Comparison of Ablation Performance in Laser Lightcraft and Standardized Mini-Thruster (Briefing Charts, POSTPRINT)

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On our 31st trip to the laser facility at WSMR we carried out experiments on laser ablation of black and white Delrin [also called polyoxymethylene, polyformaldehyde, (HCHO)x]. Mass ablation and thrust generation (Impulse) were accurately measured as a function of input laser energy in one shot experiments. The efficiency of conversion of laser energy to jet kinetic energy depended on the geometry of the energy absorption/conversion zone. The most ideal geometry, an axis symmetric mini thruster, produced ~ 60% conversion efficiency. The extensively studied 10-cm diameter Lightcraft (with inverted paraboloid, plug nozzle geometry) produced ~ 50% conversion efficiency. The upper limit to energy conversion was computed with CEA code to be 73% for the well defined mini thruster geometry. Thus, total losses amount to ~ 13% and ~ 23%. This is a significant finding and helps to validate the concept of "momentum calorimetry", in which experiments like those accomplished here may be conducted to obtain reliable heats of formation. The performance of candidate chemically enhanced laser ablation or other solid propellants may be measured on a small scale. In these most recent experiments, a near-exact match of coupling coefficients (1%) was achieved in a 14-fold scale-down of the 10-cm Lightcraft to the mini thruster.
Comparison of Ablation Performance in Laser Lightcraft and Standardized Mini-Thruster

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On our 31st trip to the laser facility at WSMR we carried out experiments on laser ablation of black and white Delrin [also called polyoxymethylene, polyformaldehyde, (HCHO)x]. Mass ablation and thrust generation (Impulse) were accurately measured as a function of input laser energy in one shot experiments. The efficiency of conversion of laser energy to jet kinetic energy depended on the geometry of the energy absorption/conversion zone. The most ideal geometry, an axis symmetric mini thruster, produced ~ 60% conversion efficiency. The extensively studied 10-cm diameter Lightcraft (with inverted paraboloid, plug nozzle geometry) produced ~ 50% conversion efficiency. The upper limit to energy conversion was computed with CEA code to be 73% for the well defined mini thruster geometry. Thus, total losses amount to ~ 13% and ~ 23%. This is a significant finding and helps to validate the concept of “momentum calorimetry”, in which experiments like those accomplished here may be conducted to obtain reliable heats of formation. The performance of candidate chemically enhanced laser ablation or other solid propellants may be measured on a small scale. In these most recent experiments, a near-exact match of coupling coefficients (1%) was achieved in a 14-fold scale-down of the 10-cm Lightcraft to the mini thruster.
Outline

• Collaboration Network/Why Laser Propulsion?
• Flavor of PLVTS
• The Laser and EL measurement (Joules)
• The Pendulum and I measurement (Newton seconds)
• The Mettler Balance and m measurement (milligrams)
• Compare the EL, I, m measurements on 2 Test Articles
  – Light Craft, model 200-3/4
  – Mini Thruster Standard for momentum calorimetry/prop devel
• Elementary considerations (energy/momentum)
• Comparison of experiments to 1-D equilib code (CEA)
• Conclusions/Work in progress/Flight Tests Movie
Phase II Program Collaborations
X-50LR: Experimental 50-cm Laser Ramjet

X – 50LR
Dr. Frank Mead, Jr.
Dr. C. “Bill” Larson
AFRL/PRSP

= Government Agencies
= Contractors
= Foreign Research

Thrust Measurement
U. Alabama, Huntsville
Dr. Andrew Pakamov

Computer Launch Model
Penn State U.
Dr. Michael Micci
(Mr. Sean Knecht)

Laser Consultant
Trex Enterprises
Dr. Victor Hasson

Attitude Control
Polaris Sensors
Mr. John Harchanko

CO2 Laser: Lab & Flight Testing
HELSTF/WSMR - Mr. Steve Squires

Laser Propulsion for Navy
Michael Libeau
NSWCDD, Dahlgren, VA

System Study
Flight Unlimited
Mr. Dave Froning

Beam Propagation
DS&S
Dr. Alan Pike

SiC Parabolas
DARPA
Dr. Christodoulou

Vehicle Fabrication
COI Ceramics
Dr. Tim Easler

Ablation of Liquid Fuels
Inst. for Laser Technology
Dr. Shigeaki Uchida

Laser Launchers
AFOSR MURI
Dr. Mitat Birkan

Ablation of Solid Fuels
Inst. of Technical Phys.
Mr. Wolfgang Schall

Distribution A – Approved for public release, Distribution Unlimited
Team December 2004
Pulsed Laser Vulnerability Test System

Frank Mead, Bill Larson, AFRL/PRSP
Jim Shryne, RSI
John Harchanko, POLARIS TECHNOLOGIES
Steve Squires, Chris Beairsto, Mike Thurston, JaySpray, WSMR/HELSTF/PLVTS

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$\mathbf{E_f} = \frac{1}{2}mv^2 = \eta \alpha \beta \gamma \delta \mathbf{E_{wall}}$

$\eta =$ propulsion efficiency (jet kinetic energy to vehicle kinetic energy)
$\alpha =$ expansion efficiency (internal propellant energy to jet kinetic energy)
$\beta =$ absorption efficiency (laser energy at vehicle to internal propellant energy)
$\gamma =$ transmission efficiency (laser energy at ground to laser energy at vehicle)
$\delta =$ laser efficiency (electric energy to laser energy at ground)

***** Issue: separability of $\eta \alpha \beta \gamma \delta$ and $\mathbf{E_{wall}}$ *****

“$500 worth of electricity to put 1 kg into LEO.”
At $0.10/KWH, \$500 buys 18,000MJ = E_{wall}$ (1 KWH = 3.6 MJ);
1 kg at 10 km/s has $E_f = 50$ MJ, so $\eta\alpha\beta\gamma\delta = 0.0028 = 50/18000$
But if 28% overall efficiency, then $\$5/kg


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Laser Specifications

- Pulsed CO$_2$ Laser
- 10 KW
- ~5 to 30 $\mu$s pulse width
- Up to 30 Hz
- Up to 1000 J/pulse ($E_L \pm 10\%$)
- Near Field Burn Pattern
  ~10 feet

Pulse Shape

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FFT and Far Field Burn Patterns

Burn Patterns:

500 feet  1000 feet  1500 feet

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Pendulum Test Stand

Y = 0.2043x R² = 0.9997

Impulse (Ns)

RVDT Volts

RVDT Volts

Time (s)
Comparison of Pendulum Impulse to Hammer Impulse

\[ I_{\text{pend}} = m_{\text{pend}} \sqrt{gL(1 - \cos \Theta)} \approx \left( \frac{m_{\text{pend}} \pi \sqrt{gL}}{720} \right) \Theta \]

![Graph showing comparison of pendulum impulse to hammer impulse with data points for test articles 1, 2, and 3.](graph.png)

Larson, Mead AIAA 2001-0646

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NIST Traceable Impulse Calibration

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Mettler Balance or Digital Balance

Measure $m$ to $\pm 0.3$ mg
Model 200 Lightcraft Series: An AF-Patented Laser Vehicle Concept

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Lightcraft and Mini-Nozzle Standard

200-3/4 Lightcraft

Mini-nozzle
26° divergence angle

ε(ideal plug nozzle) = 14
m=40g
Delrin surface area ~ 25 cm²
350 J/25 cm²/18 μs = 0.8 MW/cm²
C_m=450 N/MW, E_l/m=5.1 MJ/kg
V_e= 2270 m/s, efficiency = 0.51
T/W=C_mP/mg = 11 at P=10 KW

ε = 8
m=7.8 g
Delrin surface area ~ 0.71 cm²
25 J/0.71 cm²/18 μs = 2.0 MW/cm²
C_m=442 N/MW, E_l/m=6.3 MJ/kg
V_e=2795, efficiency=0.62

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Laser Light Craft Flights

Light Craft Flights with Air or Delrin
Model 200-3/4, m=40g 10kW at 25 Hz 400 J/Pulse

Larson, Mead AIAA 2001-0646
Air Plasma
Mini Thruster 25 J, 18 $\mu$s, 0.71 cm$^2$
I, m, E_L for Mini Thruster

I/E_L = 444 Ns/MJ

m/E_L = 0.160 mg/J

V_e = (I/E_L)/(m/E_L) = 2775 m/s

Efficiency = ½(I/E_L)^2/(m/E_L) = 0.616 = αβΦ

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10 cm Light Craft 322 J, 18 μs

Black Ser 7
322 J
59.8 mg/shot

White Ser 6
322 J
68.7 mg/shot

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$I, m, E_L$ for Light Craft 200-3/4

$I/E_L = 447 \text{ Ns/MJ}$  \hspace{1cm}  $m/E_L = 0.201 \text{ mg/J}$

$V_e = (I/E_L)/(m/E_L) = 2224 \text{ m/s}$

Efficiency $= \frac{1}{2}(I/E_L)^2/(m/E_L) = 0.497 = \alpha \beta \Phi$

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CONVERSION OF LASER ENERGY TO JET KINETIC ENERGY

\[ Q^* = \frac{\beta E_L}{m_p} \quad \text{Specific internal energy} \]

\[ E_{\text{jet}} = \frac{1}{2} m_p \langle v_e^2 \rangle = \alpha m_p Q^* = \alpha \beta E_L \]

\[ I = m_p \langle v_e \rangle \]

\[ \frac{I^2}{2m_p E_L} = \alpha \beta \frac{\langle v_e \rangle^2}{\langle v_e^2 \rangle} = \alpha \beta \Phi \]

\[ C = \frac{I}{E_L} = \frac{2\alpha \beta}{\langle v_e \rangle} \left[ \frac{\langle v_e \rangle^2}{\langle v_e^2 \rangle} \right] = \frac{2\alpha \beta \Phi}{\langle v_e \rangle} \]

\[ \frac{1}{2} C < v_e > = \alpha \beta \Phi \leq 1 \]

For propellants with chemical energy

\[ (\alpha \beta \Phi)_{\text{apparent}} = \alpha \Phi \left( \beta + \frac{m_p \Delta u_{\text{chem}}}{E_L} \right) \]

Larson, Mead, Kalliomaa,

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Performance map of known laser materials and theoretical air

$\frac{1}{2} C_m V_e = \alpha \beta \Phi$, $C_m = \frac{m}{E_L} V_e$

Coupling coefficient $C_m = \frac{I}{E_L} \text{Ns/MJ}$

Exit velocity $V_e = \frac{I}{m} \text{m/s}$

Larson, Mead, Knecht, AIAA 2004-0649

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Experimental Results December 2004
200-3/4 Light Craft and Mini Thruster

\[ \alpha_\beta \Phi = \frac{1}{2} C_m V_e \]

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Instantaneous Energy Addition to Delrin

4 mg per shot evaporated
20 μm layer/18 μs
6 J/mg = Q*/β

Specify energy and density of heated layer
Q*_{delrin} < 6 MJ/kg, ρ < 1420 kg/m³
Obtain P ~ 20,000 bar T ~ 3700 K via CEA

Specify expansion ratio
ε = 4, 8, 16, 32, 64
Obtain Isp, thermo props in exit plane via CEA

563x740
\[ E_L = 25 \text{ J} \]
\[ \tau_p = 18 \mu \text{s} \]
\[ F = 35 \text{ J/cm}^2 \]
\[ I = 2.0 \text{ MW/cm}^2 \]
6 J/mg Energy Addition to Delrin

\[
\text{HCHO} (g) (u, \rho) \rightarrow \text{CO(g) + H}_2(g) (u, \rho) + 1\text{mg O}_2
\]

\[
\text{HCHO(g) (g, STP)} \rightarrow \text{CO(g) + H}_2(g) (g, \text{STP})
\]

\[
\text{HCHO (g) (u, \rho)} \rightarrow 2.3 \text{J/mg}
\]

\[
\text{HCHO(g) (g, STP)} \rightarrow 2.7 \text{J/mg}
\]

\[
\text{CO(g) + H}_2(g) (g, \text{STP}) \rightarrow \text{CO}_2(g) + \text{H}_2\text{O(g)} (\text{STP})
\]

\[
\text{Exit} 293 \text{ s}
\]

\[
\text{Exit} 420 \text{ s}
\]
Lifetime of Formaldehyde, $\tau(T,P)$

HCHO + M = H + HCO + M, $k=5\times10^{15}\exp-308\text{kJ/mol/RT cm}^3/\text{mol-s}$


Mechanism:
(i) HCHO + M = H + HCO + M
(p) H + HCHO = H2 + HCO
(t) H + HCO = H2 + CO
(t) H + H + M = H2 + M
(t) HCO + HCO = CO + HCHO

Temperature (K)

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# Mole Fractions at Equilibrium

Formaldehyde expansion from P=22694 bar, T=3732K
\[ \rho=1227 \text{ kg/m}^3, u=1.975 \text{ MJ/kg} \]

<table>
<thead>
<tr>
<th>Species ( \varepsilon )</th>
<th>chamber ( \varepsilon=8 )</th>
<th>chamber ( \varepsilon=64 )</th>
<th>species ( \varepsilon=8 )</th>
<th>chamber ( \varepsilon=64 )</th>
</tr>
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<tbody>
<tr>
<td>CO</td>
<td>0.47502</td>
<td>0.48415</td>
<td>CH3OH</td>
<td>0.00015</td>
</tr>
<tr>
<td>H2</td>
<td>0.39082</td>
<td>0.39891</td>
<td>CH3CHO,ethanal</td>
<td>0.00014</td>
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<tr>
<td>H2O</td>
<td>0.06058</td>
<td>0.04282</td>
<td>C3H4,allene</td>
<td>0.00013</td>
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<tr>
<td>CH4</td>
<td>0.03818</td>
<td>0.05811</td>
<td>C3H6,propylene</td>
<td>0.00013</td>
</tr>
<tr>
<td>CO2</td>
<td>0.00856</td>
<td>0.01574</td>
<td>CH2</td>
<td>0.00012</td>
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<tr>
<td>C2H2</td>
<td>0.00742</td>
<td>0.00002</td>
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<td>0.00472</td>
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<td>H</td>
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<td>0</td>
<td>C3H5,allyl</td>
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<td>C2H4</td>
<td>0.00267</td>
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<td>C4H2</td>
<td>0.00006</td>
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<td>HCO</td>
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<td>0</td>
<td>COOH</td>
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<td>HCHO</td>
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<tr>
<td>CH2CO</td>
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<td>CH3O</td>
<td>0.00003</td>
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<tr>
<td>C3H3,2-ptyl</td>
<td>0.00039</td>
<td>0</td>
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<tr>
<td>C2H3,vinyl</td>
<td>0.00035</td>
<td>0</td>
<td>C3O2</td>
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<tr>
<td>OH</td>
<td>0.00032</td>
<td>0</td>
<td>C4H6,butadiene</td>
<td>0.00003</td>
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<td>C2H6</td>
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<td>0.00005</td>
<td>C2O</td>
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<td>HCOOH</td>
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<td>C2H5OH</td>
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<td>C3H4</td>
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<td>C3H4,cyclo-</td>
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<tr>
<td>C2H5</td>
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<td>0</td>
<td>C4H6,1butyne</td>
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</tr>
<tr>
<td>(gr)</td>
<td></td>
<td></td>
<td>C</td>
<td>0</td>
</tr>
</tbody>
</table>

Distribution A – Approved for public release, Distribution Unlimited
## Mole Fractions at Equilibrium

Formaldehyde expansion from $P=230$ bar, $T=3433$ K, $[\rho=12.02\ \text{kg/m}^3, u=1.907\text{MJ/kg}]$

<table>
<thead>
<tr>
<th>mole fractions</th>
<th>Chambr</th>
<th>throat</th>
<th>$\varepsilon=4$</th>
<th>$\varepsilon=8$</th>
<th>$\varepsilon=16$</th>
<th>$\varepsilon=32$</th>
<th>$\varepsilon=64$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.49263</td>
<td>0.49587</td>
<td>0.49955</td>
<td>0.49553</td>
<td>0.47166</td>
<td>0.43233</td>
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<tr>
<td>H2</td>
<td>0.47969</td>
<td>0.48865</td>
<td>0.49681</td>
<td>0.4913</td>
<td>0.48006</td>
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<td>H</td>
<td>0.02313</td>
<td>0.01223</td>
<td>0.00003</td>
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<td>0</td>
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<tr>
<td>H2O</td>
<td>0.00239</td>
<td>0.00173</td>
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<td>C2H2, acetylene</td>
<td>0.00105</td>
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<td>0</td>
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<td>CH4</td>
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<td>0.00033</td>
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<td>0.00224</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>HCO</td>
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<tr>
<td>CH2</td>
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<td>0</td>
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<tr>
<td>HCHO, formaldehyde</td>
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<td>C2H</td>
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<td>C2H2, vinylidene</td>
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</table>

Distribution A – Approved for public release, Distribution Unlimited
Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)

\(P_c = 20.2\) bar, \(T_c = 3060\) K, \(\rho_c = 1.18\) kg/m\(^3\)

Mole Fraction

Expansion ratio

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Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)
Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)
Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)
Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)

![Graph showing temperature (K) vs. expansion ratio (\(\varepsilon\)). The graph indicates that for a 'Mini thruster' with \(\varepsilon = 8\), the temperature decreases significantly as the expansion ratio increases.](Image)

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Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)

![Graph showing pressure versus expansion ratio]

- Mini thruster \(\varepsilon = 8\)

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Blowdown from specified initial state \((u, \rho)\) with specified expansion ratio \((\varepsilon)\)

Density (kg/m^3)

\(\varepsilon\) expansion ratio

Mini thruster \(\varepsilon = 8\)

Distribution A – Approved for public release, Distribution Unlimited
Experimental data (I, EL, m) and derived parameters (Cm, Ve, efficiency, EL/m)

<table>
<thead>
<tr>
<th>Geometry</th>
<th>I vs EL slope</th>
<th>m vs EL slope</th>
<th>Cm</th>
<th>Ve</th>
<th>Efficiency</th>
<th>E_L/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mNs/J R²</td>
<td>mg/J R²</td>
<td>Ns/MJ</td>
<td>m/s</td>
<td></td>
<td>MJ/kg</td>
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<td>Mini thruster</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>white</td>
<td>0.444 0.97</td>
<td>0.160 0.99</td>
<td>444</td>
<td>2775</td>
<td>0.616</td>
<td>6.3</td>
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<tr>
<td>black</td>
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<td>0.156 0.98</td>
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<td>2814</td>
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<td>AIR</td>
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<td>-</td>
<td>253</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>10-cm Model</td>
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<td>2335</td>
<td>0.529</td>
<td>5.2</td>
</tr>
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</table>
Conclusions/Work in Progress

- $C_m = 450 \text{ N/MW}$ for Light Craft/Delrin (350 J, 18 $\mu$s)
- $C_m = 442 \text{ N/MW}$ for Mini Thruster/Delrin (25 J, 18 $\mu$s)
- 51% efficiency for $E_L$ to jet KE for Light Craft
- 62% efficiency for $E_L$ to jet KE for Mini Thruster
- Future Experiments
  - Vary pulse width, 5 and 30 $\mu$s, expansion ratio, $\varepsilon = 4, 16, \ldots$
  - Increase $E_L$ up to ~ 100 J/pulse in mini thruster
  - Measure time resolved thrust with piezoelectric
  - Develop chemically enhanced ablative propellants
- Future Calculations with Chemical Equilibrium Applications Code
  - Factor pressure thrust into analysis
  - Analyze Chemically Energetic Propellants

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THE END
For Bimodal velocity distribution

Chunks of propellant
Hot gases

\[ f_{\text{heavy}} \text{ mass fraction, } v_{\text{slow}} \text{ velocity} \]
\[ f_{\text{light}} \text{ mass fraction, } v_{\text{fast}} \text{ velocity} \]

\[ \langle v \rangle^2 = (f_{\text{heavy}} v_{\text{slow}} + f_{\text{light}} v_{\text{fast}})^2 \]
\[ \langle v^2 \rangle = f_{\text{heavy}} v_{\text{slow}}^2 + f_{\text{light}} v_{\text{fast}}^2 \]

\[ \Phi = \frac{\langle v \rangle^2}{\langle v^2 \rangle} = \frac{(f_{\text{heavy}} + f_{\text{light}} r)^2}{(f_{\text{heavy}} + f_{\text{light}} r^2)} \text{ where } r = \frac{v_{\text{fast}}}{v_{\text{slow}}} > 1 \]
Divergence Loss

\[ \alpha = \frac{1}{2} \text{ (divergence angle)} \]

Ratio 2D or 3D to 1D

\[ 3D: 0.5(1+\cos \alpha) \]
\[ 2D: \frac{\sin \alpha}{\alpha} \]

NASA 1960

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