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a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) (661) 275-5015

MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TI) (STINFO)

19 Jun 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-135**
Mead, F., "Beamed Energy (Laser) Propulsion"

AIAA Short Course
(Huntsville, AL, 21-22 Jul 2000)

(Statement A)
(Submission Deadline: 9 Jun 2000)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

Comments: _____

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2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release and/or b) possible higher headquarters review.

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Comments: _____

APPROVED/APPROVED AS AMENDED/DISAPPROVED

LESLIE. S. PERKINS, Ph.D (Date)
Staff Scientist
Propulsion Directorate



BEAMED ENERGY (LASER) PROPULSION (A Perspective)

by

Dr. Franklin B. Mead, Jr.

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Distribution Statement: Approved for public release; distribution unlimited



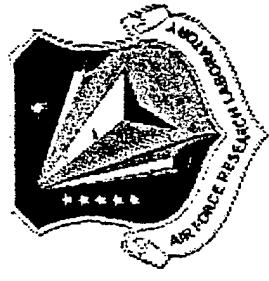
Outline



- Preliminaries
- Historical Overview
 - The Early Years 1970-1990
- Concepts From The Early Years
 - Project Outgrowth
 - Paraboloid
 - Absorption Chamber
 - Heat Exchanger
- Developments In The 90's
 - Domenstic
 - NASA
 - Air Force (Lightcraft)
 - Foreign
- References



What is Laser Propulsion?



- Propulsion System Using (typically) External Laser Power Source (ground and/or space based)
 - Heats Propellant to Very High Temperatures
 - Provides Energy Source For Electrical Power Generation
 - Provides Direct Photon Force

“Laser propulsion is an idea that may produce a revolution in space technology.”

JASON Laser Propulsion Study, Summer 77



Background



- **Why Laser Propulsion**

- Decoupled Energy Source
- High Specific Impulse (Isp) Potential
- High Thrust Relative to Electric Concepts
- Avoids the Radiation and Mass Penalties Inherent With Nuclear Propulsion
- Technical Problems are not Fundamental
- Economic Justification Concluded in Separate Studies by AF, NASA, & DARPA

- **Mission Potential**

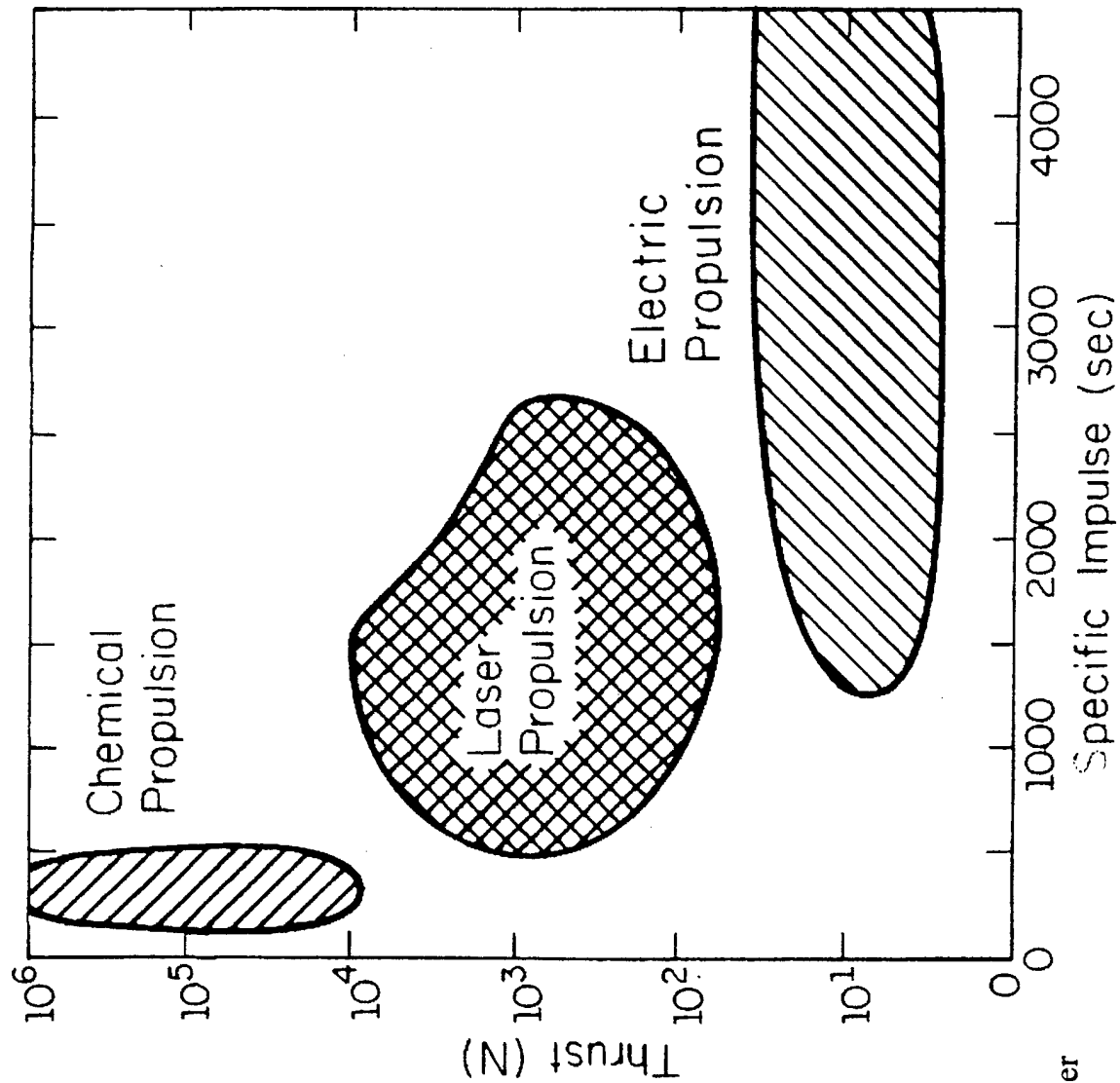
- Low Cost Access to Space
- Orbit Raising
- Kinetic Kill Vehicles (KKV)

- **Problems**

- Lacks Complete Demonstration After 31 Years From Conception
- Reduced Funding for Demonstration
- Low Interest



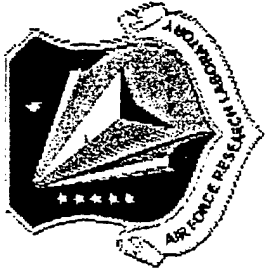
Laser Propulsion Performance Relationships*



*U. of Illinois report by Dr. Krier
Under AFOSR Contract



Propulsion Relations



Rocket:

F = Thrust
_ = Weight Flowrate
g = Gravitational Acceleration

- $I_{sp} = F / _$ ← Specific Impulse (s)
- $P = _ g F I_{sp}$ ← Exhaust Power (J)

weight flow rate is not the same as mass flow rate and is not the same as thrust

Pulse Jet:

I = Impulse Bit (N-s/pulse)
E = Total Energy in a Laser Pulse (MJ/pulse)
t = Pulse Length or Width (s)
f = Pulse Frequency (s⁻¹)

- $\eta (CC \text{ or } C_m) = I/E$ ← Coupling Efficiency (N-s/MJ)
- $F = \eta(E/t) = I/t$ ← Thrust per Pulse (N)
- $F_{av} = f(Ft) = f(\eta E) = fI$ ← Average Integrated Thrust
- $F_{lbs} = F_N / 4.45$ ← Conversion to Pounds Thrust of ?



Brief History



Beamed Energy Rockets

- Microwaves - Willinski (1959)
- Lasers - Light Sails - Forward (1962)
- Rockets - Geisler (1969), Kantrowitz (1972)

Propulsion Activities

- AFRPL 1972 - Inhouse (Project Outgrowth Report) & Contracted Efforts - TRW, PSI
- NASA 1972 - NASA Lewis Inhouse & Contracted Efforts - PSI, Lockheed, Rocketdyne
- Micom, 1977 - NASA Marshall Inhouse & Contracted Efforts - PSI, U.S. Army Lockheed, BDM, UTSL, UAH
- DARPA 1977 - JPL - System Studies - Lockheed, Boeing
- AFOSR 1977 - AVCO Everett Study
- SDIO 1983 - Contracted Efforts - Penn State, PSI, UTSL, U. Illinois
- 1986 - LLNL Inhouse & Contracted Efforts - AVCO, Spectra Technologies, NRL, PSI, RPI



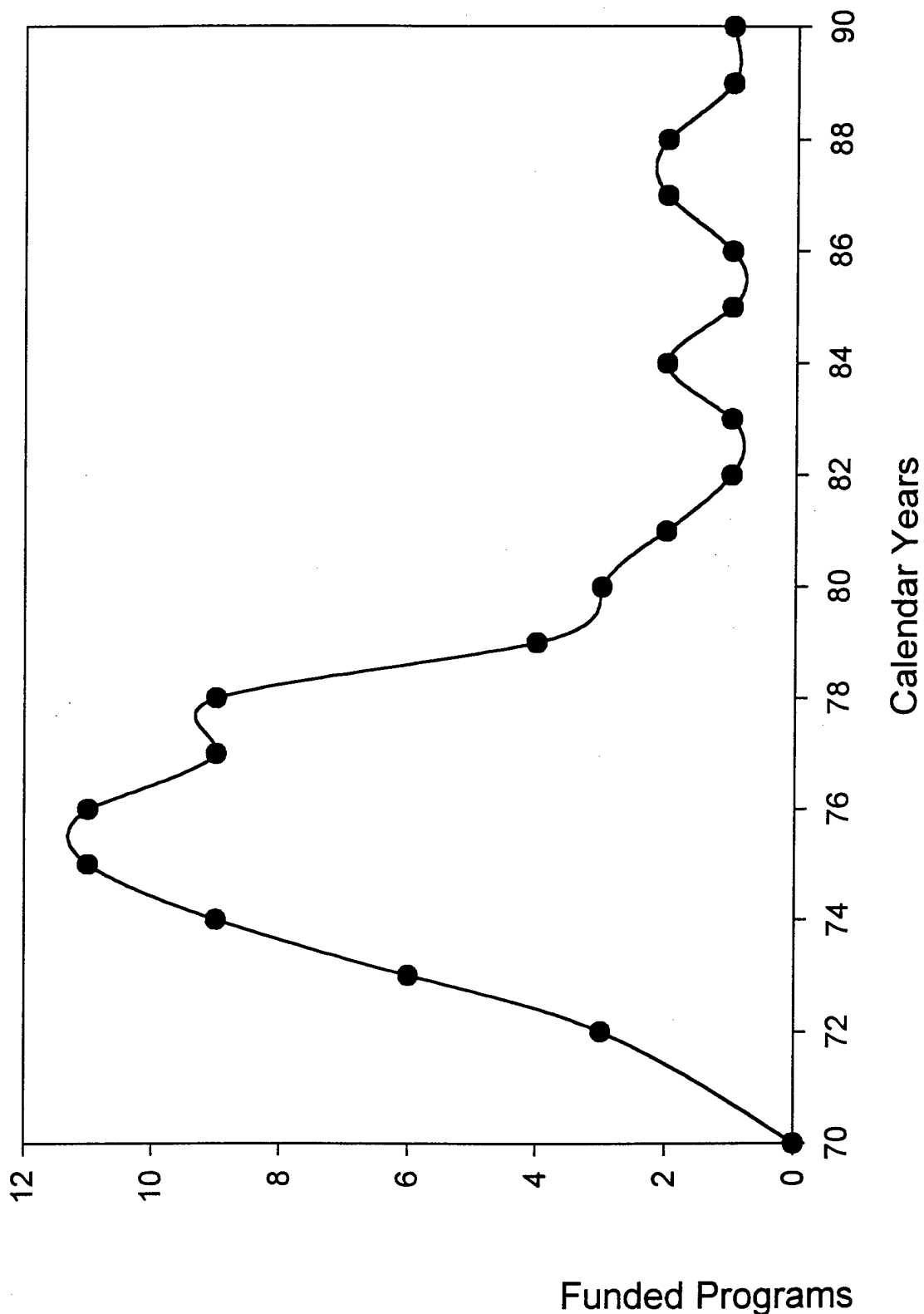
Major Laser Propulsion Funding Agencies and Contractors

The Early Years: 1972-1990



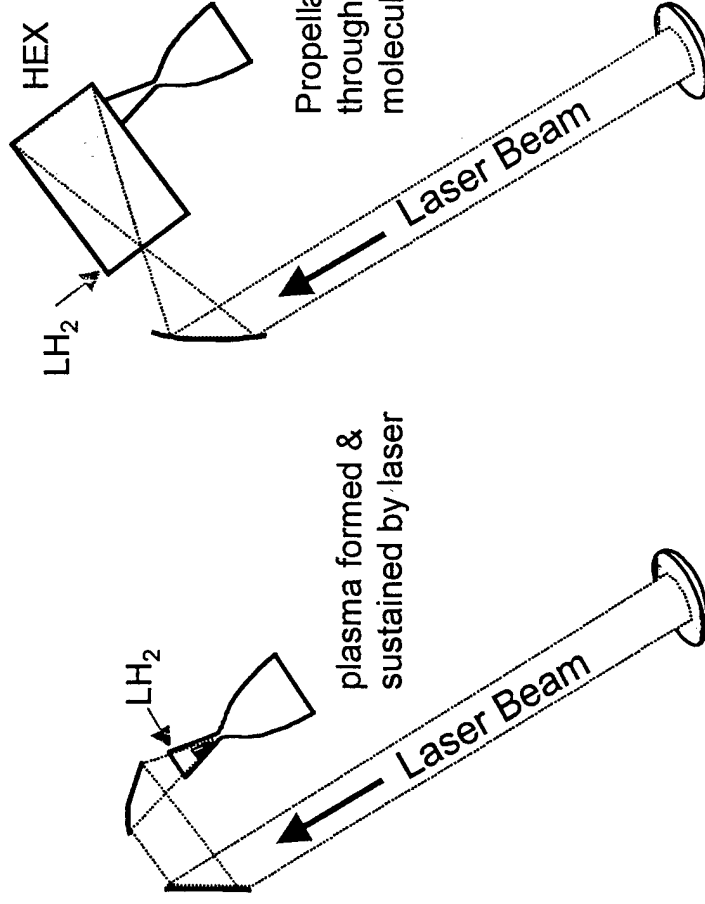
Contractors →		→ Funding	
AF Rocket Propulsion Lab.	80/81	Physical Sciences Inc.	AVCO Everett Research Lab. Inc.
AF Office of Scientific Research	83/84	Mathematical Sciences NW Inc.	Lincoln Lab.
SAMSO (Los Angeles AF Station)	73	Lockheed Missiles & Space Co.	TRW
NASA/MSFC	78/80	75/76	Rocketdyne
NASA/LEWIS	74/77	76/78	75/77
NASA/JPL			
DARPA (ARPA)	76/82	74/78	75
US Atomic Energy Commission			74
US Energy Research & Dev.			75
Army			
SDIO			87/90
			77
			74
			75
			73/75
			75
			84
			74/75
			74/77
			73/74
			85/91
			87/88
			77/79
			U. of Illinois
			Photonic Associates
			Hughes Research Lab
			JPL
			Redstone Arsenal
			Aberdeen Proving Ground
			Harry Diamond Lab.
			Battelle Lab.

Laser Propulsion Interest During the Early Years



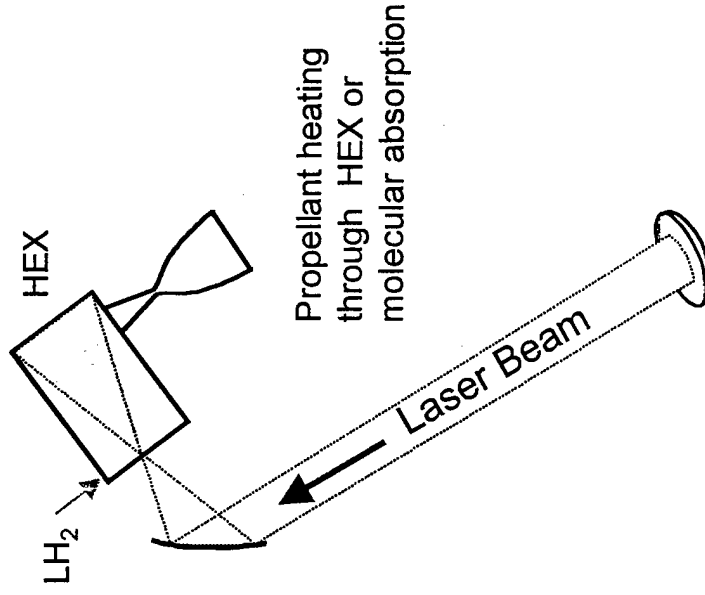


Laser Propulsion Concepts*



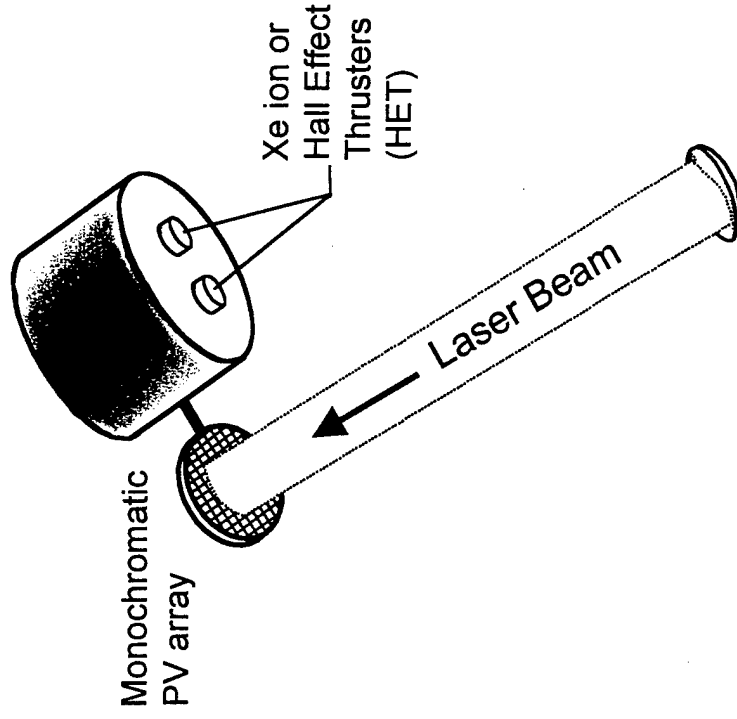
Laser Plasma

(Is = 1000 to 1500 sec)



Laser Thermal

(Is = 700 to 1100 sec.)



Laser Electric

(Is = 1200 to 4000 sec.
at low thrust)

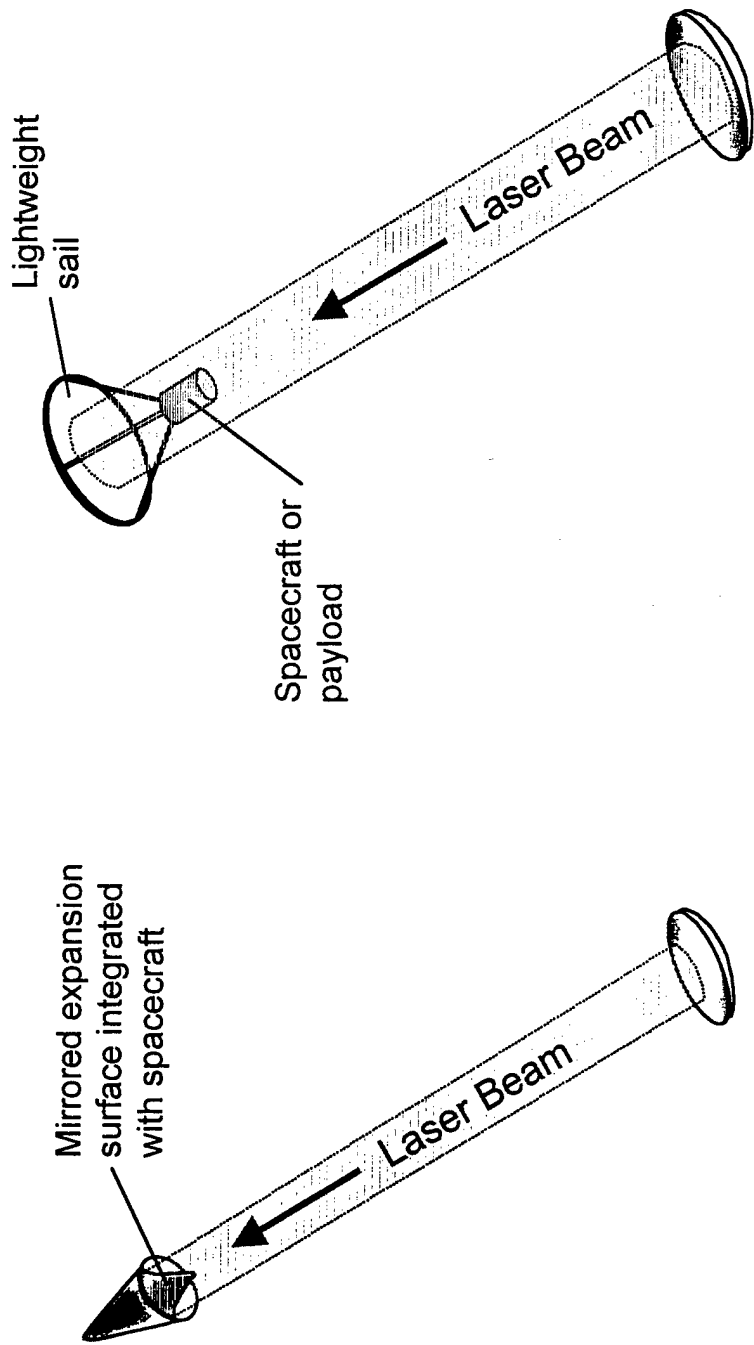
*Taken from Mr. Jim Shoji, Rocketdyne, Boeing Co.



Laser Propulsion Concepts*

(cont'd)

concluded



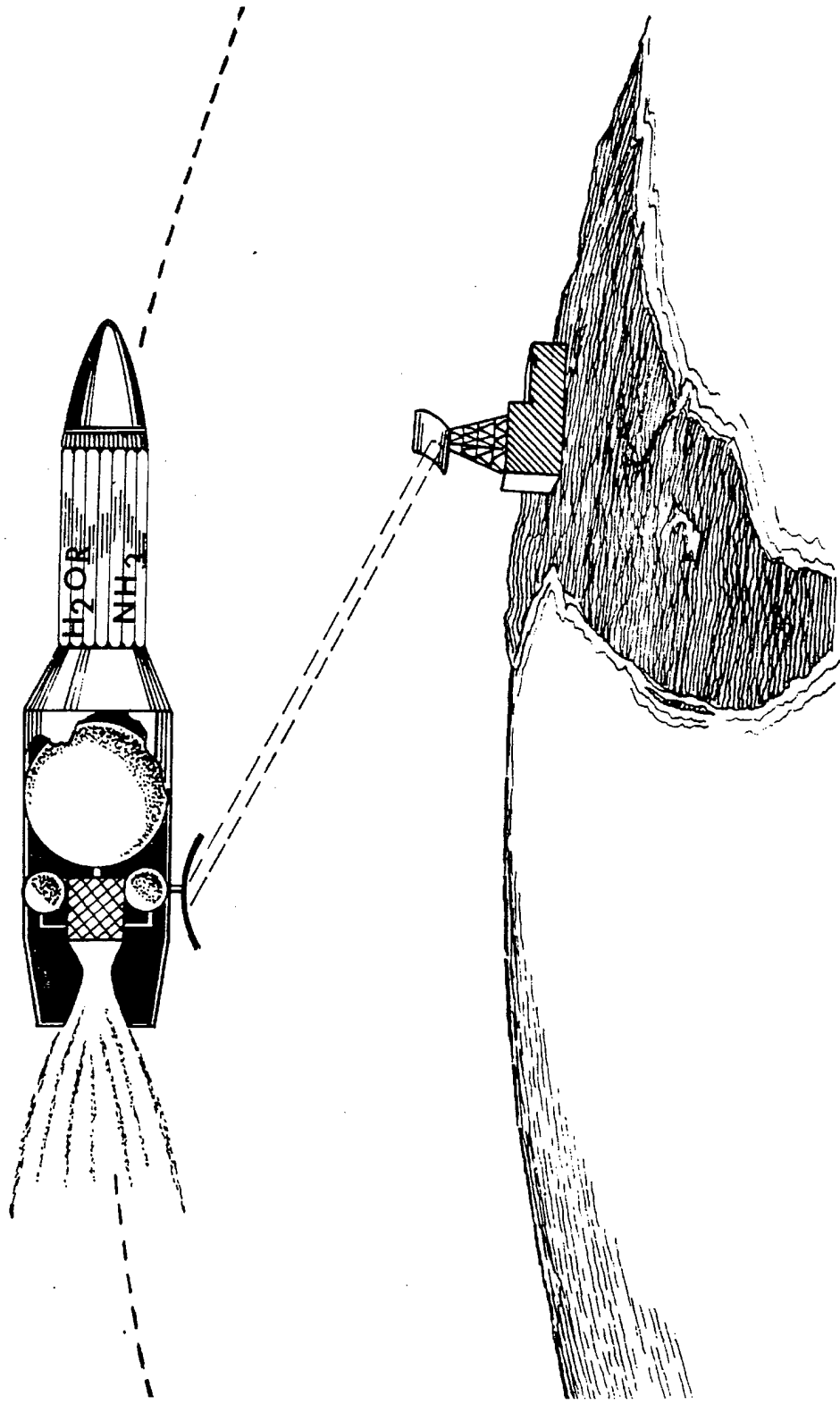
Laser Detonation
(Isp: Essentially infinity in air)

Laser Sail
(Isp: Essentially infinity)

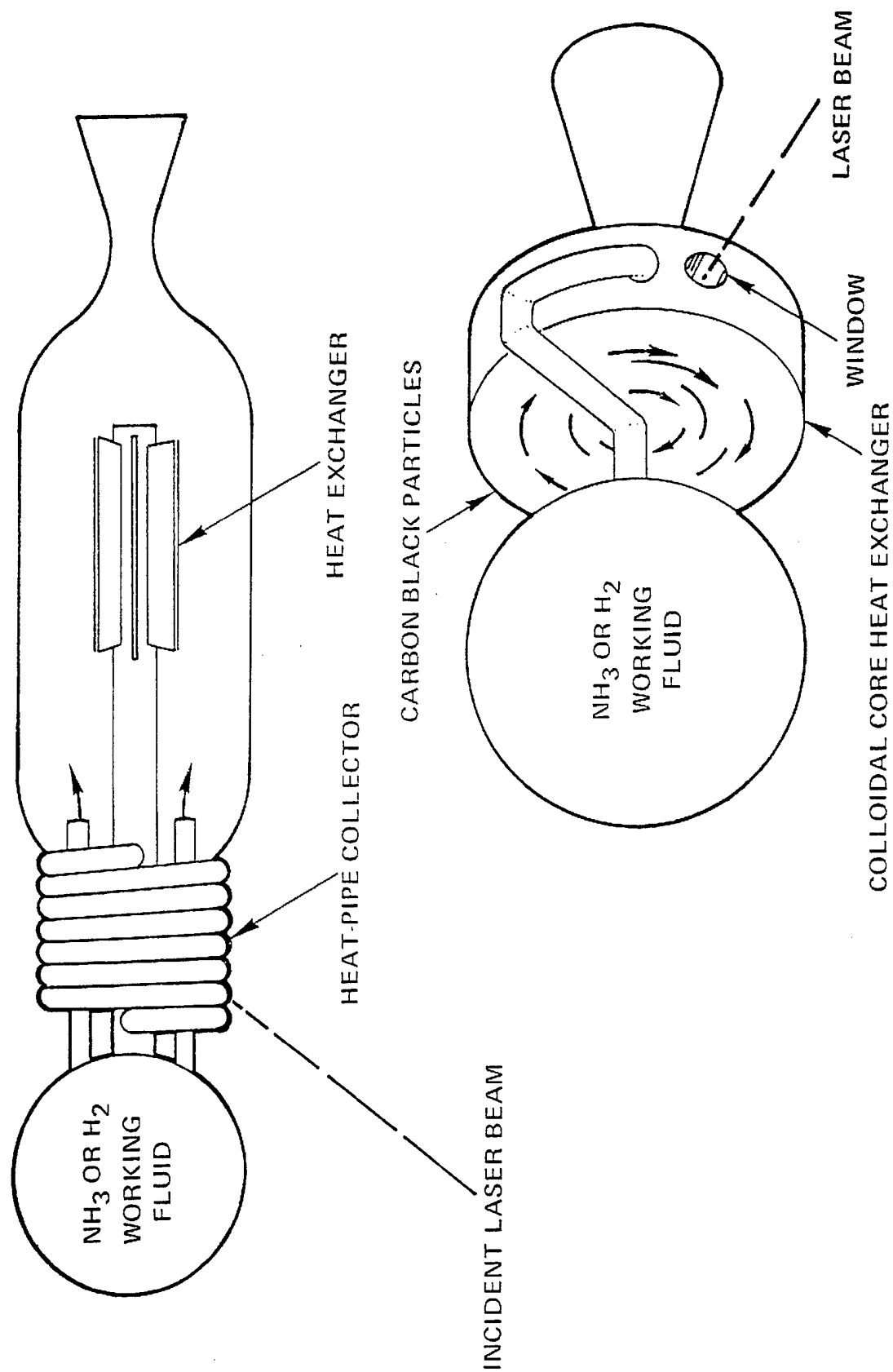
*Taken from Mr. Jim Shoji, Rocketdyne, Boeing Co.



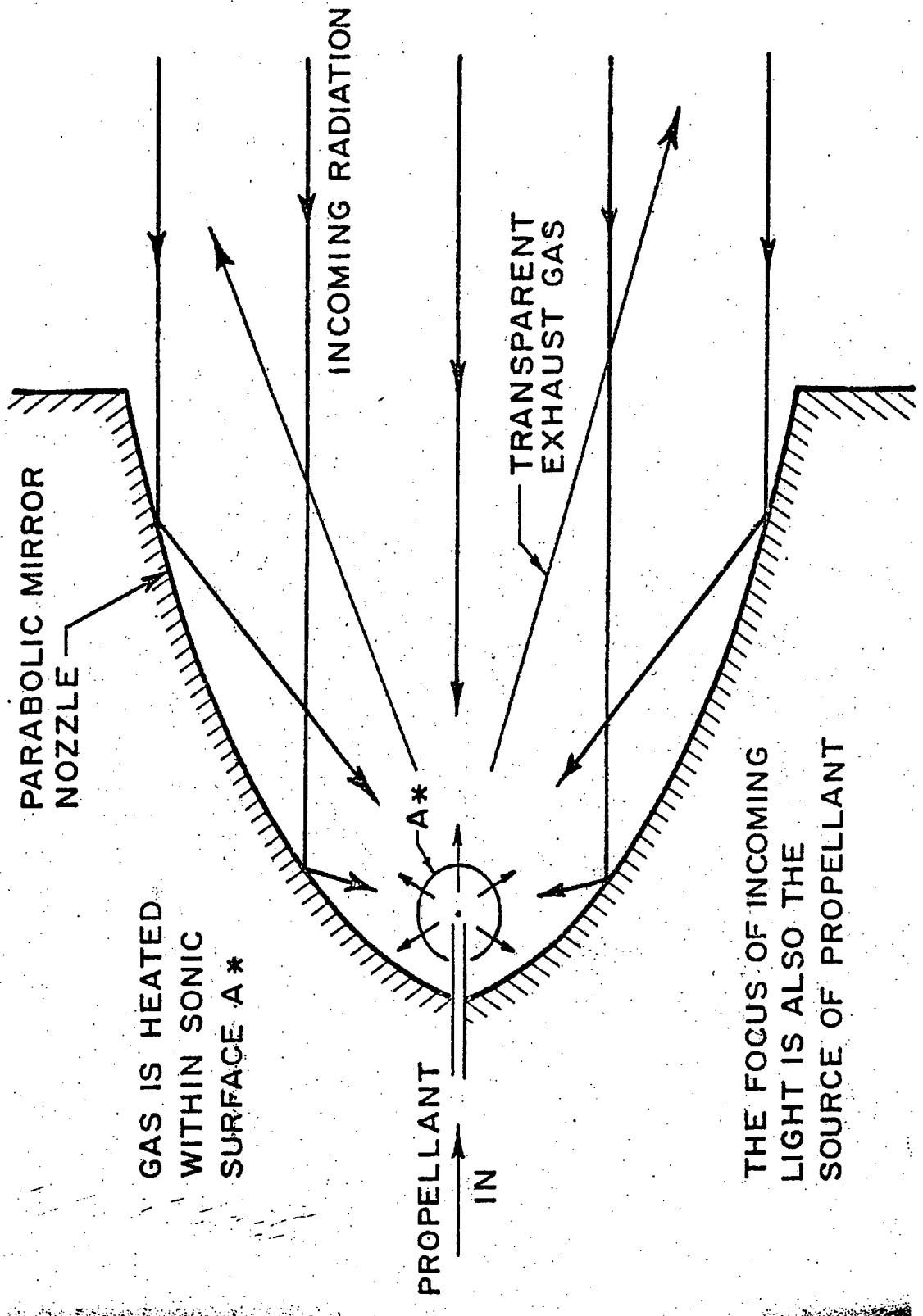
Laser Propulsion (Project Outgrowth) (Circa 1970)



Laser Propulsion (Project Outgrowth) (Circa 1970)

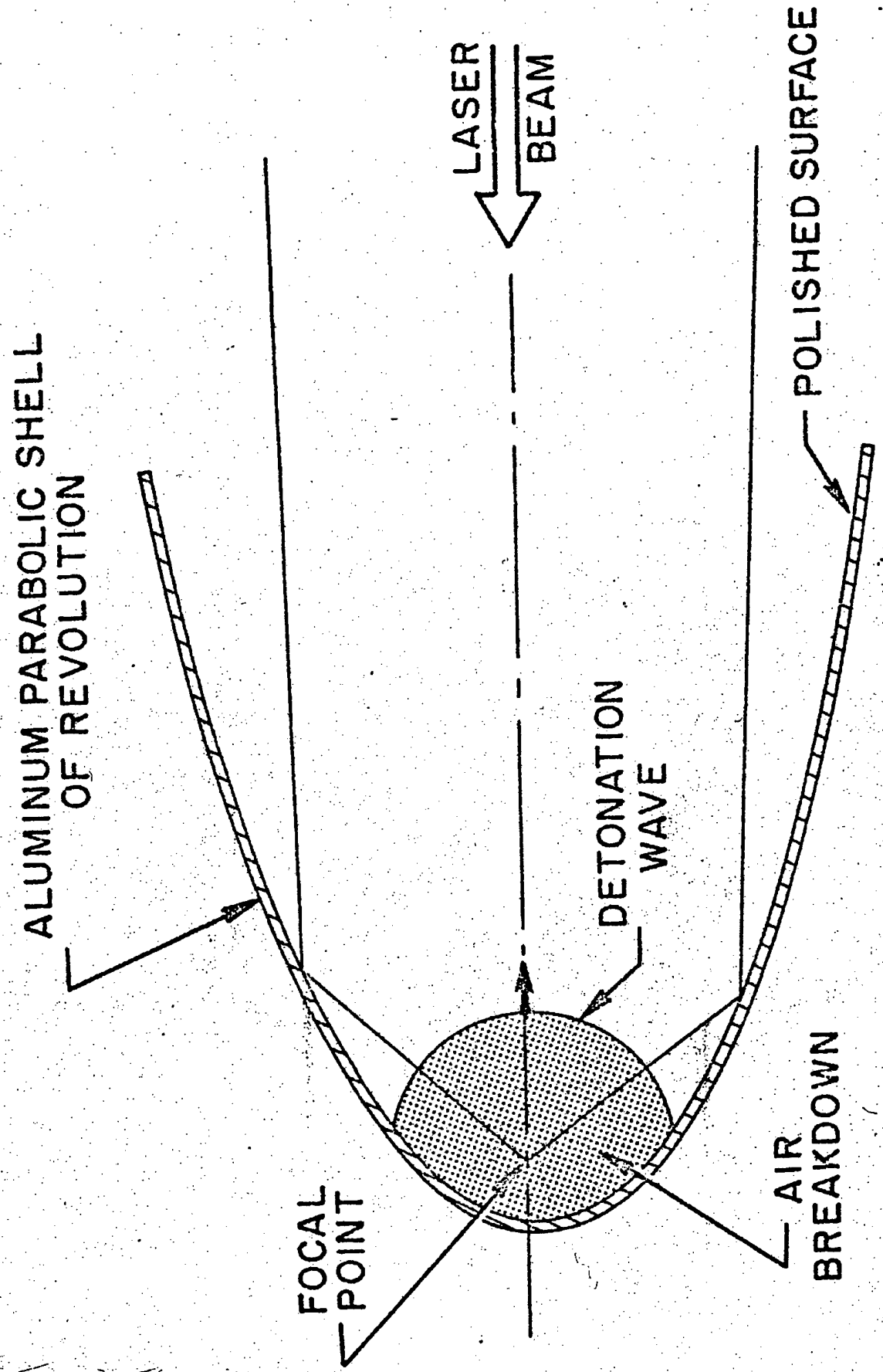
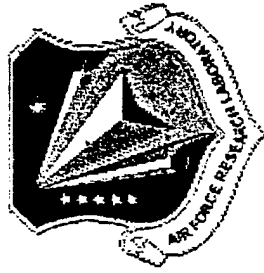


AVCO Liquid Propellant Rocket Using CW Laser (Circa 1973)





AVCO Laser Pulsejet (Circa 1973)

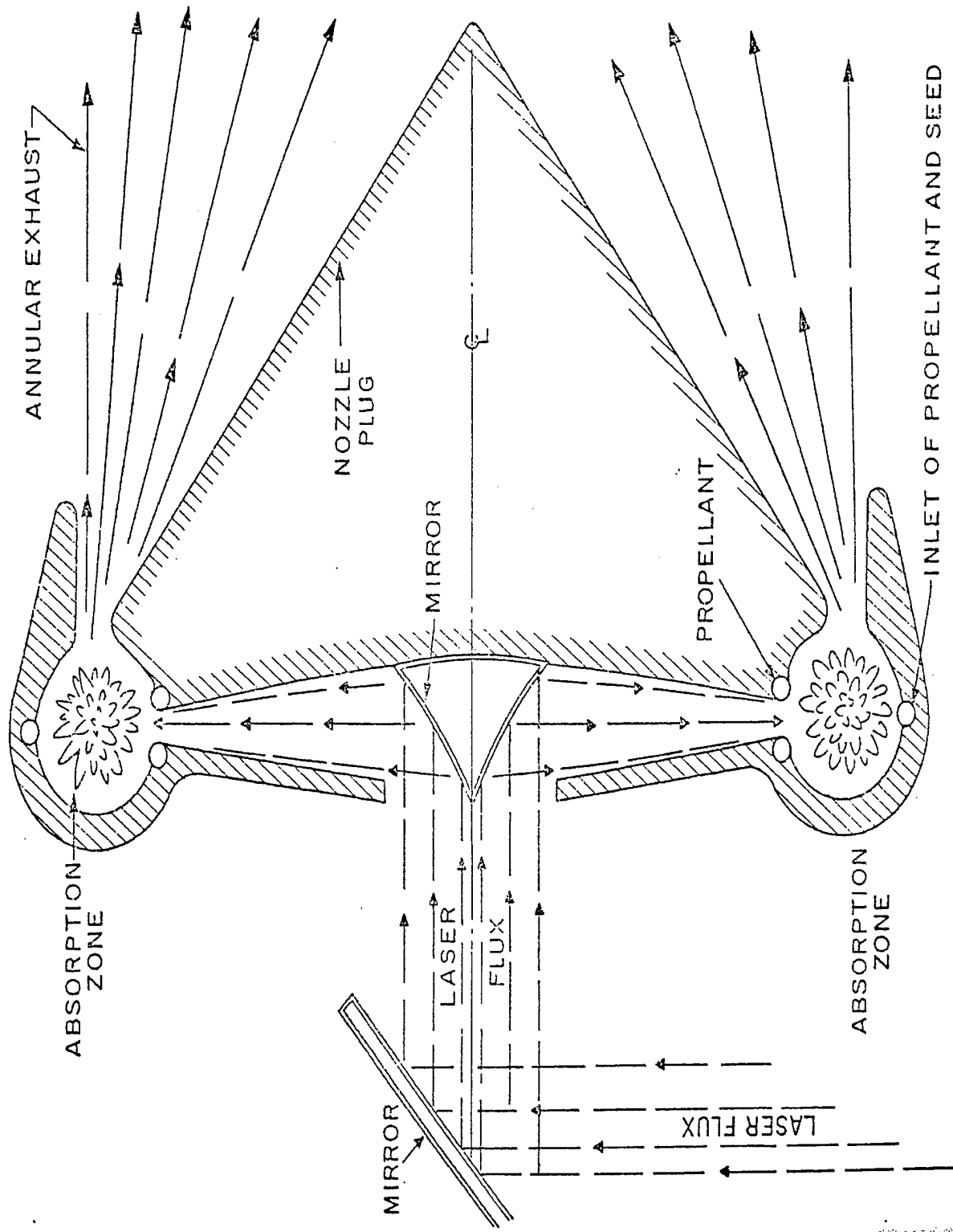
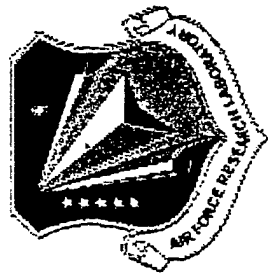




AVCO Advanced Laser Rocket

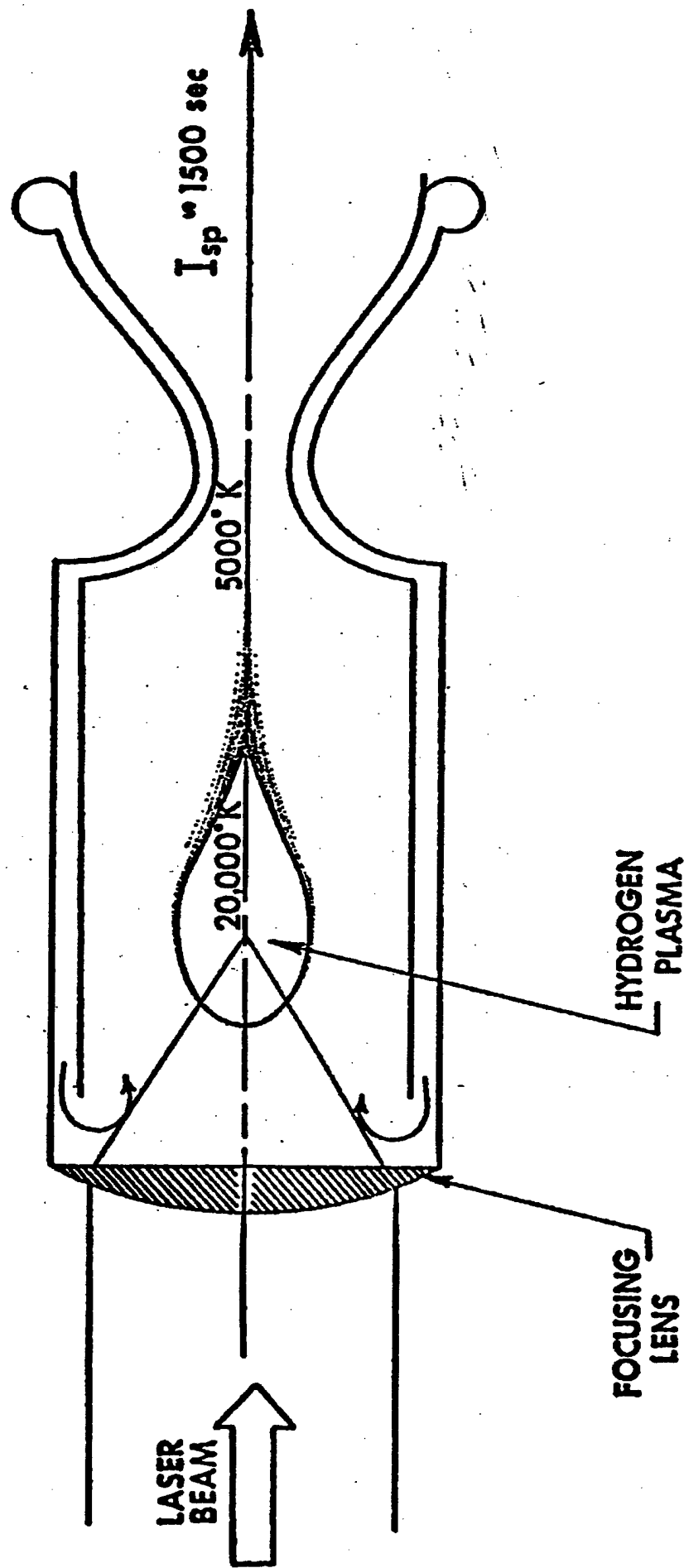
Toroidal Combustion Chamber, Plug Nozzle

(Circa 1973)





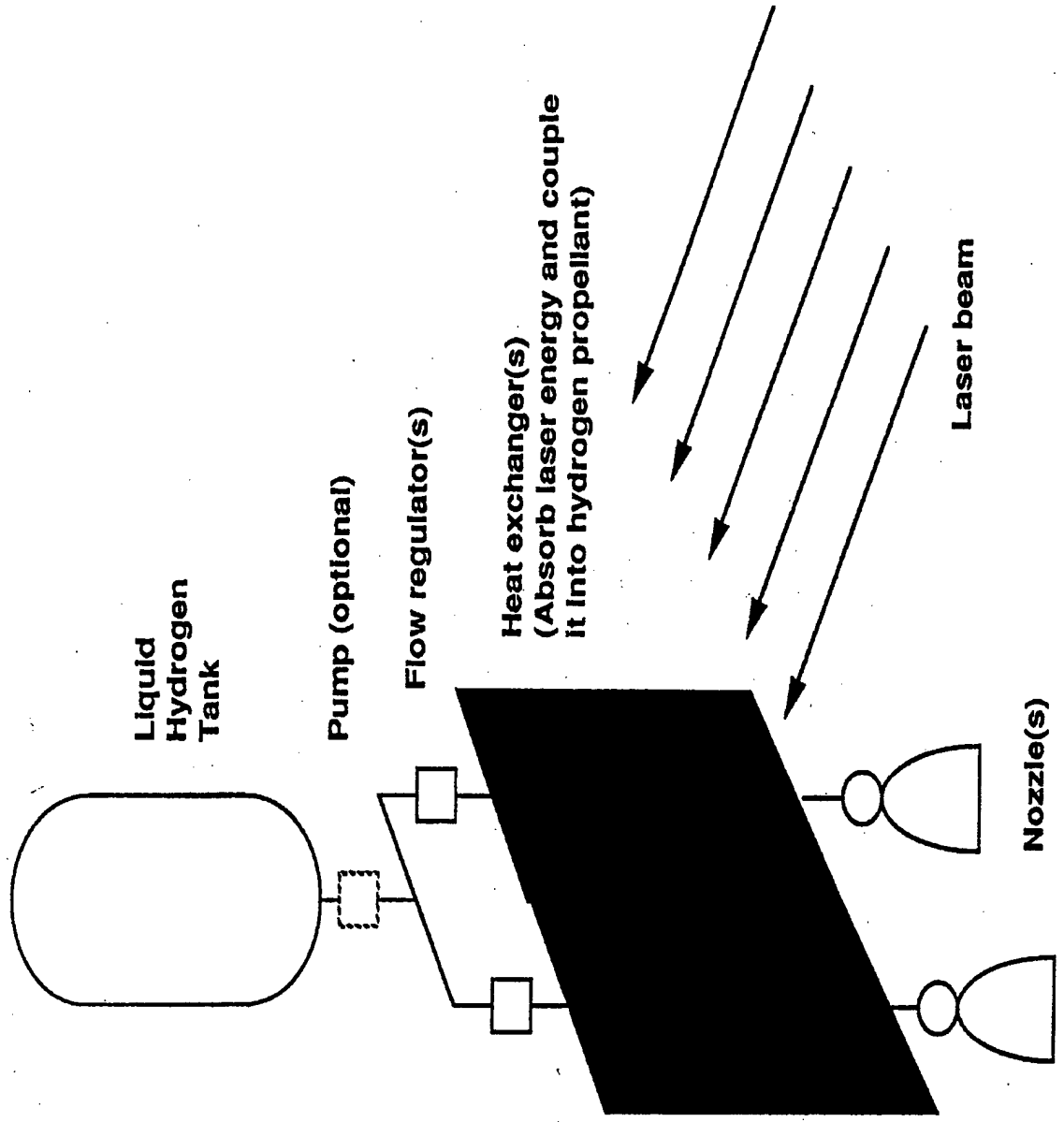
“Keefer” Laser Absorption Chamber (Circa 1986)





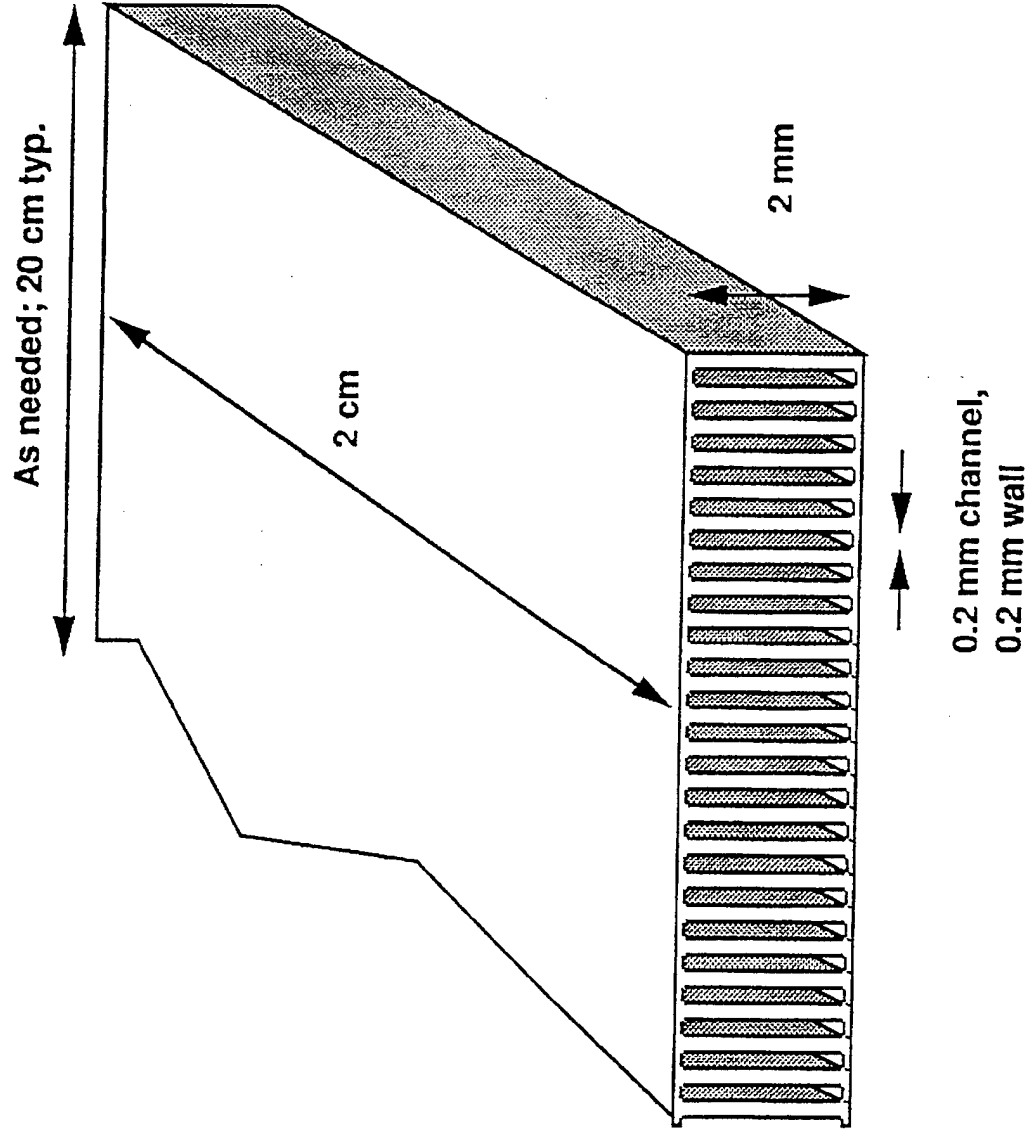
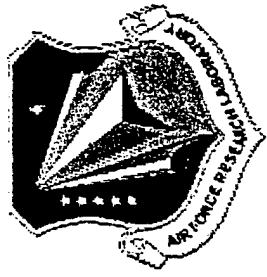
“Kare” Heat Exchanger Concept

(Circa 1992)



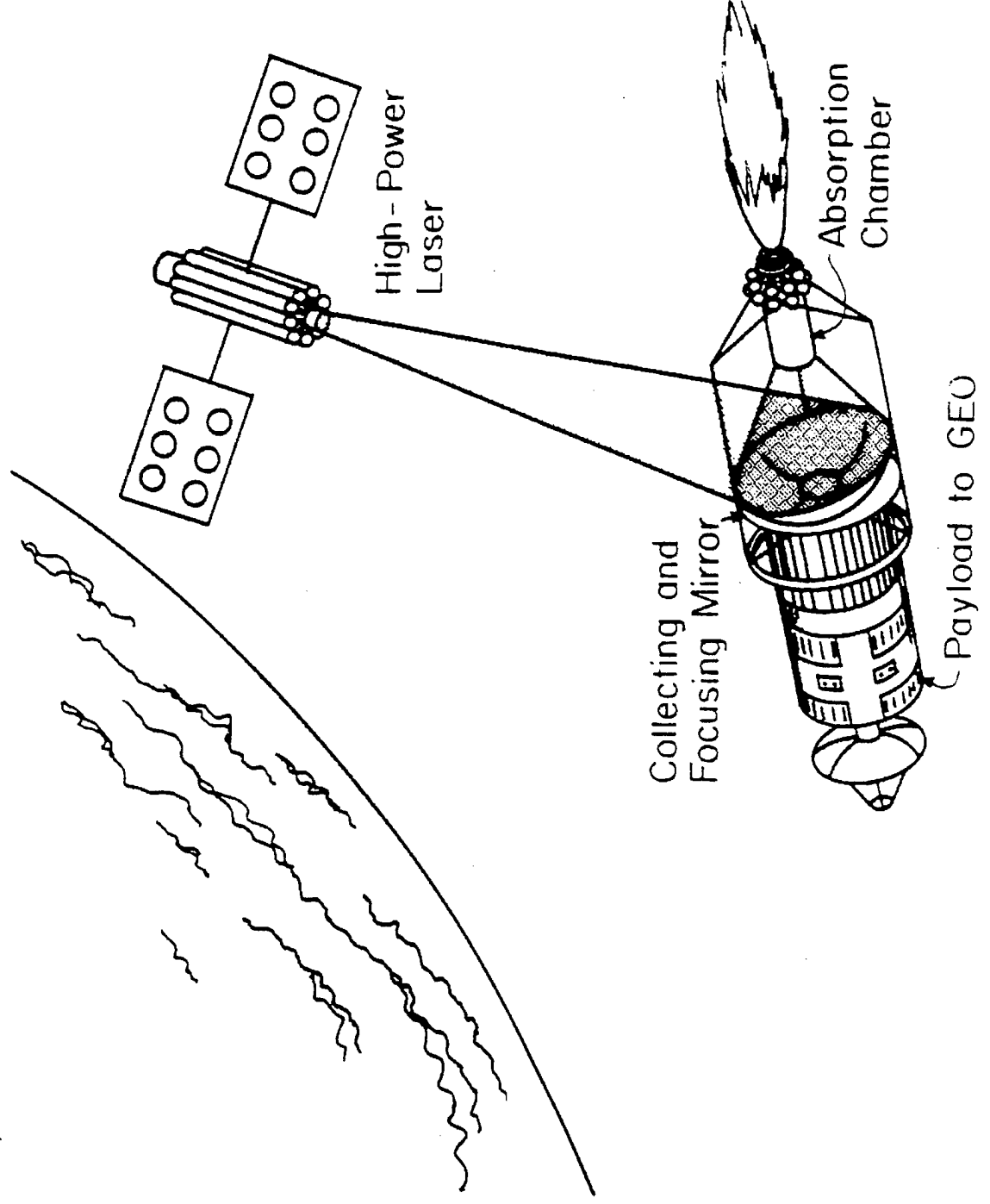
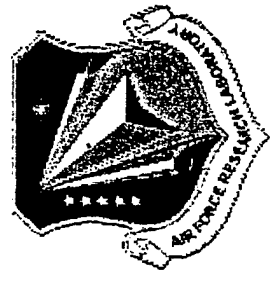


Kare's Microchannel Heat Exchanger Structure





University of Illinois Laser Propulsion Concept (Circa 1987)



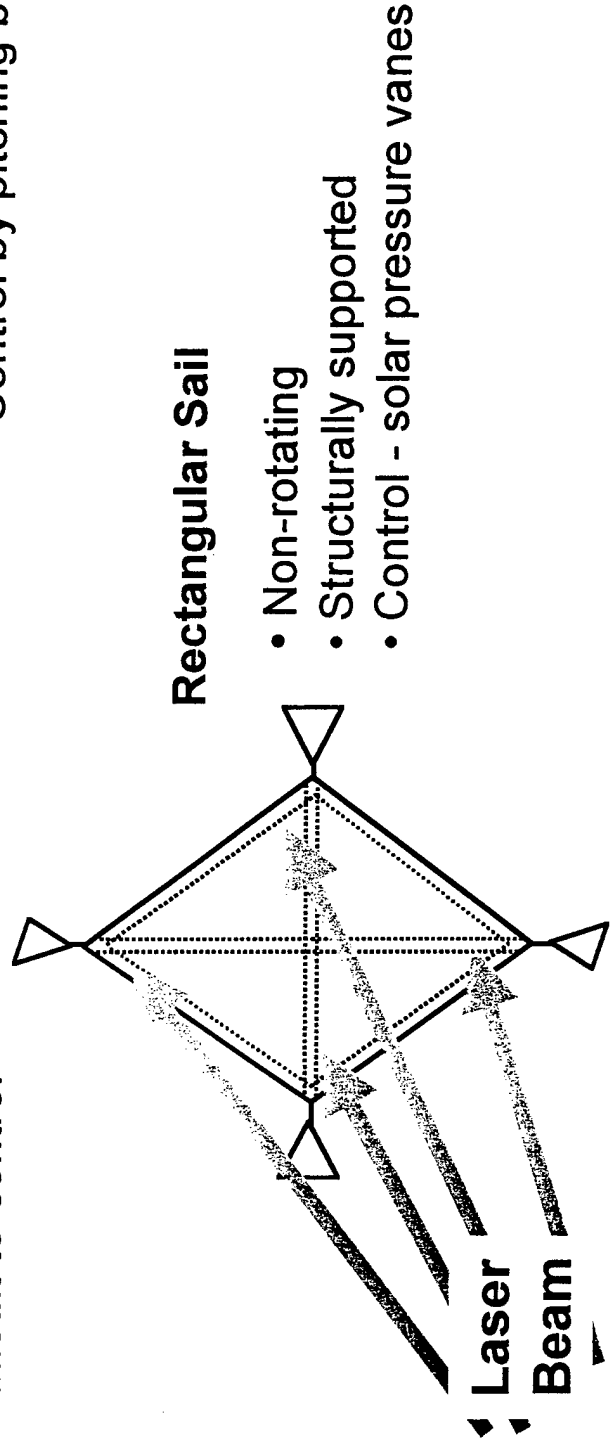
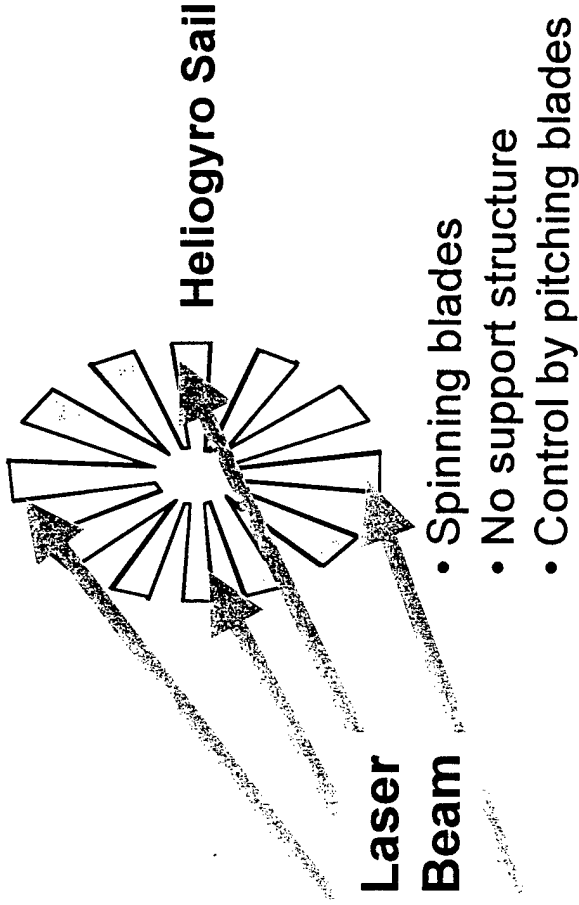
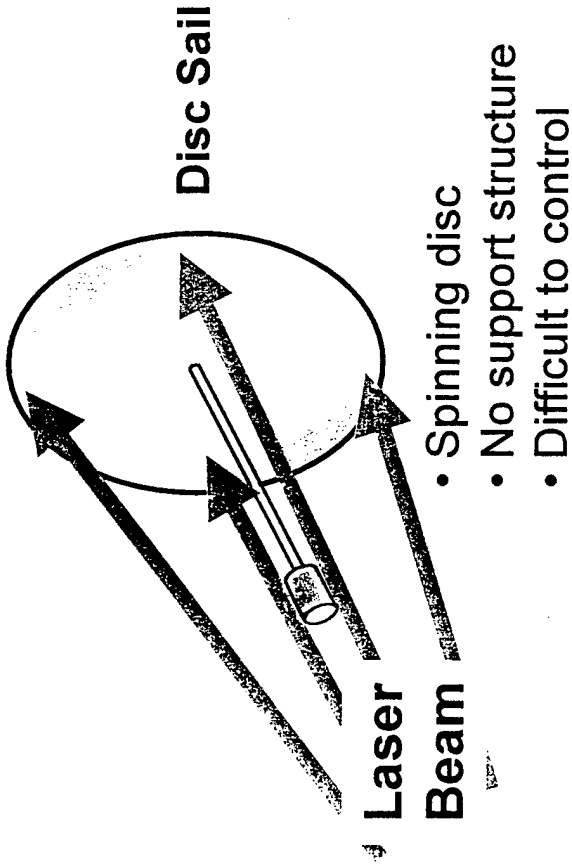


Laser Sail Propulsion



- **Features**
 - Large, lightweight structures
 - Very, very high power space-based laser
 - Low thrust and low acceleration
 - High spacecraft velocity potential (0.1 to 0.5c)
- **Performance Potential**
 - Specific Impulse : Infinite
 - Thrust : *space after conversion* Dependent on laser power, flux, sail area, and efficiency
- **Technology Status**
 - Concepts developed
 - Synergistic with solar sail technology
 - Russian solar mirror ZNAMIA deployed in space (1993)
 - On-going NASA/JPL efforts
 - Other university/small group/industry activities
- **Issues**
 - Very, very high power space-based laser
 - Fabrication and deployment of very large structures (lens and sail)
 - Verification of multi-function laser sail sections

Laser Sail Design Concepts





Developments in the 90's



- **NASA/MSFC**

- Financially Contributed to the Air Force program during FY 97 & 98.
- Initiated their own program in FY 99
 - FY 99 Study Phase
 - Initiated Testing in FY 2000
 - Concepts include parabolic pulsejet, Lightcraft, & “Phipps” laser concept.

- **Air Force**

- Lightcraft Development Program Started FY 96
- The AFRL and NASA/MSFC have a Memorandum of Agreement (MOA) to work together on the Lightcraft.
- German parabolic pulsejet tests conducted in 1999.

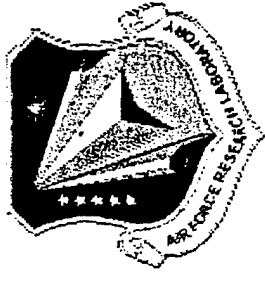


Laser Propulsion At MSFC

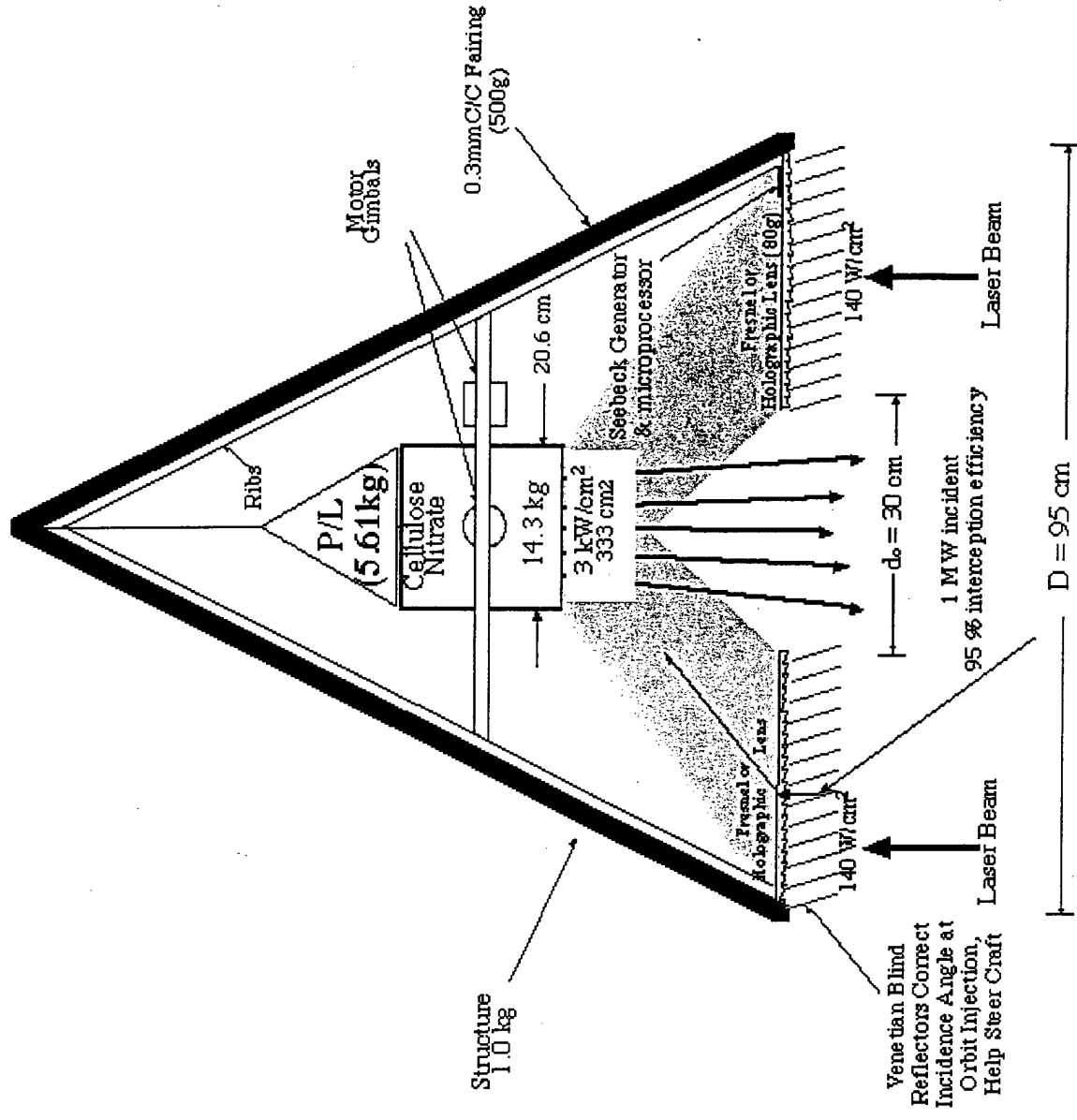
By
Mr. Sandy Kirkindall
NASA/MSFC, TD40
Bldg. #4666
Huntsville AL 35812



Phipps/NASA Design



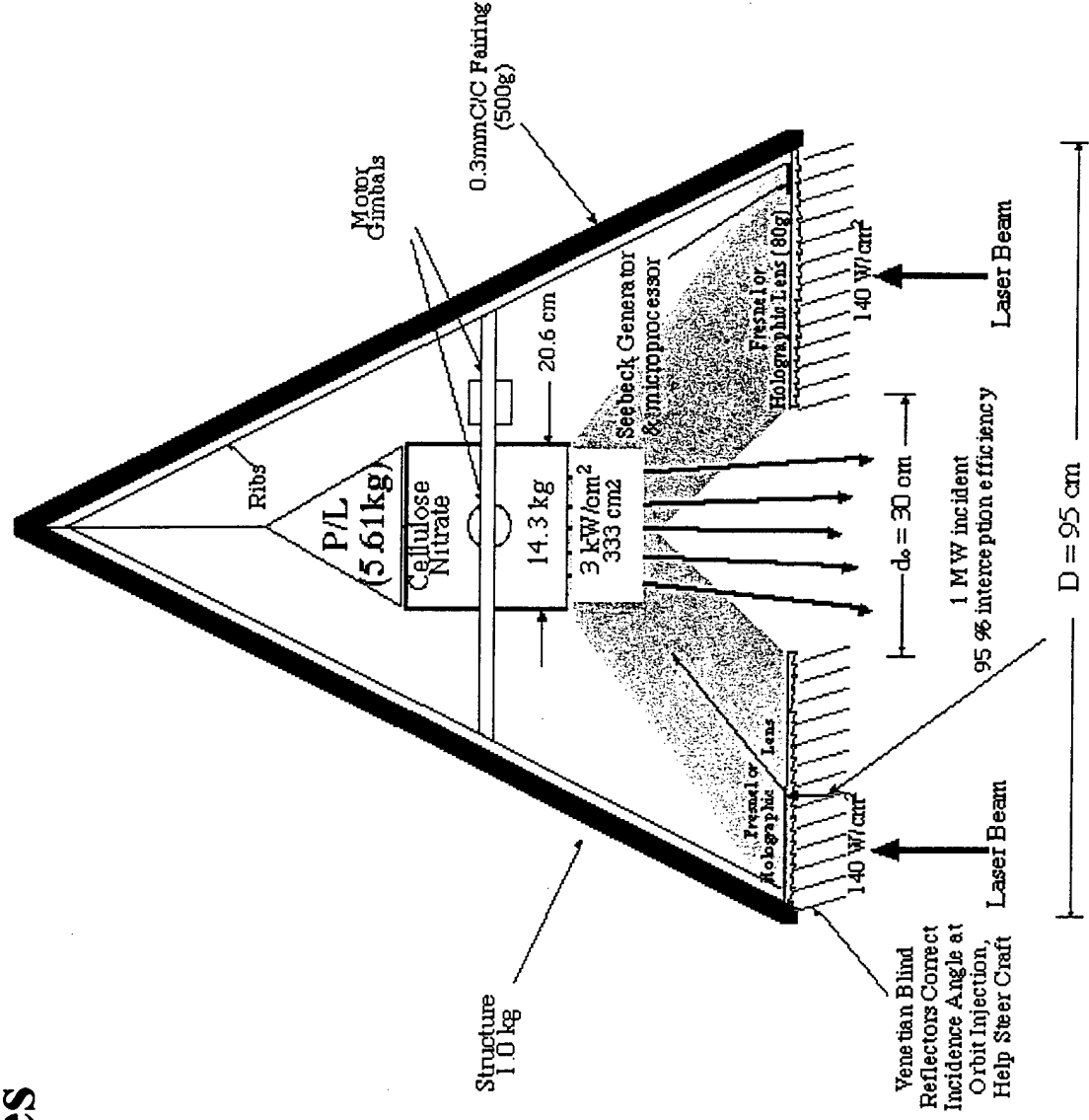
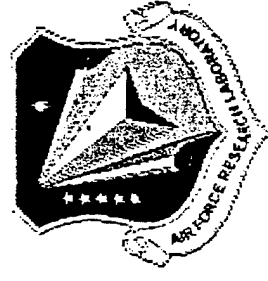
- $D/L=1$ optimizes
 - Drag
 - Center of thrust
 - Jet/lens clearance
- Heat shield dumped at 120km
- “Venetian blinds”
 - For orbit insertion
 - For partial steering



Phipps/NASA Design (Cont)

Concluded

- Fresnel lens concentrates light
- Seebeck generator provides 100W system power *space or dash?*
- μ processor controls actuators

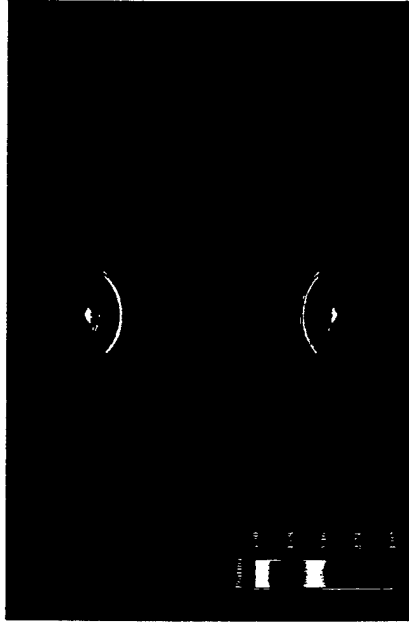




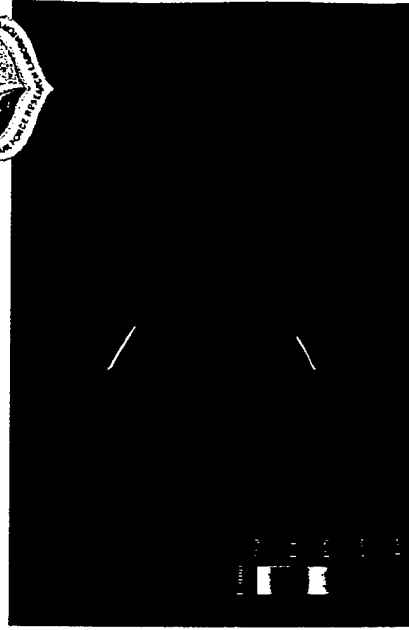
NASA CFD Studies of Lightcraft Pulse Dynamics



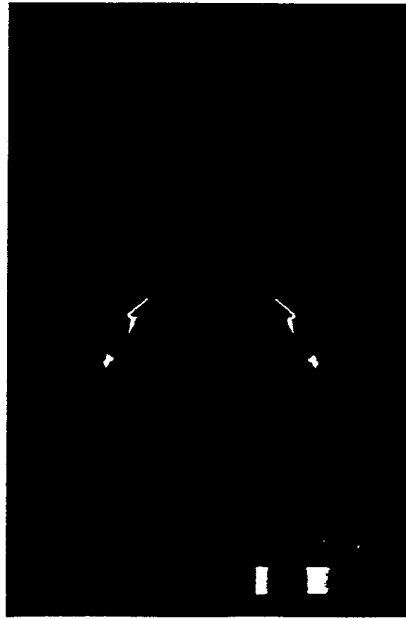
10 usec



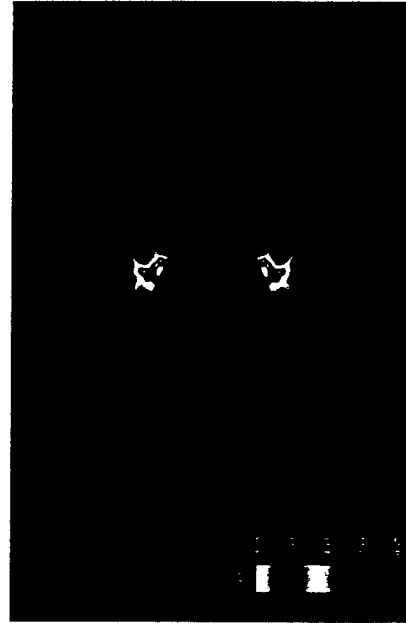
20 usec



30 usec



40 usec



60 usec



80 usec



122 usec

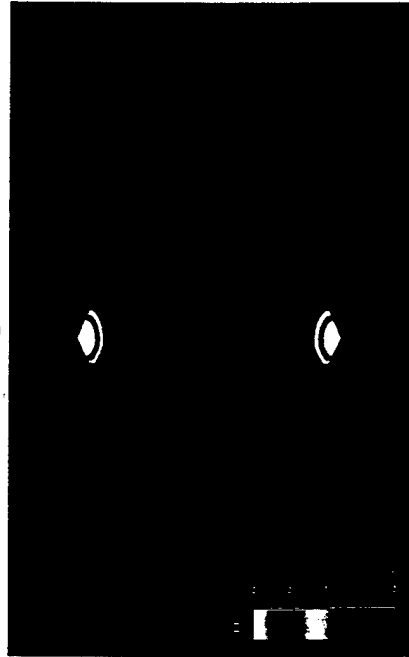
PRESSURE (ATM)



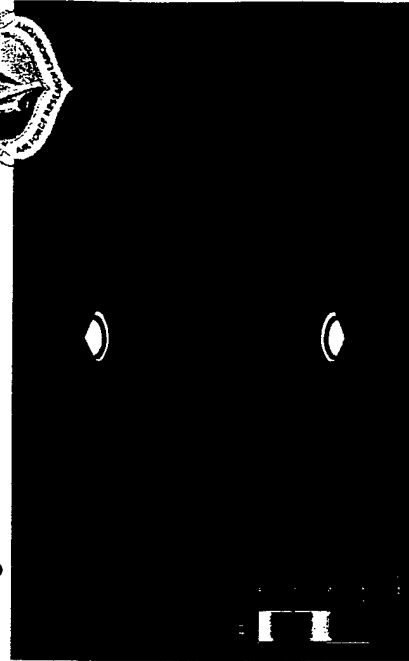
NASA CFD Studies of Lightcraft Pulse Dynamics



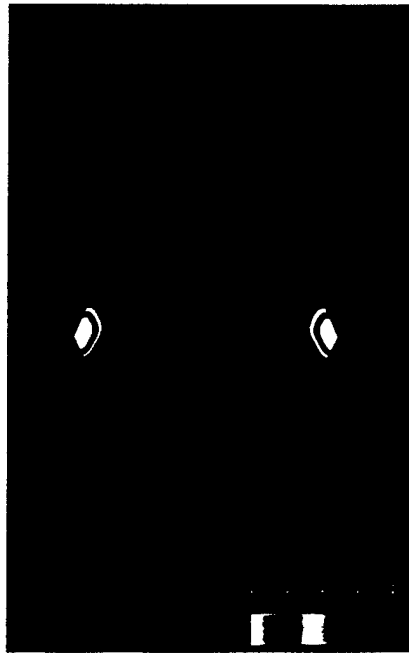
10 usec



20 usec



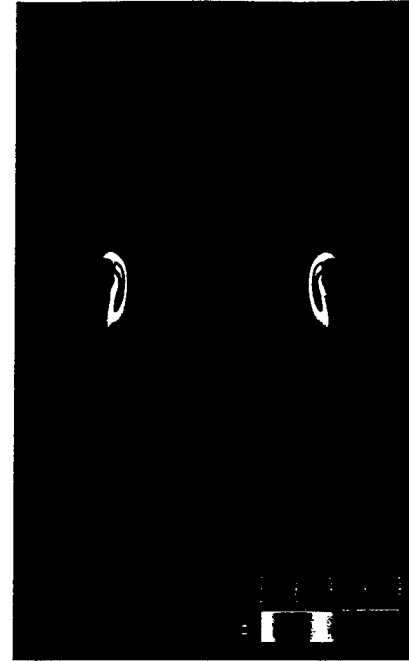
30 usec



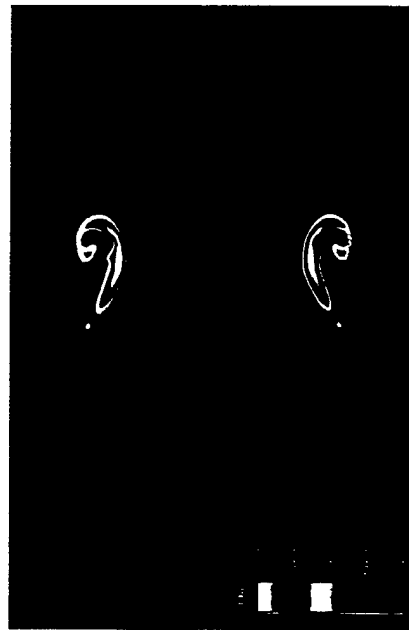
40 usec



60 usec



80 usec

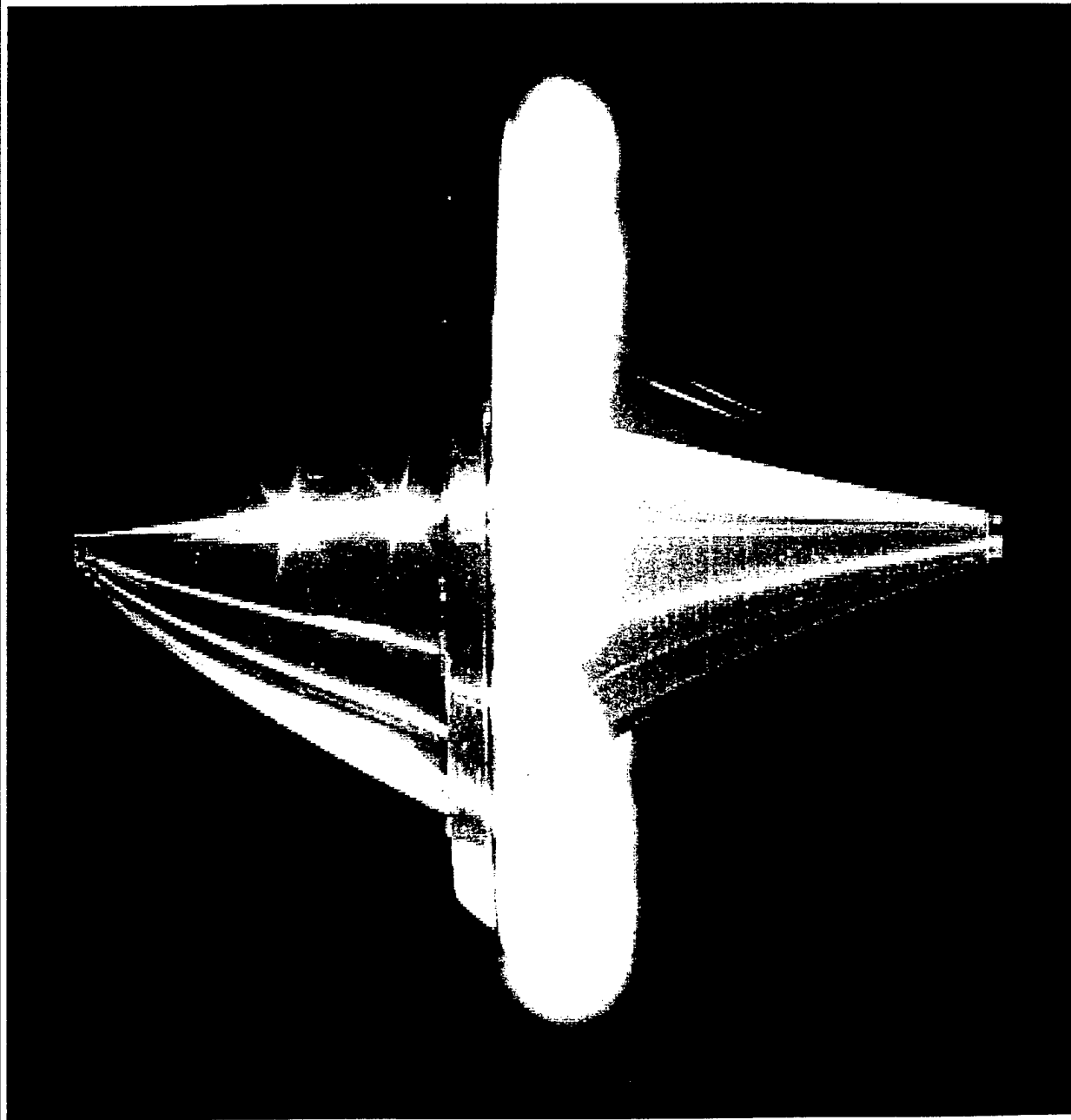


122 usec

TEMPERATURE (K)

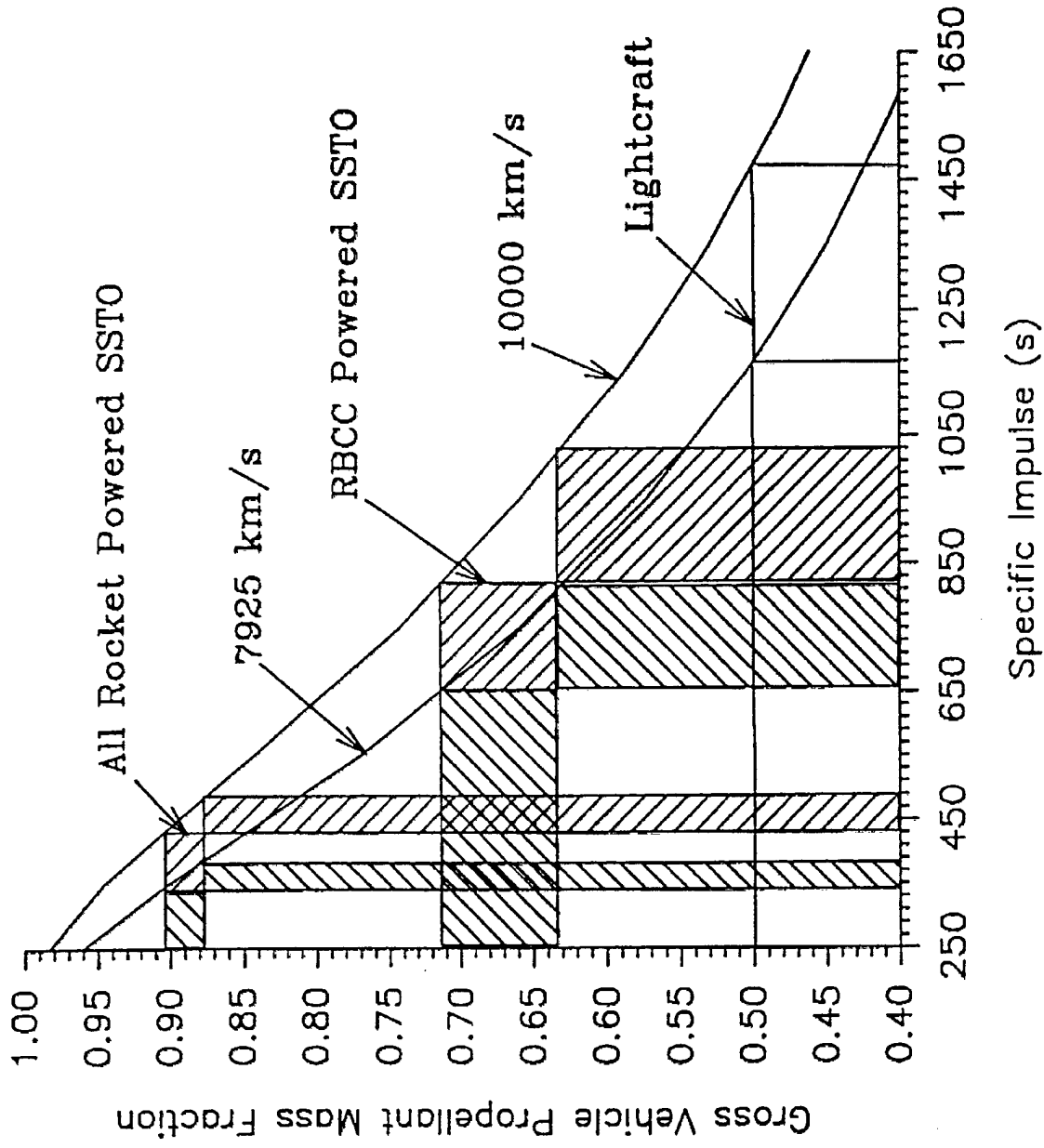


LASER LIGHTCRAFT DEVELOPMENT PROGRAM





The "Rocket Equation" Applied to Single-Stage-to-Orbit (SSTO) Space Transportation Concepts





LOW COST ACCESS TO SPACE



Unique Features

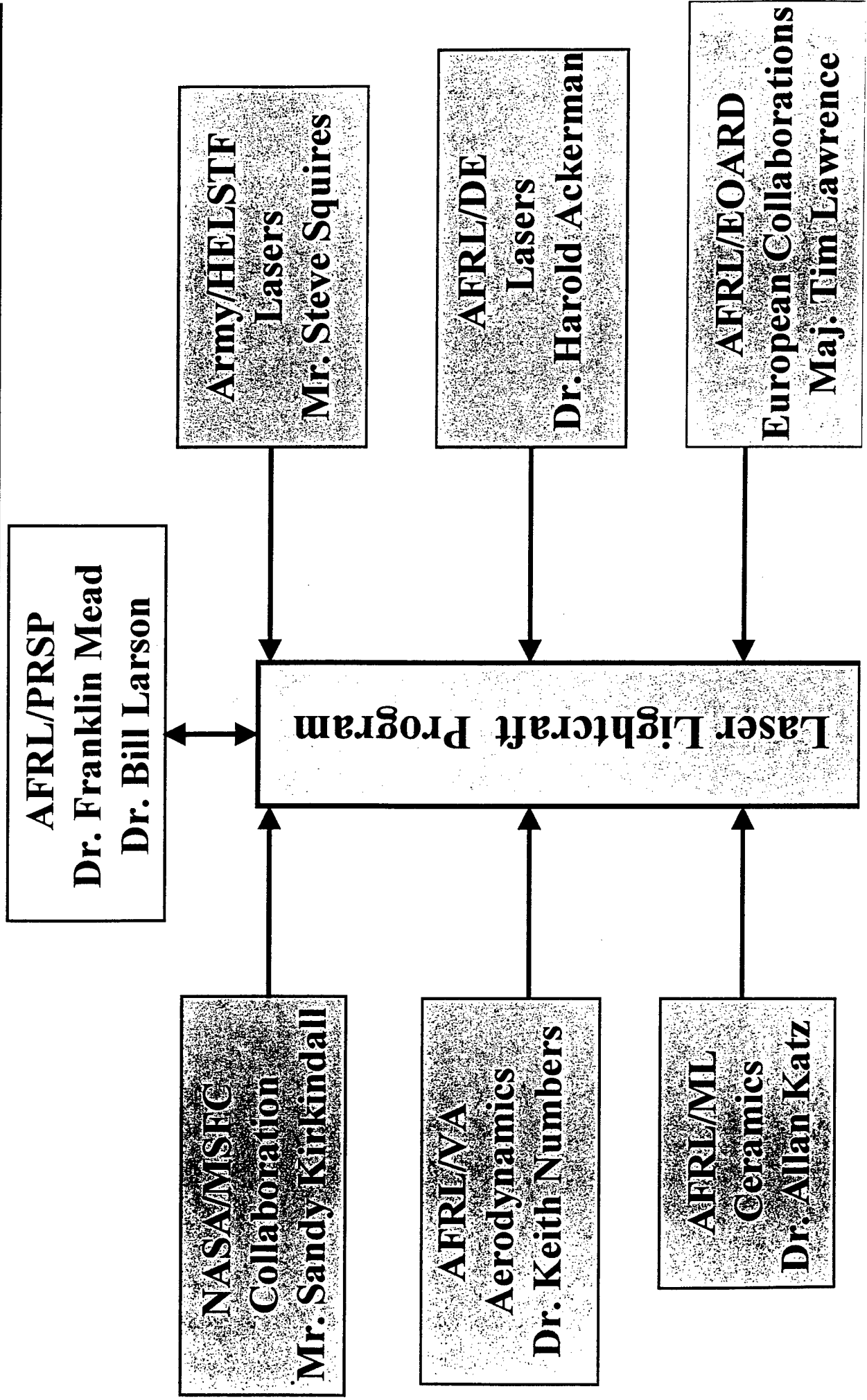
- Laser-Propelled Beam Rider
 - Decoupled Energy Source (1 MW class infrared G/B laser)
 - Single Stage to Orbit (~2 kg initial weight; $M_f=0.5$)
 - Very High Isp (Airbreathing to $M=5$ at 30 km; 1,000 to 3,000 s in space with H_2)
 - Combined-Cycle Pulsed Detonation Engine



- Multiple/Shared Functional Components
- One-Meter Diameter Parabolic Telescope (Resolution=8 to 15 cm from LEO)
 - Simple*
- *Reliable* Simplicity, Reliability, Safety, Environmentally Clean
- *Safe* High Launch Rate (All azimuth, On-demand)
- Less Than \$500 of Electrical Power For Launch to LEO



Program Alliances

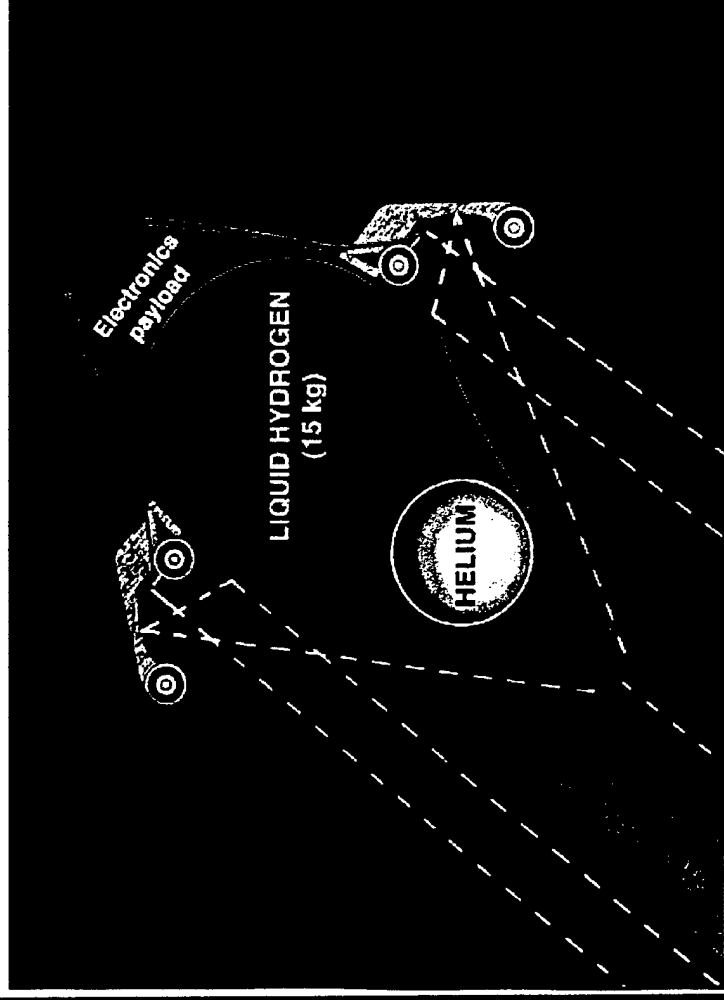




The Lightcraft Concept

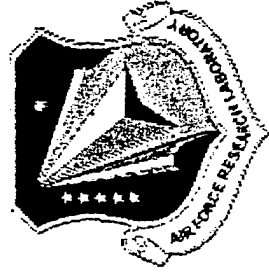


- **Three Main Components**
 - Forebody Aeroshell (External Compression Surface)
 - Shroud (Air Inlet & Impulsive Thrust Surface)
 - Afterbody (Parabolic Mirror & Plug Nozzle)
- **Tankage**
 - Liquid Propellant (LN2, NH3 or LH2)
 - Helium Pressurant
- **Nanosatellite (1 kg & 1 m Dia. Focus Telescope)**
- **Electronics in Forebody**
- **Reentry Capability**
- **Solar Powered in Orbit**





APPLICATIONS



- Nanosatellite “low cost” launch on demand
 - Air Force, NASA, BMDO, Communication Industry
- High Resolution Imaging, Surveillance, and Mapping (i.e., Earth Resources)
- Global Positioning and Tracking
- Threat Detection and Tracking
- Astronomical Telescope (i.e., Amateur & Professional)
- Communications and Relay (i.e., Cellular Phone)
- Tactical Laser Propulsion (i.e., Hypersonic KKV)



Lightcraft Development Objectives



- Broad Application Based Nano-/Microsatellites
 - All Azimuth, Launch-on-demand_q *comp take sentence don't need because it's with a trade*
 - Air Force, NASA, BMDO, NRO, Communication Companies, Private Industry, Individuals_{qq}
- Near-term (7 yrs.)
 - Launch to LEO of 1 kg vehicles for less than \$500 of electrical power, and less than \$20K total cost_{qq}
 - Meet a variety of NASA/AF/Industry requirements for low cost access to space_{qq}
- Far-term (10 to 12 yrs.)
 - Launch 100 kg (220 lbs) AF/NASA vehicles to LEO for less than \$1.5M*_{qq}
 - Commercial laser launch services become viable contenders, as the lowest cost provider_{qq}

* NASA requirement for Bantam-class payloads by FY 2006.



Pulsed Laser Vulnerability Test System (PLVTS)

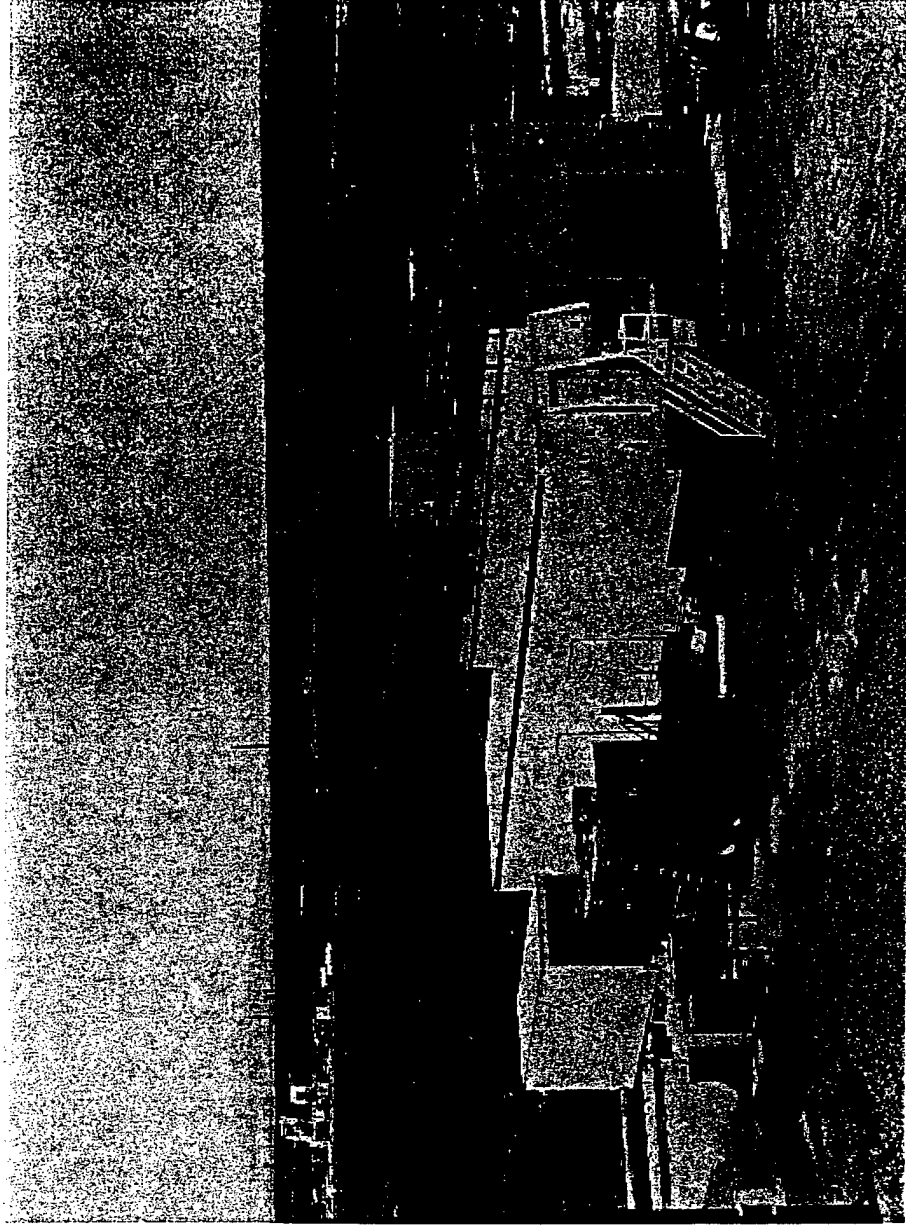


- Original Performance

- 800 joules/pulse
- 10 Hz ^{30-sec?}
- (30 :sec pulses

- Modified Performance

- 1998
 - 400 joules/pulse
 - 28 Hz ^{18-sec?}
 - 18 :sec pulses
- 1999
 - 150 joules/pulse
 - 30 Hz ^{5-sec?}
 - (5 :sec pulses





Phase I Accomplishments

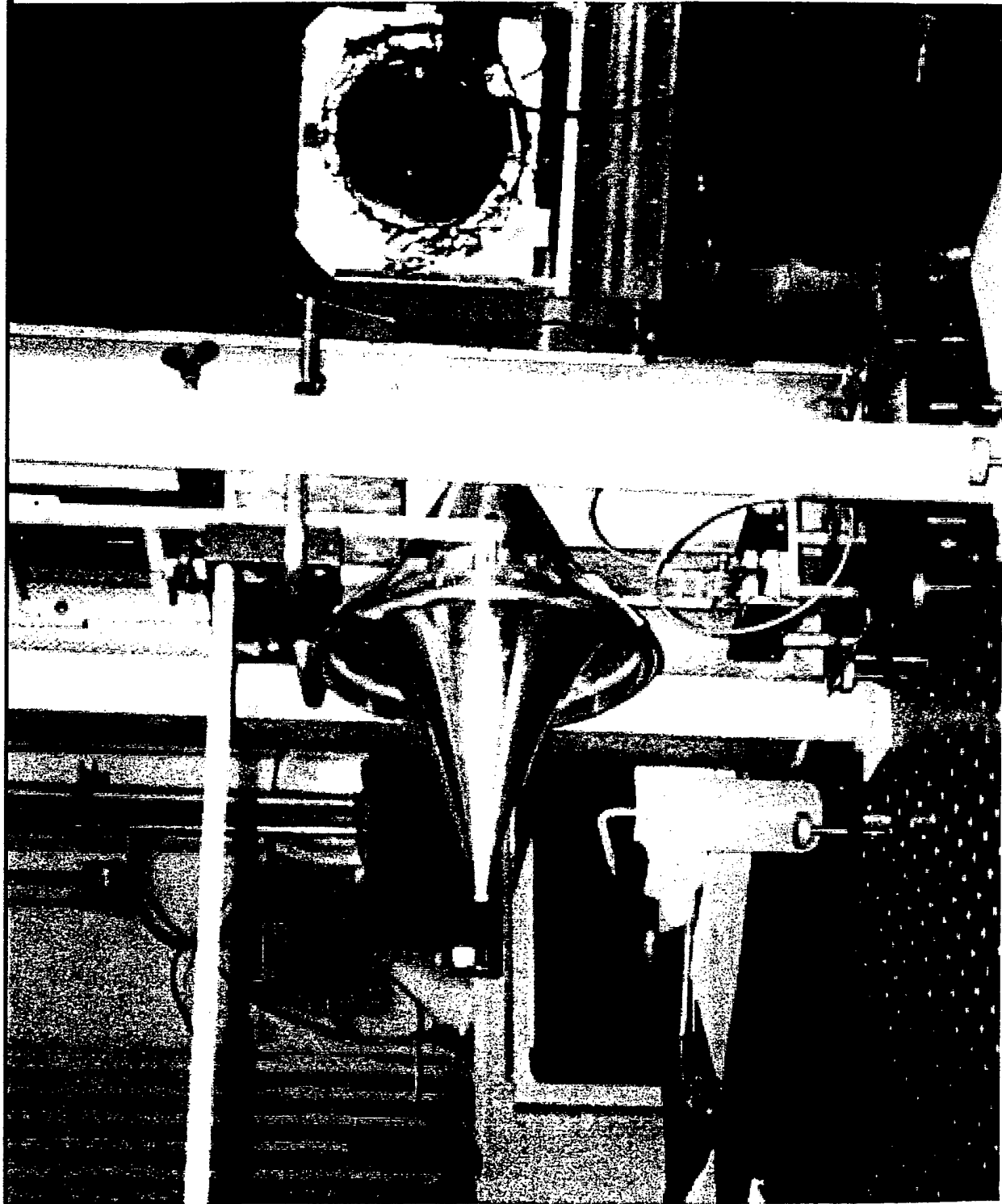


- Phase I - Completed Dec 98
 - A 3-Year Program To Demonstrate Concept Feasibility
 - Lightcraft Concept Feasibility Demonstrated By:
 - Impulse, thrust, and pressure measurements accomplished.
 - Shadowgraph, and beam propagation (to ~90 m) studies accomplished.
 - Lightcraft optics/engine vehicle geometry optimized.
 - Pointing & tracking system demonstrated on horizontal wire-guided flights to ~122 m.
 - Outdoor vertical free-flights to ~29 m accomplished.

one word

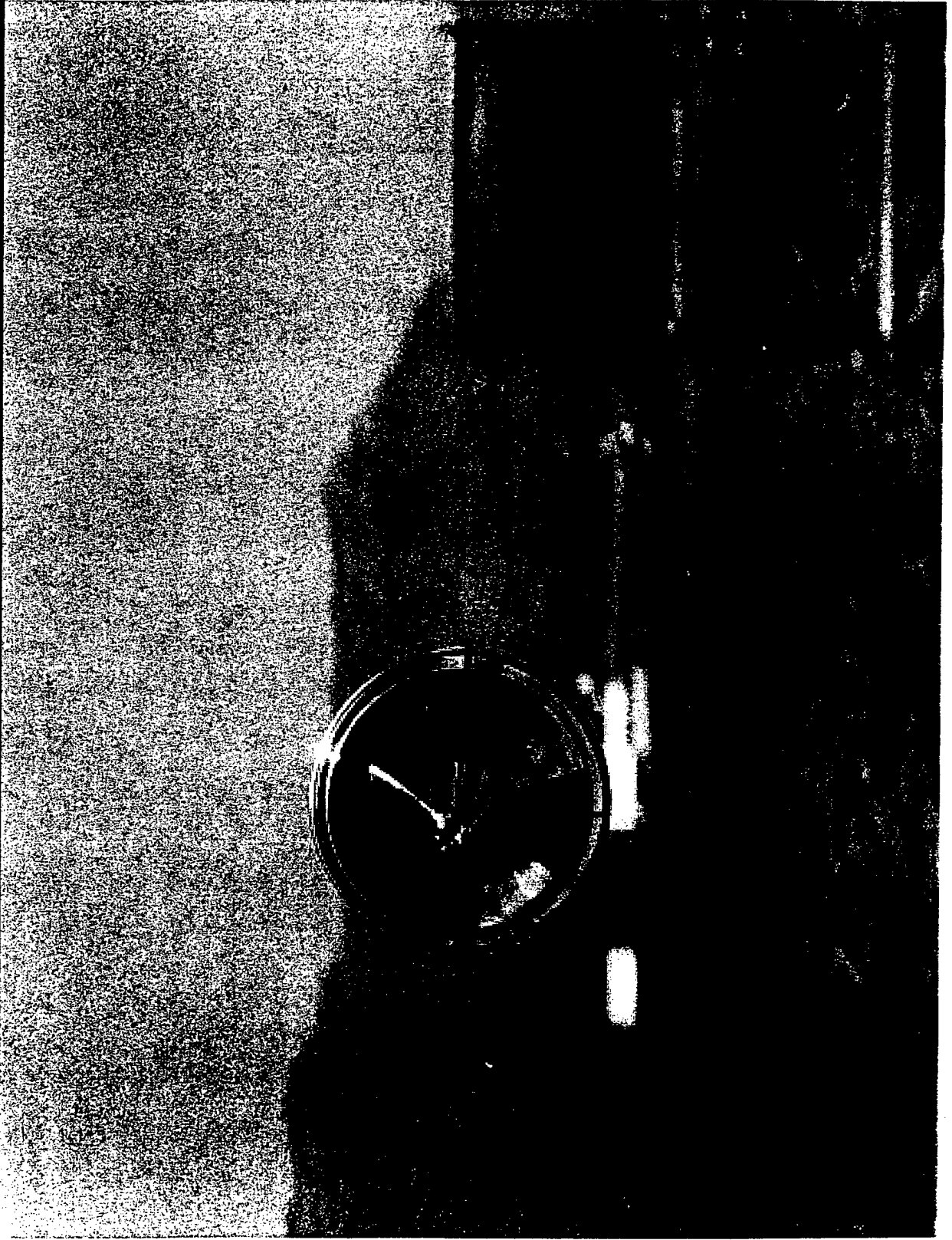


Lightcraft Mounted to Ballistic Pendulum "Impulse Stand"



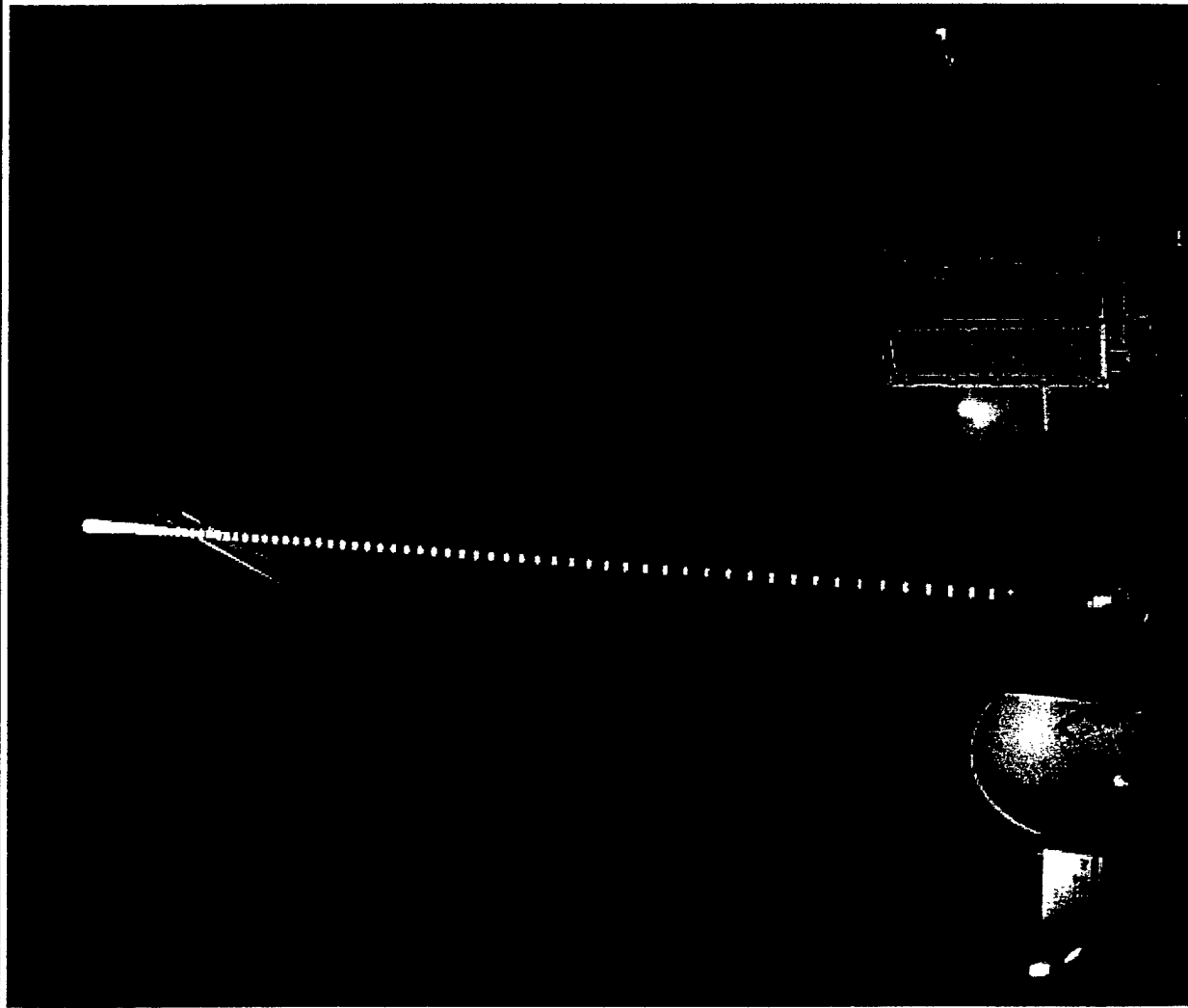


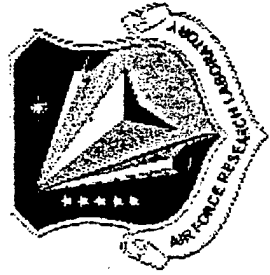
FOUR HUNDRED FOOT OUTDOOR WIRE TEST CONFIGURATION





29-Meter Outdoor Vertical Flight





Model #200 Lightcraft Series

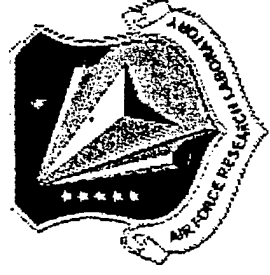




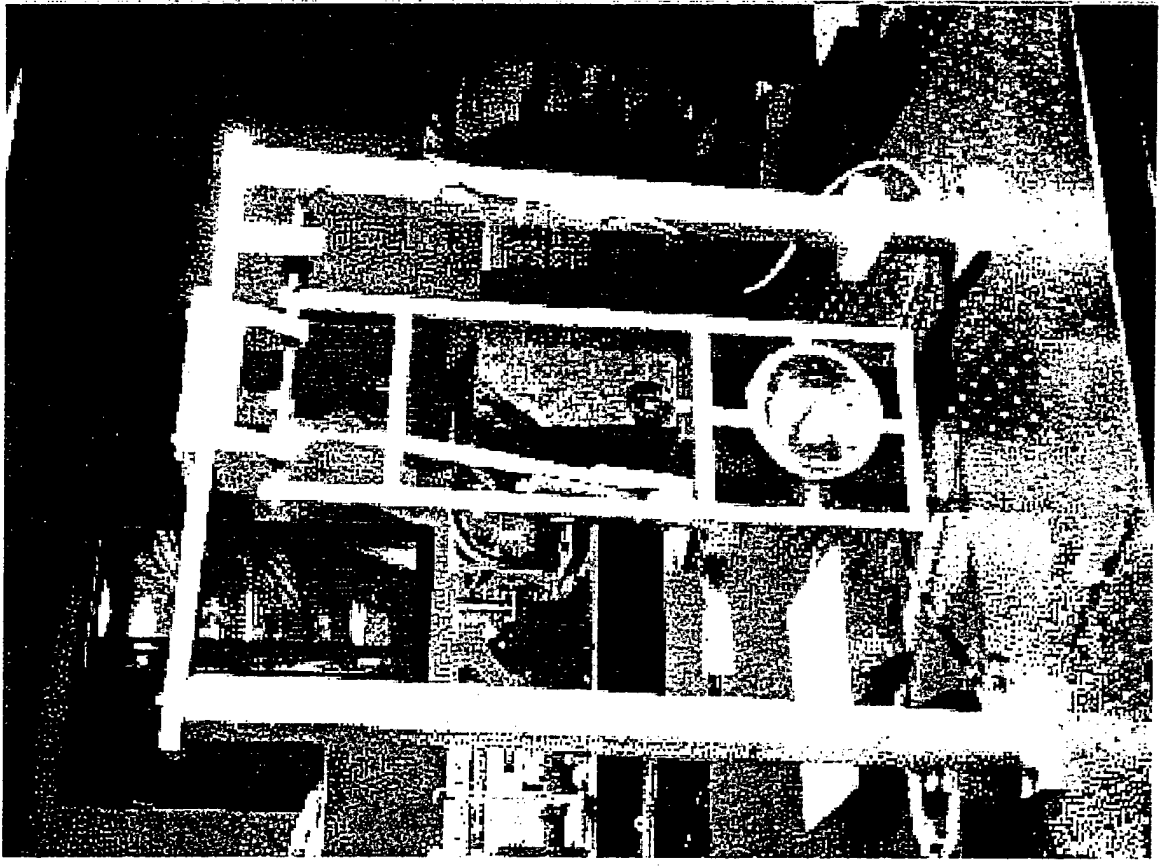
Phase II Accomplishments



- Phase II – Initiated Jan 99
 - A 5-Year Effort To Accomplish Vertical Launches to 30 km
 - With a 100 kW Laser *does this phrase go at the end of*
 - Current Effort: Out Door Free Flight Tests To ~300 m.
 - Out door vertical free flights to ~40 m accomplished using *↑*
 - ✕ ablative fuel in near-field beam *u*
 - Lightcraft far-field beam performance measured with pendulum using
 - ✕ Laboratory and FTT telescopes to ~533 m *u*
 - First, short (<1 m), vertical free flights conducted with *↑*
 - ✕ FTT telescope inside 500-meter building *u*
 - Continued Developments, Studies and Analyses
 - Characterize Model #200-3/4th with ceramic shroud *u*
 - Develop high temperature, lightweight ceramic optic with reflective *u*
 - ✕ coating *u*
 - Continue flight dynamics and air inlet studies/design *u*
 - Obtain funding for 100 kW class CO2 electric discharge laser *u*

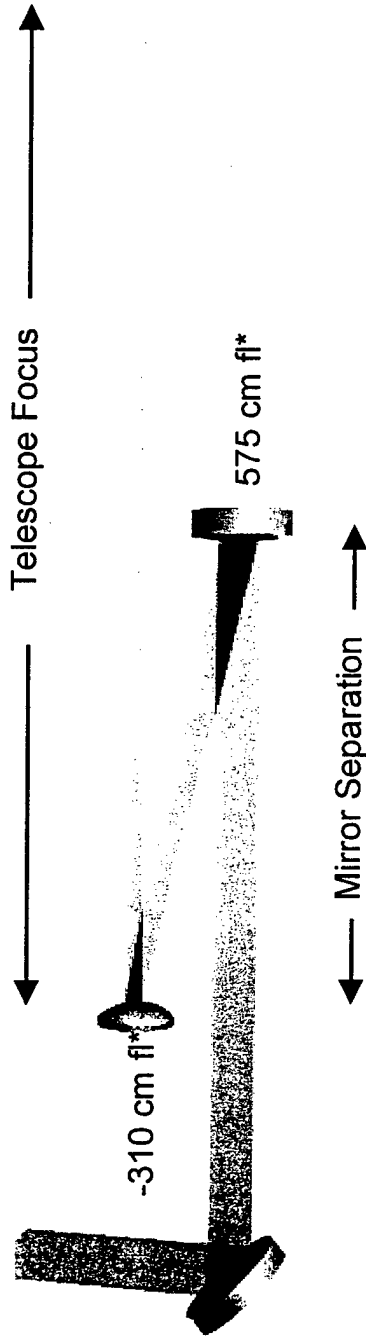


Pendulum Impulse Test Stand



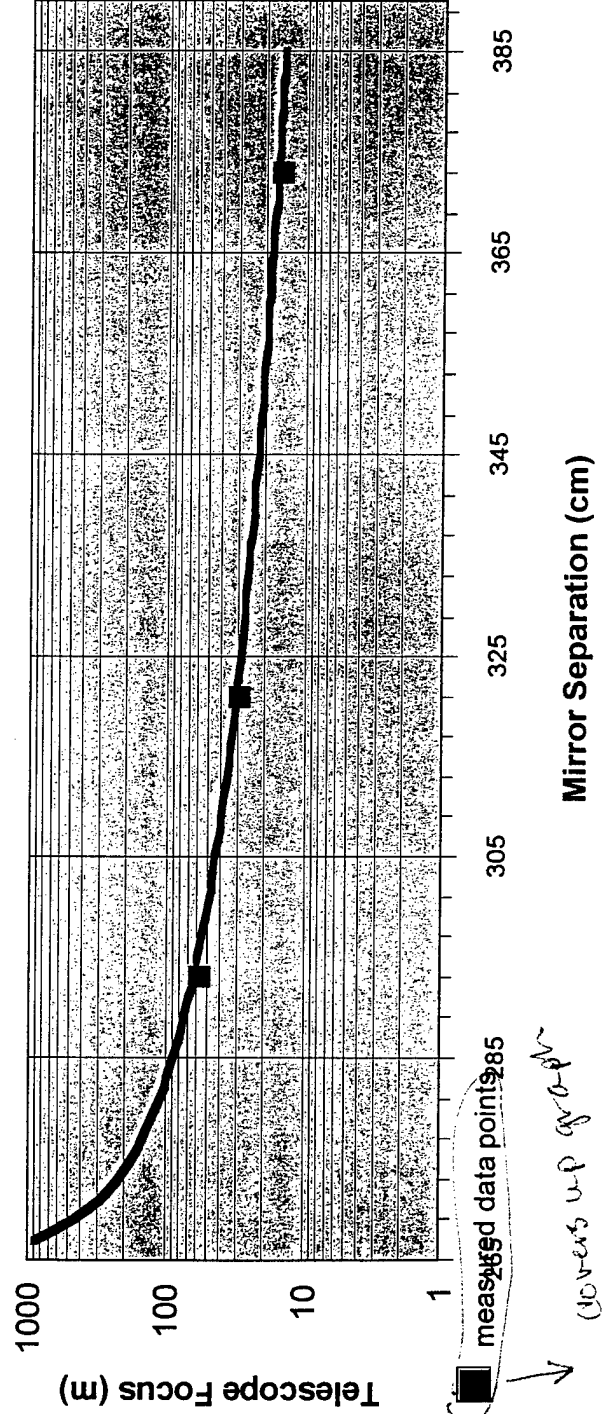


Beam Reducing Telescope Used For Near Field Flights



*focal lengths adjusted for curve fit

Beam Reducing Telescope

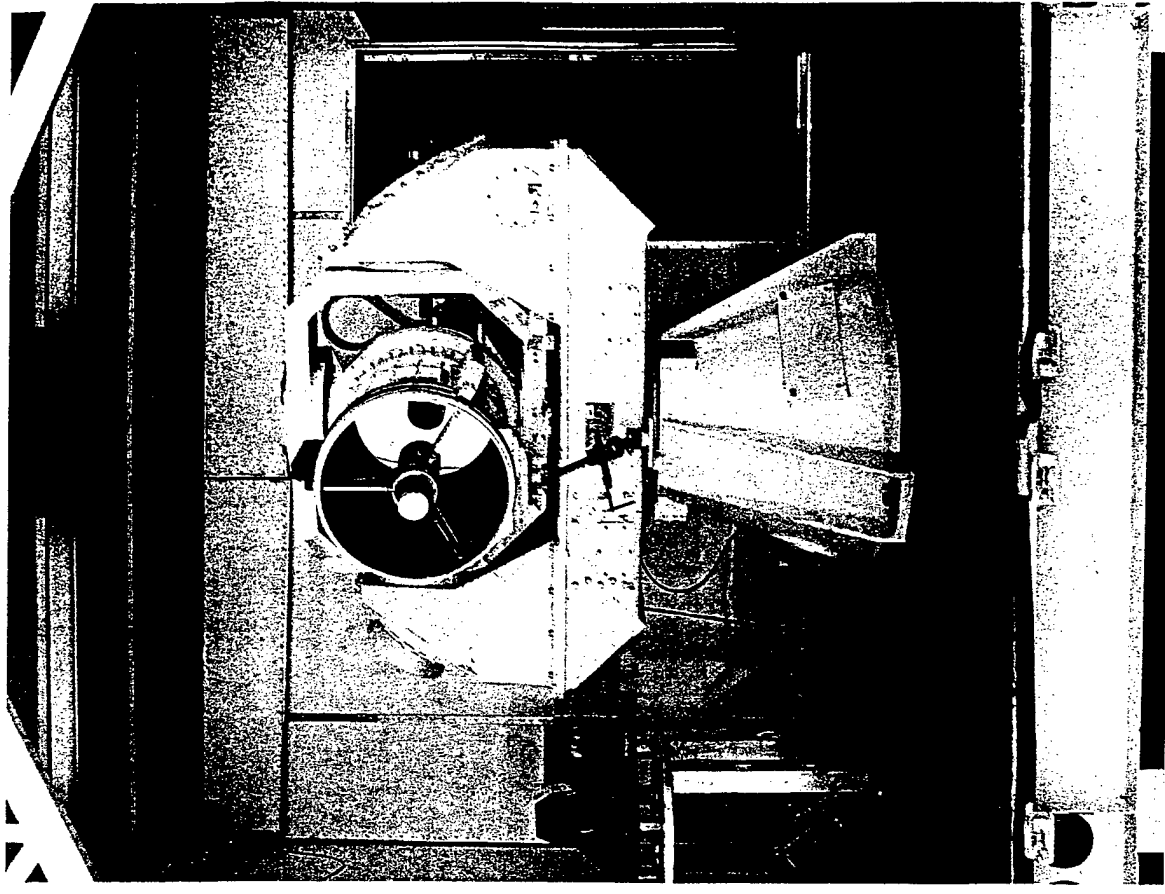




Field Test Telescope (FTT)

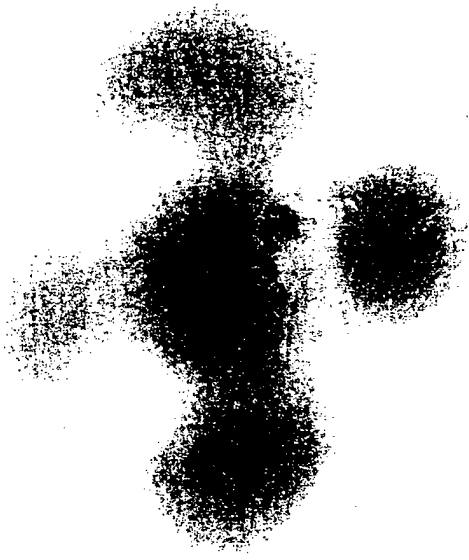
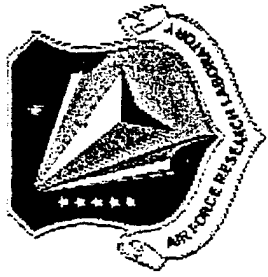


- A Laser Beam Handoff to This Telescope Should Allow Flights to Altitudes of ~300 m (1,000 ft).
 - 50 cm Diameter
 - Cassegrainian
 - Dynamic focusing

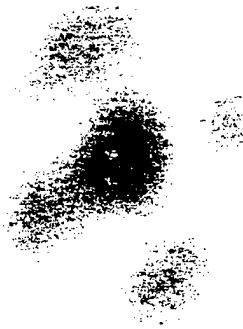




FTT Beam Burn Patterns



1,500 Ft



1,000 Ft

11 cm Ref.

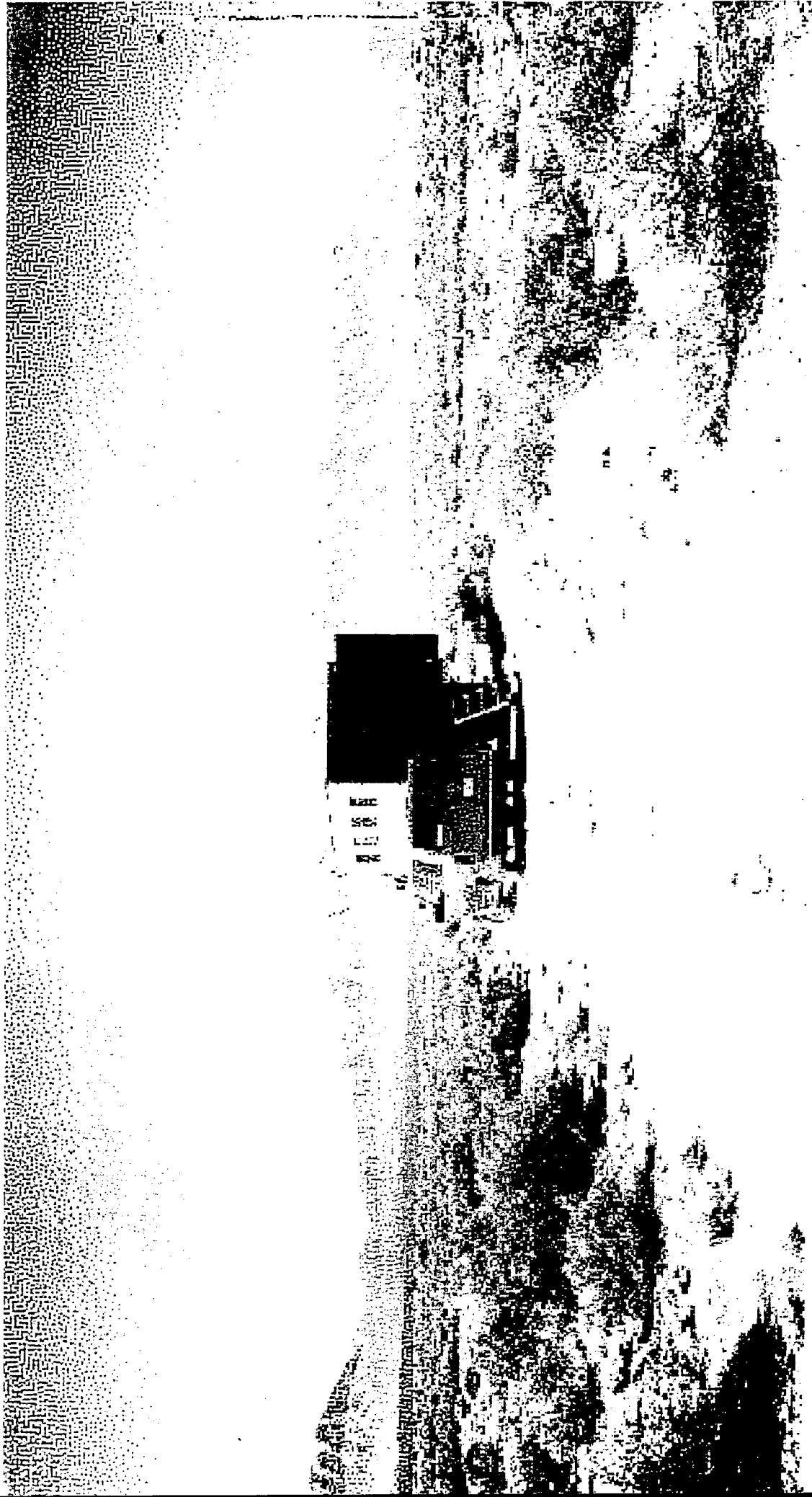


500 Ft





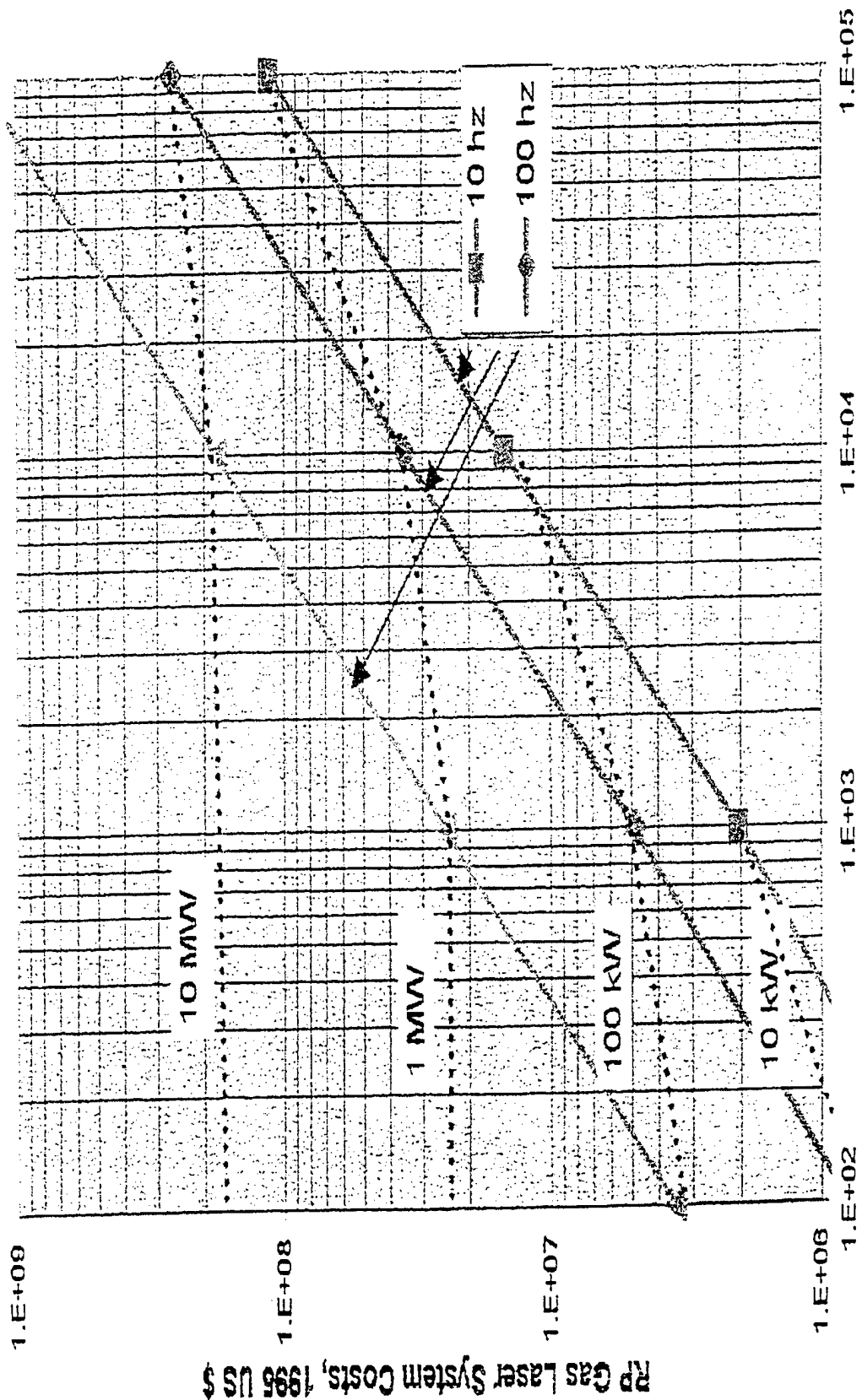
Optical Bench Set Up At 500-Ft Mark





RP GAS LASER COSTS ($\eta = 10\%$)

remove extra space



RP Gas Laser Output Energy, Joules / Pulse



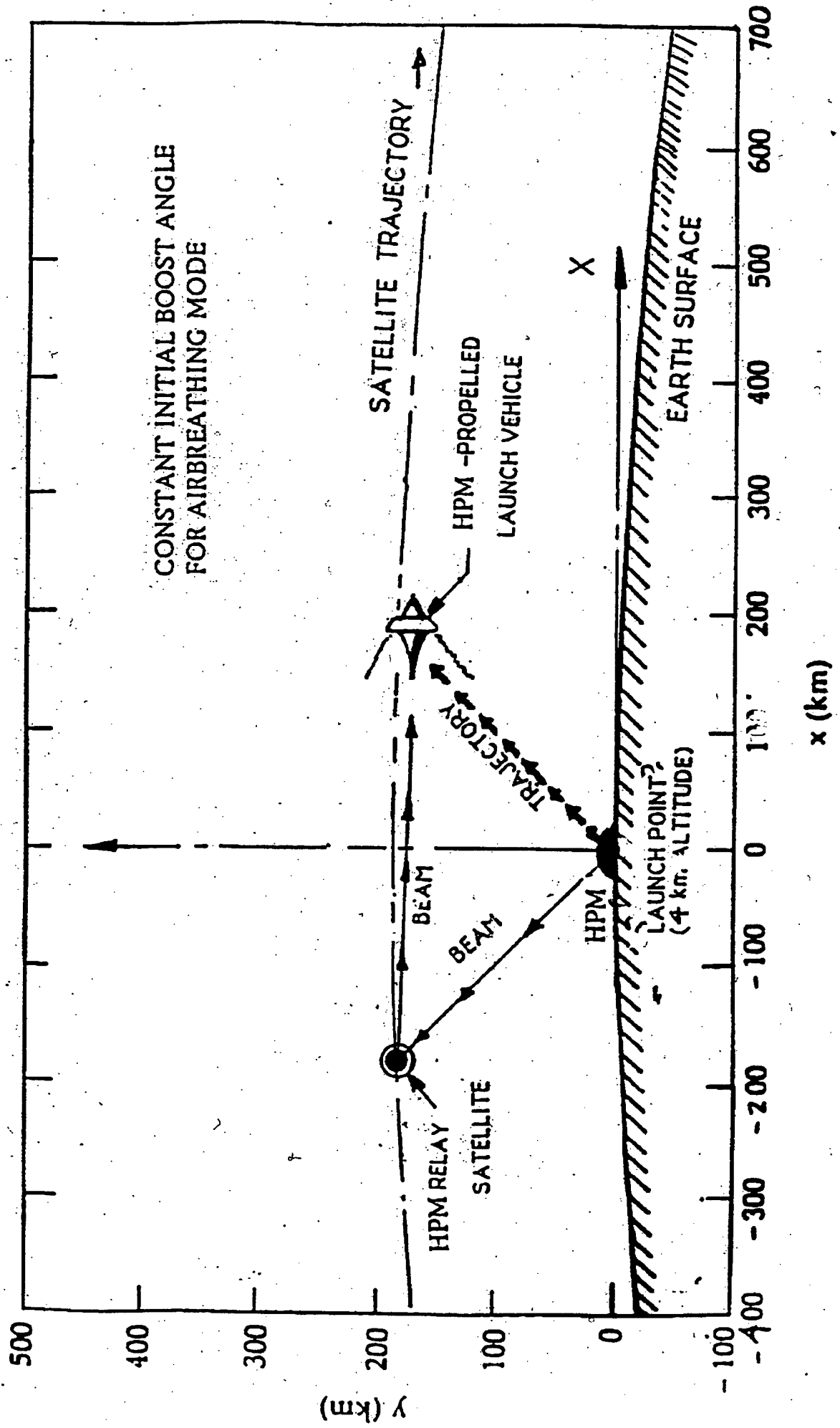
Introduction:

Rules of Thumb for a Laser Launch System

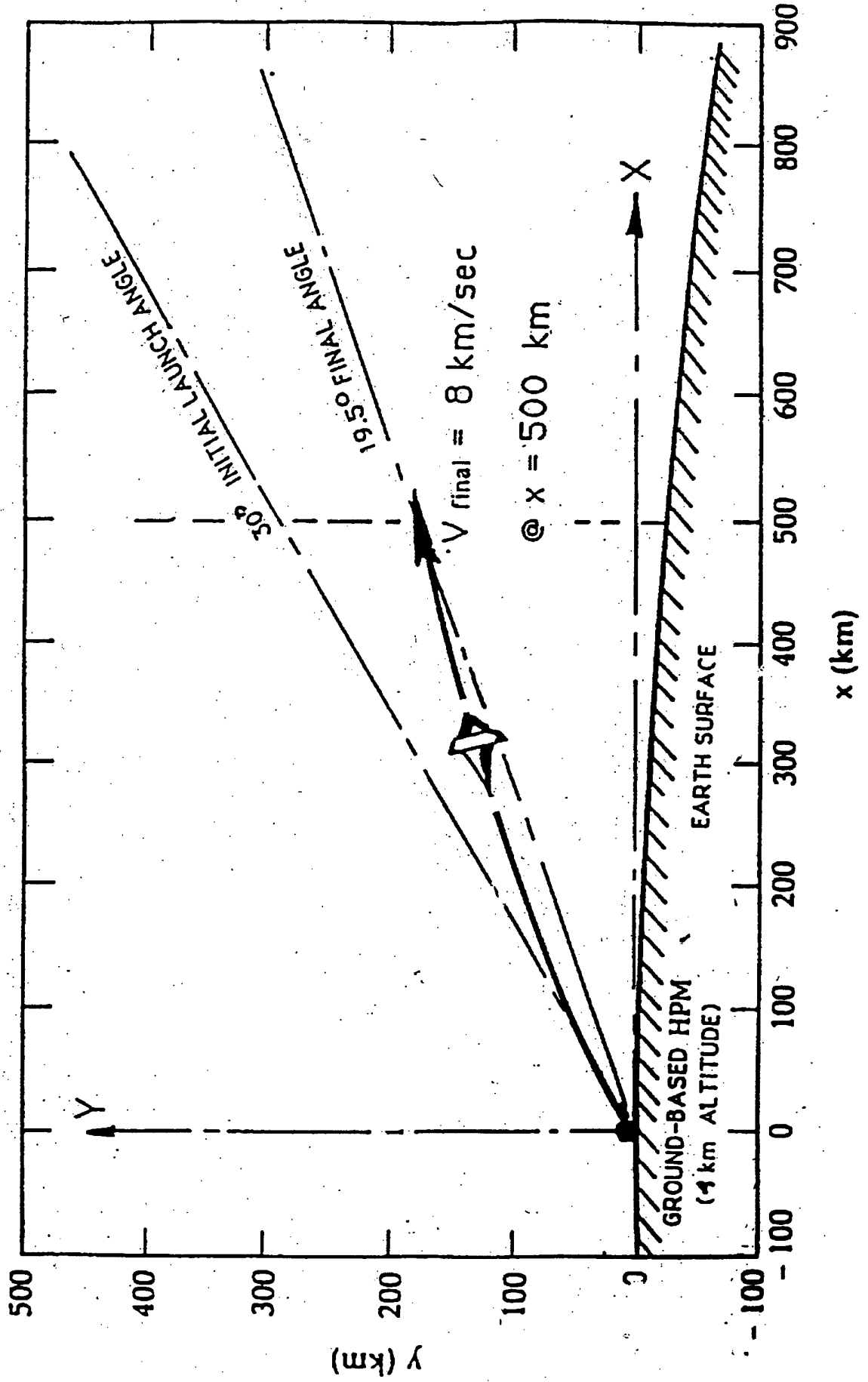
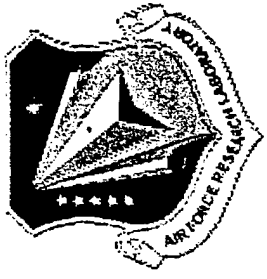
- **Payload to LEO: 1 kg/MW (within a factor of 2)**
- **Time to orbit: 400 to 1000 seconds**
- **Laser range required: 400 to 1500 km**
 - Longer ranges require space-based laser or relay mirror
- **Electrical energy per kg to LEO:**
150 - 300 kW-hr / laser efficiency
- **Max. launch rate**
 - To any orbit: 4 - 8 per hour, 100 - 200 per day
 - To one plane at 28.5°: ~ 8 - 32 per day
 - To one plane at 90°: ~ 2 - 8 per day



Launch With Relay Satellite



Direct Launch to Orbit (No Relay Satellite)





Laser Lightcraft Performance

A Paper By

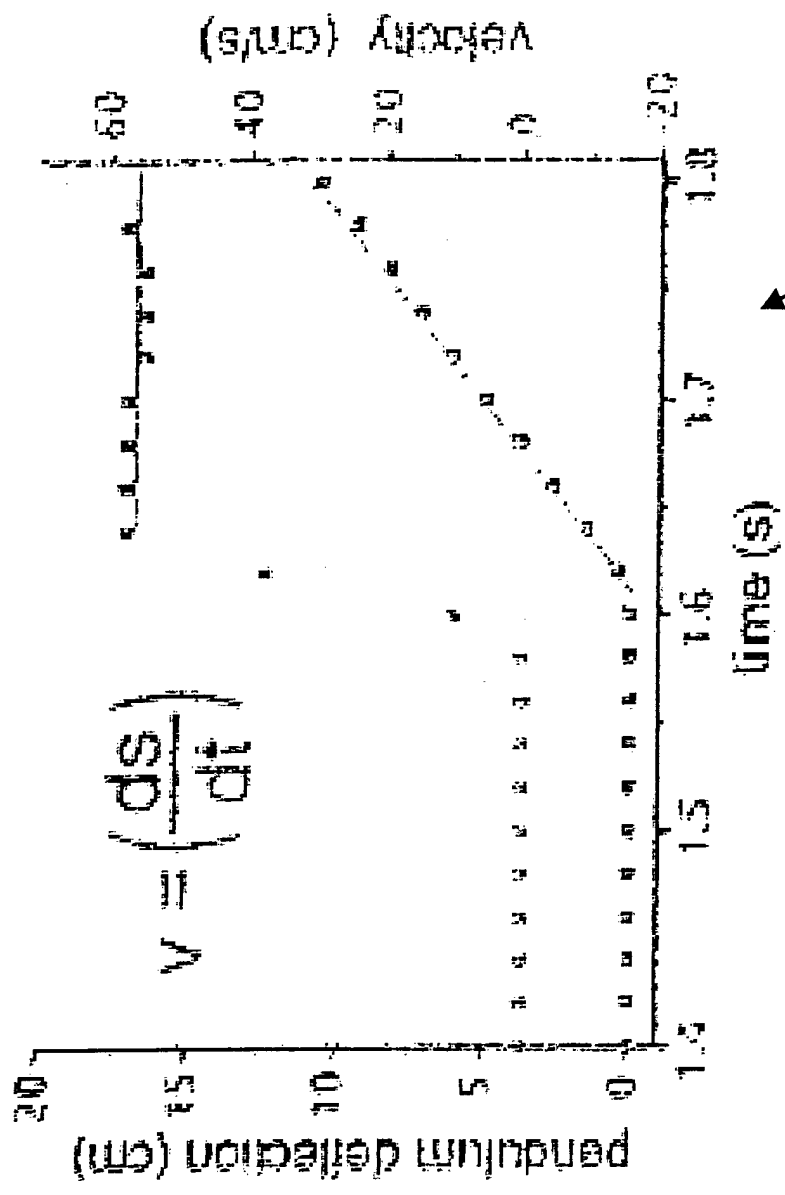
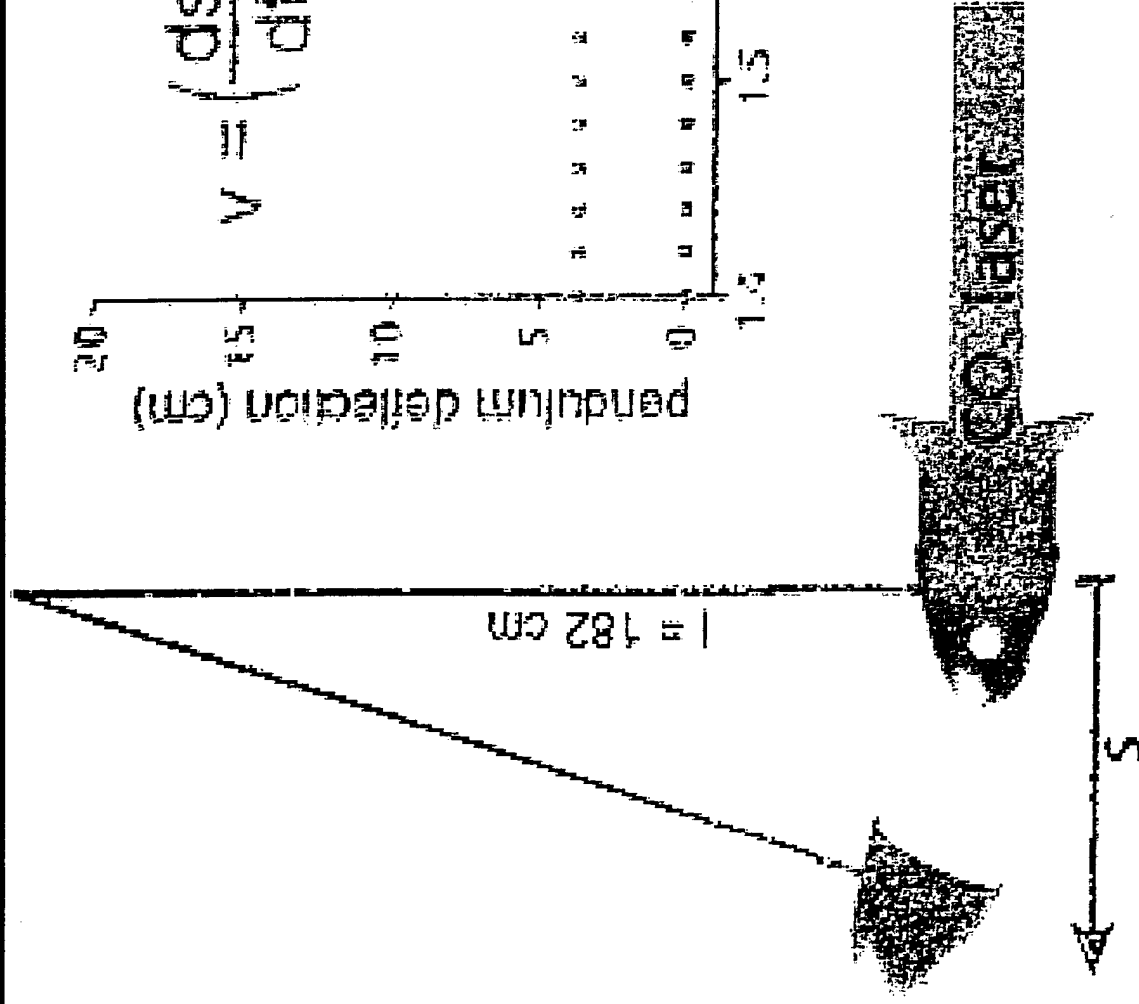
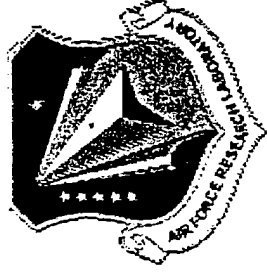
Dr. Willy L. Bohn

DLR Institute of Technical Physics

D-70569 Stuttgart, Germany



Schematic Of Dr. Bohn's Pendulum Experiment*



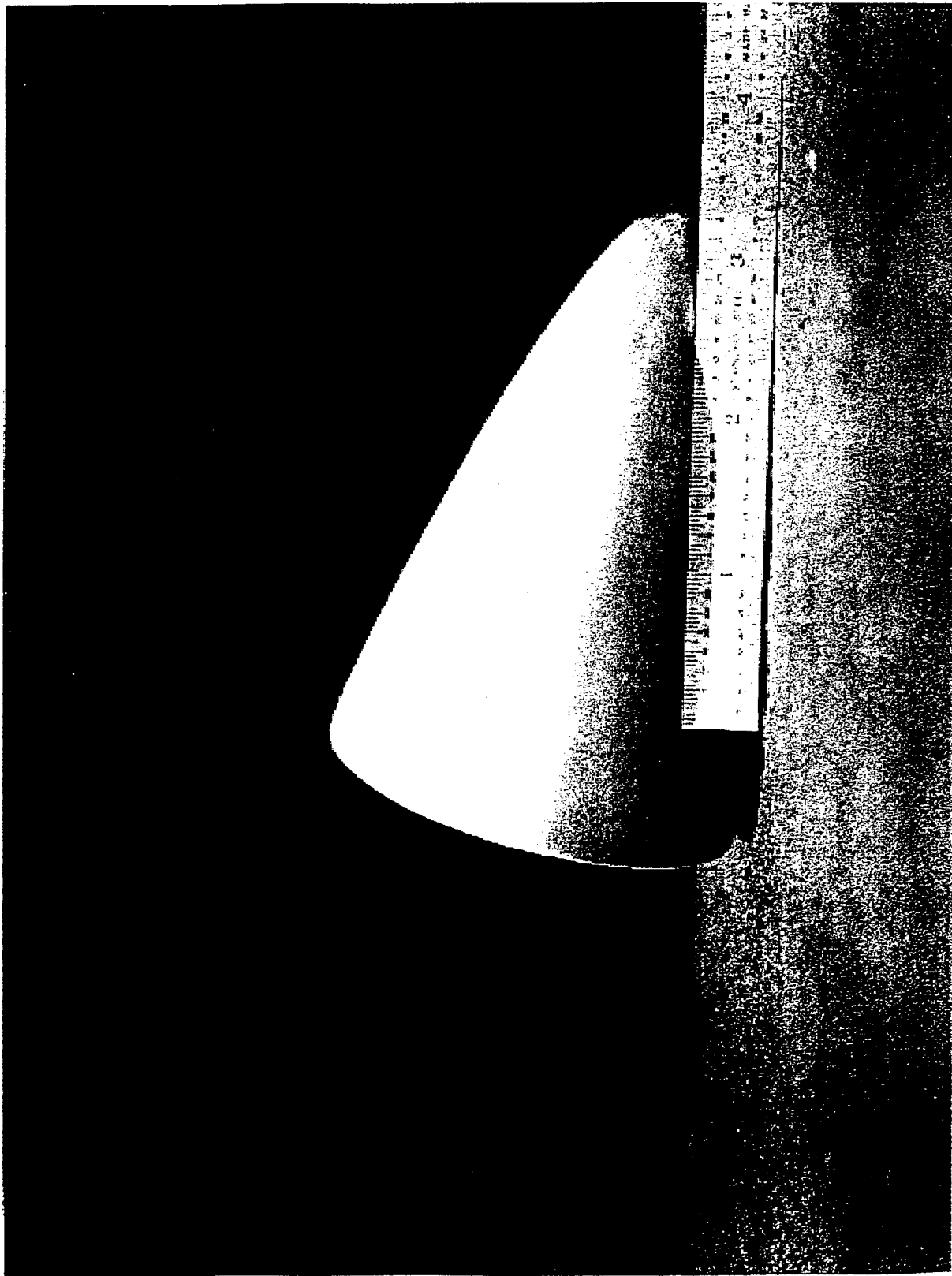
“Insert shows the deflection as a function of time and the corresponding lightcraft velocity”

* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics



AVCO Pulsejet Test Thruster

(White Sands Missile Range, July 99)





AVCO Pulsejet Test Thruster

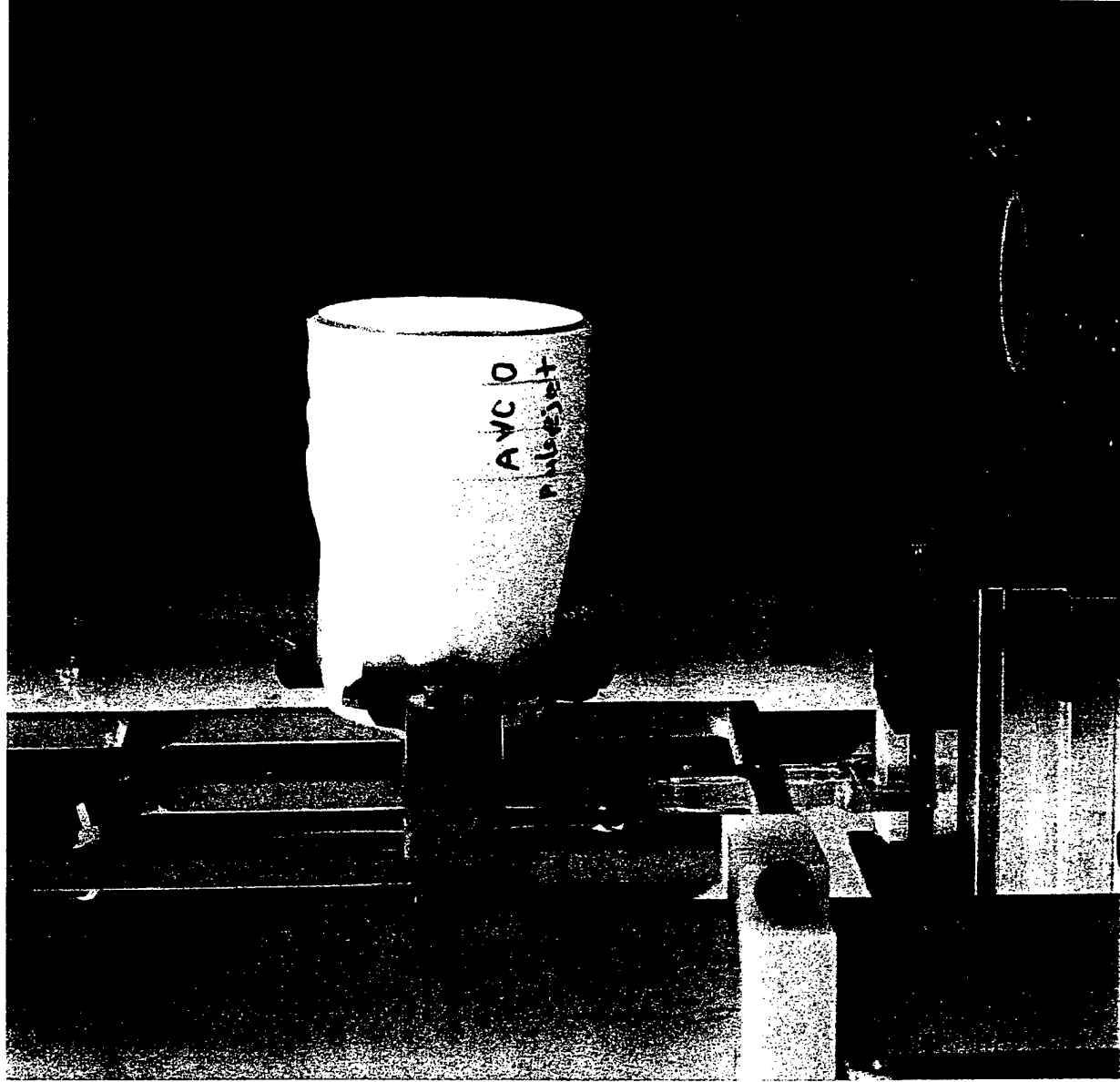
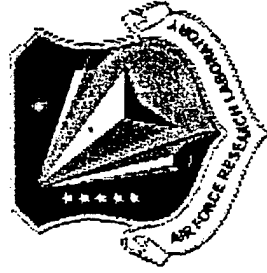
(White Sands Missile Range, July 99)





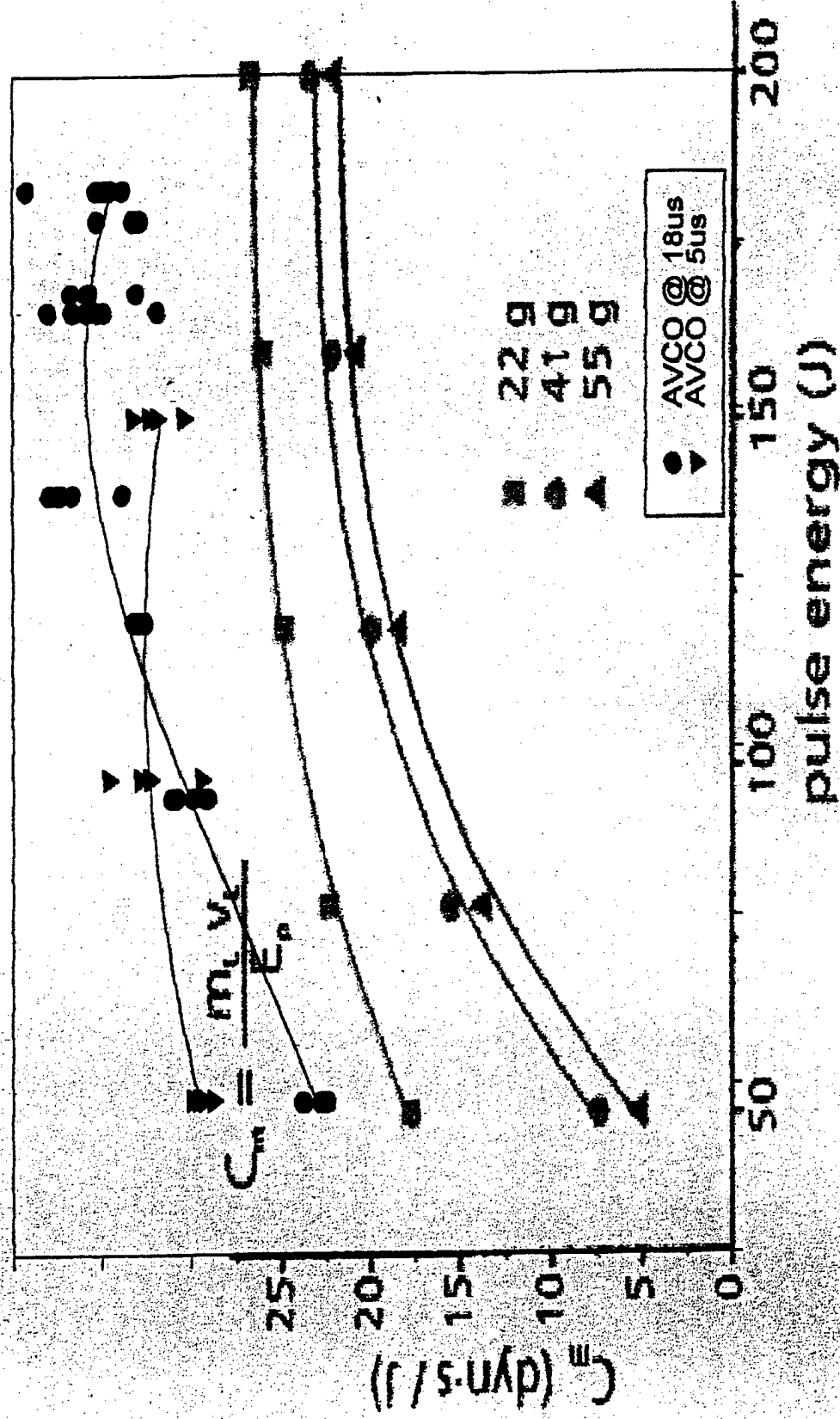
Test of AVCO Pulsejet Thruster Mounted on Pendulum Impulse Test Stand

(White Sands Missile Range, July 99)





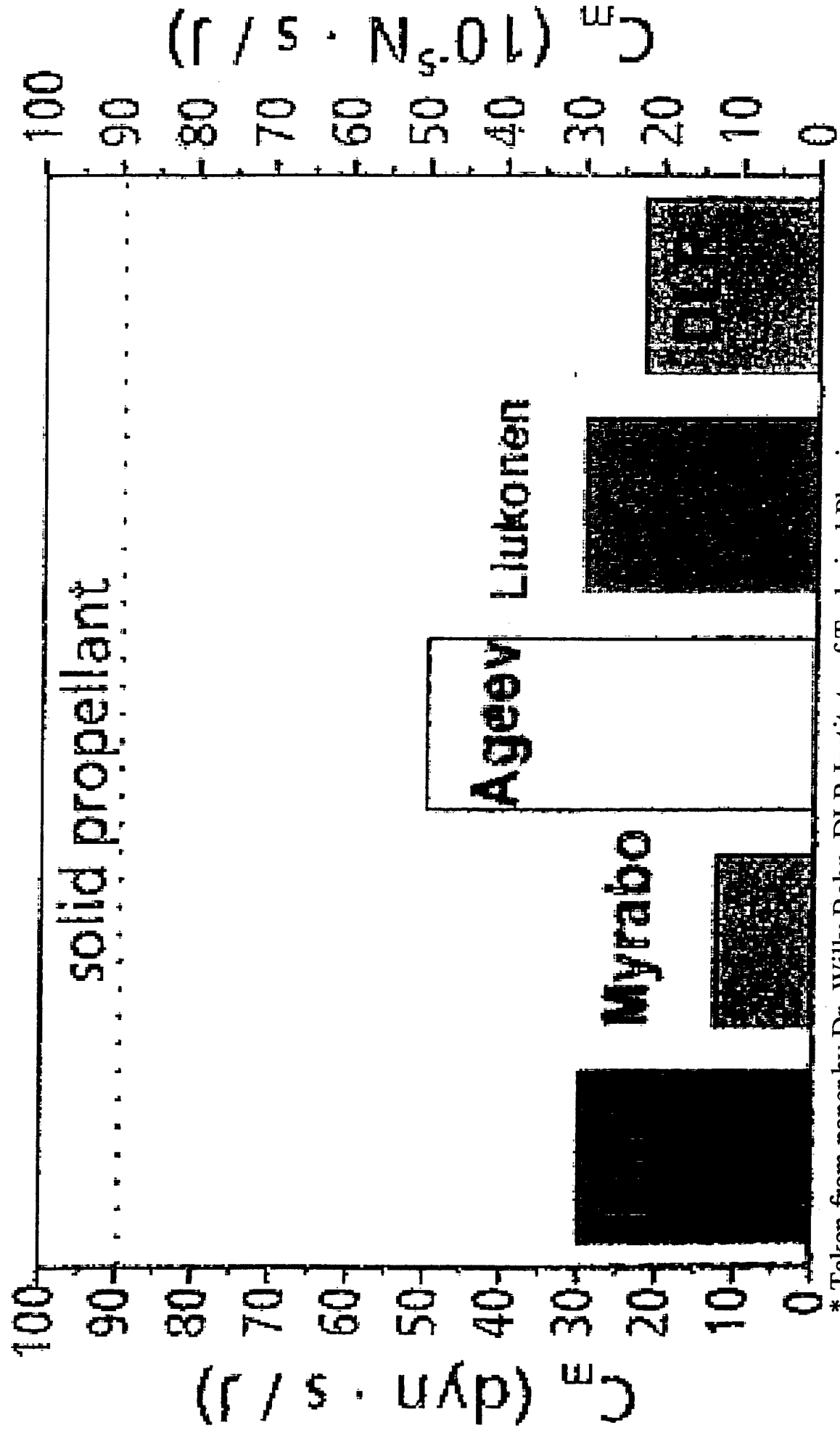
Comparison Of Dr. Bohn's Tests With AVCO Pulsejet Data Obtained At WSMR, July 99*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

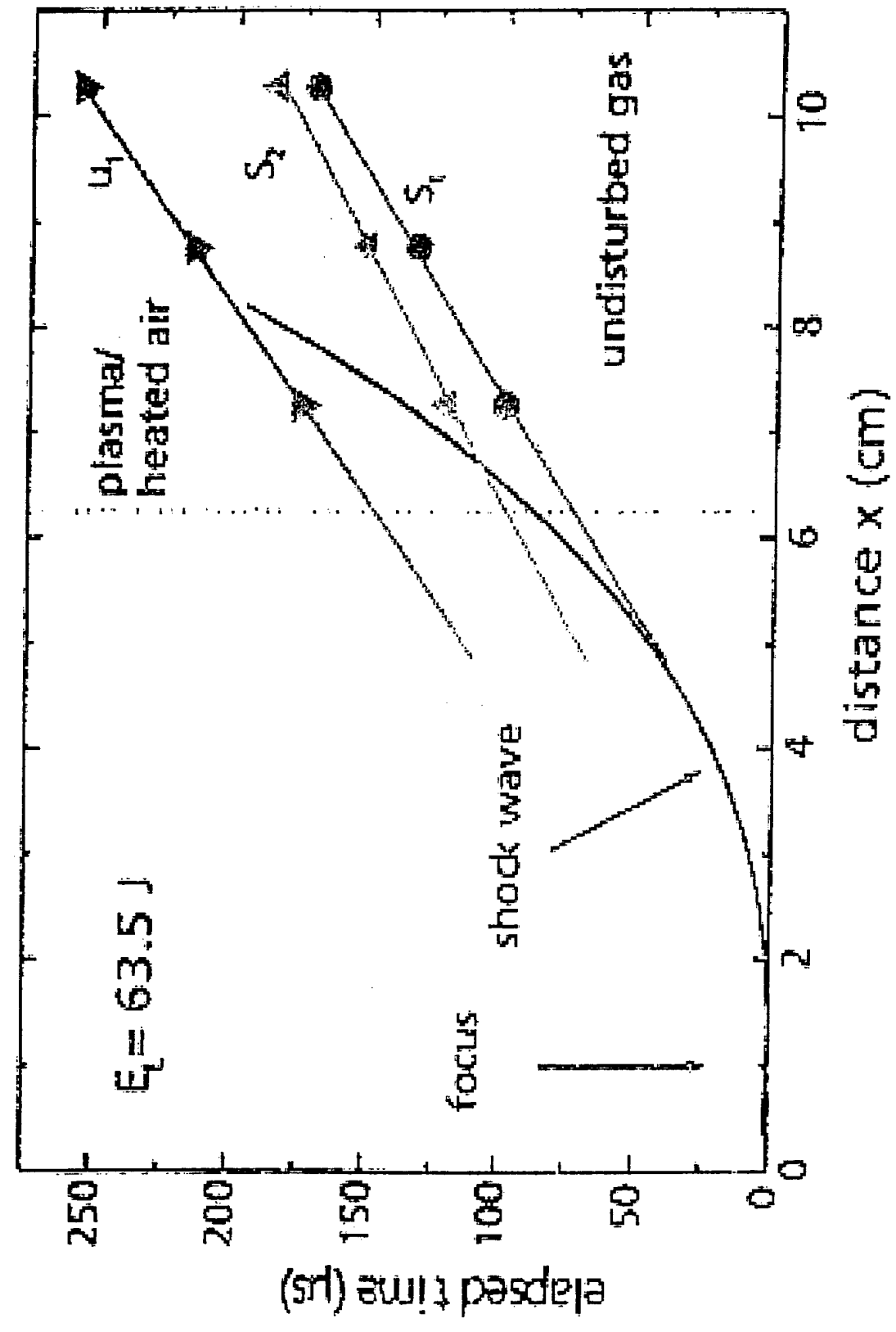
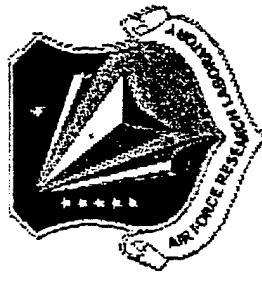


Comparison Of The Coupling Coefficient Obtained By Different Authors*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

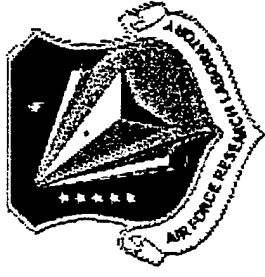
Evolution Of Shock Waves And Plasma In The Time-Space Domain*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics



Laser Propulsion Wrap-Up



- Many viable propulsion concepts possible using a laser source (mostly space propulsion)
- Laser propulsion system architecture cost dominated by laser source
- Promising near term concepts
 - Laser pulsejets (i.e., Lightcraft) and laser sail (e.g.)

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*spell out 'conference'

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