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TITLE: LASER CONTROLLED THERMONUCLEAR REACTOR MATERIALS REQUIREMENTS

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AUTHOR(S): James M. Williams
Thurman Frank

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os alamos
ientific laboratory
f the University of California
LOS ALAMOS, NEW MEXICO 87544

No. 836
2629

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MASTER

INTRODUCTION

GENERAL CHARACTERIZATION OF LCTR MATERIALS ENVIRONMENTS

Commercial power production from laser-driven fusion may be achieved by either of two conceptual approaches. The approach which enjoys the greatest support and which is judged to have the greatest potential for success is based on the use of lasers to compress and heat "pellets" of thermonuclear fuel to thermonuclear ignition and burn conditions. For the second approach, which is not the subject of this paper and is mentioned only for completeness, laser energy is used to heat a magnetically confined plasma of thermonuclear fuel to sufficiently high temperatures for thermonuclear ignition to take place. The second approach might more properly be referred to as laser-enhanced fusion.

The only fuel cycle which is being seriously considered at this time for laser-fusion systems is the DT cycle. Pellet energy yields in the range of a few tens to perhaps a few hundred MJ are expected to be necessary for economic power production. Preliminary investigations of LCTR concepts have been based on DT pellet yields of 100 to 200 MJ. Energy release from bare DT pellets has been investigated analytically, and typical results for a 100 MJ pellet microexplosion are summarized in Table I. Approximately 1% of the energy is released in the form of x rays with a spectrum which peaks at ~ 4 keV. The 3.5 MeV α particles resulting from the thermonuclear reactions share their energy with other pellet constituents; however, a large fraction eventually escape the plasma with an average particle energy of ~ 2 MeV, accounting for ~ 7% of the total energy release. The kinetic energy, ~ 0.4 MeV average per particle, of the pellet debris represents some 15% of the energy release, and the remainder, 77%, is in the kinetic energy of the 14.1 MeV neutrons. Fractional pellet burns are estimated to be ~ 25%.

All LCTR concepts which have evolved to date employ a central cavity within which repeated pellet microexplosions are contained. Reactor cavities are enclosed by relatively thick blanket regions containing flowing lithium for tritium breeding and heat removal. Penetrations of the blanket and cavity are required for high-powered laser beams and for fuel-pellet injection systems. The sequence of events associated with a pellet microexplosion which establishs materials environments are listed in Table II.

CAVITY CONCEPTS

The several cavity concepts which are receiving current consideration can be catagorized according to the physical processes by which energy depositions by x rays, α particles and pellet debris are accommodated by the cavity wall.

Energy deposition by relatively soft x rays in stainless steels and refractory metals occurs very near surfaces of incidence, i.e., a large fraction of the x-ray energy resulting from a DT microexplosion is deposited within a depth of ~ 10 μm. Energy deposition from xrays can lead to very large metal-surface temperature increases for unprotected surfaces; however, surface temperature increases are reduced appreciably by protective layers of materials with low atomic number. Included among the materials being considered for this purpose are lithium, beryllium and carbon.

The ranges in liquid metals and structural materials of the α particles and particles in the pellet debris described in Table I are of the order of 1 mg per cm^2 leading to penetration depths less than 5 μm for materials of interest. These considerations have led to reactor cavity concepts which employ evaporation and ablation of protective layers on the interior surfaces of cavity walls. Two such cavity concepts are the lithium-wetted-wall concept and ~~the~~ a much more speculative dry-wall concept.

The reactor cavity for the wetted-wall concept is formed by a porous niobium wall through which coolant lithium flows to form a protective coating on the inside surface (see Fig. 1). The protective layer of lithium absorbs the energy of the α particles and pellet debris and part of the x ray energy, is vaporized and subsequently exhausted through a supersonic nozzle into a condensor. The ablative layer is restored between pulses by radial inflow of lithium from the blanket region. A detailed description of the wetted-wall concept and its response to pellet microexplosions is given in Ref. 1.

The dry-wall concept is also provided with an ablative cavity liner. A promising cavity liner material is carbon. For such a design, a relatively small mass of cavity-liner material would be ablated by each pellet microexplosion. The mass of material ablated would depend on characteristics of the pellet burn, ionized particle ranges in the ablative material, and the cavity diameter. The cavity wall would cool sufficiently during the time intervals between successive pellet microexplosions to permit condensation of the ablated material. This concept will require much more detailed analysis before its credibility can

Protection of reactor cavity walls from energetic ionized particles by means of magnetic fields is an attractive conceptual alternative to ablative cavity liners. A very simple rendition of this concept is shown schematically in Fig. 2. The cavity is cylindrical in shape with an axial magnetic field. The α particles and the ionized particles in the pellet debris are diverted along magnetic field lines to energy sinks at the ends of the cavity. It is assumed in the concept shown that energy deposition in the energy sinks results in the evaporation of lithium from reservoirs. A staged vacuum system is shown for removal of the lithium vapor. Minimum cavity sizes would be determined by permissible x-ray energy deposition on cavity walls. Cavity liners of carbon or beryllium would be advantageous for increasing the tolerance for x rays.

Another reactor concept, generally referred to as the BLASCON[2], which was conceived by A. P. Fraas, Oak Ridge National Laboratory, has no cavity wall, per se; rather, a cavity is formed by a vortex in a rotating pool of lithium in which pellet microexplosions take place. Rotational velocity is imparted to the circulating lithium by tangential injection at the periphery of the reactor pressure vessel. Bubbles are entrained in the rotating lithium to facilitate attenuation of the energy of shock waves created by pellet microexplosions. Energy deposition by x rays and charged particles results in evaporation of lithium from the interior surface of the vortex. A schematic drawing of this concept is shown in Fig. 3.

BLANKET CONCEPTS

The functional requirements of blanket regions include the breeding of tritium and the removal of heat. There are also requirements related to the dissipation of the energy of accoustical shocks which result from neutron energy deposition in the blanket and structural regions and cavity related phenomena.

Conceptual blanket designs are based on the assumption that liquid lithium will be circulated through the blankets for removal of heat and the various hydrogen isotopes that are produced by neutron reactions with blanket materials. Containment of tritium within the blanket and associated piping and heat exchangers is of extreme importance both because of the biological hazard resulting from release of tritium to the environment and because of the value of tritium to the DT fuel cycle.

Acoustical shocks are produced in the blanket region from forces on the cavity wall due to energy deposition and ablation of protective liner materials and from pressures generated within the lithium through hydrodynamic coupling between walls and lithium expansion caused by neutron heating. It may be difficult to prevent high-frequency oscillation (ringing) of inner and outer walls.

Alternative blanket compositions may be advantageous for some concepts, especially the magnetically-protected design. Alternatives include stagnant lithium metal, lithium alloys, and lithium compounds either of which could be combined with gas or heat-pipe cooling. In addition, circulating lithium salts will be considered.

LASER SYSTEMS

Laser research and development is advancing rapidly, and it is not possible to predict the specific type or types of lasers that will be most advantageous for application in LCTR power systems. Characteristics of two lasers which are now being developed and which may ultimately be applicable to LCTR power production are listed in Table III. Calculations indicate that a total laser pulse of ~ 1 MJ with a pulse width of ~ 1 nsec will be required. The laser system technology which is developing most rapidly and which shows promise of achieving the required performance at reasonable cost and operating efficiency is the CO_2 system.

Experimental CO_2 lasers now in existence at LASL provide the basis for designing larger laser systems. The annular power amplifier design, shown schematically in Figs. 4 and 5,[3,4] is an extrapolation of this work.

A conceptual CO_2 laser design has been developed for use in reference LCTR design studies. The operational characteristics of the reference laser design are given in Table IV. Eight laser-amplifiers would be required to provide the anticipated requirement of 1 MJ per pulse.

The power amplifier is pumped by an electric discharge with ionization by an electron beam. The annular lasing cavity is subdivided into eight subcavities which can be pulsed simultaneously or individually in a programmed manner. Sequential pulsing of individual cavities may provide some capability for pulse shaping by superimposing beams. Annular pulses are collected and focused by means of a toroidal, catoptric beam-focusing device. Laser pulse repetition rates of from 35 to 50 per sec would require circulation of cavity gas for convective cooling.

At 35 pulses per sec, cooling the circulating laser gas in the reference design laser amplifier will require ~ 40 MW of cooling capacity. Moreover, since amplifier performance is significantly degraded by excessive temperatures, it will be necessary to dump this heat at relatively low temperatures. Several manifolds of intake and exhaust ports will probably be required to permit radial flow distribution of the laser gas in the lasing cavity.

One of the most restrictive limitations on laser amplifier design is due to laser light damage to window materials. The experimentally determined damage threshold for the alkali halides is ~ 3 J per cm^2 for repeated, short laser pulses. In order to avoid thermal stresses in windows, it will be necessary to cool them to prevent excessive temperature gradients.

LASER-BEAM TRANSPORT SUBSYSTEM

The laser-beam subsystem transports laser light from the laser power amplifier into the reactor cavities and focuses the laser pulse on fusion pellets at the center of the cavity. Efficient beam transport requires a number of optical components and a system of evacuated light pipes. Optical elements are required for:

Separation of gases of different composition or pressure (windows);

Beam focusing, diverging, deflection and splitting (mirrors);

Fast switching of beams; and

Component isolation to decouple the laser from reflected light.

The alkali halides are being developed for infrared laser window materials and typical metallic reflectors for mirrors. Research on bulk and on surface damage mechanisms is being actively pursued as is the search for materials with improved performance. Limits on beam intensity are imposed by damage to windows and mirrors from laser light which results in LCTR requirements for large diameter components. Elements for fast switching and component isolation include both active elements (electro-optic, acousto-optic, expendable membranes, etc.) and passive elements (saturable absorbers and diffraction gratings).

Since the laser subsystem represents a significant fraction of the capital investment of an LCTR plant, it may be economically advantageous to centralize components so that each laser system serves several reactor cavities. Centralized laser systems require fast beam switching from laser power amplifiers to selected beam ports. Beam switching, which would be required for central laser systems, might be accomplished by rotating mirrors. This scheme would require moving parts in a vacuum system with associated requirements for bearings and seals. Very long light pipes could also be required for large multicavity plants with centralized laser systems. It will be necessary to maintain precise alignment of optical components which will require compensations for effects of temperature changes, earth tremors and plant vibrations; and, of course, the laser beam transport systems must penetrate the biological shielding surrounding reactor cavities by indirect paths to prevent radiation streaming.

Beam focusing on target will probably require sophisticated pointing and tracking systems with feed-back servo systems controlling large mirrors in vacuum and radiation environments. The final optical surface with its associated blow-back protection devices and contaminated vacuum and cooling systems may have to be engineered for frequent replacement.

FUEL CYCLE

The DT cycle is the only fuel cycle which is being seriously considered at this time for laser-fusion systems. Deuterium is easily and cheaply obtained from conventional sources, but tritium is expensive to produce and is not available in large quantities. Thus, it is expected that tritium will be produced by reactions between neutrons and lithium in the blanket regions of LCTR plants.

In order to prevent significant loss of tritium by diffusion through the intermediate heat exchanger and reactor containment, very low tritium concentrations must be maintained in the circulating lithium. This requirement further complicates the difficult task of separating the tritium from the lithium. Several separation schemes have been proposed but none has yet been demonstrated to be superior for this application.

MATERIALS CONSIDERATIONS

Materials requirements for laser controlled thermonuclear reactors are similar in many respects to those for other approaches to fusion reactors. There are, however, some environments in LCTR systems that pose unique materials problems. Some of these materials considerations are discussed above. Some of the more pressing problems are discussed in greater generality here.

Cavity and Blanket Structures

The reactor cavity is the most hostile material environment associated with an LCTR power plant. Interactions between the products of fusion-pellet microexplosions and first-wall materials are expected to result in severe limitations on cavity lifetimes for high-power-density, minimum-size cavities.

Cavity walls will be subject to severe radiation damage from 14 MeV neutrons. Degradation in the physical and mechanical properties of structural materials can be expected. A large body of experimental data exists from the fission reactor program on the effects nuclear irradiation has on the physical and mechanical properties of stainless steels, nickel-base alloys, and zirconium based alloys. Very little information has been generated for the high-temperature refractory materials usually considered for fusion-reactor cavity walls. Based on the relatively small amount of data available, it appears that neutron irradiation may result in significant decreases in the elastic moduli; although, these effects are apparently minimized if operating temperatures can be maintained above half the material melting point.[n] An irradiation materials problem which is of concern for magnetically confined concepts but which may be avoided for LCTR concepts is that of sputtering damage from charged particles that escape the plasma. Protective layers of ablative materials should serve to eliminate this problem for current LCTR cavity designs. There may be some sputtering due to neutron collisions; however, this is not expected to be a significant problem for refractory metals.

The greatest uncertainty with regard to the effects of neutron irradiation of structural materials is due to the production of copious amounts of interstitial gas from (n,p) and (n,α) reactions. Loss of ductility due to helium has been investigated by injection of helium by means of cyclotron irradiations.[n+1]

Severe losses of ductility resulted in stainless steel which becomes gressively worse with increasing temperature and ~~h-elium~~ helium concentration. Loss of ductility due to helium implantations have been reported[n+2] to be severe for barradium and niobium alloys but minimal for alloys of molybdenum (TZM).

There are also large amounts of hydrogen and tritium produced in the structural materials and in the lithium coolant. The formation of hydrides and the resulting embrittlement could be a serious problem. Niobium and vanadium form stable hydrides at low temperatures, however, hydrogen solubility in these materials decreases rapidly with increasing temperature. If reactor cool-downs can be programmed in such a manner that hydrogen is allowed to diffuse out of these materials before room temperatures are reached, hydrogen embrittlement may not be a problem for these materials. Molybdenum does not form hydrides and has a very low hydrogen solubility. More information about the hydriding effect in steel is required.[n+3]

Neutron irradiation of composite cavity walls consisting of carbon or beryllium and a refractory metal or steel substrate can result in problems due to differences in irradiation induced swelling rates. Nonuniform swelling could result in spall of the protective layer. Similar difficulties could arise from differences in thermal expansion coefficients for materials in a composite wall.

Becau~~s~~se of the cyclic stresses which are imposed on reactor cavity and blanket-region wall structures, the failure mode which is most likely to determine limits on lifetimes is fatigue. It is this consideration that accentuates the importance of experimental determination of radiation induced changes in elastic moduli of structural materials for LCTR application.

There are also neutronics considerations relating to after-heat and induced activity in structural materials. Although the problems resulting from induced activity are much less severe for fusion reactors than for fission reactors, it will be necessary to replace and dispose of radioactive components from fusion reactors. Because of limited material resources, it may also be necessary to "rework" irradiated materials for the fabrication of replacement parts. The only potential structural material which offers a significant advantage in this respect is vanadium.[n+4] The afterheat and biological hazard for vanadium will be several orders of magnitude lower than for niobium for times-after-shutdown of the order of 100 days and greater. (However, helium and hydrogen production will be significantly greater for vanadium than for niobium.)

The problem of liquid metal corrosion of structural materials must also be considered. Lithium is compatible with the refractory metals up to temperatures of 1000 °C or greater.[n+5] The use of stainless steel presents difficulties from solution type corrosion and mass transfer at temperatures above 500°C. One of the major materials problems will remain that of maintaining adequate corrosion resistance in welds and brazes necessary for fabrication of the walls.

Techniques for fabricating large structures from refractory metals remain to be demonstrated. Some experience has been gained in fabricating large structures from niobium in the space program. Fabrication procedures such as welding apparently pose no significant problem for any of the candidate materials except molybdenum which forms brittle weld zones. There has, however, been recent promising progress in developing brazing techniques for molybdenum.[n+6]

There is little freedom in the choice of blanket coolants because of anticipated operating temperatures (500-1000°C) and the necessity to breed tritium. Candidate materials are lithium, flibe (Li_2BeF_4), helium, and possibly heat pipes (containing potassium as the working fluid). Unless it proves to be too costly or difficult to remove tritium from circulating lithium, there are apparently fewer problems associated with the use of lithium than with flibe. The disadvantages of flibe result from the corrosive nature of it and some of its transmutation products. Gas and heat-pipe cooling might be advantageous when coupled with tritium breeding materials such as stagnant lithium, lithium alloys, or lithium compounds.

It should be noted that the restrictions on blanket design due to the necessity of obtaining adequate breeding ratios are much less demanding for LCTR concepts than for magnetically confined concepts. Assuming that tritium doubling times of the order of a year are satisfactory, very rugged cavity and blanket structures with natural lithium coolant are acceptable.

Laser and Beam Transport Systems

Although laser designs for LCTR application have not been determined in detail, there appear to be no particularly unique or demanding materials problems associated with CO_2 laser system except for window materials. Windows must have good optical transmission and be resistant to damage from intense laser light and possibly x rays, γ rays and neutrons. They must also have mechanical and thermal properties which are compatible with other system requirements. Candidate materials for windows include the alkali halides (NaCl, KCl, etc.), germanium, and the chalcogenides (GaAs, CdSe, etc.).

Damage from laser light to infrared window materials is generally assumed to be thermal in origin. Major importance is attached to increasing the mechanical strength by the development of polycrystalline materials and to reducing the absorption constant to its lowest possible value.$^{n+7}$ Recent experience indicates that limitations on laser light intensity in infrared window materials are determined more by impurities than by intrinsic material properties. Changes in window geometry and possible fracture are important materials problems resulting from temperature gradients due to repeated short pulses of intense laser light through large windows. The experimentally measured threshold for damage from repeated, short (~ 1 ns) infrared pulses is ~ 3 J/cm^2.$^{n+8}$

There has been substantial progress within the last few years in the understanding of laser damage mechanisms in window materials and in the development of materials which are resistant to such damage. Continued improvement is expected, especially from better quality control.

The beam transport system will include, in addition to windows, optical elements for fast switching, component isolation, and beam deflection and focusing. There are a number of acceptable elements in use for fast switching and component isolation (electro-optic, magneto-optic, expendable membranes, (repetitious) etc.).

Typical metallic reflectors (Cu, Au, Ni, Mo, etc.) are being developed for mirrors. Little is understood about damage from laser light to metallic surfaces, other than to assume it is thermal in character. There is also a lack of experimental damage data for repeated short laser pulses. Extrapolation of existing data to the ns pulse range indicates a laser light damage threshold of ~ 10 J/cm^2.[n+9]

Very significant progress is being made in the development of mirrors. Surface finishing techniques including superpolishing, sputtering and micromachining are being rapidly improved. There has also been recent successful research in developing dielectric coatings for mirrors.[n+10] Coating with reflectivities > 99.8% can now be fabricated routinely.

The focusing mirror that "looks" into the reactor cavity is subject to damage from x rays, γ rays, neutrons, charged particles and possibly cavity ablative material. Energy deposition on this reflecting surface may result in distortion and even surface spall. Atomic dislocations due to neutron collisions may result in damage to the optical surface as a result of the formation of color centers. The deposition of cavity ablative material on the reflecting surface could enhance damage due to laser light as well as generally degrading the quality of the surface. There is essentially no data on which to base damage thresholds due to cavity related phenomena. Experimental data must be generated to provide answers to these questions.

PELLET FABRICATION AND INJECTION

It is not possible to anticipate detailed materials problems related to pellet fabrication and injection at this time since proven pellet designs do not exist. Fabrication techniques for solid, cryogenic DT pellets have received some thought, and a very rudimentary conceptual approach is illustrated in Fig. 6.[n+11] Solid, cryogenic, stoichiometric DT is extruded through a die and is cut to length by a laser beam. The cylindrical pellet assumes a spherical shape due to surface tension and viscous effects during passage through a warmer injection chamber.

High velocity pellet injection will probably be necessary to minimize pellet heating and to maintain stable pellet trajectories. Pellet injection could be accomplished by mechanical, electrostatic or pneumatic methods. Pneumatic pellet acceleration is indicated in Fig. 6.

Blowback protection is provided by a rotating valve which operates synchronously with the pellet injection system. This valve permits passage of the pellet without direct exposure of the injection system to the products of pellet microexplosions.

Another system which is closely associated with pellet fabrication is that of tritium separation and handling. Tritium separation from lithium to levels of a few ppm is expected to be a formidable problem which may contribute significantly to the cost of power from fusion reactors. This problem may provide impetus for serious consideration of alternative blanket materials such as lithium-aluminum alloys from which tritium is readily released.

CONCLUSIONS

Feasibility evaluations and engineering analyses of LCTR systems are of a very preliminary nature at this time. It is, however, obvious that significant extensions in materials technologies will be necessary to satisfy the requirements for clean, safe, economical power from LCTR power plants.

The severity of materials problems will be estimated by detailed studies of the various conceptual approaches. The results of these studies together with overall plant systems studies will guide the planning of experimental investigations. The selection of materials investigations to be conducted will be determined to some extent by the availability of testing environments, and there are many opportunities for innovative approaches to obtaining the required materials data.

There is a severe time lag between the initiation of experiments and the reduction of experimental data for use in engineering design. This is particularly true for such areas as radiation, fatigue, and corrosion testing. Fortunately, much of the required data will be applicable to the design of both magnetically-confined and LCTR concepts.

Intensive efforts to reconcile materials problems for LCTR concepts awaits successful achievement of thermonuclear burn from laser fusion.

REFERENCES

1. Booth unclassified report.

2. A. P. Fraas, "The BLASCON ...

3,4 Laser papaers presented at Princton meeting L-1

n J. Motiff, "Irradiation Effects on the Mechanical Properties of BCC Metals", Fusion Reactor First Wall Materials, WASH-1206, 4/72.

n+1 D. Kramer, et. al., "Helium Embrittlement in Type 304 Stainless Steel", J. Nuc. Mat. 25, 121 (1968).

n+2 D. Kramer, "Helium Embrittlement", Fusion Reactor First Wall Materials, WASH-1206

n+3 G. L. Kulcinski, "Major Technological Problems for Fusion Reactor Power Stations", International Conference, World Energy Problems: Nuclear Solutions ~~Sta' ons~~, 1972.

n+4 D. Steiner, "The nuclear Performance of Vanadium as a Structural Matarial" ORNL-TM-4353, 10/73.

n+5 Eugene Edward Hoffman, "Corrosion of Materials by Lithium at Elevated Temperatures" ORNL-2674, 3/23/59.

n+6 N. C. Cole and G. M. Slaughter, "Brazing of Molybdenum", ANS Winter Meeting, SF, CA, 11/11-15/73.

n+7 Alexander J. Glass and Arthur H. Guenther, "Laser INduced Damage of Optical Elements", Proc. of the Japan-US-Seminar on Laser Interaction with Matter, Kyoto, Japan, 9/24-29/72.

n+8 Walter Reichelt, LASL, priv. com.

n+9 J. Y. Wada, O. P. Judd, G. M. Janney, and V. Wang, "High Power Optical Components and MOde Control Problems in High Energy CO_2 Lasers", loc cit (n+7)

n+10 W. H. Reichelt, LASL, Int. Memo, 10/19/73.

n+11 F. T. Finch, LASL, Int. Memo, 5/73

Table I

TYPICAL ENERGY RELEASE MECHANISMS FROM A 99 MJ DT PELLET MICROEXPLOSION

Mechanism	Fraction Of Total Energy Release	Particles Per Pulse	Average Energy Per Particle	
Rays	0.01		~4 keV peak	
Particles that Escape Plasma	0.07	2.2×10^{19}	2 MeV	
asma Kinetic Energy	0.15			
α Particles		1.3×10^{19}	0.6 MeV	Total Ave. 0.37 MeV
Deuterons		1.2×10^{20}	0.3 MeV	
Tritons		1.2×10^{20}	0.4 MeV	
utrons	0.77	3.3×10^{19}	14.1 MeV	

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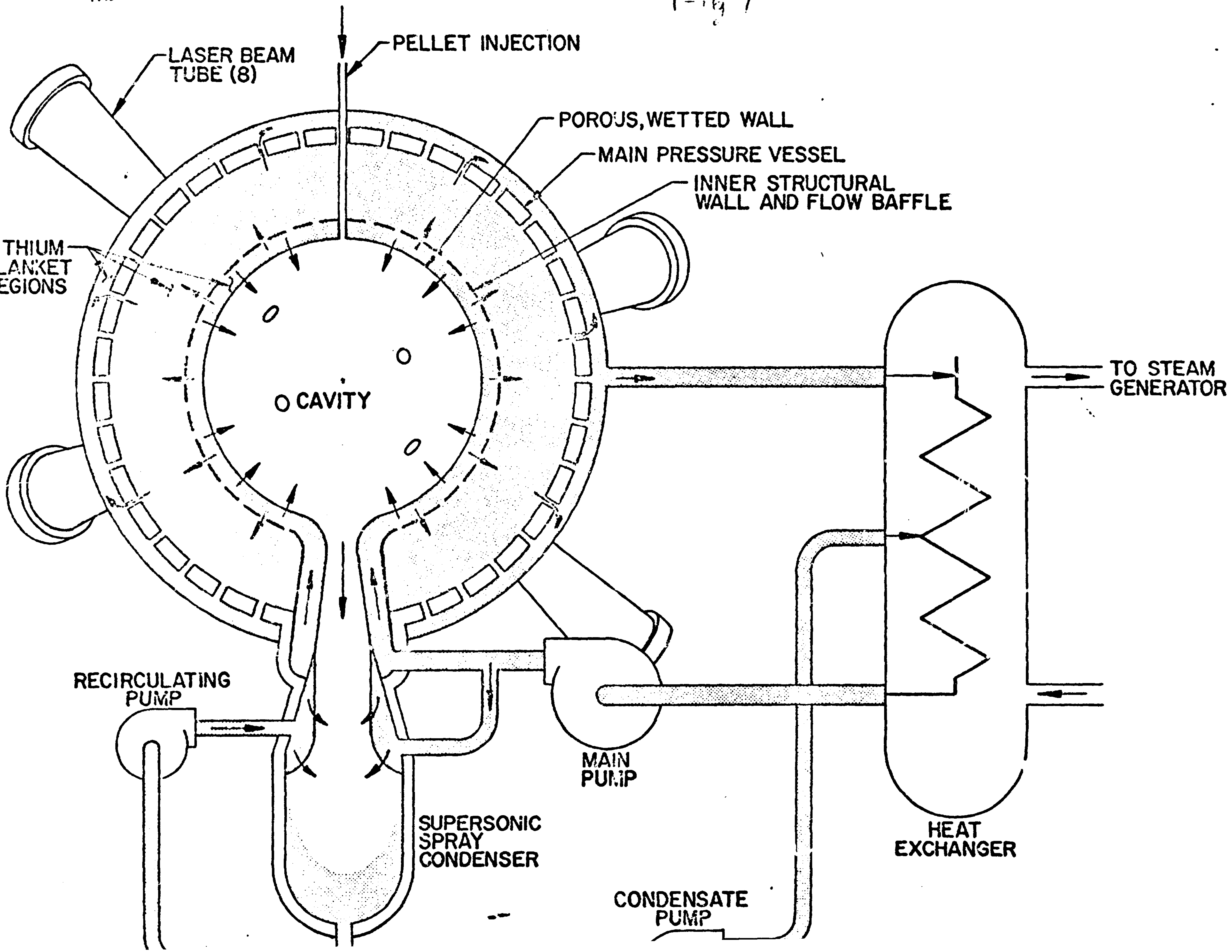
actional Burnup 0.25

Table II

TIMESCALE OF EVENTS FOR LCTR PELLET FUSION PULSE

TIME	PRIMARY EVENTS	SECONDARY EVENTS
-20 to -5ms	Pellet Enters Cavity	
-150ns	Laser Pulse Fired	
-10ns	Laser Pulse Arrives at Pellet Surface	
0	Thermonuclear Burn Begins	
+10ps	TN Burn Complete	
+6ns	X rays strike first wall	
		Ablative material begins expansion from first wall
+30ns	X rays strike last optical Surface	
+20-100ns	Neutrons Deposited in Reactor Vessel	Shock wave induced in lithium
+60ns	Neutrons Strike last optical surface	
		Ablative material and pellet debris interact
0.3 to 1.2μs	Pellet Debris Strikes First Wall	
		Cavity atmoshpere equilibrated
+1ms	Cavity Blowdown Begins	
0.01 to 10 sec	Restoration of original cavity conditions complete	Wetted wall blowdown complete, lithium vortex restored, turbulence in rarified dry wall cavity dissipated.

Fig 1


PELLET INJECTION
LASER BEAM TUBE (8)
POROUS, WETTED WALL
MAIN PRESSURE VESSEL
INNER STRUCTURAL WALL AND FLOW BAFFLE
LITHIUM BLANKET REGIONS
CAVITY
TO STEAM GENERATOR
RECIRCULATING PUMP
MAIN PUMP
SUPERSONIC SPRAY CONDENSER
HEAT EXCHANGER
CONDENSATE PUMP

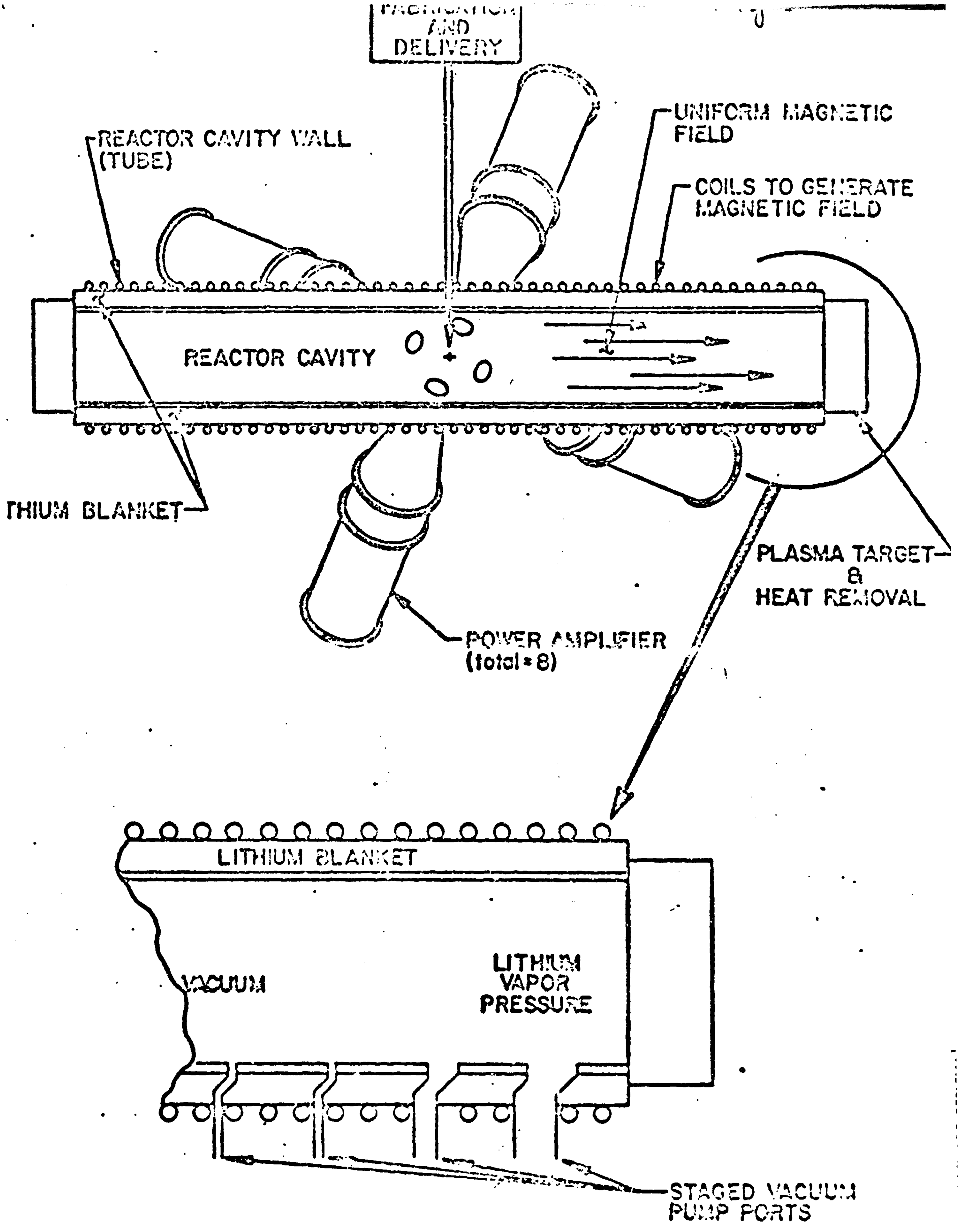

AND DELIVERY
REACTOR CAVITY WALL (TUBE)
UNIFORM MAGNETIC FIELD
COILS TO GENERATE MAGNETIC FIELD
REACTOR CAVITY
THIUM BLANKET
PLASMA TARGET & HEAT REMOVAL
POWER AMPLIFIER (total = 8)
LITHIUM BLANKET
VACUUM
LITHIUM VAPOR PRESSURE
STAGED VACUUM PUMP PORTS

Fig 3

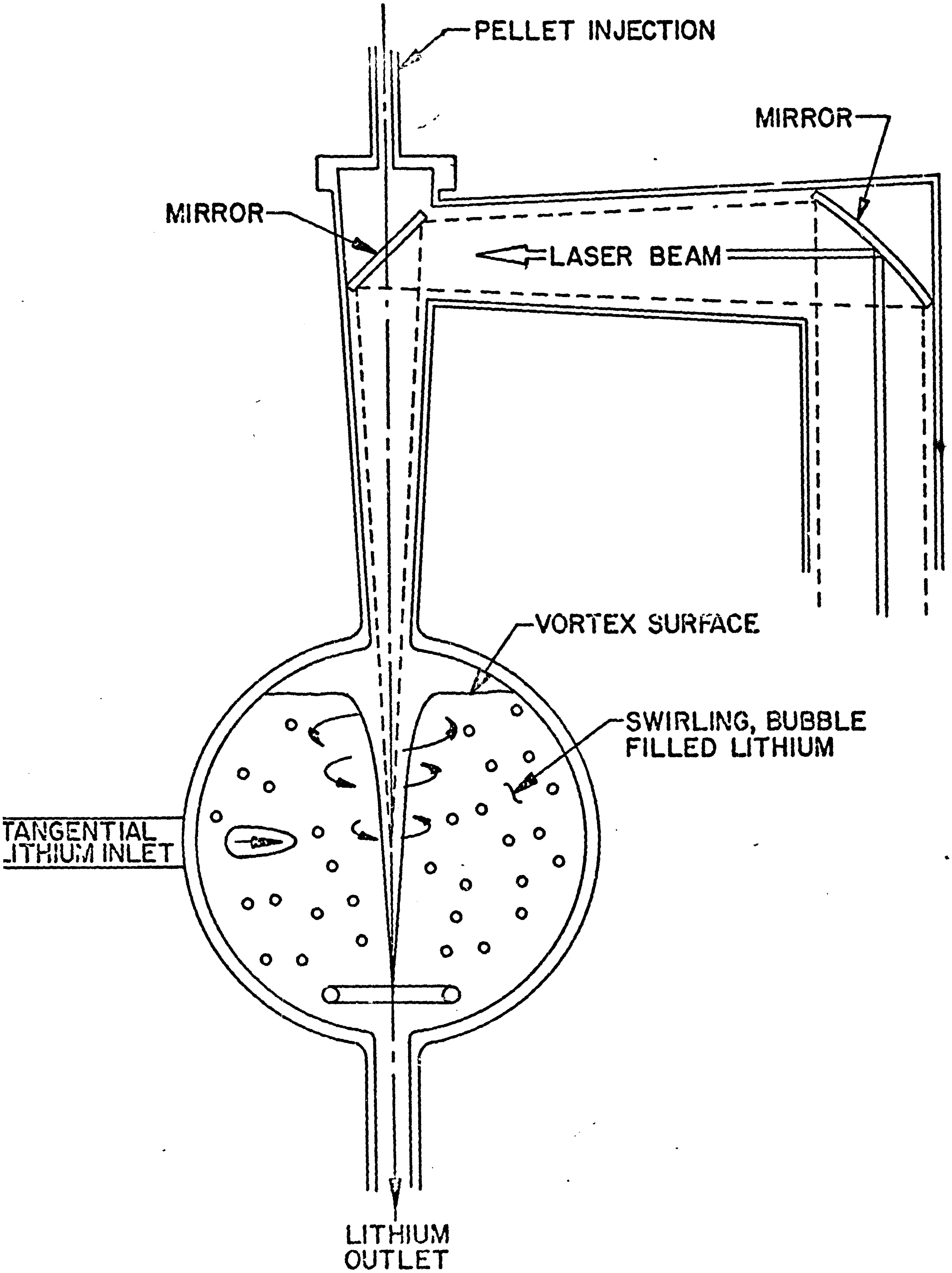
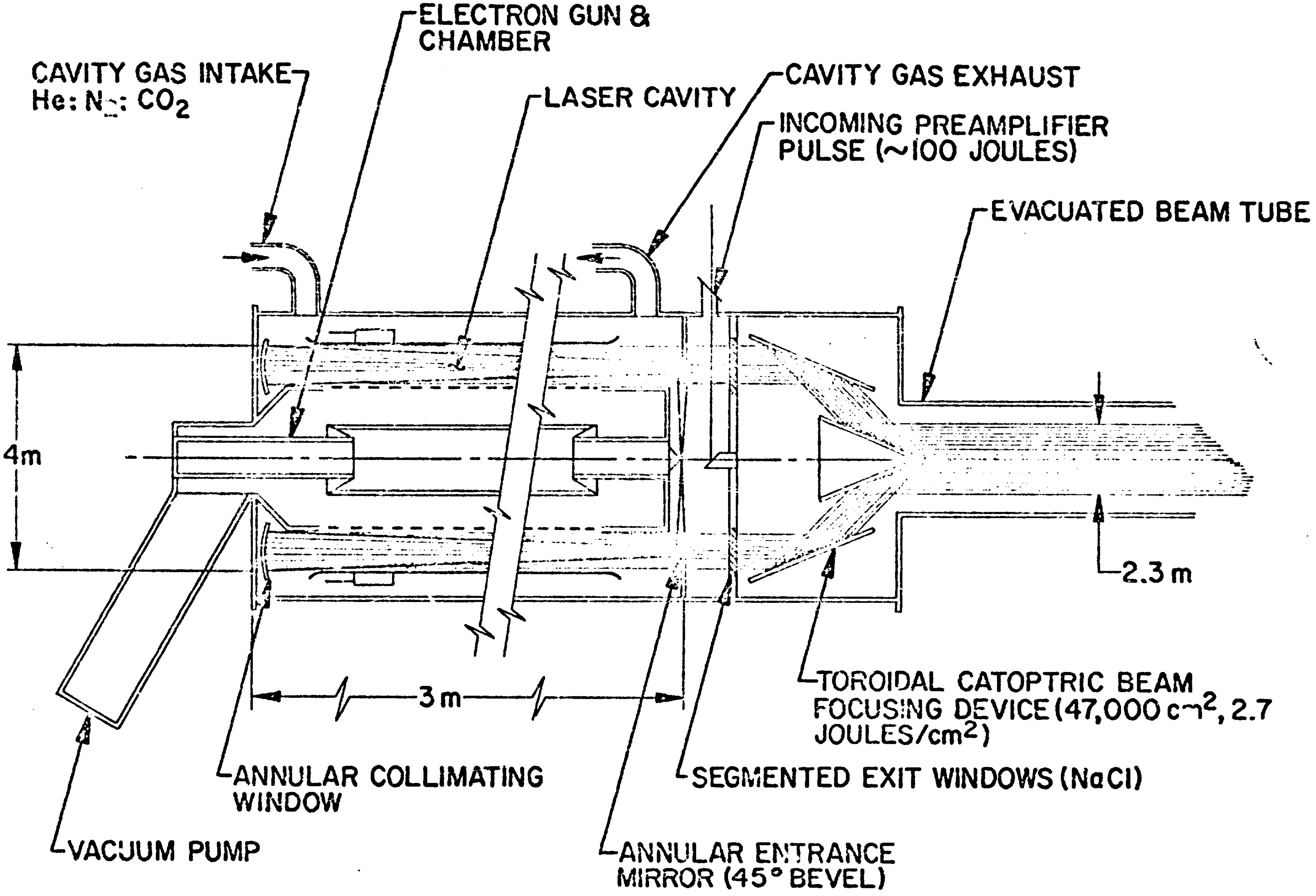

PELLET INJECTION
MIRROR
MIRROR
LASER BEAM
VORTEX SURFACE
SWIRLING, BUBBLE FILLED LITHIUM
TANGENTIAL LITHIUM INLET
LITHIUM OUTLET

Fig 4

Annular Power Amplifier with 42,000 cm^2 Output Aperature Delivering 125,000 Joules to Pellet.



Conceptual Gas Laser Power Amplifier

Cross section of annular power amplifier showing radially segmented ~onstruction.

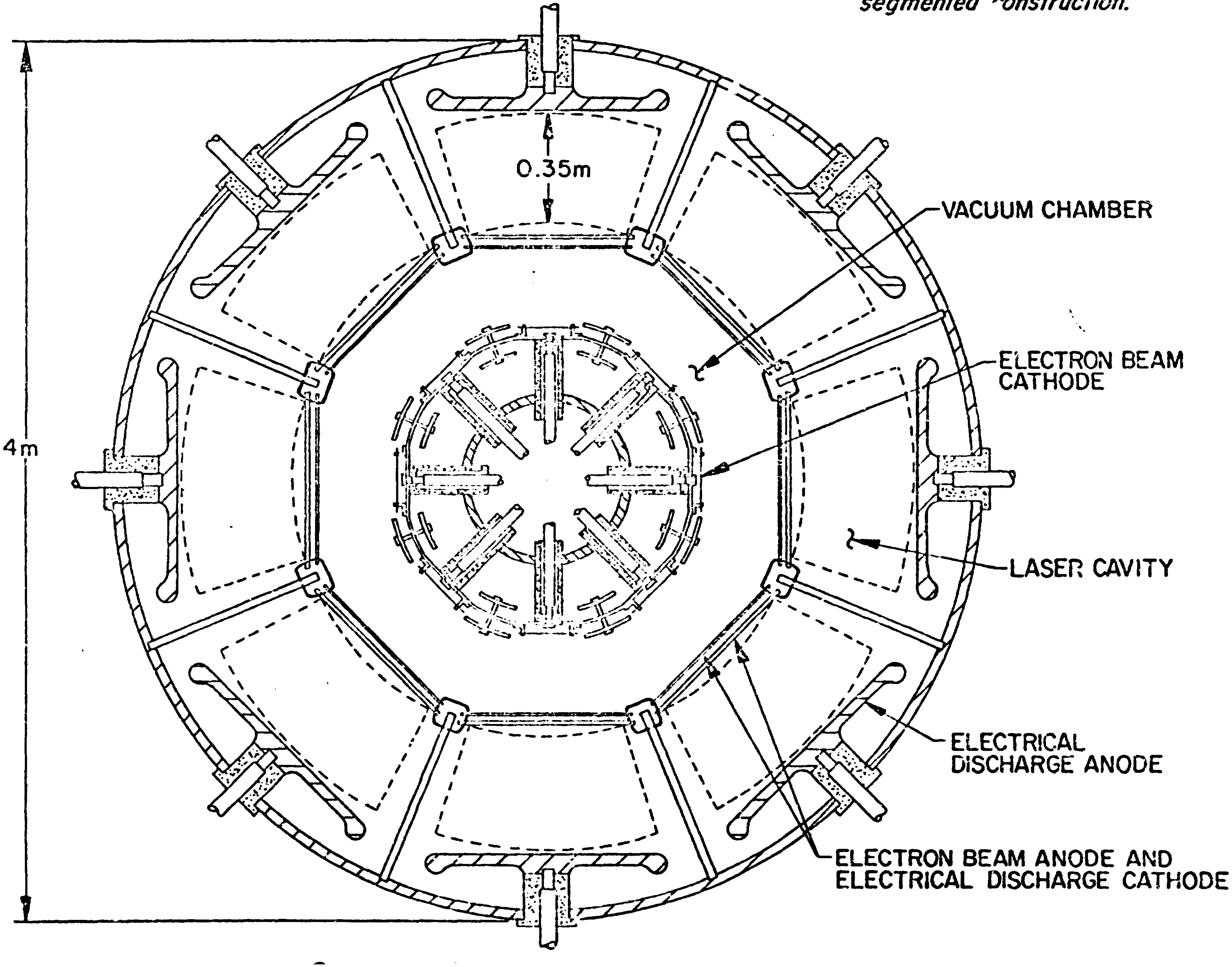


Table III

LASER TECHNOLOGY

SUBSYSTEM

LASERS

TYPE

	CO_2	~~CO~~	~~Xe_2~~	CHEMICAL HF W/RECYCLE
CHARACTERISTICS				
TYPICAL λ, μM	10.6	~~5.38~~	~~0.17~~	2.7
NET EFF., %	≤10	~~>20~~	~~~20~~	<5
PULSE, NSEC	0.1-10	~~>10~~	~~>1~~	<10
EXTRACTABLE, J/ℓ ENERGY	30-50	~~~100~~	~~~500~~	~500
OPERATING, ATM PRESSURE	3-5	~~~1~~	~~>10~~	~10

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Table IV ~~IV~~

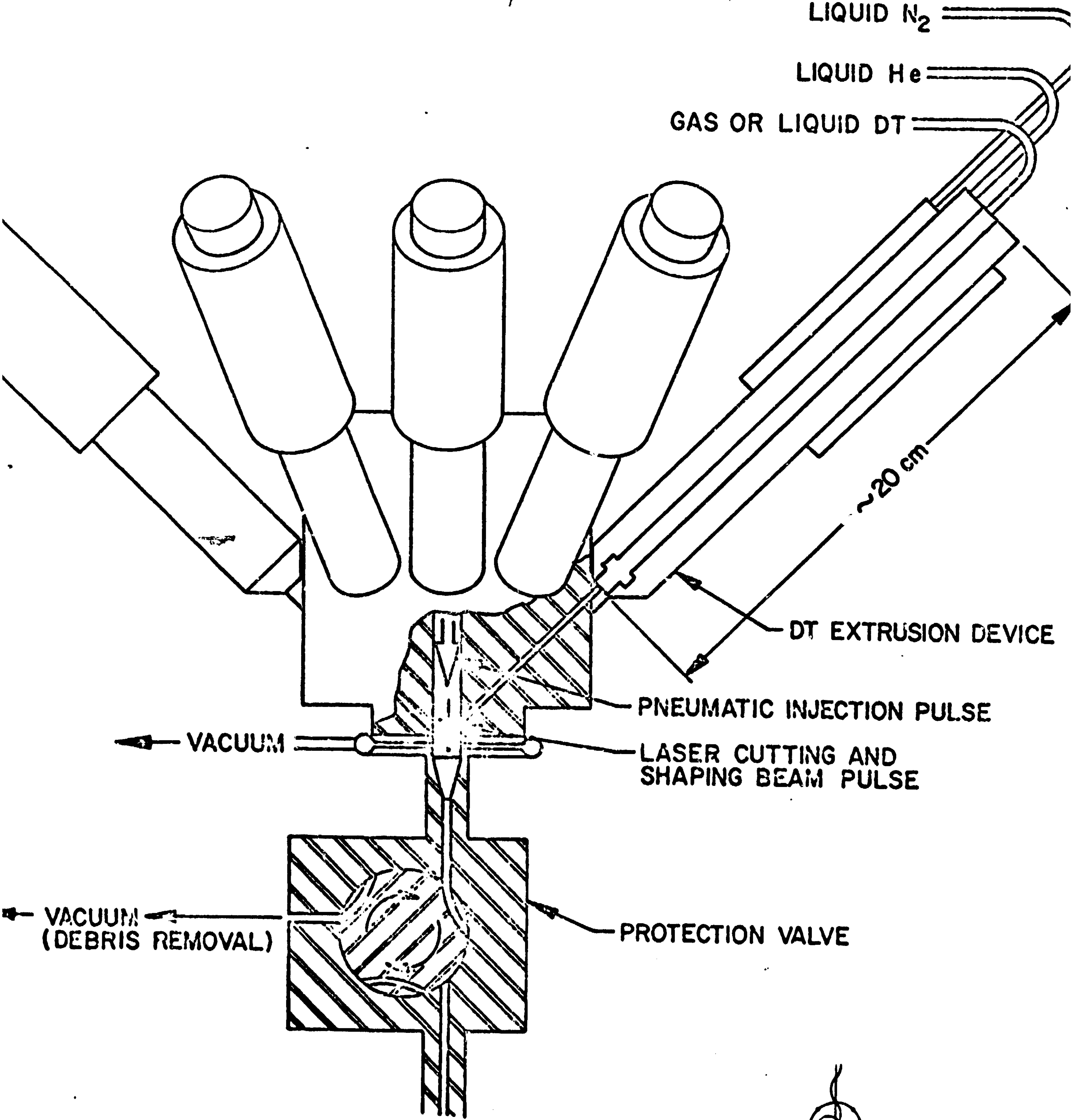
REFERENCE DESIGN LASER SYSTEM

DESCRIPTION OF SYSTEM:

OSCILLATOR, PREAMPLIFIER, POWER AMPLIFIER CHAIN CONCEPT WITH THE POWER AMPLIFIER AN ANNULAR, SUBDIVIDED CAVITY.

LASER CAVITY GAS MIXTURE	$3:1/4:1; He:N_2:CO_2$
OUTPUT PER POWER AMPLIFIER	0.125 MJ
NUMBER OF SECTORS PER POWER AMPLIFIER	8
LASER ~~OUTPUT~~ PULSE DURATION	1 NSEC
PULSE REPETITION RATE	$30\text{-}50\ SEC^{-1}$
OSCILLATOR ~~OUTPUT~~ SPECTRUM	MULTI-LINE MULTI-BAND
BEAM FLUX AT OUTPUT WINDOW APERTURE	$3\ J/CM^2$
LENGTH AND OUTSIDE DIAMETER OF CAVITY	3 x 1.5 TO 4 M
THERMAL ENERGY REMOVAL REQUIREMENT	40 MW
LASER ENERGY OUT:ELECTRICAL ENERGY IN	10%

Fig 6



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