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INERTIAL CONFINEMENT FUSION REACTOR SYSTEMS

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ABSTRACT

A variety of reactor cavity concepts, drivers, and energy conversion mechanisms are being considered to realize commercial applications of ICF. Presented in this paper are: (1) a review of reactor concepts with estimates of practically achievable pulse repetition rates, (2) a survey of drivers with estimates of the requirements on reactor conditions imposed by beam propagation characteristics, and (3) an assessment of compatible driver-reactor combinations.

1. INTRODUCTION

Since about 1969, research has been carried out to develop an alternative to magentically confined controlled thermonuclear fusion -- that of compressing, heating and confining thermonuclear fuel by inertial forces generated by the interaction of an intense, pulsed beam energy source (or driver) with a pellet containing the fuel. The outer region of a fusion pellet consists of an absorber/ablator material in which energy from a driver source is deposited. This material is blown off creating a recoil impulse which, together with plasma pressure, heats and compresses the fuel. Thermonuclear ignition occurs at the center of the fuel and propagates radially outward in a time that is short compared to the time required for the pellet to disassemble, resulting in fusion of an appreciable fraction of the fuel. Understanding of the fundamental physics of driver-pellet interactions and pellet dynamics is being developed through combined theoretical and experimental investigations.

Inertial confinement fusion (ICF) experimental programs have, thus far, relied principally on the use of short-pulse lasers in pellet implosion experiments, and the construction and use of lasers as research tools will be emphasized during the next several years to establisn the technical feasibility of ICF. Ion beam accelerators are promising alternatives to lasers for driving fusion pellet microexplosions, and programs for development of accelerators with acceptable characteristics are being conducted.

For commercial applications, fusion pellet microexplosions must be repeatedly contained in reactor cavities in a manner that prevents severe damage to reactor components and permits convenient, economic recovery of the energy for conversion to electricity or some other usable form. First-generation ICF applications will be based on the tritium-deuterium fuel cycle. Reactor cavities must be surrounded by blanket regions containing lithium because tritium for the fuel cycle must be produced in interactions between fusion neutrons and lithium. Different driver types impose different conditions on reactor cavity environments so that facility design for commercial applications must be done for integrated systems.

In the remainder of this paper, reactor concepts now being studied and acceptable driver-reactor combinations are discussed.

2. REACTOR CONCEPTS

Fusion pellet microexplosions release energy as x rays, energetic pellet debris, and high-energy neutrons. Reactor components must be protected from excessive damage by x rays and pellet debris, which may cause material loss by evaporation and/or sputtering of exposed surfaces. Several different approaches to protecting cavity walls from x rays and pellet debris are being studied to assess their feasibility, to identify technology requirements, and to determine their acceptability for use in combination with various drivers. Serious damage to reactor structures also results from exposure to high fluences of high-energy neutrons. Provision for moderating neutron energies to minimize damage to reactor structures are included in some reactor concepts.

Inertial-confinement-fusion reactor concepts can be divided into two major categories with regard to accommodating the photon and debris energy released by pellet microexplosions: (1) concepts in which the energy absorbing surfaces are significantly perturbed by photon and debris energy deposition but are regenerated between pellet microexplosions and (2) concepts in which photon and debris energy are either directly absorbed in solid reactor cavity components or in which the debris may be diverted from the reactor cavity.

For concepts in the first category, the cavity wall is protected against damage from photons and pellet debris by either a gas or a protective liquid metal layer. Soft x-ray and pellet-debris energy is deposited in the protective material. For some designs, there are restrictions on pellet microexplosion repetition rate due to the time required to restore the cavity after a pellet microexplosion to conditions necessary for pellet injection and beam transport.

In the second category of reactor concepts, photons and pellet debris are deposited in semi-permanent cavity liners. Near-surface energy deposition can cause evaporation and the pellet debris can cause sputtering of the liner surface. A variant in this category is the use of magnetic fields to divert the ionized pellet debris out the ends of a cylindrical cavity leaving only the x rays to be accommodated by the cavity wall. There are tradeoffs for minimum damage to material surfaces between relative x ray and pellet debris energy yields and energy spectra. There are generally no practical constraints on maximum pellet microexplosion repetition rate for reactor designs in this category.

There have been a large number of ICF reactor concepts proposed during the past decade. Through analytic evaluations of performance, studies of interface conditions in integrated systems, and comparative economic assessments, the most attractive features of these concepts are being incorporated into a few designs that are compatible with the different driver types being developed.

2.1 Lithium Wetted-Wall Concepts

The wetted-wall reactor concept was originally proposed in 1971 [1]. It has been studied and occasionally modified throughout the past decade. A schematic of this concept is shown in fig. 1. The reactor chamber is spherical and is surrounded by a blanket region containing liquid lithium and structural components. The cavity wall is formed by a porous metal through which coolant lithium flows to form a protective layer on the inside surface. The soft x-ray and pellet-debris energy is deposited in the protective lithium layer resulting in partial evaporation and ablation. The lithium vapor is subsequently exhausted through a supersonic nozzle at the bottom of the reactor into a condensor. The protective layer is restored between pellet microexplosions by radial inflow of lithium from the blanket region.

The wetted-wall reactor is proposed for use with a laser driver. The vapor density in the cavity must be reduced after a pellet microexplosion to 10^{15} to 10^{16} atoms/cm^3 for efficient transport of laser beams. The exhaust nozzle is appropriately sized to evacuate the cavity to this lithium vapor density in ~ 0.8 s. From this and other considerations the pellet microexplosion repetition rate is constrained to ~ 1 Hz or less.

The wetted-wall reactor concept suffers from two potential disadvantages: (1) a perceived difficulty in monitoring the reestablishment of the protective lithium layer on the cavity interior surface and (2) the limitation on pellet microexplosion repetition frequency. In addition, this concept is not readily adapted to very low cavity vapor density operation. These disadvantages are circumvented by a modified concept [2] shown in fig. 2. In the modified concept, liquid lithium is injected tangentially through a circular slit nozzle at the top of the spherical reactor cavity at a rate sufficient to remove the x-ray and pellet-debris energy as sensible heat of the liquid with only a modest increase in temperature. Positive coverage of the cavity interior surface is assured by centrifugal forces. Vaporized lithium from pellet microexplosions recondenses on the surface of the injected lithium stream in time intervals much less than required for exhaust through a nozzle. The exhaust nozzle is replace by a simple drain at the bottom of the cavity. The injection nozzle and diverter vanes around beam ports are protected by lithium films that are maintained by forced flow through porous structures.

This reactor concept could be operated with very low cavity vapor densities by limiting the maximum temperature of the fluid inside the cavity to values corresponding to low vapor pressures. Separate coolant streams of different materials could be used in the reactor cavity and blanket to provide flexibility in choices of vapor pressure and temperature.

A large fraction (60 to 70%) of the energy release from pellet microexplosions is deposited directly in the blanket regions of wetted-wall reactors by high-energy neutrons. Blanket coolant is introduced near the cavity wall by structures concentric with the beam transport tubes. The lithium then flows radially outward through the 1-m-thick blanket. Uniform radial flow is achieved by including sufficient impedance to flow in successive structural shells.

Reference design studies have been done for 150-MJ pellet microexplosions at repetition rates of 1 and 10 Hz, respectively, for the wetted-wall and the modified-wetted-wall concepts. The cavity radii were chosen to be 2 m from neutron damage considerations. For the modified-wetted-wall concept, a lithium flow rate of 2.4 m^3/s is required to limit the temperature increase of the cavity coolant to an arbitrary 100 K. This flow rate could be provided by a circular nozzle with a 1-cm-wide slit with an injection velocity of 100 m/s. Analyses of flow profiles through a 2-m-radius cavity indicate that the lithium thickness increases from 1 cm at the top of the cavity to 7 cm at the bottom. Pumping requirements are less than 1 of the electric power produced.

The dominant stresses induced in wetted-wall reactor concepts result from the recoil impulse of the lithium ablated from the interior surface of the cavity wall and from thermal expansion of the lithium blanket due to neutron energy deposition. Stainless steel reactor cavity and blanket structural walls ~ 1-cm thick provide adequate strength to accommodate the generated pressures and impulses.

2.2 High Yield Lithium Injection Fusion Energy (HYLIFE)

The HYLIFE reactor concept [3] was developed to satisfy several specific requirements and objectives, including: modification of the flux and energy spectra of radiation emitted by pellet microexplosions with flowing fluids that can be reestablished after each microexplosion, 30-year operational lifetime without replacement of damaged or radioactive structure, and minimization of development time.

The reference HYLIFE concept, shown schematically in fig. 3, consists of an 8-m-high, 10-m-diameter chamber in which a blanket of liquid lithium shields the ste 1 wall from x rays, pellet debris and high-energy neutrons. The liquid lithium blanket is composed of a dense hexagonal array (0.5 packing fraction) of 20-cm-diameter jets. A 300-jet array provides an effective blanket thickness of 1 m between the pellet microexplosion and the first structural steel wall. The pellet and the driver beams are injected horizontally through specially arranged corridors in the array of jets as shown in fig. 4.

The energy of the volumetric expansion of lithium, which results from neutron absorption, is primarily deposited in liquid-liquid interactions of colliding jets. The pressure of the lithium vaporized from the inner surface of the blanket by soft x rays and pellet debris exerts an outward force on the blanket, after coalescence of the jets, causing the lithium to expand outward and collide with the pressure vessel wall; however, the resulting stress is estimated to be acceptable. The large surface area of flowing lithium acts as a condensation pump on which the vaporized lithium is condensed between pellet microexplosions. It is estimated that the jet array will be reestablished and the cavity pressure reduced to that corresponding to the lithium vapor pressure in ~ 1 s following a pellet microexplosion. An attractive feature of the HYLIFE concept is that the neutron energy wall loading is reduced by a factor of ~ 20 by the lithium blanket leading to an anticipated chamber lifetime equal to plant lifetime.

Lithium vapor densities at the time of pellet injection and beam transport can be predetermined by limiting the maximum lithium temperature in the cavity. The nominal maximum lithium temperature for use with laser drivers is 770 K, corresponding to a lithium vapor density of ~ 3×10^{15} atom/cm^3. If a lithium vapor density limit of 10^{13} atom/cm^3 is required, the lithium temperature cannot exceed ~ 620 K.

The operating characteristics of the reference HYLIFE power plant includes a pellet yield of 2700 MJ at a repetition rate of 1 Hz. The circulating lithium flow rate is 140 m^3/s of which 8% is diverted to a heat exchanger. The temperature increase of the lithium as it flows through the reactor chamber is 13 K. The pumping power required for the primary lithium loop is 1.6% of the net electric power produced.

2.3 Gas Filled Reactor Cavities

The use of a noble gas in reactor cavities to minimize the damaging effects of x rays and pellet debris has been investigated in two regimes of gas pressure. Inclusion of a low-pressure gas in reactor cavities has been considered for use with laser drivers, whereas higher presures are appropriate for use with light particle beam drivers.

The most exhaustively studied gas-filled reactor concept for use with laser drivers is the SOLASE design [4]. The SOLASE cavity wall and blanket structure is made of graphite, and the reactor coolant is circulating lithium oxide particles. The cavity is filled with 10^{15} to 10^{16} atoms/cm^3 of xenon or neon. This gas stops the ion debris and attenuates the soft x rays. This energy deposition heats the gas to 1-3 eV. The gas then reradiates the absorbed energy in a time interval much longer than the pulse in which it was originally released. Residual heat is removed from the cavity by flowing the gas through the cavity.

The SOLASE reference cavity design has a 6-m radius. The pellet yield is 150 MJ and the repetition rate is 20 Hz. The anticipated lifetime of the structure is 1 yr. An advantage of the graphite structure is its low-induced radioactivity permitting limited hands-on maintenance two weeks after shutdown.

Light-ion-beam reactor concepts require a relatively high-density gas (10^{18} to 10^{19} atom/cm^3) in the cavity for beam propagation along ionized channels from the particle source to the pellet. For cavity gas pressure greater than 10^{18} atom/cm^3, all of the pellet debris energy and most of the x-ray energy released by the pellet microexplosion are deposited at relatively short ranges resulting in the formation of a hydrodynamic shock. Accommodation of the shock overpressure by the cavity structure leads to optimized cavity designs with relatively large radii. The energy deposited in the cavity gas is reradiated and conducted to the cavity wall in times very long compared to deposition times. Equilibrium gas temperatures are quite high which may pose a pumping problem if the cavity gas is continuously circulated.

Typical operating characteristics for a light-ion-beam driven reactor include 75-MJ pellet yields in 3×10^{18} atom/cm^3 gas with a repetition rate of 10 Hz and a cavity radius of 4 m [5].

2.4 Ablative Liners

For applications requiring a very good vacuum in the reactor cavity, the most attractive cavity concept may be a steel or refractory metal structure with protection from x rays and pellet debris provided by a liner that is allowed to evaporate and ablate at a controlled rate. Protective liners made of carbon have been investigated for this purpose. The cavity radius is made sufficiently large to limit surface erosion of the liner so that replacement is not required more often than once per year.

An example of a reactor with a carbon-lined cavity is shown in fig. 5. The cavity radius required to limit surface erosion to 2 to 3 cm in one year of operation with 150 MJ microexplosions at 10 Hz is 10.5 m.

2.5 Magnetic Deflection

Since the debris from fusion pellet microexplosions is ionized, it can be defelected away from sensitive reactor components by magnetic fields [6]. The use of magnetic deflection to protect cavity walls and optical components has been investigated. The essential features of such a reactor concept are shown schematically in fig. 6. The reactor cavity is cylindrical, with an impressed steady-state magnetic field produced by a solenoid located concentric with, and exterior to, a lithium blanket region. The ionized pellet debris are diverted by the magnetic fields either through magnetohydrodynamic ducts or to specially designed energy sinks in the ends of the cavity.

Conceptual designs of reactors protected by magnetic deflection are constructed of steel or a refractory metal with additional cavity wall protection provided by carbon liners. Designs have been evaluated for use with 150 MJ pellet yields with 10-Hz repetition rates. Cavity radii corresponding to 1-yr. carbon liner lifetimes are ~ 2.5 m for cavities filled with 10^{15} atoms/cm^3 of xenon and 7.5 m for high-vacuum cavities.

3. Driver-Reactor Compatibility

There are three classes of pulsed beam energy sources now being investigated and evaluated for possible use as drivers for ICF; they are lasers, heavy-ion beams, and light-ion beams. Each of these drivers imposes different conditions on reactor interfaces and on cavity conditions suitable for beam injection.

For laser drivers, it is necessary to have optical components (mirrors) in direct line of sight of the pellet microexplosion. These components are protected from damage from x rays and pellet debris by distance and by a tenuous gas in the beam transport tubes and/or magnetic fields to divert ionized debris.

Laser beam transport inside reactor cavities can be accomplished through low-density gas; however, there are a great many processes that can result in scattering and defocusing of laser beams, and the upper limit on gas density for efficient transport of focused beams has not been accurately determined.

A combination of experimental results and theoretical analyses indicate that gas densities less than ~ 5 x 10^{15} atom/cm^3 do not affect beam propagation significantly.

Driver-reactor interface conditons for heavy-ion beam drivers are currently being assessed. Important considerations will include pressure differences between the reactor cavity and the accelerator, protection of focusing and other magnets from damage by high-energy neutrons, beam propagation distances, and beam injection configurations. Although several approaches to beam transport and focusing inside the reactor cavity are being studied, the least uncertainty is associated with ballistic propagation of singly ionized atoms. For particle kinetic energies now being considered, an upper limit on reactor cavity density of 10^{12} to 10^{13} atoms/cm^3, where two-stream instability is not too serious, is expected to be the prevailing requirement. However, even gas densities in this range are several orders of magnitude higher than can be tolerated in the accelerator so that vigorous differential pumping at the interface will be required. Beam propagation and focusing in gas densities below 10^{13} atom/cm^3 for distances from the focusing magnets of several meters is straightforward; however, space-charge effects may require that the number of beams be large.

Light-ion beams impose entirely different conditions than lasers or heavy-ion beams on driver-reactor interface and cavity conditions. A relatively high-density gas is required in the cavity for beam propagation along ionized channels from the particle source to the pellet. Gas densities which satisfy requirements for beam propagation are in the range 10^{18} to 10^{19} atoms/cm^3. Preionization along beam paths in the cavity is provided by low-power lasers. Voltage is then applied to the channel electrodes establishing arcs along the preionized paths and creating low-density plasma channels. The ion beam is then magnetically confined to the channel as it propagates to the pellet.

Compatible driver-reactor combinations that have been identified in this discussion are indicated in Table I.

TABLE 1

Compatible Driver-Reactor Combinations for Inertial Confinement Fusion

Reactor Concept	Driver Type: Lasers	Heavy Ion Beams	Light Ion Beams
Wetted-Wall	X		
Modified-Wetted-Wall	X	X	
HYLIFE	X	X	
Low-pressure gas-filled	X		
High-pressure gas-filled			X
Sacrificial liner	X	X	

4. REFERENCES

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[3] Meier, H. R. et al., 2nd International Conference on Liquid Metal Technology in Energy Production, Richland, WA, 20-24 April 1980.

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[6] Booth, L. A. Proceedings of the IEEE 64, 10, 1460-1482 (1976).

FIGURE CAPTIONS

Figure 1. Wetted-wall reactor concept.

Figure 2. Modified-wetted-wall reactor concept.

Figure 3. HYLIFE reactor concept.

Figure 4. Beam transport corridor in HYLIFE reactor concept.

Figure 5. Sacrificial reactor concept.

Figure 6. Magnetic deflection of ion debris in ICF reactor.

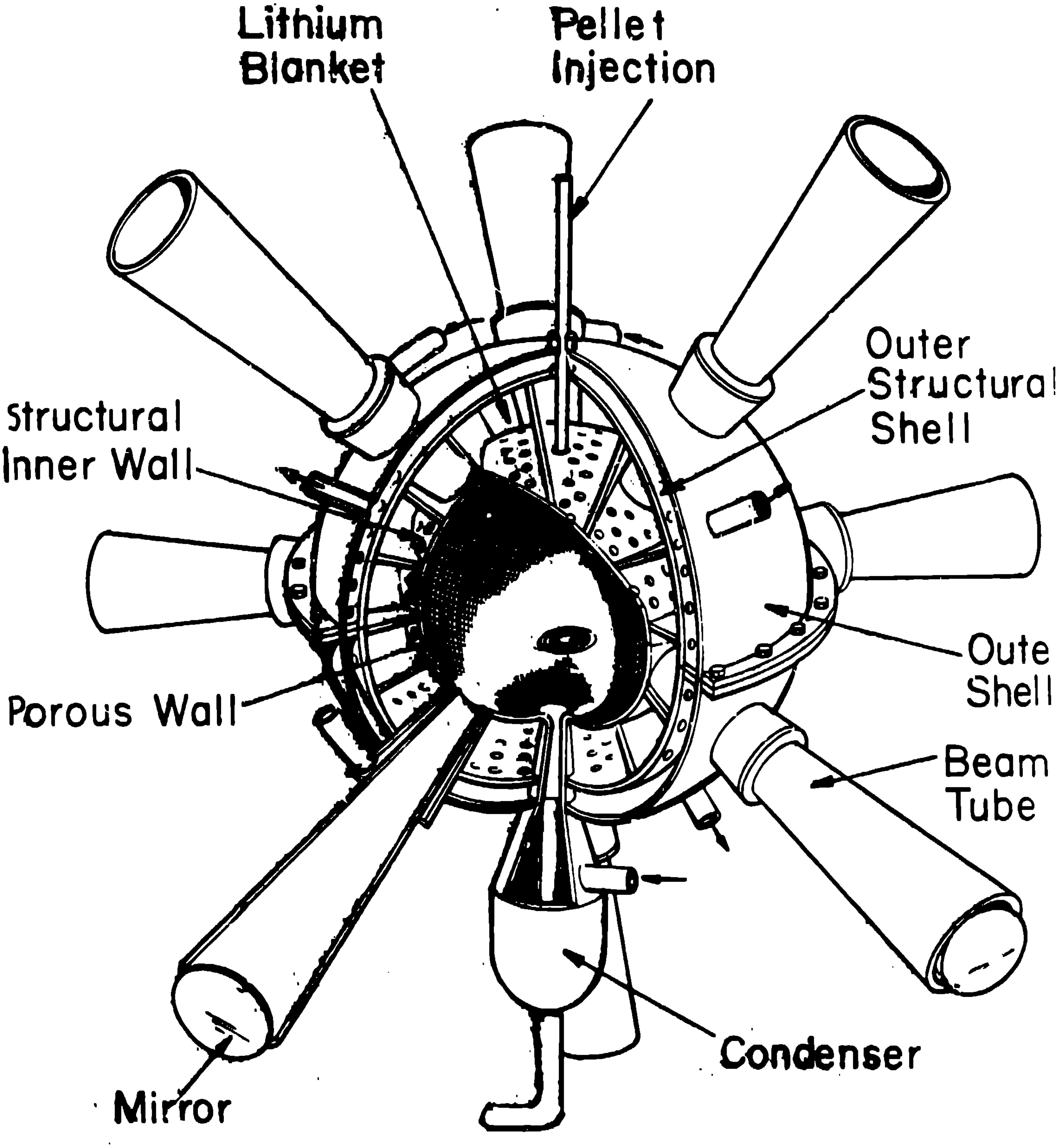

Lithium Blanket
Pellet Injection
Outer Structural Shell
Structural Inner Wall
Porous Wall
Oute Shell
Beam Tube
Condenser
Mirror

Fig. 1

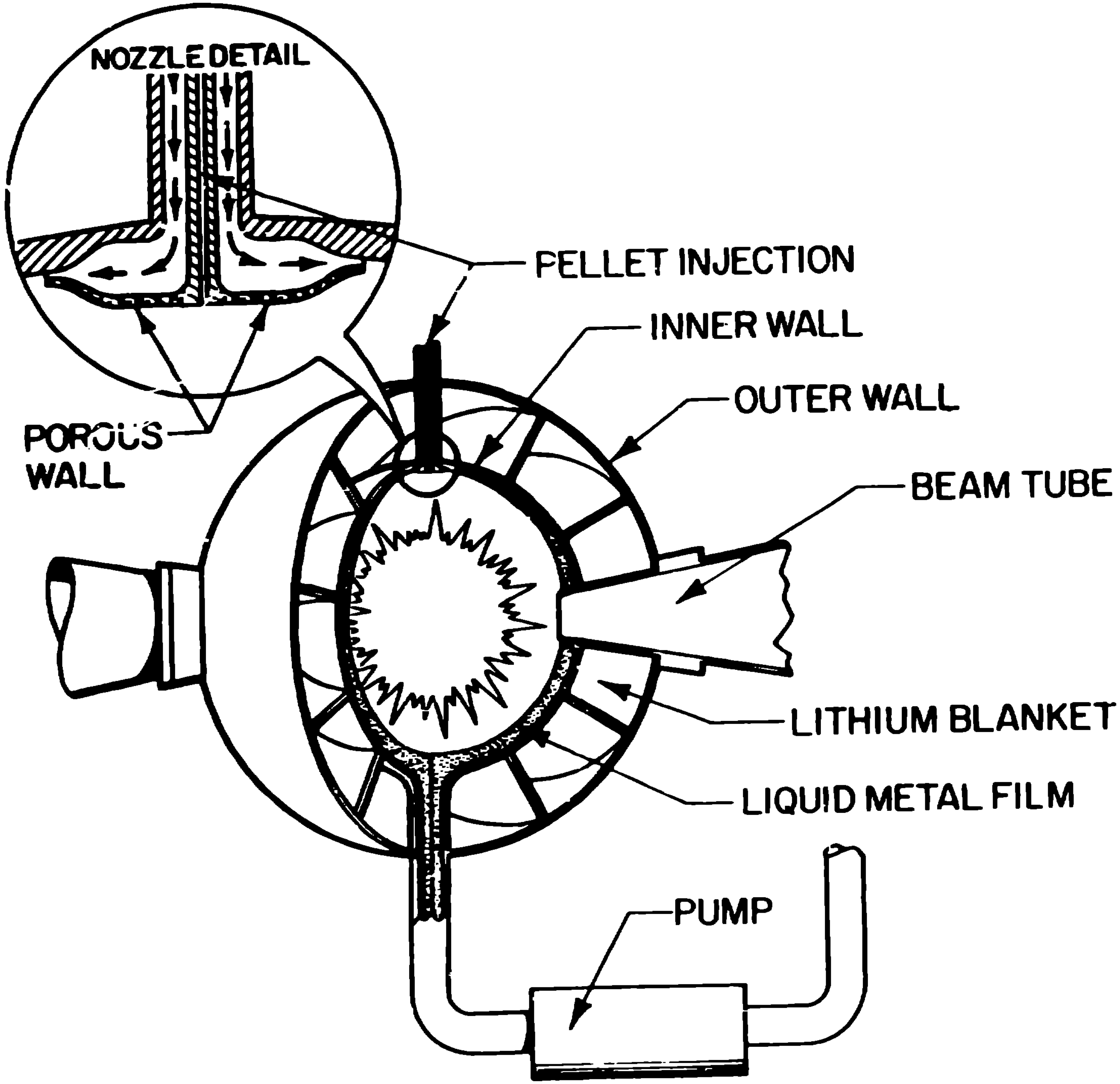

NOZZLE DETAIL
PELLET INJECTION
INNER WALL
OUTER WALL
BEAM TUBE
POROUS WALL
LITHIUM BLANKET
LIQUID METAL FILM
PUMP

Fig. 2

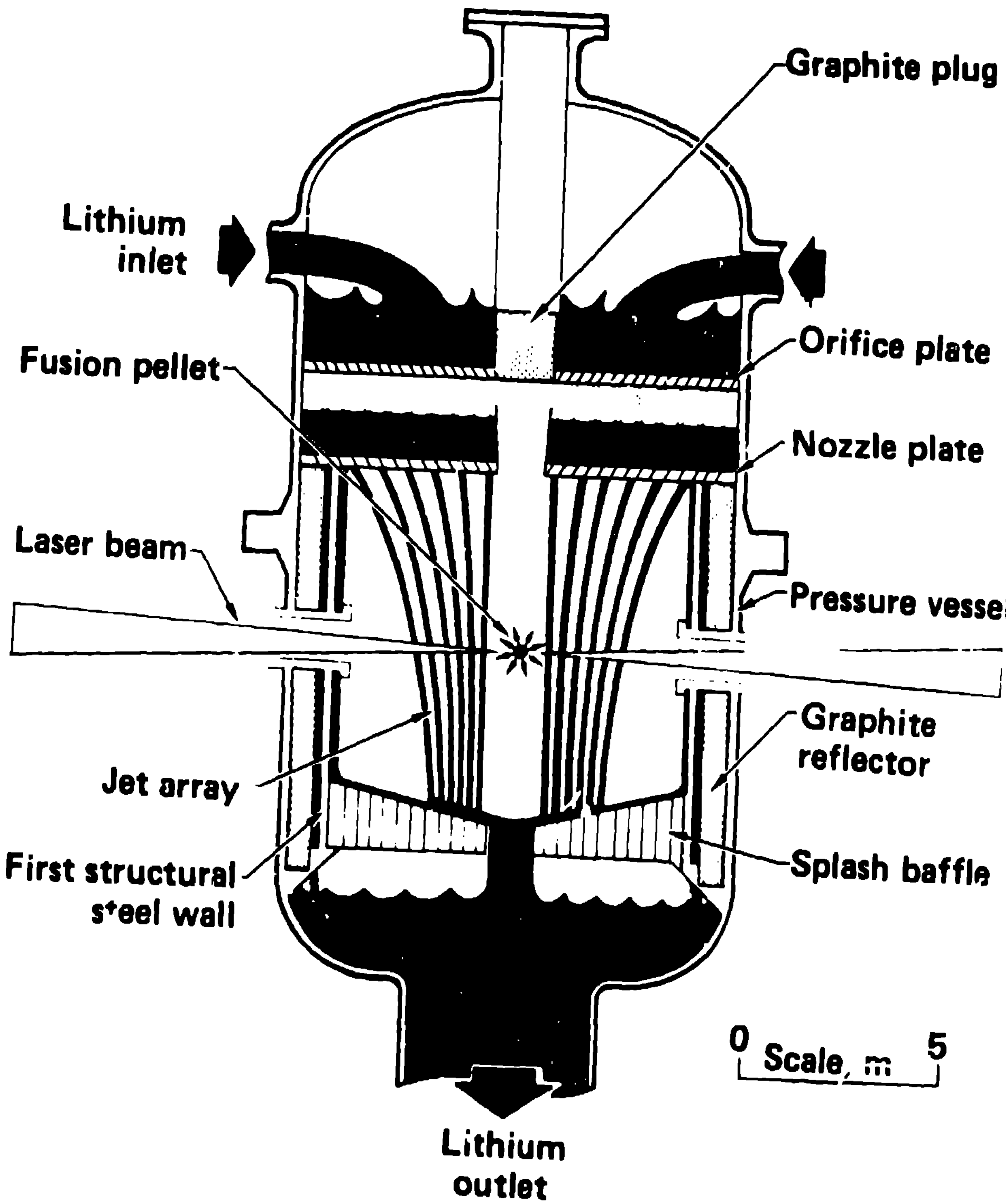

Graphite plug
Lithium
inlet
Orifice plate
Fusion pellet
Nozzle plate
Laser beam
Pressure vessel
Graphite
reflector
Jet array
First structural
steel wall
Splash baffle
0 Scale, m 5
Lithium
outlet

Fig. 3

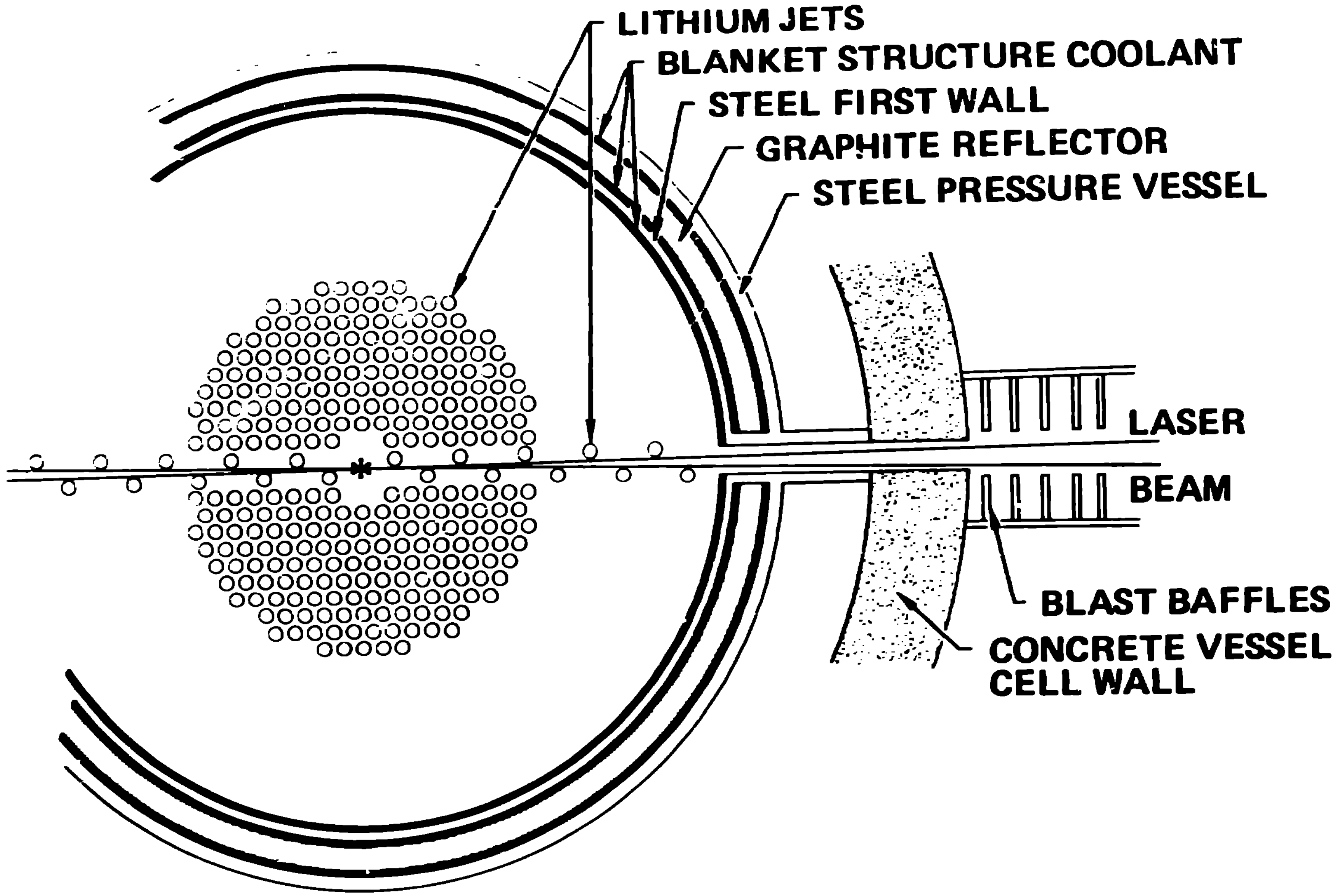
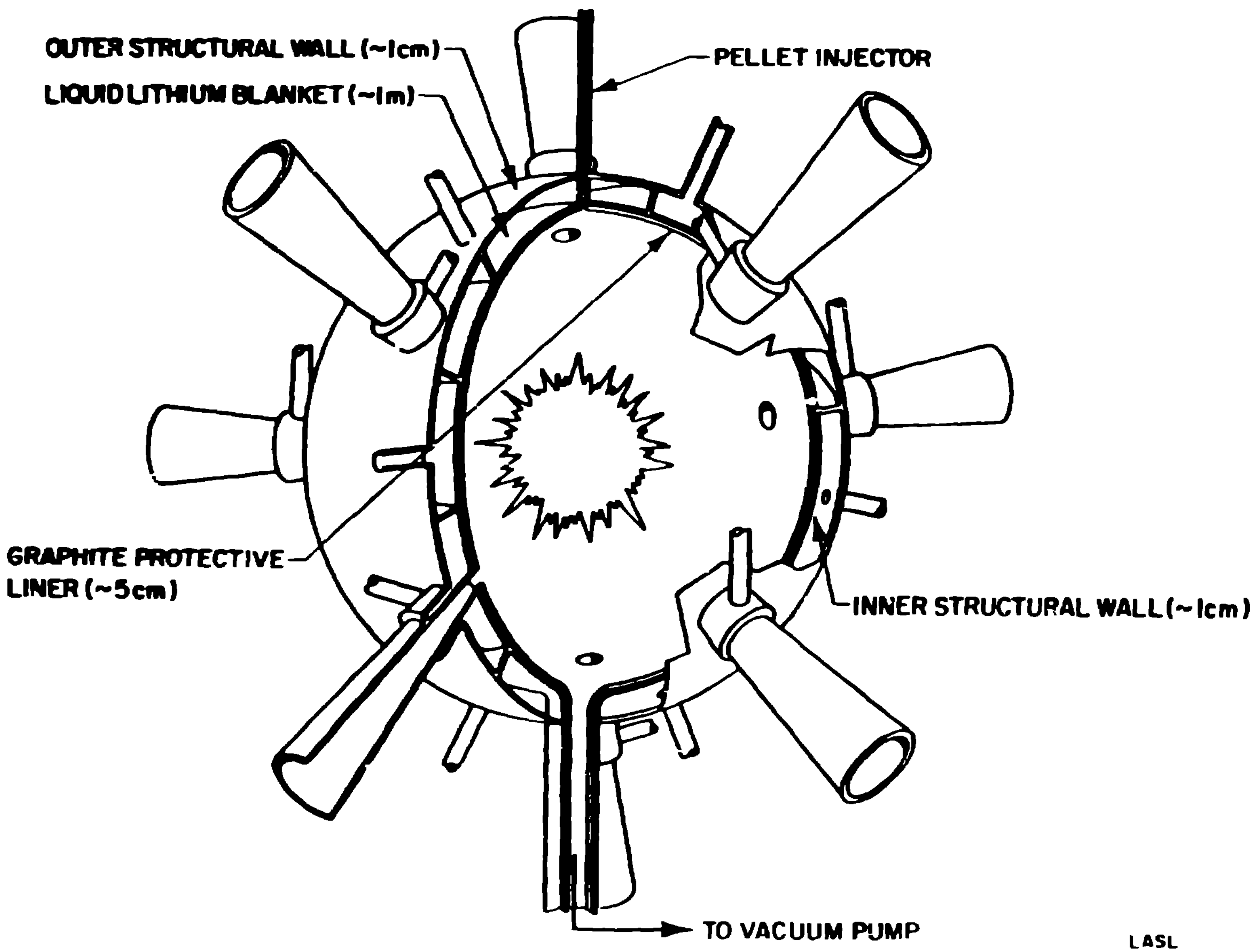

LITHIUM JETS
BLANKET STRUCTURE COOLANT
STEEL FIRST WALL
GRAPHITE REFLECTOR
STEEL PRESSURE VESSEL
LASER
BEAM
BLAST BAFFLES
CONCRETE VESSEL
CELL WALL

Fig. 4

5



OUTER STRUCTURAL WALL (~1cm)
LIQUID LITHIUM BLANKET (~1m)
PELLET INJECTOR
GRAPHITE PROTECTIVE LINER (~5cm)
INNER STRUCTURAL WALL (~1cm)
TO VACUUM PUMP
LASL

Fig. 5

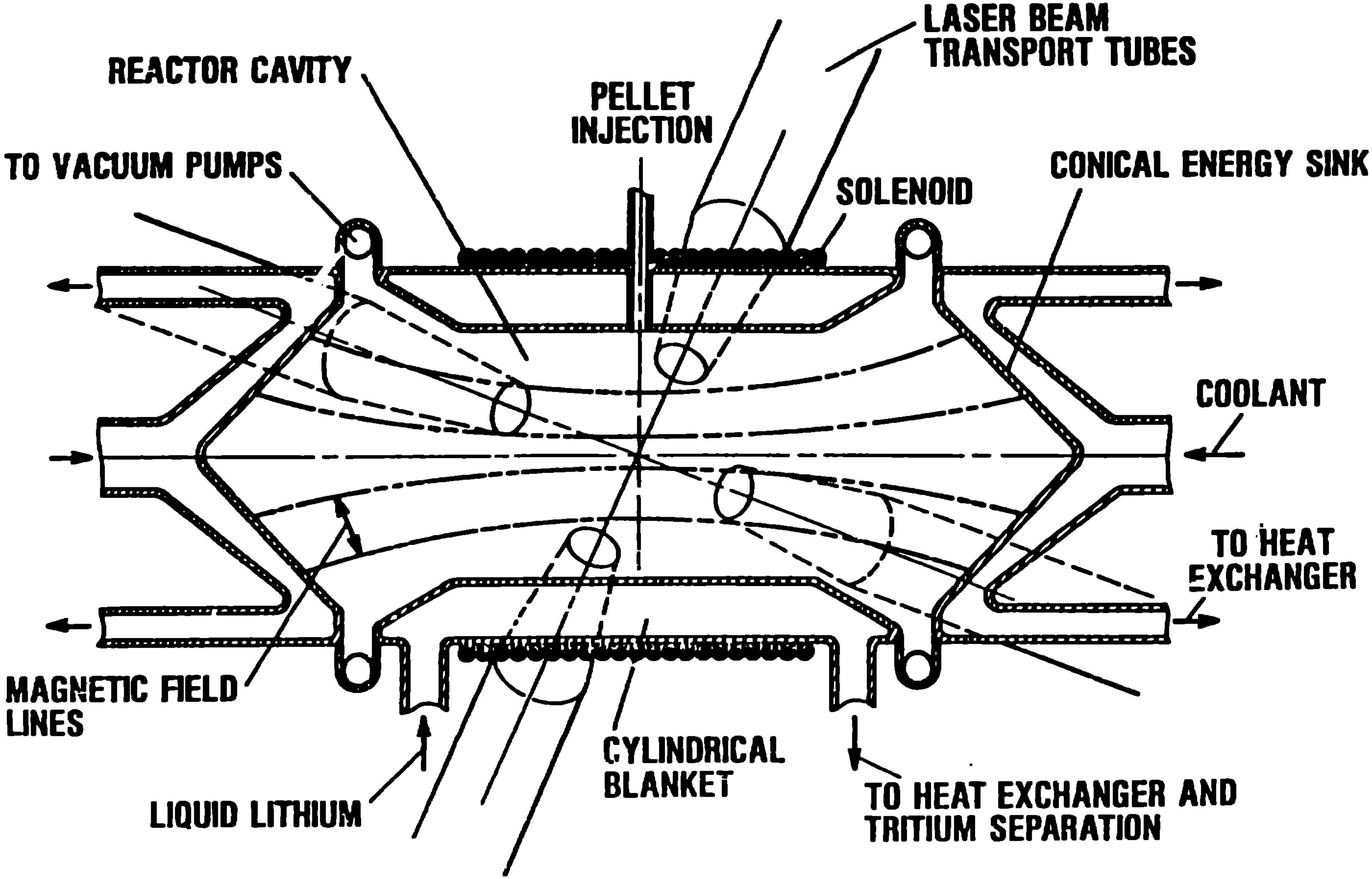

LASER BEAM
TRANSPORT TUBES
REACTOR CAVITY
PELLET
INJECTION
TO VACUUM PUMPS
CONICAL ENERGY SINK
SOLENOID
COOLANT
TO HEAT
EXCHANGER
MAGNETIC FIELD
LINES
CYLINDRICAL
BLANKET
LIQUID LITHIUM
TO HEAT EXCHANGER AND
TRITIUM SEPARATION

Fig. 6