Seymour
      256-544-7116

Office of Naval Research's
Multi-University Research Initiative on
Pulse Detonation Engines

*For the PDRI, see the team next page for contact on Advanced Chemical Propulsion*
Pulse Detonation Engine / Pulse Detonation Rocket Engine

- PDE Concept

- NASA MSFC PDRE Activities
  - ASTP PDRE Development Projects
    - POC NASA/MSFC Hueter/Richard M Ryan - 256-544-4172
  - ASTP PDRE Research projects
    - In-House PDR Testing
      - POC NASA/MSFC Cole/Ron Litchford - 256-544-1740
    - Analysis
      - POC NASA/MSFC Cole/Dave Seymour - 256-544-7116

- Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Revolutionary Rockets
Two contracts awarded to develop PDRE technology
  • ASI
  • UTRC

Each exploring different back pressure control mechanisms
  • Fixed throat
  • Aerodynamic throat

In 3rd year of 3 year contract

Further work will require new procurement activity


ASTP PDRE Projects
ASI Accomplishments to Date

♦ In Just Four Years, ASI/NASA/AFRL Have Demonstrated:
  • PDRE proof-of-concept
  • 30-sec firing durations
  • Repeatability & reliability at high frequencies
  • Performance prediction
  • Back pressurization with a common nozzle
  • Vacuum start capability
  • Working injector concept
  • Full-scale, high-speed valves (simulant testing)

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ASTP PDRE Projects
UTRC Accomplishments to Date

♦ Proof-of-Concept Tests
  • Demonstrated PDRE operation with physical throat
  • Developed operating-characteristics database

♦ Aerovalve Development
  • Developed design and analysis capabilities
  • Demonstrated concept in single-shot, cold-flow tests

♦ Advanced Concept Engine Demonstration
  • Identified test facility; Test Requirements Document distributed
  • Completed demonstrator design; testing summer/fall 2000

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ASTP PDRE Projects
PDRE Future Planning Guidelines

- Project given $2.5M per year for next 3 years to mature technology before commitment to demonstrator
  - $200K of FY2001 money must be used to reimburse GRC for testing support for the UTRC on going activity

- This level of funding will force some hard decisions in the next procurement
  - Could result in a partnering between current contractors or
  - Will probably result in a down select between concepts

- For next 3 years need to focus on critical questions that support demonstrator decision in FY2004
  - Can the PDRE concept meet advertised performance and weight goals?
  - Is the physics of the concept well understood and accepted by industry and academia?
  - Are there any fundamental technologies that must be proven before commitment to a flight weight demonstrator?

- Money for the demonstrator program has not been identified at this time

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ASTP PDRE Projects
Key Objectives of the Next Few Years

♦ Demonstrate feasibility of PDRE to achieve performance and weight goals
  • Must have solid credible system concept that can be used in vehicle trades to assess benefits

♦ Develop and release a public performance code that is anchored with experimental data
  • Must be able to pass scrutiny of industry and academia
  • Necessary to have an analytical code that matches test data to demonstrate that physics of concept is understood

♦ Enable all critical technologies necessary for PDREs
  • Cannot have any critical enabling technologies not developed before commitment to flight weight demonstration

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ASTP PDRE Projects
Gaseous H₂/O₂ laboratory-scale rocket engine simulator
- Support development of theoretical/CFD analysis tools
- Improve definition of system operational requirements
- Test bed for major sub-systems/components
- Explore strategies for optimizing propellant injection
- Explore strategies for optimizing nozzle shape
- Explore alternative engine design configurations
- System performance optimization
- Develop/validate PDE design scaling laws
- Lay groundwork for liquid propellant PDEs
- Improve understanding of detonation physics

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ASTP Research PDRE Projects:
In-House ASTP Research
Development status

- **Electronic control circuits designed, fabricated and tested**
  - computer based low-voltage digital (TTL) signal pulses
  - fiber optic signal transmission (low power / electrical isolation)
  - high precision timing of duty cycle and phase lag

- **Spark ignition system designed, fabricated, and tested**
  - automotive type capacitor discharge system

- **Detonation initiator designed, fabricated, and tested**
  - coaxial gaseous injector
  - industrial solenoid valves
  - demonstrated DDT with Schelkin spiral (40 Hz / >2000 m/s)

- **Bench unit assembly designed, fabricated, and tested**
  - integrated initiator/injector head design
  - 2-inch diameter/ 36-inch long primary tube
  - coaxial gaseous injectors
  - industrial solenoid valves
  - demonstrated detonation propagation to primary tube

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ASTP Research PDRE Projects:
In-House ASTP Research
UTSI Performance Analysis

- **1-D Pulsed Detonation Engine Cycle Deck (PDECD) Modification**
  - Include the effects of variable mixture ratio
    - Provision for opening and closing the fuel and oxidizer valves independently so that effects such as a fuel purge and variable O/F ratio during a cycle can be simulated
  - Include global dynamic effects in the feed lines and valves.
    - A lumped parameter analysis of the feed line dynamics for use in simulating representative experimental test facilities will be added.
  - Modeling of Multiple Tube PDE Operation:
    - Simulations of the effects of multiple pulsed detonation tubes exhausting to a common nozzle. Flow from the common nozzle shall be exhausted through a divergent or convergent-divergent tube using quasi-steady flow analysis.
  - Air Augmented PDE:
    - Predicting the performance characteristics of an air-augmented pulsed detonation engine rocket. The model should be appropriate for making qualitative assessments of the effect of coupling a PDE into a combined cycle engine.


**ASTP Research PDRE Projects:**

In-House ASTP Research
Future MSFC Research Plan

- Continuation of current activities
- PDR/PDRE Standard Performance Analysis Code
  (Government team sponsorship is desirable)
  - System level Code
  - Subsystem CFD Code
    - Generic
    - Full 3D Transient
    - Experiments for Code Validation

- Advanced Fuel for PDRE
  - Advanced hydrocarbon fuels for a rocket are in development.
    Are these fuels applicable for PDRE?
- Pulse Detonation Engine / Pulse Detonation Rocket Engine
  - PDE Concept
  - NASA MSFC PDRE Activities
  - Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

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Revolutionary Rockets