529 49P

Advanced Chemical Propulsion

S. Don Bai

don.bai@msfc.nasa.gov

Propulsion Research Center (TD-40)

Space Transportation Directorate

Marshall Space Flight Center /NASA

Huntsville, AL 35812

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

Agenda

- **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)**

- 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

Advanced Fuels Development Objective & Goal

Agenda

- 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)

- **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**

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

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

Strained Ring Hydrocarbons

Strained Ring Hydrocarbons

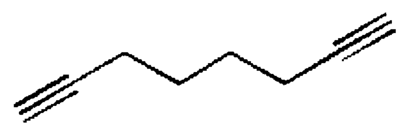
- Structural Requirement for High Energy Contents

  - The energy contents can be increased by adding unsaturation in the molecule

	$-(CH_2)-$	$CH_2=CH_2$	$HC\equiv CH$	
• $\Delta H_f/C$	~ -5	~ 6.25	~ 27.1	Kcal/mole

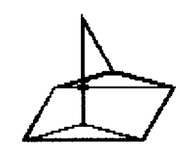
Fuels

1,5-Hexadiyne
ΔH_f = 91.8 Kcal/mole
= 1.18 Kcal/g
I_{sp} = 311.8 Sec



1,7-Octadiyne
ΔH_f = 79.9 Kcal/mole
= 0.75 Kcal/g
I_{sp} = 308.2 Sec

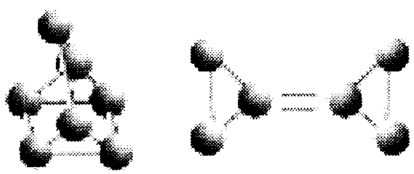
C8H10

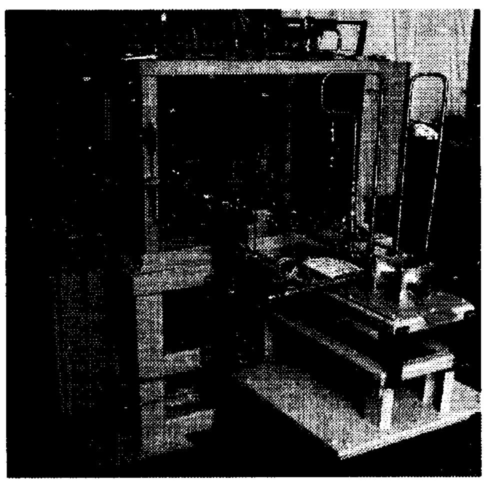


Quadricyclane
ΔH_f = 72.2 Kcal/mole
= 0.78 Kcal/g
I_{sp} = 307 Sec

C7H8

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





- 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 ehtyl 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 don.bai@msfc.nasa.gov

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

Strained Ring Hydrocarbon Fuel Testing

Project Team Members

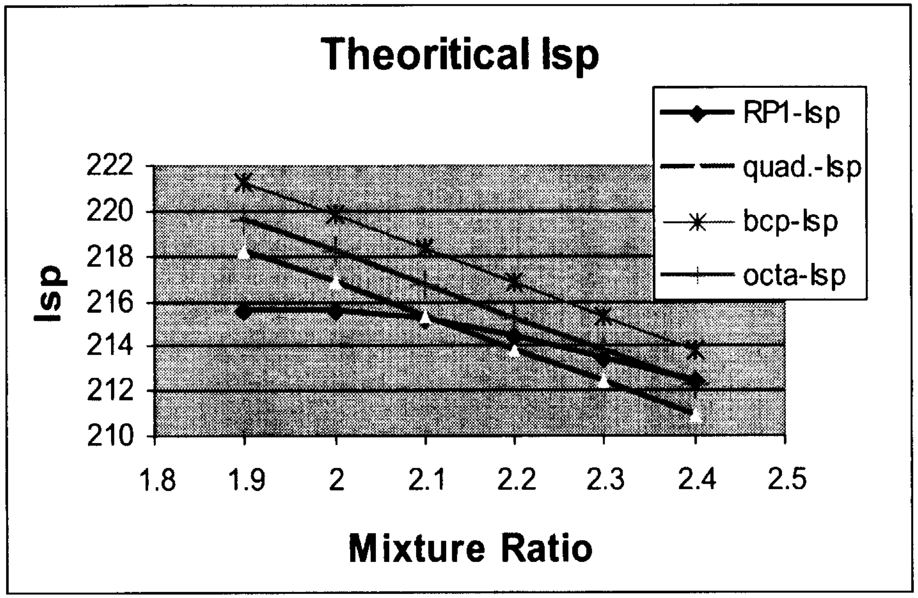
♦ Project Manager	John Cole	TD-15
♦ System Engineer	Scott Jackson	TD-15
♦ MSFC PI	S. Don Bai	TD-40
♦ NASA/GRC		
♦ AFRL		

MSFC Test Team Members

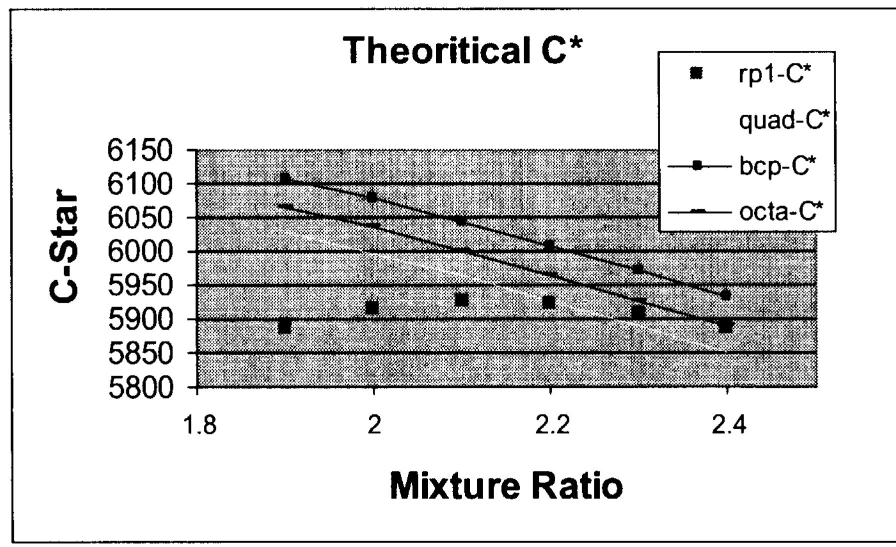
♦ Test Requester	S. Don Bai	TD-40
♦ Test Project Engineer	Paul Dumbacher	TD-71
♦ Test Instrument Engineer	Smith/Wiley	TD-72
♦ Test Control Engineer	Gregory/Trieu	TD-73
♦ Material Testing	James Perkins	ED-36
♦ Safety	Rosalyn Patrick	QS-10

- **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 Is**
    - Integrated thrust per mass over the time.

Theoretical Comparison



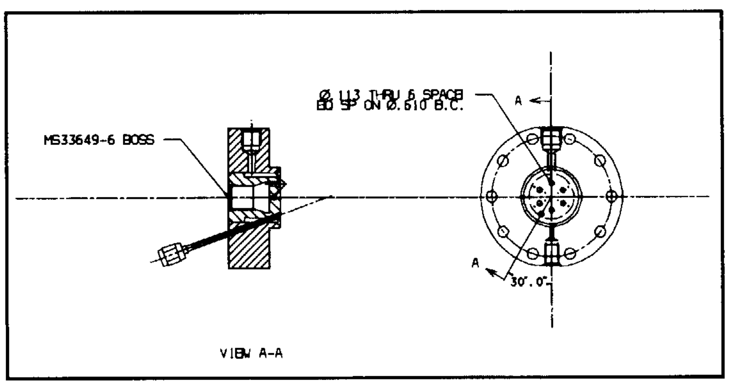
Estimated Performances

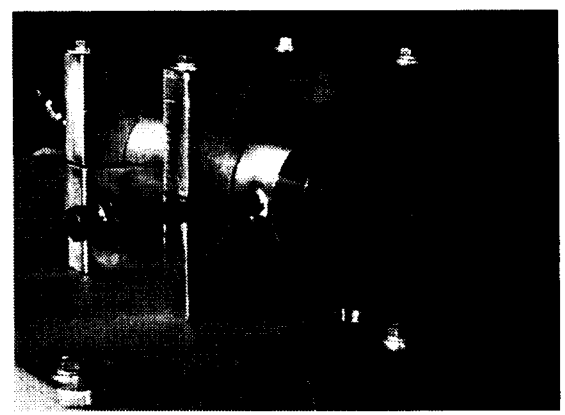


"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

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.

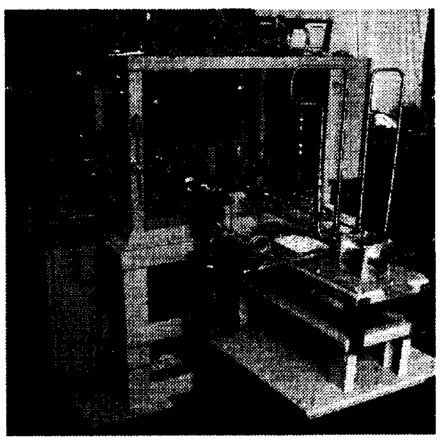




"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

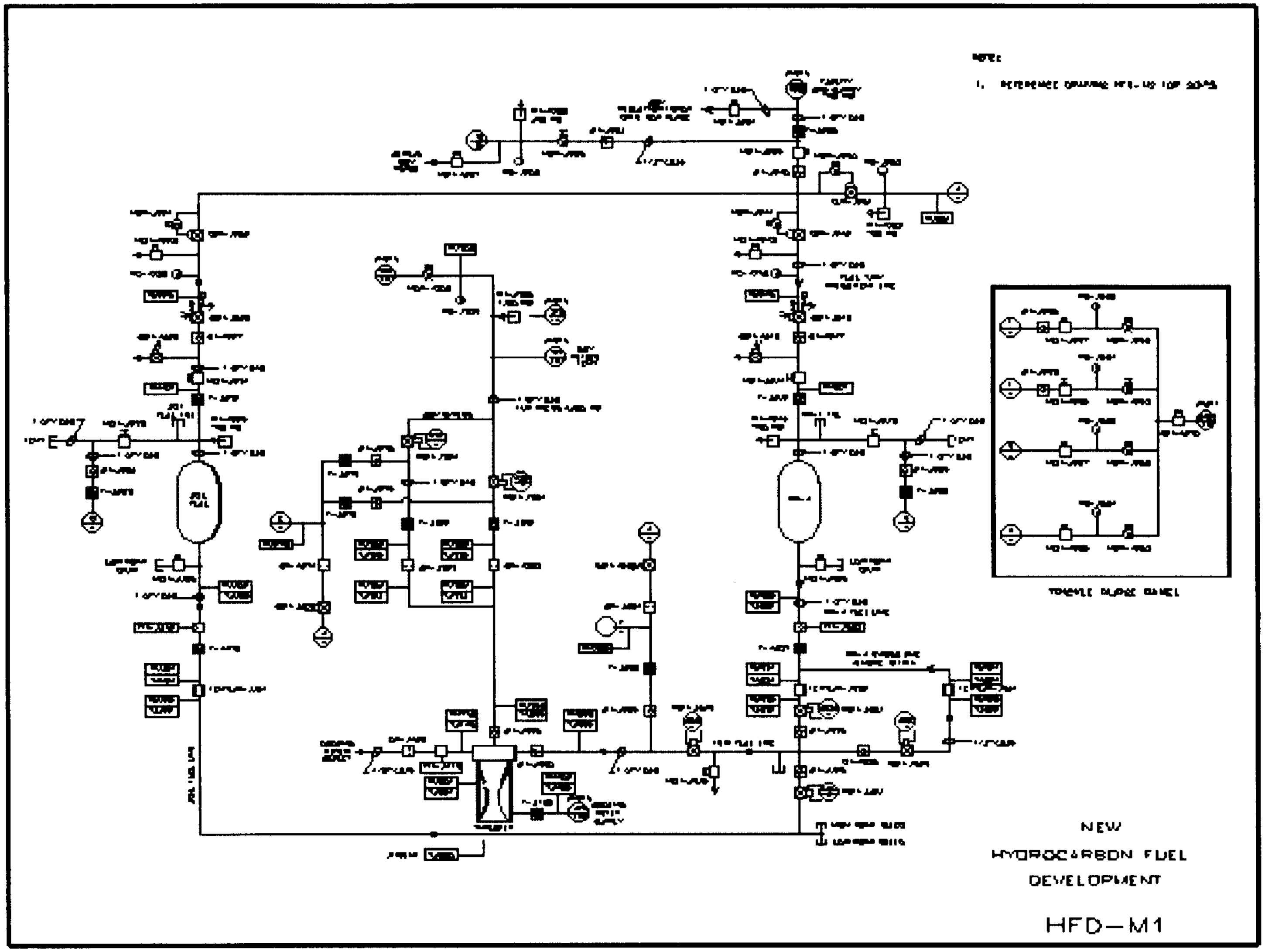
Strained Ring Hydrocarbon Fuel Testing

- **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



Strained Ring Hydrocarbon Fuel Testing

Test Rig - Schematic Diagram



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

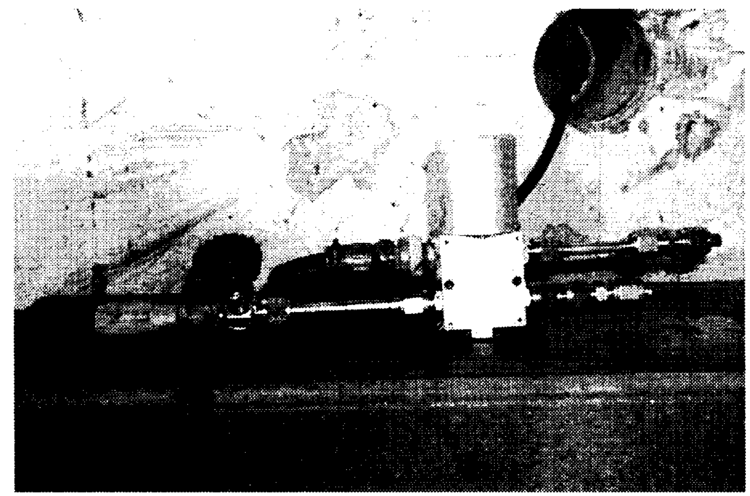
Strained Ring Hydrocarbon Fuel Testing

- **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.**

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

- Pre-testing Activities
  - Valve Impact Tests at AFRL
  - Short Term Aging Study
  - Material Comparability Tests
  - Dynamic Load Test of Thrust Measurement System

- 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.

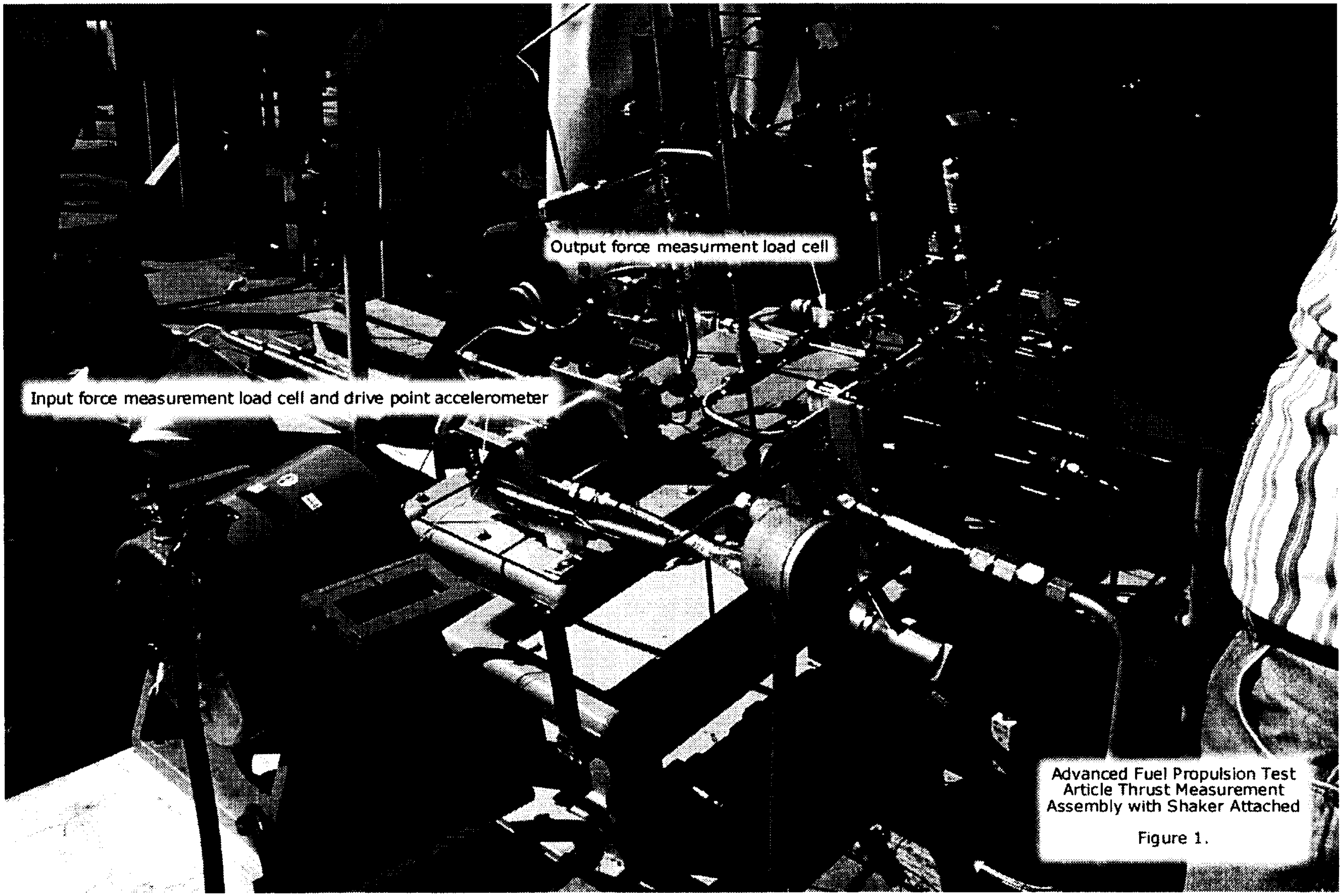


Valve Impact Tests at AFRL

Handling of Fuels require personal protective equipment

	Quadracyclane Lot #1001	Bicyclopropylidene (aged)	1,7 Octadiyne 99%	Dimethyl-2-Azido Ethylamine	AFRL-1	RP-1 Fuel
Alumel Ribbon	Strong Odor No visible reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction
Chromel Ribbon	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction
Magnesium Oxide Core	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction		Some Odor No visible reaction
Krytox 240AC	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction		Some Odor No visible reaction
Sauerisen Cement	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction
E Constantan	Strong Odor No visible Reaction	Very Strong Odor No visible Reaction Did form residue	Some Odor No visible Reaction	Not a very strong odor No visible Reaction	Very strong odor No visible Reaction	Some Odor No visible reaction

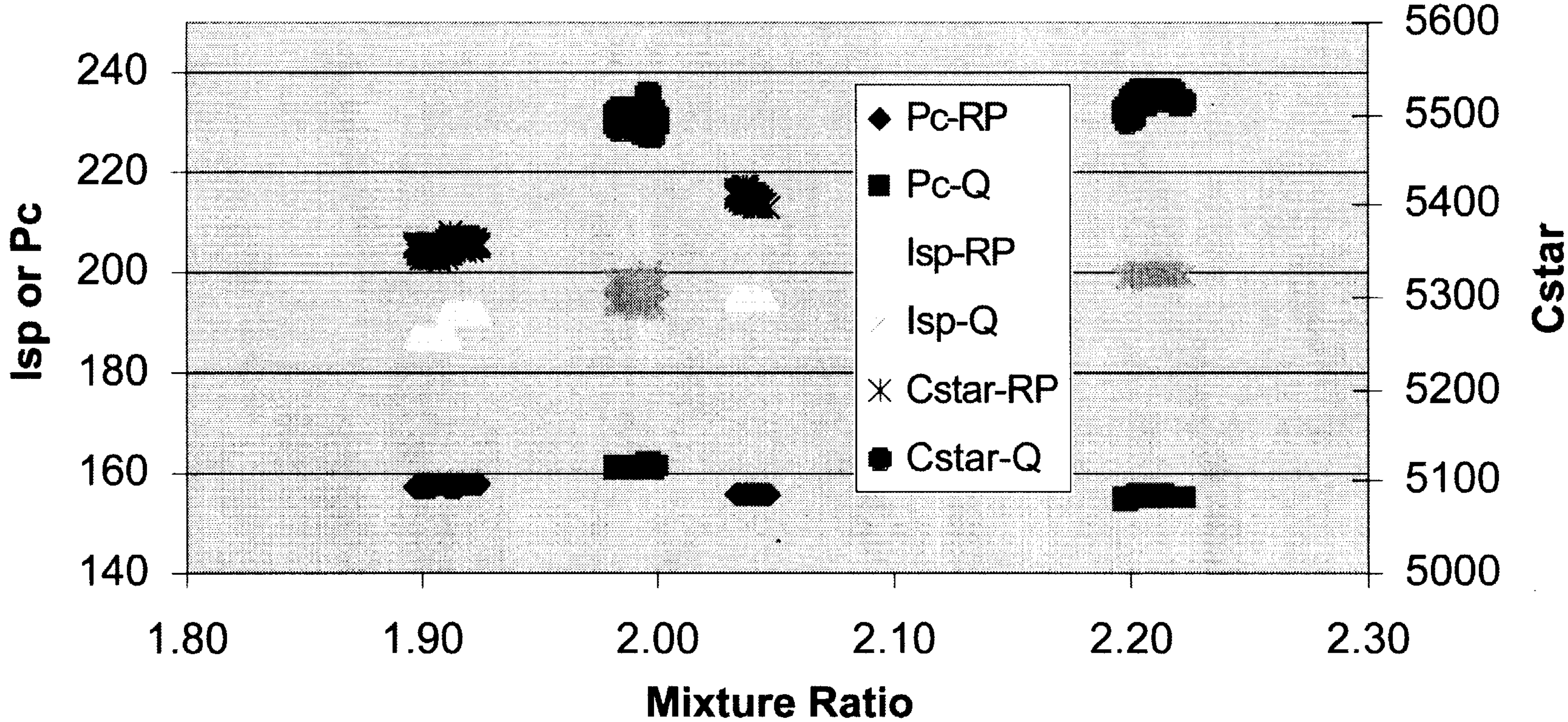
Short Term Aging Study
Material Comparability Tests



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

Dynamic Load Test of Thrust Measurement System

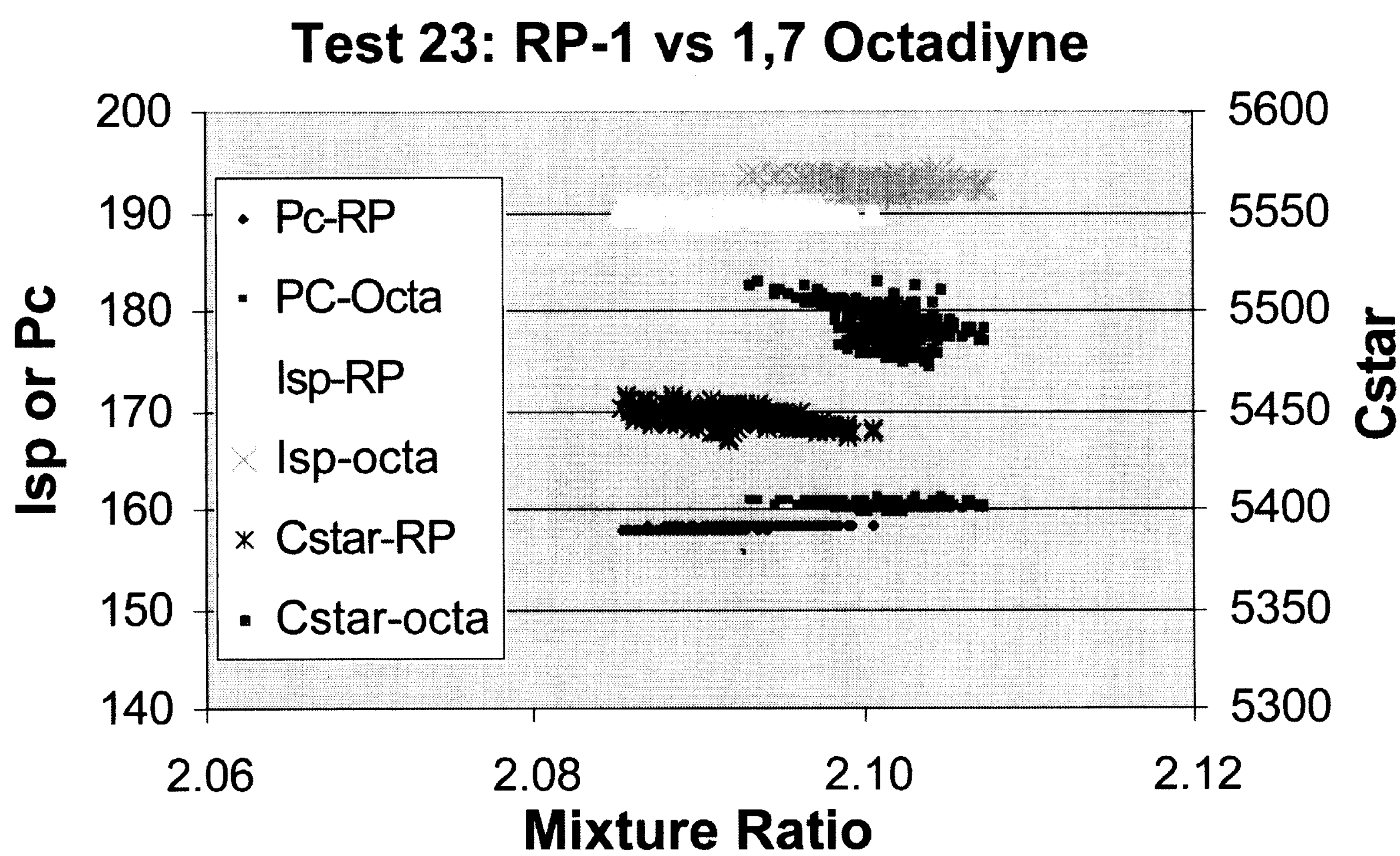
RP & Quadricyclane



- Specific Gravity Ratio   Quadricyclane / RP-1 = 1.17
- Cstar efficiency (~1.8%) & Isp(~5 sec) are better than RP-1

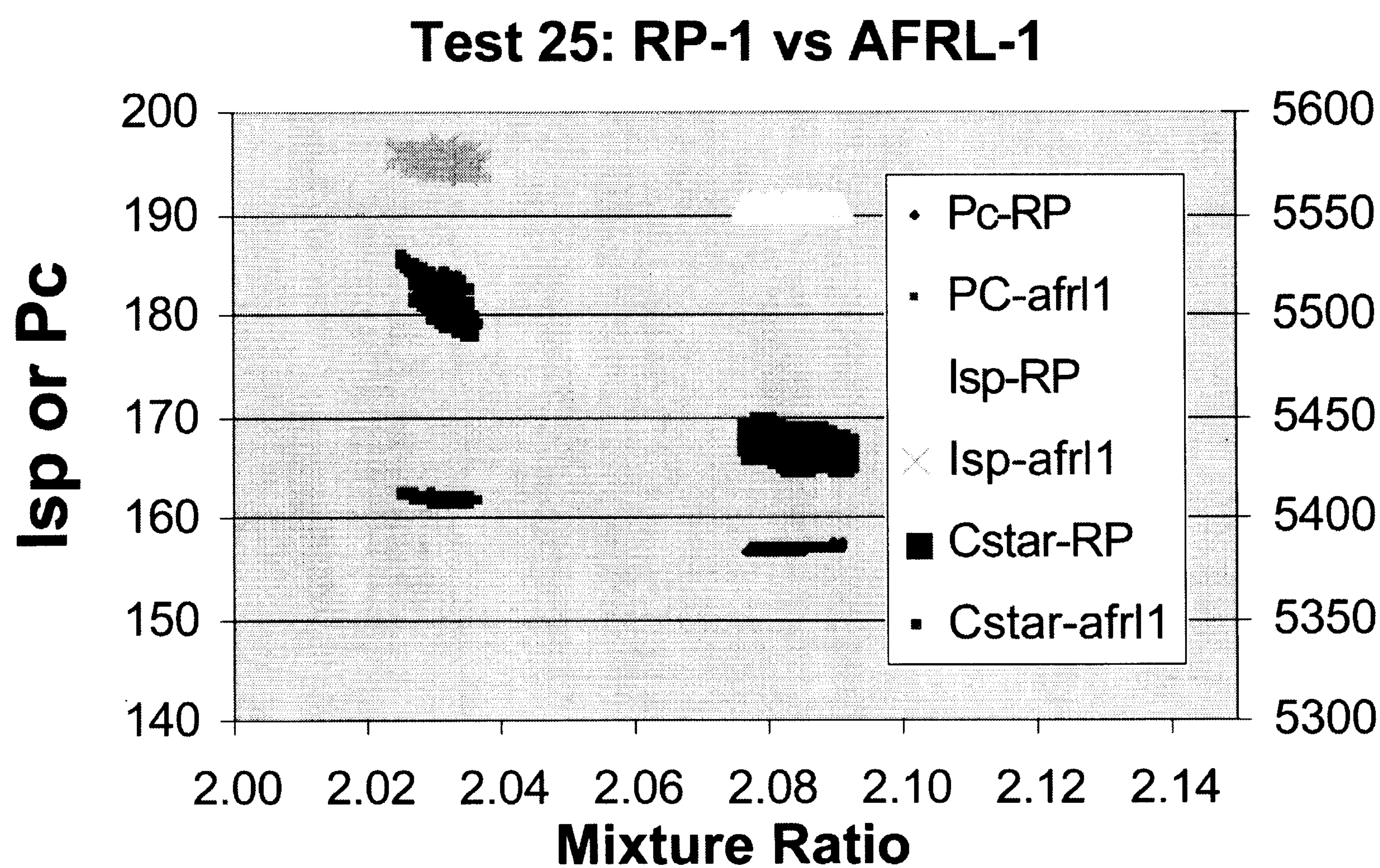
"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Test Results: Quadricyclane



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

Preliminary Test Result: 1,7 Octadiyne

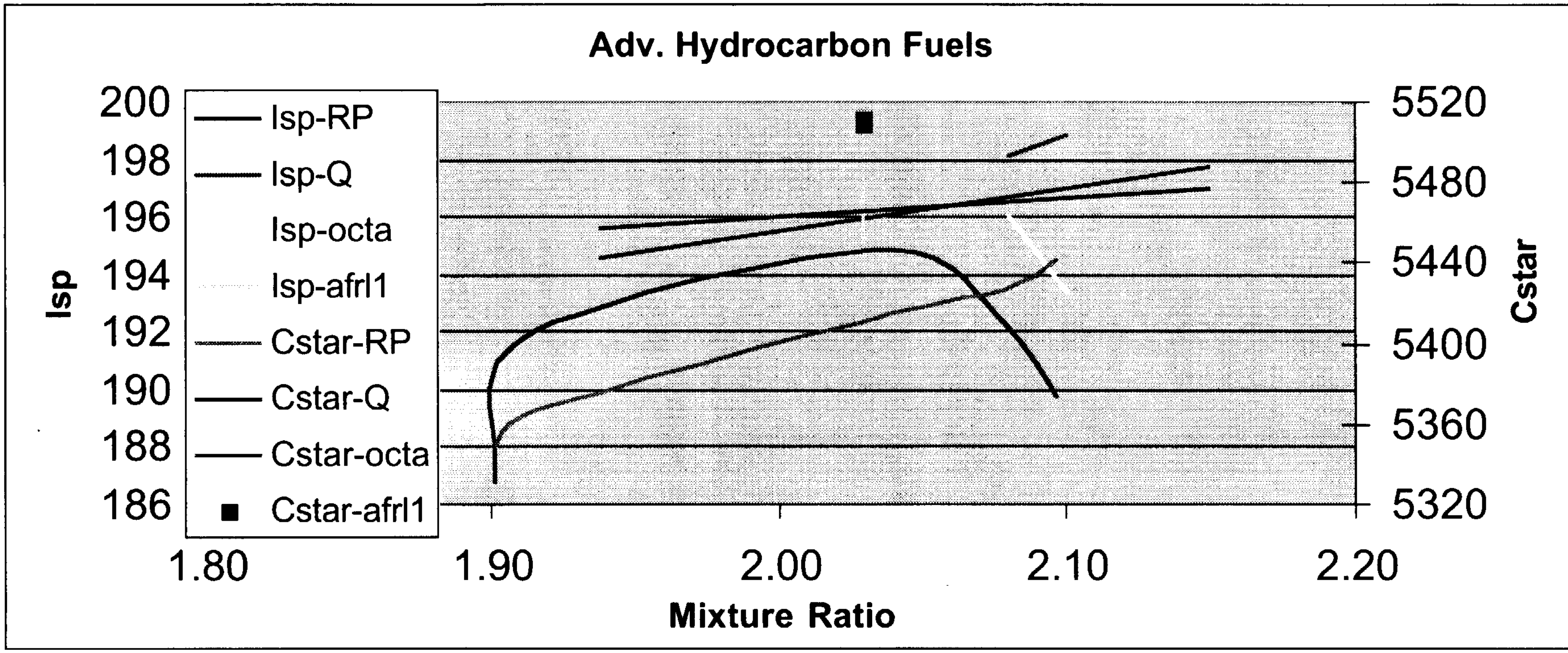


"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Preliminary Test Result: AFRL-1

Preliminary Test Result

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



	RP-1		Quadricyclane		1,7 Octadiyne
Mixture Ratio	1.9	2.04	*1.94*	*2.15*	2.1
Cstar(Theory)	5887(100%)	6020(100%)	6017(100%)	5942(100%)	6000(100%)
Cstar(Experiment)	5348(90.8%)	5414(90%)	5456(90.7%)	5476(92.1%)	5503(91.7%)
Isp(Theory)	273.1(100%)	279.1(100%)	279.4(100%)	275.7(100%)	278.5(100%)
Isp(Experiment)	186.7(68.4%)	194.8(69.8%)	194.5(69.6%)	197.7(71.7%)	193.3(69.4%)

- BCP
- DMAZ
- AFRL-?
- LM-1 ?
- RG-1 ?

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

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......

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

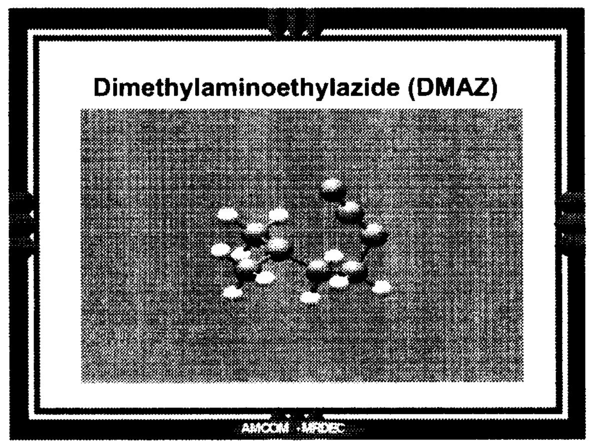
Strained Ring Hydrocarbons: Joint Project with AFRL

- **Revolutionary Rockets**
- **Advanced Fuels and High Energy Density Materials**
  - **Strained Ring Hydrocarbons (Bai/TD40)**
  - **Azide Fuel (US Army - Bai/TD40)**
  - **Solid Hydrogen**
    - 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)**

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



Darren M. Thompson
U.S. Army AMCOM
AMSAM-PS-RD-R
(256)955-8556, Fax: (256)955-7748
darren.thompson@redstone.army.mil

"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 LHe 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

Atomic Propellants

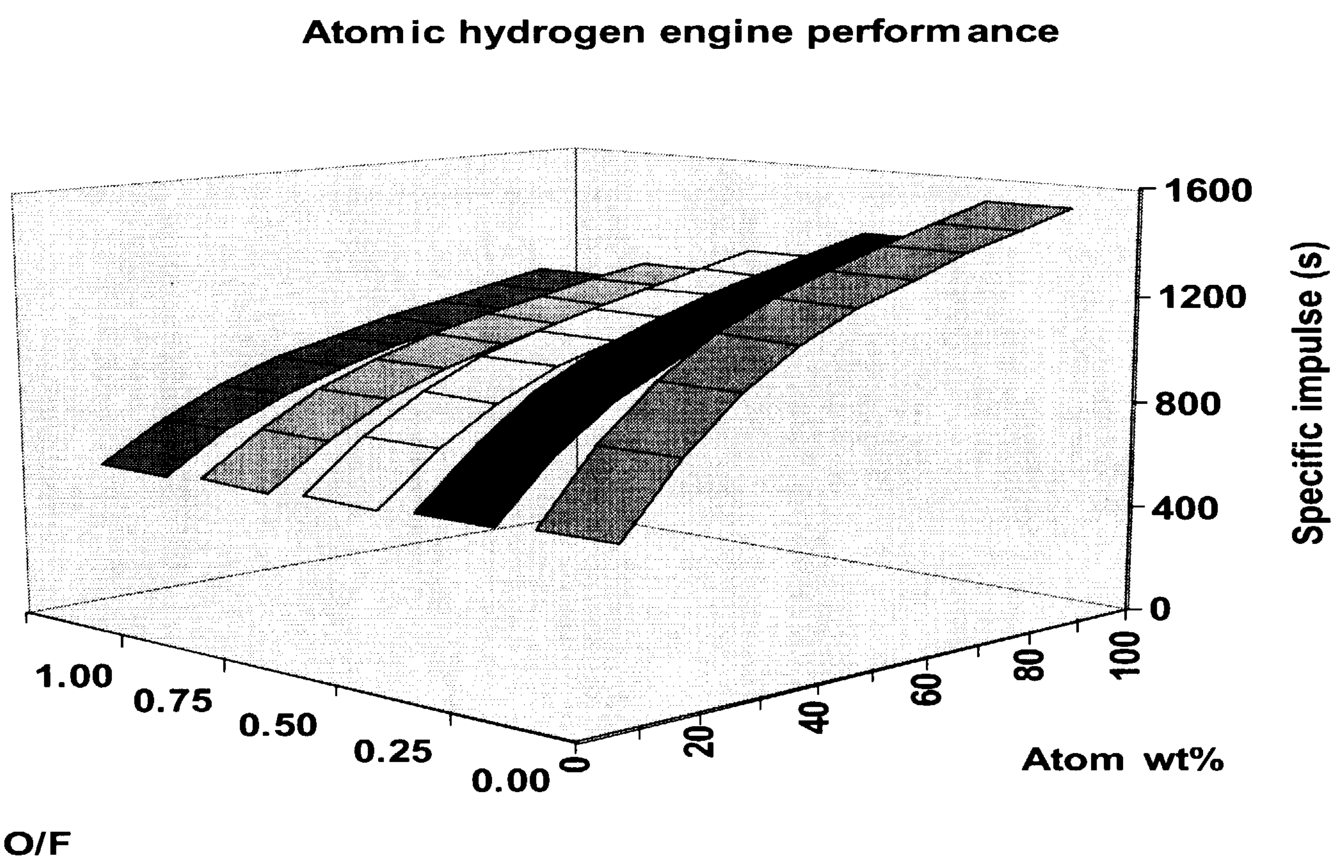
- **Revolutionary Rockets**
- **Advanced Fuels and High Energy Density Materials**
  - **Strained Ring Hydrocarbons (Bai/TD40)**
  - **Azide Fuel (US Army - Bai/TD40)**
  - **Solid Hydrogen**
    - Recombination Energy Fuels (Palaszewski /GRC)
    - Penta Nitrogen (Palaszewski /GRC)
    - Poly-Oxygen (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)**

Agenda

- Vision
  - Atomic propellant offer large potential increases in rocket specific impulse (Isp)
  - Isp increases of hundreds of seconds over O_2 /H_2 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

Atomic Propellants: Why Atomic Propellants?

Specific Impulse (Isp) Map for Atomic Hydrogen



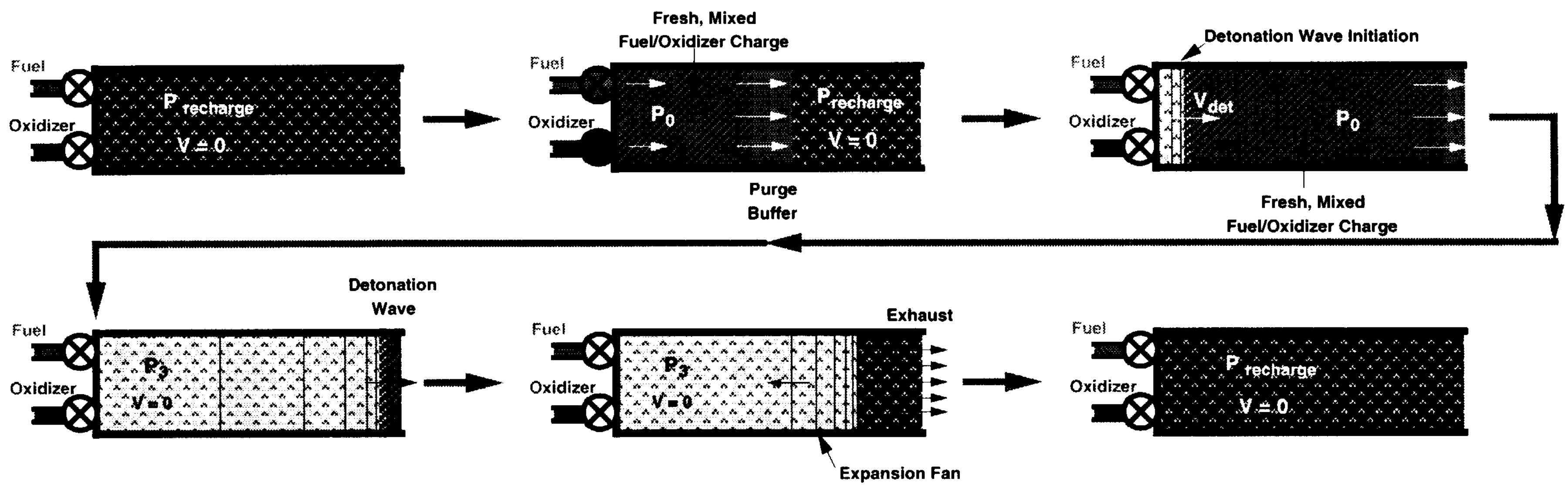
"ST Day 2000: Reducing Risk for the Next Generations" - Advanced Chemical Propulsion

Atomic Propellants

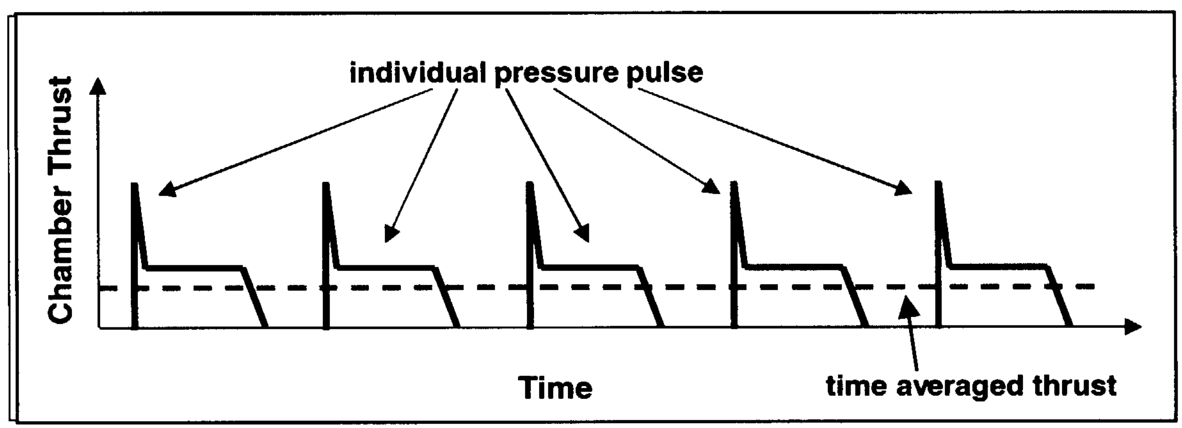
Agenda

- **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**

- **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**



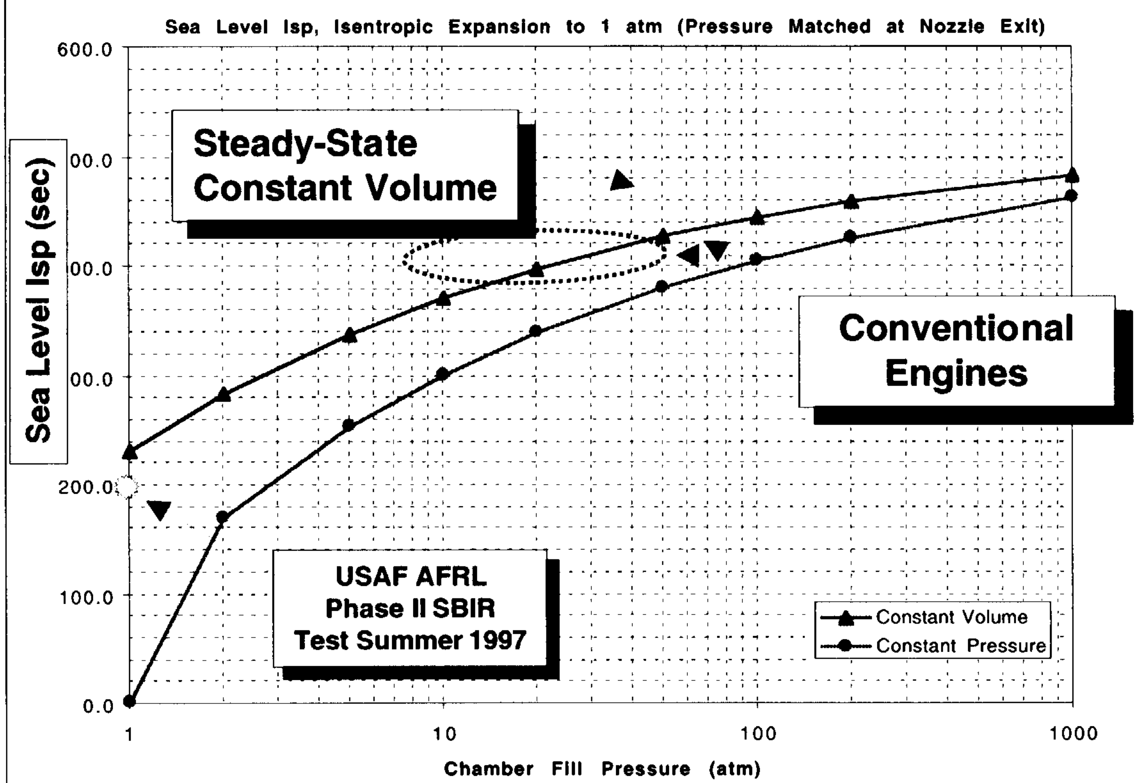
- Detonation process is self pressurizing
- High peak temperatures and pressures occur at microsecond time scales
- High cycle rates and multiple combustors produce even thrust



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

Pulse Detonation Propulsion Uses "Fill and Fire" Operations

- **Preliminary ASI tests are successfully demonstrating PDRE performance at 1 atm test condition**



Pulse Detonation Cycle May Provide Equivalent Performance for Significantly Reduced Injection Pressure

Potential to Lower Injection Pressure by factor of 3 at an Isp of 375 seconds

Decreased System Risk and Cost are Realized with Lower Injection Pressures

"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

Overarching Tasks:

- SE&I
- Performance Modeling

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

ADROIT SYSTEMS INC.

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

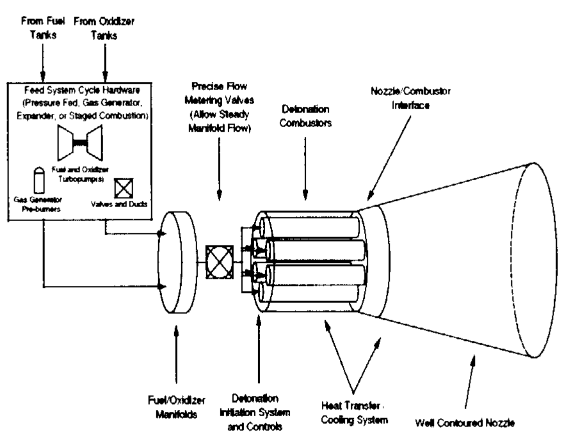
Office of Naval Research's Multi-University Research Initiative on Pulse Detonation Engines

- **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**

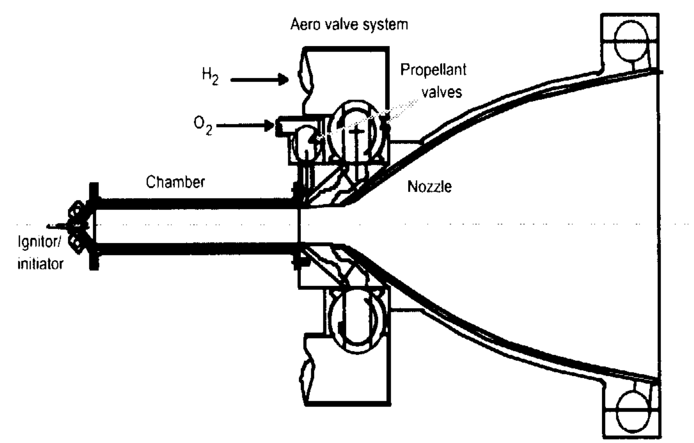
ASTP PDRE Projects

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

- 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



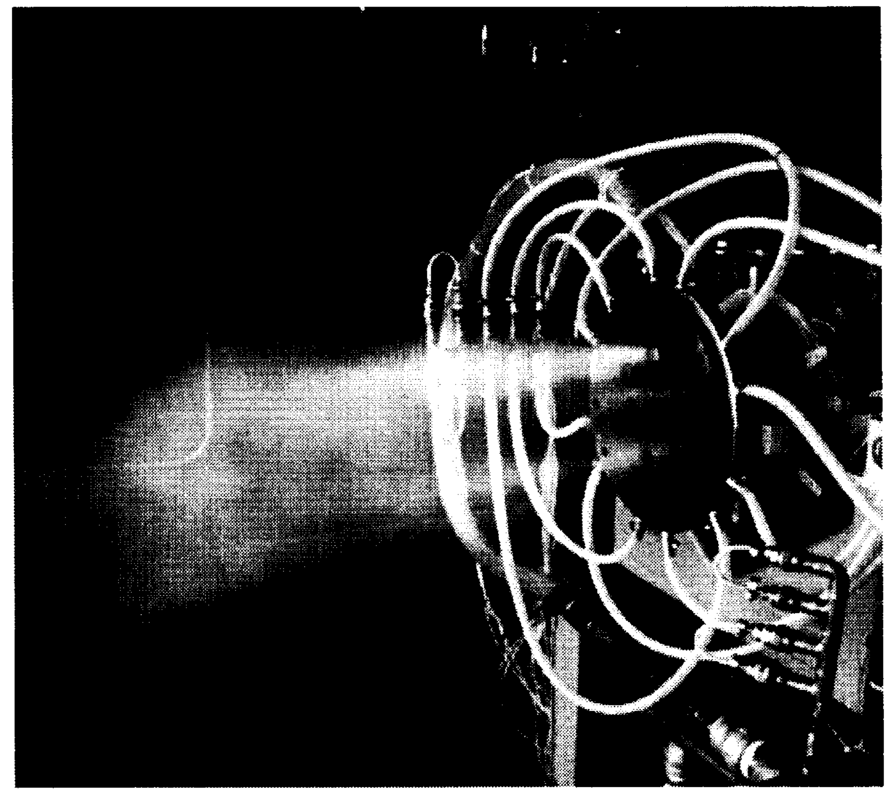
Multi tube PDRE w/ nozzle



Single tube PDRE w/ nozzle and aerodynamic throat

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)



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

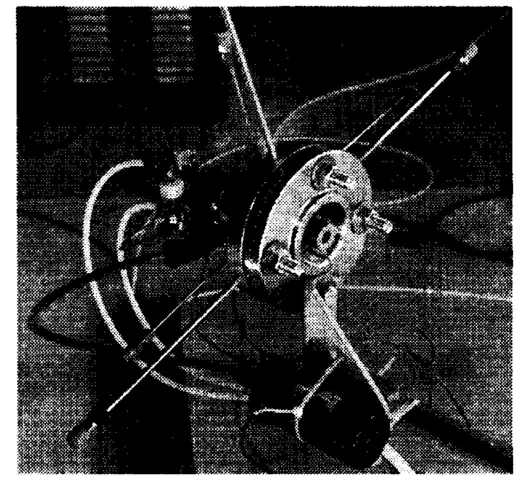
PDRE Future Planning Guidelines

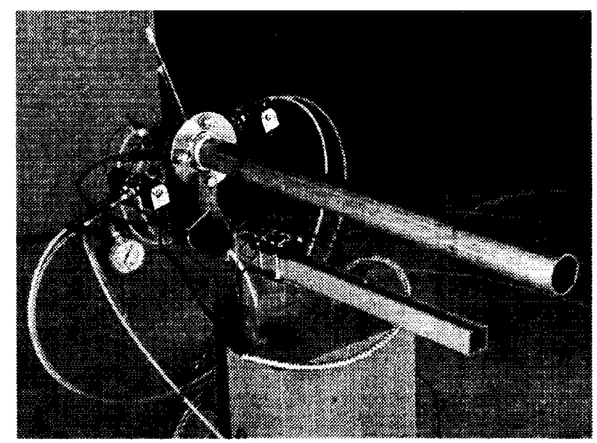
- Project given \$2.5M per year for next 3 years to mature technology before commitment to demonstrator
  - \$200K of FY2001 money must be used to reimburse GRC for testing support for the UTRC on going activity
- This level of funding will force some hard decisions in the next procurement
  - Could 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

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

- Gaseous H_2/O_2 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





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

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

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.

- **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 ?

ASTP Research Future Planning

- 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

ONR CHARTS