1. REPORT DATE (DD-MM-YYYY) | 2. REPORT TYPE Technical Papers | 3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Please see attached

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
5503

5e. TASK NUMBER
003P

5f. WORK UNIT NUMBER
4966

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S NUMBER(S)
Please see attached

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

<table>
<thead>
<tr>
<th>1. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>classified</td>
<td>Unclassified</td>
<td>Unclassified</td>
</tr>
</tbody>
</table>

17. LIMITATION OF ABSTRACT

18. NUMBER OF PAGES

19a. NAME OF RESPONSIBLE PERSON
Leilani Richardson

19b. TELEPHONE NUMBER
(Include area code)
(661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18
MEMORANDUM FOR PRR (Contractor/In-House Publication)

FROM: PROI (TI) (STINFO)  


Joe Levine, “AFRL Propulsion Directorate Propulsion Sciences & Advanced Concepts Division”

(Diagram)
Air Force Research Laboratory

Propulsion Directorate

Propulsion Sciences & Advanced Concepts Division
Rocket-Propulsion Research

- Advanced propellants
- Propulsion materials and components
- Aerophysics
Propulsion Sciences & Advanced Concepts Division

Edwards AFB CA
- Aerophysics
  - Jay Levine
  - 525-6179
- Propulsion Material Applications
  - Maj Mike MacLachlan
  - 525-5230
- Propellants
  - Dr. Pat Carrick
  - 525-5883

Dr. Steve Rodgers
- 525-5230
Dr. Phil Kessel
- 525-5591

Wright-Patterson AFB OH
- Lubrication
  - Maj Walt Lauderdale
  - 785-5568
- Combustion
  - Charlotte Eigel
  - 785-6814
- Fuels
  - Bill Harrison
  - 785-6601
- High Speed Systems
  - Maj Kenneth Phillipart
  - 785-5221
Technical Specialties

- Combustion
- Hypersonics
- Lubricants and mechanical systems
- Advanced-concept system analysis
- Fuels and propellants
- Plume phenomenology
- Advanced components
Aerophysics

Rocket Combustion–from Propellant Injection to Plume Dissipation

- Non-equilibrium flows
- Supercritical combustion
- Plumes
Nonequilibrium Flow Phenomena

**Payoff**
- Reduced production/launch costs for satellites
- Robust tracking via dual mode IR / UV sensors
- Increased spacecraft lifetime & survivability
- Speed deployment of new energetic propellants

*Microthruster concept (1 to 100 μN thrust range)*

**Goals**
- Identify the key mechanisms which control:
  - The performance characteristics of microthrusters
  - The intensity and spectrum of plume radiation signatures
  - The decomposition and combustion of emerging energetic materials
  - Contamination effects on spacecraft systems
- Design and evaluate novel microthruster concepts
- Provide 3D simulation tools for signature/contamination modeling
Air Force Micropropulsion Mission Requirements

• Near-Earth orbital maneuver requirements
  – Fast response time ⇒ High thrust
  – Kinetic kill ⇒ Very high thrust
  – Many maneuvers ⇒ High specific impulse

• Satellite size requirements
  – Microsatellites (1 g to 1 kg) ⇒ Communication/surveillance constellations
  – Small satellites (> 100 kg) ⇒ Dedicated satellite communication and surveillance

• A whole range of thrusters is needed to fulfill this broad spectrum of requirements ⇒ Chemical, solid, electric, PDE

• Simple scaled-down versions of existing thrusters do not maintain performance levels needed ⇒ Critical need for advanced propulsion concepts and approaches
Microwave Microthruster

Description

- Electrodeless, vortex-stabilized arcjet thruster
- Higher specific impulse than chemical systems; more thrust than higher specific-impulse electric devices
- Reduced erosion; increased payload mass; increased lifetime
- Broad range of propellants: $\text{N}_2$, He, $\text{H}_2$, $\text{NH}_3$, $\text{H}_2\text{O}$
- Broad range of power levels: 60 watts - 30 kilowatts ⇒ Versatile mission profile

Operation: Magnetron converts electrical energy to microwaves that heat propellant gases to plasma temperatures.

Mission Applications

- Station keeping, attitude control, orbit boost
- Systems: Spartan, Mighty Sat, International Space Station, Shuttle payload boost

Program

- Improve thrust and efficiency by reducing energy loss (heat) to the boundary layer through viscous dissipation
- Joint experimental and analytical effort by AFRL/PRS with Penn State University
Comprehensive Propulsion Research

Rocket Propulsion
- Liquid
- Solid
- Hybrid
- RBCC
- PDRE

Airbreathing Propulsion
- Ramjet
- Scramjet
- TBCC
- RBCC
- PDE

Combined Rocket and Aeropropulsion expertise
Manifold Cross Flow Can Cause Fan Misalignments and Reduce Chamber Lifetime

A variation in discharge coefficient could shift the spray angle, potentially allowing oxidizer to reach the wall and cause failure or reduce lifetime.

Cant angles as large as 13° have been predicted.

Misalignment in the Fasttrac outer row would be 5° at most.

Potential canting due to cross flow effects
COLD FLOW INJECTOR CHARACTERIZATION FACILITY

**Hardware**
- Gas simulant: N$_2$(g), He(g)
- Liquid simulant: H$_2$O(l)
- Window Purge gas: N$_2$(g), He(g)
- N$_2$ mass flow rate: 0.20 lbm/s
- He mass flow rate: 0.20 lbm/s
- H$_2$O mass flow rate: 4.0 lbm/s
- Max. test art. press.: 2000 psi
- Max. Fuel sim. press.: 3000 psi
- Max. Ox sim. press.: 3000 psi
- Electrical connections: 120V, 208V (1φ: 10A, 3φ 20A and 50A)

Windowed test chamber with 5.5” of axial injector travel and a linear translating injector stage with 5” total radial travel inside chamber.

Ability to simulate manifold cross velocities to 30 ft/s

**Data acquisition and control**
- 16 Channel, 12 Bit National Instruments A/D board run by a 486/33 PC running MS Quick Basic.
- Allen-Bradley PLC system for Remote Valve Operation
- Mechanical Diagnostics
  - 27 tube traversable linear patternator
- Optical Diagnostics
  - Oxford 20 kHz, 20W Cu vapor laser.
  - Innova 4W and 10W Argon Ion lasers.
  - Inj. seed, 2 plse Yag (1.5J at 1064 nm)
  - Continuum ND6000 Dye laser.
  - Princ. Inst and Stanford gated CCD cams.
  - Infinity and Questar LD microscopes.
  - Aerometrics 2 comp. PDPA.
  - Malvern 2600 particle sizer.
  - CCD camera with strobelight and VCR

Injector/Combustor Technology
## SUPERCritical DROP/JET INJECTION FACILITY

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Data acquisition and control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber</td>
<td>64-channel National Instrument AMUX-64T analog multiplexer with special provision for temperature sensor.NB-MIO-16X multifunction I/O board with analog-to-digital converter for Macintosh NuBus computer.</td>
</tr>
<tr>
<td>Optical access</td>
<td>Labmaster DMA Counter/timer/ ADC/ Digital I/O</td>
</tr>
<tr>
<td>Max chamb. press.</td>
<td>Scion Corp frame grabber</td>
</tr>
<tr>
<td>Chamb. temp.</td>
<td>LabView GUI control interface.</td>
</tr>
<tr>
<td>Injected fluid</td>
<td>Several PC and Power Macintosh</td>
</tr>
<tr>
<td>Ambient fluid</td>
<td>HP programmable timing/pulse generator</td>
</tr>
<tr>
<td>Injected mass flow rate</td>
<td>Infinity long-distance microscope</td>
</tr>
<tr>
<td>Cryogenic cooler</td>
<td>PL-8010 Continuum Nd:YAG pulsed dye laser,</td>
</tr>
<tr>
<td>Mass flowmeters</td>
<td>high speed strobe light,</td>
</tr>
<tr>
<td>Gas detection</td>
<td>Princeton Instrument camera,</td>
</tr>
<tr>
<td>Electrical connections</td>
<td>Interlaced PULNix CCD camera</td>
</tr>
<tr>
<td>20A, 3φ 30A and</td>
<td></td>
</tr>
<tr>
<td>Stainless</td>
<td></td>
</tr>
<tr>
<td>2 facing sapphire windows of 5.25” dia</td>
<td></td>
</tr>
<tr>
<td>2 facing slot-shaped quartz (4.75”x0.50”)</td>
<td></td>
</tr>
<tr>
<td>2000 psi</td>
<td></td>
</tr>
<tr>
<td>473 K</td>
<td></td>
</tr>
<tr>
<td>O2, N2, HC, and mixtures</td>
<td></td>
</tr>
<tr>
<td>N2, He, and mixtures</td>
<td></td>
</tr>
<tr>
<td>400 mg/s</td>
<td></td>
</tr>
<tr>
<td>85 K</td>
<td></td>
</tr>
<tr>
<td>up to 10,000 SLPM</td>
<td></td>
</tr>
<tr>
<td>O2, CO, HC</td>
<td></td>
</tr>
<tr>
<td>120V, 208V (1φ: 50A).</td>
<td></td>
</tr>
</tbody>
</table>
FMMR Design

Expansion Angle, $\alpha$

Escaping Propellant Molecule Path

Expansion Wall at $T_w$

Thin Film Heater, $T_w$

Propellant Inlet

Low Thermal Conductivity Material

Valve, Filter, Propellant Tank

Heating Element Pedestal

Thermal Insulation

$w \sim 1$ to 100 $\mu$m

$T_w \sim 600$ to 1200 K

$\alpha = 54.74^\circ$

$t \sim 100 - 250 \mu$m

Desired:

$w = 100$ $\mu$m

$T_w = 600$ K

$\alpha = 54.74^\circ$

$t = 200$ $\mu$m

Slot length = 1 cm

No. of slots = 40
PERSONNEL

Aerophysics Branch Organization
(PRSA)
Branch Chief : Jay Levine

Marietta Krissack : Secretary (Shared with other Branches)
Chris Sandstrom : Administration and Finance (Shared with other Branches)

Working Groups

Plumes
(Tom Smith)
1. Marty Venner
2. Dustin Ziegler
3. Roy Hilton
4. Robert Lyon
5. Alan Kawasaki
6. Bill Calhoon

Combustion Devices
(Doug Talley)
1. Victor Burnley
2. Rodger Benedict
3. Ed Coy
4. Pete Strakey
5. Cliff Lusby
6. Mike Mckee
7. Richard Cohn
8. Tim Auyeung
9. Mike Griggs
10. Bruce Cheroudi
11. Mark Wilson

Nonequilibrium Flows
(Ingrig Wysong)
1. Andrew Ketsdever
2. David Campbell
3. Dean Wadsworth
4. Ghanshyam Vaghjiani
5. Angelo Alfano

Palace Knights
Mark Archambault : Stanford 5/99
PRESSURE DEPENDENT MIXING LAYER STRUCTURE

Nitrogen/nitrogen system ($P_{cr} = 493$ psi, $T_{cr} = 126$ K)

$T_{inj} = 128$ K, $T_{amb} = 300$ K, mass flow = 350 mg/s

Low Pres. Subcritical Droplets

Mod. Pres. Supercritical Ligaments

High Pres. Supercritical Gas layers
High Pressure and Supercritical Combustion (6.1)

OBJECTIVE
Determine the mechanisms which control the breakup, transport, mixing, and combustion of supercritical droplets, jets, and sprays.

APPROCACH
• Piezoelectric cryogenic jet and drop generator in chilled helium.
• Produce acoustic waves using metallic actuators, design resonant modes, focus acoustic waves.
• Reduce optical path lengths.
• Use spontaneous Raman scattering from a frequency doubled Nd-YAG laser.

Transcritical Oxygen Drops in Nitrogen
Basic Research in Nonequilibrium Flow Phenomena

Objectives/Goals

- Identify the key mechanisms which control:
  - The performance characteristics of microthrusters
  - The intensity and spectrum of plume radiation signatures
  - The decomposition and combustion of emerging energetic materials
  - Contamination effects on spacecraft systems
- Design and evaluate novel microthruster concepts
- Provide 3D simulation tools for signature/contamination modeling of missiles and spacecraft