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C. William Larson, Franklin B. Mead, Jr., Sean D. Knecht (AFRL/PRSP)

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Benefit of Constant Momentum Propulsion for Large ΔV Missions -- Application to Laser Propulsion

C. William Larson, Franklin B. Mead, Jr., and Sean D. Knecht
Propulsion Directorate
Air Force Research Laboratory
Edwards AFB, CA 93524-7680

42nd AIAA Aerospace Sciences Meeting and Exhibit
4-8 January 2004
Reno, Nevada

Outline

Tour of White Sands Laboratory (HELSTF/PLVTS) and Video of Flight Testing.

Comparison of Constant Momentum Mission and Constant Specific Impulse Mission. Δv, v_{jet}, f, m_o, v_o, P_{jet}, m/E_{jet}

Efficiency of conversion of laser energy to propellant kinetic energy, $\alpha\beta$.

Upper limit to conversion of laser energy to jet kinetic energy from energy conservation and definitions: $\frac{Cv_{jet}}{2} = \alpha\beta\Phi < 1$.

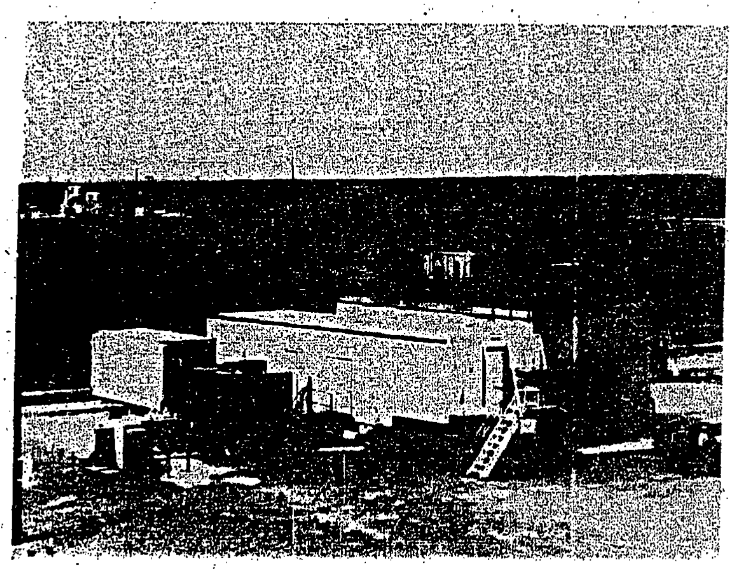
Comparing momentum quantities to energy quantities. The "Phi Factor" $\Phi = \langle v\rangle^2/\langle v^2\rangle$ and velocity distributions in propellant jet. Φ values for delta function, Maxwellian, Gaussian, Chunks and gas, supersonic expansion, etc.

Upper limits to performance based on chemical thermodynamics. Blowdown from defined equilibrium state (u, ρ) of known volume.

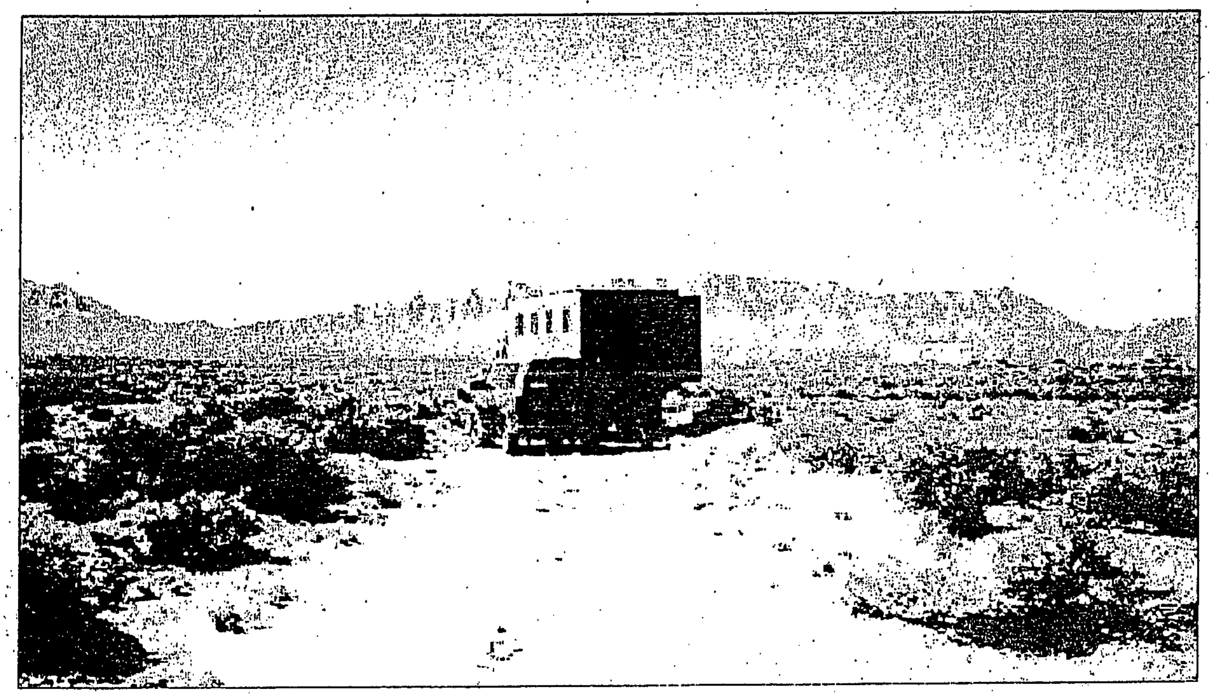
Conclusions

Pulsed Laser Vulnerability Test System (PLVTS)

- Original Performance
  - 800 joules/pulse
  - 10 Hz
  - 30μsec pulses
- Modified Performance
  - 1998
    - 400 joules/pulse
    - 28 Hz
    - 18μsec pulses
  - 1999
    - 150 joules/pulse
    - 30 Hz
    - 5μsec pulses



Optical Bench Set Up At 500-Ft Mark



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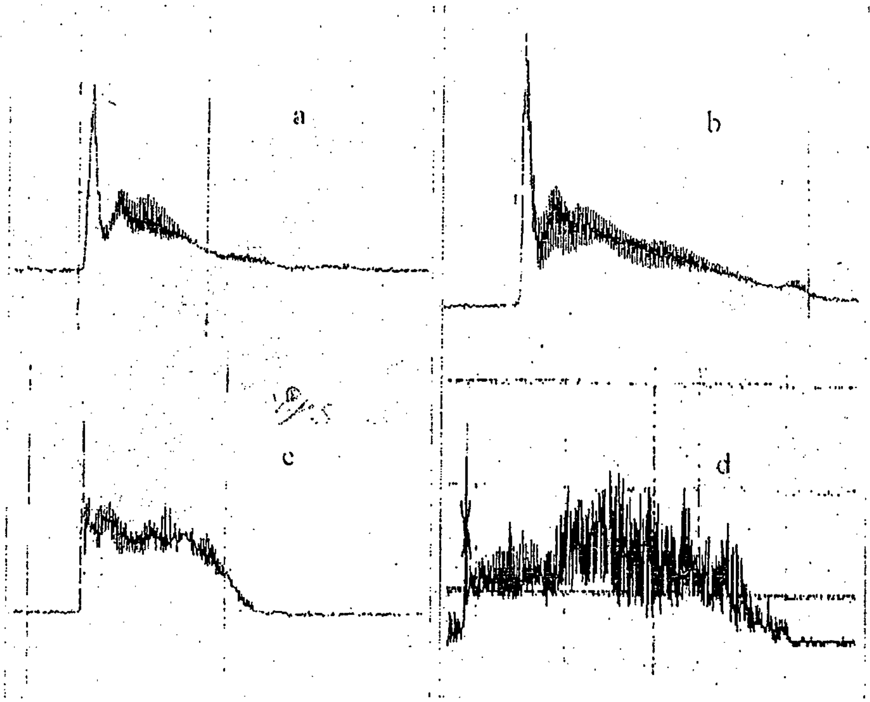
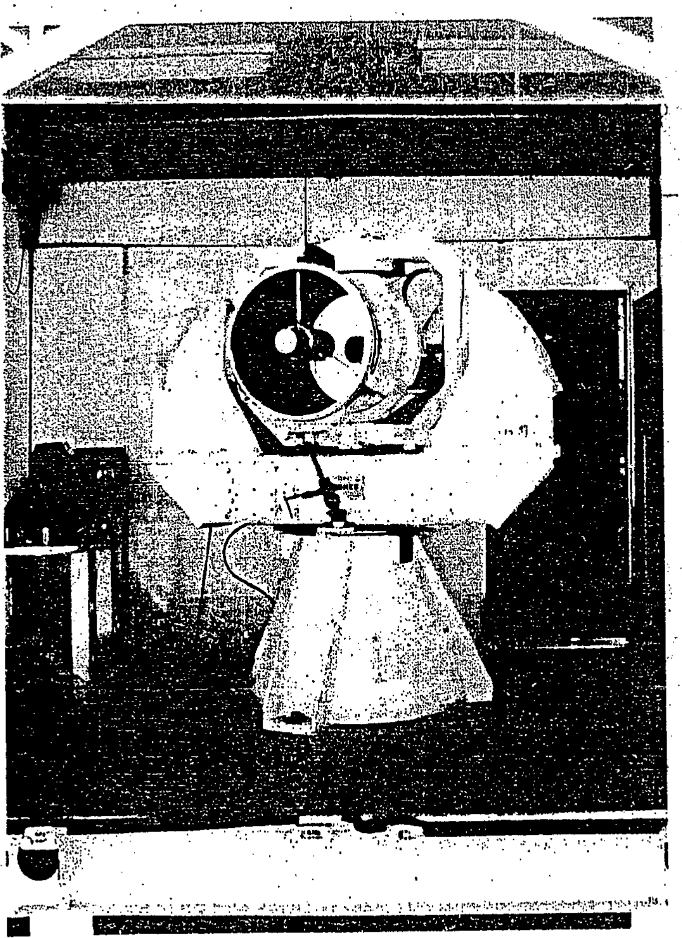
Optical Power vs Time:
a) 2.5µs; b) 5µs; c) 18µs; d) 35µs



Field Test Telescope (FTT)

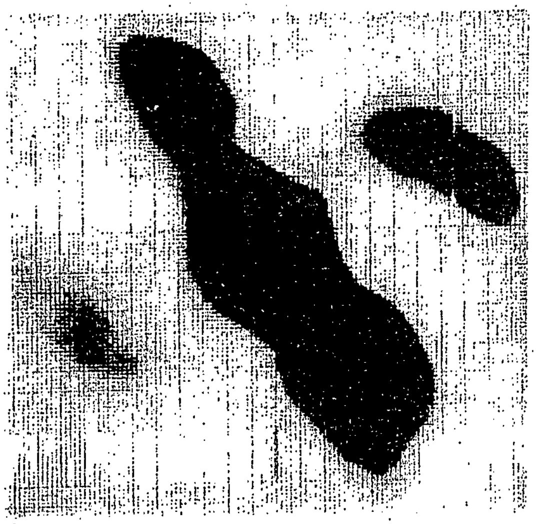
- 50 cm
- Cassegrainian
- Dynamic Focusing
- Minimum Acquisition Distance is 200 m



Laser Beam Handoff to This Telescope Should Allow Altitudes of ~300 m (1,000 ft)

Laboratory Telescope Burn Patterns

Near Field
At ~10 Ft



500 Ft

5 cm Ref.

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FTT Beam Burn Patterns

500 Ft

1,000 Ft

1,500 Ft

11 cm Ref.

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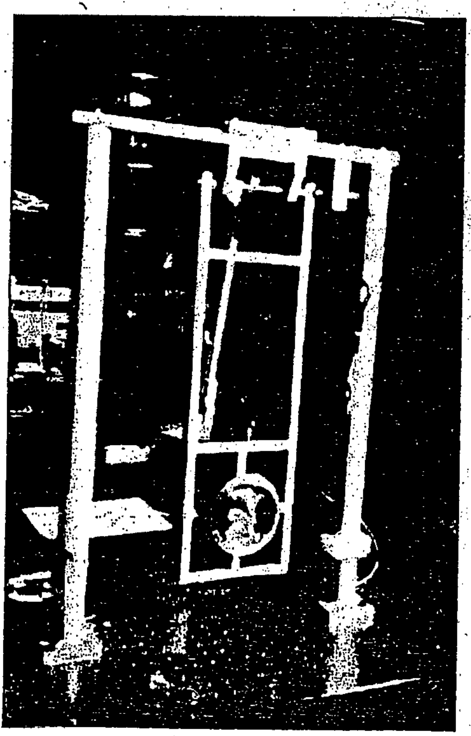
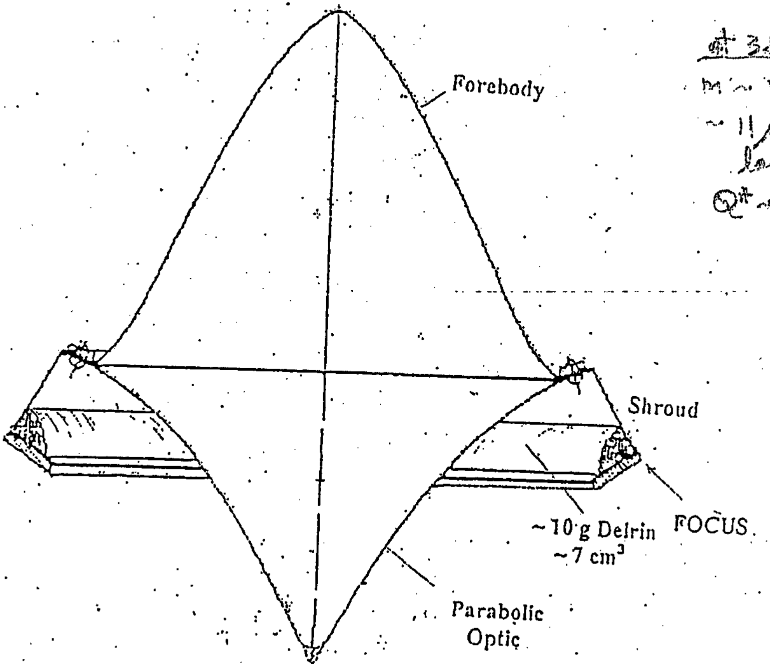
Pendulum Impulse Test Stand



Measure:
1. Impulse
2. Laser Energy
3. Mass ablated

350 J / 25 cm^2 / 18 μs
14 J/cm^2 0.8 MW/cm^2

@ 350 J
m ~ 40 mg
~ 11 μm thick layer.
Q* ~ 7 to 8 MJ/kg



ε ≤ 14
Ideal Plug Nozzle

Figure 2. Cross-sectional view of Myrabo Laser Lightcraft, Model 200-3/4. The maximum diameter of the test article at the shroud is ~ 10 cm. The indicated ring of Delrin weighs ~ 10 g and has a volume of ~ 7 cm^3 and a surface area ~ 25 cm^2. The idealized maximum plug nozzle exit area is ~ 350 cm^2.

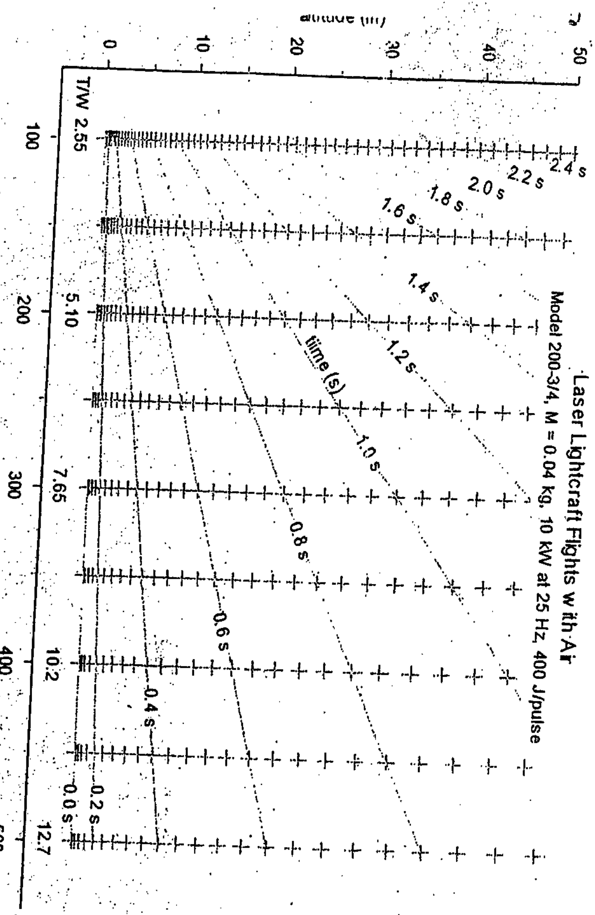


Figure 6. Laser Lightcraft flights with air with various coupling coefficients for a Model 200-3/4 laser Lightcraft, with mass of 40 grams. These flight patterns are also valid for flights with onboard propellant provided that the mass of ablated propellant is much less than the test article mass, $f > 0.99$. T/W = 1 when $C_2 = 39.2$ Ns/MJ.

Figure 7. Time exposure of nighttime flight of Myrabo Laser Lightcraft. The time between flashes of the air plasma is 0.04 s.

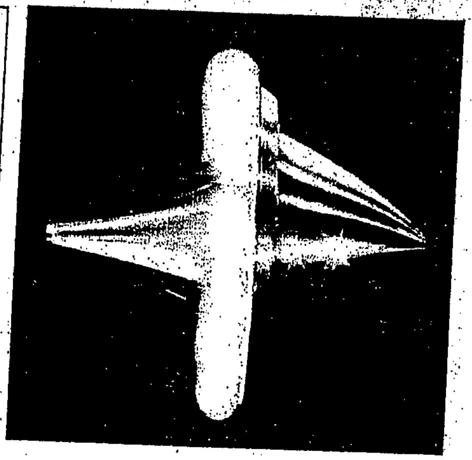


Figure 8. The Myrabo Laser Lightcraft showing air plasma. The Model 200-3/4 is ~0.1 m diameter at largest circumference. The aluminum model weighs ~30 g without Delrin. About 10 g of Delrin was used in the Solid Ablative Rocket (SAR) of which ~0.3 g was ablated during a typical flight with about 100 shots.

Overall Energy Conversion in Laser Propulsion Mission

$$E_f = \tfrac{1}{2}\, m_f v_f^2 = \eta\, \alpha\, \beta\, \gamma\, \delta\, E_{wall}$$

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 $\eta\, \alpha\, \beta\, \gamma$ *****

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

At \$0.10/KWH, \$500 buys 18,000MJ (1 KWH = 3.6 MJ); 1 kg at 10 km/s → $E_f = 50$ MJ, so $\eta\alpha\beta\gamma\delta \geq 0.0028$

Phipps, Reilly, Campbell, *Laser & Particle Beams* 18 (2001) 661-695
Pirri, Monsler, Nebolsine, *AIAA Journal* 12 (1974) 1254-1261

6

Definitions and Energy Conservation

Propellant Kinetic Energy: $E_p = \frac{1}{2} m_p \langle v_e^2 \rangle = \alpha\beta\, E_L$ $\qquad \langle v_e^2 \rangle = \dfrac{\int_{\rho_c}^{\rho_f} d(\rho v_e^2)}{\int_{\rho_c}^{\rho_f} d\rho}$

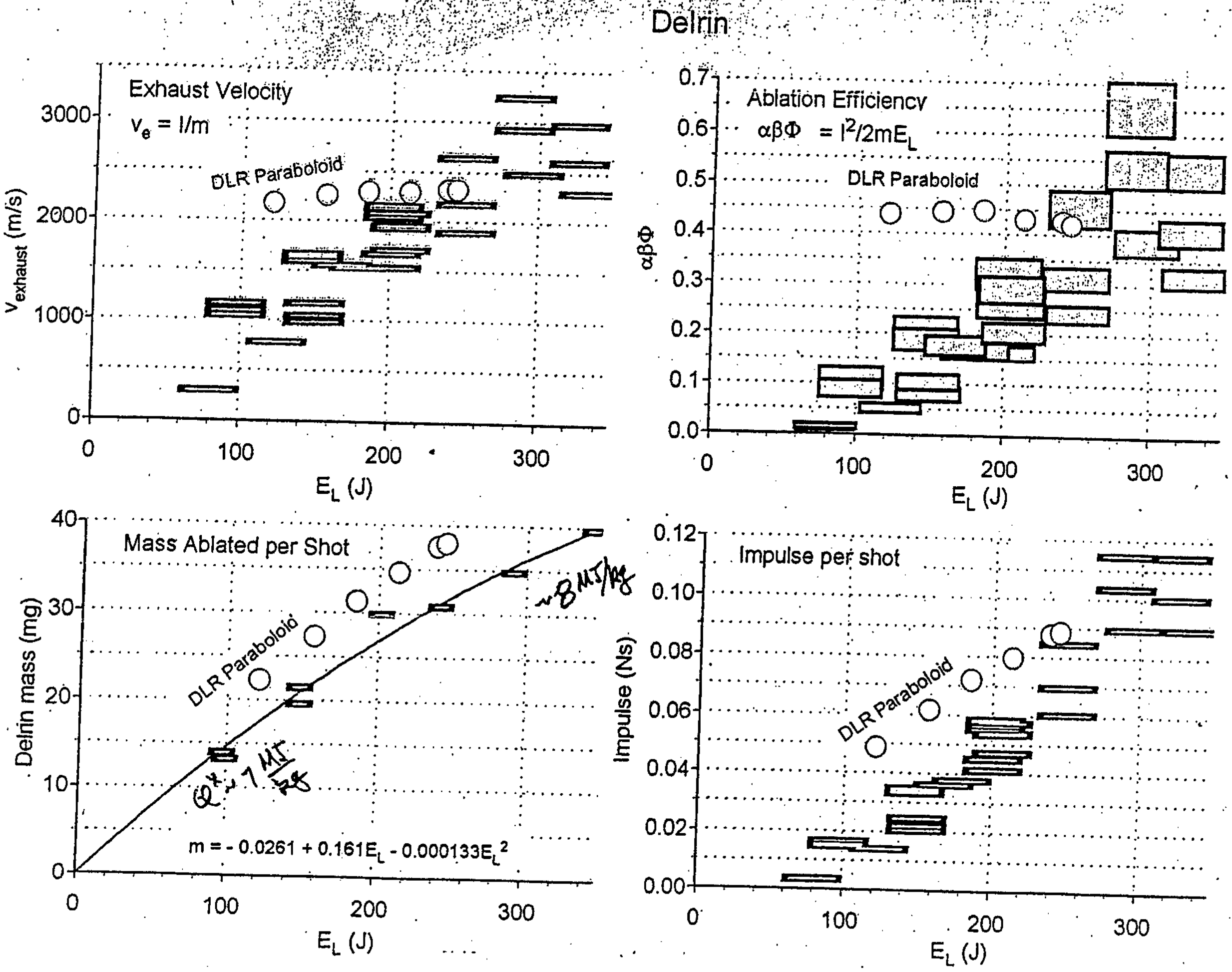
Propellant Impulse: $I = m_p \langle v_e \rangle$ $\qquad \langle v_e \rangle = \dfrac{\int_{\rho_c}^{\rho_f} d(\rho v_e)}{\int_{\rho_c}^{\rho_f} d\rho}$

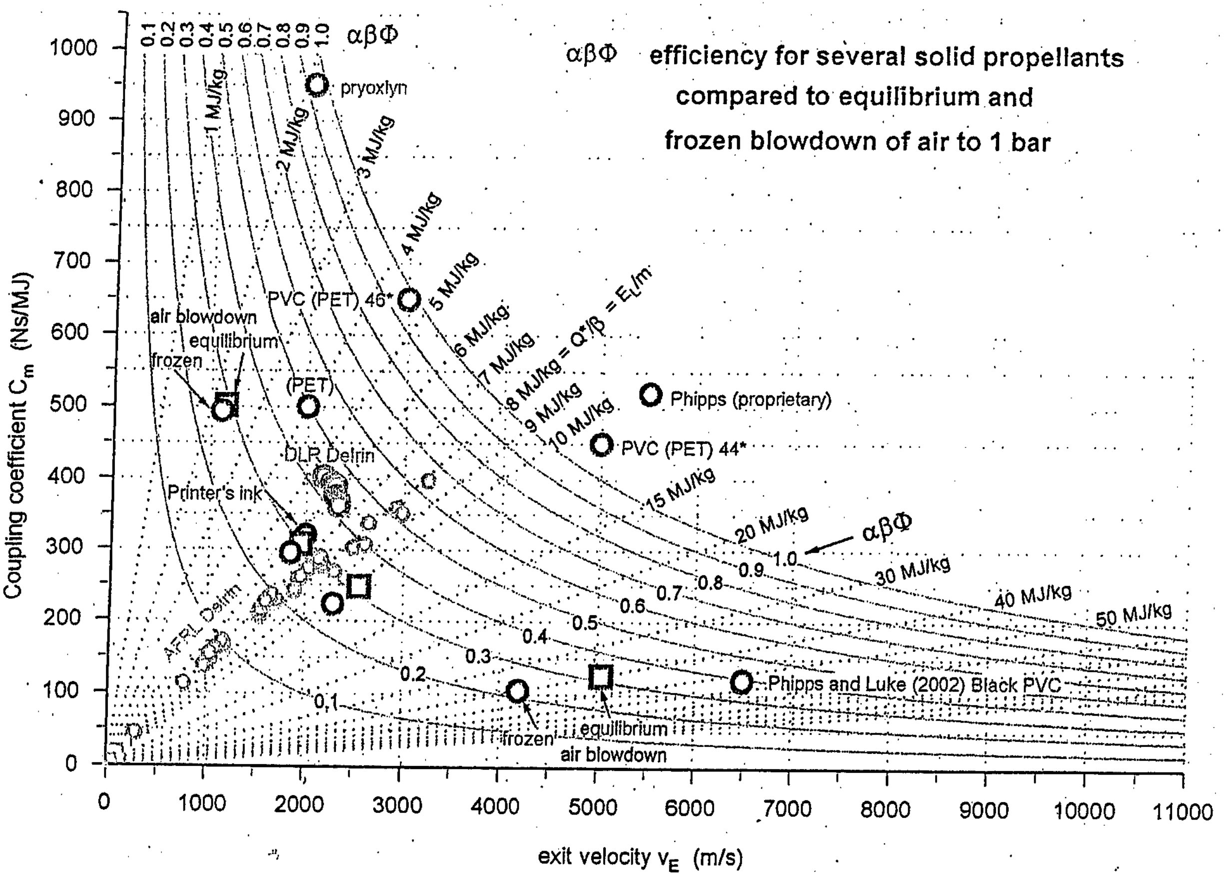
Coupling Coefficient: $C = \dfrac{I}{E_L}$ $\qquad C = \dfrac{2\alpha\beta}{\langle v_e \rangle}\left[\dfrac{\langle v_e \rangle^2}{\langle v_e^2 \rangle}\right] = \dfrac{2\alpha\beta\Phi}{\langle v_e \rangle}$

Energy Conservation: $\boxed{\alpha\beta\Phi = \dfrac{I^2}{2m_p E_L}} = \dfrac{CI}{2m_p} = \dfrac{C\langle v_e \rangle}{2} = \dfrac{I\langle v_e \rangle}{2E_L} \le 1$

Propellant Internal Energy: $Q^* = u_c - u^0 = \dfrac{\beta E_L}{m_p}$ $\qquad C = \dfrac{\beta \langle v_e \rangle}{u_c - u^0}$

Propellant with added chemical energy, Δu: $(\alpha\beta\Phi)_{apparent} = \alpha\Phi(\beta + m_p \Delta u / E_L)$





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INSTANTANEOUS PROPULSION EFFICIENCY

$$\eta_i = \frac{2\,(v/v_{jet})}{1+(v/v_{jet})^2}$$

$\eta_i = 1$ if $v = v_{jet}$
$\eta_i < 1$ if $v \neq v_{jet}$

CONSTANT MOMENTUM COMPARED TO CONSTANT SPECIFIC IMPULSE MISSION

The Constant Specific Impulse Mission

$$\int_{m_o}^{m} \frac{dm}{m} = \frac{-1}{v_{jet}} \int_{v_o}^{v} dv$$

$$f = \frac{m}{m_o} = \exp -\left(\frac{v - v_o}{v_{jet}}\right) = \exp\frac{-\Delta v}{v_{jet}}$$

The Constant Momentum Mission

$$\int_{m_o}^{m} \frac{dm}{m} = -\int_{v_o}^{v} \frac{dv}{v}$$

$$f' = \frac{m}{m_o} = \frac{v_o}{v} = 1 - \frac{\Delta v}{v} = \left(1 + \frac{\Delta v}{v_o}\right)^{-1}$$

$m_0 v_0 = m v$

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Figures of Merit for Laser Propulsion: m/E_{jet}

The Constant Specific Impulse Mission

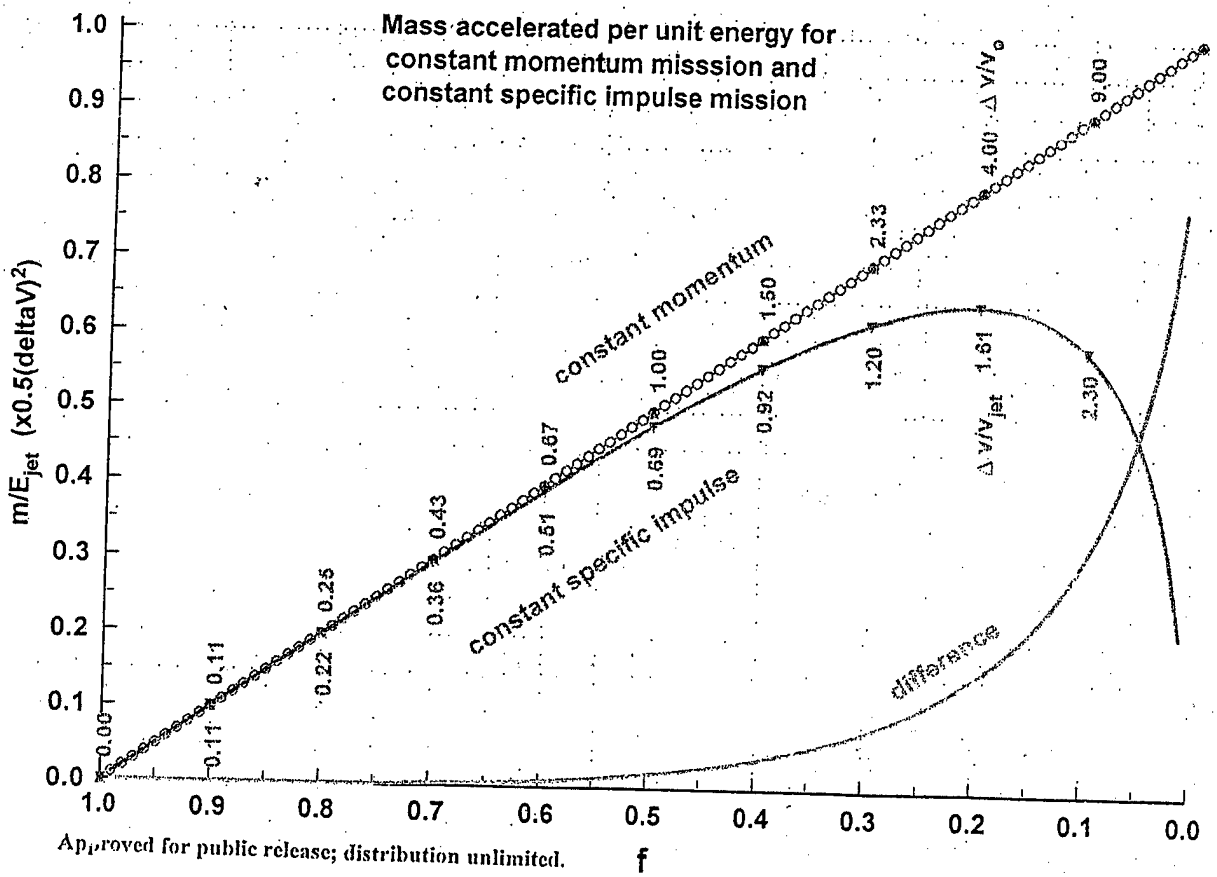
$$E_{jet} = -\frac{1}{2}\int_{m_o}^{m} v_{jet}^2\,dm = \frac{1}{2}(m_o - m)v_{jet}^2$$

$$B = \frac{m}{\frac{1}{2}(m_o - m)\,v_{jet}^2} = \frac{2x^2}{(e^x - 1)[\Delta v]^2} = \frac{2f(\ln f)^2}{(1 - f)[\Delta v]^2}$$

The Constant Momentum Mission

$$E'_{jet} = -\frac{1}{2}\int_{m_o}^{m} v2dm = -\frac{1}{2}(m_o v_o)^2\int_{m_o}^{m}\frac{dm}{m^2} = \frac{1}{2}mv^2 - \frac{1}{2}m_o v_o^2 = \frac{1}{2}mv\Delta v$$

$$B' = \frac{m}{\frac{1}{2}mv\Delta v} = \frac{2(1-f')}{[\Delta v]^2}$$



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Constant Specific Impulse

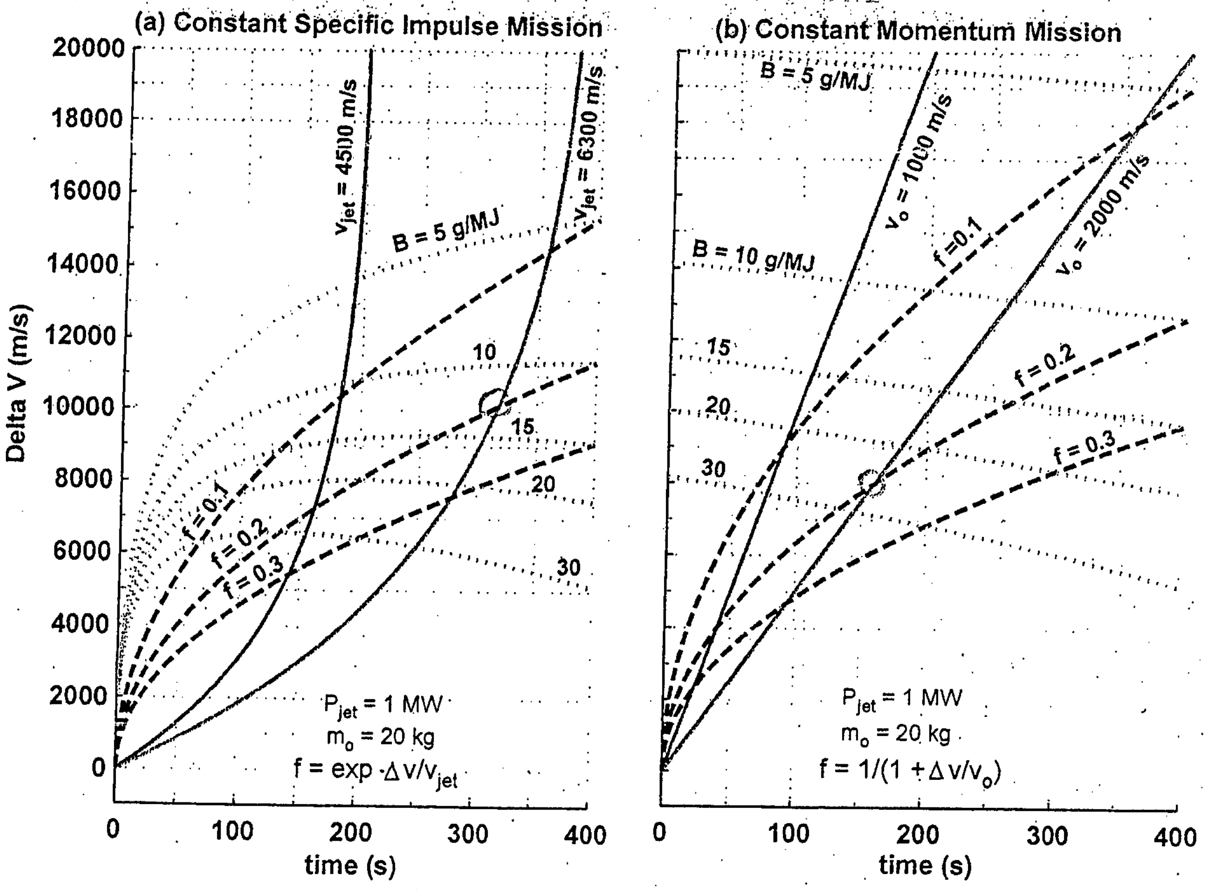
$$P_{jet} = \tfrac{1}{2} v_{jet}^2 \frac{dm}{dt} = \tfrac{1}{2} F v_{jet} \qquad f = \frac{m}{m_o} = 1 - \frac{2P_{jet}}{m_o v_{jet}^2} t \qquad t = \frac{m_o}{2P_{jet}} (\Delta v)^2 \frac{(1-f)}{(\ln f)^2}$$

$$\Delta v = -v_{jet} \ln\left(1 - \frac{2P_{jet}}{m_o v_{jet}^2} t\right) = \sqrt{\frac{2P_{jet}}{m_o} \frac{(\ln f)^2}{(1-f)} t} = \ln\left(\frac{BP_{jet}}{m_o} t\right) \sqrt{\frac{\frac{2P_{jet}}{m_o}}{\left(1 - \frac{BP_{jet}}{m_o} t\right)} t}$$

Constant Momentum

$$P_{jet} = \frac{1}{2} v^2 \frac{dm}{dt} = \frac{1}{2} F v \qquad f' = \frac{m}{m_o} = \left[1 + \frac{2P_{jet}}{m_o v_o^2} t'\right]^{-1} \qquad t' = \frac{m_o}{2P_{jet}} (\Delta' v)^2 \frac{f'}{(1-f')}$$

$$\Delta' v = \frac{2P_{jet}}{m_o v_o} t' = \sqrt{\frac{2P_{jet}}{m_o} \frac{(1-f')}{f'} t'} = \sqrt{\frac{2}{B'} - \frac{2P_{jet}}{m_o} t'}$$



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Conclusions

When $P_{laser}/m_o \sim 0.05$ MW/kg small payloads (2 to 4 kg) may be launched into low earth orbit, $\Delta v \sim 10{,}000$ m/s.

At the same mass fraction, $f = 0.2$, m/E_{jet} for constant momentum mission is 23% greater than for constant specific impulse mission.

For $\Delta v = 10{,}000$ m/s, $m_o/P_{jet} = 20$ kg/MW, $f = 0.2$, $v_o = 0$, the mission time for constant specific impulse propulsion is ~ 315 sec.

For $\Delta v = 10{,}000$ m/s, $m_o/P_{jet} = 20$ kg/MW, $f = 0.2$, $v_o = 2000$ m/s, the mission time for constant momentum propulsion is ~ 155 sec.

At the same $m/E_{jet} = 0.013$ kg/MJ and Δv, f(constant momentum) = 0.35, and f(constant specific impulse) = 0.20.

Based on measured I, E_L, and ablated mass, overall energy conversion efficiencies (laser energy to jet kinetic energy) of $\alpha\beta \sim 50\%$ were obtained with Delrin propellant in the laser lightcraft.

Jet exit velocities of ~ 2000 m/s with Delrin (based on measured mass) and ~ 3000 m/s with air (based on estimated mass).

BACKUP VU-GRAPHS ↓ →

Thermodynamic properties of equilibrium air,
$\rho = 1.18$ kg/m^3.

u MJ/kg	T 10^3 K	P bar	h MJ/kg	s KJ/kg K	c_p KJ/kg K	M_m kg/kmol	X(e)	v_a km/s	c_p/c_v
-0.9	0.298	1.00	0	6.864	1.005	28.965	0	0.35	1.40
1	1.6	5.4	1.5	8.2	1.25	29.0	4E-10	0.77	1.30
2	2.5	8.6	2.7	8.7	1.51	28.9	3.E-09	0.95	1.24
3	3.2	11.1	3.9	9.0	2.16	28.6	3.E-08	1.06	1.20
4	3.7	13.1	5.1	9.3	2.83	27.8	3.E-07	1.15	1.19
5	4.1	15.0	6.3	9.6	3.15	26.9	2.E-06	1.23	1.19
6	4.5	16.9	7.4	9.8	3.04	26.1	5.E-06	1.32	1.21
7	4.9	19.1	8.6	10.0	2.69	25.3	2.E-05	1.41	1.23
8	5.4	21.5	9.8	10.2	2.56	24.7	4.E-05	1.50	1.23
9	5.9	23.9	11.0	10.4	2.86	24.2	8.E-05	1.57	1.21
10	6.3	26.0	12.2	10.6	3.43	23.8	1.E-04	1.62	1.19
15	7.5	34.1	17.9	11.3	6.70	21.7	5.E-04	1.84	1.17
20	8.3	41.3	23.5	11.9	8.93	19.8	9.E-04	2.02	1.17
30	9.7	56.2	34.8	13.0	9.09	16.9	3.E-03	2.38	1.19
40	11.5	75.4	46.4	14.0	5.13	15.0	1.E-02	2.81	1.24
50	14.4	101	58.5	14.8	4.81	14.0	4.E-02	3.26	1.25
60	16.6	124	70.5	15.4	6.62	13.2	1.E-01	3.60	1.24
70	18.4	145	82.3	16.0	8.25	12.4	1.E-01	3.91	1.24
80	19.9	167	94.1	16.5	9.51	11.7	2.E-01	4.20	1.24
90	21.3	189	106.0	17.0	10.40	11.1	2.E-01	4.48	1.25
100	22.6	211	118.0	17.4	10.90	10.5	3.E-01	4.76	1.26
110	23.9	235	130.0	17.9	11.10	10.0	3.E-01	5.03	1.27

THE COUPLING COEFFICIENT AND THE SPECIFIC IMPULSE

$$Q^* = \beta E_L/m$$

$$E_{jet} = \tfrac{1}{2}\, m\langle v^2\rangle = \alpha m Q^* = \alpha\beta E_L$$

$$\mathbf{I} = m\langle \mathbf{v}\rangle$$

$$C = \frac{\mathbf{I}}{E_L}$$

$$\tfrac{1}{2}C\langle v\rangle = \alpha\beta\Phi \leq 1$$

$$P_L = \omega E_L$$

$$\mathbf{F} = \omega E_L \mathbf{C}$$

$$\tfrac{1}{2}\mathbf{F}\langle \mathbf{v}\rangle = \alpha\beta\Phi\, P_L$$

$$P_{jet} = \frac{1}{2}\frac{\mathbf{F} < \mathbf{v} >}{\Phi} = \alpha\beta\, P_L$$

$$(\alpha\beta\Phi)_{apparent} = \alpha\Phi(\beta + m\Delta u_{chem}/E_L)$$

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Laser Lightcraft Flights with Air: $h = 1/2t^2(CE_Lw/M\text{-}g) = 1/2gt^2(T/W-1)$

Model 200-3/4, M = 0.04 kg, 10 kW at w = 25 Hz, E_L = 400 J/pulse

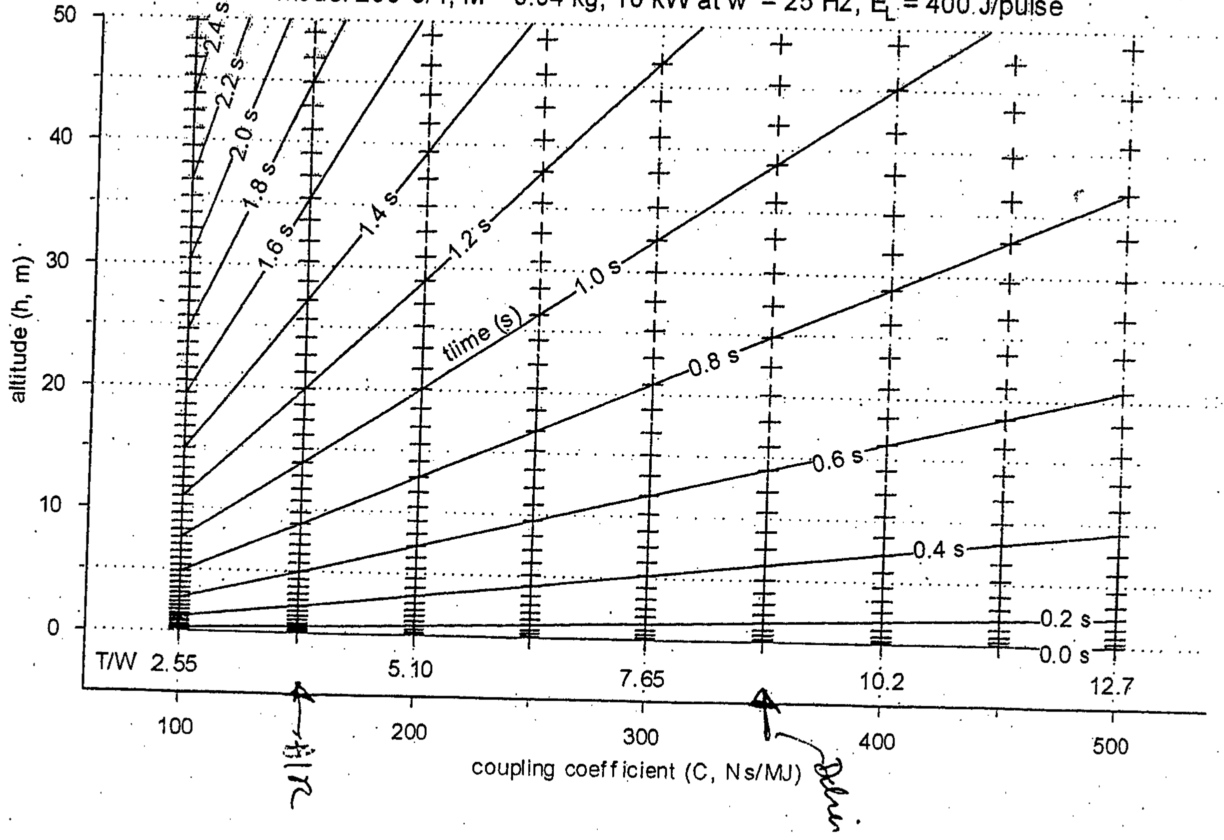

Table 1. Normalized absorption volume for air at 1.18 kg/m^3 as a function of internal energy and laser energy.

u	V_{abs}/β, normalized absorption volume, cm^3					
MJ/kg	E_L=50 J	E_L=100 J	E_L=150 J	E_L=200 J	E_L=300 J	E_L=400 J
1	42.3	84.7	127.1	169.4	254.2	338.9
2	21.1	42.3	63.5	84.7	127.1	169.4
3	14.1	28.2	42.3	56.5	84.7	112.9
4	10.5	21.1	31.7	42.3	63.5	84.7
5	8.47	16.9	25.4	33.9	50.8	67.8
6	7.06	14.1	21.1	28.2	42.3	56.5
7	6.05	12.1	18.1	24.2	36.3	48.4
8	5.30	10.5	15.8	21.1	31.7	42.3
9	4.71	9.42	14.1	18.8	28.2	37.6
10	4.24	8.47	12.7	16.9	25.4	33.9
15	2.82	5.65	8.47	11.3	16.9	22.6
20	2.12	4.24	6.36	8.47	12.7	16.9
30	1.41	2.82	4.24	5.65	8.47	11.3
40	1.06	2.12	3.18	4.24	6.36	8.47
50	0.85	1.69	2.54	3.39	5.08	6.78
60	0.71	1.41	2.12	2.82	4.24	5.65
70	0.61	1.21	1.82	2.42	3.63	4.84
80	0.53	1.06	1.59	2.12	3.18	4.24
90	0.47	0.94	1.41	1.88	2.82	3.77
100	0.42	0.85	1.27	1.69	2.54	3.39
110	0.39	0.77	1.16	1.54	2.31	3.08

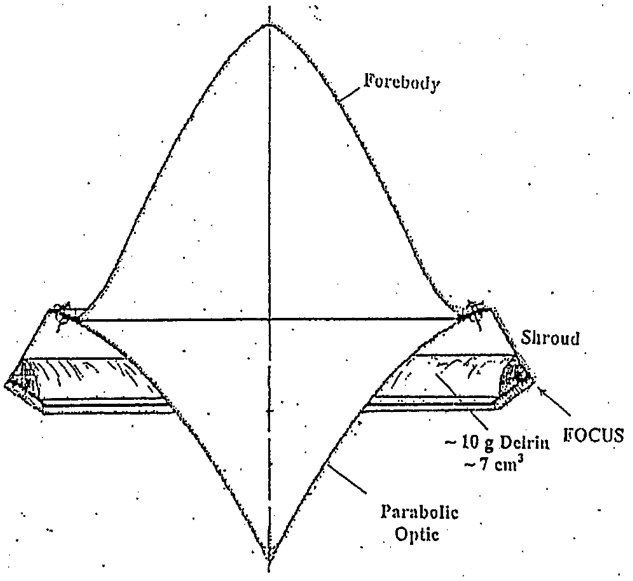

Figure 1. Cross-sectional view of Myrabo Laser Lightcraft, Model 200-3/4. The maximum diameter of the test article at the shroud is ~ 10 cm. The indicated ring of Delrin weighs ~ 10 g and has a volume of ~ 7 cm^3 and a surface area ~ 25 cm^2. The idealized plug nozzle exit area is ~ 350 cm^2.

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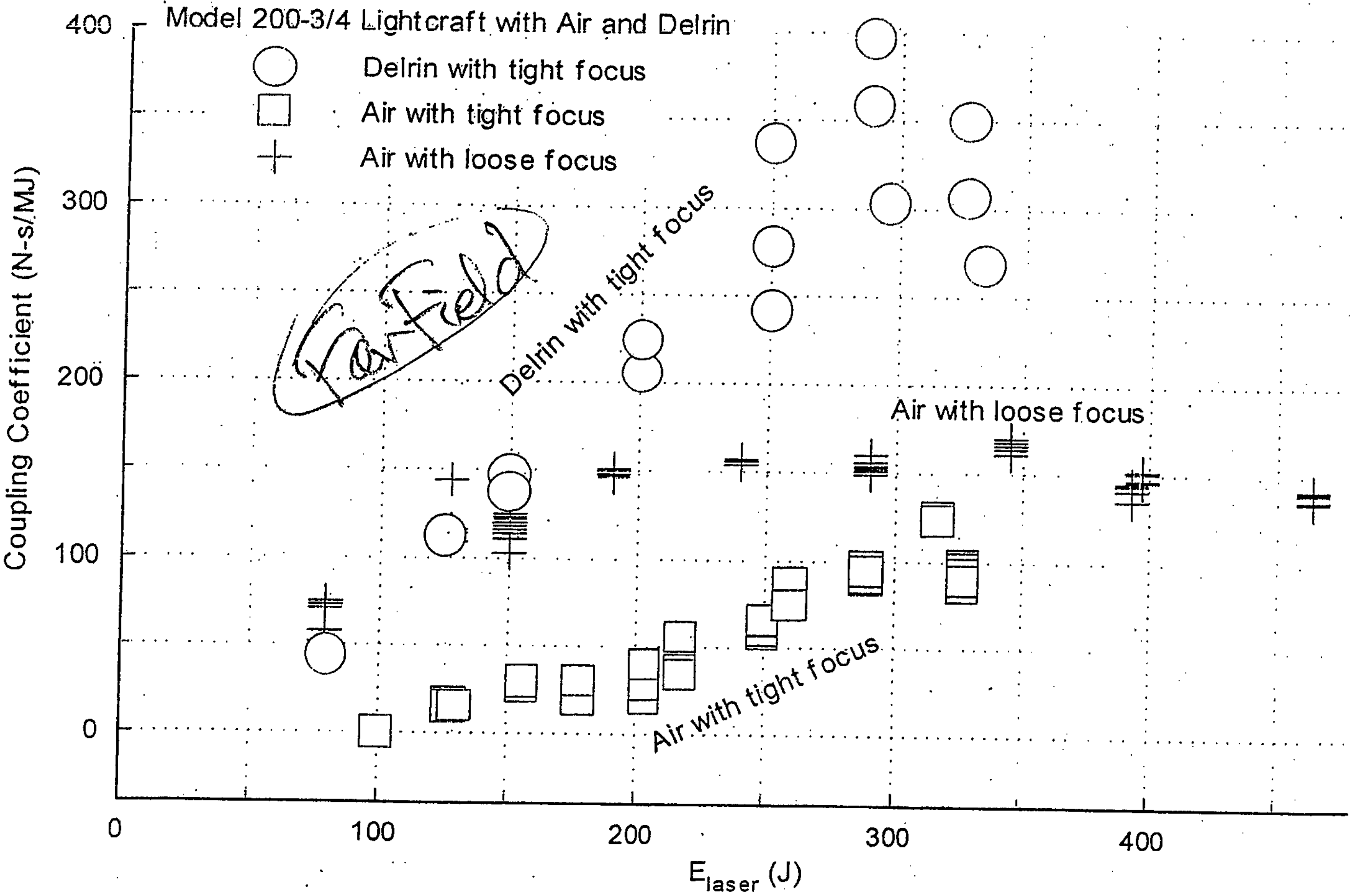

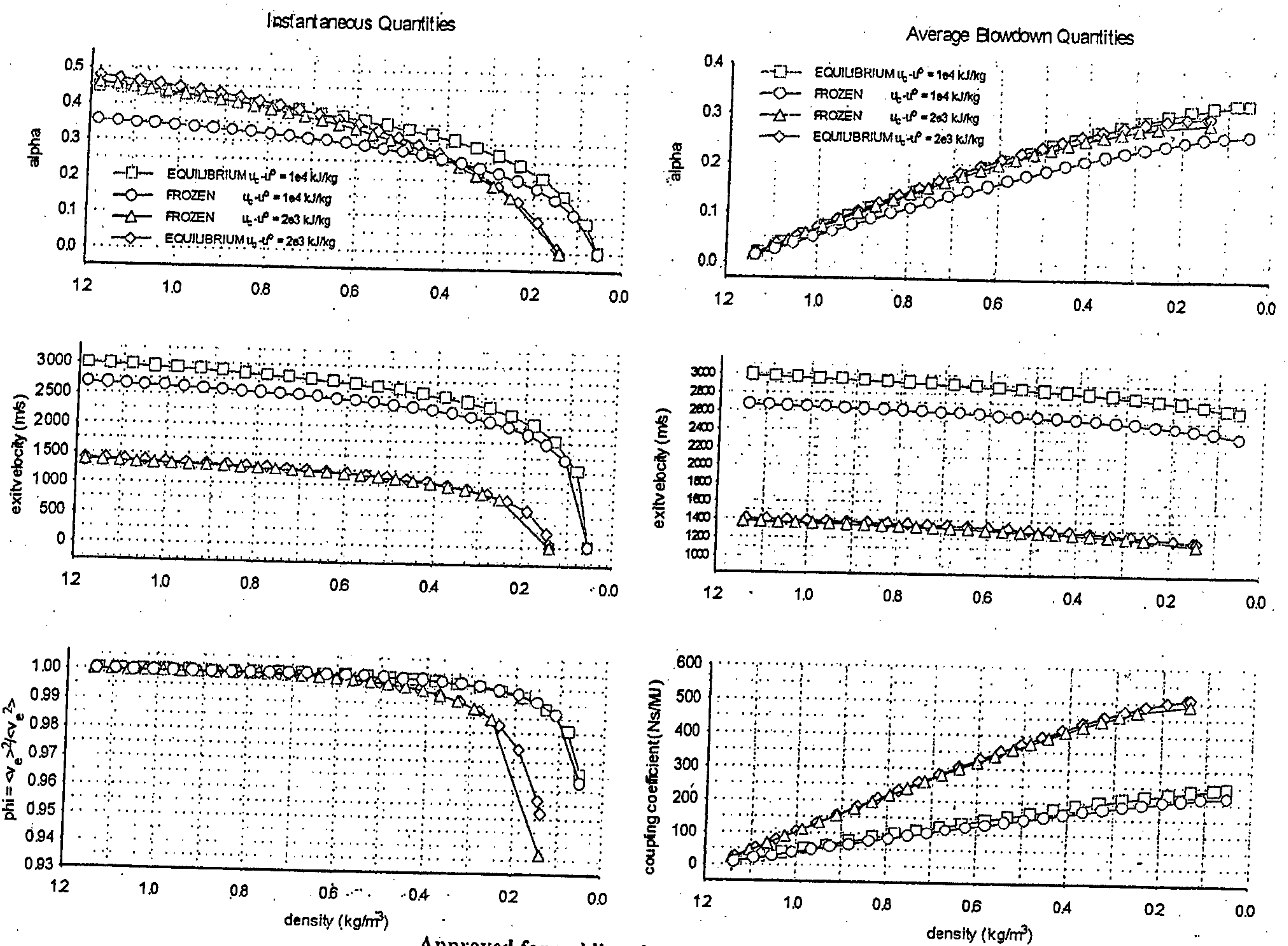

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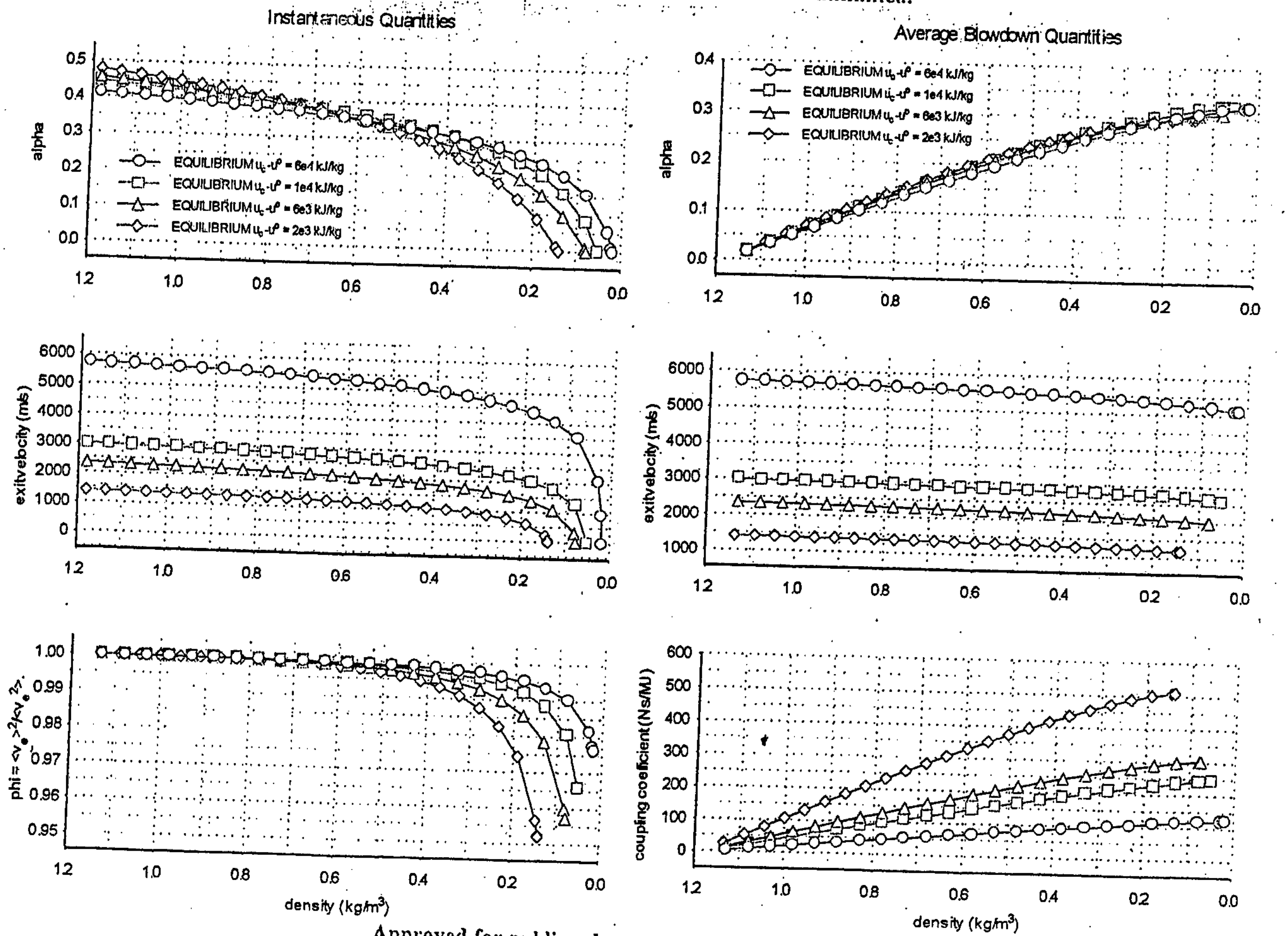

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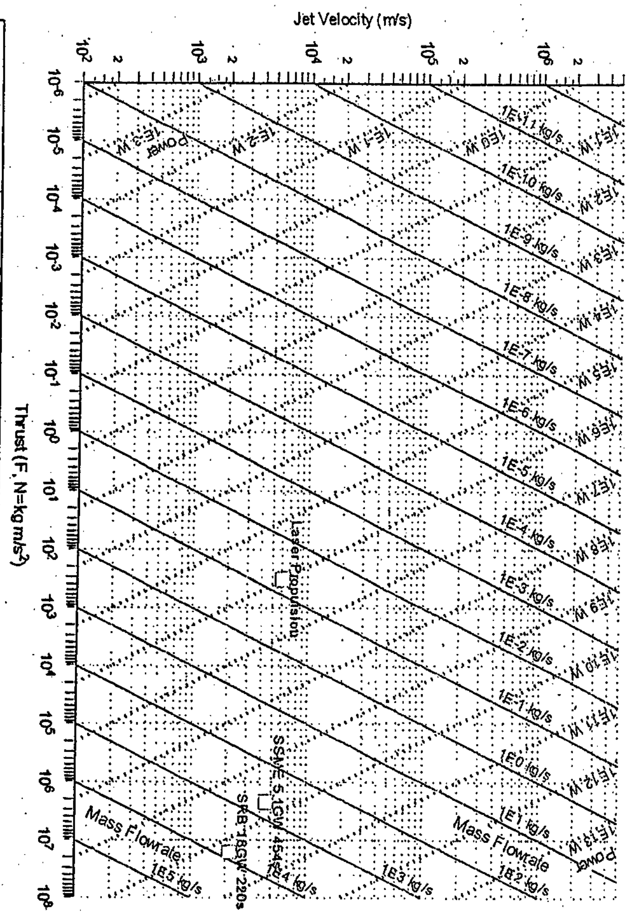


Figure 1. Parameter space for rockets: $F = v_e\,dm/dt$, and P (power) $= \frac{1}{2}\,dm/dt\,v_e^2$.

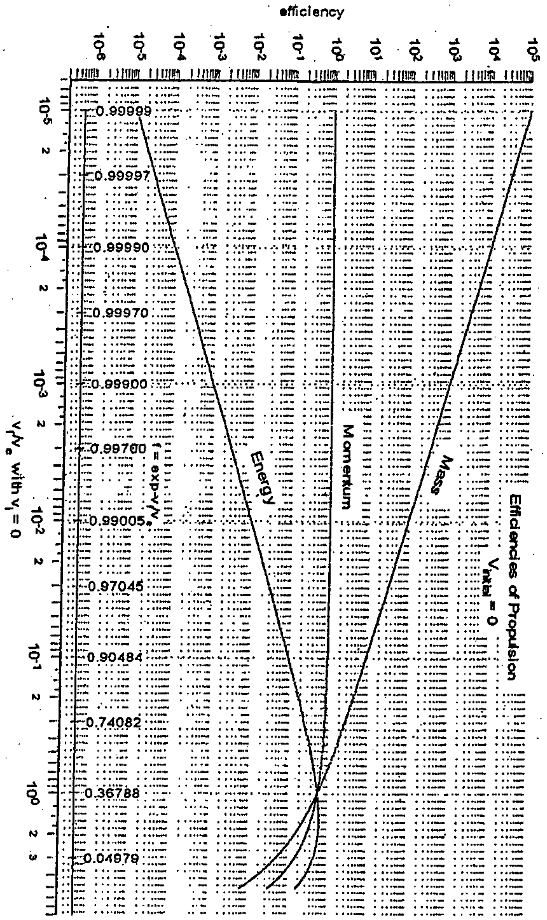
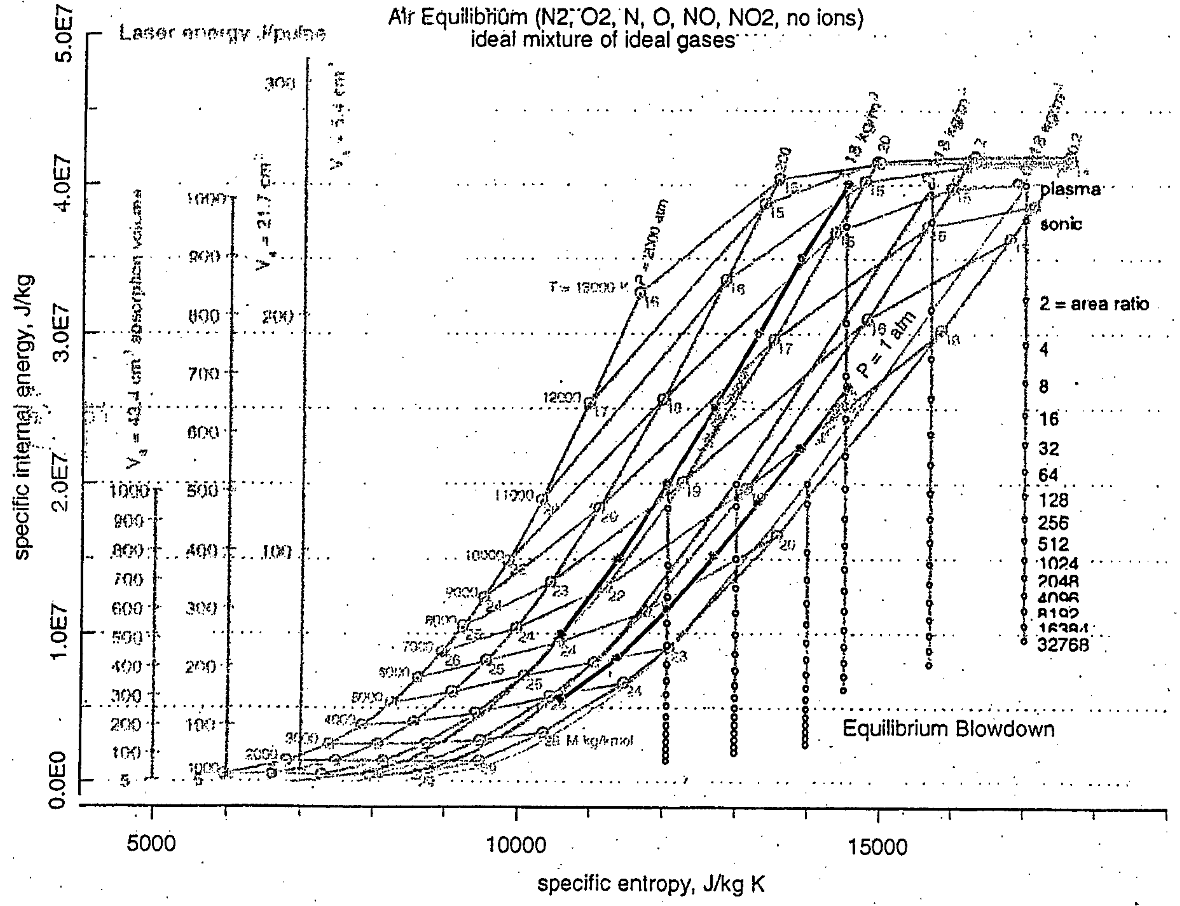


Figure 2a. Propulsion efficiencies for missions with zero initial velocity.



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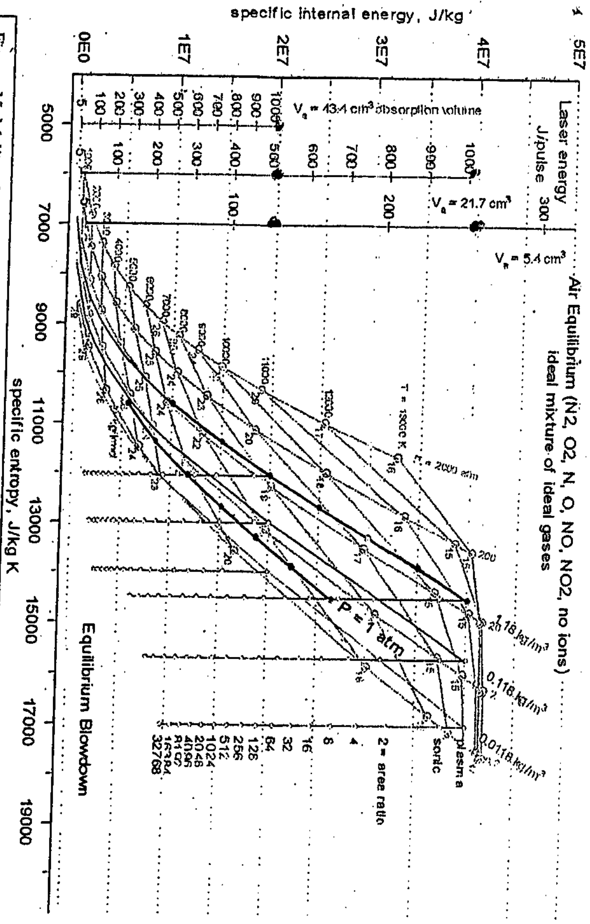


Figure 15. Mollier diagram for equilibrium air without ions. Numbers adjacent to intersections of isobars and isotherms indicate average molecular weight. Upper heavy line is a constant density = 1.18 kg/m³ line. three isentropes from u = 4e7 and 2e7 J/kg represent equilibrium blowdown for the indicated area ratios, 1 to 32768. The P = 1 atm isobar is reached with an area ratio ~ 8 from the initial u = 4e7 and ~ 4 from the u = 2e7 J/kg state, respectively. The exit velocities from these two expansions are ~ 5000 and 3000 m/s, respectively.

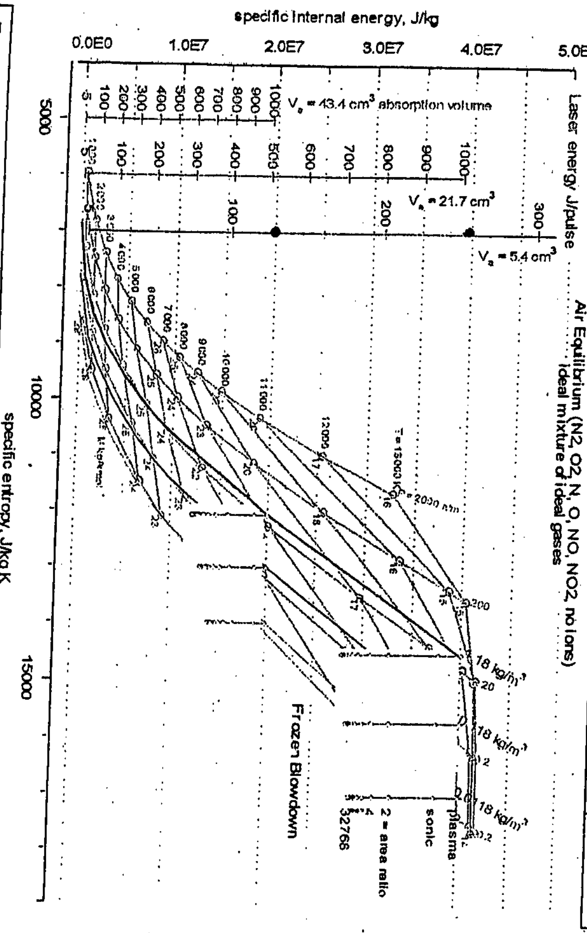
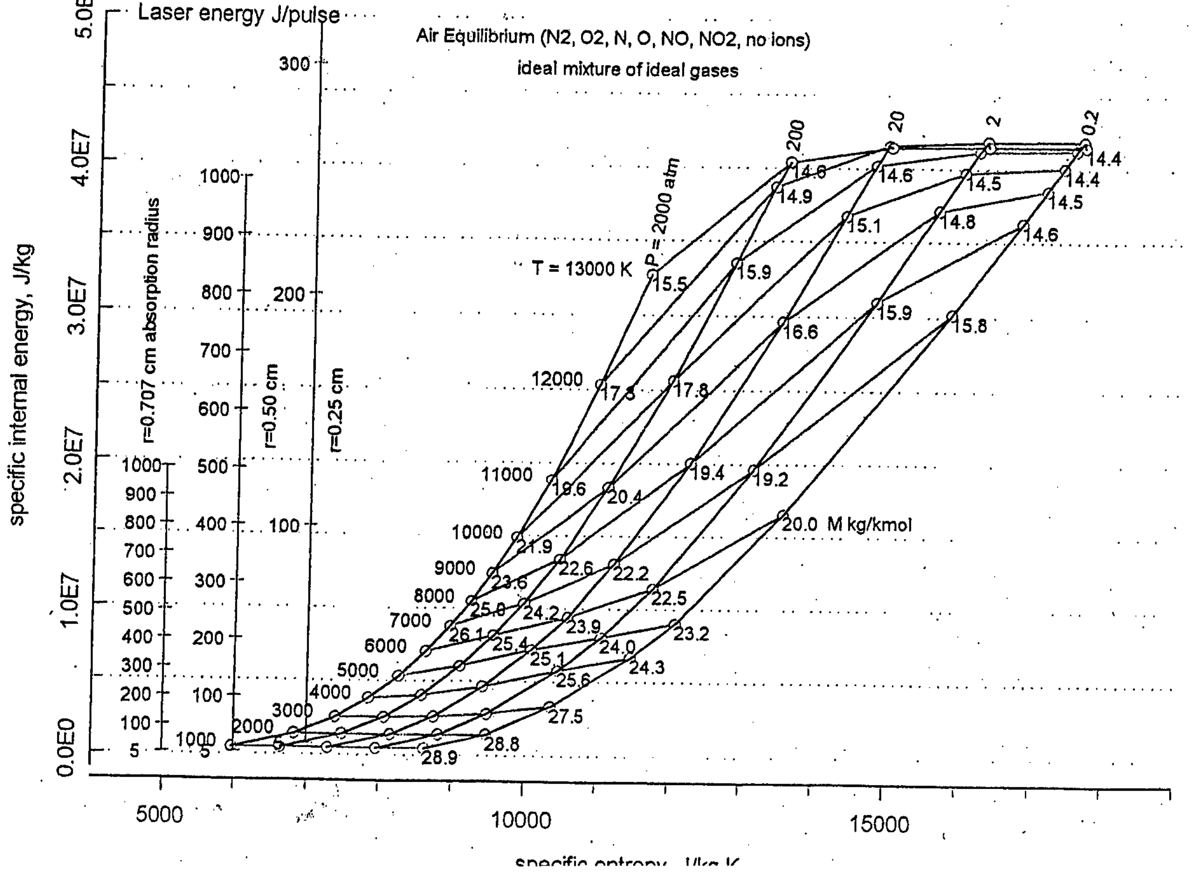


Figure 16. Process representations of air expansion with frozen blowdown, as in Figure 15. The frozen isentropic expansions from u = 4e7 and 2e7 J/kg and 1.18 kg/m3 to 1 atm produce exit velocities of 5000 and



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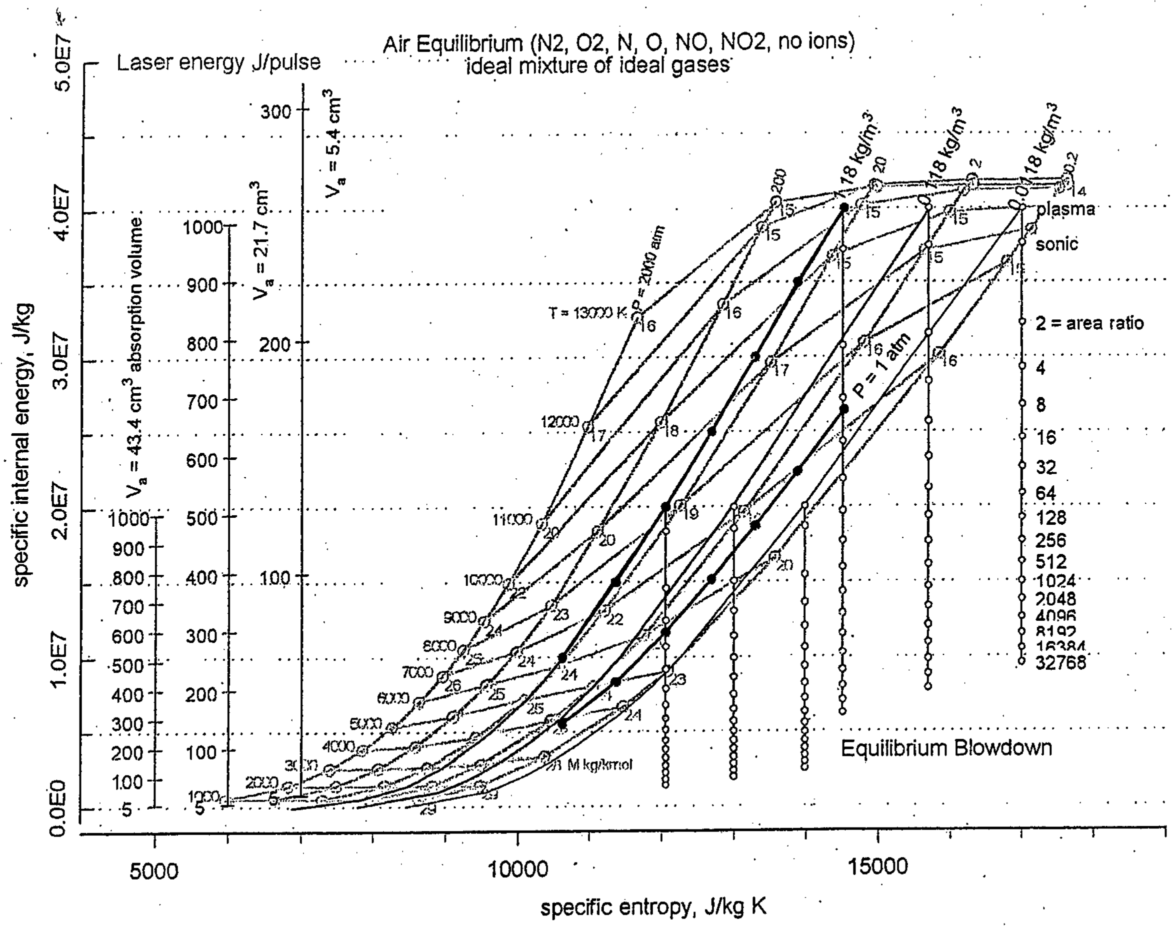

Air Equilibrium (N2, O2, N, O, NO, NO2, no ions)
ideal mixture of ideal gases

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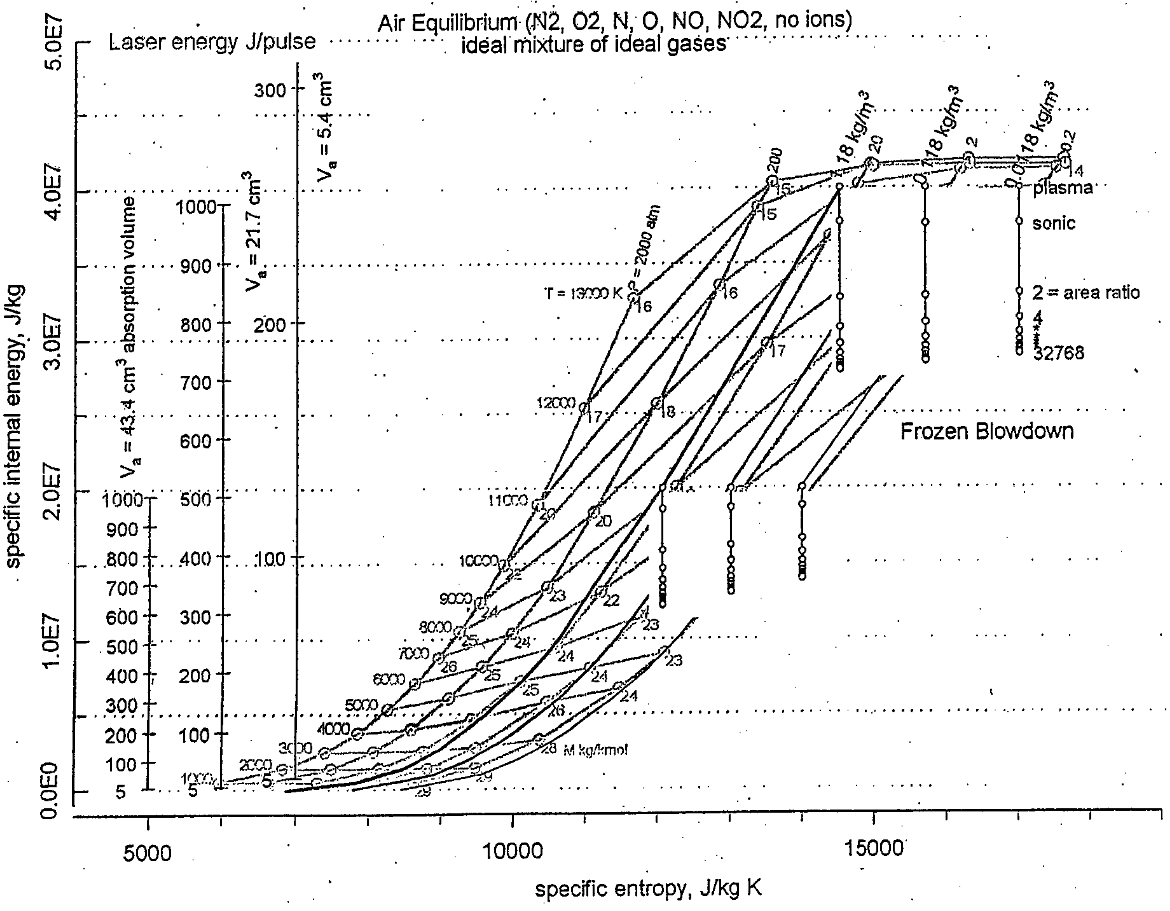


Air Equilibrium (N2, O2, N, O, NO, NO2, no ions)
ideal mixture of ideal gases

Thermodynamic properties of Mach 5 air at stagnation density,

$\rho = 5.90$ kg/m^3.

u MJ/kg	T 10^3 K	P bar	h MJ/kg	s KJ/kg K	c_p KJ/kg K	M kg/kmol	$X(e^-)$	v_a km/s	c_p/c_v
0.102	0.560	9.492	0.263	6.864	1.042	28.965	0	0.471	1.38
1	1.6	27.1	1.5	7.7	1.25	28.97	4e-13	0.77	1.30
2	2.6	43.2	2.7	8.2	1.45	28.95	6.E-11	0.96	1.25
3	3.3	56.5	4.0	8.6	1.85	28.73	2.E-08	1.08	1.21
4	3.9	67.7	5.1	8.9	2.33	28.19	3.E-07	1.17	1.20
5	4.4	78.2	6.3	9.1	2.65	27.46	2.E-06	1.26	1.20
6	4.8	88.9	7.5	9.3	2.71	26.69	6.E-06	1.35	1.22
7	5.3	100.3	8.7	9.5	2.61	25.96	2.E-05	1.45	1.23
8	5.8	112.4	9.9	9.7	2.55	25.32	4.E-05	1.53	1.23
9	6.3	124.5	11.1	9.9	2.69	24.79	8.E-05	1.61	1.22
10	6.7	135.8	12.3	10.0	3.04	24.32	1.E-04	1.67	1.21
15	8.2	182.0	18.1	10.7	5.49	22.19	6.E-04	1.91	1.18
20	9.2	222.3	23.8	11.2	7.36	20.32	1.E-03	2.11	1.18
30	10.8	304.9	35.2	12.2	8.05	17.41	3.E-03	2.49	1.20
40	12.7	404.9	46.9	13.1	5.52	15.45	1.E-02	2.92	1.24
50	15.6	534.8	59.1	13.8	4.28	14.33	3.E-02	3.39	1.27
60	18.4	667.9	71.3	14.4	5.20	13.54	8.E-02	3.78	1.26
70	20.8	794.6	83.5	14.9	6.32	12.81	1.E-01	4.13	1.27
80	22.8	919.9	95.6	15.4	7.26	12.14	2.E-01	4.45	1.27
90	24.6	1046.6	107.7	15.8	7.99	11.52	2.E-01	4.76	1.28

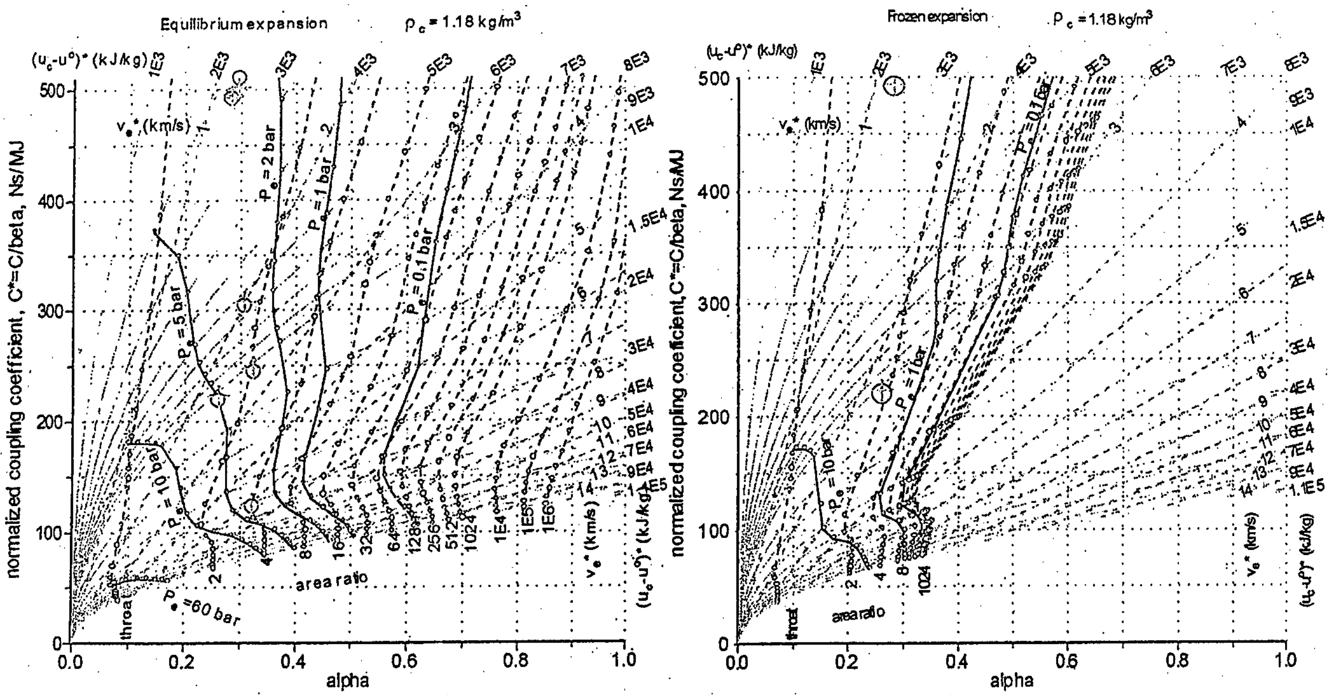


Figure 10. Comparison of Equilibrium expansion and frozen expansion of air. The circles and nearby crosses represent the blowdown quantities obtained from initial $[u_c\text{-}u^o]^*$ states of 2E3, and 1E4 J/kg for the frozen expansion and 2E3, 6E3, 1E4, and 4E4 kJ/kg for the equilibrium expansion. The results of the two frozen blowdown integrations to P_{exit} = 1 bar are plotted with those of the equilibrium blowdown to show that the differences in alpha are small, i.e., at low energy (2E3) 0.30 and 0.29 and at high energy (1E4) 0.32 and 0.27 for equilibrium and frozen blowdown, respectively.

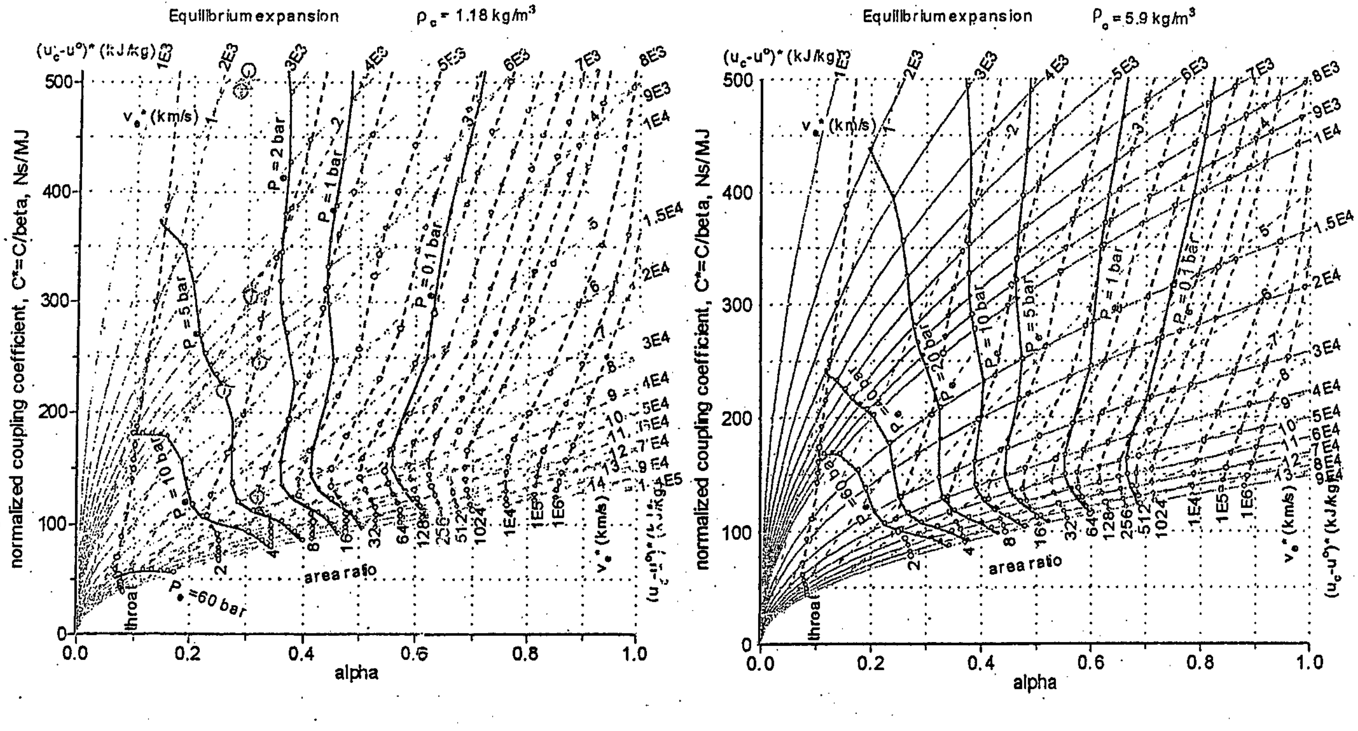
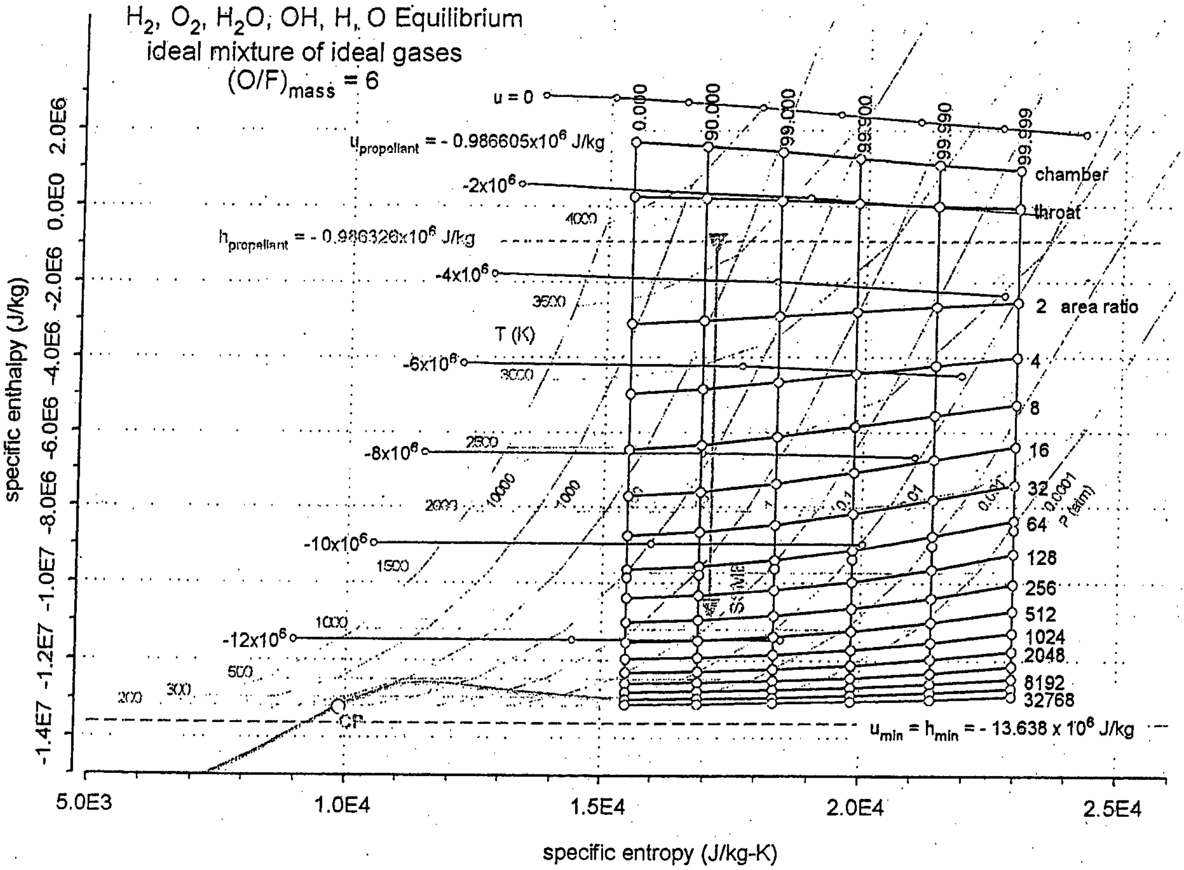


Figure 11. Comparison of Equilibrium expansion from laser heated STP air (1.18 kg/m^3) and Mach 5 air at stagnation density (5.9 kg/m^3). In the STP air diagram (on left), the circles and nearby crosses represent the blowdown quantities obtained from initial $[u_c\text{-}u^o]^*$ states of 2E3, and 1E4 J/kg for the frozen expansion and 2E3, 6E3, 1E4, and 4E4 kJ/kg for the equilibrium expansion.



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