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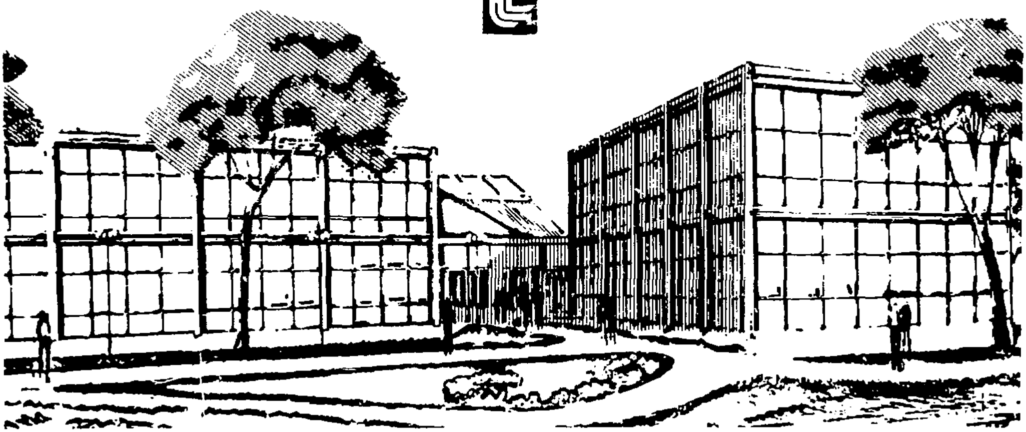

REACTOR CONCEPTS FOR LASER FUSION*

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ABSTRACT

Scoping studies were initiated to identify attractive reactor concepts for producing electric power with laser fusion. Several exploratory reactor concepts were developed and are being subjected to our criteria for comparing long-range sources of electrical energy: abundance, social costs, technical feasibility, and economic competitiveness. The exploratory concepts include:

- A liquid-lithium-cooled stainless steel manifold
- A gas-cooled graphite manifold
- Fluidized wall concepts, such as a liquid lithium "waterfall", and a ceramic-lithium pellet "waterfall".

Two of the major reactor vessel problems affecting the technical feasibility of a laser fusion power plant are:

- The effects of high-energy neutrons and cyclical stresses on the blanket structure
- The effects of x-rays and debris from the fusion microexplosion on the first-wall.

The liquid lithium "waterfall" concept is presented here in more detail as an approach which effectively deals with these damaging effects.

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REACTOR CONCEPTS FOR LASER FUSION

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Scoping studies were initiated to identify attractive reactor concepts for producing electric power with laser fusion. Several exploratory reactor concepts were developed and are being subjected to our criteria for comparing long-range sources of electrical energy: abundance, social costs, technical feasibility, and economic competitiveness. Two of the major reactor vessel problems affecting the technical feasibility of a laser fusion power plant are:

- The effects of high-energy neutrons and cyclical stresses on the blanket structure
- The effects of x-rays and debris from the fusion microexplosion on the first wall

Our level of confidence in developing the technology to solve these problems has been determined by the amount of system development required beyond the state-of-the-art. Economic feasibility will be strongly dependent on the solution to these technical problems; it has been assessed in terms of factors including reactor size, power density, first-wall and blanket lifetimes, duty cycle, fabrication costs, stored energy requirements, and recirculating power fractions.

The reactor concepts that have been developed and are being compared include:

- A liquid-lithium-cooled stainless steel manifold
- A gas-cooled graphite manifold
- Fluidized wall concepts, such as a liquid lithium "waterfall," and a ceramic-lithium pellet "waterfall"

Before describing these concepts we introduce some background information on fusion reactor technology and the design parameters and constraints that are common to all of the reactor concepts. This discussion of reactor technology deals primarily with the functions that a blanket system is required to perform and the problems associated with peforming these functions in the hostile environment created by the fusion microexplosion.

All of the reactor concepts are based on an inertially confined deuterium-tritium fusion reaction. We have selected thermonuclear yields ranging from 400 to 4000 MJ and pulse repetition rates from 1 to 10 Hz. Selected combinations of these parameters result in reactor systems that produce 400 to 4000 MW of thermal power and 120 to 1500 MW of electrical power with net efficiencies ranging from 30 to 40%. The variance in net efficiency results from the different thermal efficiencies and recirculating power requirements of the various concepts. The selected parameter space for fusion neutron flux at the first wall ranges from 1 to 10 MW/m^2, resulting in first wall radii ranging from 1.5 to 15 m.

The effects of neutrons, x-rays, and debris from the thermonuclear microexplosion represent the primary technical concerns that must be dealt with in laser-fusion reactor concepts. All of our reactor concepts employ large focal length optics to mitigate the damaging effects to the final focusing elements. At a focal length of 10 m the final optics would survive the microexplosion, but may have to be replaced at relatively short intervals. At a focal length of 100 m the damaging effects are reduced by two orders of magnitude, thus assuring the survival of the final focusing elements for intervals that are long enough not to adversely affect the plant capacity factor. High energy neutrons also damage and activate most structural materials. The large amounts of radioactive waste thus generated represent a maintenance and disposal problem that is common to all types of DT fusion systems. X-ray and debris damage to first-wall materials is a problem primarily associated with inertial confinement fusion systems.

Several different approaches to the first-wall problem have been discussed in the literature, including use of a dry wall,[1] wetted wall,[2,3] and magnetically protected wall.[4] These approaches differ primarily in the way in which the inner surface of the first wall interacts with the x-rays and microexplosion debris. In the dry wall approach a sacrificial metal or ceramic liner is placed between the fusion chamber and the blanket. The wetted wall concepts feature a thin layer of liquid metal that covers the metal wall and protects it from the blistering and structural ablation that would otherwise occur. The magnetic protection concept uses a solenoid to divert the pellet debris away from the sides of a cylindrical blanket and into conical collectors at the top and bottom.

The fluidized wall concept is a new and promising approach which has been developed in our scoping studies. In this approach, the first structural wall is shielded from x-rays, neutrons and debris by a thick falling region of lithium in liquid or solid pellet form. The fall will contain enough moderating material to degrade the fusion neutron spectrum to the point where neutron damage levels in structural materials are low enough to allow us to consider smaller blanket structures which could last for the useful lifetime of the plant.

The blanket system must perform several functions while coping with the hostile environment created by the fusion microexplosion. It must:

1. Convert the fusion energy into thermal energy
2. Provide for efficient removal of the thermal energy
3. Breed enough tritium to replace that which was burned in the fusion reaction
4. Maintain the required vacuum in the fusion chamber

Sixty-five to seventy-five percent of the fusion energy is in the form of high-energy neutrons. Therefore, a neutron-moderating material is required to convert kinetic energy to thermal energy. In general, elements with low atomic numbers and high scattering cross sections are effective moderators; water, hydrides, beryllium, and graphite are common examples. Although somewhat less effective, lithium can also be considered as a neutron-moderating material.

Because there is no significant natural supply of tritium, a DT fusion reactor must breed its own tritium. Several neutron reactions produce tritium, but the only tritium-producing reactions with high enough cross sections to be useful are those involving lithium. Natural lithium is isotopically 7.4% ^{6}Li and 92.6% ^{7}Li, and tritium can be produced from either isotope by:

$$^{6}Li + n \rightarrow {}^{4}He + T,$$
$$^{7}Li + n \rightarrow {}^{4}He + T + n.$$

The ^{7}Li reaction has a threshold of approximately 4 MeV and a much lower cross section than the ^{6}Li reaction; nevertheless, it is very important because it produces a T atom without depleting the neutron population. If the neutrons are moderated before reaching the fertile lithium, the ^{7}Li reaction is not utilized (since it requires a high-energy neutron) and any lost neutrons would result in a tritium-breeding ratio less than 1.0. In such cases, the blanket must also contain some sort of neutron multiplier to maintain an adequate breeding ratio. Beryllium and lead with high (n, 2n) and low capture cross sections are examples of good neutron multipliers. However, beryllium is an example of a limited resource material whose use could significantly reduce fusion's potential as a long-range source of energy.

The vacuum requirements in the fusion chamber are primarily determined by considerations of laser beam propagation and damage to the injected fuel pellet. If the DT fuel can be incorporated into the pellet in a noncryogenic or insulated form, and hence be less subject to heat damage, laser beam propagation will be the primary factor determining the vacuum requirements in the fusion chamber. Our results[5] indicated that beam defocusing and attenuation of 1 μm light by cascade breakdown and/or thermal blooming can be reduced to acceptable levels with fusion chamber pressures of 0.1 torr or less. The pumping requirements needed to maintain this vacuum will depend on the material vaporized and the type of pump used. For a lithium wetted first-wall concept, the 0.1-torr vacuum can be maintained under the worst conditions with a vacuum pump that requires about 2% of the gross electrical power and approximately 10% of the surface area (the worst conditions resulting when all the debris and x-ray energy is used to vaporize lithium).

Liquid-Lithium-Cooled Stainless Steel Manifold

This concept (Fig. 1) represents a more conventional approach to a laser-fusion power plant, requiring less advanced technology than the fluidized wall concepts. In this concept, the microexplosion is surrounded by a cylindrical annulus of stainless steel into which vertical coolant channels have been drilled to form a manifold. Liquid lithium flows down these channels and is recirculated to the top through a bulk coolant region, which separates the annular

LIQUID LITHIUM COOLED STAINLESS STEEL MANIFOLD CONCEPT

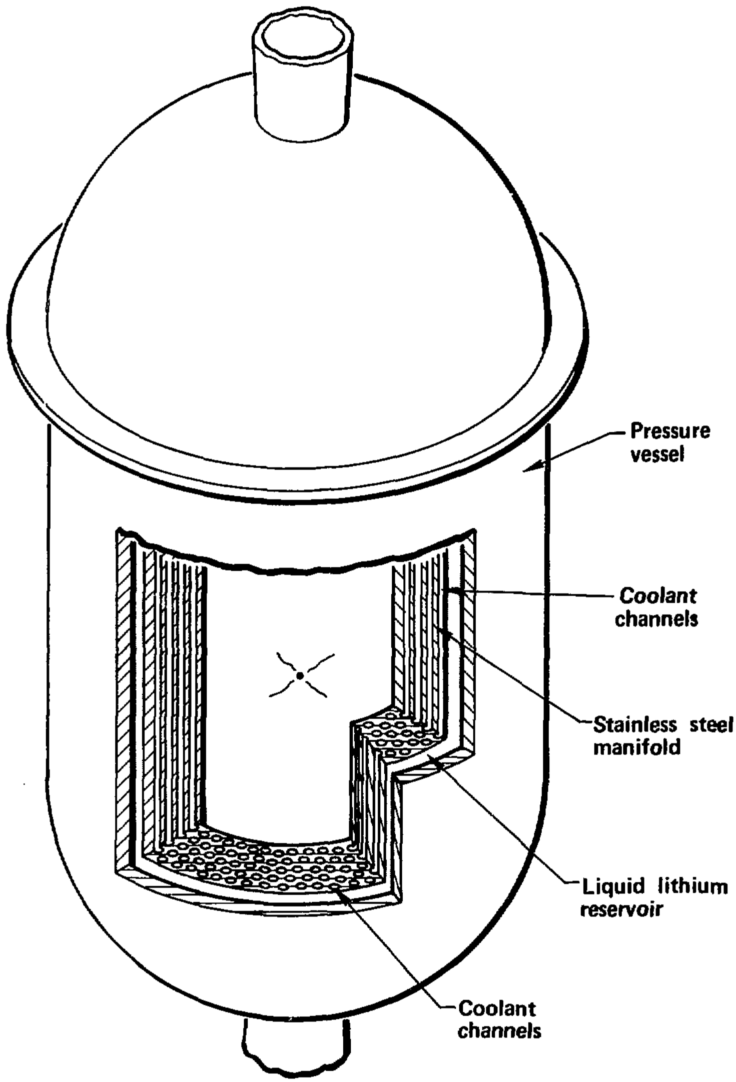


Fig. 1

manifold from an outer pressure vessel. Liquid lithium serves as the primary coolant, neutron moderator, and fertile material.

The stainless steel manifold concept is compatible with either a dry or wetted first-wall approach. In the dry-wall approach, we are analyzing a graphite liner that is supported by stainless steel and cooled with liquid lithium. The graphite liner is being designed for an operational lifetime of one year. In the wet-wall approach we are investigating the possibility and effects of maintaining a thin (3-mm) film of liquid lithium on the inner surface of the manifold.

Tritium-breeding considerations limit the thickness of a structural wall of solid stainless steel to less than 10 cm. However, it would be impossible to utilize a structural wall even this thin without internal cooling. The solid manifold design was conceived to provide additional cooling and improve the tritium-breeding performance for a given mass of structural material. In fact, we have obtained tritium-breeding ratios greater than 1 for 40-cm-thick manifolds containing 50% stainless steel and 50% lithium by volume.[6,7]

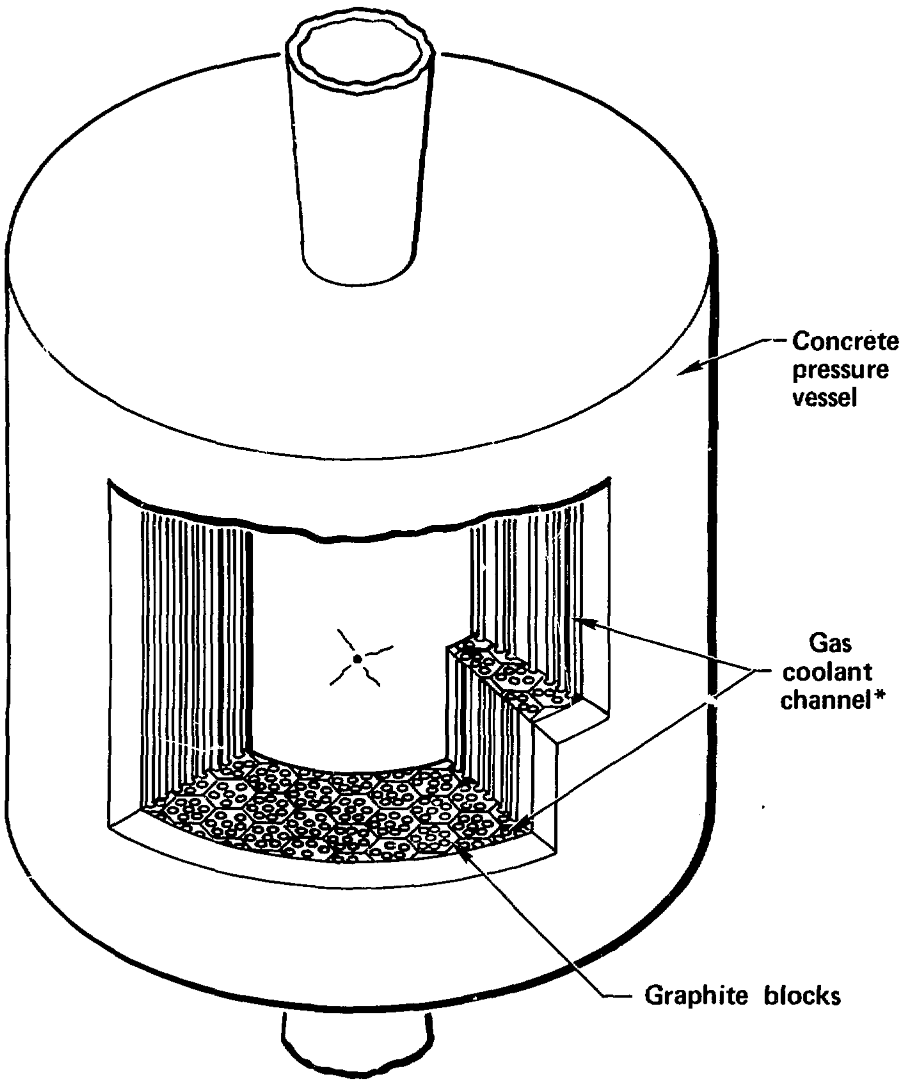
The stainless steel manifold will operate at a neutronic first-wall loading of about 1 to 2 MW/m^2, and this will require a relatively large chamber radius (10 to 15 m for a 4000 MW_{th} system). A major disadvantage will result if cyclical stresses and neutron damage limit the lifetime of the manifold to a few full-power years; this concept will then produce large amounts of radioactive waste in the form of activated steel. It should also be noted that lithium is a corrosive element whose corrosive effects increase with increasing temperature. For use with stainless steel, lithium temperatures must be limited to about 500°C. This peak temperature corresponds to a conventional steam cycle thermal efficiency of 38%.[8]

Gas-Cooled Graphite Manifold

The graphite manifold (Fig. 2) is similar to the stainless steel manifold concept except that the vertical coolant channels are drilled into an array of graphite blocks that make up the fusion chamber. The vacuum vessel is an outer shell of reinforced, prestressed concrete. High-pressure helium gas is pumped through the coolant channels, some or all of which are filled with pellets of a lithium-bearing ceramic. Tritium is removed from these channels by the gas coolant as it diffuses out of the lithium compound in which it is bred.

The graphite manifold design is a reactor concept that exhibits low activation and low tritium inventories. Moreover, the possibility of an accident occurring that could release radioactivity to the environment is greatly reduced because the lithium is present in a less reactive solid form (Li_2O, $LiAL_2O_3$). The graphite moderates the neutrons below activation energy levels. It also moderates the neutrons to energies below the threshold for the ^7Li tritium-producing reaction. This makes it advantageous to enrich the lithium in ^6Li, thereby reducing the required lithium and tritium inventories. Depending on

GAS COOLED GRAPHITE MANIFOLD CONCEPT



*Coolant channels filled with ceramic lithium

Fig. 2

the particular design, a neutron multiplier, such as beryllium, may be required to maintain a tritium-breeding ratio greater than 1. The use of a gas coolant will allow high operating temperatures and result in high thermal conversion efficiencies.

Some potential problem areas with this concept have been identified. The use of beryllium to multiply neutrons and enhance tritium-breeding presents a problem in terms of beryllium's toxicity a. relative scarcity. We are presently investigating the possibility of using lead as the neutron-multiplying material. Large amounts of pumping power will be required for cooling the system and purging the tritium from the pellet-filled channels. Finally, the structural integrity of the graphite chamber in the microexplosion environment may be inadequate.

Fluidized Wall Concepts

Wet walls and sacrificial dry-wall liners have previously been proposed as methods of protecting the metallic first-wall from the soft x-rays and pellet debris of fusion microexplosions. The fluidized wall concepts were conceived to provide protection to the first metallic wall from high-energy neutrons in addition to the x-rays and debris. We have investigated two types of fluidized walls; they are the ceramic-lithium pellet "waterfall," and the liquid lithium "waterfall." It has been demonstrated in the nuclear fission industry that once scientific feasibility has been achieved, the materials development program paces the demonstration of technical and economic feasibility.

Fluidized wall concepts will be less dependent on materials development because radiation damage is significantly reduced. The analysis of the liquid lithium system is further facilitated by the availability of data on the properties of liquid lithium and the existence of liquid-metal experimental facilities constructed in support of the LMFBR program.

The principal feature of the ceramic-lithium pellet waterfall (Fig. 3) is a thick layer of falling solid ceramic-lithium pellets that shields the first structural wall from the microexplosion. The pellets are continuously recirculated to the top of the vacuum chamber through a reservoir region between the first wall and the pressure vessel. The pellets are either transported through heat exchangers or cooled by the flow of high-pressure helium gas in the reservoir region. Tritium is bred in the ceramic lithium compound and recovered as it diffuses out. Preliminary calculations indicate a tritium breeding ratio greater than 1.0 can easily be achieved.

The thick region of falling pellets will moderate and absorb neutrons before they reach the first structural wall, resulting in a significant reduction in the degree of first-wall damage and possibly the amount of radioactive waste produced by neutron activation. The use of lithium in a ceramic form is an important feature of this concept in that it eliminates the corrosive problems of liquid lithium and significantly reduces the associated chemical hazard.

FALLING BALLS CONCEPT

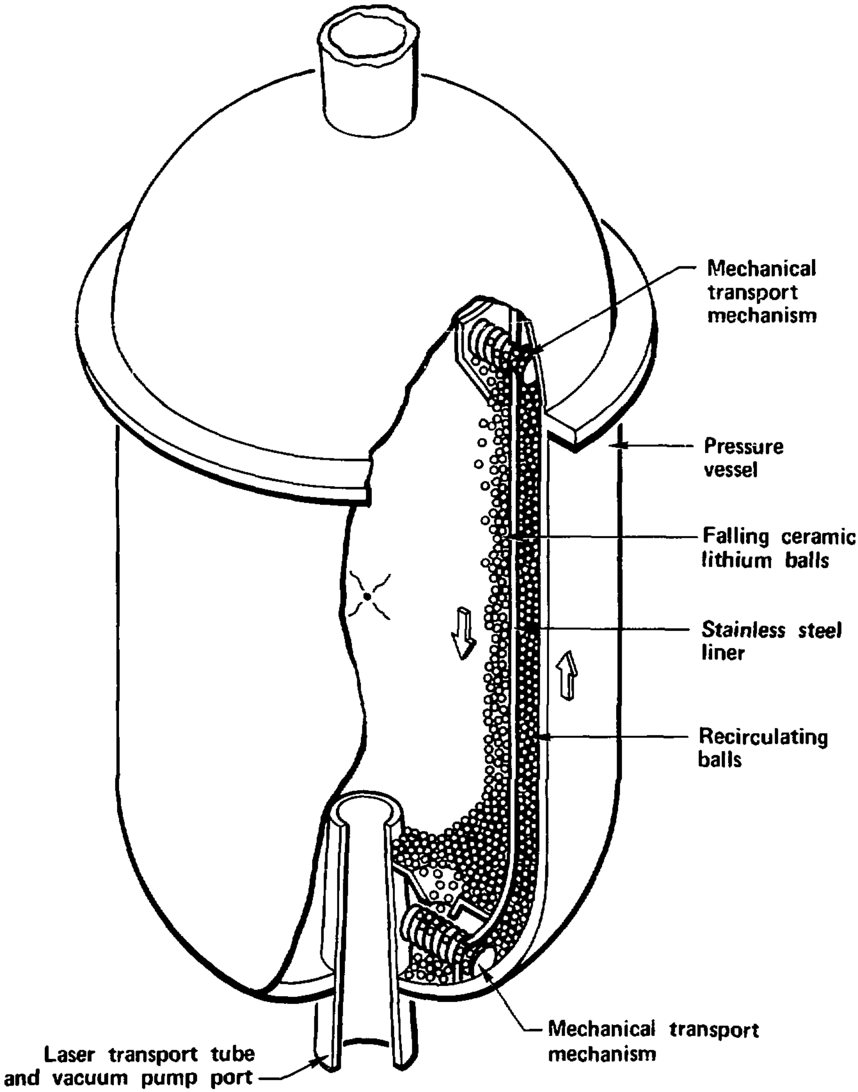


Fig. 3

Major questions, such as tritium diffusion from the pellets and structural integrity of the ceramic compound, cannot be answered satisfactorily with existing data. More information may be forthcoming from the University of Wisconsin study, which uses Li_2O as a blanket and heat-transport material.[9] A means of efficiently transporting the pellets, particularly into and out of the vacuum chamber, is another area of major uncertainty.

The liquid lithium "waterfall" concept (Fig. 4) has emerged as an extremely promising reactor concept for a laser-fusion power plant. It features a thick continuous fall of liquid lithium that protects the first structural wall, allowing it to last for the useful life of the plant. Besides moderating neutrons the fall also absorbs the photons (x-rays and reflected laser light) and pellet debris (alpha particles, unburnt fuel, and other pellet material). By keeping the fall off the chamber wall shock waves generated in the fall are not directly transmitted to the structural wall. The majority of the fusion energy is thus deposited in the liquid lithium, which serves as the primary coolant, fertile material for tritium breeding, and first wall.

It should be pointed out that fluids other than liquid lithium could certainly be used to perform the neutron moderating function of the fall. The primary constraints on the fall material are that the substance must:

1. Have a reasonably low melting point (less than about 200°C) so the fluid state can be effectively maintained.

LIQUID LITHIUM "WATERFALL" CONCEPT

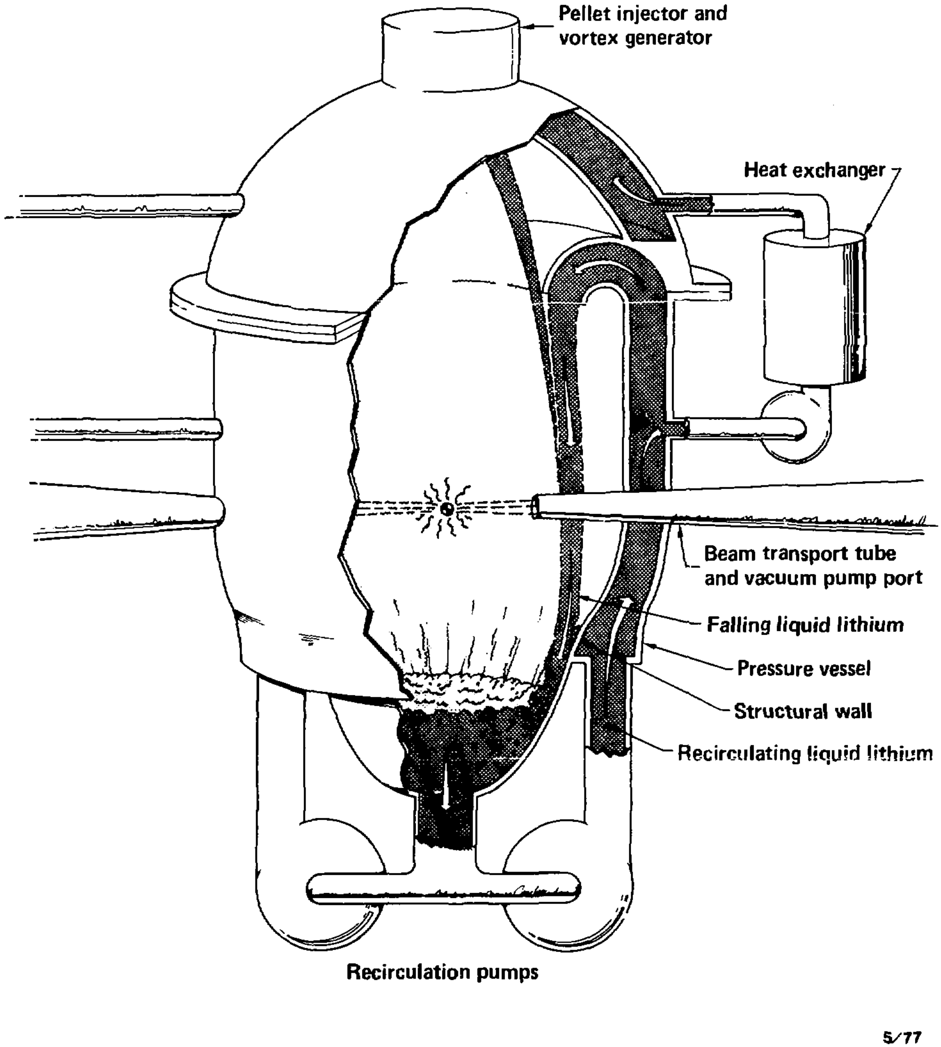


Fig. 4

2. Have a low enough vapor pressure at the selected operating temperature (>400°C but as high as possible) to permit an adequate vacuum condition to be maintained.

3. Have neutronic characteristics that permit an adequate tritium breeding ratio to be achieved.

Tritium breeding considerations preclude the use of a neutron absorber and require that lithium be incorporated in the reactor system in a suitable manner.

One possibility is to use lead, which effectively degrades the high-energy neutron spectrum through (n, 2n) and inelastic scatterings, as the primary constituent of the fall. Our TART calculations indicate that a few volume percent of ^{6}Li in the Pb fall would be enough to maintain a tritium breeding ratio greater than 1.[6] Alternatively, a small vol. % of lead could be added to the lithium fall more efficiently to moderate the neutron spectrum. The use of Pb-Li alloys would allow a lowe system tritium inventory to be maintained. On the negative side, recirculation pumping power would increase and grain boundary corrosion of steels may present compatibility problems. The various aspects of such a system are being investigated. For the present, however, the discussion will be confined to a natural liquid lithium fall.

Laser fusion reactors have a flexibility of geometry that is not available in magnetic confinement reactors. While a point source of energy is more effectively utilized in spherical geometry, we have selected a cylindrical geometry for several reasons. A vortex generator injects a sheet of lithium to protect the top of the reactor (primarily from x-rays and debris). This sheet is thinner than the waterfall and does not provide the same degree of protection from neutron damage. Therefore, it is advantageous to have the top of the chamber farther from the microexplosion than are the side walls. The spherical end cap on the cylindrical chamber effectively accomplishes this. The lithium is in direct contact with the walls at the bottom of the vacuum chamber; however, the vessel is structurally supported in this region. Shock waves can be directly transmitted to the chamber walls at this point. By moving the bottom region farther away and decreasing the surface area of the lithium pool at the bottom, the intensity of the directly transmitted shock wave is reduced.

Near horizontal irradiation of the target will be required to take advantage of long-focal-length final optics. The tip of the laser beam tubes must therefore penetrate the waterfall and be directly exposed to the microexplosion in a distance equal to about 1/2 the chamber wall radius. Fortunately, these high damage areas represent only a minute fraction of the total surface area (a few hundredths of a percent) and sophisticated measures and/or special materials could be used to protect them. Alternatively, sacrificial tube ends could be used and remotely fed inward as the tips slowly vaporize.

As previously stated, the fall will contain enough lithium to significantly degrade the spectrum of incident neutrons before they can reach the first structural wall. Neutron damage levels in structural materials are reduced by more than an order of magnitude, and structural members can thus survive for the life of the plant. Reducing neutron damage also allows the reactor cavity to be made smaller and less expensive than other inertial or magnetic confinement fusion reactors of the same power.

To facilitate comparison of our concept to others, we quote structural wall loadings MW/m^2 in terms of equivalent drywall 14 MeV neutron loading. That is

$$L = \frac{.8P}{4\pi R^2}$$

where

L = Wall loading, MW/m^2
P = Thermonuclear power, MW (80% in neutrons)
R = Chamber radius, m

Of course, our actual wall loading is considerably less due to neutron interactions in the compressed fusion target and the lithium fall.

The primary neutron damage mechanisms are atomic displacements and gas production (primarily helium). Displacement damage is expressed as displacements per atom (dpa) and gas production is expressed as atom-parts-per-million (appm). The damage limits for 316-SS at an operating temperature of 500°C are estimated to be 150 dpa and 500 appm helium.[10] For an unprotected first wall of 316-SS, the displacement damage rate is ∿10 dpa per full power year, and the helium production

ALLOWABLE FIRST WALL FLUENCE INCREASES EXPONENTIALLY WITH LITHIUM THICKNESS

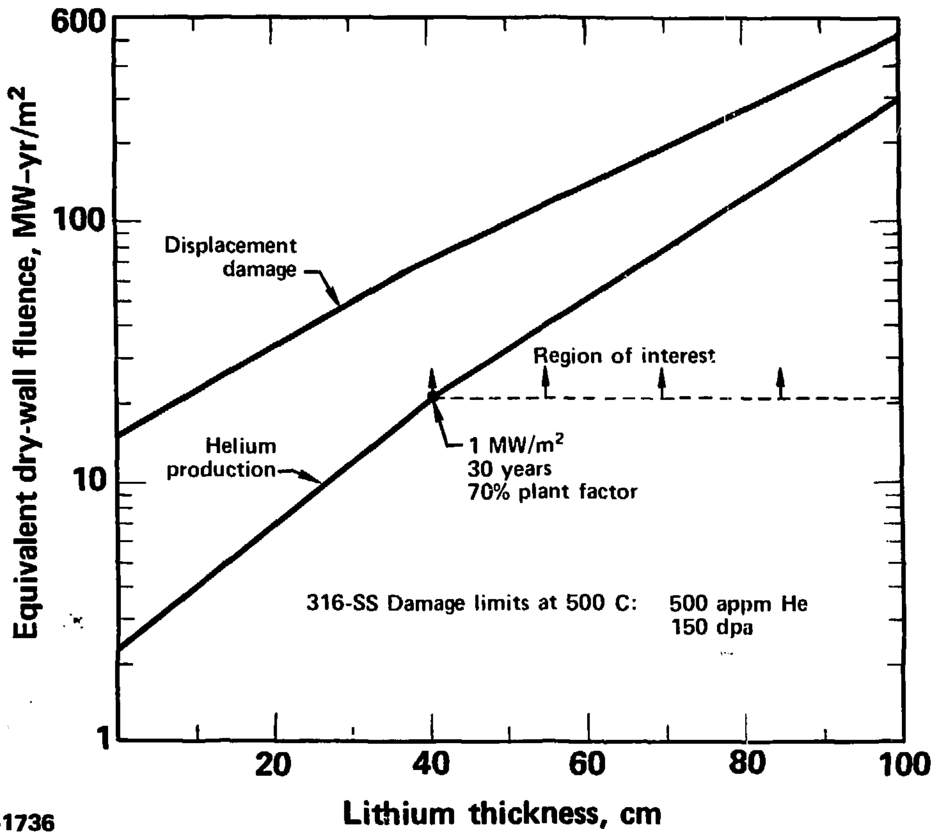


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Fig. 5

rate is $\sim$ 220 appm per full power year at a neutronic wall loading of 1 MW/m^2.[10] The damage limits for He production would thus be reached in only 2.3 years at this wall loading. As seen in Fig. 5 the allowable first-wall fluence increases exponentially with lithium thickness. Note that 40 cm of lithium is required to reduce helium production to the point where the first structural wall could last for 30 years at 1 MW/m^2 (at 70% capacity factor). Displacement damage is less restrictive.

We have evaluated the requirements of a system that maintains a minimum protective lithium thickness of 60 cm. In determining the neutron damage to the first structural wall, we have also taken advantage of the fact that the emitted 14 MeV neutrons are attenuated by compressed DT fuel; a characteristic unique to inertial confinement fusion. Our Monte-Carlo neutronics calculations indicate that a fusion target with a compressed density-radius product, ρR, of $\sim$ 3 gm/cm^2 is roughly equivalent to 13 cm of Li in terms of reducing helium production; hence, the compressed target increases the effective blanket thickness to 73 cm. Since helium production dominates, the allowable fluence is 90 $MW\text{-}Yr/m^2$. In other words, the system could be operated at 4.3 MW/m^2 for the 30 year plant life at a 70% capacity factor.

As a candidate reactor vessel for our reference power plant design we have selected a reactor system producing 1000 MW of thermonuclear power in a chamber with a cylindrical radius of 4 m. This corresponds to a neutron first-wall loading of $\sim$ 4.0 MW/m^2 and thus represents a design in which the blanket structure could last for the life of the plant.

In the process of attenuating neutrons and interacting with the microexplosion plasma the lithium fall absorbs a large fraction of the total nuclear energy deposited in the reactor. Fig. 6 presents the cumulative energy deposition through the lithium fall and blanket region as a function of the distance from the front surface of the fall.

Again a compressed target ρR of 3.0 gm/cm^2 has been assumed resulting in a neutron energy deposition of nearly 2.2 MeV per DT reaction in the target itself. This combined with the 3.5-MeV alpha energy per DT reaction accounts for 32% of the thermonuclear yield. This energy will be deposited essentially at the surface of the lithium fall in the form of x-rays, alpha particles, and other energetic debris.

The compressed target also has an advantage in terms of neutron energy multiplication. The high-energy fusion neutrons undergo (n, 2n) reactions with both D and T resulting in an increase of about 6% in the neutron population leaving the fusion target. The multiplied lower energy neutron spectrum results in a larger number of exoergic ^{6}Li(n,α)T reactions and a smaller number of endoergic ^{7}Li(n, n'α)T reactions than a 14 MeV neutron spectrum would. As a result, the fusion neutron energy leaving the compressed target which accounts for approximately 68% of the total yield, is multiplied by 1.24 in the lithium regions.

CUMULATIVE ENERGY DEPOSITION

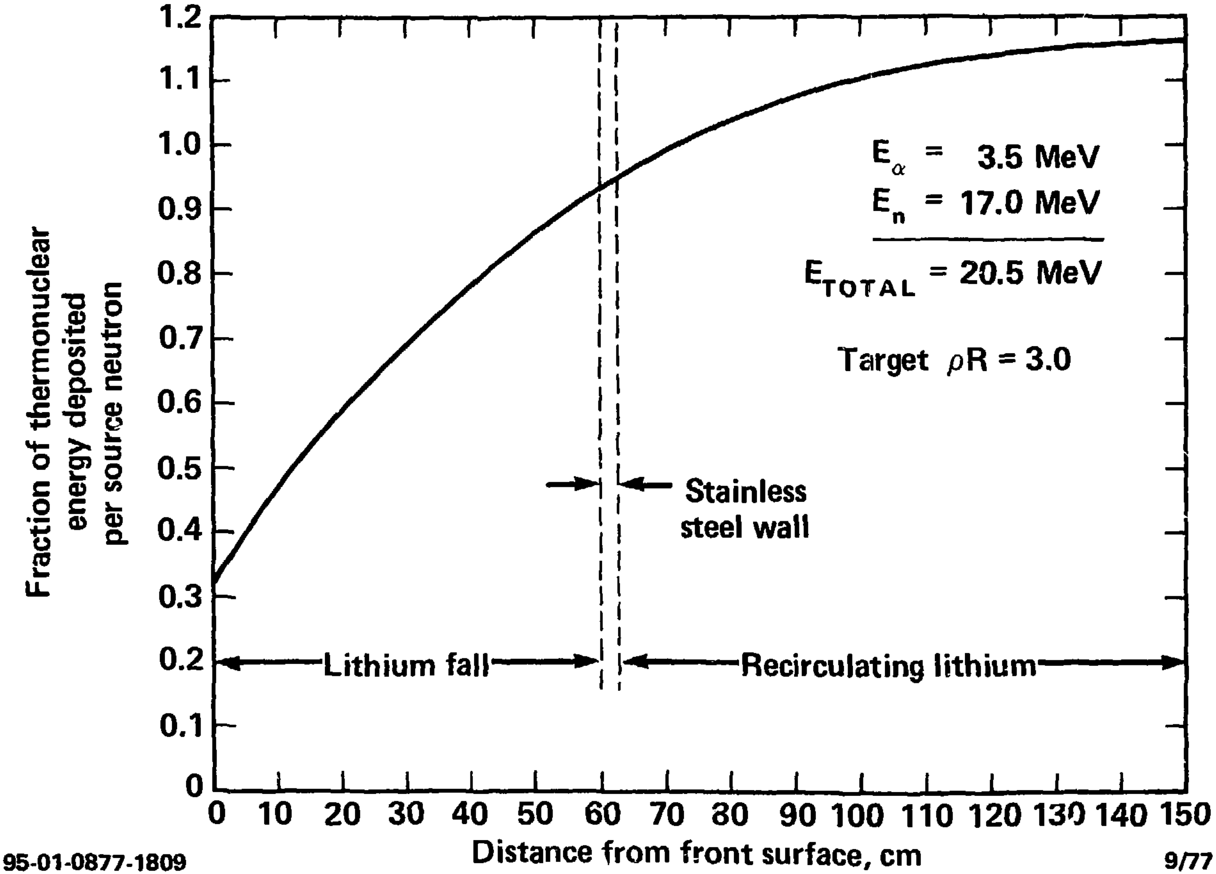

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Fig. 6

The total energy deposited in the reactor is 20.5 MeV per fusion reaction giving a system energy multiplication factor of 1.16. As indicated, the majority of this energy is deposited in the 50-cm-thick lithium fall. Because lithium is the primary coolant, the system does not have to rely on conduction of heat through structural materials to remove the thermal energy. Lithium is in fact an excellent coolant with a specific heat capacity equal to that of water and three times better than that of soium. In addition, its low density of 0.5 g/cm^3 is advantageous in terms of pumping power considerations. A major advantage of absorbing all the x-ray and debris energy and much of the neutron energy in the coolant is that the cyclical thermal stresses in the structural walls may be essentially eliminated.

An alternative scheme proposed by the University of Wisconsin[10] for the liquid lithium waterfall would be to make the fall thick enough (>80 cm) to absorb over 90% of the total energy. In this way the recirculating reservoir region would not be required for tritium breeding or energy removal and the structural first wall could be independently cooled at a lower temperature. A decrease in the wall temperature would significantly relax radiation damage limits for dpa and appm He.[10] The first wall could then be operated at a higher wall loading and thus increase the power density of the reactor system. Nautrally the higher the power density, the smaller the reactor vessel size will be for a given power system, thereby reducing the capital cost of the reactor.

As one might suspect, the liquid lithium waterfall concept has excellent tritium breeding characteristics. With no structural material between the fusion neutrons and the lithium fall, the design takes full advantage of the high-energy ^{7}Li (n, n'T) reaction. Fig. 7 shows the distribution of tritium breeding from ^{6}Li and ^{7}Li reactions in a 50-cm lithium fall and recirculating lithium blanket region. A one-dimensional spherical model was used in these Monte Carlo calculations.[6] A compressed target ρR of 3.0 gm/cm^2 was assumed. A tritium breeding ratio of 1.0 is obtained in the fall alone, and the total tritium breeding ratio is 1.7. The excess tritium produced in the reactor could in fact supply fuel for other laser fusion application where tritium breeding is difficult or impractical. Two examples of such applications are radiolytic hydrogen production where it is desirable to deposit the neutron energy in steam rather than lithium blankets, and propulsion applicaitons where weight and volume considerations are extremely important.

As previously stated, the vacuum condition required for laser beam propagation is on the order of 0.1 torr. Fig. 8 shows that the vapor pressure of lithium is orders of magnitude less than 0.1 torr at reasonably high temperatures. Corrosion considerations require that, for use with stainless steel, lithium temperatures must be limited to less than 500°C. The vapor pressure at this temperature is less than 5 x 10^{-3} torr.

TRITIUM BREEDING PERFORMANCE

Lithium fall

$T_6 = 0.44$

$T_7 = 0.56$

$T_{FALL} = 1.00$

Recirculating lithium region

$T_6 = 0.62$

$T_7 = 0.11$

$T_{RECIRC} = 0.73$

$T_{TOTAL} = 1.73$

- 50 cm natural lithium fall
- 100 cm natural lithium recirculating region
- Target $\rho R = 3.0\ gm/cm^2$

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Fig. 7

LITHIUM VAPOR PRESSURE VS TEMPERATURE

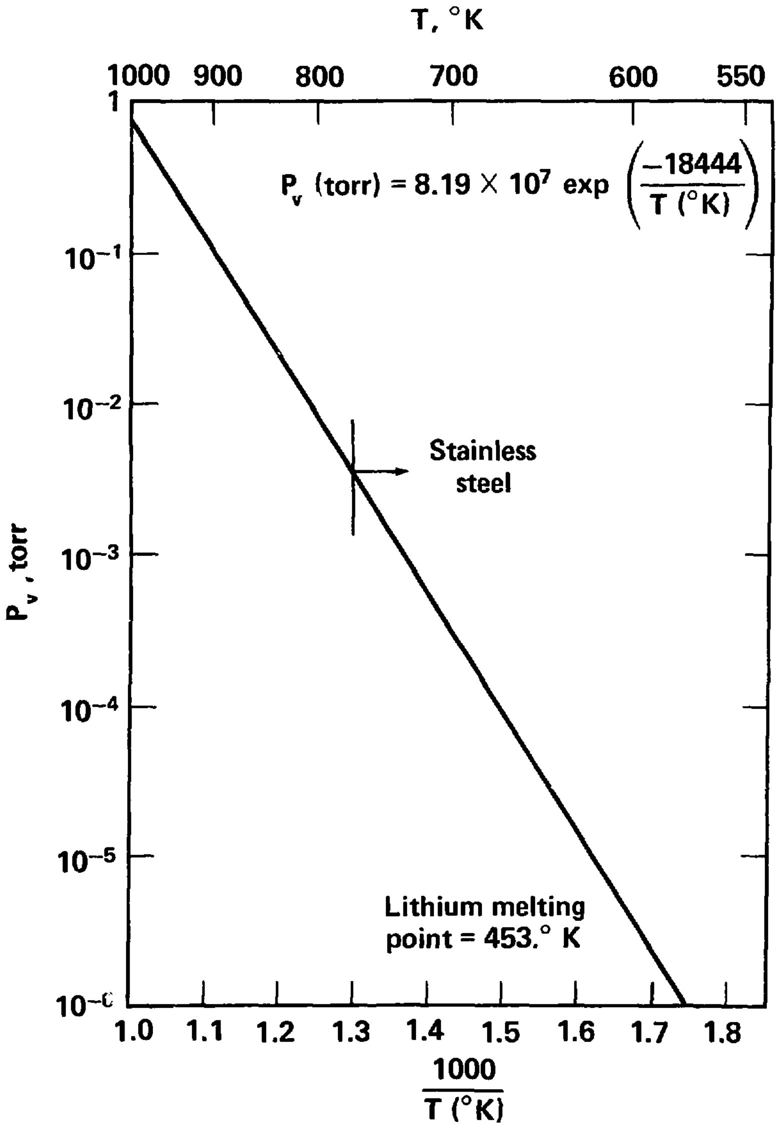

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Fig. 8

Each microexplosion will vaporize a certain amount of lithium thus increasing the chamber pressure above the required 0.1-torr vacuum condition. The amount of lithium vaporized and the resulting chamber pressure will depend on the initial system conditions and on the way the fusion energy couples with the liquid lithium. Various portions of the fusion energy could conceivably be used to heat liquid lithium, vaporize lithium, and heat lithium vapor. If the chamber pressure equals the liquid vapor pressure prior to the microexplosion, even deposited neutron energy could vaporize lithium. The debris and x-ray energy, which is deposited over a very short range at the fluid surface, is expected to blow off lithium vapor.

After the initial transient events, a certain amount of lithium vapor will exist in the chamber. The resulting quasi-equilibrium pressure will most certainly be higher than the required vacuum condition of 0.1 torr and must therefore be reduced prior to the next microexplosion. There is so much liquid lithium in the chamber at the time of the microexplosion that the mixed-mean temperature rise of the fall per pulse is quite small. The vapor will therefore be in a supersaturated condition and proceed to recondense on the liquid lithium in the chamber. In effect, the liquid lithium waterfall acts as a condensing vacuum pump for the chamber.

The effectiveness of the lithium liquid in condensing the vaporized lithium will depend on the condition of the fall (bulk temperature, surface temperature, total surface area of the fluid) and on the condition of the vapor (temperature, pressure) shortly after the microexplosion. The liquid fall conditions are important for determining the vapor pressure of the liquid and the sticking coefficient, defined as the probablity that a gas molecule incident on the liquid surface will stick. If the sticking coefficient is greater than ∿ .5 (which is almost certainly the case for a liquid metal) the vaporized lithium will be driven by a pressure gradient to the condensing liquid surface at the local sonic velocity.[11] Assuming adiabatic, frictionless flow of an ideal monatomic gas, the pressure decays according to[12,3]

$$\frac{P}{P_0} = \left[\left(\frac{8.33\ AS\sqrt{T}}{V}\right)t + 1\right]^{-5}$$

where

A = condensing surface area, m^2

S = sticking coefficient

T = vapor temperature, °K

V = vacuum chamber volume, m^3

t = time, sec

P_0 is the quasi-equilibrium pressure immediately after the micro-explosion but before recondensation begins.

Figure 9 shows the pressure decay as vaporized lithium is recondensed by the fall. This curve represents a worst-case calculation in which all the fusion energy, 700 MJ, is used to vaporize lithium at 700°K in a 4 m chamber. While an increase in vapor temperature would result in a higher value of P_0, the sonic velocity of the gas would also be higher and the gas would condense more quickly. The sticking coefficient of 0.5 is pessimistically low for a liquid metal vapor. Also, if the fall is disassembled by the neutron energy deposition, the condensing surface area will be much larger than the original surface area of the fall assumed here.

Even with these assumptions, the vacuum conditions return to the required 0.1 torr in $\sim$ 0.1 sec for a 4-m chamber. Flow considerations will limit operation to a pulse repetition rate of a few times per second. Thus while the exact time-dependent chamber conditions have not been determined, this analysis indicates that vacuum conditions can be maintained and are in fact aided by the presence of the liquid lithium fall.

We now turn our attention to what is required in terms of pumping power and flow rates to maintain the thick fluidized wall of lithium.

Figure 10 shows the model and constraints used to calculate the pumping power required to recirculate the lithium fall. The fall

PRESSURE DECAY AS VAPORIZED LITHIUM IS RECONDENSED BY THE FALL

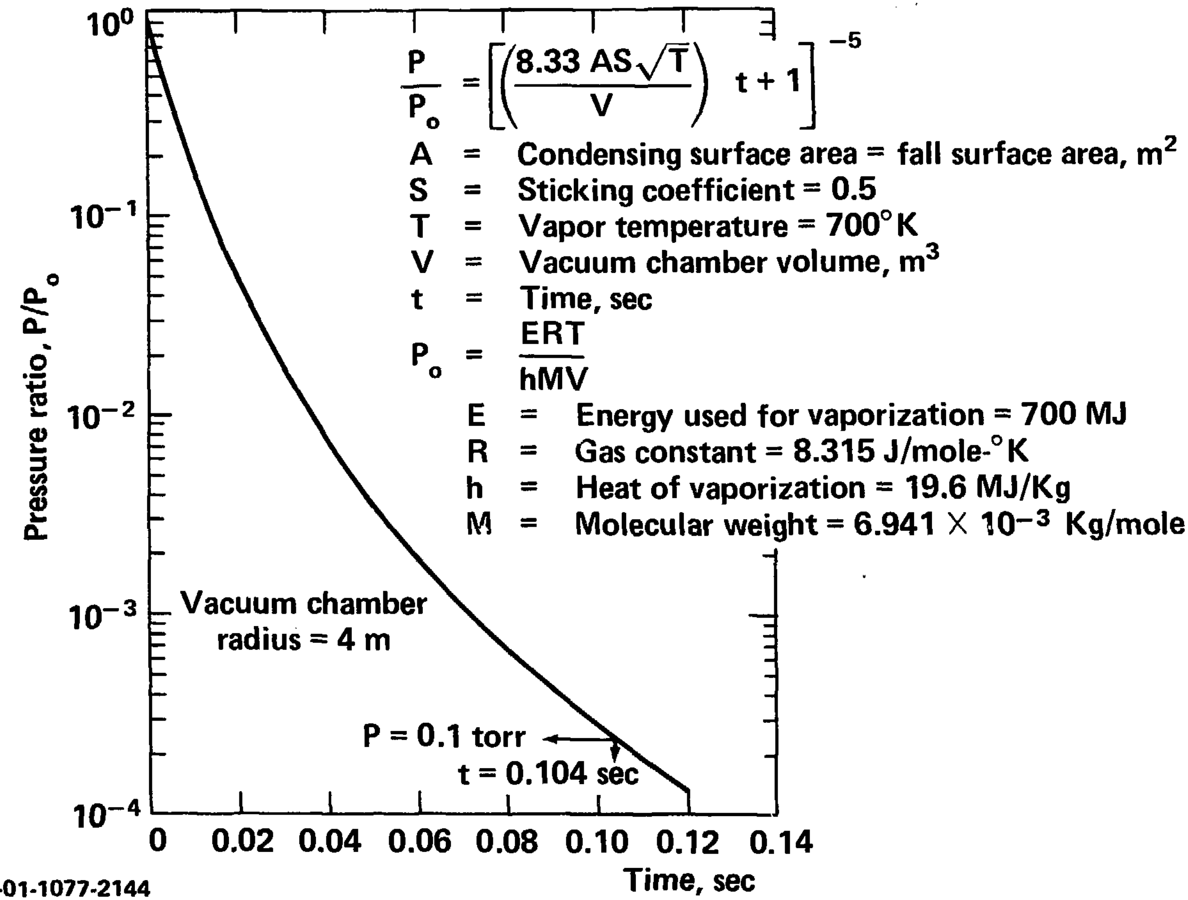

Fig. 9

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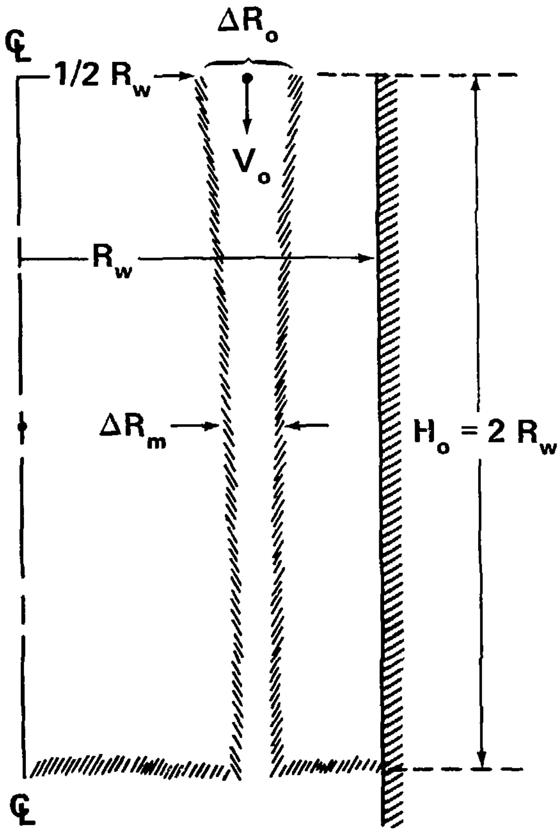
RECIRCULATION PUMPING POWER CALCULATION – SINGLE FALL



Pumping power $\simeq (1/2\, V_o^2 + g\, H_o)\, \rho\, V_o A_o$

Constraints:

1. Fall clearing ratio of at least unity

   $H_o \leqslant V_o \tau + 1/2\, g\, \tau^2$

   where $1/\tau$ = repetition rate

2. Fall thickness at midplane of at least 60 cm

   $\Delta R_m \geqslant 60$ cm

3. Inlet thickness less than ½ R_W

   $\Delta R_0 < ½\, R_W$

Fig. 10

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protects the cylindrical portion of the chamber wall, which has a height-to-diameter ratio of 1. The flow inlet forms an annulus of thickness ΔR_0 with the inner edge of the ring at one-half the chamber wall radius, R_w. The fall is injected vertically downward with an inlet velocity V_0. The pumping power is then estimated on the basis of the kinetic and static head requirements.

$$P.P. = (1/2\ V_0^2 + gH_0)\ \rho\ V_0\ A_0$$

where:

$$H_0 = \text{fall height} = 2R_w$$

$$A_0 = \text{inlet flow area} = \pi\left[(1/2\ R_w + \Delta R_0)^2 - (1/2\ R_w)^2\right].$$

Preliminary calculations indicate that the fall will be disassembled by the microexplosion. If this is the case, the inlet velocity must be sufficient to allow the fall to reestablish itself prior to the next microexplosion. A clearing ratio of unity should be adequate. The first constraint is therefore:

$$H_0 = 2R_w \leq V_0\tau + 1/2\ g\tau^2,$$

$$1/\tau = \text{pulse repetition rate.}$$

As previously noted, 60 cm of lithium is thick enough to provide adequate protection to the first structural wall up to 4.3 MW/m^2. The second constraint is therefore that source neutrons must be attenuated by at least 60 cm of lithium at any point through the fall. Flow continuity requires that the thickness of the fall decrease as the fluid is accelerated by gravity. The minimum path length for neutrons actually occurs slightly below the horizontal midplane, but it is a very shallow minimum. The constraint on minimum effective thickness has, therefore, been taken at the midplane to simplify the calculations. The second constraint is:

$$\Delta R_m \geq 60 \text{ cm}.$$

The third constraint is that the inlet thickness must be less than one-half the chamber wall radius. This is a constraint of our selected geometry.

$$\Delta R_0 \leq 1/2\ R_W$$

For small chambers the clearing ratio constraint is less important than the midplane thickness and total inlet thickness constraints. For example, a 3-m radius chamber requires an inlet velocity of only $\sim$ 1 m/sec. At this velocity, however, the midplane thickness is only 13% of the inlet thickness which would thus have to be over 4.6 m thick to provide 60 cm of protection at the midplane. Because this is larger than 1/2 the chamber radius, a higher inlet velocity must be used in calculating the pumping power.

For equivalent first-wall loadings the gross power produced by reactors of varying size will be porportional to R_W^2. The fraction of the gross power required to recirculate the fall for the various sized reactors is plotted in Fig. 11. A gross power of 440 MW for a 5-m radius chamber has been used as the basis (1160 MW_{th} at 38% thermal conversion efficiency. As indicated, at 1 Hz the pumping power is only a few percent of the gross electric power. At the higher repetition rate the inlet velocity required to cover the length of the chamber in the 1/2 second between microexplosions is quite large. In this case the fraction of the gross power used becomes substantial and, in fact, prohibitive for large chambers.

The use of liquid lead with a low concentration of lithium results in an increase in the pumping power due to the $\sim$ 20-fold increase in density. Lower thickness requirements with the Pb-Li alloy somewhat reduce this disadvantage. Depending on the specific case, pumping powers for a Pb-Li mixture are thus a factor of 5-10 greater than for lithium alone.

The possible advantages of using multiple falls entering the chamber at different vertical positions have also been investigated. The primary advantage would be a reduction in the velocity head required to obtain a clearing ratio of 1. Each fall would be required to re-establish only to the inlet of the next lower fall. This is especially important at higher repetition rates. A second advantage is that the static head requirement is reduced for the fraction of the flow delivered to the lower falls. Also, if the injected fall should tend to break up into separate streams instead of forming a continuous curtain, additional lower falls could replenish the primary fall.

A similar calculation model was used for a system with two falls, one inletting at the top as before and one at the midplane. The constraints on the fall are the same as for the single-fall case, with

FRACTION OF GROSS POWER REQUIRED TO RECIRCULATE LIQUID LITHIUM FALL

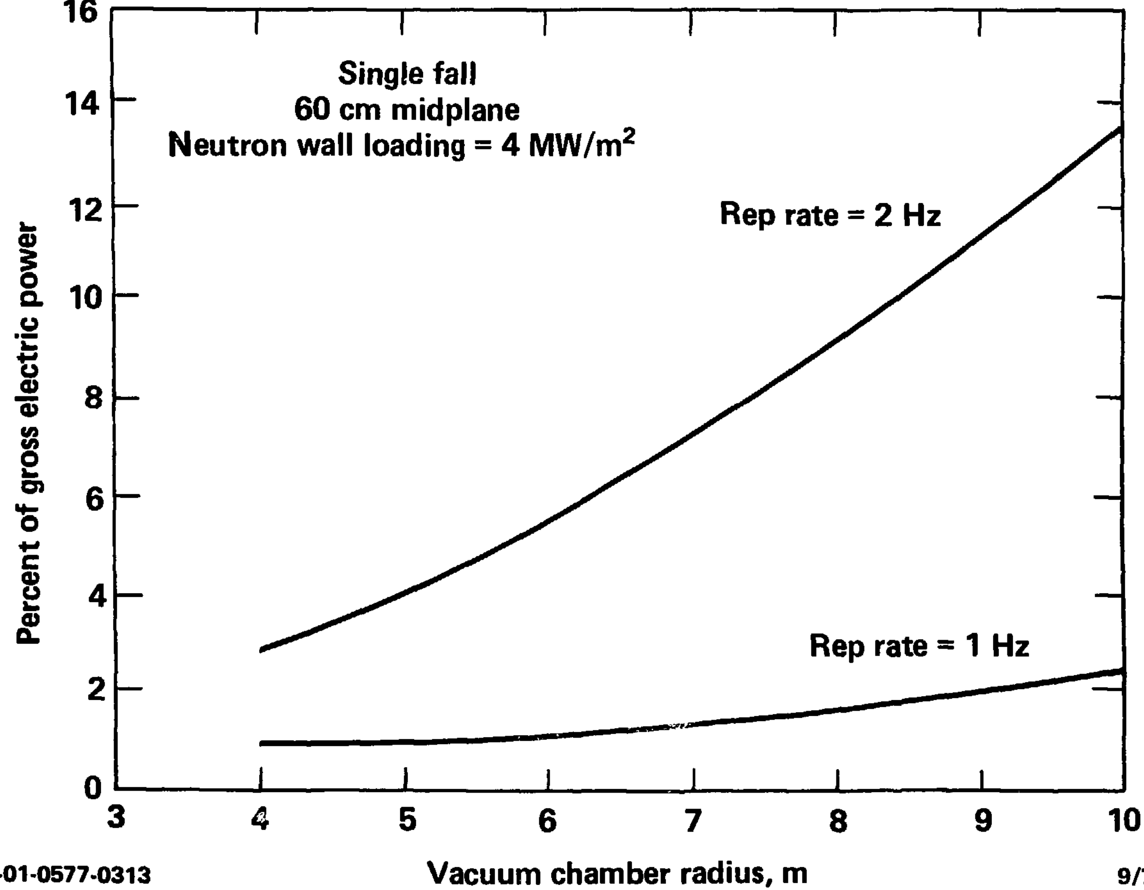

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Fig. 11

the actual positions of minimum effective thickness used to determine the required inlet thicknesses. As before, the inlet thickness (now equal to the sum of ΔR_{10} and ΔR_{20}) must be less than 1/2 R_w.

The fraction of the gross power required to recirculate the double fall is shown in Fig. 12. Note particularly the substantial reduction in pumping power for the larger chambers at 2 Hz (5% compared to 14% for the 10-m chamber). The advantages of reduced velocity and static heads have been offset by larger flow area requirements for the smaller chambers at a repetition rate of 1 Hz.

It should be pointed out that the double-fall geometry is not by any means optimal. It is presented only to illustrate the possible advantages of multiple falls. Also note that a theoretical pumping power has been calculated that does not include the efficiency of the pump or drive motor. These factors will depend on the specific design, but for large axial flow pumps the combined efficiency could be ∿ 80%.[13]

This precursory evaluation of the liquid lithium waterfall concept has been encouraging. The protection afforded by the thick fluidized curtain of lithium will allow first-wall and blanket structures to retain their integrity for the life of the plant. In addition, constraints on vacuum conditions, tritium breeding, and energy removal are easily met. Analysis of the liquid lithium waterfall concept is continuing; some aspects currently being investigated include:

1. The trade-offs between higher first-wall loadings and increased fall thickness requirements.

FRACTION OF GROSS POWER REQUIRED TO RECIRCULATE LIQUID LITHIUM FALL

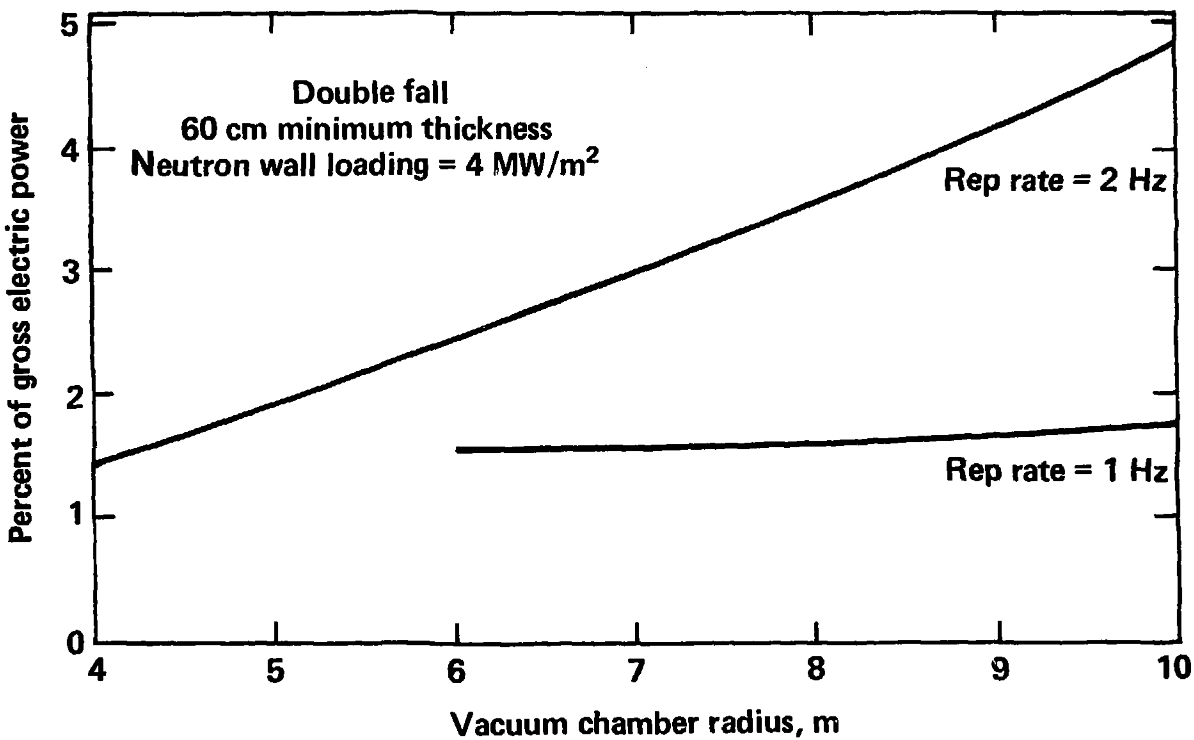

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Fig. 12

2. The formation and stability of the fall and pumping requirements for various flow configurations.
3. The compatibility of various structural materials with lithium and Pb-Li alloys.
4. Methods of recovering tritium from the fluid stream.
5. Neutron activation of structural materials.

A complete conceptual design study of a laser fusion power plant based on this reactor concept and coupled with one of the lasers discussed has been initiated. In addition to a more detailed analysis of the reactor chamber, a balance of plant layout and economic analysis of the system will be incorporated.

References

1. J. Hovingh, "First Wall Studies of a Laser-Fusion Hybrid Reactor Design," Proc. 2nd Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, Washington, 1976, Vol II, p. 765.

2. J. Hovingh, J. A. Maniscalco, M. Peterson, R. W. Werner, "The Preliminary Design of a Suppressed Ablation Laser Induced Fusion Reactor," Proc. 1st Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, California, 1974, Vol. I, p. 96.

3. L. A. Booth (compiler), "Central Station Power Generation by Laser-Driven Fusion," Los Alamos Scientific Laboratory, Report LA-4858-MS, February, 1972, Vol. I.

4. D. A. Freiwald, T. G. Frank, E. A. Kern, L. A. Booth, "Laser-Fusion Generating Stations Based on the Magnetically Protected Reactor Cavity," Los Alamos Scientific Laboratory, Report LA-UR-75-2035, 1975.

5. M. Sparks, Xonics Corporation, Santa Monica, California, personal communication, 1977.

6. E. F. Plechaty, J. R. Kimlinger, "TART Monte Carlo Neutron Transport Code," Lawrence Livermore Laboratory, Report UCID-17026, 1976.

7. R. J. Howerton et al., Integrated System for Production of Neutronics and Photonics Calculational Constants, Vol. 15, "The LLL Evaluated Nuclear Data Library (ENDL)," Lawrence Livermore Laboratory, Report UCRL-50400, September, 1975.

8. A. P. Fraas, "Comparative Study of the More Promising Combinations of Blanket Materials, Power Conversion Systems, and Tritium Recovery and Containment Systems for Fusion Reactors," Oak Ridge National Laboratory, Report ORNL-TM-4999, November, 1975.

9. R. W. Conn et al., "Studies of the Technological Problems of Laser Driven Fusion Reactors, Annual Report - I," University of Wisconsin, Report UWFDM-190, December, 1976.

10. H. I. Avii, G. L. Kulcinski, "The Effects of a Liquid ISSEC on Radiation Damage Parameters in Laser Fusion Reactor First Walls," University of Wisconsin, Report UWFDM-205, April, 1977.

11. G. Davey, "Cryopumping in Transition and Continuum Pressure Regions," Vacuum, Vol. 26, p. 17, January, 1976.

12. V. L. Streeter, Fluid Mechanics, McGraw-Hill, Inc., 1966, p. 301.

13. B. Atz, Liquid Metal Engineering Center, Canoga Park, California, personal communication, April, 1977.