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FUSION TECHNOLOGY INSTITUTE

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KrF LASER DRIVEN IFE POWER REACTOR

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Abstract

SOMBRERO is a conceptual design study of a 1000 MWe KrF laser driven IFE power reactor utilizing direct drive targets with near symmetric illumination. The chamber is constructed of a low activation carbon/carbon composite and the blanket consists of a moving bed of solid Li_2O particles flowing through the chamber by gravity. The particles are transported through the intermediate heat exchanger and around the loop in a fluidized state by He gas at 0.2 MPa. There are 60 laser beams in near symmetric distribution, the laser energy is 3.4 MJ, the target gain is 118 and the rep-rate is 6.7 Hz. The chamber has a cylindrical central region with conical ends, has a minimum radius of 6.5 m and a blanket/reflector thickness of 1 m at the midplane giving a tritium breeding ratio of 1.25 and an overall energy multiplication of 1.08. The first wall is protected from x-rays and ions by 0.5 torr of Xe gas. A grazing incidence metallic mirror is located at 30 m from the target and the final focusing dielectric coated mirror which is shielded from direct neutrons is located at 50 m. Source neutrons are directed into neutron traps making it possible for the final focusing mirrors to be lifetime components. The inlet temperature of the Li_2O particles is 550°C, the equilibrated outlet temperature 740°C and the power cycle efficiency is 47%. Using a laser efficiency of 7%, the driver power is 325 MWe. The gross power output is 1360 MWe, giving a net power output of 1000 MWe, with 360 MWe used for the driver and auxiliary equipment.

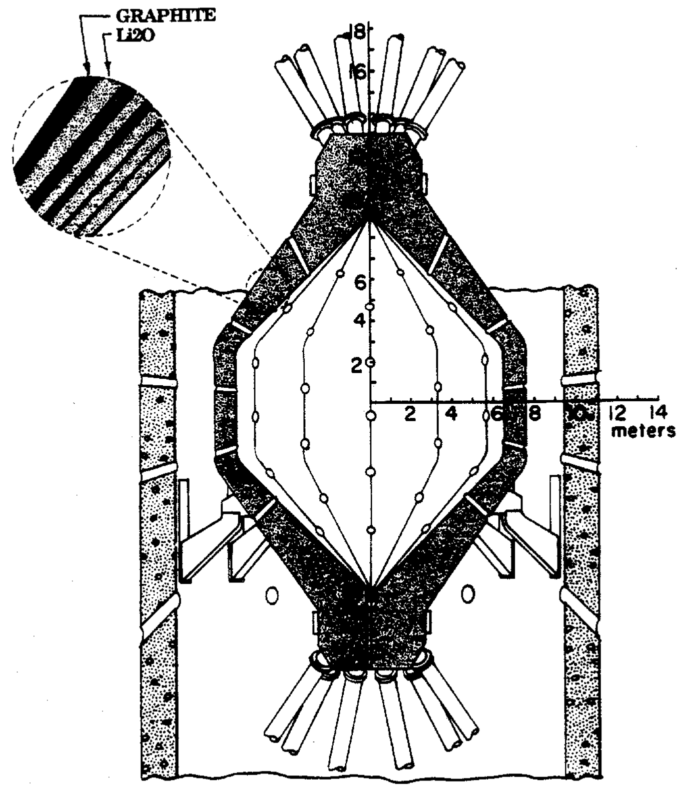

Fig. 1. Cross section of SOMBRERO chamber.

Introduction

Solid breeding materials have always been considered front runners for use in fusion reactors with research and development programs in place investigating them in the U.S., Japan and Europe. They offer the potential for high temperature capability, low activation, safety, no corrosion issues and a good data base. Many of the recent tokamak studies both near term [1] and long term [2] have proposed static solid breeder blankets. Static solid breeder blankets, however, have some problems. Typically they have to be cooled with a high pressure He gas at 5-8 MPa and require a separate loop of low pressure He gas for T_2 extraction. Temperature control in these blankets is difficult, because it depends on the effective thermal conductivity of the packed bed which can change with time and with radiation fluence in unpredictable ways. The operating temperature windows for solid breeders is relatively narrow. This tends to exacerbate temperature control. Further, static beds suffer from problems of Li burn-up, phase changes, swelling and hot spots. A moving bed of solid breeder particles retains all the advantages of static beds while eliminating the problems. This scheme has been proposed for tokamaks [3] but has not been taken seriously because of the geometric limitation due to the encumbering magnet systems. A moving bed of solid Li_2O particles was used in the SOLASE [4] CO_2 laser driven conceptual reactor design (1977) at a time when relevant properties of Li_2O were not well characterized. The issues that have to be dealt with in moving beds are the large inventory of solid breeder material, the large volumetric transport around the loop, and relatively poor heat transfer at the first wall, which also results in a large intermediate heat exchanger.

In this paper we describe the chamber design, neutronics, thermal hydraulics, preliminary tritium analysis and some considerations of reactor building design. First wall protection and laser issues are covered in companion papers in these proceedings [5,6].

Chamber Description

SOMBRERO is a conceptual design study of a 1000 MWe KrF laser driven IFE power reactor. The laser energy is 3.4 MJ, the gain is 118 and the rep-rate is 6.7 Hz. Figure 1 is a cross section of the SOMBRERO chamber. It consists of 12 wedge shaped modules which when assembled together form the chamber. These modules are totally independent of each other with separate supply and return tubes. The chamber has a cylindrical central region and conical ends, has a radius of 6.5 m at the midplane and an overall vertical height of 18 m. It is constructed of a carbon/carbon composite with the internal passages sealed with a thin coating of SiC. Each module is subdivided both radially and circumferentially, with the carbon fraction increasing from the front at 3% to the rear at 50%. In this way, a carbon reflector is built into the chamber and does not require separate cooling. The 60 beam ports are built into the sides of the modules. When assembled, the beam ports lie on 10 horizontal planes as shown in Fig. 1 with 6 beam ports in each plane forming a cone with the vertex at the chamber center. The blanket thickness at the midplane is 1 m, and gets thicker towards the chamber extremities. The first wall thickness is 1 cm and at the midplane the first wall cooling channel is 7 cm deep, increasing to 37 cm at the extremities. This is done to maintain a constant velocity of particles at the first wall where a high heat transfer coefficient is needed.

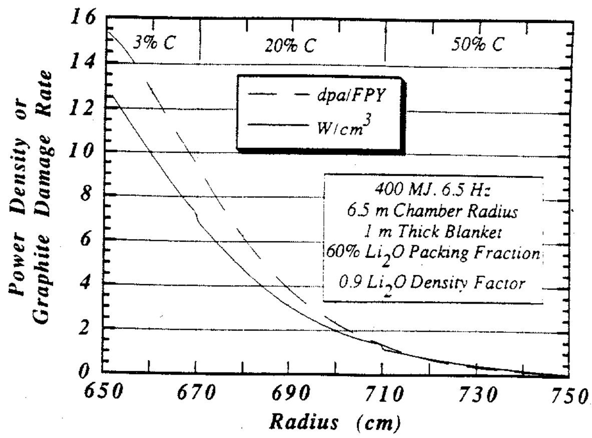

Fig. 2. Power density and dpa rate variation in the blanket location.

The Li_2O particles are from 300-500 μm in diameter, have a void fraction of 40% in the moving bed, and the grains are 90% of theoretical density. They are admitted at the top of the chamber, flow by gravity through the blanket and exit at the bottom. Their velocity at the first wall is 1.15 m/s, but is progressively lower in succeeding channels toward the back of the blanket. Flow control baffles are located at the exit from each channel to insure that no voids will exist in the blanket at any time. The inlet temperature to all the channels is 550°C, but the outlet temperature at the FW is 700°C, while in the rear zones it is 800°C. The equilibrated outlet temperature is 740°C and the mass flow rate is 2×10^7 kg/hr. Although the Li_2O particles flow by gravity through the chamber, they are transported around the loop and through the intermediate heat exchangers (IHX) in a fluidized or entrained state by He gas at 0.2 MPa. This He pressure will also exist in the chamber which will have a trickle of He gas flowing counter-current to the particles. A thin coating of SiC is used on the inner surface of the channels to prevent leakage of He into the reactor chamber which will have Xe gas at $\sim$ 0.5 torr. The Xe gas is needed to stop the x-rays and ions from depositing their energy instantaneously on the first wall. Instead, this energy is reradiated to the first wall over a longer period resulting in no evaporation of first wall material [5].

Neutronics Analysis

The neutronics analysis for the SOMBRERO reactor is aimed at optimizing the blanket to achieve adequate tritium breeding while maximizing the overall reactor energy multiplication. Spherical geometry calculations have been performed using the ONEDANT code with neutron cross section data based on the ENDF/B-V evaluation. A point source is used at the center of the chamber emitting neutrons and gamma photons with energy spectra determined from target neutronics calculations for a generic single shell target.

The neutronics performance of the blanket has been investigated as a function of several blanket design variables. Enriching the lithium in ^{6}Li results in a significant reduction in the tritium breeding ratio (TBR) and only a small ($< 3\%$) increase in the overall energy multiplication (M_o) defined as the ratio of total thermal power to fusion power. Hence, natural lithium is used in the Li_2O. To reduce the excessive neutron leakage at the back of the blanket, the option of using a 0.5 m thick graphite reflector was considered. This results in increasing TBR by 8.6% and M_o by 4.5% and decreasing neutron leakage from 0.124 to 0.017 neutrons per DT fusion for a 0.7 m thick blanket with 5% graphite structure. Similar neutronics performance was obtained with a thinner and simpler blanket by integrating the graphite reflector into the blanket. A 1 m thick blanket with the graphite content increasing toward the back was chosen for the reference SOMBRERO blanket design. The graphite structure content varies from 3% at the front to 50% at the back as shown in Fig. 1.

The 1-D local TBR for the reference blanket is 1.25. The overall

Table I. Relevant SOMBRERO Reactor Parameters

Laser energy (MJ)	3.4
Target gain	118
Reactor rep-rate (Hz)	6.7
Fusion power (MW)	2688
Reactor energy multiplication	1.08
Tritium breeding ratio	1.25
Blanket thickness at midplane (m)	1.0
Thermal power (MW)	2903
Power cycle efficiency (%)	47
Gross electric power (MWe)	1364
Laser efficiency (%)	7
Laser power (MWe)	325
Net electric power (MWe)	1000

TBR value is expected to be close to the 1-D value since the solid angle fraction subtended by the 60 beam penetrations is less than 0.3%. The overall reactor energy multiplication is 1.08. For a DT fusion power of 2688 MW, the total thermal power is 2903 MW with 803 MW deposited at the surface of the first wall by x-rays and debris and 2100 MW deposited volumetrically in the blanket by neutrons and gamma photons. Figure 2 shows the radial variation of power density and graphite damage rate in the blanket. The peak first wall power density is 10.9 W/cm^3 and the peak blanket power density is 12.6 W/cm^3. The peak dpa and helium production rates in graphite are 15.3 dpa/FPY and 3770 He appm/FPY. The first wall is expected to last for about 5 FPY.

The concrete reactor building thickness required to achieve an operational dose rate of 2.5 mrem/hr depends on the location of shield and material between target and shield. Several 1-D calculations have been performed to determine the required shield thickness. It was found that 25 cm of the steel reinforced concrete shield will reduce the dose rate by an order of magnitude. The shield required behind the unshielded final focusing mirror is 3.2 m. For a reactor wall located 9.5 m from the target behind the blanket, the required shield thickness is 2.7 m. The results of this neutronics analysis were used to evaluate several reactor building layout options.

The lifetime of the final focusing mirrors depends on the neutron fluence limit for the dielectrically coated or metallic mirror, the distance from the target, damage recovery with annealing and the solid fraction subtended by the beam ports. For a metallic mirror exposed to primary neutrons at 30 m from the target and a fast neutron fluence limit of 10^{20} n/cm^2, the lifetime is 3 FPY with 80% recovery by annealing. If the limit is 10^{21} n/cm^2, the grazing incidence (GI) mirrors would be lifetime components. The currently allowed fluence to dielectrically coated mirrors is 10^{18} n/cm^2. In our design, the source neutrons are directed into high aspect ratio neutron traps. Secondary neutrons scattered from the GI mirrors and those exiting from the neutron traps will provide a fluence of $\sim 10^{18}$ n/cm^2 in 30 FPY making the FF mirrors lifetime components. Table I gives the relevant reactor parameters.

Thermal Hydraulics

In moving beds, the solid particles are in contact with each other as opposed to fluidized beds, where they are separated by a film of gas. Heat transfer is dominated by the effective thermal conductivity of the solid and interstitial gas instead of the conductivity of the fluidizing gas alone. To determine heat transfer coefficients it is necessary to know the effective viscosity of the moving bed. In this study we have relied on moving bed experiments performed at the University of Wisconsin [6], in which Nusselt numbers were obtained as a function of velocity in electrically heated tubes, for several ranges of solid particles from 100 μm $-$ 600 μm made of soda-lime glass. Effective viscosities were obtained for different range of sizes from these Nusselt numbers and the other known and measured parameters using the Dittus Boelter formulation. These viscosities were plotted against velocity and an analytic expression obtained. With

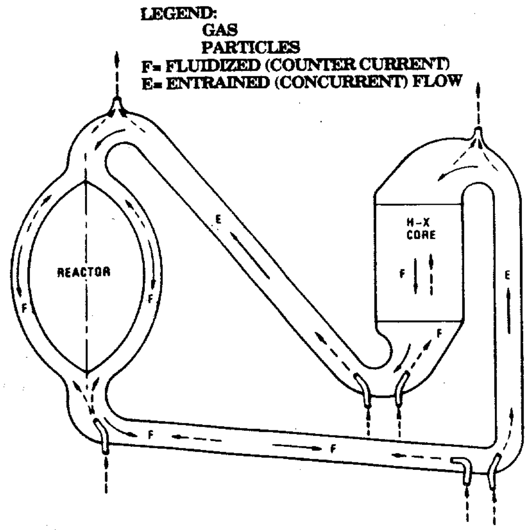

Fig. 3. Particle transport around the loop.

the effective viscosities in hand, as well as effective thermal conductivities which depend on the materials and void fractions, and the specific heat of Li_2O, we then use the Dittus Boelter formulation to obtain the heat transfer coefficients. Since Li_2O is harder than soda lime glass, it is expected that the actual effective viscosities will be lower yet, making our heat transfer coefficients estimates conservative. A heat transfer coefficient of 2758 W/m^2K is obtained at the first wall on the midplane where the velocity is 1.15 m/s and the channel depth is 7 cm. The maximum steady state temperature at the outside surface of the first wall occurs at the midplane and is 1485°C, where on the inside surface it is 1220°C. At the extremities the heat transfer coefficients are lower, but because the surface heat is lower, the maximum temperatures on both inside and outside surfaces are lower than at the midplane. The structure temperature in the rear zones is close to the Li_2O temperature which is 800°C at the outlet from the blanket.

The fact that the carbon/carbon first wall runs at a high temperature can be viewed as an advantage. Since the lifetime of the chamber is going to be limited by radiation induced swelling, and carbons display a reduction in swelling at temperatures of > 1200°C, it would be possible to design the first wall, which experiences the highest dpa to operate in that temperature regime. Further, the remaining rear zones which will have lower dpa will be at temperatures between $500 - 800$°C where swelling is also low, or roughly comparable to that at > 1200°C.

Figure 3 is a schematic of the Li_2O granule transport system around the loop. As they leave the chamber, the particles travel in a fluidized mode to the IHX of which there are four, then are lifted in an entrained mode to the top of the IHX. They are fluidized in the IHX and then entrained again for the lift back up to the top of the chamber. In all cases, the He gas flows upward, while the particles flow down when fluidized and up when entrained. In the IHX, the granules exchange heat with liquid lead, entering at 740°C and exiting at 550, while the lead goes from 400°C - 600°C. The four IHX's are rectangular 4.1 m long $\times$ 3 m deep $\times$ 5.7 m high, with the lead in horizontal tubes making four passes, while the granules flow down in a single pass. The heat transfer coefficient in the IHX on the granules side is 2063 W/m^2K and on the lead side it is 19200 W/m^2K. Table II gives the thermal hydraulic parameters.

Table II. Thermal Hydraulics Parameters

Li_2O in/out temp. at FW (C)	550/700
Li_2O in/out temp. in rear (C)	550/800
Li_2O equilibrated out temp. (C)	740
Li_2O mass flow rate (kg/s)	5590
Max. Li_2O velocity at FW (m/s)	1.15
Nusselt number at midplane FW	240
Ht. tram. coeff. at midplane FW (W/m^2K)	2758
Max. steady state outside surf. temp. (C)	1485
Max. steady state inside surf. temp. (C)	1220
Liquid lead in/out temp. (C)	400/600
Li_2O heat trans. coeff. (W/m^2K)	2063
Lead heat trans. coeff. (W/m^2K)	19,200
Avg. heat transfer area (m^2)	17,150
Lead mass flow rate (kg/s)	114,450
Lead flow velocity (m/s)	0.89
Lead pumping power (MW)	3.0

Tritium Consideration

Tritium desorption from Li_2O can be in the form of molecular T_2 or tritiated water T_2O, depending on the oxygen concentration in the gas phase. Molecular tritium diffuses readily through metallic surfaces, but T_2O does not. Therefore it is important to insure that the predominant species in the He gas traveling with the granules is T_2O. This can be done by maintaining an oxygen partial pressure in the He of 10^{-5} Pa by adding water vapor such that the H_2O partial pressure is 64 Pa. This will insure that the HTO partial pressure will be 4 Pa while that of T_2 will be 2×10^{-6} Pa. Under these conditions if we assume that only 10% of the entraining He gas flows through the IHX and a barrier factor of 100 will exist on the outer tubes of the IHX due to an oxide layer, the tritium permeation rate into the IHX will be 15 Ci/day. These assumptions are reasonable, since most of the entraining He gas will be cycloned off before the particles will enter the IHX. Further, a barrier factor of 100 for a self-replenishing oxide layer on a metallic surface is also conservative. It is also important to insure that the H_2O partial pressure stays below 7700 Pa to prevent formation of LiOH(T) which will erode the carbon. The large margin of two orders of magnitude between 64 Pa and 7700 Pa should be easy to maintain. A bypass of 2.5 m^3/s of the He gas is needed for T_2O extraction which will occur on dessicants.

Tritium solubility in the Li_2O at an average temperature of 650°C is .081 wppm. For a total Li_2O inventory of 2000 tonnes, the inventory is 162 g. Although the Li_2O mean particle size is 300-500 μm, the grains are much smaller, about 10-20 μm. Therefore, tritium retention due to diffusivity is negligible. The reactor building has not yet been sufficiently defined to determine the amount of T_2 adsorbed on the walls. This, however, is not expected to be a dominant factor.

Preliminary Building Design and Chamber Maintenance

Figure 4 is a plan view and Fig. 5 a side view of the reactor building which is a 110 m diameter right cylinder with a dome roof 120 m high. There is another cylindrical internal wall at 9.5 m radius on which the chamber is supported. Figure 4 shows the building divided into 24 equal sectors with only 12 occupied by optical equipment and 4 by IHXs and steam generators. The laser beams are routed in the space below the building and come up vertically through windows in the second floor. The beams are then directed to dielectrically coated final focusing (FF) mirrors located at 50 m from the target, then reflected off grazing incidence (GI) mirrors located 30 m from the target. The beams then pass through beam ports in the inner wall and the chamber to converge at the target in the chamber center. The FF mirrors are out of

line of sight of primary neutrons which only see the GI mirrors and are

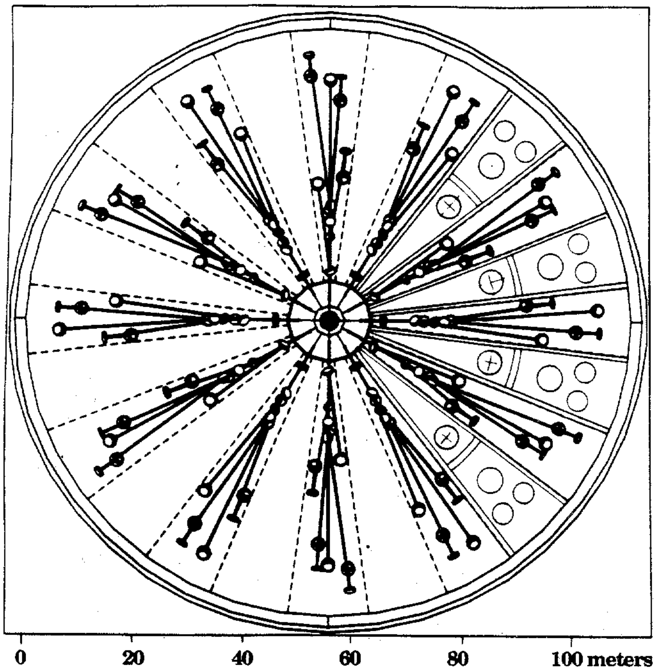

Fig. 4. Top view of reactor building.

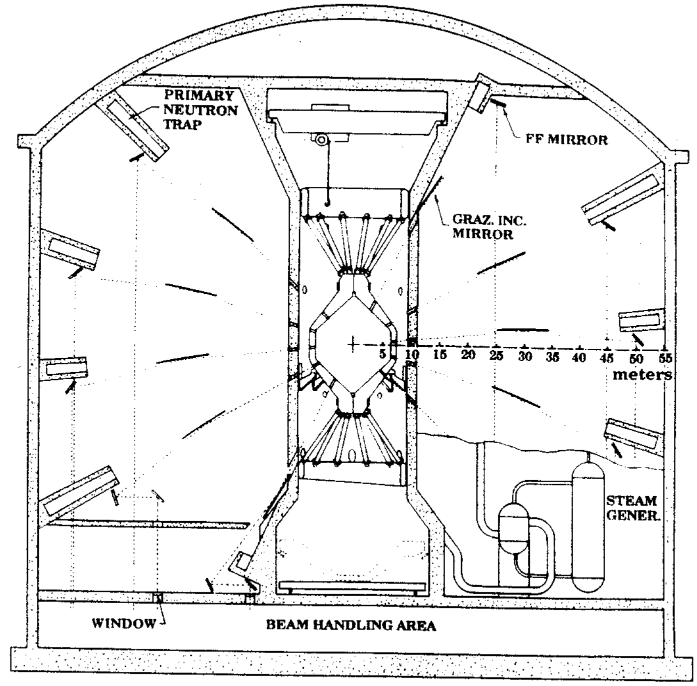

Fig. 5. Side view of SOMBRERO reactor building.

directed into neutron traps which act like black holes for neutrons. The vacuum boundary is defined by the inner wall and by 12 of the optical sectors leading to the windows in the building floor. Figure 5 shows the chamber supported on 12 retractable supports and each module connected by individual supply and return tubes. A single module can be disconnected from the reactor, the support retracted and the module lowered by an overhead crane onto a polar carriage located below the chamber. The carriage can then take the module through one of the unoccupied building sectors to a maintenance area.

The FW fluence of 15.3 dpa/FPY gives a 5 FPY life to the modules assuming 75 dpa as the limiting dose for a c/c composite. At 75% plant capacity, the chamber components will be replaced at 6.7 CY intervals. The GI mirrors can survive 30 FPY at a limiting dose of 10^{21} n/cm^2 if 80% damage recovery with annealing is assumed. At a limiting dose of 10^{22} n/cm^2 they will survive 30 FPY without annealing. The effect of the neutron traps is to give the FF mirrors a full lifetime. The FF mirrors are estimated to survive 30 FPY at a limiting dose of 10^{18} n/cm^2 to the dielectric coating. 3-D neutronics will be performed to verify this. The building sectors which contain the mirrors are relatively uncluttered and will allow remote maintenace machines to be able to service the mirrors if the need arises. The thickness of the walls in the steam generator areas is configured to allow hands on maintenance (2.5 mr/h) within 24 hours after shutdown.

Conclusions

The Li_2O solid breeder moving bed concept in a carbon/carbon composite structure results in a relatively simple, low activation reactor chamber, operating at low pressure with a high degree of safety potential. The moving bed retains all the outstanding features of static solid breeders while eliminating the disadvantages. An intermediate heat exchanger utilizing lead is proposed from safety rather than tritium diffusion considerations. There appears to be a potential for making both GI and FF mirrors lifetime components. The c/c composite chamber modules have a lifetime of 6.7 CY. Although yet to be confirmed, preliminary indications are that a 7% laser efficiency and a 47% power cycle efficiency are adequate from the economic standpoint.

Acknowledgement

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