LA-UR-73-1603

Conf-731114--44

ENGINEERING DESIGN CONSIDERATIONS FOR LASER CONTROLLED THERMONUCLEAR REACTORS*

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INTRODUCTION

During the brief history of Laser Controlled Thermonuclear Reactor (LCTR) concepts, there has been little opportunity to do more than identify some of the important engineering design problems.[1,2] Primary efforts have been dedicated to assessing the feasibility of laser compression and heating of DT pellets to thermonuclear ignition and burn conditions. The current pace of development of laser-driven fusion, together with the urgency of providing sources of safe, clean, low-cost electrical energy have prompted more serious recent consideration of engineered power reactor systems.

Thermonuclear energy released from fusion pellet microexplosions must be contained in a manner that both prevents excessive damage to reactor components and permits efficient recovery of the energy for power production. Reactor cavities are surrounded by relatively thick blanket regions containing lithium for breeding tritium and for circulating lithium coolant.

Theoretical investigations indicate that very short, high-power laser pulses are necessary for compression and heating of DT pellets. Laser energy must be transported to and focused on small DT pellets at the center of each reactor cavity. Reactor cavities with multiple penetrations for symmetrically arranged laser beams are in the early conceptual design stages.

Cryogenic fuel-pellet injection systems in close proximity to relatively hostile cavity environments may be necessary. High velocity injection will probably be necessary to minimize heating of pellets during injection and to maintain stable trajectories.

MASTER

CHARACTERIZATION OF DT PELLET MICROEXPLOSIONS

Reference design LCTR studies have been conducted based on a pellet yield of 100 MJ. Energy release yields and spectra from bare DT pellets have been estimated analytically; typical results for a 100 MJ pellet microexplosion are summarized

*Work performed under the auspices of the U. S. Atomic Energy Commission, Contract Number W-7405-ENG-36.

in Table I. It should be emphasized that energy release yields and spectra are very sensitive to pellet mass, composition, and temperature-density profiles during the time of thermonuclear burn and may vary significantly from the results given in Table I.

Although we have chosen a 100 MJ microexplosion for our initial reference LCTR studies, thermonuclear energy gain as a function of laser energy absorbed in homogeneous, solid DT spheres have been calculated.[3] Results of these calculations are shown in Fig. 1.

REACTOR CAVITY AND BLANKET DESIGN

Current LCTR studies are considering several cavity and lithium-blanket designs. These designs can be catagorized according to the physical processes by which energy deposition from pellet microexplosions is accomodated by the first wall of the reactor cavity. Energy deposition from incident x rays, α particles, and pellet debris occurs in a very thin layer at the surface of the reactor cavity; whereas the kinetic energy of the neutrons is deposited volumetrically throughout the blanket and reactor structure. Thus, the inner surfaces of cavity walls to depths of a few μm must be designed to withstand energy deposition on the order of 23 MJ per microexplosion for each 100 MJ pellet. Blanket-coolant regions must accept total volume energy depositions of ~ 77 MJ per microexplosion in addition to heat that must be conducted through the cavity wall.

Evaporation and ablation of lithium from the cavity surface characterizes dominant phenomena which occur in both the wetted-wall and the BLASCON[4] concepts. These concepts are shown schematically in Figs. 2 and 3, respectively. 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. The protective layer of lithium absorbs energy of the α particles and pellet debris and part of the x-ray energy, is vaporized and ablates into the reactor cavity and is subsequently exhausted through a supersonic blowdown nozzle. The ablative layer is restored between pulses by radial inflow of lithium from the blanket region.

In the BLASCON concept, 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 can be entrained in the rotating lithium to attenuate the 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.

The possibility of lining cavities with other ablative materials, such as carbon, is also being investigated. For such a design, a relatively small mass of cavity-liner material would be ablated by each pellet microexplosion. The mass of material ablated depends upon 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.

Protection of cavity walls from α particles and charged particles in the pellet debris by means of a magnetic field is also a potential conceptual alternative. A very simple rendition of this concept is shown schematically in Fig. 4. The reactor 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. In the concept shown, energy deposition in the heat sinks results in the evaporation of lithium. A staged vacuum system is shown for removal of the lithium vapor and maintaining cavity pressure at vacuum levels at the cavity center. Minimum cavity sizes would be determined by permissible x-ray energy deposition limits on cavity walls. Cavity liners of carbon or beryllium would be advantageous for increasing the tolerance for x rays.

Major functional requirements for blanket performance include the breeding of tritium and the removal of heat. In our preliminary conceptual studies it is assumed that lithium in the blanket regions will be circulated through an intermediate heat exchanger for thermal energy removal from the reactor. Initial estimates indicate that acceptable tritium breeding ratios can be obtained from blanket designs utilizing natural lithium for coolant and either stainless steel or a refractory metal for the reactor structure.[4,5]

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

Many opportunities exist to apply engineering ingenuity to the design of reactor cavities. There are economic incentives to design reactor cavities of minimum size and for high pellet-microexplosion repetition rates. Some of the more important problem areas in engineering design are directly related to cavity performance. Examples are:

> Evaporation and ablation of first wall materials leading to hydrodynamic effects and to stresses in reactor vessel.
>
> Evacuation of the ablated lithium from the cavities of the lithium-wetted-wall and the magnetically-protected concepts prior to successive pellet microexplosions. Preliminary investigations indicate that sufficiently intense, focused laser light cannot be transported efficiently through lithium vapor at densities greater than 10^{16} atoms per cm^3.[6,7]
>
> Restoration of the lithium vortex between pellet microexplosions in the BLASCON concept. Experimental work is being done at the Oak Ridge National Laboratory to investigate this problem.
>
> Ablative material condensation kinetics in the carbon-lined dry-wall concept. Complete confidence in the feasibility of this concept will require extensive investigation.
>
> Design and fabrication of composite walls for the dry-wall and magnetically-protected concepts. Significant problems result from thermal-expansion and irradiation-induced swelling mismatches between protective and structural materials.
>
> Protection of pellet-injection systems and beam-transport-system components from x rays, energetic charged particles, neutrons and cavity ablative materials. The use of distance, magnetic fields and fast operating mechanical devices is envisioned.

Engineering design problems related to blanket design include thermal-hydraulic requirements for adequate heat removal, structural integrity with minimum penalties to breeding ratio, and containment of tritium. These problems, while not routine, appear to be amenable to solution with essentially established technology.

The design of reactor cavity, blanket and coolant systems in a manner that permits replacement of irradiated components constitutes a major engineering problem. Fast-neutron and charged-particle irradiation data indicate severely limited cavity-wall lifetimes for minimum-size reactors which are operated at high power levels. The down time required for reactor maintenance, the cost of auxillary equipment, and the complexity of reactor component replacement operations will be important factors affecting optimum design choices and the ultimate cost of power from LCTR systems.

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 II. Calculations indicate that a total laser pulse of ~ 1 MJ with a pulse width of ~ 1 nsec will be required (see Fig. 1). 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. 5 and 6,[8,9] 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 III. 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 (Cu, Au, Ni, etc.) 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 vaccum 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.

GENERAL

In addition to the complexities associated with the design of various LCTR subsystems, there are many engineering design considerations associated with subsystem interfaces and system design for large power plants. In the ultimate analysis, the performance of the reactor power plant as a whole is the most important overall consideration. System studies can be useful in examining the impact of subsystem alternatives, sizes, arrangements, and the degree of necessary redundancy provided to ensure adequate system reliability and minimum adverse impact to the environment.

Because of relatively large circulating power fractions, gross electrical power production will be significantly larger than net power production; also, a significant fraction (15 to 20%) of the waste heat must be dumped at low temperatures. These factors may influence reactor siting decisions.

CONCLUSIONS

Preliminary engineering analyses of LCTR power plants have revealed many challenging engineering problems, some of which transcend present technology. However, much of the technological development which has resulted from the fission reactor and space programs is applicable to the fusion reactor program as well. Although much analytical and experimental investigation remains to be done, no problems have been discovered for which there are not reasonable conceptual solutions. Intensive efforts to resolve these engineering design problems awaits successful achievement of thermonuclear burn from laser fusion.

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Table I

~~TYPICAL~~ ENERGY RELEASE [illegible] ~~MECHANISMS~~ FROM A 99 MJ DT PELLET MICROEXPLOSION

Mechanism	Fraction Of Total Energy Release	Particles Per Pulse	Average Energy Per Particle	
X Rays	0.01		~4 keV peak	
α Particles that Escape Plasma	0.07	2.2×10^{19}	2 MeV	
Plasma 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	
Neutrons	0.77	3.3×10^{19}	14.1 MeV	

Fractional Burnup 0.25

Table II

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 ENERGY, J/ℓ	30-50	~~~100~~	~~~500~~	~500
OPERATING, ATM PRESSURE	3-5	~~~1~~	~~>10~~	~10

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Table III

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	30-50 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%

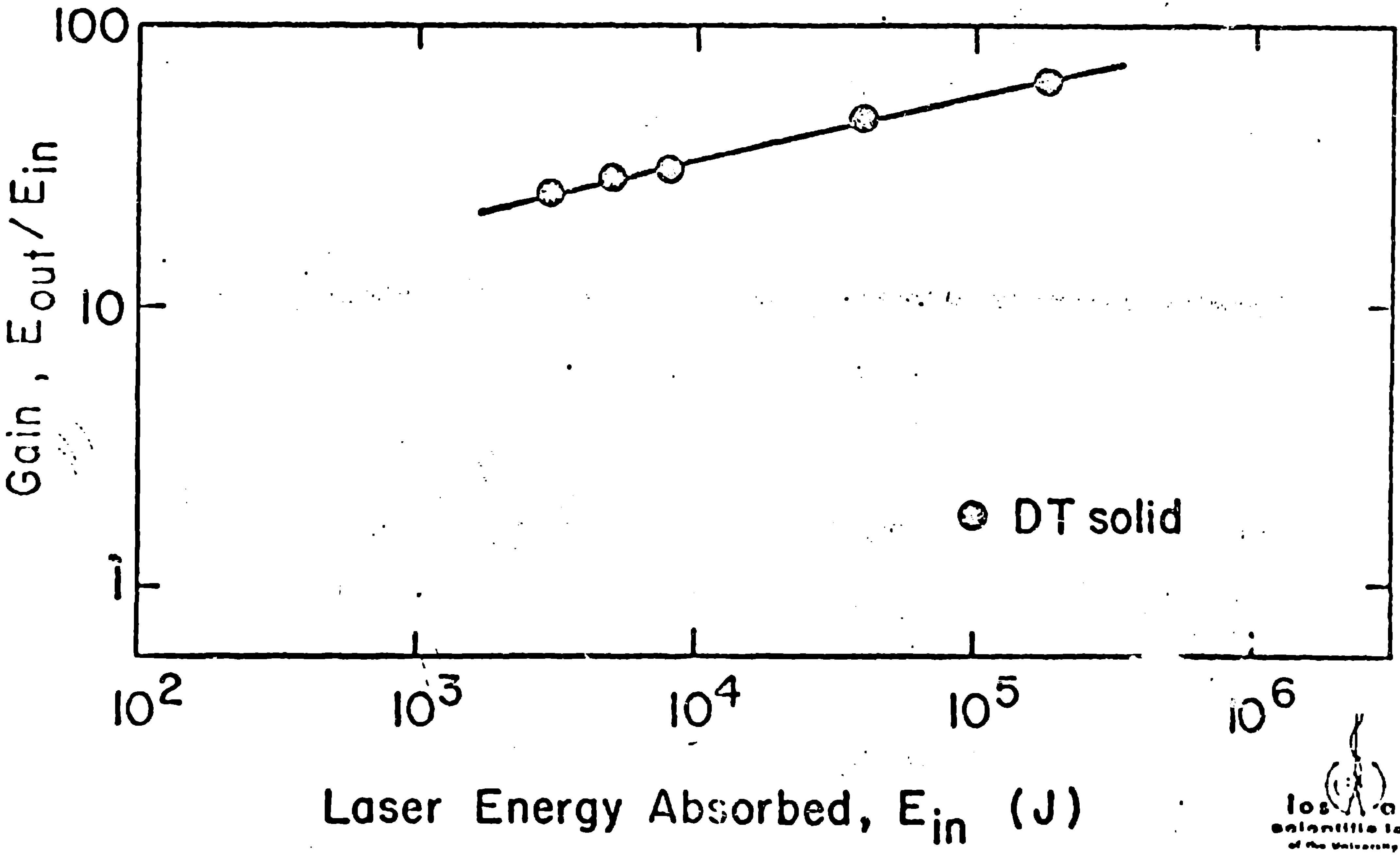

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Fig 2. p. 3

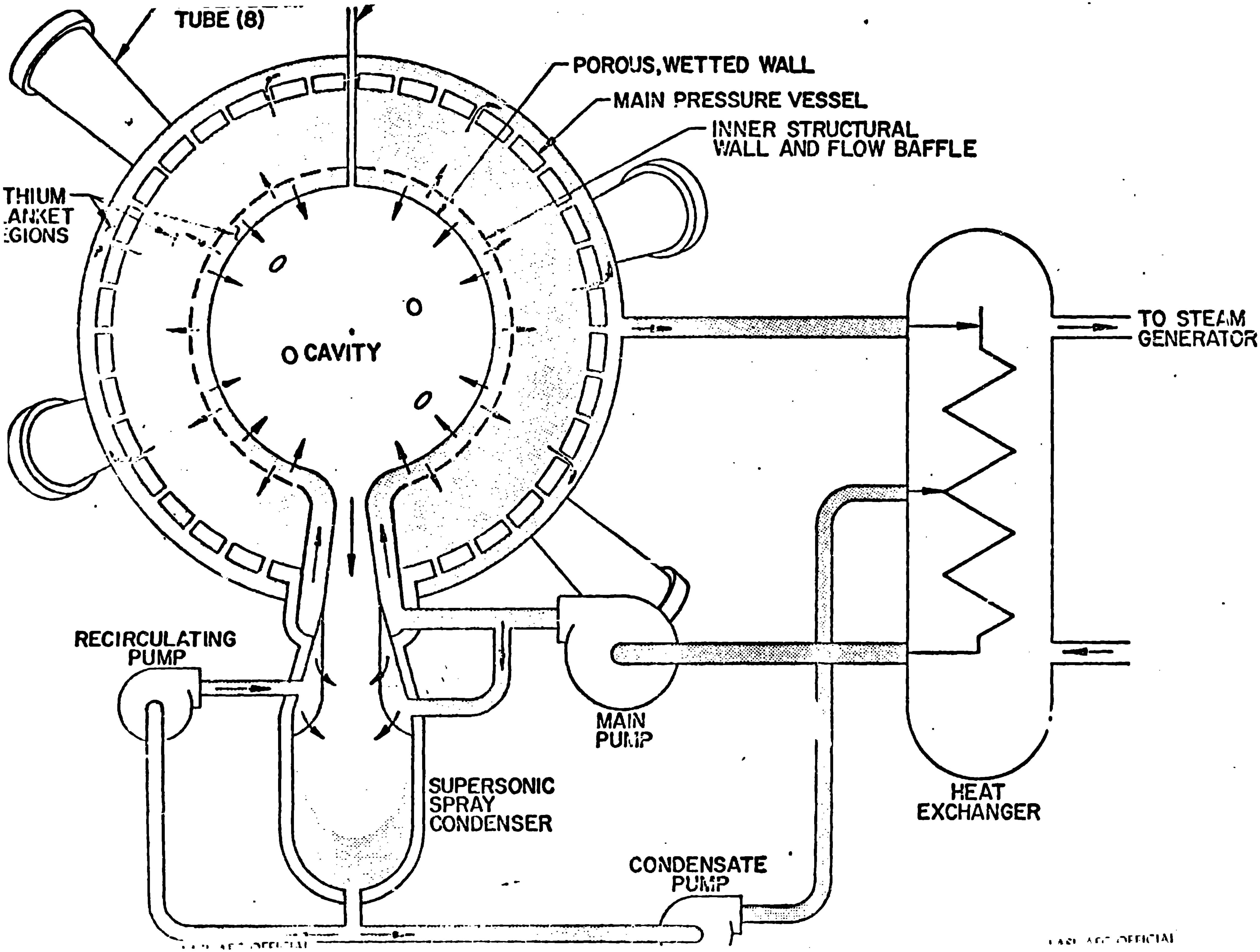
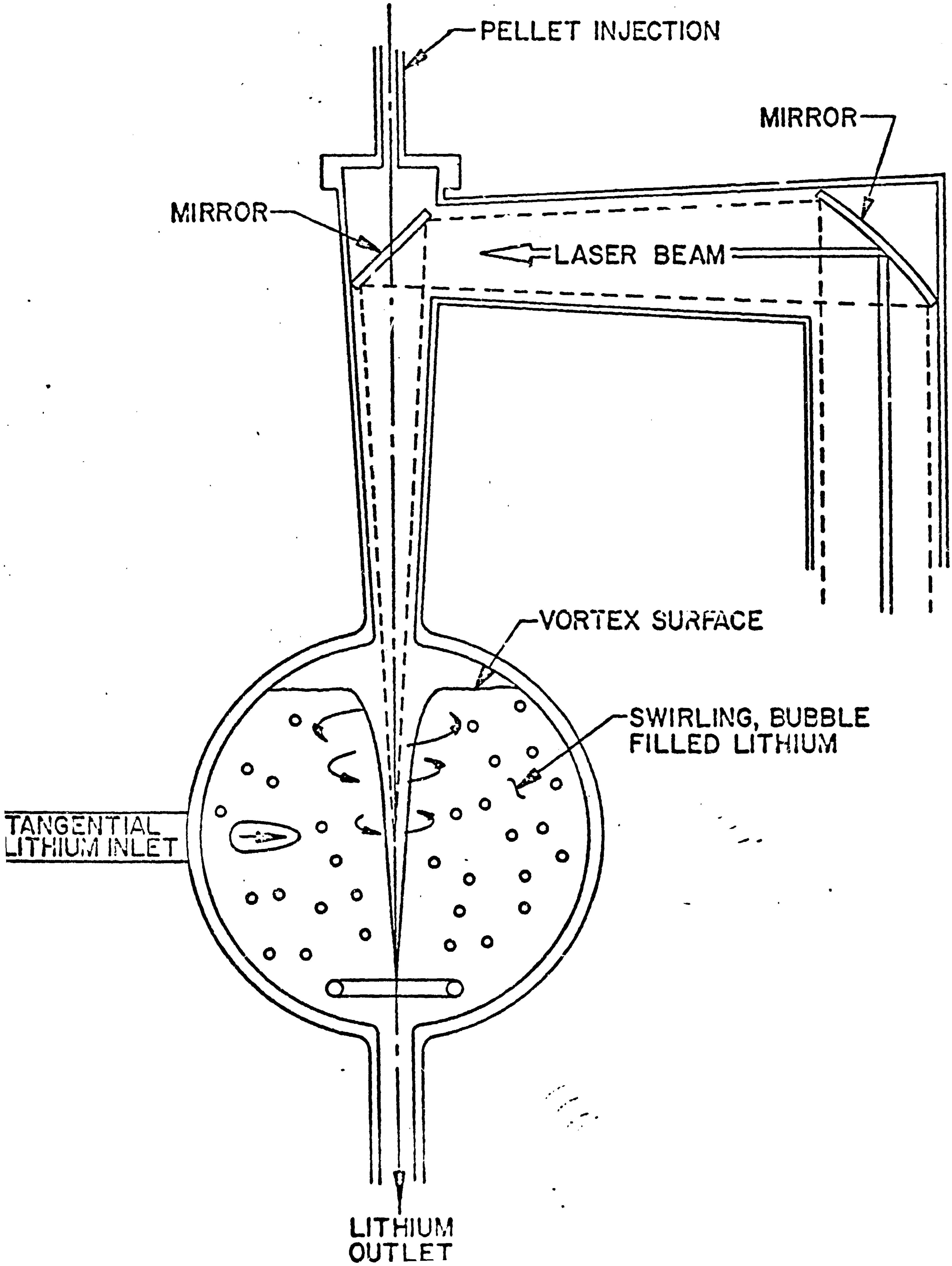

TUBE (8)
POROUS, WETTED WALL
MAIN PRESSURE VESSEL
INNER STRUCTURAL WALL AND FLOW BAFFLE
THIUM
ANKET
EGIONS
CAVITY
TO STEAM GENERATOR
RECIRCULATING PUMP
MAIN PUMP
SUPERSONIC SPRAY CONDENSER
HEAT EXCHANGER
CONDENSATE PUMP

Fig 3


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

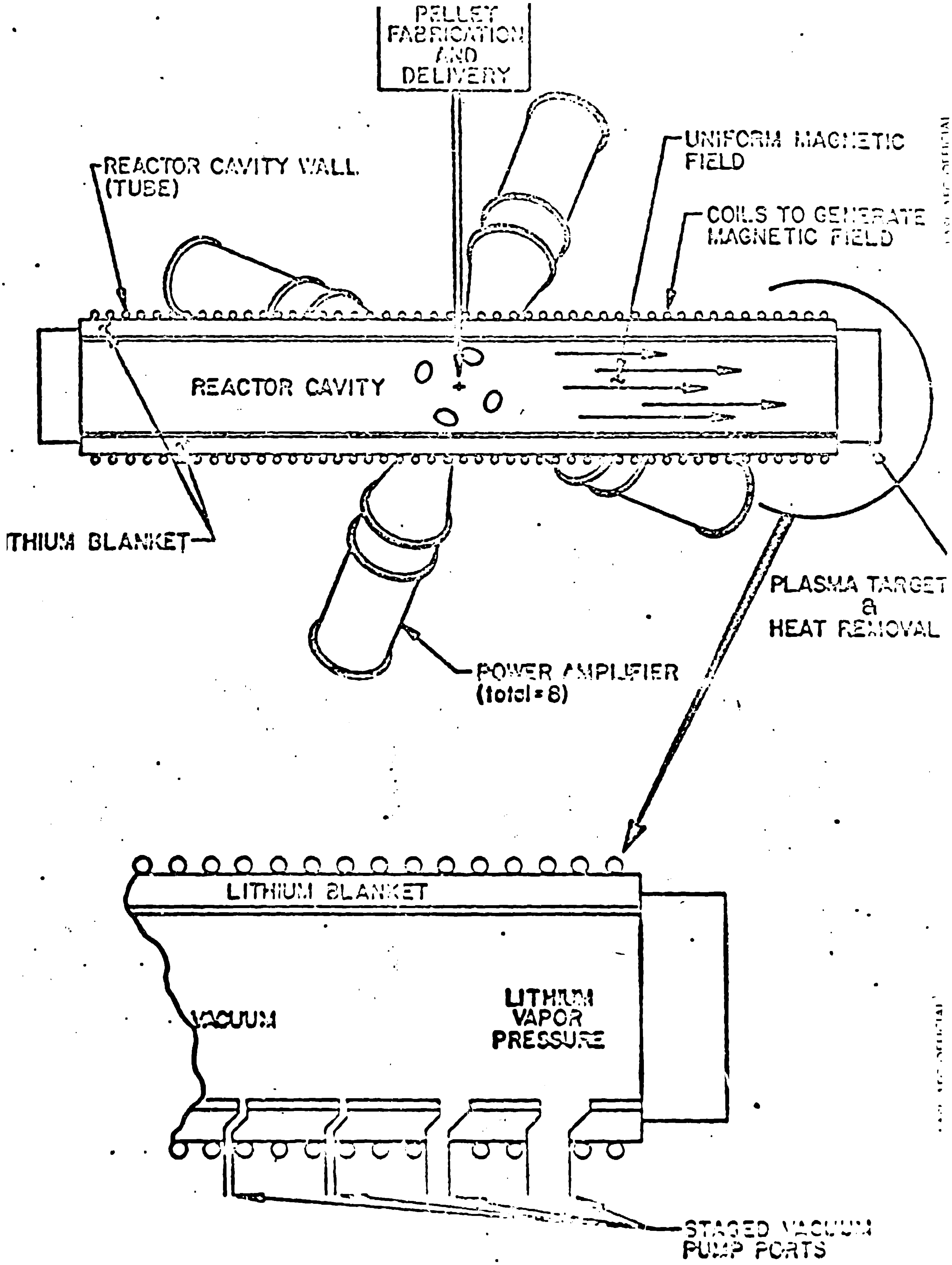
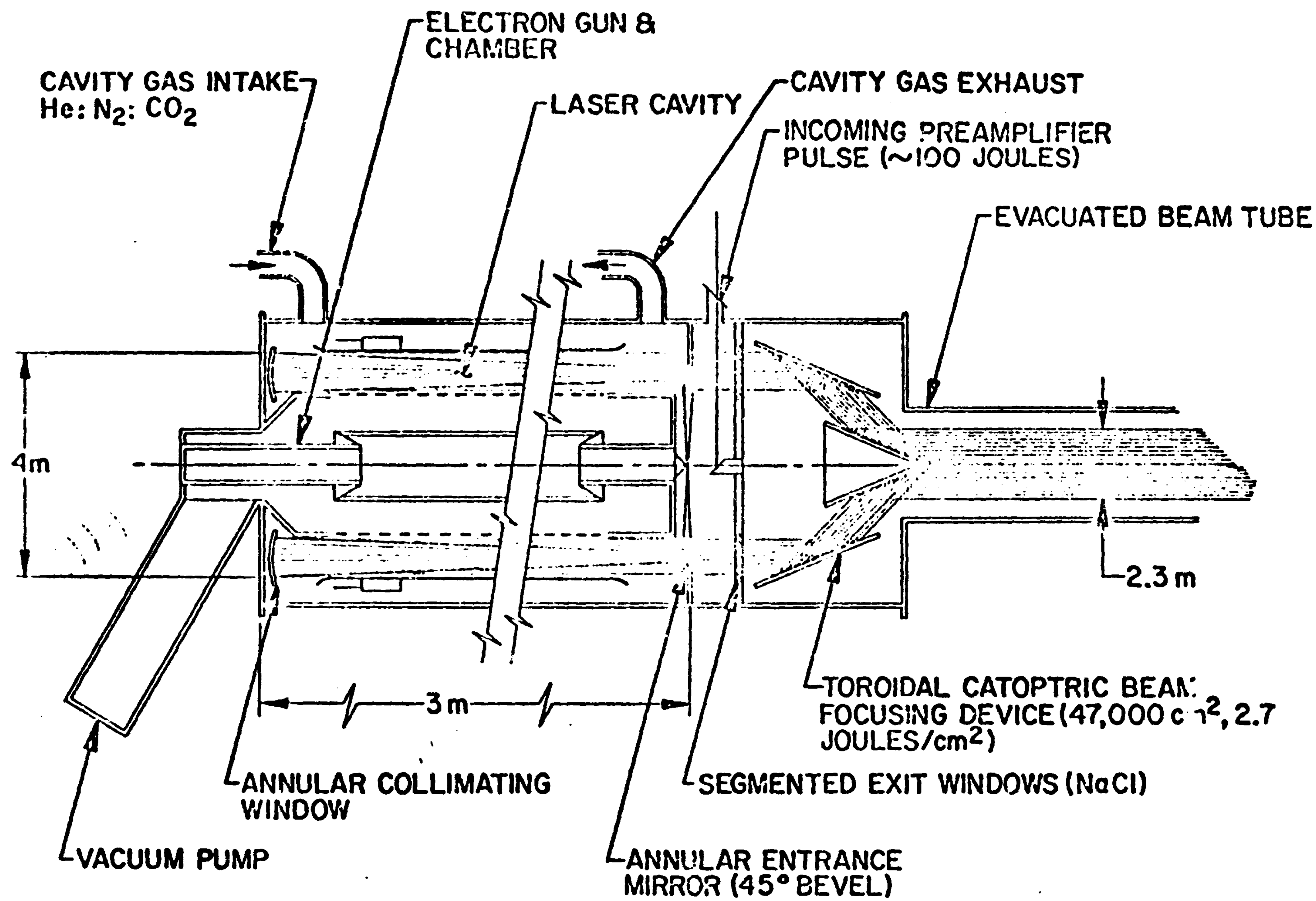

PELLET FABRICATION AND DELIVERY
UNIFORM MAGNETIC FIELD
REACTOR CAVITY WALL (TUBE)
COILS TO GENERATE MAGNETIC FIELD
REACTOR CAVITY
ITHIUM BLANKET
PLASMA TARGET & HEAT REMOVAL
POWER AMPLIFIER (total=6)
LITHIUM BLANKET
VACUUM
LITHIUM VAPOR PRESSURE
STAGED VACUUM PUMP PORTS

Fig 3

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



Conceptual Gas Laser Power Amplifier (for Central Laser System)

Cross section of annular power amplifier showing radially segmented construction.