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HEAT TRANSFER IN INERTIAL CONFINEMENT FUSION REACTOR SYSTEMS

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MASTER

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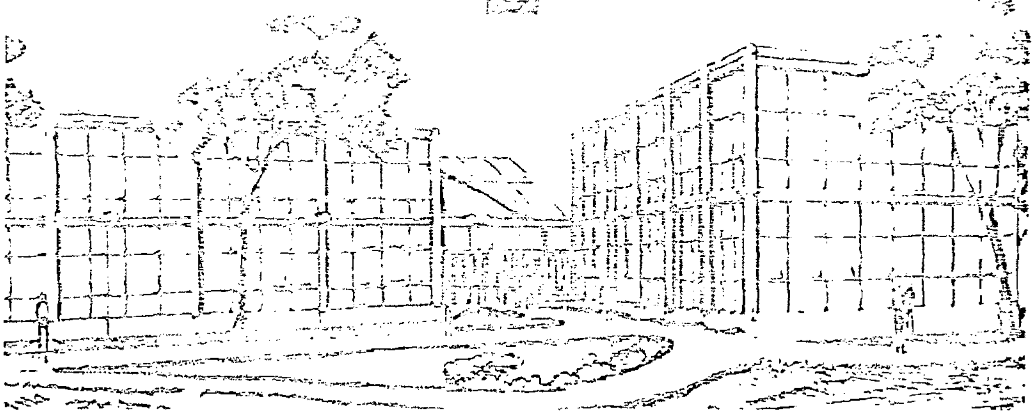

N 1/3-9

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Jack Havingh N1/3-4 *

The transfer of energy produced by the interaction of the intense pulses of short-ranged fusion microexplosion products with materials is one of the most difficult problems in inertially-confined fusion (ICF) reactor design. The short time and deposition distance for the energy results in local peak power densities on the order of 10^{18} watts/m^3. High local power densities may cause change of state or spall in the reactor materials. This will limit the structure lifetimes for ICF reactors of economic physical sizes, increasing operating costs including structure replacement and radioactive waste management.

The goals of the various ICF reactor design groups have been designs with small physical size (low capital cost) and long structural lifetime (low operating cost). These designs are primarily different in the protection of the first structural wall from the short-ranged intense particles and unburned fusion pellet debris. Four basic first wall protection methods have evolved: A dry-wall, a wet-wall, a magnetically shielded wall, and a fluid wall. These approaches are distinguished by the way the reactor wall interfaces with fusion debris as well as the way the ambient cavity conditions modify the fusion energy forms and spectra at the first wall. Each of these approaches requires different heat transfer considerations.

The trend in conceptual designs of ICF reactors is toward higher nominal energy fluxes on the first structural walls. This trend, based on economic considerations, tends to increase the heat transfer problems in ICF reactors. Thus, heat transfer considerations may set the minimum size limit on ICF reactors.

Jack Havingh N 1/3-4 *

INTRODUCTION

Inertial confinement of thermonuclear reactions is becoming a viable alternate to magnetic confinement of thermonuclear reactions as a future energy source. Inertial confinement consists of compressing a tiny pellet of deuterium-tritium to very high densities and temperature using intense beams of photons or particles. This beam can consist of light,[1] electrons,[2] or ions.[3] At the present time, most of the inertially confined reactor design is orientated toward using light beams, although some work has been published on design consideration of an electron-beam induced reactor system,[4-6] and a design study is being carried out on an ion-beam induced reactor system.[7]

The reactor design for inertially confined fusion (ICF) power plants will have different design constraints than magnetically confined fusion (MCF) reactors. The ICF reactors will have more geometric flexibility and easier maintenance as well as more freedom in material choices because they are unencumbered by the large magnet systems of MCF reactors. However, the energy from the microexplosions in the ICF reactors is deposited as a sequence of intense pulses while the energy from the plasma in the MCF reactor is deposited at a relatively constant rate.

This paper discusses the effects of the deposition of energy from D-T microexplosions in intense pulses. A number of reactor concepts which have been proposed to cope with the intense energy pulses are also discussed.

REACTOR SYSTEM

An inertially-confined fusion reactor has many potential applications including the production of electric power, fissile fuel, synthetic fuel, process heat, etc. But whatever the application, all the reactors will have common subsystems. The fuel system includes the fuel pellet factory and injector, as well as the vacuum system that collects the unburned pellet debris. The ignition system includes a driver system (electron beam, ion beam, or laser) and its associated beam transport hardware. The blanket system utilizes the neutron energy from the microexplosion to fulfill the reactor application requirements, as well as to breed tritium. Finally, there is the first wall which separates the blanket from the microexplosion cavity and is the recipient of the short-ranged microexplosion debris energy. This paper focuses on the first wall of the reactor.

BEAM-PELLET INTERACTION AND MICROEXPLOSION

In a beam driven, inertially confined fusion-reaction, the high intensity beam is focused on a pellet containing fusionable material, usually a mixture of deuterium and tritium (DT). The surface of the pellet is instantaneously vaporized into a low density plasma atmosphere. As the ablated mass accelerates outward into the microexplosion cavity, it generates an equal and opposite force that drives the pellet toward its center, increasing the density of the pellet. The high temperature required for fusion will be obtained during the compression of the pellet by compressive work. Under the appropriate conditions, ignition at the center of the pellet occurs, and a thermonuclear burn front propagates outward from the center of the pellet due to energy deposition of the fusion products in the pellet material. The thermonuclear burn continues until the temperature and/or density of the fuel in the pellet decreases to a point where a thermonuclear reaction cannot occur.

ENERGY DISPOSITION FROM BEAM-PELLET INTERACTION AND MICROEXPLOSION

The energy partition and spectra of the laser-pellet interaction and microexplosion are dependent on several parameters. These include the laser characteristics such as wavelength, energy, and peak power as well as pellet mass, composition, and design. These characteristics will determine the amount of laser light reflected from the pellet, the pellet compression, and the gain Q, defined as the ratio of thermonuclear yield to the laser energy incident on the target. The physics of the laser induced implosion and thermonuclear burn of the pellet is very complex.[8] Large computer codes such as LASNEX have been developed to calculate the transport and interaction of laser photons, electrons, ions, x-rays and fusion reaction products, together with the magnetic and electric fields and hydrodynamics behavior of the pellet.[9]

Theoretical energy-release forms from a 100 MJ bare DT pellet microexplosion are shown in Table 1.[10] From the outside of the pellet, prompt x-rays will be observed first. Next in time will be the 14 MeV neutrons, the high energy alpha particles that escape the plasma, and finally the unburned pellet debris.

Table 1 - Typical Energy Release Mechanisms From A 100-MJ Bare DT Pellet Microexplosion[10]

Mechanism	Fraction of Total Energy Release	Particles Per Pulse	Average Energy Per Particle
X-rays	0.01	-	4 keV peak
particles that escape plasma	0.07	2.2×10^{19}	2 MeV
Plasma kinetic energy	0.15		
particles	-	1.3×10^{19}	0.8 MeV
Deuterons	-	8.5×10^{19}	0.4 MeV
Tritons	-	8.5×10^{19}	0.6 MeV
Neutrons	0.77	3.5×10^{19}	14.1 MeV

ENERGY DEPOSITION IN FIRST WALL AND BLANKET

The microexplosion energy deposition in the first wall can be found by inserting spectra of the various forms of energy from LASNEX into special deposition computer codes, shown in Table 2. Other institutions may use different codes to assist in their analyses of the energy deposition and first wall response.[11]

Jack Hovingh

N 113-44

Table 2 - Computational Tools For Inertially Confined Fusion

Information Provided	Computational Tool	Description
Yields and spectra (temporal and energy) for x-rays, charged particles, and neutrons at the first wall	LASNEX[9]	A two-dimensional Lagrangian hydrodynamic code which mathematically simulates thermonuclear microexplosions
X-ray energy deposition profiles in the first wall	BUCKLE[12]	An x-ray transport code which treats photoelectric absorption, compton scattering, pair production, and fluorescence
Charged particle energy deposition profiles	Range-Energy[13] Relationships	Solves LSS derived transport equation with particle energy distribution
Neutron energy deposition profiles	ANISN[14]	One-dimensional discrete ordinates code which treats coupled neutron-gamma ray transport
Response of the first wall (temperature, pressure and stress) to the energy deposition profiles	CHART D[15]	A one-dimensional coupled energy flow and Lagrangian hydrodynamic code

EFFECTS OF ENERGY DEPOSITION TIME ON TEMPERATURE AND STRESS

The sudden deposition of the burn product energy in the first wall results in stress due to the thermal gradients in the material from non-uniform heating and conduction, as well as inertial effects. The boundary value problem is of considerable mathematical difficulty as it combines the theories of elasticity and viscoelasticity as well as heat conduction. Usual engineering solutions are obtained by omission of the mechanical coupling term in the energy equation and the inertia terms in the equation of motion. The basis for the omission of the mechanical coupling term and the inertial term is a consideration of the characteristic times of the system. These time considerations will be discussed below.

The response of a continuum to internal energy deposition is dependent on temporal-spatial deposition profiles, and the thermal-physical properties of the continuum. We consider first the effects of the temporal-spatial deposition profiles by assuming that a pulse of energy is deposited in the continuum in a time τ and spatially in the form

$$q_0''' (x) = q_0''' \exp[-\mu x], \tag{1}$$

Jack Havingh N 1/3-4 *

where q_0''' is the energy deposition from a given source in the surface layer of the continuum and μ is the energy attenuation coefficient through the continuum. We define the characteristic thermal time of the energy deposition in the continuum as the ratio of the energy storage in the distance μ^{-1}, to the rate of heat conducted across the distance μ^{-1}, or

$$\tau_T = [\mu^2\alpha]^{-1}, \qquad (2)$$

where α is the thermal diffusivity of the continuum material. We also define the characteristic mechanical response time of the continuum due to the energy deposition as time required for a disturbance to propagate the distance μ^{-1} or

$$\tau_m = [\mu c]^{-1}, \qquad (3)$$

where c is the wave velocity in the continuum.

Two cases are of special importance for inertial fusion. These cases are:

Case I $\quad \tau < \tau_m << \tau_T$

Case II $\quad \tau_m << \tau_T \approx \tau$

For Case I the time variation effects produced by heat conduction are small compared to those produced by the pressure wave. Because the energy is deposited in a short time the initial temperature rise and pressure rise can be estimated by simple models,

$$\Delta T(x) = \frac{q'''(x)}{\rho C_v} \qquad (4)$$

$$\Delta p(X) = \Gamma\, q'''(x) \qquad (5)$$

where $q'''(x)$ is the energy deposition at position x in the continuum, ρ, C_v and Γ are the density, specific heat at constant volume, and Gruneisen constant, respectively, of the continuum. Approximate theories of uncoupled dynamic thermoelasticity and viscoelasticity can then be used to determine the moving stress pulse produced by the energy deposition.

For energy deposition in times that are long compared to the thermal characteristic time, which is long compared to mechanical characteristic time (Case II), the stress can be determined by quasi-static thermoelastic or viscoelastic theory while the temperature history can be determined using classical diffusion theory.

There are several parameters that should be minimized to reduce the temperature rise and pressure rise per fusion pulse from the fusion energy deposited in the continuum. The amplitude of the temperature pulse can be minimized by minimizing the ratio of the energy attenuation coefficient to the specific heat at constant volume, μ/C_v. The amplitude of the pressure pulse can be minimized by minimizing the product of the Gruneisen constant and energy attenuation coefficient, $\Gamma\mu$. Generally, for fusion products this involves using materials of low atomic number.

Jack Havenigh N 1/3-4 *

If the fusion energy is deposited in such a short time that the pressure cannot relieve itself during the deposition time, a relief wave moves into the continuum from the surface. If the continuum is a solid, and if the tensile strength is exceeded, the surface will spall.

The results of a 10 MJ microexplosion in a 3.5 m radius microexplosion chamber with a graphite first wall are shown in Table 3. The temperature history is shown in Fig. 1. The lifetime of the graphite liner is about one year for a fusion power of 200 MW.[16]

Table 3 Graphite First Wall Energy Deposition and Reponse Characteristics

Source	Fluence kJ/m^2	Surface deposition kJ/g	Deposition depth m	Deposition time ns	Surface temperature rise C	Peak tensile stress MPA**
Reflected laser light	1.0	28.6	0.02*	0.20	2900.0	100***
X-rays	0.65	0.0006	7.2*	0.01	2.0	0.2
14 MeV neutrons	50.0	-	-	0.01	-	-
High energy alphas	4.5	0.40	6.9	0.01	200.0	33.0
Pellet debris	12.0	4.7	1.6*	1200.0	950.0	0.1

*Depth at which energy deposition is e^{-1} of the surface deposition
**Spall strength of graphite is 10^2 MPa
***Spalls at a depth of 0.1 m. Reflected laser light surface deposition for no spall is 20 kJ/g

CONCEPTUAL REACTOR DESIGNS FOR LASER FUSION SYSTEMS

Several conceptual designs have been proposed for pure laser-fusion reactors to cope with the characteristic first-wall problems typical of inertially confined fusion reactors. Four different types of first wall have been proposed: A dry wall, a wet wall, a magnetically shielded wall, and a fluid wall. These approaches are distinguished by the way the blast chamber wall interfaces with the hot blast debris impinging on its surface, as well as the way the ambient cavity conditions modify the microexplosion energy release forms and spectra prior to energy deposition in the first wall. The effects of the ambient cavity conditions on the energy release forms are shown in Table 5.[10]

The dry wall concept uses an unprotected wall between the blanket and microexplosion chamber. This wall may be bare niobium, stainless steel, or another metal, or it may be graphite or carbon curtain over a metal first wall.[4,7,16-19] The short-ranged fusion energy deposited in the wall is conducted to the primary coolant system. The advantage of a metal first wall is that fabrication is relatively simple, and the vapor pressure is low resulting in small vacuum system power requirements. The major disadvantage of a metal first wall is the high x-ray stopping power of metals results in high stresses which may cause spall. With the particle fluences and energies associated with the blast debris, a

Jack Havingh N 1/3-47

short first-wall lifetime for reasonable sized chambers must therefore result from use of an unprotected metal first wall. The heat transfer from the graphite to the support structure must be considered to keep that graphite surface temperature at a level to reduce vaporization, and increase lifetime.

The wet-wall concept for fusion reactors will absorb the energy of the soft x-rays and the charged particle debris in a liquid layer over the first wall. Thus, the debris diffuses back into the vacuum chamber without causing fracture-producing stress levels in the structure. The first wet wall concept, shown in Fig. 2, developed by LASL[20,21] features a large energy fluence per pulse on a liquid lithium over-niobium first wall. This concept has received the most extensive analysis of any wet-wall reactor to date. A large mass of lithium is blown off the first surface after each microexplosion. This lithium must be pumped from the cavity into the primary coolant circuit until a pressure of less than one torr is achieved. Thus, the pulse repetition frequency is low due to vacuum pumping considerations.

The suppressed ablation[22] system is a modification to the wet wall concept that reduces the mass of lithium blown off from the wet wall. Lithium ablation is suppressed by using a liner consisting of pyramidal elements to effectively increase the surface area of the first wall. Thus, for a given reactor radius, the lithium covered niobium liner lowers blast energy fluxes to a level where serious ablation does not occur. Westinghouse has also designed a hybrid reactor to produce fissile fuel based on the wet wall design.[23]

The magnetically shielded first wall concept[24] is shown in Fig. 3. A solenoid surrounding a lithium blanket is used to divert the pellet debris from a dry niobium first wall. The energy of the pellet debris is deposited on conical surfaces at the ends of the cylinder. These surfaces are cooled by the reactor primary coolant. Note that in principle, the energy of the pellet debris can be converted directly to electricity by exhausting the debris into an MHD duct. The magnetic-shield first-wall concept does not protect the first wall from the neutron or x-ray flash during the microexplosion process. The major disadvantage of a magnetic-shield first-wall is that if a liquid metal is selected as a coolant, the pumping power required to move the liquid metal will increase if movement occurs across magnetic field lines.

The fluid wall concepts offer a method to modify the microexplosion energy release forms and reduce the damage to the reactor structure. As a result, the fusion power density is higher than the other wall protection concepts. The first fluid wall concept for inertially confined fusion reactors was BLASCON[25] which featured a swirling lithium blanket of lithium tangentially injected into a stationary vessel. Baird[26] proposed rotating the vessel containing lithium such that the lithium surface assumed a parabolic shape. Burke[27] has proposed rotating a horizontal vessel containing lithium for use as a heavy ion beam driven ICF reactor.

The University of Wisconsin has proposed a fluid wall concept which features a gas in the chamber to absorb the short-ranged x-ray and debris energy[28] as shown in Figure 4. The energy deposited is transferred over a long time period to the graphite first structural wall. This design features a high power density and a blanket composed of Li_2O pellets to reduce the neutron pressure pulse. The Li_2O pellets are the primary energy transport medium. They are circulated through the blanket into the steam generator. The blanket structure lifetime is about one year at 5 MW/m^2 wall loading since the cavity gas does not

p. 7

Jack Havingh N 1/3-4 +

modify the microexplosion neutron spectrum.

Several fluid wall concepts which feature continuously renewing first walls have been proposed. These include the "falling balls" concept which utilizes a thick curtain of Li_2O[29] or graphite[30] pellets continuously circulated between the microexplosion and the reactor structure, and the fall concept[29,31] which utilizes a thick curtain of liquid lithium or lead between the microexplosion and the structure. These curtains attenuate the neutron energy such that the reactor power density can be high and the structural lifetime based on neutron radiation damage criteria will be at least 30 years. The "falling balls" concept has several advantages over the lithium fall shown in Fig. 5. It can operate with very low chamber pressures due to the low vapor pressure of solid pellets. Safety problems concerned with the transport and storage of liquid metals are not present. Finally, the falling balls do not respond like a continuum to the microexplosion energy deposition, thus, the shock to the structure is reduced. The liquid fall is a self-pumping vacuum system because the deposition of energy in the liquid will disassemble the fall into droplets which act as condensation sites for the high temperature vapor. The liquid metal transport may be more power efficient than the ball transport. In addition, the transfer of heat from the liquid lithium blanket to a heat exchanger will be easier than from the Li_2O blanket.

Several concepts have been proposed using falling liquid lithium which minimize the continuum behavior of the falling lithium. Burke proposed a falling curtain of bubbly lithium, where the bubbles are formed by helium gas in the lithium. Monsler[32] proposed injecting jets of liquid lithium in an array surrounding the microexplosion. Both the bubbly lithium curtain and the lithium jet concept will accommodate higher yield microexplosions in a smaller vessel with higher power densities than other first wall protection methods.

CONCLUSION

The heat transfer problems in an inertially confined fusion reactor are different from those in a magnetically confined fusion reactor with the same time-averaged first-wall neutron energy flux. These differences are due to the arrival of the charged particles, x-rays, and neutrons in extremely short-time pulses in the low-duty cycle, inertially confined, laser-fusion reactor as opposed to the long-time pulse in the high duty cycle typical of the magnetically confined fusion reactors. Since plasma contamination is not a problem in inertially confined fusion reactors, the fusion cavity can operate at pressures limited only by the requirements of driver beam transmission. Therefore, the fusion product energy release forms can be altered in timing, intensity, and spectra. Judicious selection of the cavity environment and structural materials tailored to the specific laser-pellet design and fuel cycle may result in reactor structural component lifetime on the order of the plant lifetime with reactor power densities near that of current fission reactors.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

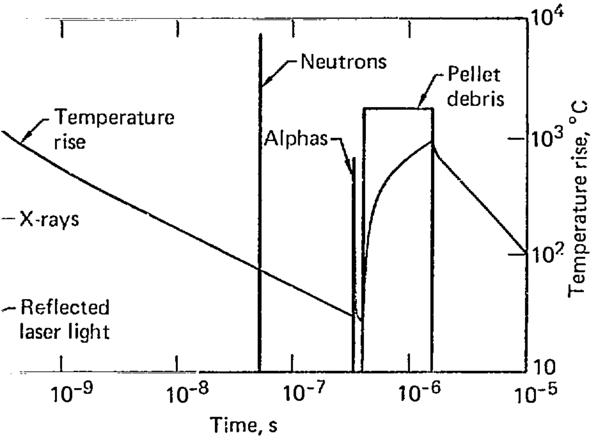
Fig. 1 Response of the Surface of a Graphite Surface Located 3.5 m from a 10 MJ Microexplosion.

Fig. 2 West Wall Concept for a Laser Driver Inertially Confined Fusion Reactor.[20,21]

Fig. 3 Magnetically Protected Wall Concept for a Laser Driven Inertially Confined Fusion Reactor.[24]

Fig. 4 Fluid Wall Concept for a Laser Driven Inertially Confined Fusion Reactor. The fluid is a low density (0.5 torr at 300 C) gas filling the cavity.[28]

Fig. 5 Fluid Wall Concept for a Laser Driven Inertially Confined Fusion Reactor. The fluid is liquid lithium which circulates continuously through the reactor.



Neutrons
Pellet debris
Temperature rise
Alphas
X-rays
Reflected laser light
10^4
10^3
10^2
10
Temperature rise, °C
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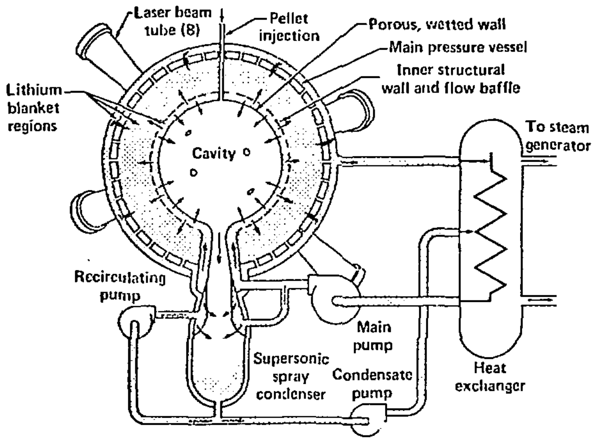
10^{-8}
10^{-7}
10^{-6}
10^{-5}
Time, s


Laser beam tube (8)
Pellet injection
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Inner structural wall and flow baffle
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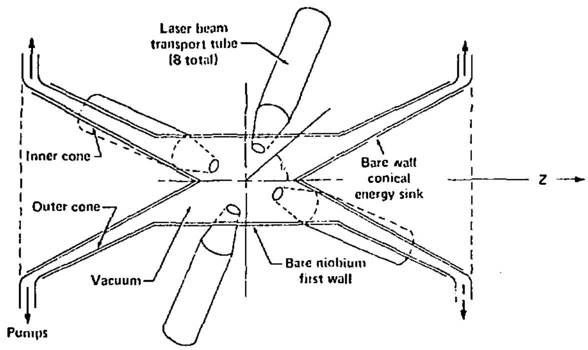
To steam generator
Recirculating pump
Main pump
Supersonic spray condenser
Condensate pump
Heat exchanger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Outer cone
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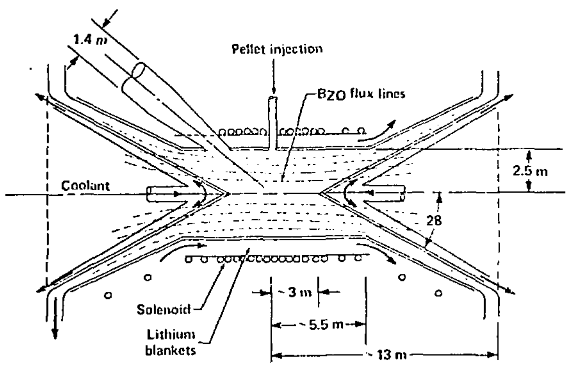
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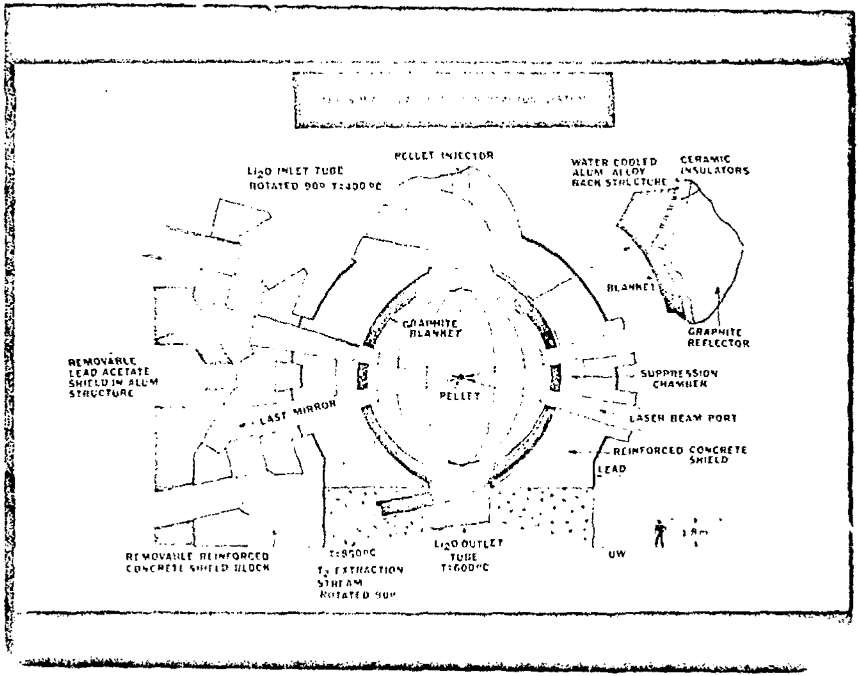
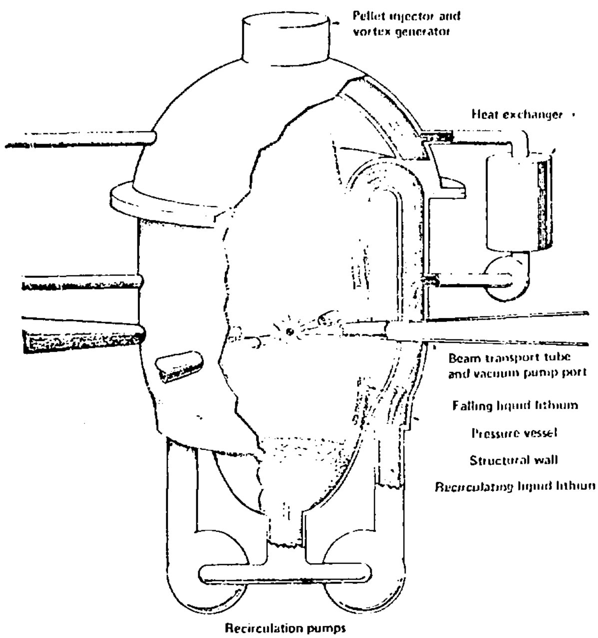
Pellet injection
BZO flux lines
2.5 m
Coolant
28
Solenoid
Lithium
blankets
~3 m
~5.5 m
~13 m


PELLET INJECTOR
Li_2O INLET TUBE
ROTATED 90° T=400°C
WATER COOLED
ALUM ALLOY
BACK STRUCTURE
CERAMIC
INSULATORS
BLANKET
GRAPHITE
REFLECTOR
GRAPHITE
BLANKET
PELLET
SUPPRESSION
CHAMBER
LASER BEAM PORT
REINFORCED CONCRETE
SHIELD
LEAD
REMOVABLE
LEAD ACETATE
SHIELD IN ALUM
STRUCTURE
LAST MIRROR
REMOVABLE REINFORCED
CONCRETE SHIELD BLOCK
T=950°C
T_2 EXTRACTION
STREAM
ROTATED 90°
Li_2O OUTLET
TUBE
T=600°C
UW
1.8m



Pellet injector and
vortex generator
Heat exchanger
Beam transport tube
and vacuum pump port
Falling liquid lithium
Pressure vessel
Structural wall
Recirculating liquid lithium
Recirculation pumps