

# RECENT LASER PROPULSION RESULTS FROM WSMR/HELSTF/PLVTS

August 2005



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# Report Documentation Page

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# Abstract



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)<sub>x</sub>]. 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

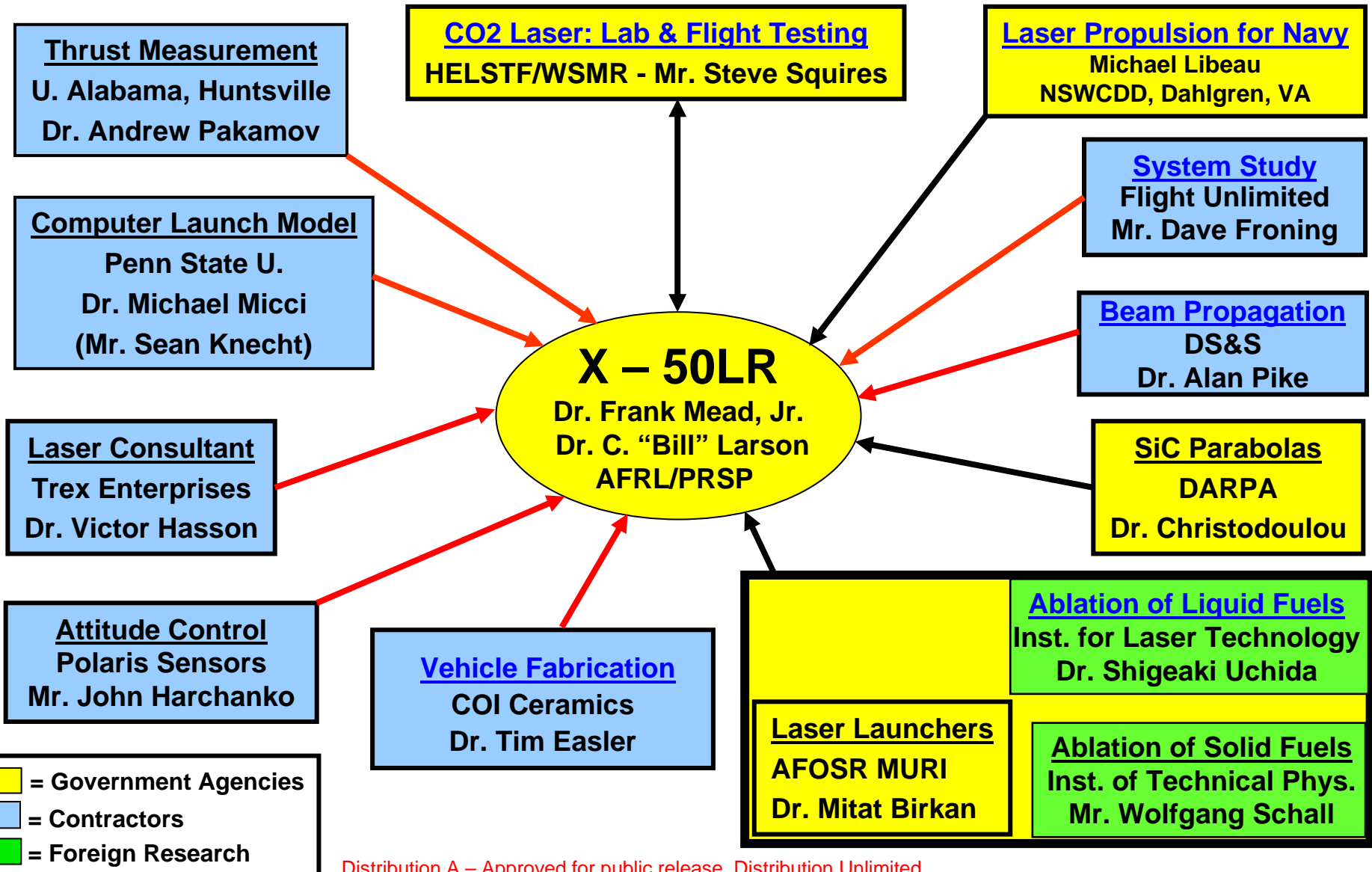


- **Collaboration Network/Why Laser Propulsion?**
- **Flavor of PLVTS**
- **The Laser and EL measurement (Joules)**
- **The Pendulum and I measurement (Newton seconds)**
- **The Mettler Balance and m measurement (milligrams)**
- **Compare the EL, I, m measurements on 2 Test Articles**
  - Light Craft, 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





# 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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# Overall Energy Conversion in Laser Propulsion Mission



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

$\eta$  = 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  $E_{\text{wall}}$  \*\*\*\*\*

“ \$500 worth of electricity to put 1 kg into LEO.”

At \$0.10/KWH, \$500 buys 18,000MJ =  $E_{\text{wall}}$  (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

Phipps, Reilly, Campbell, *Laser & Particle Beams* 18 (2001) 661-695

Pirri, Monsler, Nebolsine, *AIAA Journal* 12 (1974) 1254-1261

# Pulsed Laser Vulnerability Test System



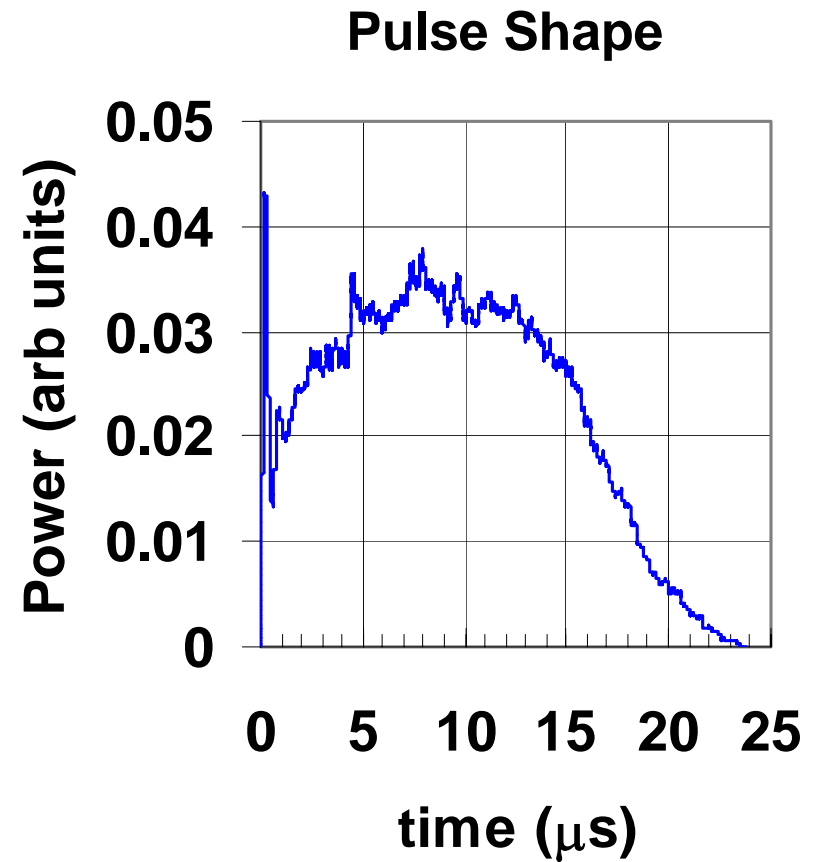
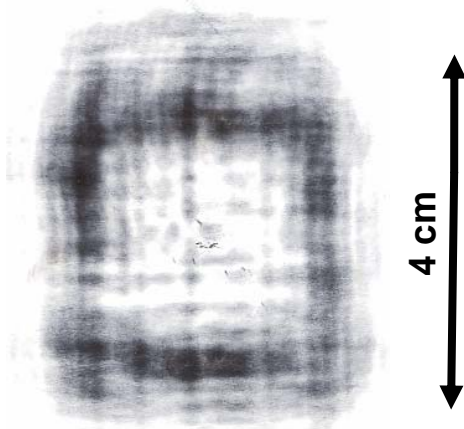




# Laser Specifications



- Pulsed CO<sub>2</sub> 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



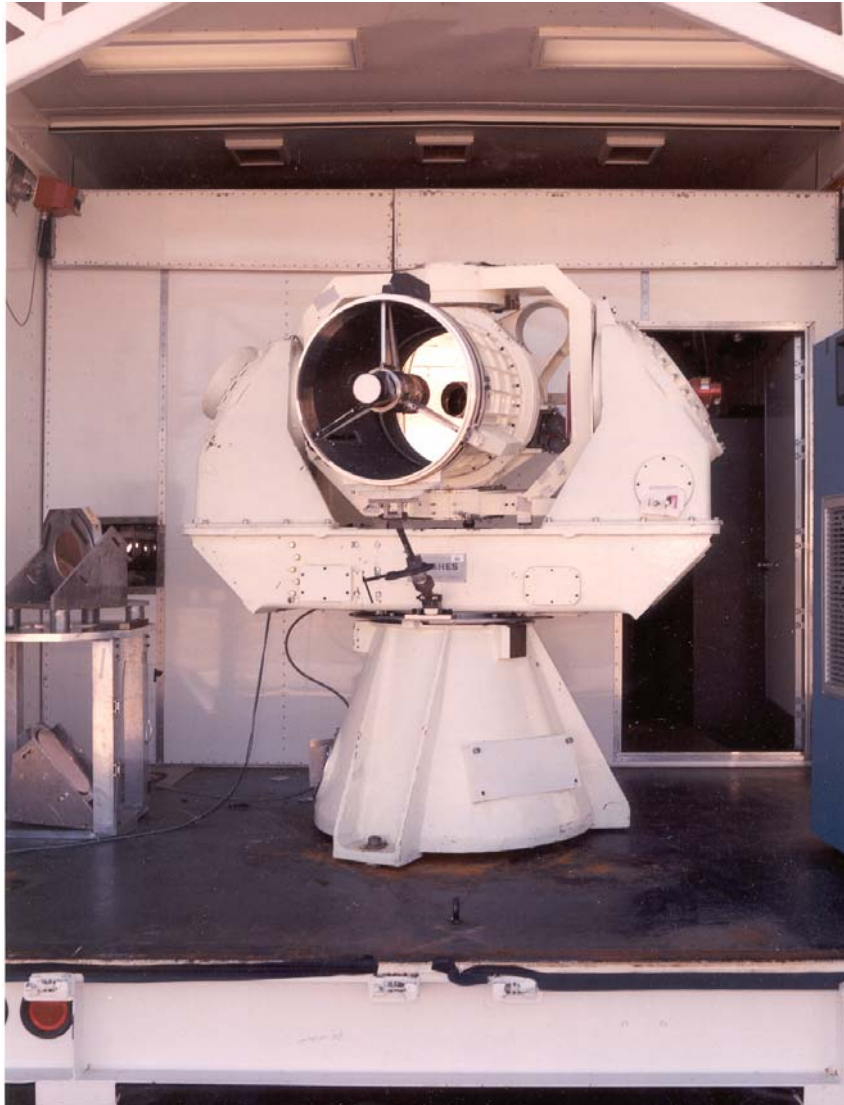


# 10 kW LASER IRRADIATION

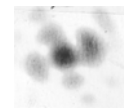




# FFT and Far Field Burn Patterns



**Burn Patterns:**



10 cm

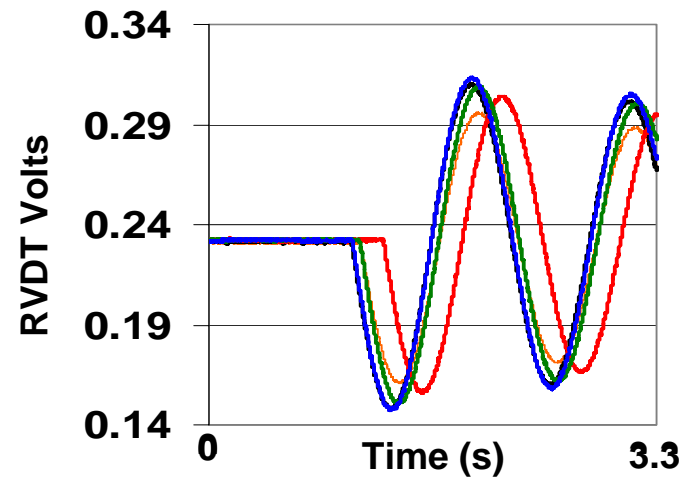
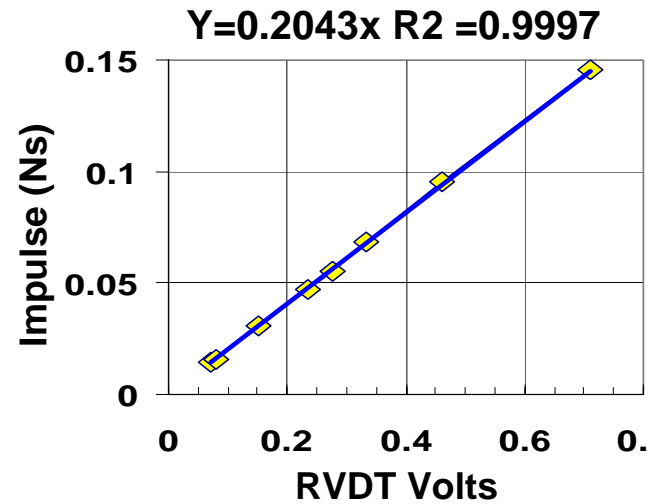
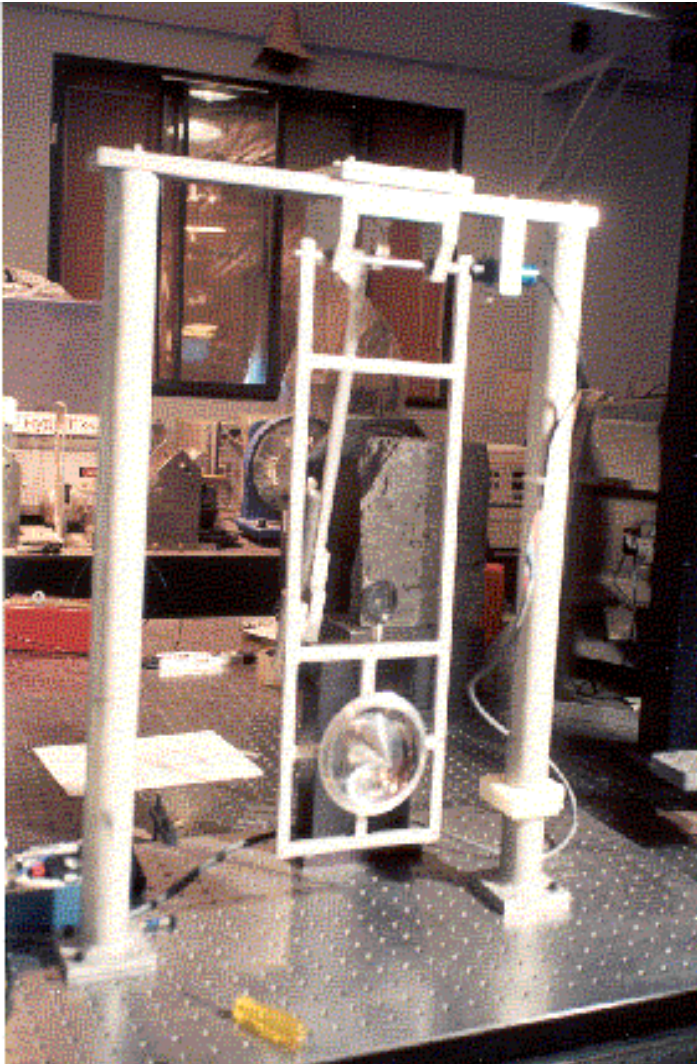
**500 feet**

**1000 feet**

**1500 feet**

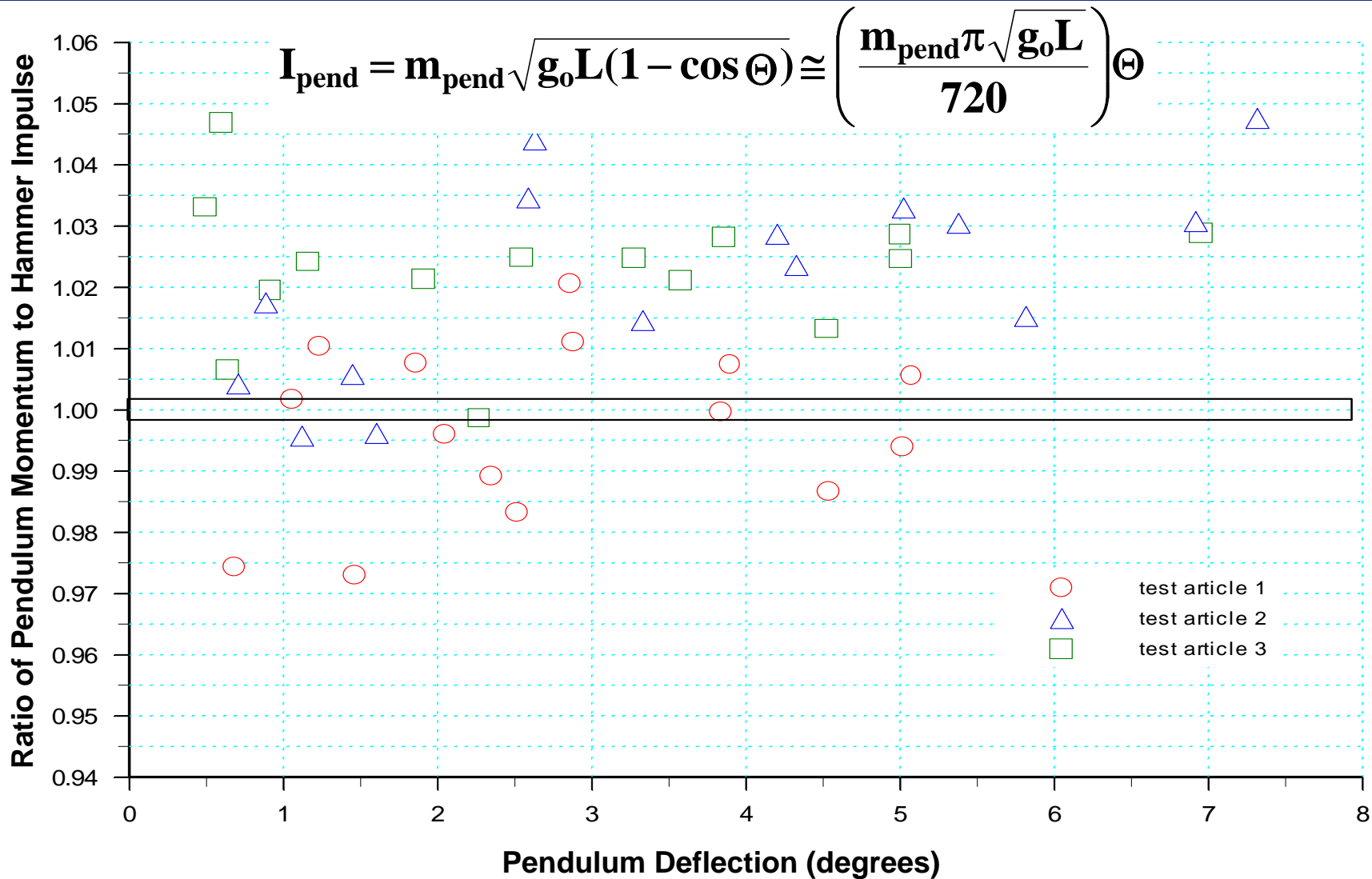


# Pendulum Test Stand





# Comparison of Pendulum Impulse to Hammer Impulse

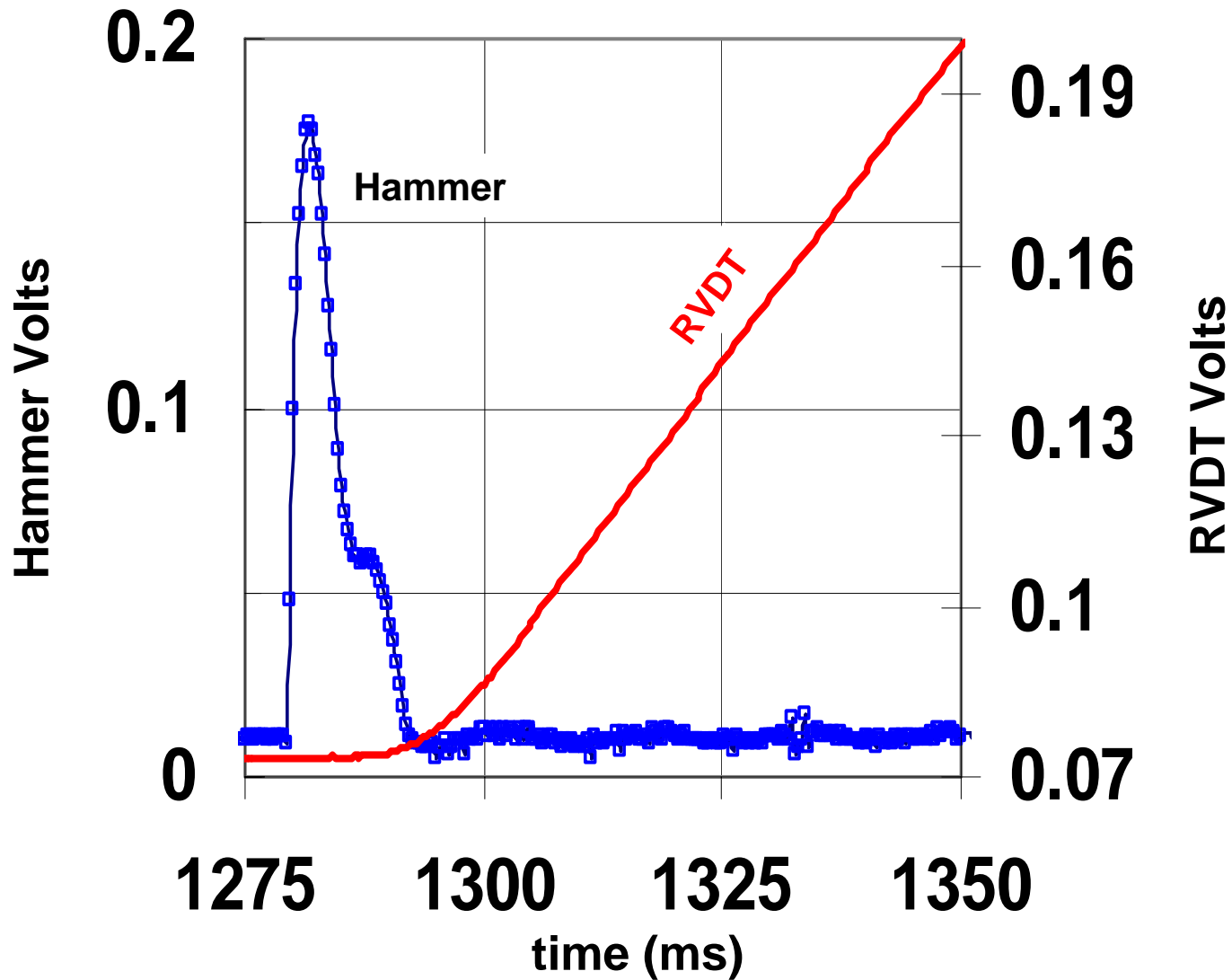


Larson, Mead AIAA 2001-0646

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# NIST Traceable Impulse Calibration



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# Mettler Balance or Digital Balance



Measure  $m$  to  $\pm 0.3$  mg



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# ***Model 200 Lightcraft Series: An AF-Patented Laser Vehicle Concept***



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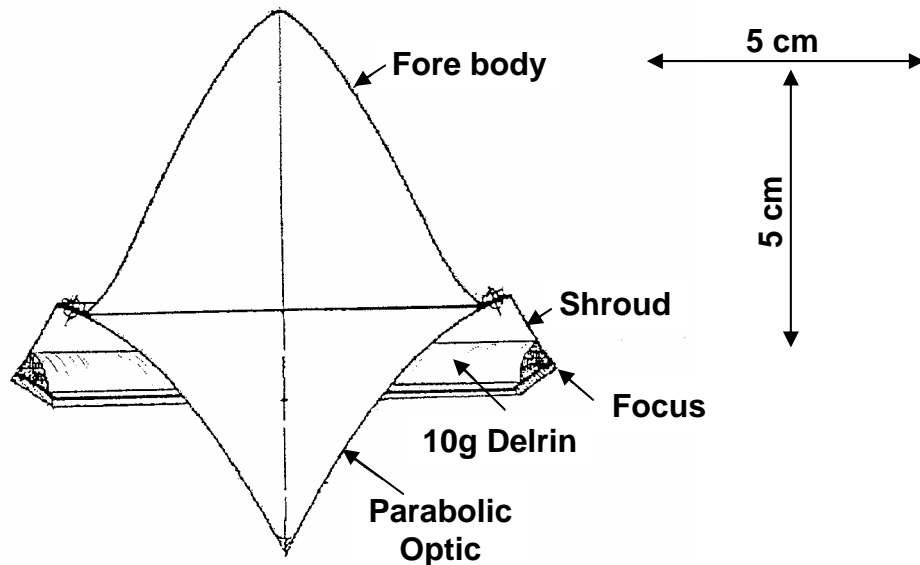




# Lightcraft and Mini-Nozzle Standard



## 200-3/4 Lightcraft



$$\epsilon(\text{ideal plug nozzle}) = 14$$

$$m=40\text{g}$$

Delrin surface area  $\sim 25 \text{ cm}^2$

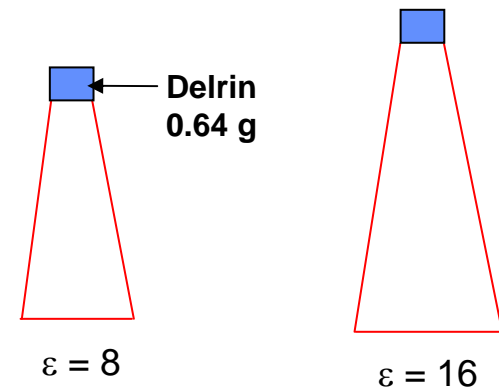
$$350 \text{ J}/25 \text{ cm}^2/18 \mu\text{s} = 0.8 \text{ MW}/\text{cm}^2$$

$$C_m=450 \text{ N}/\text{MW}, E_L/m=5.1 \text{ MJ}/\text{kg}$$

$$V_e = 2270 \text{ m}/\text{s}, \text{ efficiency} = 0.51$$

$$T/W=C_m P/mg = 11 \text{ at } P=10 \text{ KW}$$

## Mini-nozzle 26° divergence angle



$$\epsilon = 8$$

$$m=7.8 \text{ g}$$

Delrin surface area  $\sim 0.71 \text{ cm}^2$

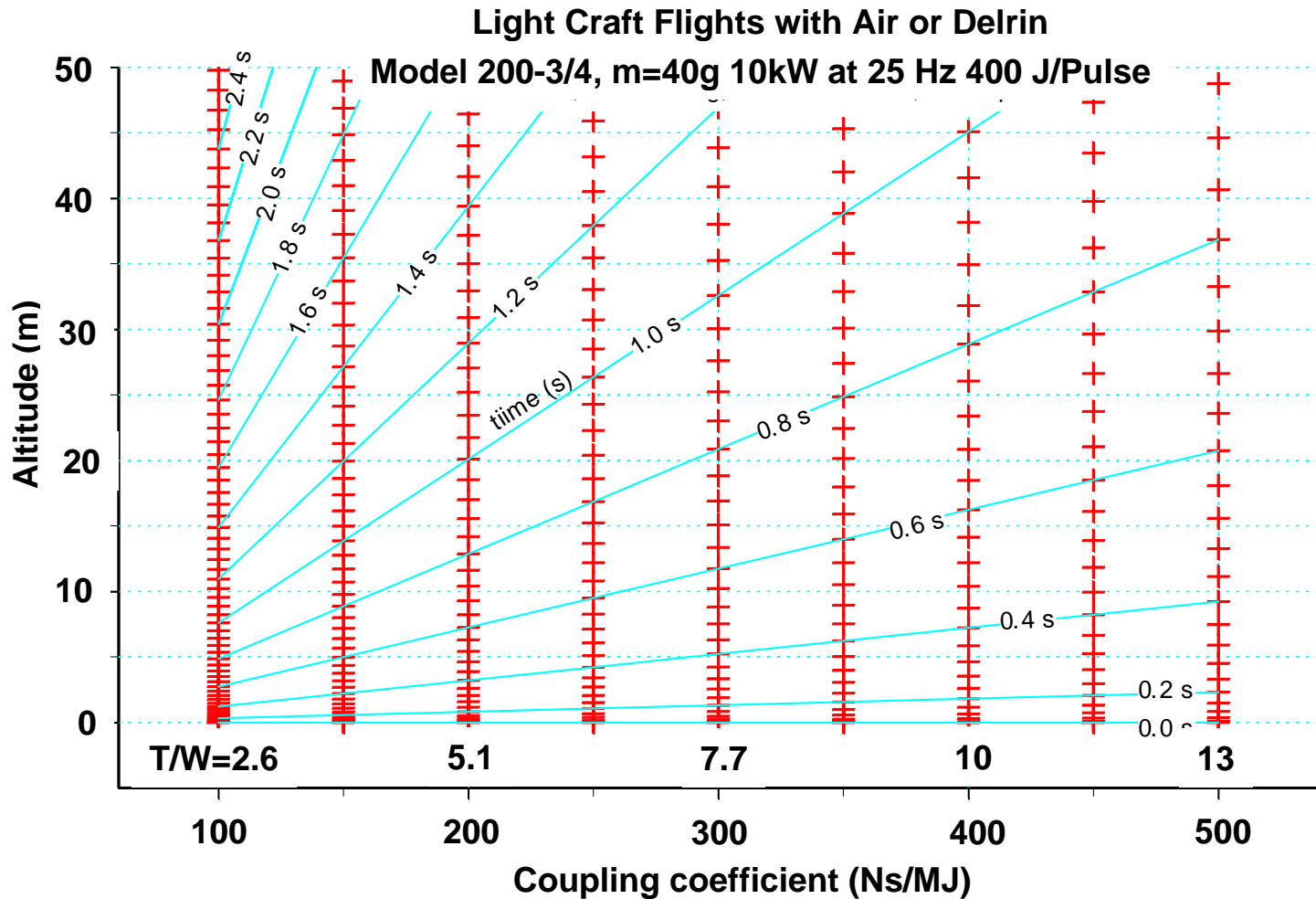
$$25 \text{ J}/0.71 \text{ cm}^2/18 \mu\text{s} = 2.0 \text{ MW}/\text{cm}^2$$

$$C_m=442 \text{ N}/\text{MW}, E_L/m=6.3 \text{ MJ}/\text{kg}$$

$$V_e=2795, \text{ efficiency}=0.62$$



# Laser Light Craft Flights



Larson, Mead AIAA 2001-0646



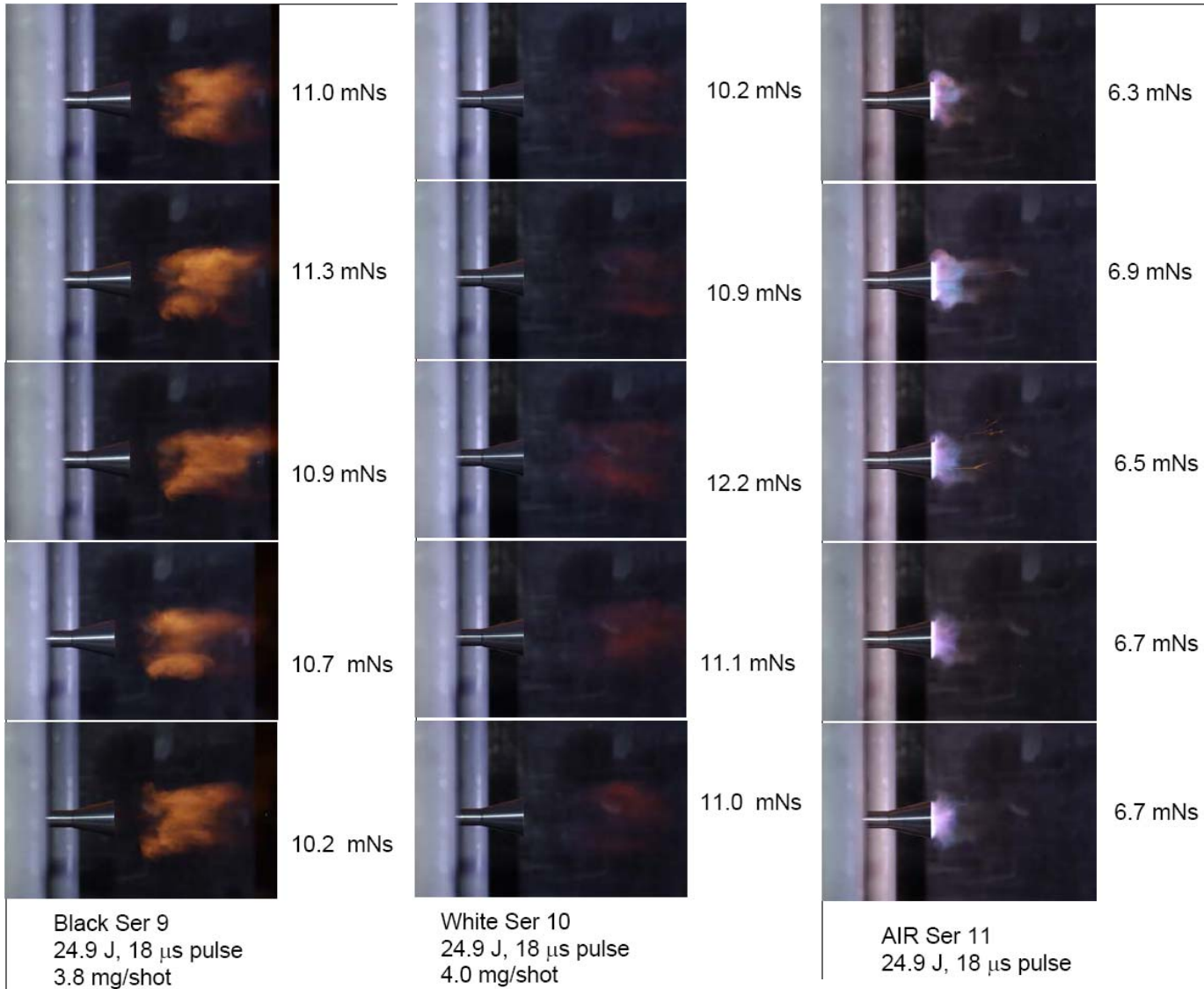
# Air Plasma



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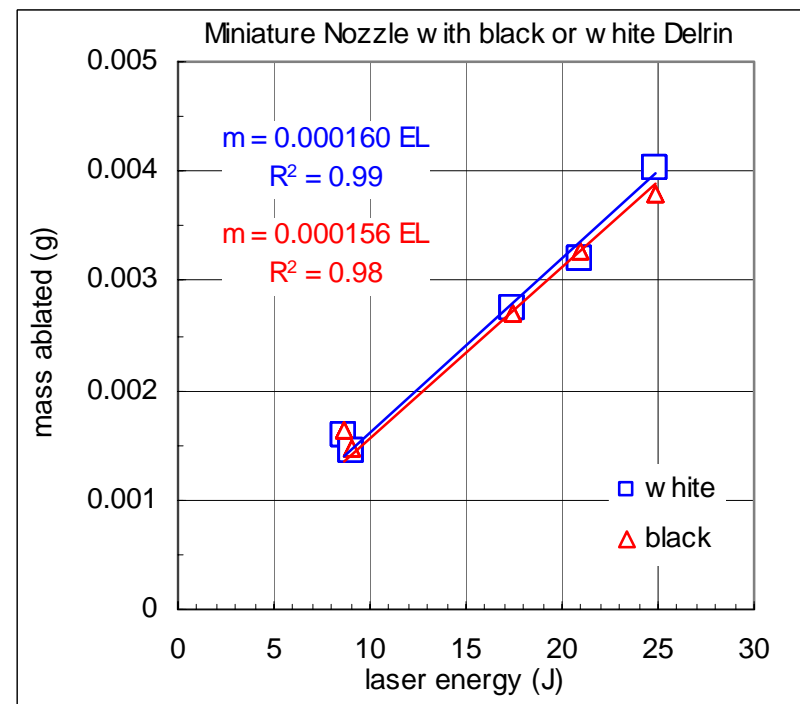
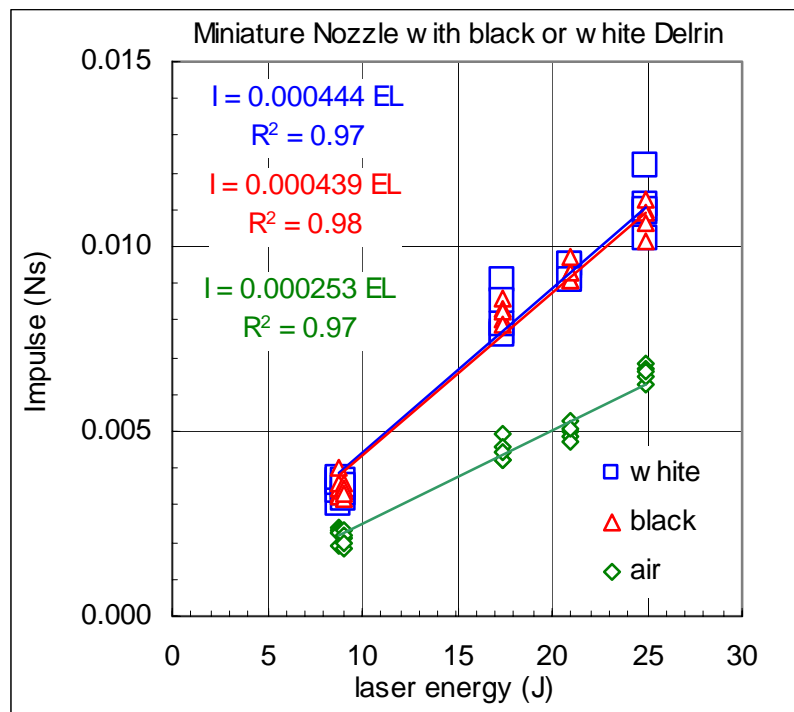


# Mini Thruster 25 J, 18 $\mu$ s, 0.71 cm<sup>2</sup>





# I, m, E<sub>L</sub> for Mini Thruster



$$I/E_L = 444 \text{ Ns/MJ}$$

$$m/E_L = 0.160 \text{ mg/J}$$

$$V_e = (I/E_L)/(m/E_L) = 2775 \text{ m/s}$$

$$\text{Efficiency} = \frac{1}{2}(I/E_L)^2/(m/E_L) = 0.616 = \alpha\beta\Phi$$



# 10 cm Light Craft 322 J, 18 $\mu$ s



139.2 mNs



144.8 mNs



153.9 mNs



146.7 mNs



150.2 mNs

**Black Ser 7**  
**322 J**  
**59.8 mg/shot**



154.1mNs



151.8 mNs



133.0 mNs



136.1 mNs

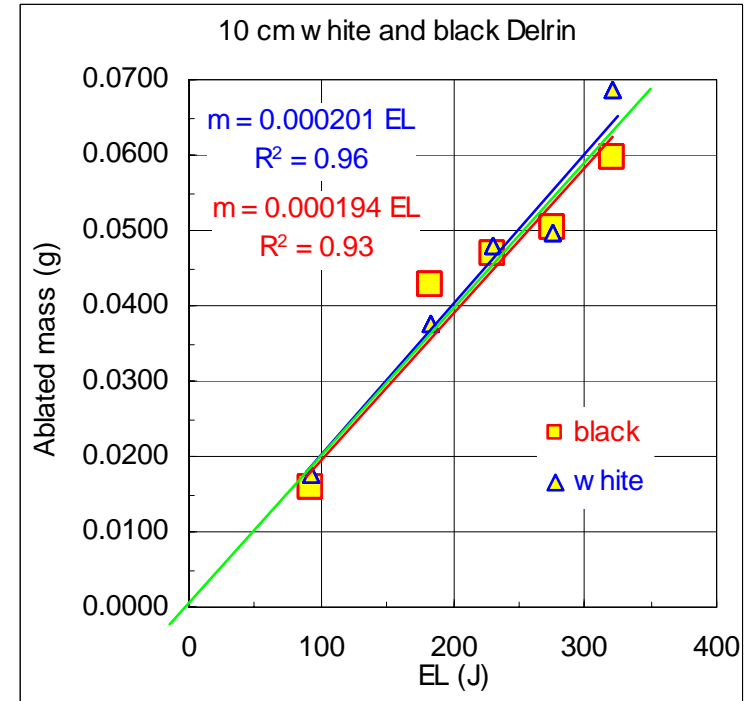
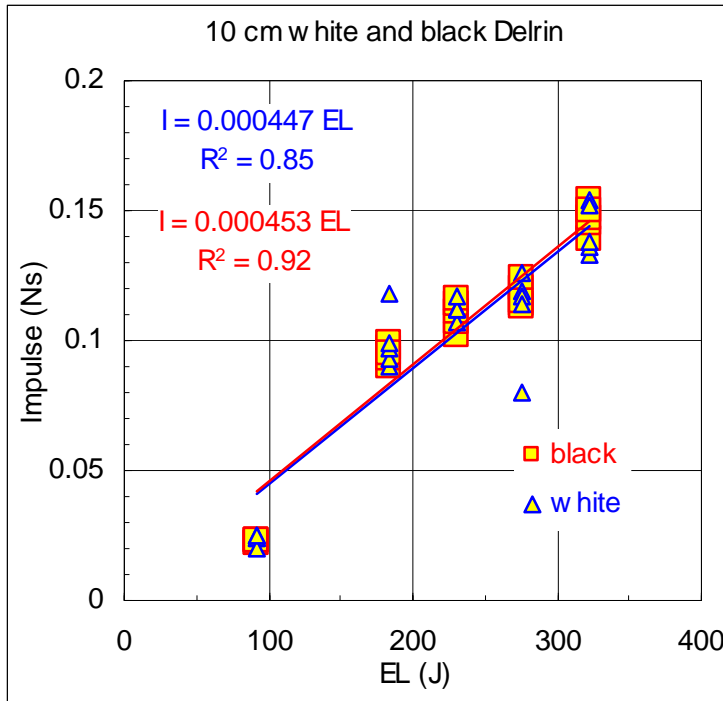


137.8 mNs

**White Ser 6**  
**322 J**  
**68.7 mg/shot**



# I, m, E<sub>L</sub> for Light Craft 200-3/4



$$I/E_L = 447 \text{ Ns/MJ}$$

$$m/E_L = 0.201 \text{ mg/J}$$

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

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



# CONVERSION OF LASER ENERGY TO JET KINETIC ENERGY



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

$$E_{\text{jet}} = \frac{1}{2} m_p \langle \mathbf{v}_e^2 \rangle = \alpha m_p Q^* = \alpha \beta E_L$$

$$\mathbf{I} = m_p \langle \mathbf{v}_e \rangle$$

$$\frac{\mathbf{I}^2}{2m_p E_L} = \alpha \beta \frac{\langle \mathbf{v}_e \rangle^2}{\langle \mathbf{v}_e^2 \rangle} = \alpha \beta \Phi$$

$$\mathbf{C} = \frac{\mathbf{I}}{E_L} = \frac{2\alpha\beta}{\langle \mathbf{v}_e \rangle} \left[ \frac{\langle \mathbf{v}_e \rangle^2}{\langle \mathbf{v}_e^2 \rangle} \right] = \frac{2\alpha\beta\Phi}{\langle \mathbf{v}_e \rangle}$$

$$\frac{1}{2} \mathbf{C} \langle \mathbf{v}_e \rangle = \alpha \beta \Phi \leq 1$$

$$\langle \mathbf{v}_e^2 \rangle = \frac{\int_{\rho_i}^{\rho_f} d(\rho \mathbf{v}_e^2)}{\int_{\rho_i}^{\rho_f} d\rho}$$

$$\langle \mathbf{v}_e \rangle = \frac{\int_{\rho_i}^{\rho_f} d(\rho \mathbf{v}_e)}{\int_{\rho_i}^{\rho_f} d\rho} = - \frac{\int_0^t \mathbf{F} dt}{\int_{m_i}^{m_f} dm} = \frac{\int_{m_i}^{m_f} d(m \mathbf{v}_e)}{\int_{m_i}^{m_f} dm}$$

$$\Phi = \frac{\langle \mathbf{v}_e \rangle^2}{\langle \mathbf{v}_e^2 \rangle}$$

For propellants with chemical energy

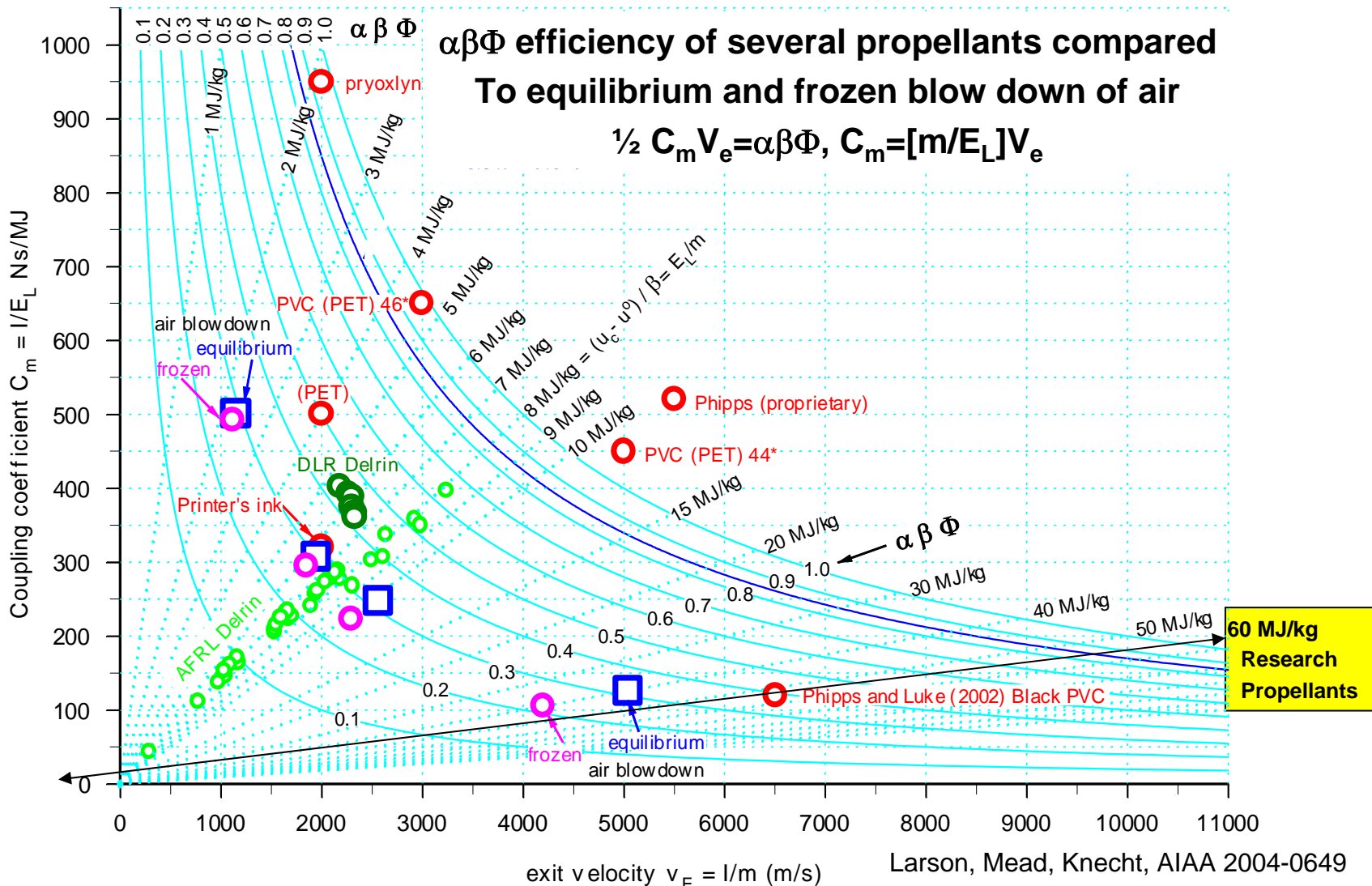
$$(\alpha \beta \Phi)_{\text{apparent}} = \alpha \Phi \left( \beta + \frac{m_p \Delta u_{\text{chem}}}{E_L} \right)$$

Larson, Mead, Kalliomaa,  
AIP Conference Proceedings,  
664 (2003) pp170-181





# Performance map of known laser materials and theoretical air

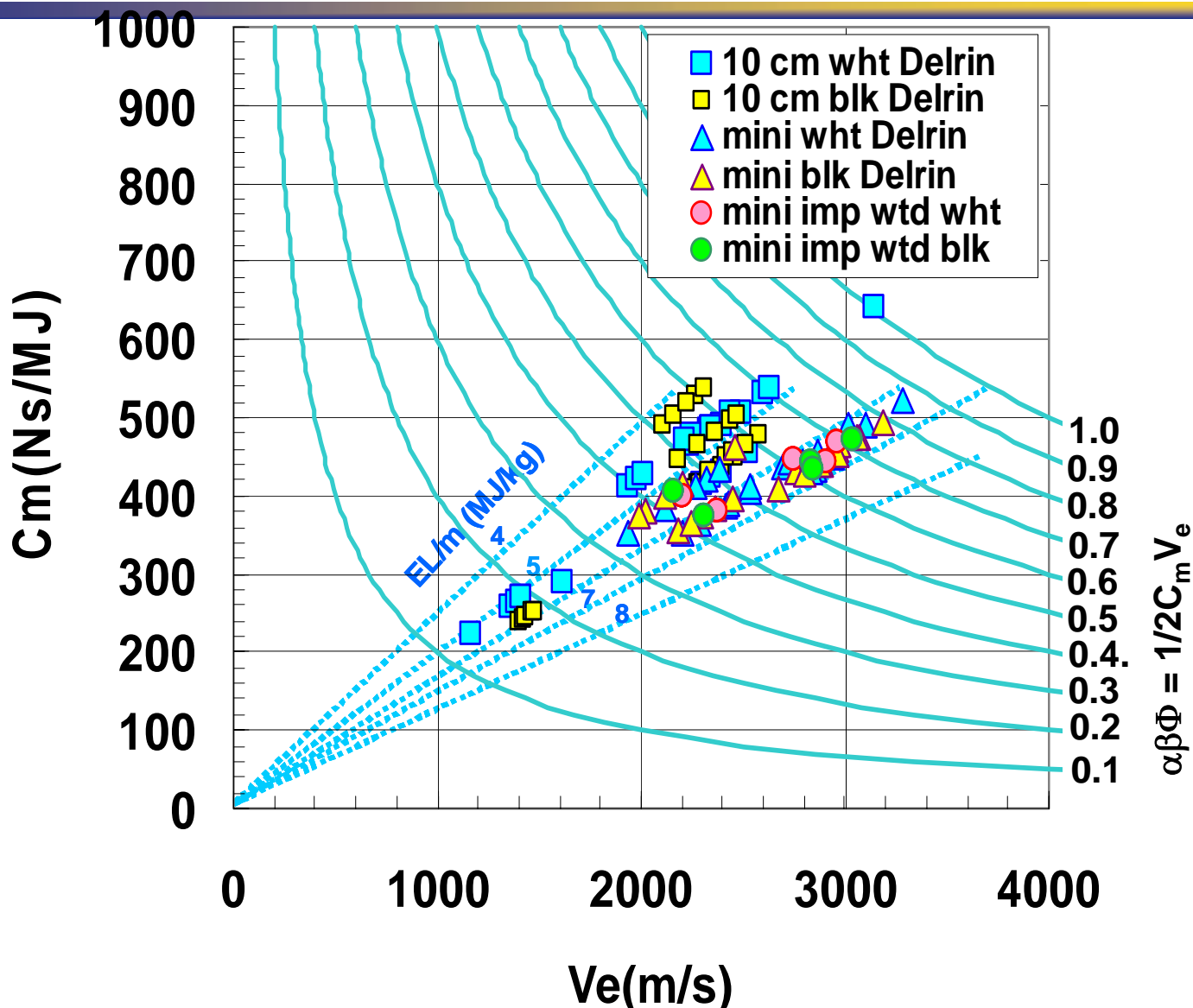


**60 MJ/kg  
Research  
Propellants**



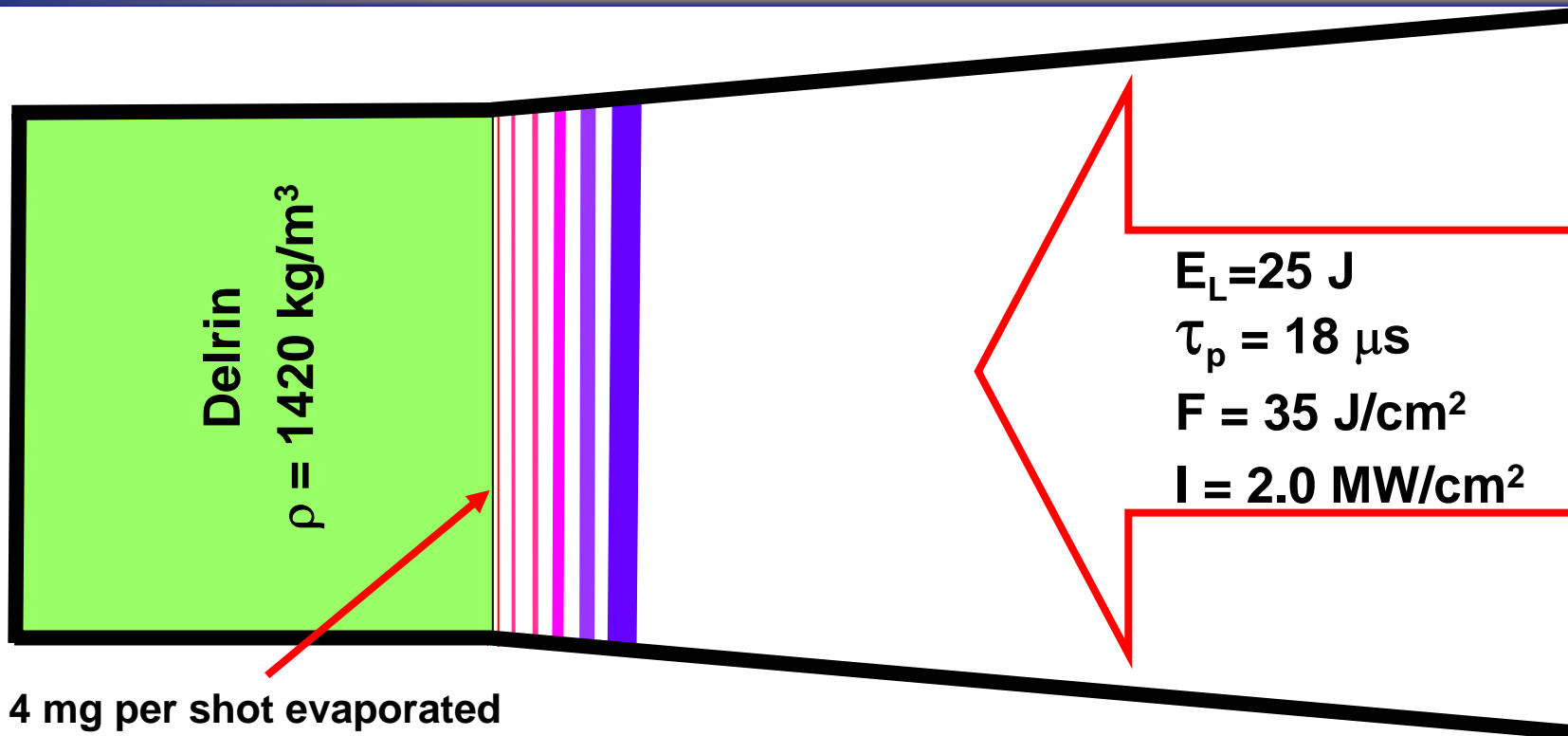
# Experimental Results December 2004

## 200-3/4 Light Craft and Mini Thruster





# Instantaneous Energy Addition to Delrin



4 mg per shot evaporated

20  $\mu\text{m}$  layer/18  $\mu\text{s}$

6 J/mg =  $Q^*/\beta$

Specify energy and density of heated layer

$Q^*_{\text{delrin}} < 6 \text{ MJ/kg}$ ,  $\rho < 1420 \text{ kg/m}^3$

Obtain  $P \sim 20,000 \text{ bar}$   $T \sim 3700 \text{ K}$  via CEA

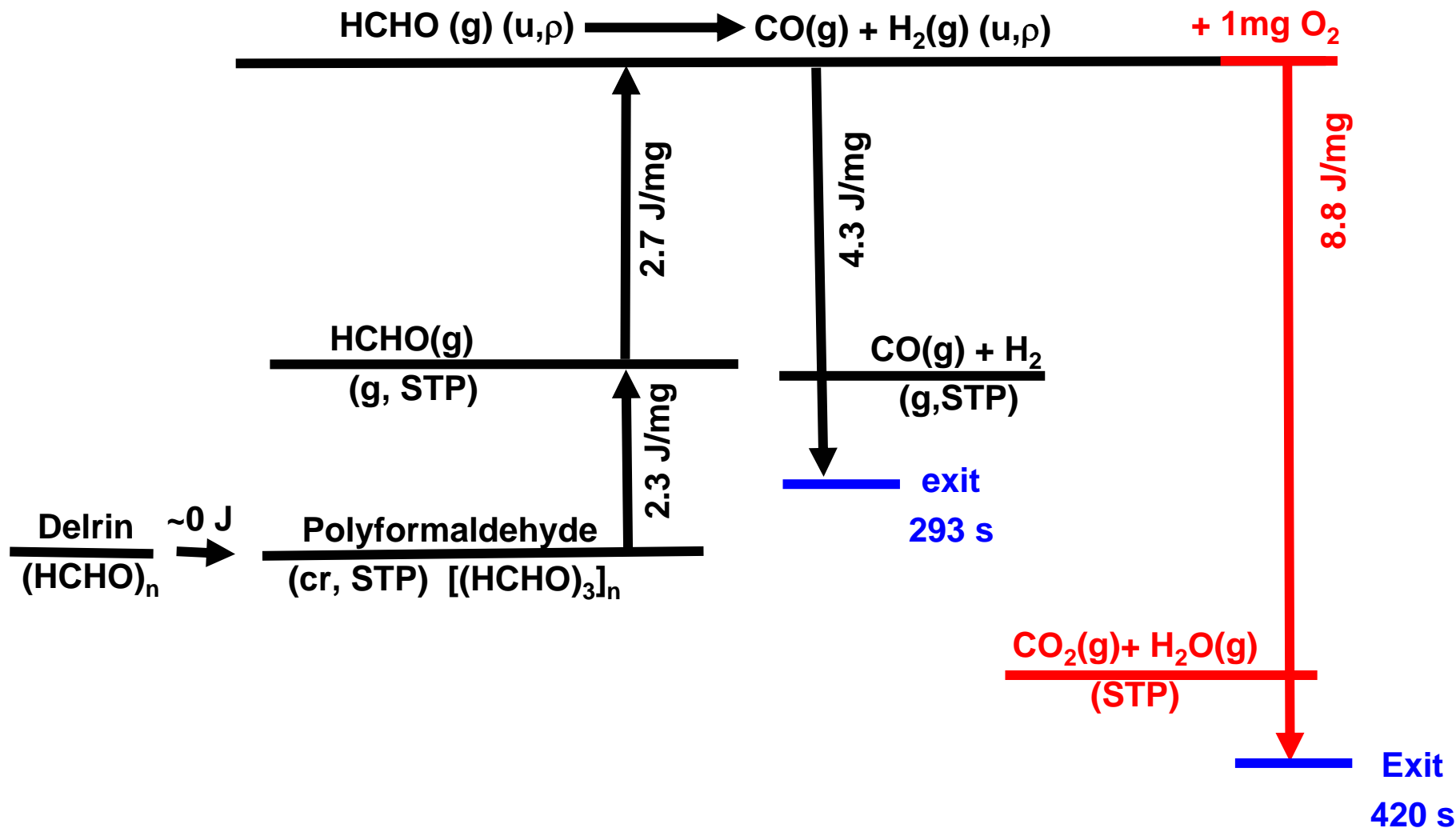
Specify expansion ratio

$\varepsilon = 4, 8, 16, 32, 64$

Obtain  $I_{\text{sp}}$ , thermo props in exit plane via CEA



# 6 J/mg Energy Addition to Delrin



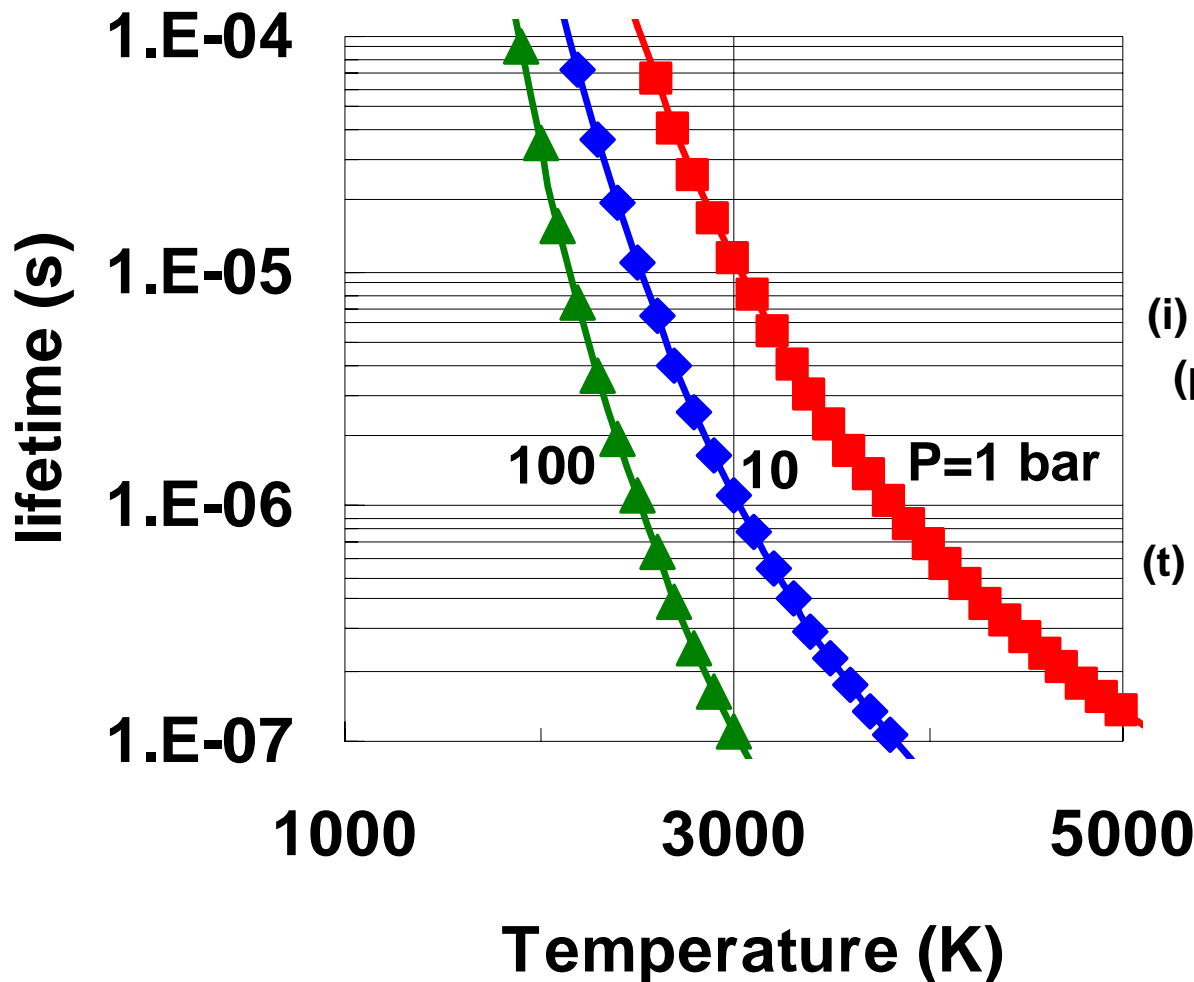
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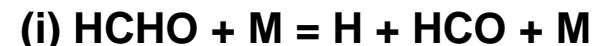
# Lifetime of Formaldehyde, $\tau(T,P)$



F. Gernot, D. F. Davidson, R. K. Hanson, *Int. J. Chem. Kinet.* **36** (2004) 157



Mechanism:





# Mole Fractions at Equilibrium

Formaldehyde expansion from P=22694 bar, T=3732K  
[rho=1227 kg/m<sup>3</sup>,u=1.975 MJ/kg]



Species	chamber	$\epsilon=8$	$\epsilon=64$	species	chamber	$\epsilon=8$	$\epsilon=64$
CO	0.47502	0.48415	0.35692	CH3OH	0.00015	0	0
H2	0.39082	0.39891	0.36466	CH3CHO,ethanal	0.00014	0	0
H2O	0.06058	0.04282	0.08215	C3H4,allene	0.00013	0	0
CH4	0.03818	0.05811	0.05318	C3H6,propylene	0.00013	0	0
CO2	0.00856	0.01574	0.05707	CH2	0.00012	0	0
C2H2	0.00742	0.00002	0	C2H2,vinylidene	0.00009	0	0
CH3	0.00472	0.00001	0	CH2OH	0.00007	0	0
H	0.00402	0	0	C3H5,allyl	0.00006	0	0
C2H4	0.00267	0.00014	0	C4H2	0.00006	0	0
HCO	0.00180	0	0	COOH	0.00005	0	0
HCHO	0.00180	0.00003	0	CHCO,ketyl	0.00004	0	0
CH2CO	0.00096	0	0	CH3O	0.00003	0	0
C3H3,2-pryl	0.00039	0	0	C2H	0.00003	0	0
C2H3,vinyl	0.00035	0	0	C3O2	0.00003	0	0
OH	0.00032	0	0	C4H6,butadiene	0.00003	0	0
C2H6	0.00027	0.00005	0.00001	C2O	0.00002	0	0
HCOOH	0.00026	0	0	C2H5OH	0.00001	0	0
C3H4	0.00025	0	0	C3H4,cyclo-	0.00001	0	0
CH3CO	0.00019	0	0	C3H8	0.00001	0	0
C2H5	0.00019	0	0	C4H6,1butyne	0.00001	0	0
				C(gr)	0	0	0.08601



# Mole Fractions at Equilibrium

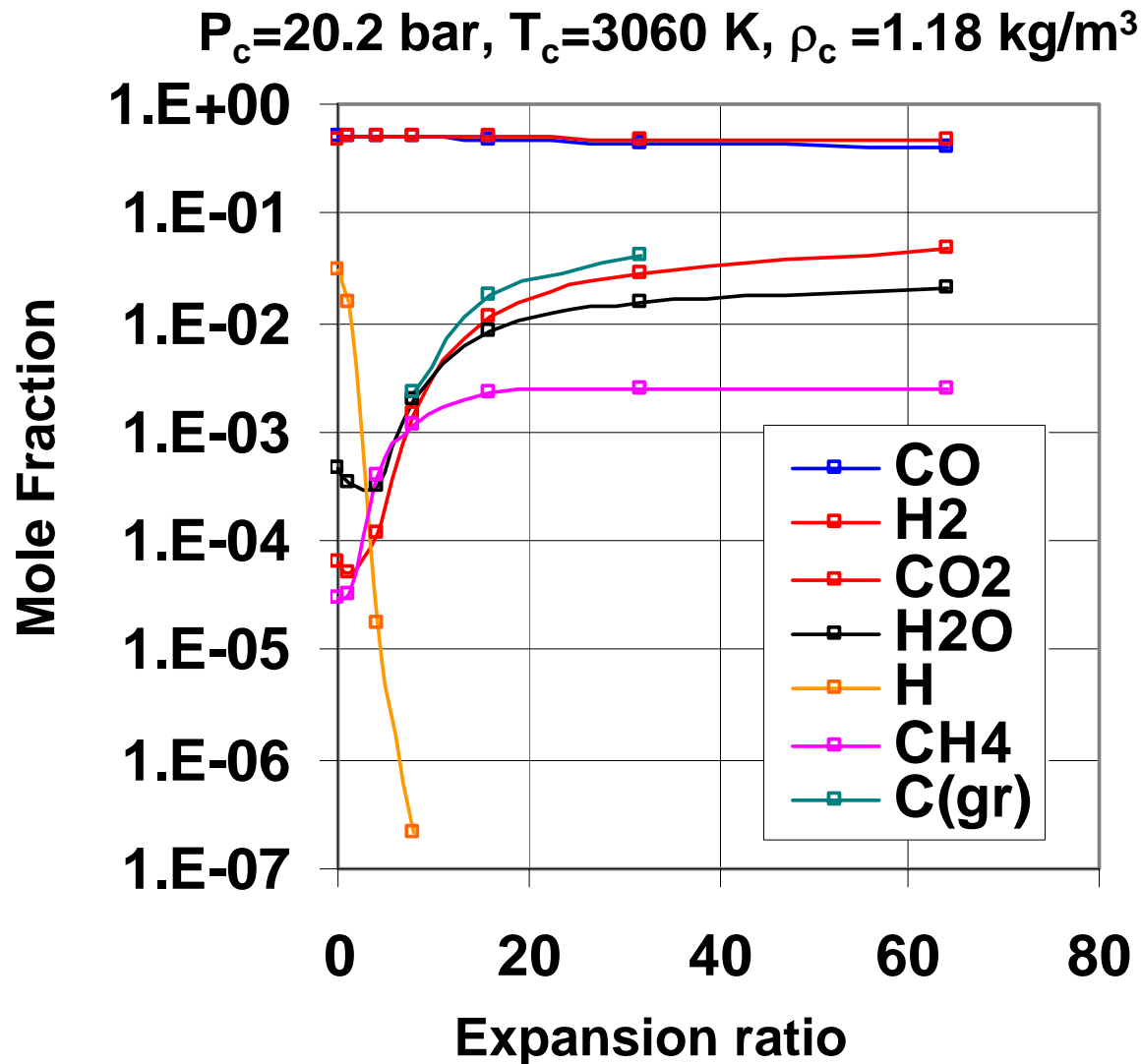
Formaldehyde expansion from  $P=230$  bar,  $T=3433$  K,  
 $[\rho=12.02 \text{ kg/m}^3, u=1.907 \text{ MJ/kg}]$



mole fractions	Chambr	throat	$\varepsilon=4$	$e=8$	$e=16$	$e=32$	$e=64$
CO	0.49263	0.49587	0.49955	0.49553	0.47166	0.43233	0.38881
H2	0.47969	0.48865	0.49681	0.4913	0.48006	0.46937	0.46168
H	0.02313	0.01223	0.00003	0	0	0	0
H2O	0.00239	0.00173	0.0014	0.00435	0.01321	0.0231	0.03105
C2H2,acetylene	0.00105	0.00074	0.00002	0	0	0	0
CH4	0.00032	0.00033	0.00176	0.00435	0.00673	0.00753	0.00728
CO2	0.0003	0.00023	0.00041	0.00224	0.01093	0.02605	0.04371
CH3	0.00021	0.00012	0	0	0	0	0
HCO	0.00014	0.00005	0	0	0	0	0
*OH	0.00005	0.00002	0	0	0	0	0
CH2	0.00002	0.00001	0	0	0	0	0
HCHO,formaldehy	0.00002	0.00001	0	0	0	0	0
C2H	0.00001	0	0	0	0	0	0
C2H2,vinylidene	0.00001	0	0	0	0	0	0
C2H4	0.00001	0.00001	0	0	0	0	0
C(gr)	0	0	0	0.00223	0.01741	0.04162	0.06748



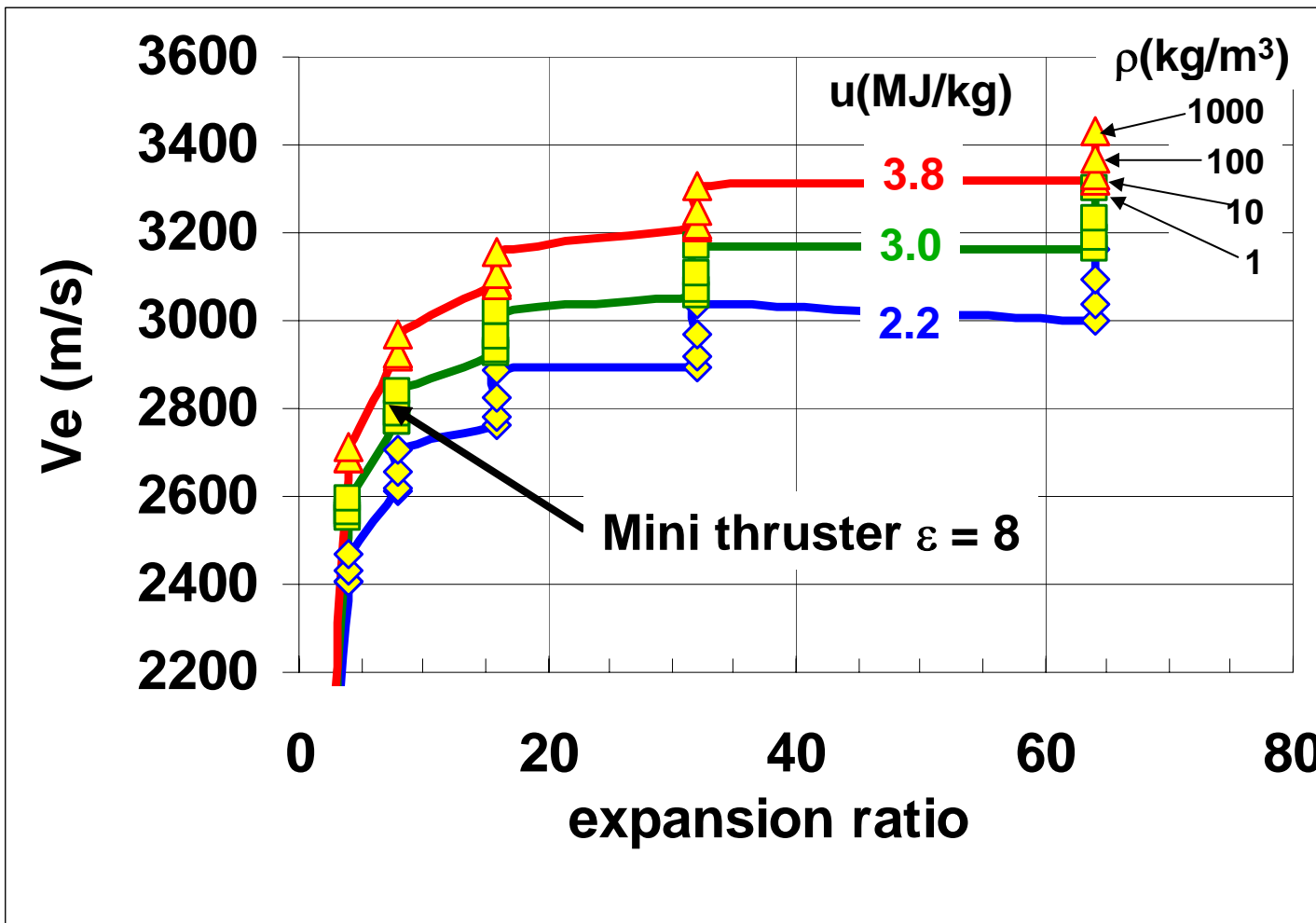
# Blowdown from specified initial state ( $u, \rho$ ) with specified expansion ratio ( $\varepsilon$ )







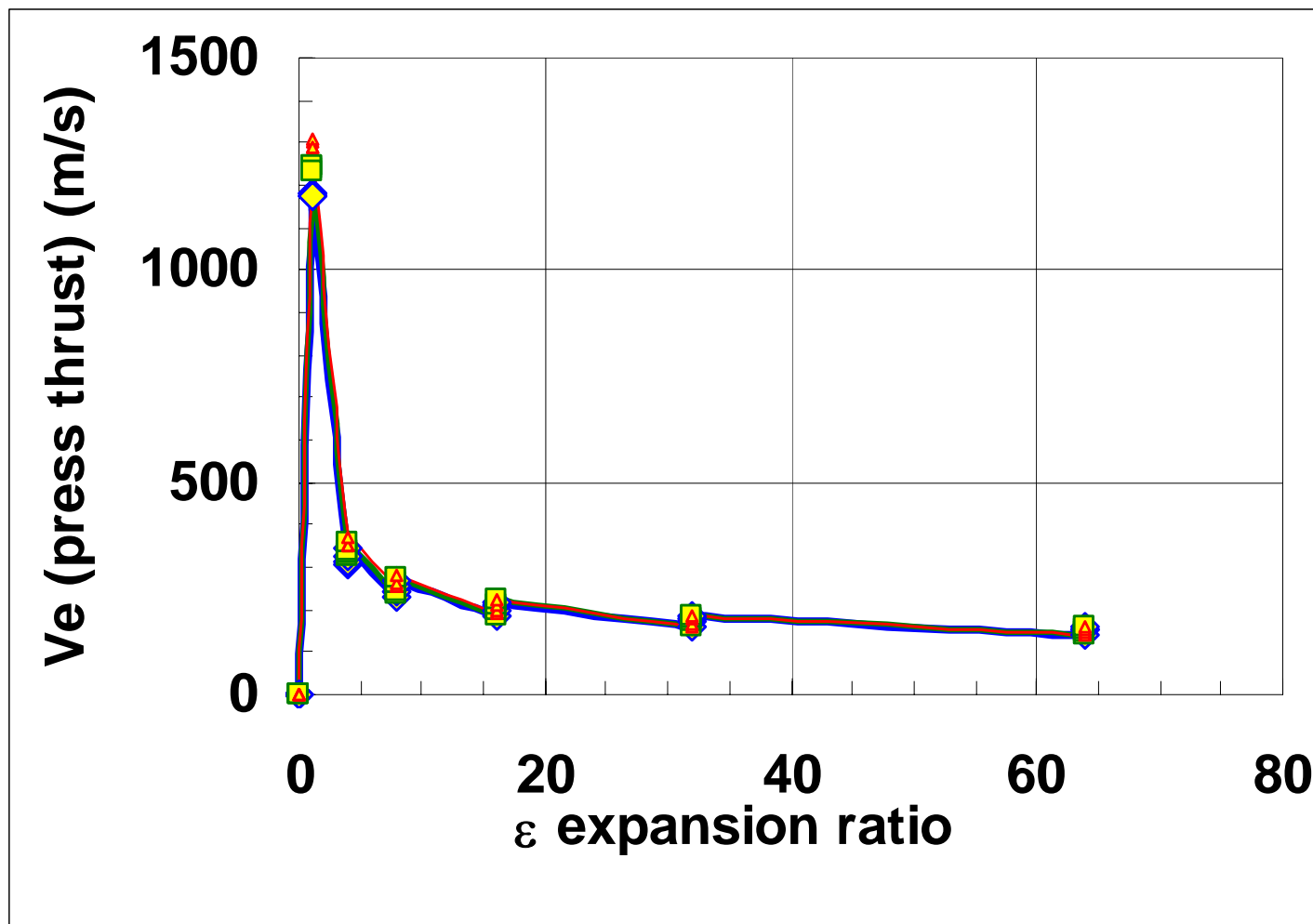
# Blowdown from specified initial state $(u, \rho)$ with specified expansion ratio $(\varepsilon)$



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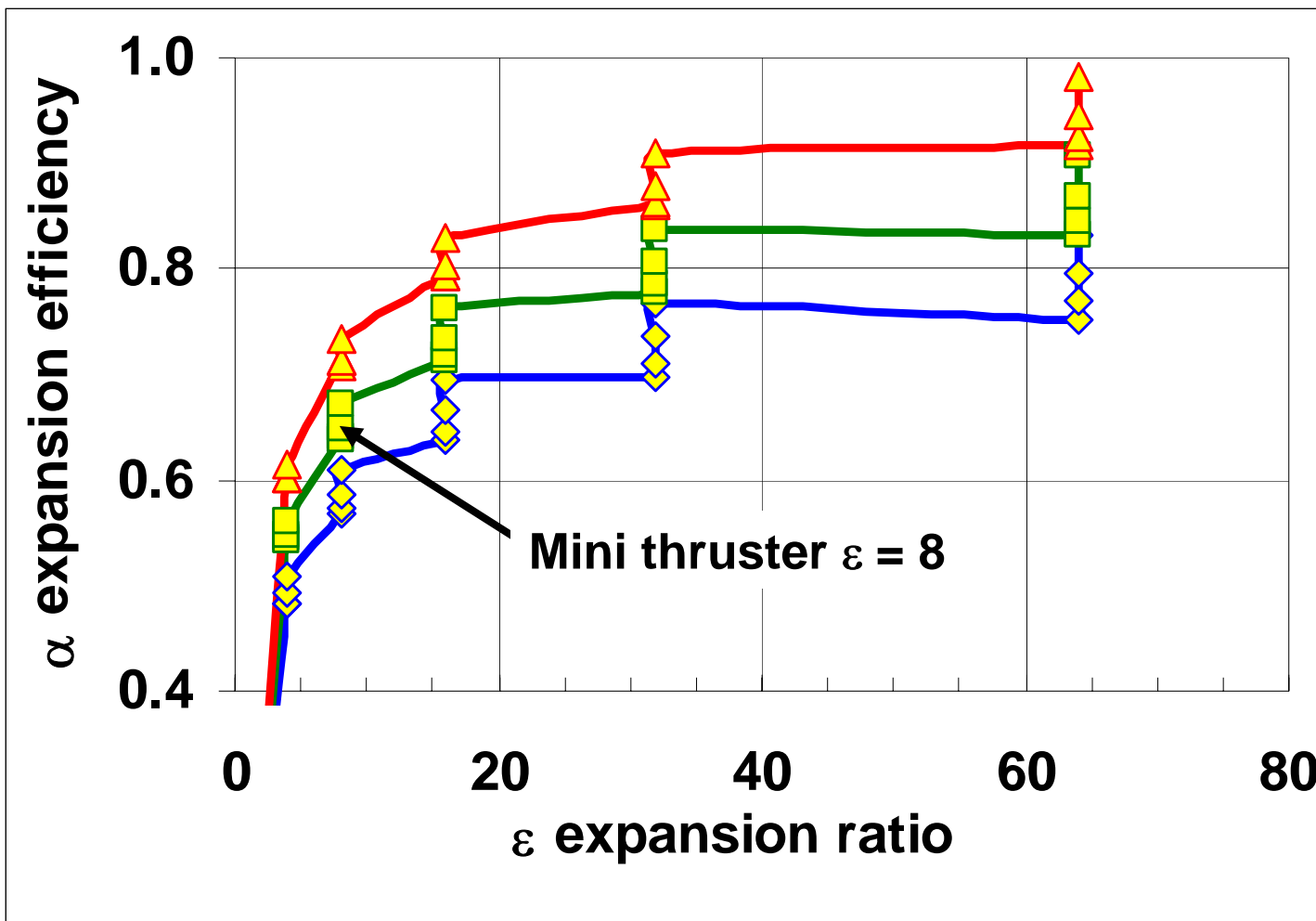


# Blowdown from specified initial state $(u, \rho)$ with specified expansion ratio $(\varepsilon)$



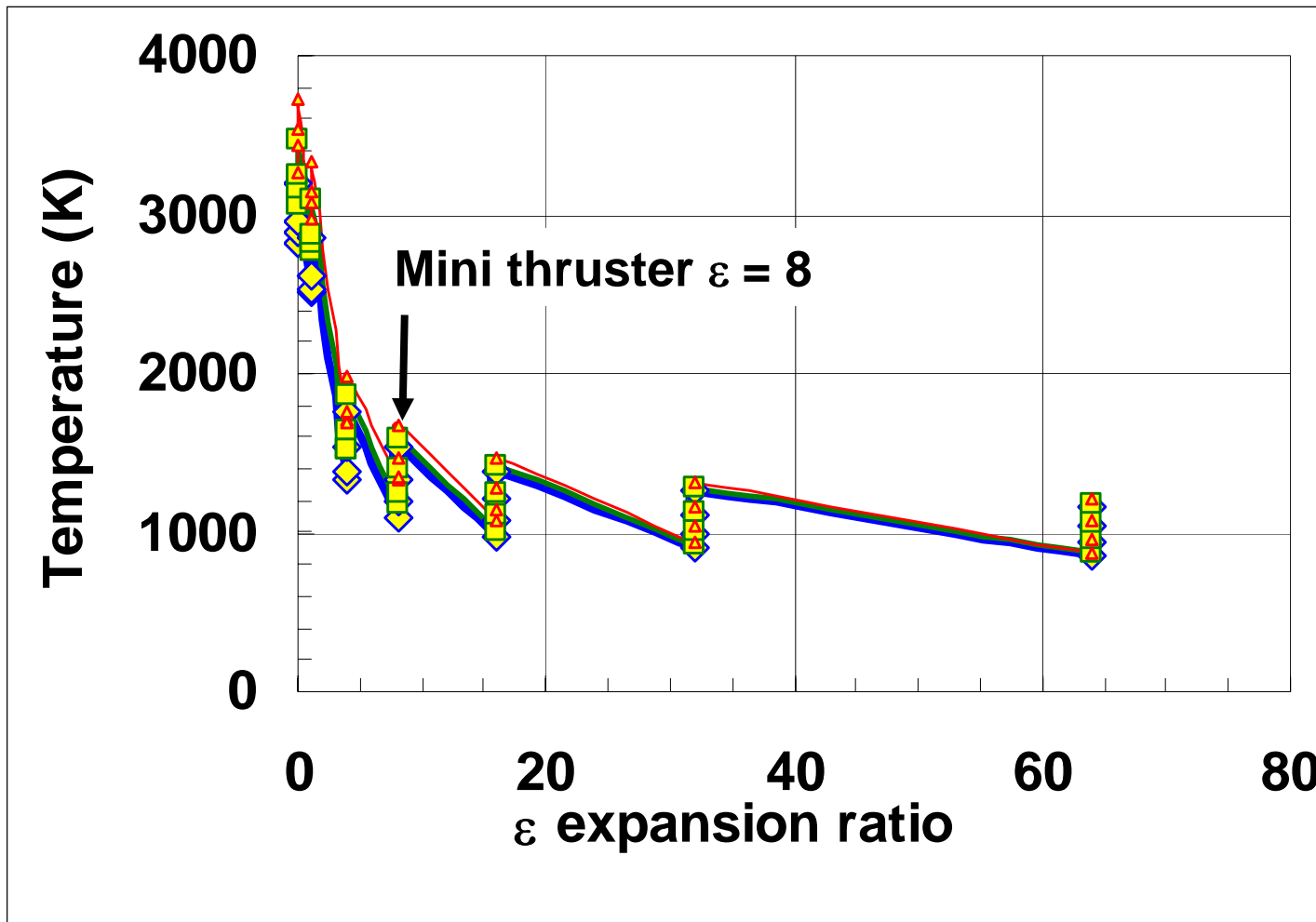


# Blowdown from specified initial state ( $u, \rho$ ) with specified expansion ratio ( $\varepsilon$ )



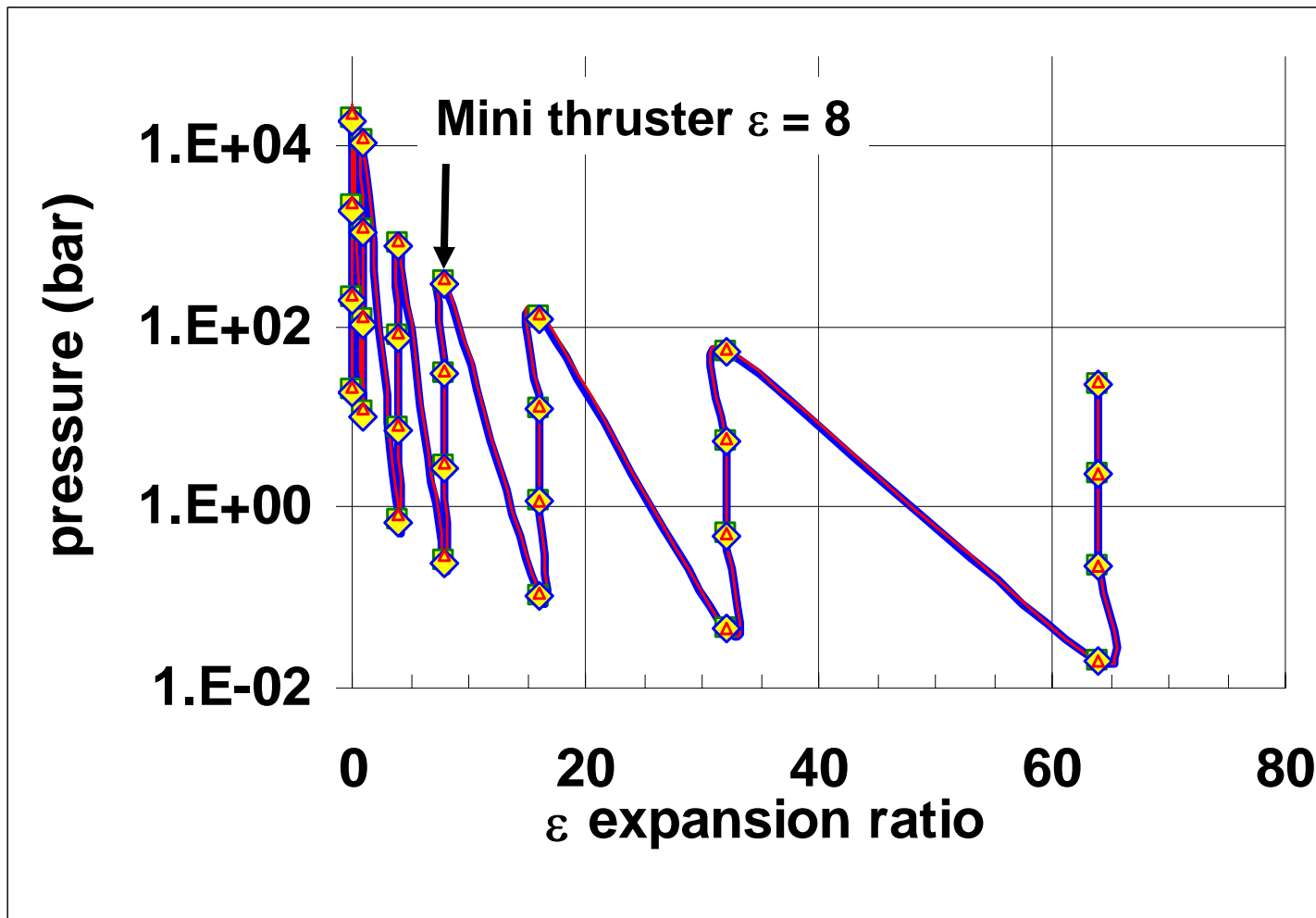


# Blowdown from specified initial state ( $u, \rho$ ) with specified expansion ratio ( $\varepsilon$ )



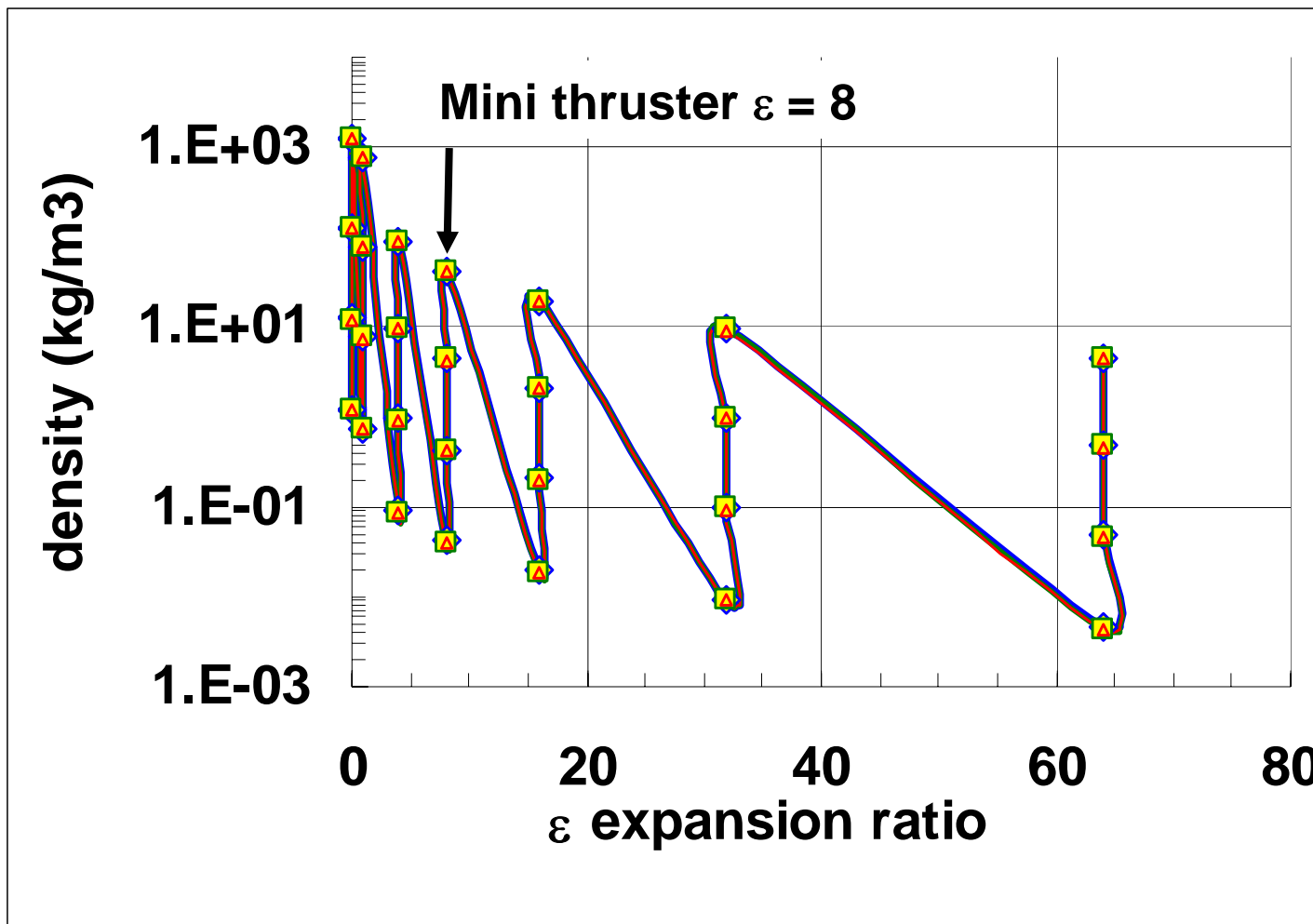


# Blowdown from specified initial state $(u, \rho)$ with specified expansion ratio $(\varepsilon)$





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





# Experimental data (I, EL, m) and derived parameters (C<sub>m</sub>, V<sub>e</sub>, efficiency, EL/m)



Geometry	I vs E <sub>L</sub> slope		m vs E <sub>L</sub> slope		C <sub>m</sub>	V <sub>e</sub>	Efficiency	E <sub>L</sub> /m
	mNs/J	R <sup>2</sup>	mg/J	R <sup>2</sup>	Ns/MJ	m/s		MJ/kg
Mini thruster white	<b>0.444</b>	0.97	<b>0.160</b>	0.99	444	2775	0.616	6.3
Mini thruster black	<b>0.439</b>	0.98	<b>0.156</b>	0.98	439	2814	0.618	6.4
Mini thruster AIR	<b>0.253</b>	0.97	-	-	253	-	-	-
10-cm Model white	<b>0.447</b>	0.85	<b>0.201</b>	0.96	447	2224	0.497	5.0
10-cm Model black	<b>0.453</b>	0.92	<b>0.194</b>	0.93	453	2335	0.529	5.2



# Conclusions/Work in Progress



- $C_m=450$  N/MW for Light Craft/Delrin (350 J, 18  $\mu$ s)
- $C_m=442$  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,  $\varepsilon = 4, 16, \dots$
  - Increase  $E_L$  up to  $\sim 100$  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



**THE END**



Distribution A – Approved for public release, Distribution Unlimited



# $\Phi$ for Bimodal velocity distribution



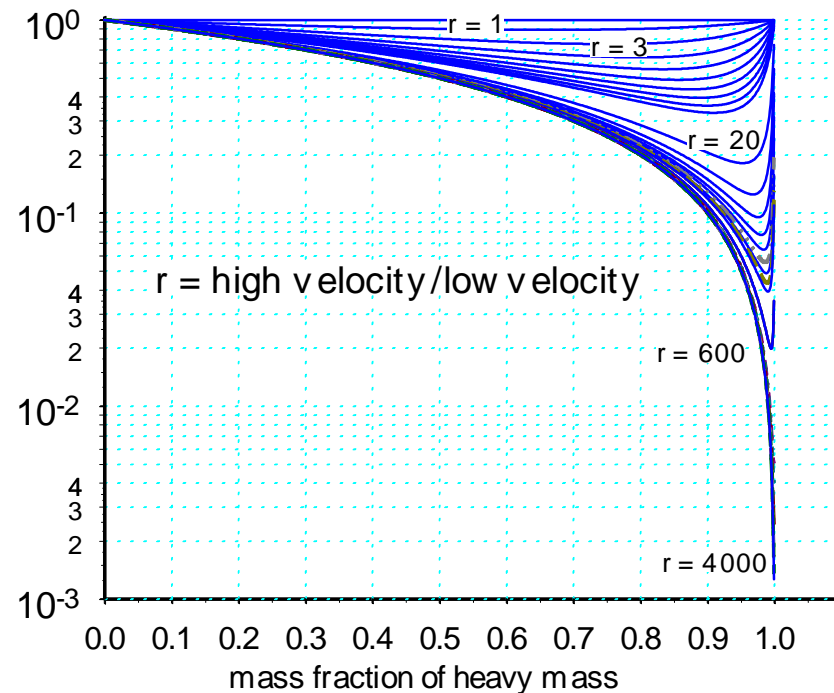
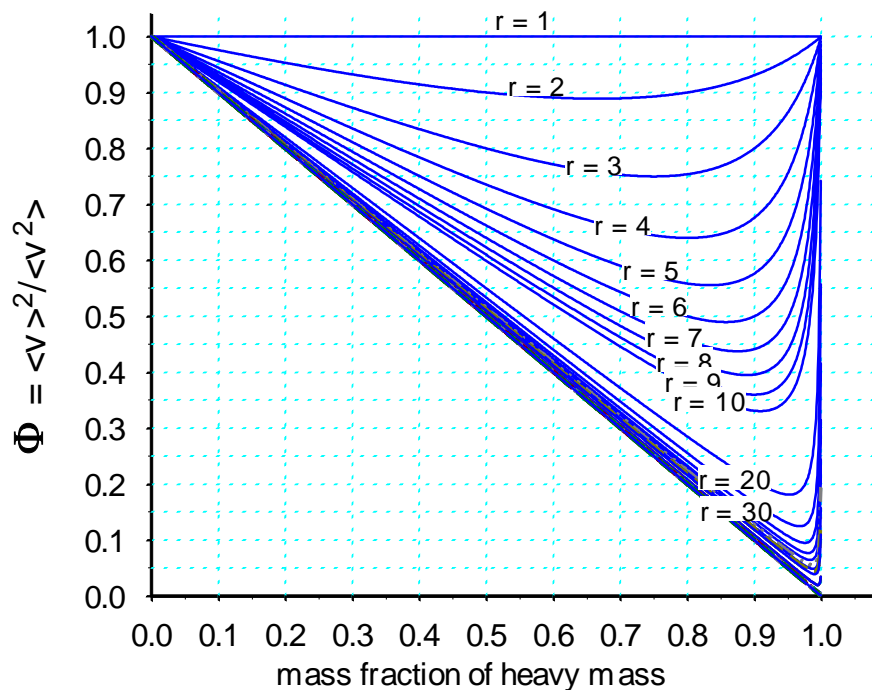
Chunks of propellant  
Hot gases

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

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

$$\langle v^2 \rangle = f_{\text{heavy}} v_{\text{slow}}^2 + f_{\text{light}} v_{\text{fast}}^2$$

$$\Phi = \langle v \rangle^2 / \langle v^2 \rangle = (f_{\text{heavy}} + f_{\text{light}} r)^2 / (f_{\text{heavy}} + f_{\text{light}} r^2) \text{ where } r = v_{\text{fast}} / v_{\text{slow}} > 1$$





# Divergence Loss

