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<td>Leilani Richardson</td>
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<td>TELEPHONE NUMBER</td>
<td>(661) 275-5015</td>
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21 separate items enclosed
MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TT) (STINFO)  


Strakey, P., "Injector/Combustor Technology" (RFT)

49th JANNAF Propulsion Meeting (Tucson, AZ, 14-16 Dec 1999)  

(Statement A)
Injector/Combustor Technology

Peter Strakey
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AFRL/PRSA, 10 E. Saturn Blvd.
Edwards AFB, CA 93524-7660
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Peter.Strakey@ple.af.mil

Overview

- MCC's & PB's on all Liquid Demos
- IHPRPT (6.2)
- Injector/Combustor Technology
- Improved Chamb. Compat. Inj.
- Lightweight, Low Cost Injector.
- High Pressure and Supercritical Combustion (6.1)

<table>
<thead>
<tr>
<th>Funding ($1,000's)</th>
<th>Prior</th>
<th>99</th>
<th>00</th>
<th>01</th>
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<tr>
<td>6.2</td>
<td>4453</td>
<td>973</td>
<td>764</td>
<td>764</td>
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(see detailed roadmap in package)
(briefed separately)
6.2 Objectives

- Develop tools to predict the effect of injector design changes on liquid rocket performance.

- Provide flexible, low cost screening of candidate injector designs.

- Reduce film cooling requirements without sacrificing combustion chamber lifetime or reliability.
The Problem

- Combustor designers are unable to adequately predict whether all design criteria will be satisfied.

- Problems not discovered until full scale testing tend to be extremely expensive to fix, and usually require sacrificing engine performance* and/or lifetime.*

- Most past engine development programs have encountered such problems.

* IHPRPT goals

Required Injector/Combustor Characteristics

- Complete combustion in the shortest possible length
  - Main injectors: performance vs weight tradeoffs
  - Preburners/GG's: downstream component interactions, eg, turbine blades, etc

- Acoustically stable
  - Chamber modes
  - Feed system coupling

- Chamber/wall compatibility
  - Heat transfer/cooling
  - Oxygen blanching

- Minimize pressure drop
- Throttling
- Ignitable; minimum ignition transients
- Cost, weight
- The "ilities:"
  - Reliability
  - Maintainability
  - Manufacturability
  - Durability
  - Operability
Technical Approach

- Develop design guidance at the subscale level. Use data to
  - Develop models.
  - Anchor codes.
  - Screen candidate designs.

- Assess the direct impact of design on relevant parameters (e.g., mixing) via windowed access, as appropriate.

- Improve scalability by make all facilities high pressure capable (1500-2000 psi).

Payoffs

Provide alternatives to trial and error development

- **Performance**: Injector related design uncertainties translate to 3-6 sec lisp on a booster class LOX/H2 engine.
  * Comparison: IHPRT 2010 lisp objective is 13.5 sec.
  * 3-6 sec lisp buys 1.6 - 3.3 tons payload on the Space Shuttle Main Engine (SSME) worth $20-40M per launch.

- **Operability and Lifetime**: Injector related performance deficit required SSME turbopumps to be run at 105% rated power, increasing pump stress.
  * Pumps are the most expensive SSME maintenance item.
  * Turb. blade cracking problem is also probably inj. related.

- **Instability**: Injector related Saturn F-1 instability problem required over 800 full scale tests to solve.
  * Present day costs: over $750K per test. Total: $600 million.

*Trial-and-error approaches risk significant cost overruns that can no longer be afforded*
**Relationship to IHRPRT Goals**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Increase Isp (3% cryo, 17% HC)</td>
<td>Incr. Isp. Eff. 5%</td>
<td>a. Reduce film cooling (d).</td>
</tr>
<tr>
<td></td>
<td>Incr. Th. Isp 6 sec.</td>
<td>b. Red. design margins (i).</td>
</tr>
<tr>
<td></td>
<td>Decr. weight 60%</td>
<td>c. Reduce F/E (i).</td>
</tr>
<tr>
<td>Increase F/W 100%</td>
<td>Incr. Isp. Eff. 5%</td>
<td>d. Incr. stability limits.</td>
</tr>
<tr>
<td></td>
<td>Incr. Th. Isp 6 sec.</td>
<td>e. Incr. Pc (i).</td>
</tr>
<tr>
<td></td>
<td>Decr. weight 60%</td>
<td>f. Lightweight materials (i).</td>
</tr>
</tbody>
</table>

*Quantitative amounts depend on design tradeoff studies

d - direct AFRL contribution, actual or planned  
i - indirect contribution

**Relationship to IHRPRT Goals**

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Red. failure rate 75%</td>
<td>Red. part count 75%</td>
<td>a. Red. parts count (d).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red. costs 35%</td>
<td>Red. costs 38%</td>
<td>a. Red. parts count (d).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Red. handworking (i).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c. Relax tolerances (d).</td>
</tr>
</tbody>
</table>

- AFRL will suggest solutions and provide subscale windowed testing support for IHRPRT injector/combustor development.
- Overall lead for injector/combustor design should remain with the contractors.
**Subscale hot fire facility**

<table>
<thead>
<tr>
<th>Propellants</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>H2(g), CH4(g)</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>O2(g)</td>
</tr>
<tr>
<td>Purge gas</td>
<td>N2(g), H2(g)</td>
</tr>
<tr>
<td>H2 mass flow rate</td>
<td>1.5 lbm/s (0.97 Kg/s)</td>
</tr>
<tr>
<td>CH4 mass flow rate</td>
<td>0.25 lbm/s (0.11 Kg/s)</td>
</tr>
<tr>
<td>O2 mass flow rate</td>
<td>1.0 lbm/s (4.5 Kg/s)</td>
</tr>
<tr>
<td>N2 mass flow rate</td>
<td>0.5 lbm/s (2.3 Kg/s)</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>16 lbm/s (7 Kg/s)</td>
</tr>
<tr>
<td>Max. system press.</td>
<td>2640 psi (179 atm)</td>
</tr>
</tbody>
</table>

**Data acquisition and control**
- VXI bus, MXI interfaced to PowerPC with 48MB RAM and optical drive.
- HP 1413B 64ch 100kHz scanning A/D board with signal conditioning modules.
- Tektronix 16 ch 200kHz /ch A/D board.
- VX4253 32 ch SPST relay switch card.

**Optics**
- 20 kHz, 20W CW vapor laser.
- Innova 4W and 10W Argon Ion lasers.
- Inj. seed, 2 pulse Yag (1.5J at 1064 nm)
- Continuum Nd6000 Yde laser.
- Princ. Inst and Stanford gated CCD cameras.
- Infinity and Questar LD microscopes.
- Aerometrics 2 comp. PDFA.

---

**Optically Accessible Rocket Engine**

- Gas/Gas engine. Similar to Penn State Optically Accessible Engine
  - H2 fuel, O2 oxidizer. Capability for other fuels.

- FY99 Accomplishments
  - Demonstrate successful firing.
  - Began heat transfer analysis to prepare for insertion of quartz viewing windows.
  - Heat transfer work suspended to prepare for PDRE testing.

- FY00 Tasks
  - Complete heat transfer analysis.
  - Raman imaging of chamber to compare with Penn State results.
  - Blasing of O2 injector.
HFTF Upgrades in 1999

- Replaced stainless steel tubing and fittings in GOX system with monel
- GOX system cleaned by NTS
- Installed filters in all systems
- Acquired parts for hydrocarbon system
- Acquired altitude chamber
- Improved data transfer rates with Ethernet switch
- Improved flexibility of Abort System Software
- Upgraded main control computer to Mac G3

Planned for 2000

- Complete liquid hydrocarbon system
- Procure and install LOX system

Single element cold flow pressure facility

Gas simulant: $N_2(\text{g}), \text{He}(\text{g})$

Liquid simulant: $\text{H}_2\text{O}, \text{O}_2(\text{g}), \text{N}_2(\text{g}), \text{He}(\text{g})$

$N_2$ mass flow rate: 20 lbm/s (0.9 Kg/s)

$\text{He}$ mass flow rate: 20 lbm/s (0.9 Kg/s)

$\text{H}_2\text{O}$ mass flow rate: 4.0 lbm/s (1.8 Kg/s)

Max. test air press.: 2000 psi (135 atm)

Max. Fuel sim. press.: 3000 psi (204 atm)

Max. Ox sim. press.: 3000 psi (204 atm)

Windowed test chamber with 5.5" (14 cm) of axial injector travel and a linear translating injector stage with 5" (13 cm) total radial travel inside chamber.

Ability to simulate manifold cross velocities to 30 ft/s (9.1 m/s).

27 tube traversable mechanical patternator

Phase Doppler, Malvern, other diagnostics
High Pressure Cold Flow Facility

Spray mass distribution is critical to:
- propellant mixing
- combustion efficiency
- wall compatibility

New system greatly increases speed at which spray mass distribution data can be collected.
Past Systems Supported by Cold Flow Facility

- SSME hot gas manifold model
- Fastrac main injector
- SSME/RLV preburner injector comparison
- Proprietary A
- SSME preburner post bias tests

FY99 Accomplishments

- PDPA small probe volume development.
  - 2 ICLASS and 2 Atomization and Sprays publications
- SSME post biasing studies (with Rocketdyne).
- Proprietary B
- Orifice hydraulics study.
  - Atomization and Sprays
- Low cost injector study (partly proprietary).
- Automated Patternator upgrade.
- 3400 psi fluid pressure upgrade.
The Effects of LOX Post Biasing on SSME Injector Wall Compatibility

AIAA 99-2888
P. A. Strakey and D. G. Talley
Air Force Research Laboratory, Edwards AFB, CA

L. K. Tseng and K. L. Minier
Rocketdyne Propulsion & Power, The Boeing Company,
Canoga Park, CA

35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit

Air Force Research Laboratory|AFRL

Motivation

- High efficiency engines require high chamber pressure and throughput.
- Problems:
  - High Heat Flux
  - Oxidative Attack (LOX)
- Wall protection methods;
  - Film Cooling
  - Mixture Ratio Biasing
  - LOX Post Biasing
- The result is Isp loss due to MR non-uniformity in the engine.
- Goal: Provide a detailed understanding, through cold-flow simulations of the effects of LOX post biasing on the liquid and gas phase distribution near a wall.

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Scaling Parameters

LOX Post ID=4.77 mm
Gas Gap=2.24 mm
LOX Post Recess=6.35 mm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SSME (LOX+gH₂+H₂O)</th>
<th>Cold-Flow (H₂O+gN₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pc (MPa)</td>
<td>19.3</td>
<td>0.74</td>
</tr>
<tr>
<td>Liq. Vel. (m/s)</td>
<td>31.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Den. Ratio (l/g)</td>
<td>117.6</td>
<td>117.6</td>
</tr>
<tr>
<td>Vel Ratio (l/g)</td>
<td>0.087</td>
<td>0.087</td>
</tr>
<tr>
<td>Mom Ratio (l/g)</td>
<td>0.286</td>
<td>0.286</td>
</tr>
<tr>
<td>Mix Ratio (l/g)</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Liq. Re #</td>
<td>1.1e6</td>
<td>4.3e4</td>
</tr>
</tbody>
</table>

Ströbelight Imaging

Biasing shifts the liquid flow away from the wall.

Unbiased
Z = 0 - 45 mm (top row)
Z = 45 - 110 mm (bottom row)

Biased 0.48 mm
Z = 0 - 45 mm (top row)
Z = 45 - 110 mm (bottom row)

Wall
Mixture Ratio Profiles

- Mixture ratio distribution is "shifted" away from the wall with LOX post biasing.
- The shift is due to a combined result of the displacement in liquid distribution away from the wall and an increase in gas flow on the wall side of injector.

Heat Flux Analysis

- Gas-Gas studies have shown a similitude between cold-flow data and hot-fire data at equivalent residence times.
- For the SSME, t=1 ms, approximately equivalent to the 51 mm cold-flow data.

\[ q'' \propto V^{0.8} \cdot T_g^b \]
\[ T_g = f(MR) \]
\[ As \ V \uparrow, \ T_g \downarrow \]
Performance Analysis

- ISP loss for SSME (Bias=0.48 mm) between 0.3 and 0.6 s.
- $\Delta q^*/\Delta Isp$ optimized at a Bias between 0.25 and 0.48 mm.

Conclusions

- LOX post biasing results in displacement of liquid flow away from the wall, and higher gas velocity near wall. Net result is a decreased MR near the wall.
- Isp loss increases with increasing LOX post bias.
- Some reduction in bias could recover a small amount of Isp, while still providing adequate wall protection.
- Optimization curves can aid injector designers in choosing a level of biasing.
- Droplet size should not play a large role.
Planned for FY00

- Extend post biasing studies to hot fire
  - Reproduce and extend Penn State gas/gas coax data
  - Duplicate hardware checkout initiated in FY99 but discontinued to support PDRE work.
  - Raman measurements to be attempted closer to the injector face.
  - Develop GOX post bias data for code anchoring

- Facility upgrades: liquid hydrocarbon and LOX capability
- Low cost injector design studies (proprietary)
- High pressure impinging injector measurements

Summary

- Strategic vision
  - Provide design guidance before committing to full scale hardware. Reduce trial-and-error expenses.

- Unique facilities
  - Cold flow, hot fire and supercritical
  - High pressure, optically accessible

- Relevance
  - Short term: problem turnaround on industry time scales (e.g., months)
  - Long term: Validated models will apply universally.

- Accomplishments
  - Numerous real-world engines impacted.
  - Numerous other metrics accomplished (publications, awards, tech transfer, etc.)