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1. REPORT DATE (DD-MM-YYYY) 18-05-2005		2. REPORT TYPE Briefing Charts		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Comparison of Ablation Performance in Laser Lightcraft and Standardized Mini-Thruster (Briefing Charts, POSTPRINT)				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Sean D. Knecht, C. William Larson and Franklin B. Mead, Jr. (AFRL/PRSP)				5d. PROJECT NUMBER 4847	
				5e. TASK NUMBER 0159	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRSP 10 E. Saturn Blvd. Edwards AFB CA 93524-7680				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-PR-ED-VG-2005-393	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-70448				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-PR-ED-VG-2005-393	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the 4 th International Symposium on Beamed Energy Propulsion, Nara, Japan, 11-14 Nov 2005.					
14. 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)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.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT A	18. NUMBER OF PAGES 43	19a. NAME OF RESPONSIBLE PERSON Dr. Franklin B. Mead, Jr.
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified			(661) 275-5929

Comparison of Ablation Performance in Laser Lightcraft and Standardized Mini-Thruster

The 4th International Symposium on Beamed Energy Propulsion
15-18 November 2005
Nara, Japan



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Air Force Research



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) 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 $\sim 60\%$ conversion efficiency. The extensively studied 10-cm diameter Lightcraft (with inverted paraboloid, plug nozzle geometry) produced $\sim 50\%$ 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 $\sim 13\%$ and $\sim 23\%$. 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

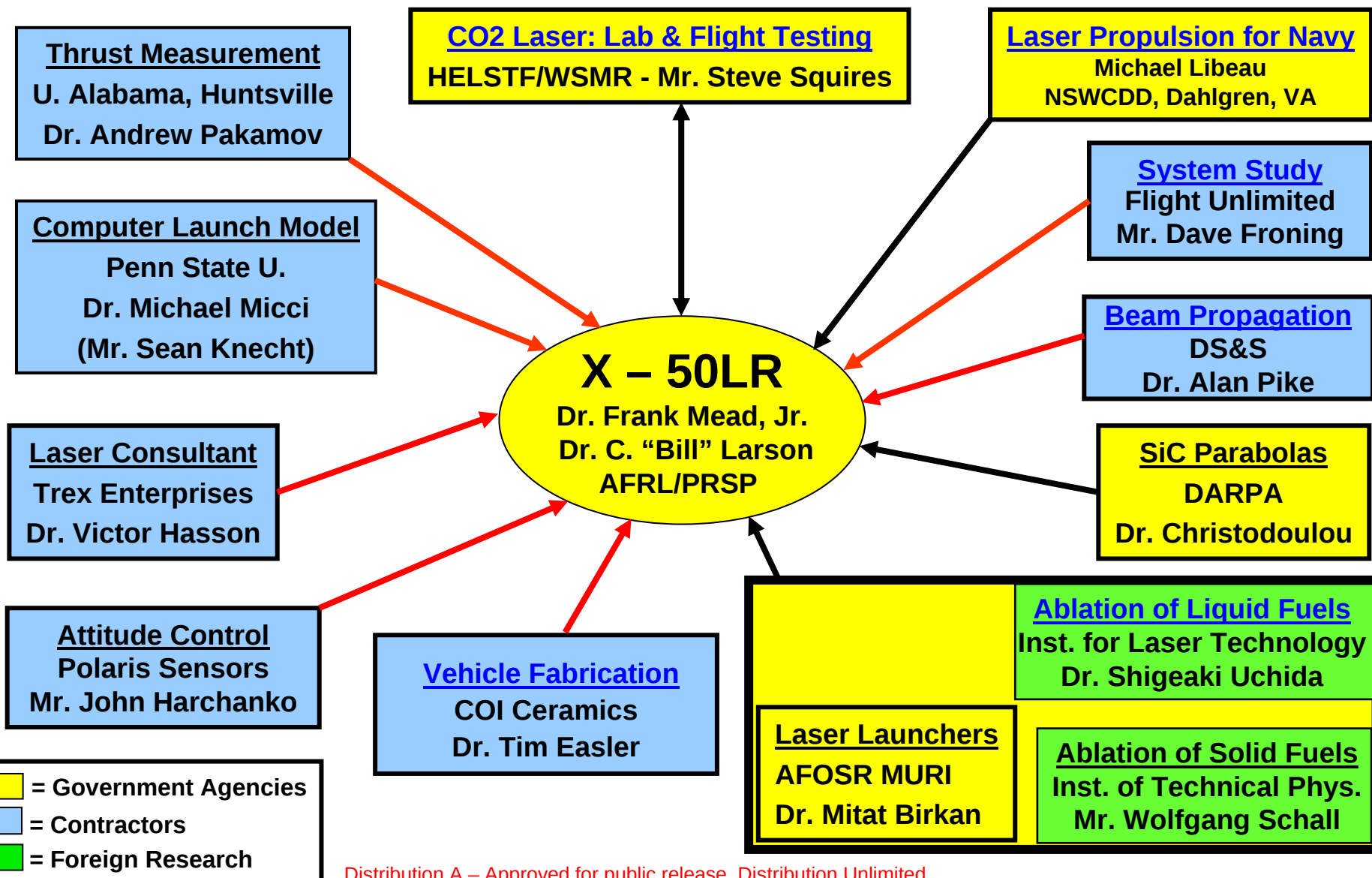


- **Collaboration Network/Why Laser Propulsion?**
- **Flavor of PLVTS**
- **The Laser and EL measurement (Joules)**
- **The Pendulum and I measurement (Newton seconds)**
- **The Mettler Balance and m measurement (milligrams)**
- **Compare the EL, I, m measurements on 2 Test Articles**
 - Light Craft,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



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

η = propulsion efficiency (jet kinetic energy to vehicle kinetic energy)

α = expansion efficiency (internal propellant energy to jet kinetic energy)

β = absorption efficiency (laser energy at vehicle to internal propellant energy)

γ = transmission efficiency (laser energy at ground to laser energy at vehicle)

δ = laser efficiency (electric energy to laser energy at ground)

***** Issue: separability of $\eta \alpha \beta \gamma \delta$ and 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

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

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

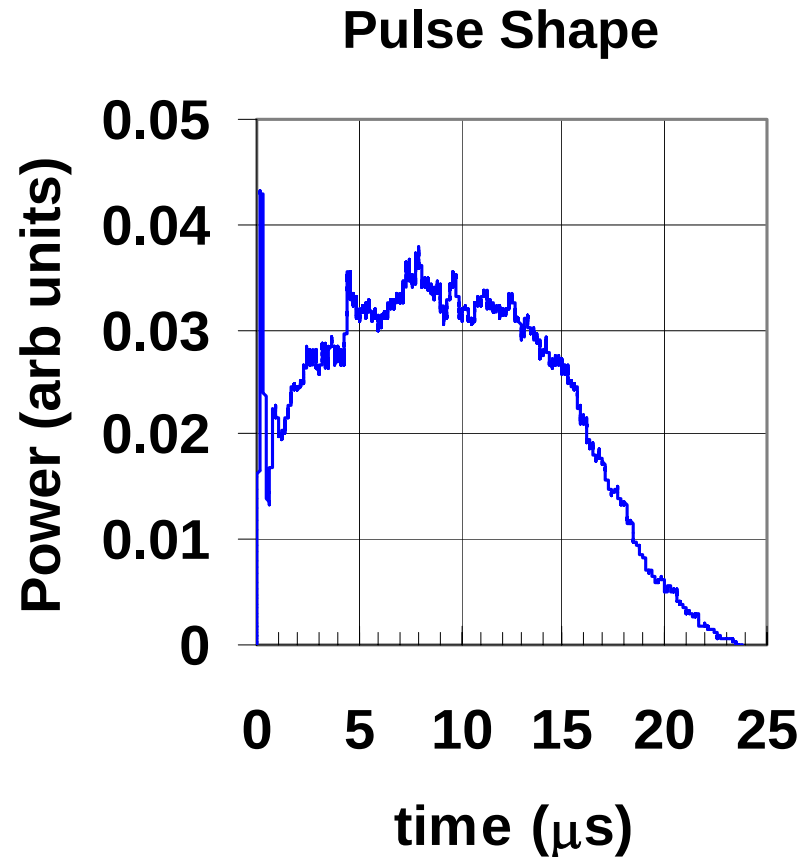
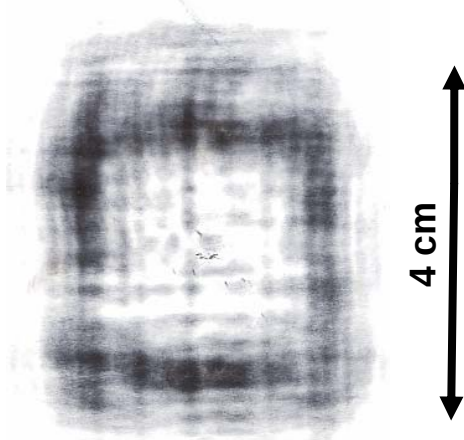
Pulsed Laser Vulnerability Test System





Laser Specifications

- Pulsed CO₂ Laser
- 10 KW
- ~ 5 to 30 μ s pulse width
- Up to 30 Hz
- Up to 1000 J/pulse ($E_L \pm 10\%$)
- Near Field Burn Pattern
~ 10 feet





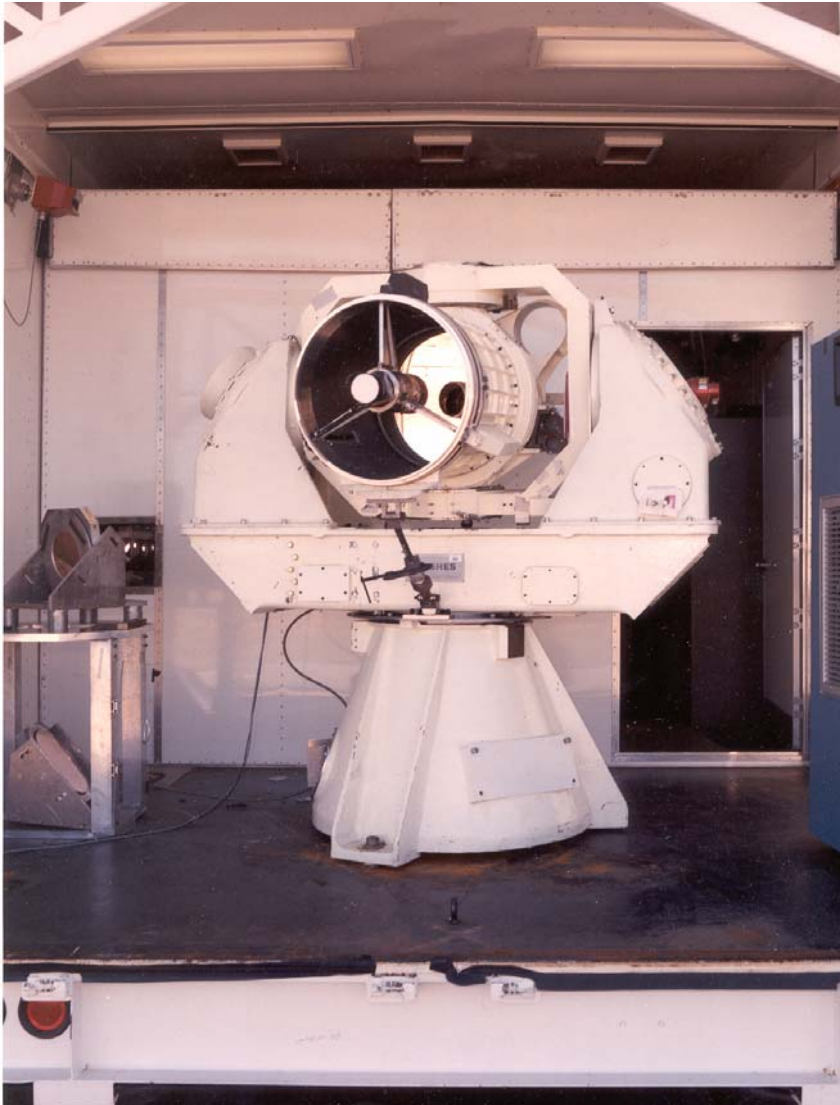
10 kW LASER IRRADIATION



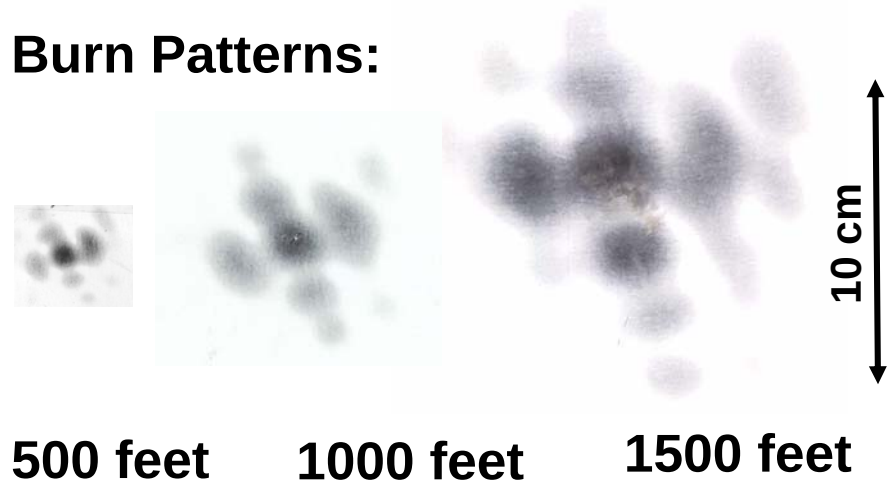
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FFT and Far Field Burn Patterns

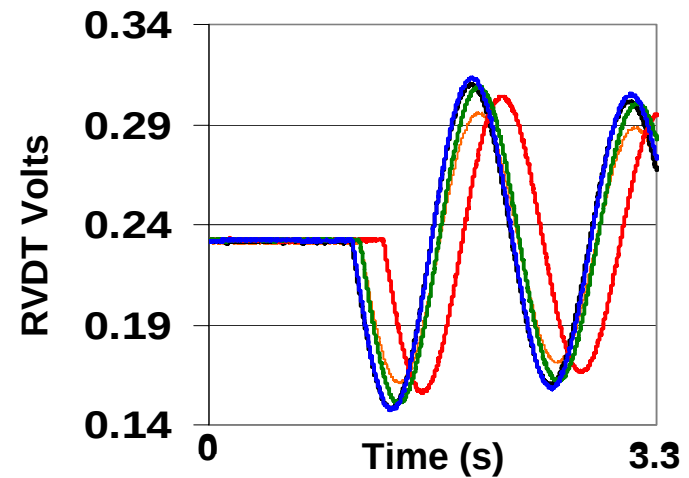
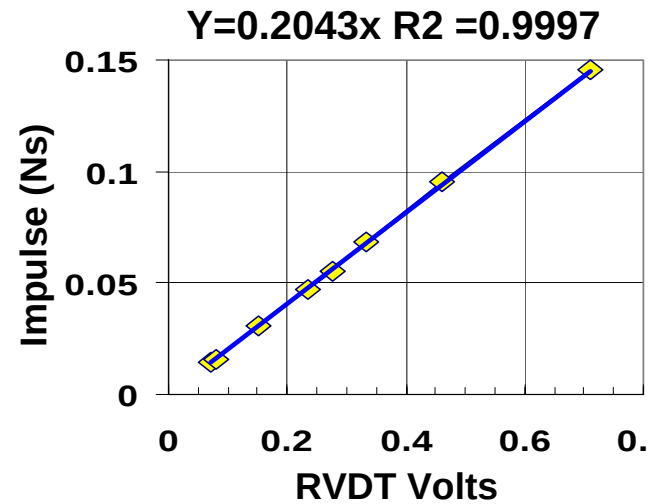
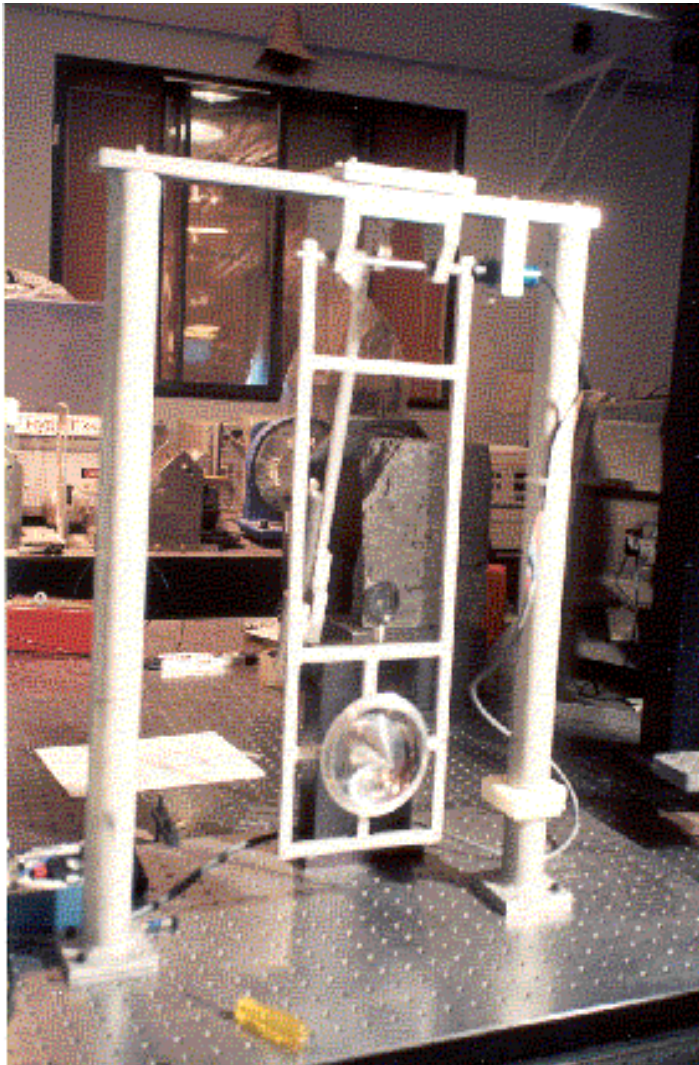


Burn Patterns:



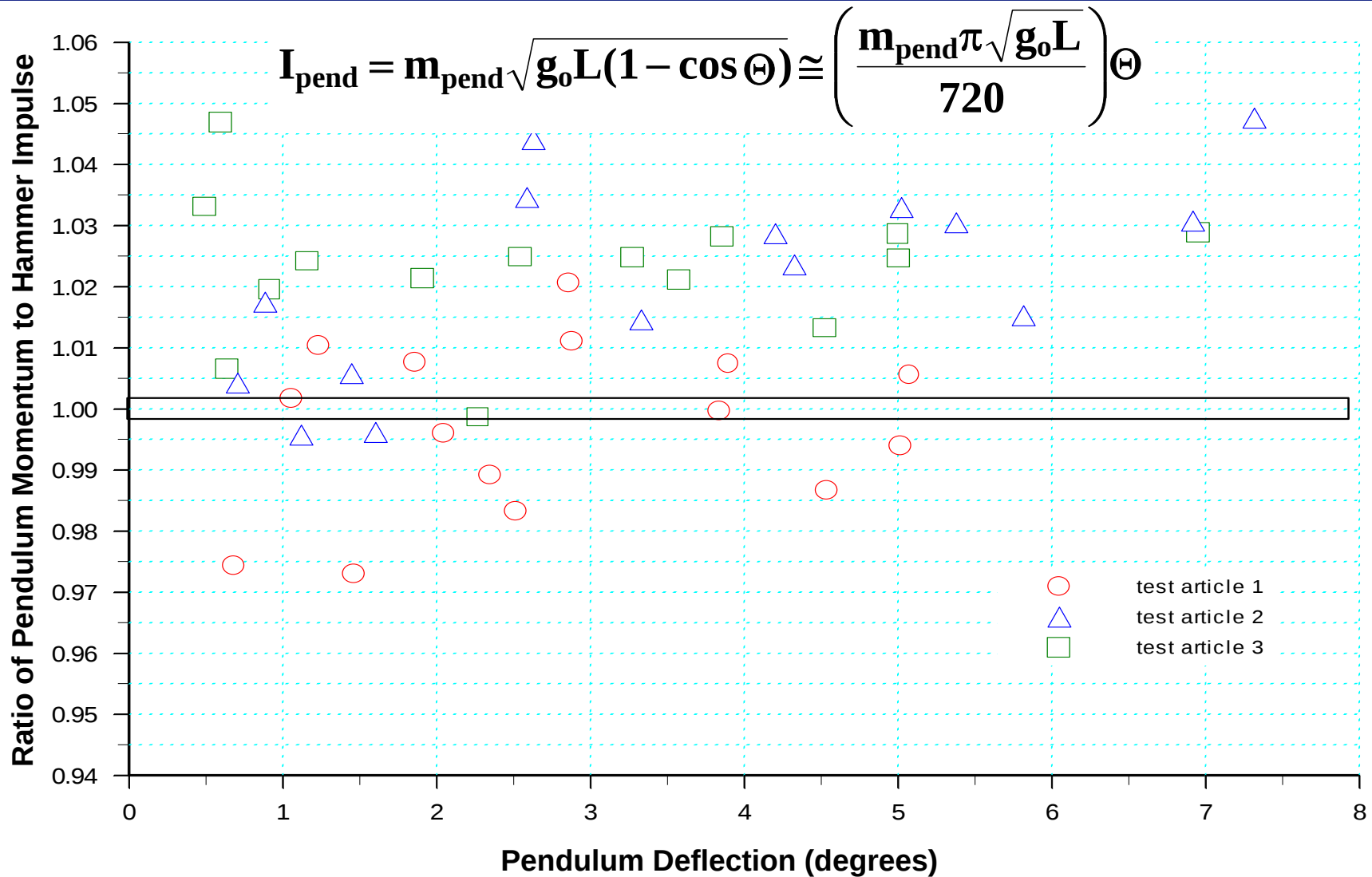


Pendulum Test Stand





Comparison of Pendulum Impulse to Hammer Impulse

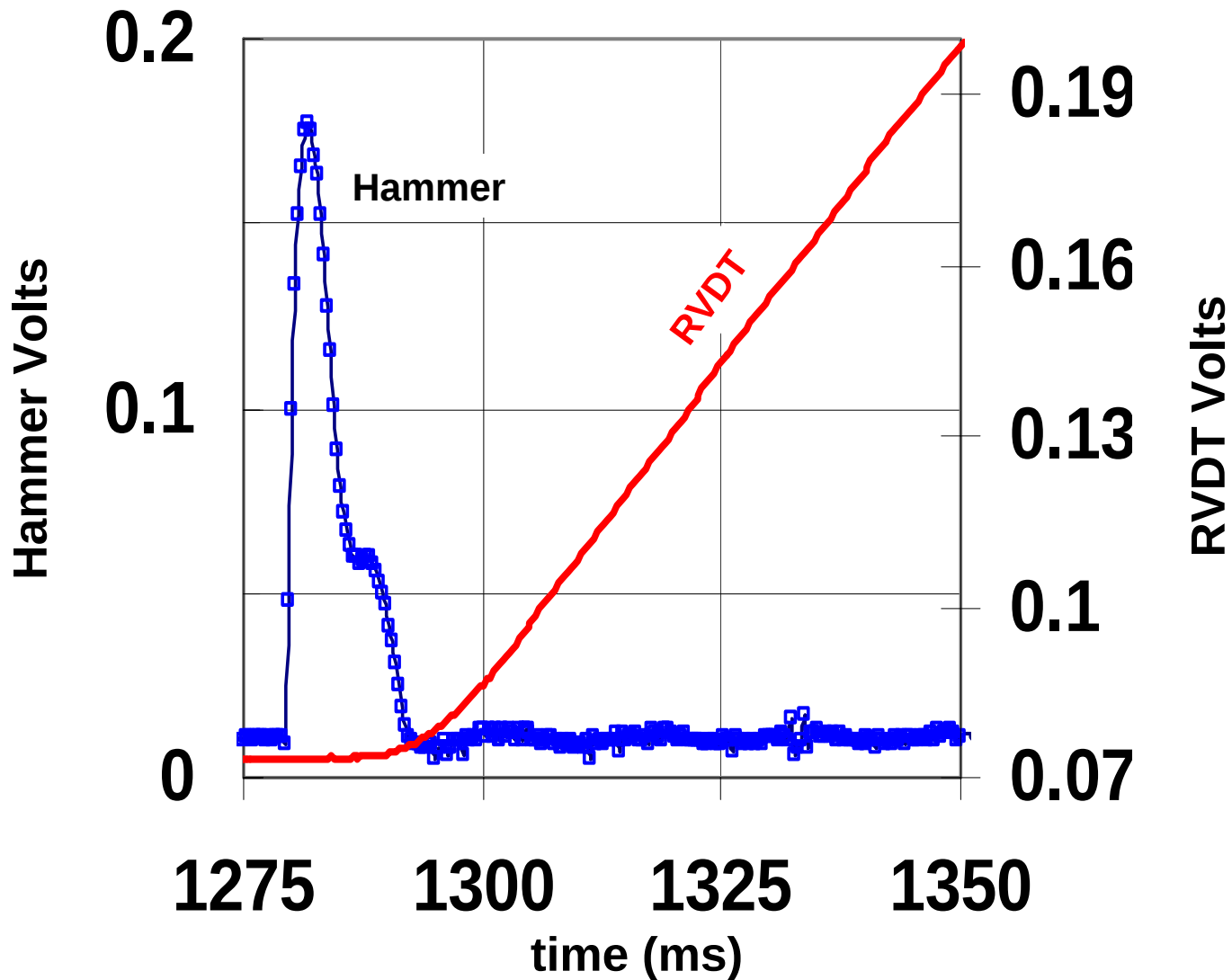


Larson, Mead AIAA 2001-0646

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NIST Traceable Impulse Calibration





Mettler Balance or Digital Balance



Measure m to ± 0.3 mg





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



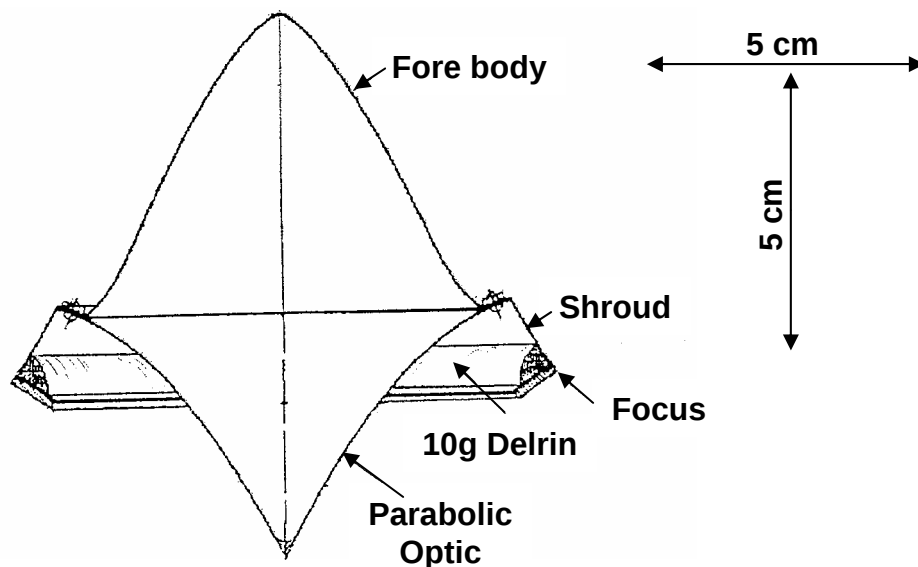
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Lightcraft and Mini-Nozzle Standard



200-3/4 Lightcraft



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

$m=40\text{g}$

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

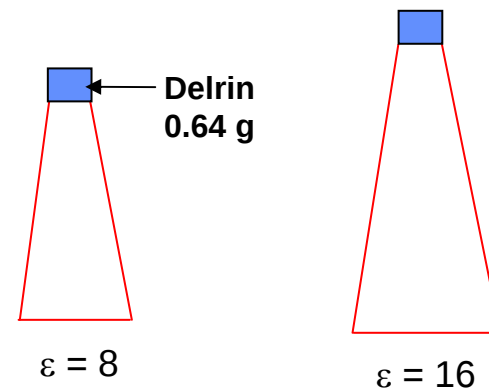
$350 \text{ J}/25 \text{ cm}^2/18 \mu\text{s} = 0.8 \text{ MW}/\text{cm}^2$

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

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

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

Mini-nozzle 26° divergence angle



$\epsilon=8$

$m=7.8 \text{ g}$

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

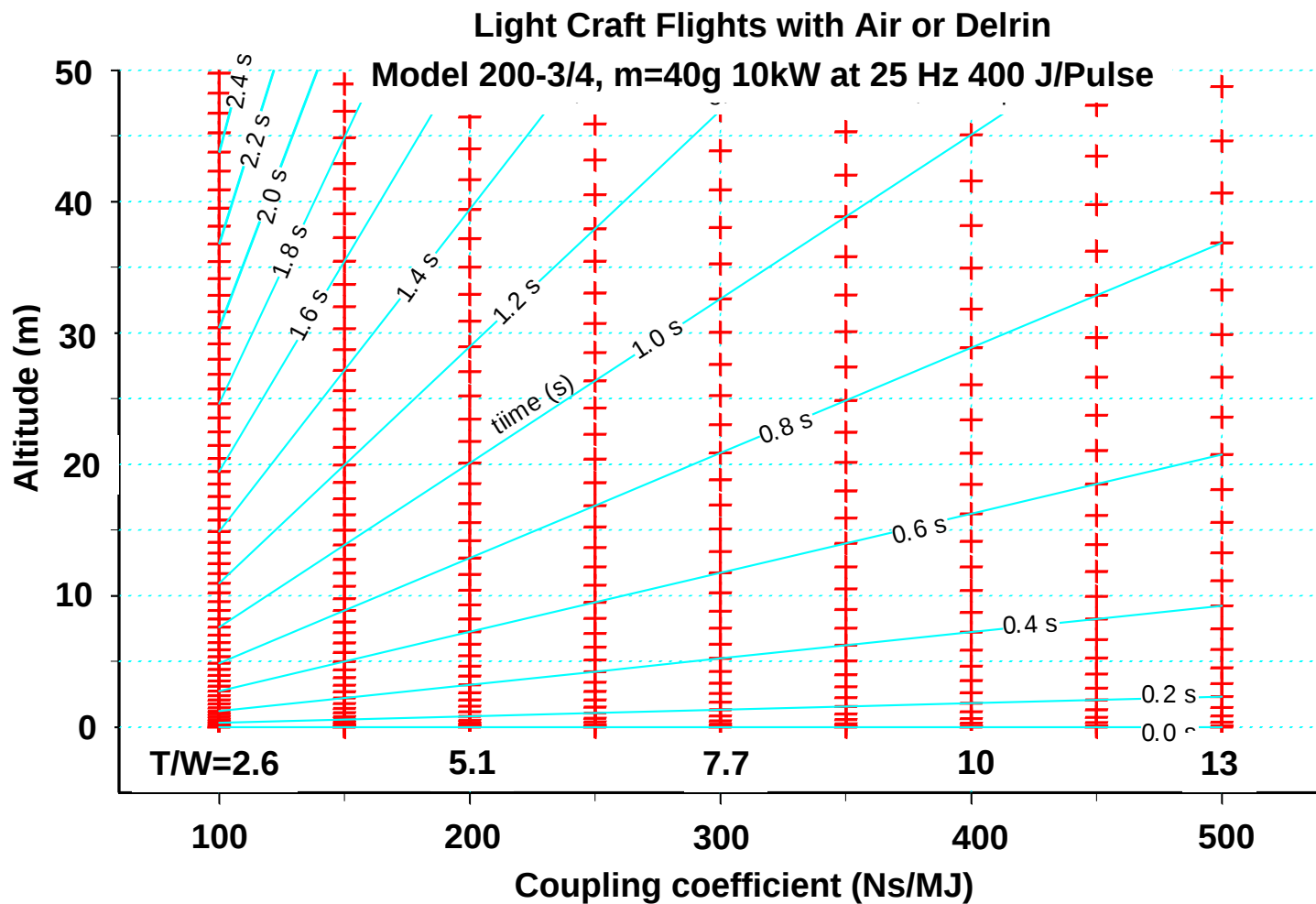
$25 \text{ J}/0.71 \text{ cm}^2/18 \mu\text{s} = 2.0 \text{ MW}/\text{cm}^2$

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

$V_e=2795$, efficiency=0.62



Laser Light Craft Flights



Larson, Mead AIAA 2001-0646



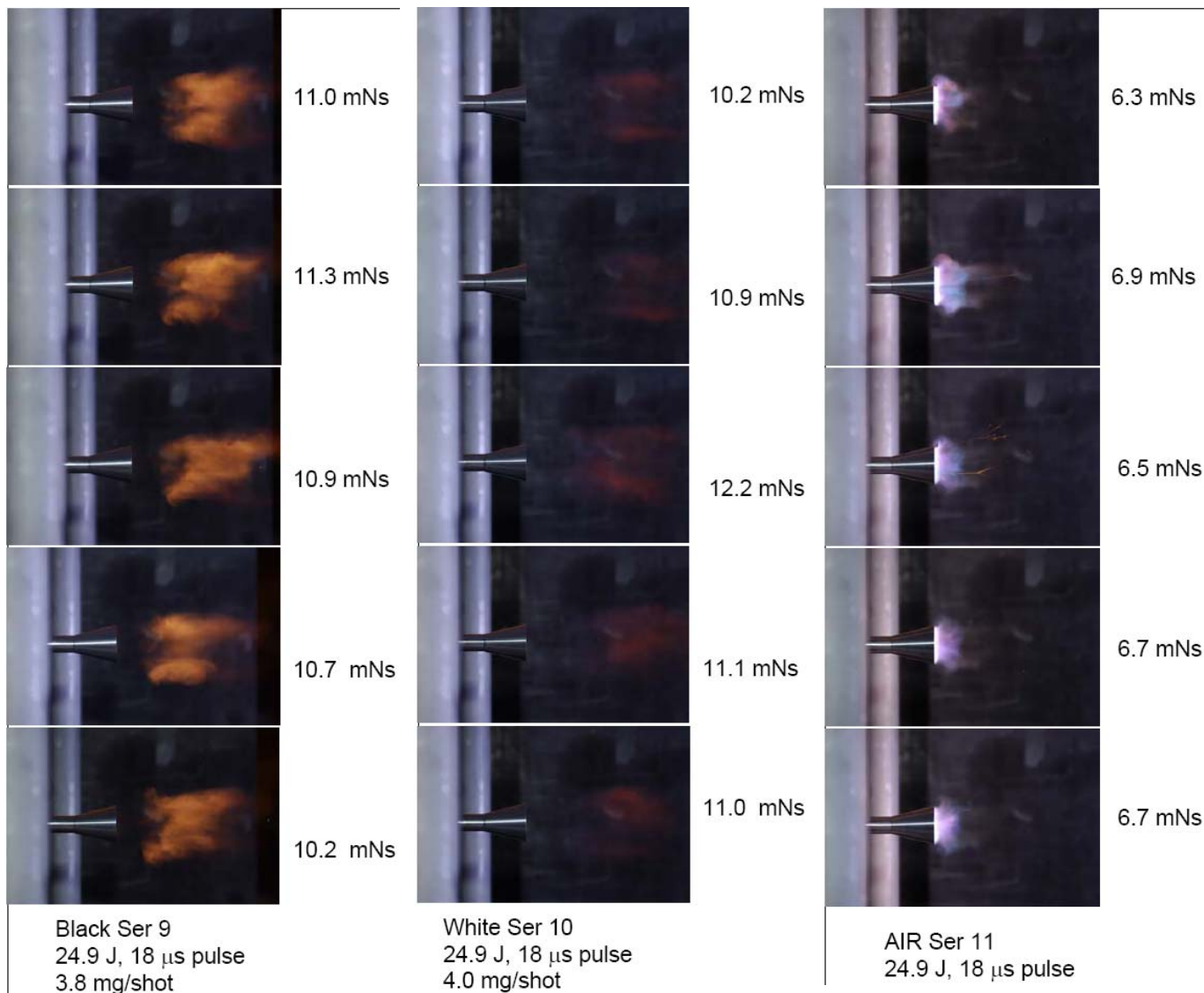
Air Plasma



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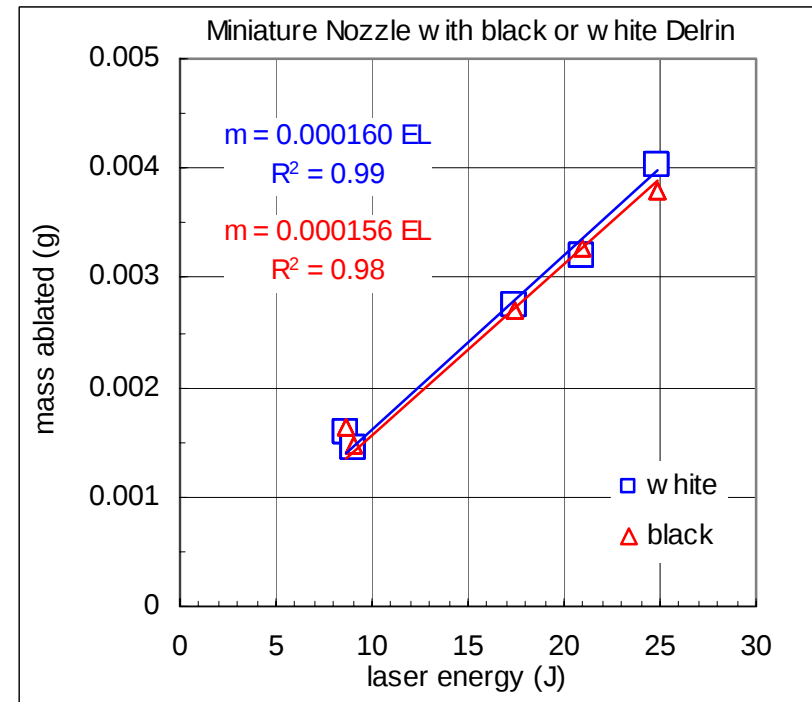
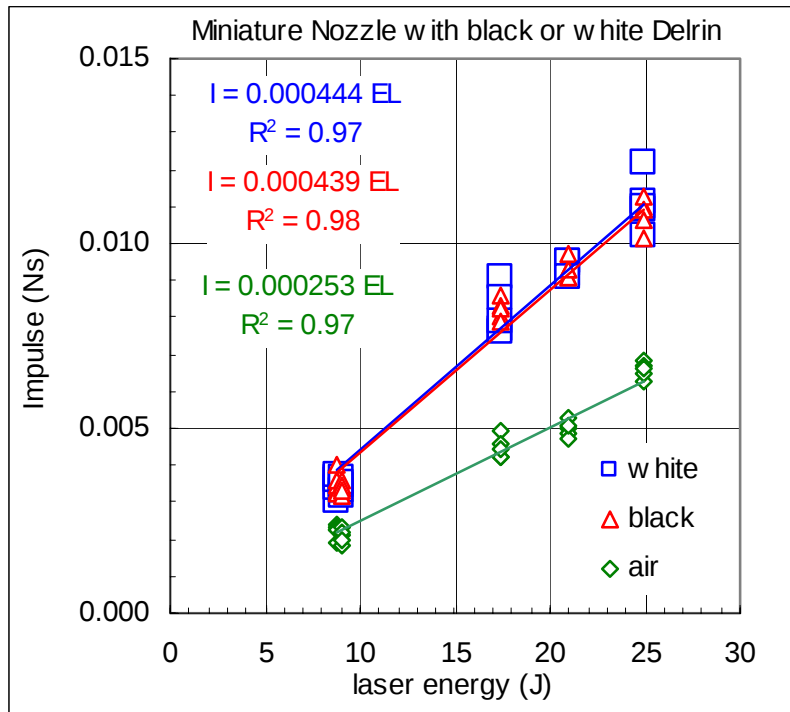


Mini Thruster 25 J, 18 μ s, 0.71 cm²





I, m, E_L for Mini Thruster



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

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

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

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



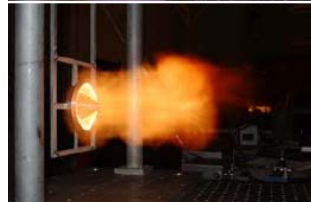
10 cm Light Craft 322 J, 18 μ s



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



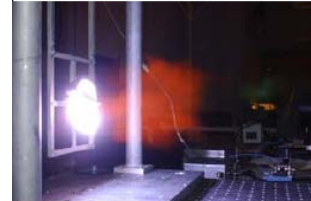
151.8 mNs



133.0 mNs



136.1 mNs

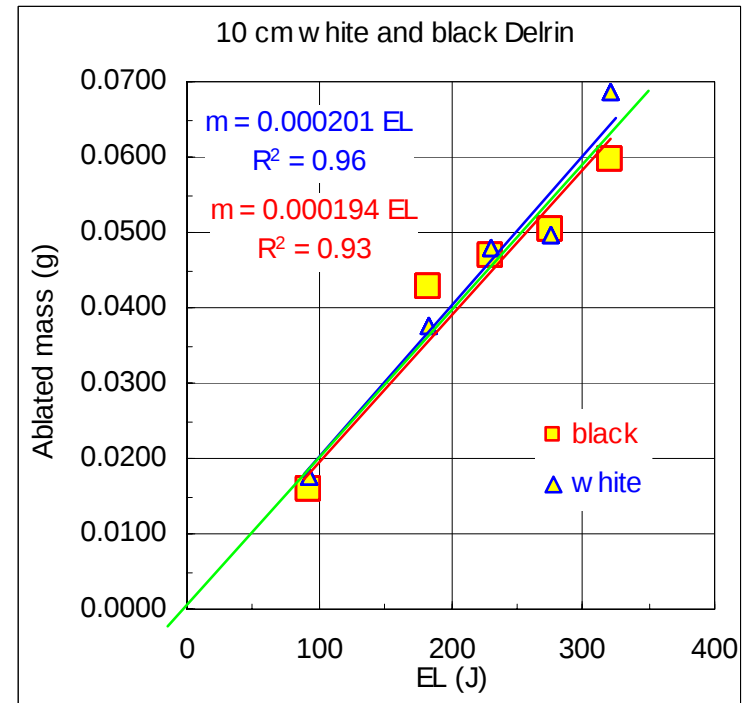
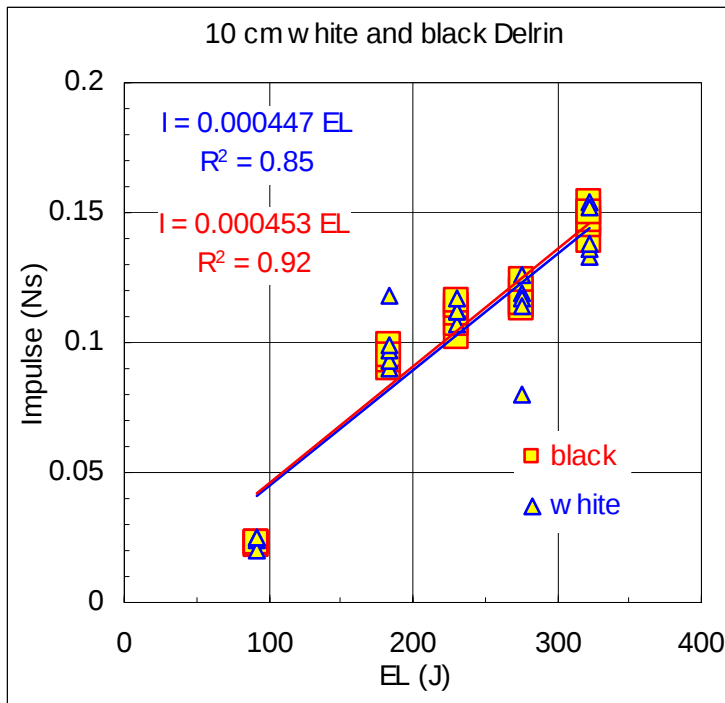


137.8 mNs

White Ser 6
322 J
68.7 mg/shot



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



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

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

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

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

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CONVERSION OF LASER ENERGY TO JET KINETIC ENERGY



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

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

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

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

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

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

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

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

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

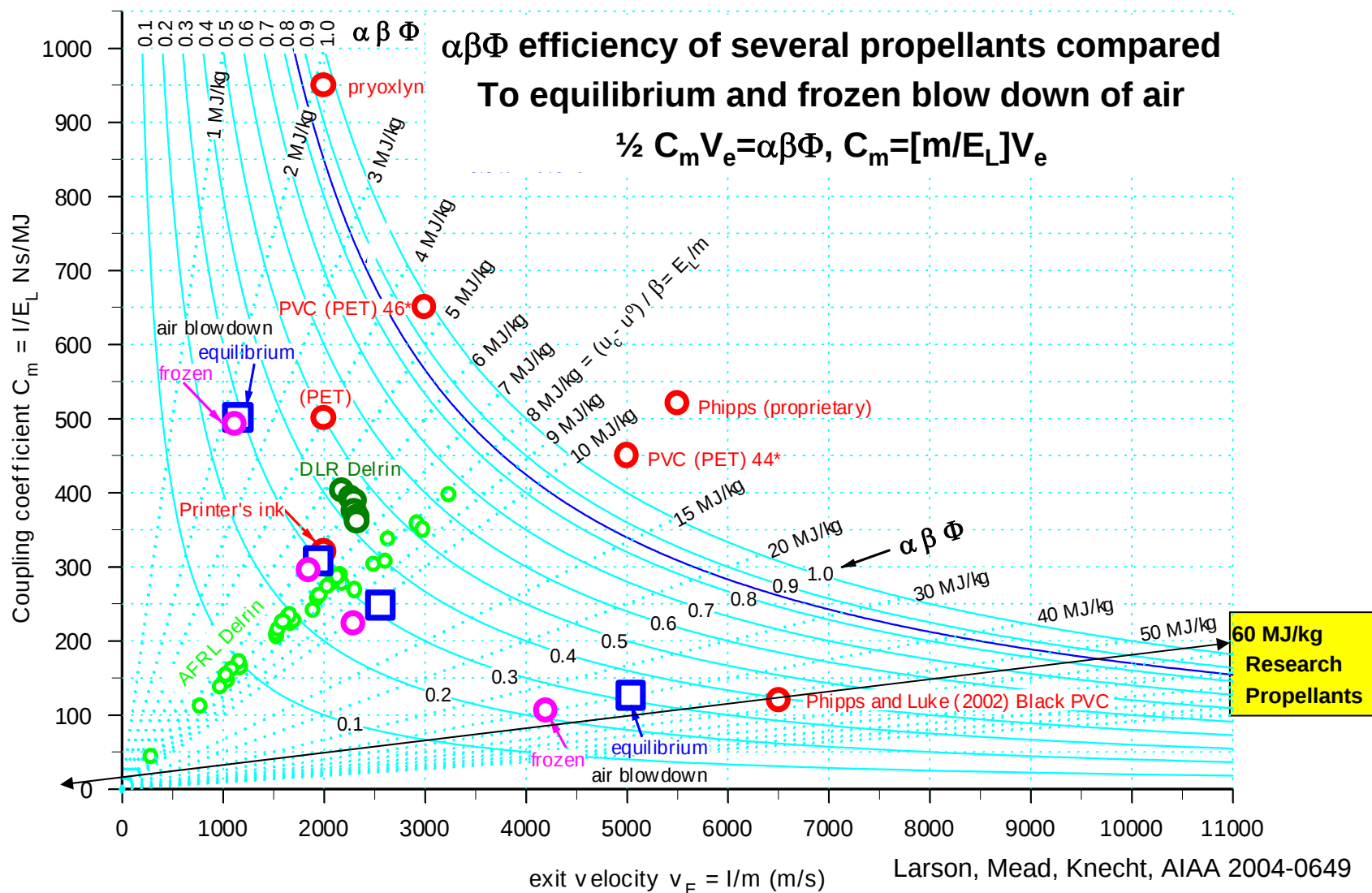
For propellants with chemical energy

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

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



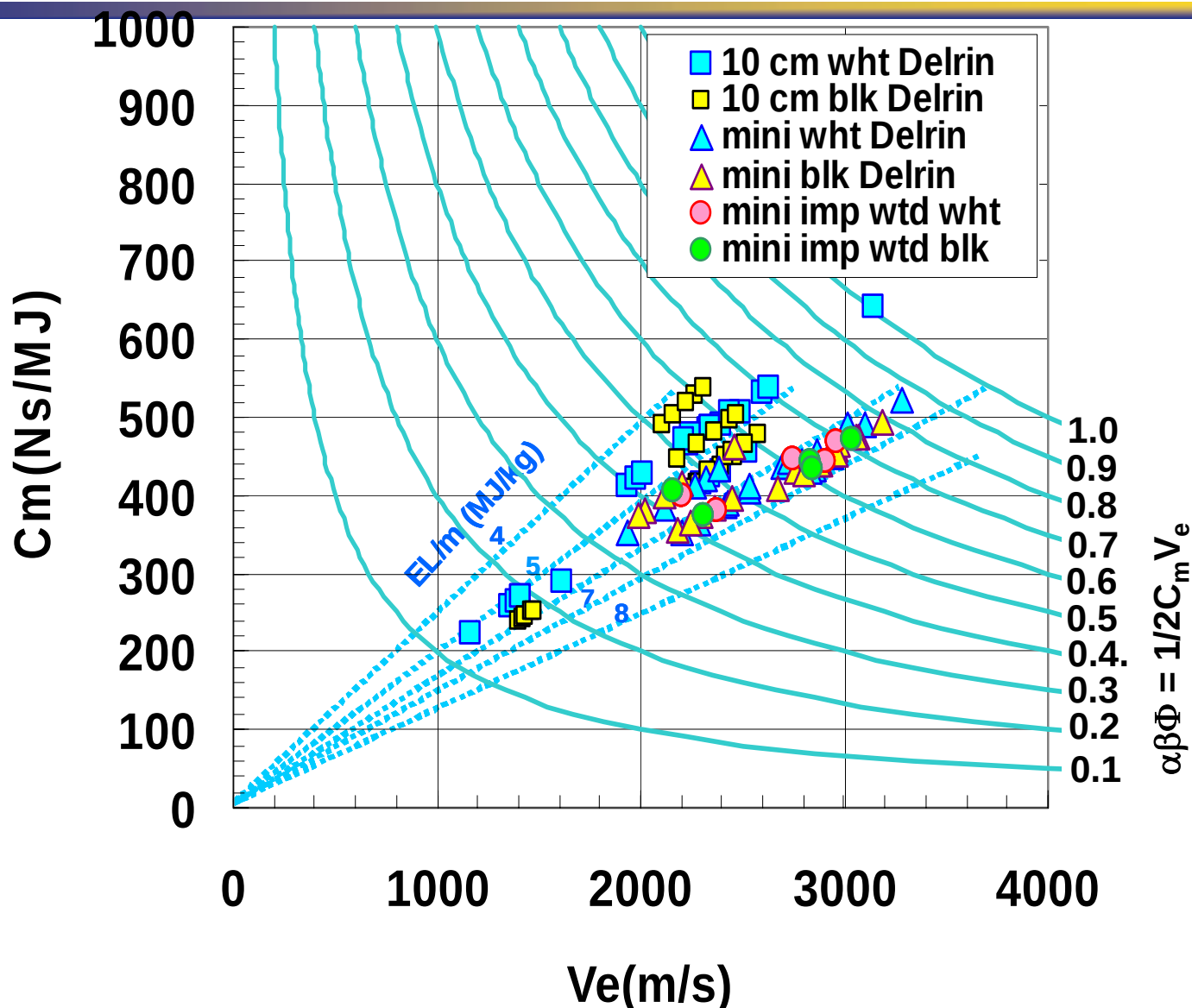
Performance map of known laser materials and theoretical air





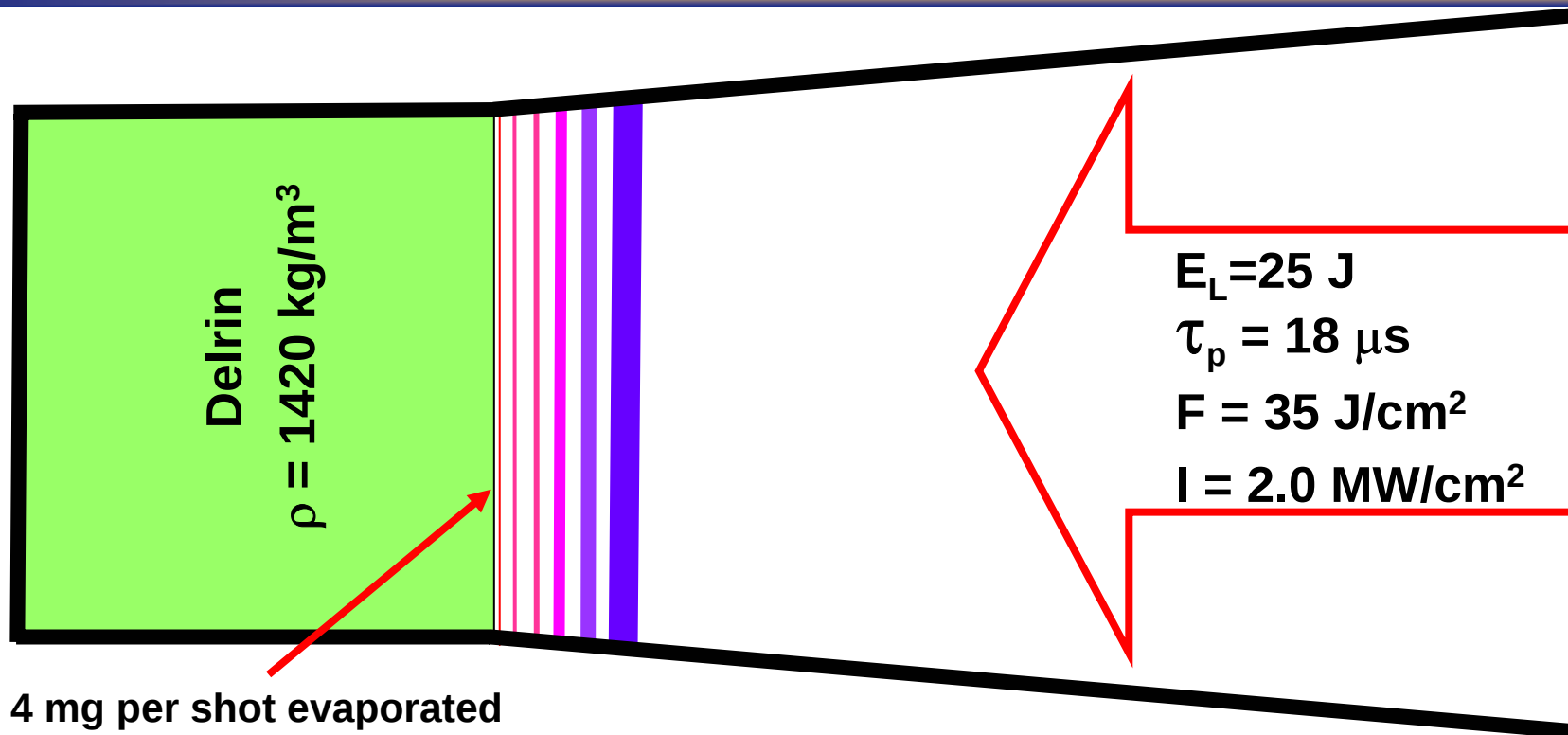
Experimental Results December 2004

200-3/4 Light Craft and Mini Thruster





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

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

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

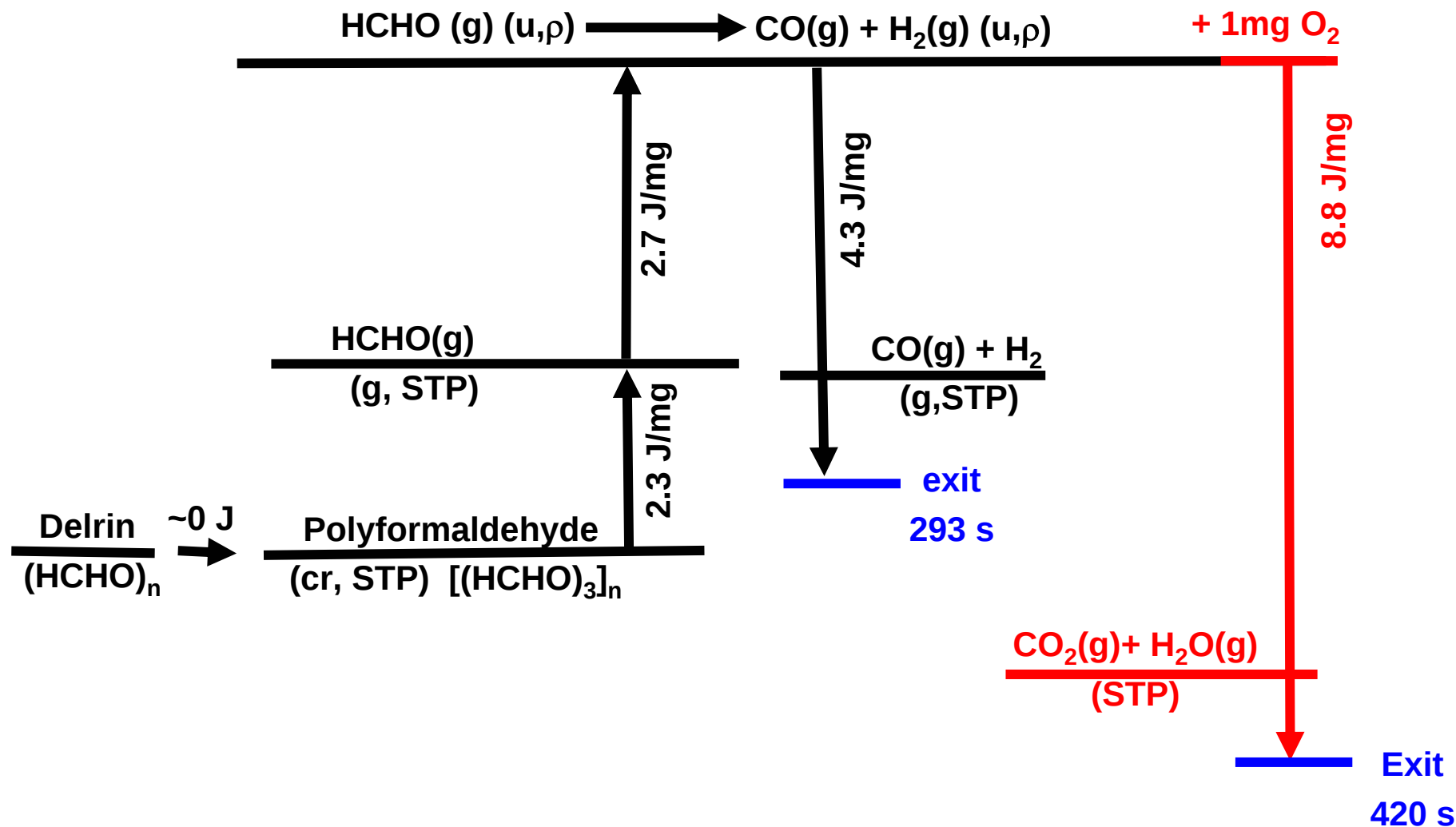
Specify expansion ratio

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

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



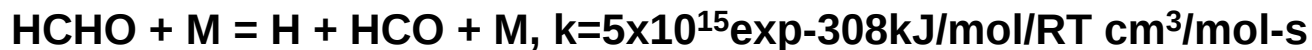
6 J/mg Energy Addition to Delrin



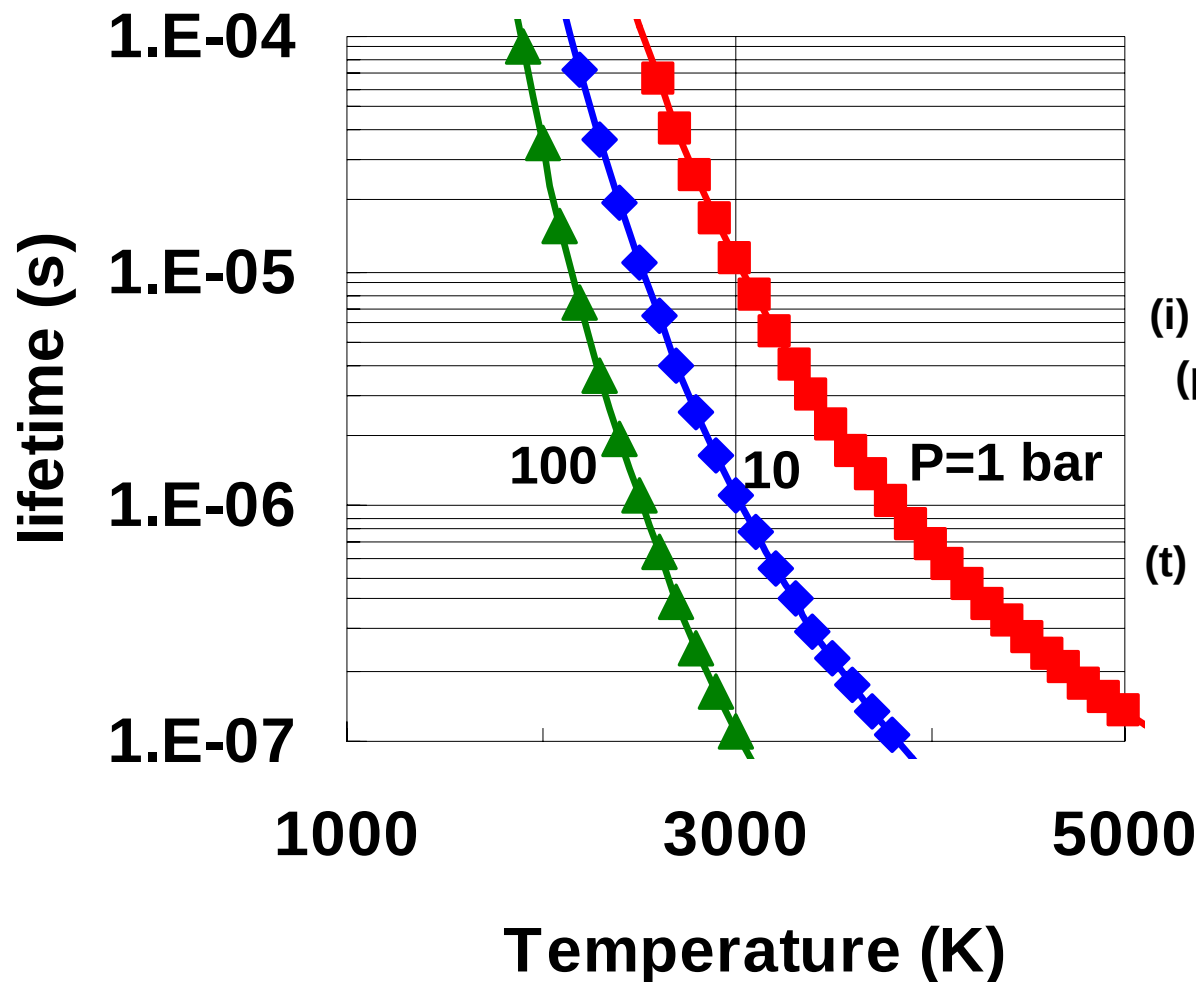
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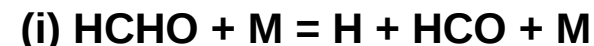
Lifetime of Formaldehyde, $\tau(T,P)$



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/m³, u=1.975 MJ/kg]



Species	chamber	$\epsilon=8$	$\epsilon=64$	species	chamber	$\epsilon=8$	$\epsilon=64$
CO	0.47502	0.48415	0.35692	CH ₃ OH	0.00015	0	0
H ₂	0.39082	0.39891	0.36466	CH ₃ CHO, ethanal	0.00014	0	0
H ₂ O	0.06058	0.04282	0.08215	C ₃ H ₄ , allene	0.00013	0	0
CH ₄	0.03818	0.05811	0.05318	C ₃ H ₆ , propylene	0.00013	0	0
CO ₂	0.00856	0.01574	0.05707	CH ₂	0.00012	0	0
C ₂ H ₂	0.00742	0.00002	0	C ₂ H ₂ , vinylidene	0.00009	0	0
CH ₃	0.00472	0.00001	0	CH ₂ OH	0.00007	0	0
H	0.00402	0	0	C ₃ H ₅ , allyl	0.00006	0	0
C ₂ H ₄	0.00267	0.00014	0	C ₄ H ₂	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
CH ₂ CO	0.00096	0	0	CH ₃ O	0.00003	0	0
C ₃ H ₃ , 2-pryl	0.00039	0	0	C ₂ H	0.00003	0	0
C ₂ H ₃ , vinyl	0.00035	0	0	C ₃ O ₂	0.00003	0	0
OH	0.00032	0	0	C ₄ H ₆ , butadiene	0.00003	0	0
C ₂ H ₆	0.00027	0.00005	0.00001	C ₂ O	0.00002	0	0
HCOOH	0.00026	0	0	C ₂ H ₅ OH	0.00001	0	0
C ₃ H ₄	0.00025	0	0	C ₃ H ₄ , cyclo-	0.00001	0	0
CH ₃ CO	0.00019	0	0	C ₃ H ₈	0.00001	0	0
C ₂ H ₅	0.00019	0	0	C ₄ H ₆ , 1butyne	0.00001	0	0
				C(gr)	0	0	0.08601



Mole Fractions at Equilibrium

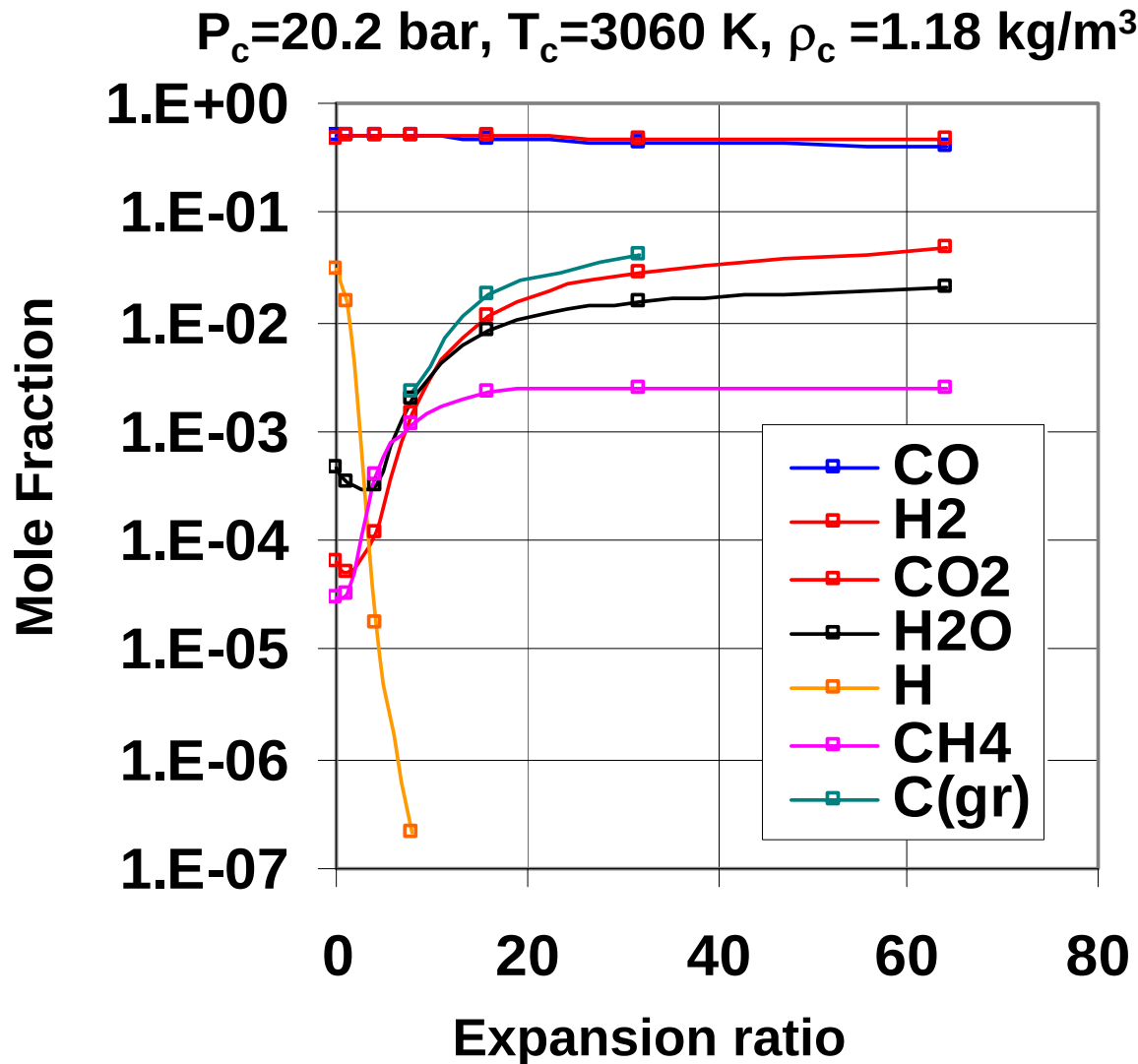
Formaldehyde expansion from P=230 bar, T=3433 K,
[rho=12.02 kg/m³, u=1.907 MJ/kg]



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

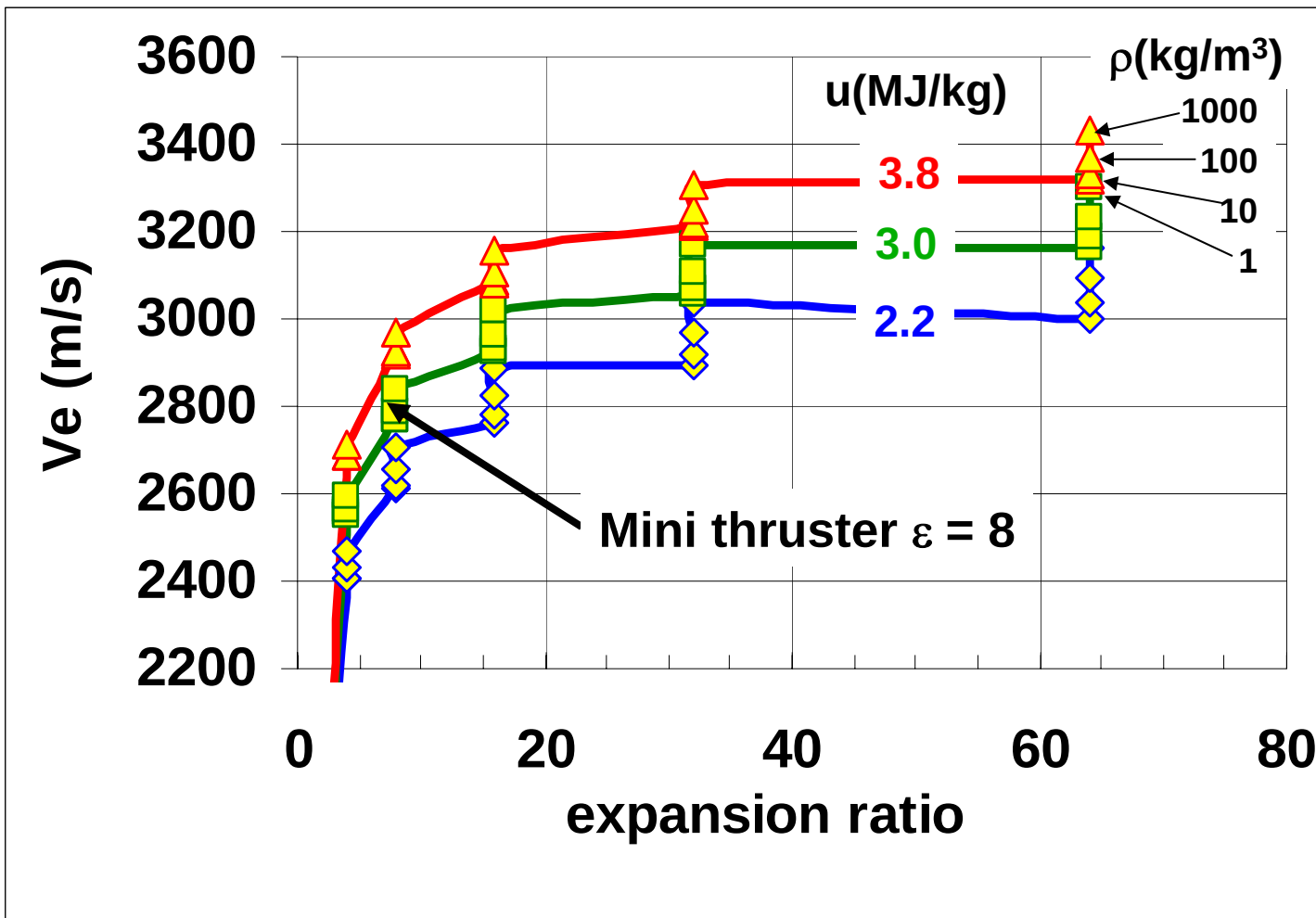


Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)





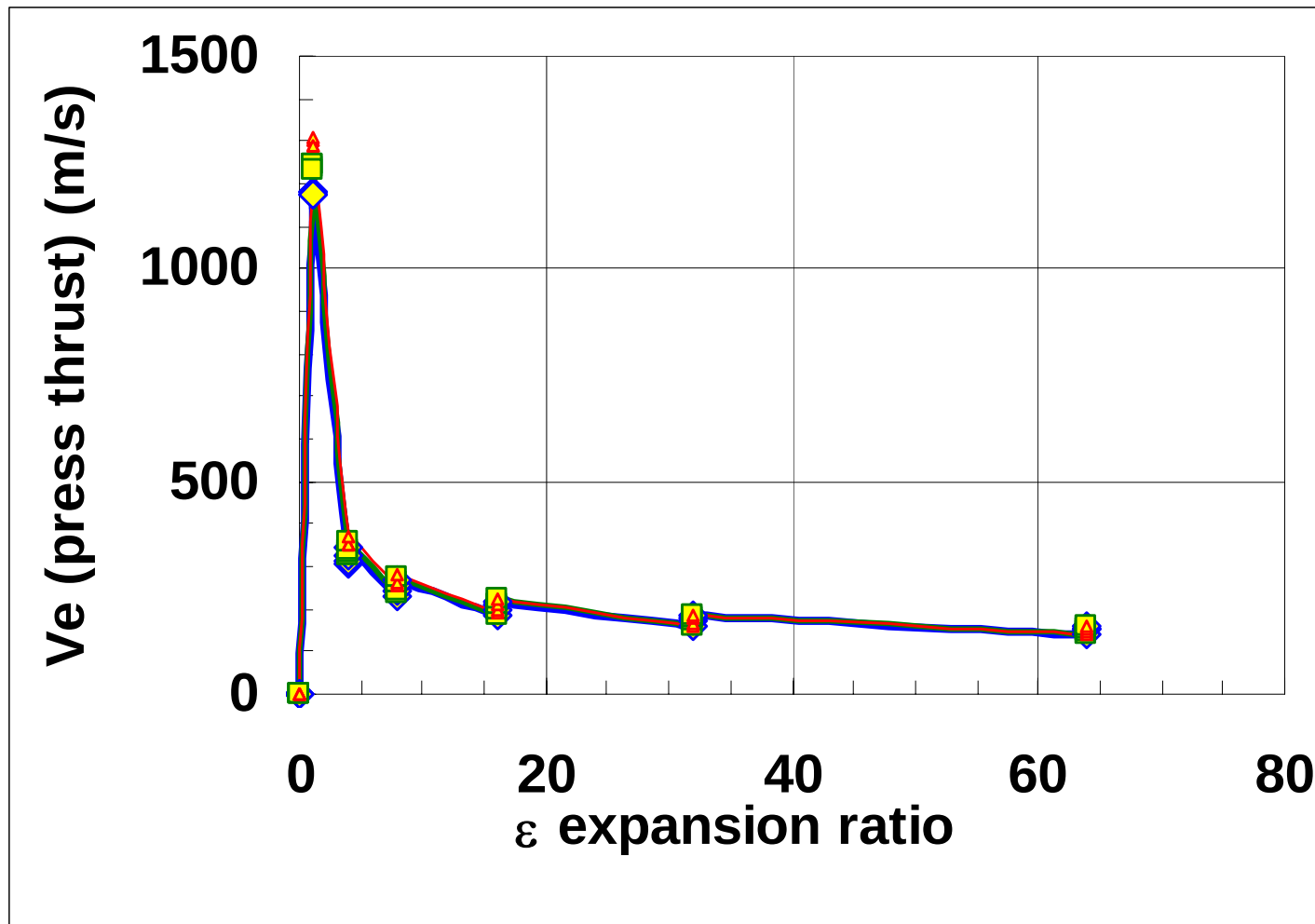
Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)



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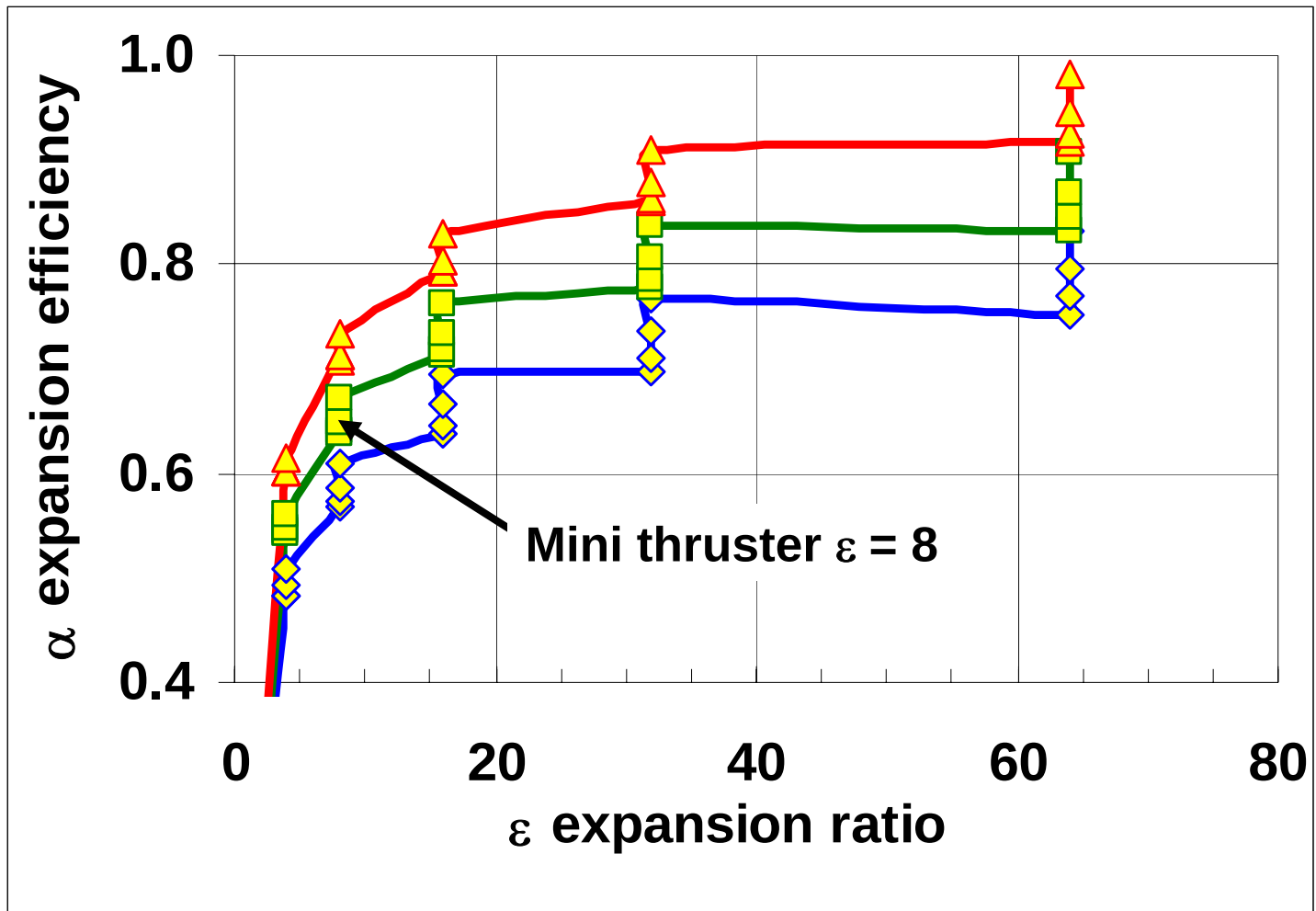


Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)



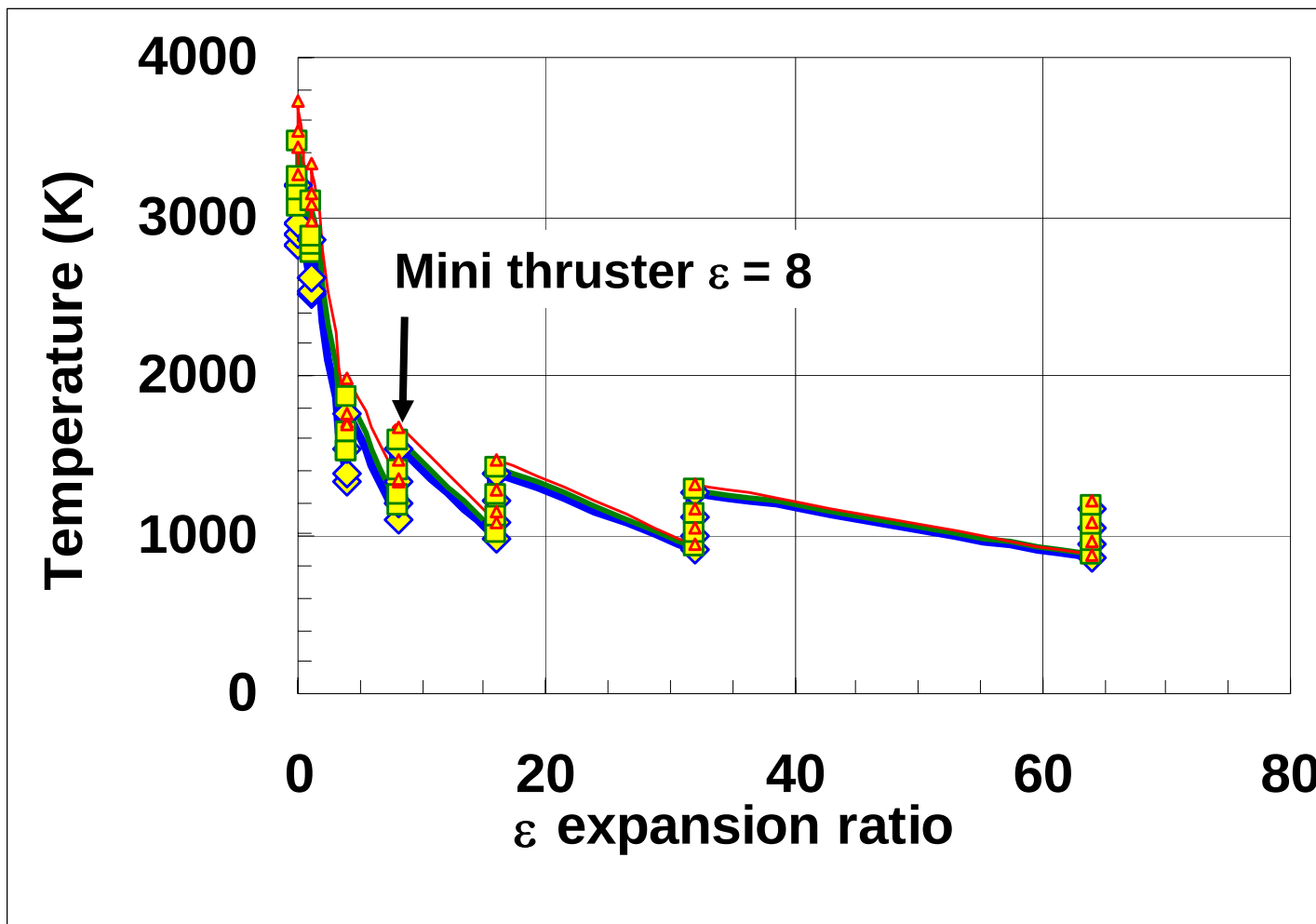


Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)



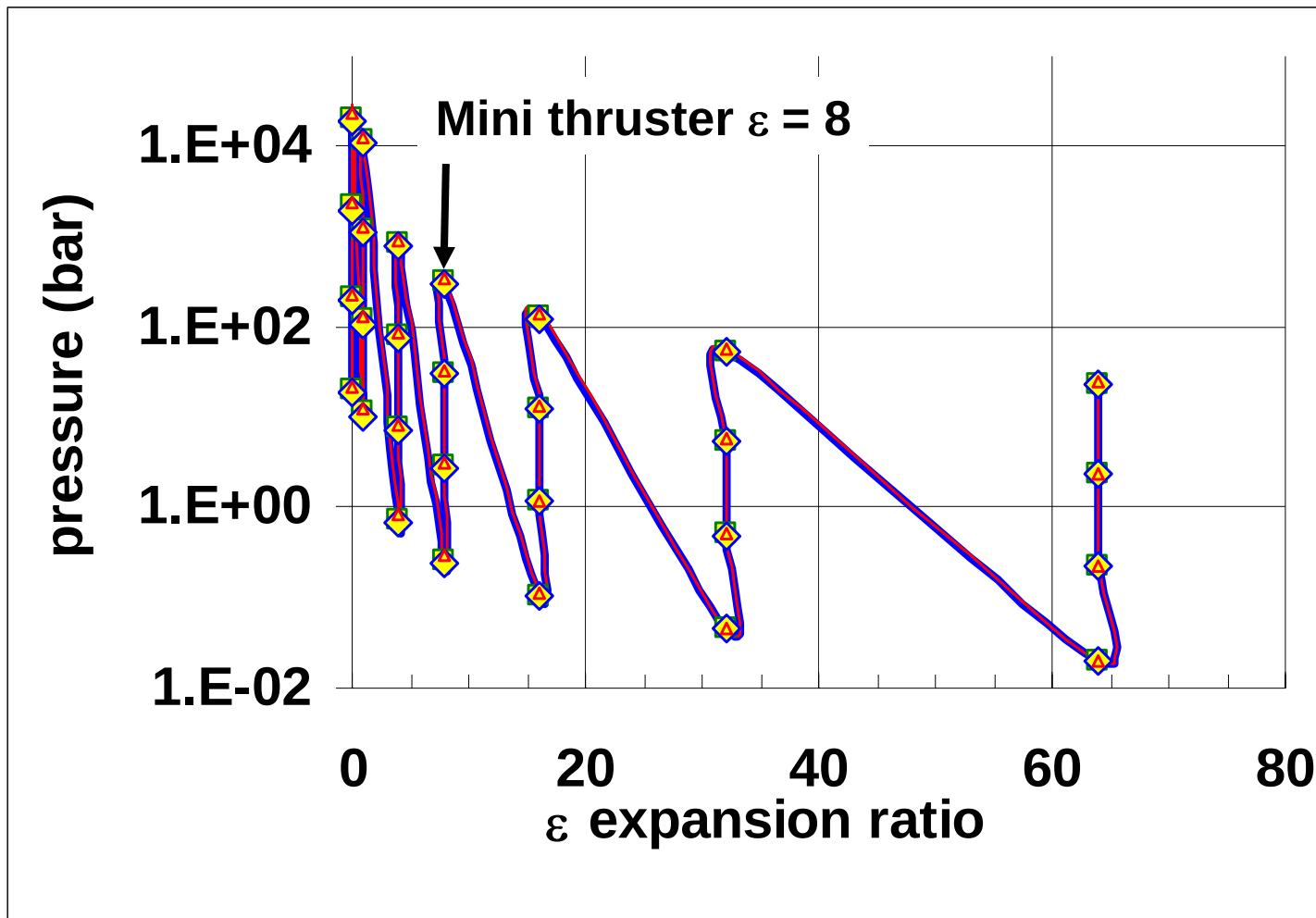


Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)



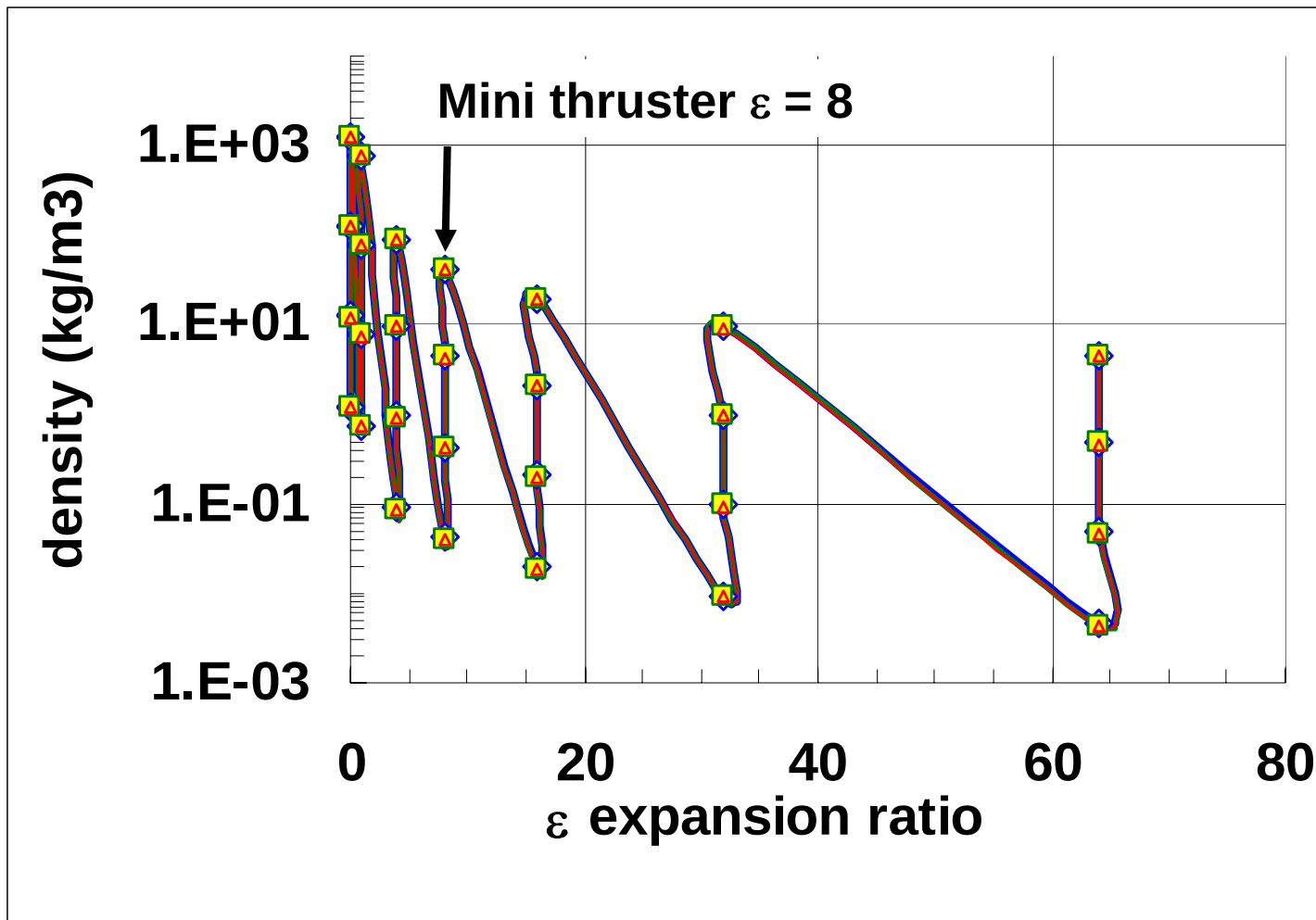


Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)





Blowdown from specified initial state (u, ρ) with specified expansion ratio (ε)





Experimental data (I, EL, m) and derived parameters (C_m, V_e, efficiency, EL/m)



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



Conclusions/Work in Progress



- $C_m=450$ N/MW for Light Craft/Delrin (350 J, 18 μ s)
- $C_m=442$ N/MW for Mini Thruster/Delrin (25 J, 18 μ 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 μ s, expansion ratio, $\varepsilon = 4, 16, \dots$
 - 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

THE END



Distribution A – Approved for public release, Distribution Unlimited



Φ for Bimodal velocity distribution

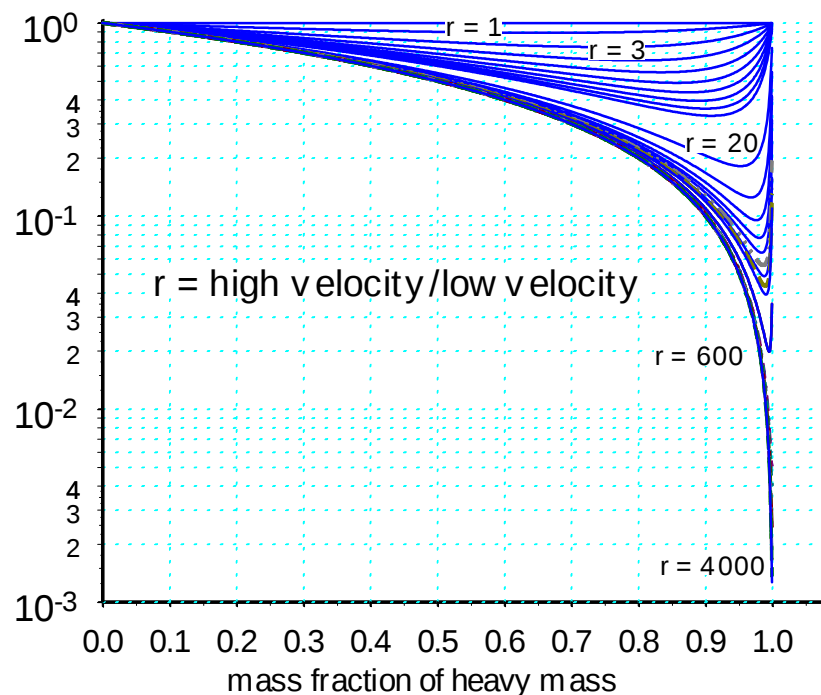
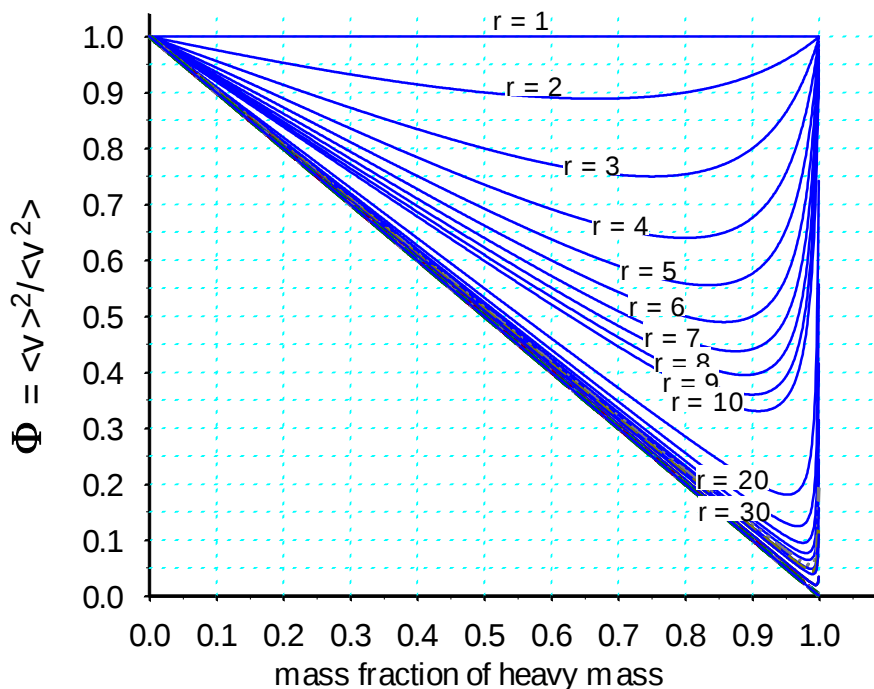
Chunks of propellant
Hot gases

f_{heavy} mass fraction, v_{slow} velocity
 f_{light} mass fraction, v_{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

