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A NEAR SYMMETRICALLY ILLUMINATED DIRECT DRIVE LASER FUSION POWER REACTOR – SIRIUS-P

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ABSTRACT

This paper describes the design of a 1000 MWe inertially confined fusion power reactor utilizing near symmetric illumination provided by a KrF laser. The nominal laser energy is 3.4 MJ, the target gain is 118 and the rep-rate is 6.7 Hz. Sixty beams are distributed on ten horizontal planes with six beams in each plane forming a cone with the vertex at the reactor chamber center. The chamber is spherical internally with a radius of 6.5 m and is divided into 12 vertical modules consisting of two independent parts, the first wall assembly and a blanket assembly. The first wall assembly is made of a C/C composite and is cooled with non-breeding granular solid TiO_2 flowing by gravity at a constant velocity. The blanket assembly is made from SiC composite and is cooled with granular Li_2O also flowing by gravity. After going through the heat exchangers, the granular materials are returned to the reactor by means of a fluidized bed. The first wall is protected with a xenon buffer gas at 0.5 torr. The chamber is housed in a cylindrical building 42 m in radius and 86 m high, and is surrounded with a 1.5 m thick biological wall at a radius of 10 m. The laser beam ports are open to the containment building, sharing the same vacuum. Two power conversion cycles have been analyzed, a steam Rankine cycle with an efficiency of 47% and an advanced He gas Brayton cycle at an efficiency of 51%. The nominal COE is ~65 mills/kWh assuming an 8% interest on capital.

I. INTRODUCTION

SIRIUS-P is a power reactor conceptual design study, representing a natural progression of a series of studies performed at the University of Wisconsin utilizing symmetrically, or near symmetrically illuminated laser driven inertial confinement fusion systems.

This design utilizes a moving bed of granular solid ceramic materials as the coolant and breeder. This idea is not new; it has been used in previous designs such as SOLASE,[1] CASCADE,[2] and more recently SOMBRERO.[3] What is unique about SIRIUS-P is that it makes use of a first wall (FW) assembly cooled with non-breeding TiO_2 flowing through constant area channels made from a C/C composite. There is a breeding blanket behind the FW, made of SiC and cooled with flowing granular Li_2O. The advantage of this scheme is that the FW assembly can operate at a much higher temperature than is possible with Li bearing ceramic materials and achieve a higher power cycle efficiency.

An inalienable fact of symmetric illumination is that it requires a large building. This is due to the need for a larger number of beams for symmetric illumination, as well as the distance required to protect sensitive dielectrically coated final focusing optics. In this design, a conscious effort has been made to minimize the size of the containment building. Further, to avoid the need for beam tubes proliferated all over the containment building, the beams are transmitted through open space within the building. The penalty is that the chamber and the building share the same vacuum, and there will be some T_2 within the building. It will be shown that this does not appear to pose any problem.

II. GENERAL REACTOR DESCRIPTION

SIRIUS-P is a 1000 MWe power reactor based on a near symmetrically illuminated configuration

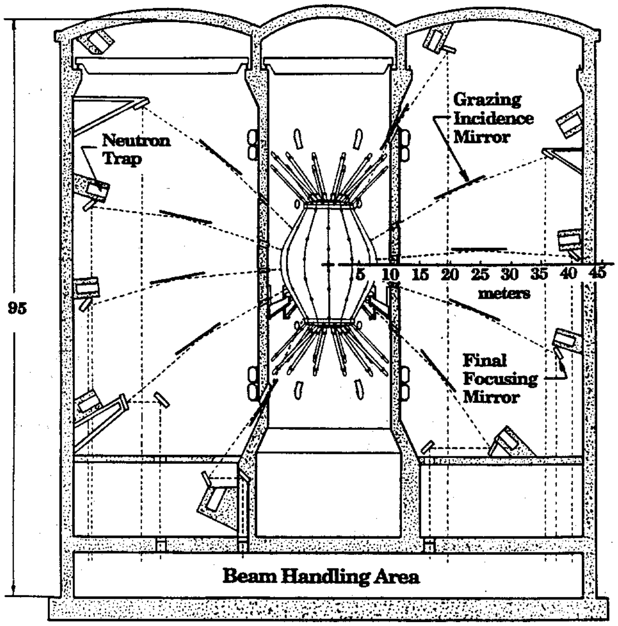

Fig. 1. Side view of containment building.

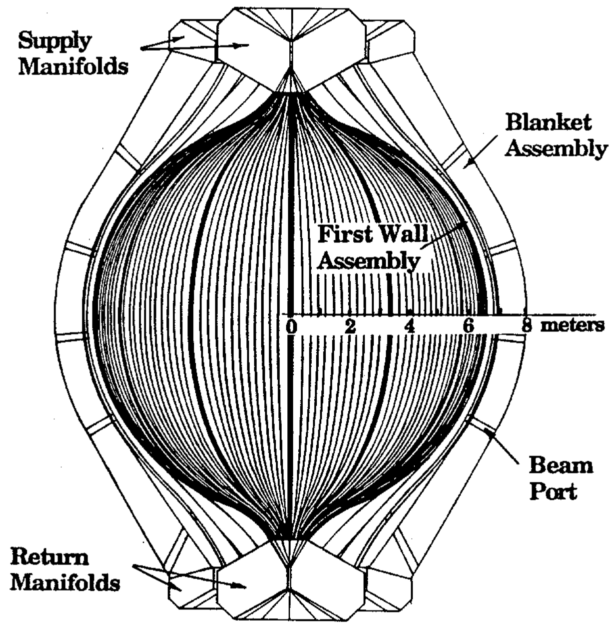

Fig. 2. Cross section of SIRIUS-P reactor.

provided by a KrF laser. The nominal laser energy is 3.4 MJ, and the target gain is 118. The near symmetric configuration makes it possible to use direct drive targets at a repetition rate of 6.7 Hz. Each target is illuminated by 60 beams lying on 10 horizontal planes with 6 beam ports in each plane forming a cone with the vertex at the chamber center. The reactor chamber is housed within a containment building which is cylindrical with a radius of 42 m and a height of 86 m internal dimensions. Figure 1 is a cross section of the reactor building with a side view of the chamber itself. It can be seen that the chamber is surrounded by an internal reinforced concrete wall at a radius of 10 m which has a dual function: it reduces the dose in the remainder of the building which contains the beam handling optics and it is the structural element on which the chamber is supported. A polar crane located at the top of the chamber enclosure is used to service individual chamber modules during routine replacement and maintenance.

The 60 laser beams, after entering the building, travel vertically and are incident onto final focusing (FF) mirrors located at a radius of 40 m from the target. They are then directed onto grazing incidence metallic mirrors (GIMM) located at a radius of 25 m from the target which deflect the beams by 10 degrees and direct them into the internal reactor enclosure through ports in the walls. As can be seen in Fig. 1, the dielectrically coated FF mirrors are out of the direct line of sight of the primary neutrons. The neutrons pass through the GIMMs and are swallowed by a neutron trap located at the building outer wall. The high aspect ratio of the neutron traps prevents appreciable back-shine, making it possible for the FF mirrors to have a much longer lifetime than they would have had if they were directly exposed to the primary neutrons.

Figure 2 shows the reactor chamber which consists of two distinct parts, the FW assembly and the blanket assembly. The FW assembly is made from a C/C composite and is cooled by non-breeding granular TiO_2 flowing by gravity at a constant velocity. It is spherical over 97% of its area with a radius of 6.5 m. The assembly is divided into 12 equal modules, each with 12 tubes in it. The unique aspect of these tubes is that they have a constant flow area from top to bottom to insure a constant coolant velocity at the FW. The tubes have a wall thickness of 1.0 cm. All the tubes in a module are attached to a common manifold at the top and bottom and each module manifold is supplied by individual feed tubes connected to common headers located above and below the chamber. The blanket assembly is made of SiC, cooled with granular Li_2O and is divided into 12 modules such that the FW and blanket together constitute a reactor chamber module. The blanket modules are manifolded in the same way as the first wall modules, and also have individual supply and return manifolds connected to common headers. After going through the heat exchangers, the ceramic

TABLE I

General Parameters for SIRIUS-PR and SIRIUS-PB

	SIR.-PR	SIR.-PB
Driver energy (MJ)	3.4	3.2
Target gain	118	114
Target yield (MJ)	401	365
Repetition rate (Hz)	6.7	6.7
Number of beams	60	60
Laser driver efficiency (%)	7.5	7.5
Chamber radius (m)	6.5	6.5
Fusion power (MWth)	2688	2444
Thermal power (MWth)	2903	2640
Power cycle efficiency (%)	47.5	51
Gross electric power (MWe)	1379	1346
Laser driver (MWe)	304	286
Net electric power (MWe)	1000	1000

materials are returned to the reactor by a fluidized bed operating with He gas at 0.15 MPa. The reaction chamber has xenon gas in it at a pressure of 0.5 torr at room temperature. The Xe gas stops the x-rays and ions, and their energy is radiated to the FW over a longer time scale. The laser beams should not break down in 0.5 torr of xenon.[4]

Two options of SIRIUS-P are considered, one designated SIRIUS-PR utilizing a Rankine power cycle conversion system and another designated SIRIUS-PB, utilizing a Brayton He gas power cycle conversion system. Since the conversion efficiency in SIRIUS-PB is higher than in SIRIUS-PR, the driver energy is 3.2 MJ and the target gain is 114, but the rep-rate is the same. Table I gives the general parameters of the two versions.

III. FIRST WALL PROTECTION

Calculations performed using our coupled radiation-hydrodynamic/collisional-radiative equilibrium code indicate that self-attenuation of line radiation in the chamber buffer gas leads to significant reduction in radiative flux. CONRAD[4] calculations for Xe gas using the multigroup radiation diffusion model without line radiation effects show that the maximum FW temperature after an explosion is 2200 K rather than 3600 K, when line effects are included. Based on Ne calculations, it is expected that the case without lines more accurately represents the actual conditions; however, more work needs to be done to verify this. In any case, both temperatures are lower than the sublimation temperatures of carbon, and no significant loss of material is expected.

IV. NEUTRONICS

For the reference SIRIUS-P breeding blanket, the thickness is taken to be 90 cm, which gives an overall tritium breeding ratio (TBR) of 1.09 and the corresponding overall energy multiplication factor M_o is 1.08. For the SIRIUS-PB design, the total thermal power is 2640 MW with 730 MW deposited at the front surface of the first wall and 1910 MW deposited volumetrically in the chamber by neutrons and gamma photons. For the SIRIUS-PR design, the total thermal power is 2903 MW, the surface heating 803 MW, and the volumetric chamber heating is 2100 MW. The peak dpa rate values in the first wall and blanket are 14.76 and 18.12 dpa, respectively, and the peak helium production rate in the first wall is 3635 appm/FPY for the SIRIUS-PB design and 4000 appm/FPY for the SIRIUS-PR design.

V. 3-D NEUTRONICS ANALYSIS OF THE FINAL FOCUSING MIRRORS

One of the most difficult problems in laser driven ICF reactors is protection of the FF optics. The FF optics are dielectrically coated mirrors which perform the dual function of focusing the beam onto, and of directing it towards the target at the center of the chamber.

The lifetime of the FF mirrors depends on the neutron fluence limit, the solid angle fraction subtended by the beam ports and the location of the mirrors with respect to the target. Current wisdom sets the lifetime of a multilayer mirror with no color centers at a fast neutron fluence ($E > 0.1$ MeV) at 10^{18} n/cm^2 which if placed in the direct line of sight of source neutrons, will accumulate such a fluence in several days. The latest innovation for extending the lifetime of the FF mirrors is the use of grazing incidence metallic mirrors (GIMM) proposed by R. Bieri and M. Guinan[5] in 1991. Here the laser beam is deflected 10° by the GIMMs into the reactor which makes it possible to place the more sensitive dielectrically coated FF mirrors out of the line of sight of the source neutrons. Furthermore, the neutrons, after passing through the GIMMs, are incident onto a neutron trap with a very high aspect ratio, essentially constituting a black hole for them. Because the GIMMs are metallic, they are not as sensitive as dielectrically coated mirrors and can survive neutron fluences of up to 10^{21} n/cm^2 and some of the damage can be recovered by annealing. Assuming an 80% recovery by annealing, the GIMMs can have a lifetime of 14 full power years (FPY). The interaction of

TABLE II

Comparison of Lifetimes of FF Mirrors

	Fluence (n/cm^2s)	Lifetime (FPY)
3D analysis of FF mirrors in the direct line of sight of source neutrons	4.8×10^{12}	0.0066
3D analysis of FF mirrors offset from line of sight (with GIMMs)	5.6×10^{10}	0.6

source neutrons with the GIMM material results in scattered secondary neutrons in the space between the inner shield and the containment building wall. Some of these scattered neutrons will reach the FF mirrors and will increase the neutron flux level to them, and consequently, shorten their lifetime. In order to quantify this effect, three-dimensional neutronics has been performed. Table II compares the FF mirror lifetimes in the cases where they are in the direct line of sight of source neutrons, and 3D analysis of the offset FF mirrors. The table shows almost two orders of magnitude increase in the lifetimes between the first and second cases. Even with this great improvement, the lifetime of the FF mirrors is 9.6 months, assuming a 75% availability.

There are several lessons to be learned from this research. The first is that the use of GIMMs has improved the outlook for the protection of very sensitive dielectrically coated mirrors by an enormous amount. But more effort is needed to extend their life even more. This can be done by the careful selection of materials for the GIMMs, such as those with low density and low neutron interaction cross sections. Furthermore, neutron absorbing materials such as boron will also help reduce secondary neutrons. Finally, this research shows that 3D analysis is essential when it comes to determining lifetimes of optics in laser driven ICF reactors.

VI. THERMAL HYDRAULICS AND STRUCTURAL ANALYSIS

In SIRIUS-P, heat transfer is accomplished by a moving bed of solid ceramic particles flowing under the action of gravity. The FW assembly is cooled with TiO_2 particles of 300-500 μm and the blanket assembly with Li_2O particles of the same size. Moving bed heat transfer is dominated by the effective thermal conductivity of the solid and the interstitial gas. This is in contrast to fluidized beds in which heat

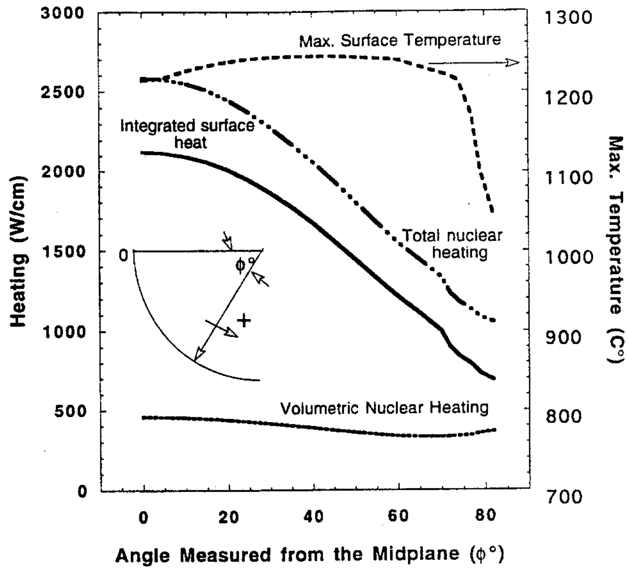

Fig. 3. Maximum FW surface temperature and nuclear heating in lower half of SIRIUS-PR chamber.

transfer is determined primarily by the conductivity of the carrier gas. It was discovered that most heat transfer coefficient formulations for moving beds depended on times or distances particles spent in contact with the heated surface. Rather than assigning arbitrary values for the distance a particle stays in contact with the heated surface, it was decided to treat the moving bed as a continuum, and use the Dittus Boelter formulation for obtaining Nusselt numbers. However, for this method, values for the effective viscosity of the moving bed as a function of velocity are needed. Fortunately, experiments performed in 1981 at the University of Wisconsin by R. Nietert[6] yielded data from which effective viscosities were obtained. With this information in hand, and assuming a continuum, the Nusselt numbers were derived.

The thermal conductivity for 4D weave C/C composites after irradiation was taken as 70 W/mK. This is reasonable considering that the conductivity degrades due to radiation to $\sim$ 50% of its normal value when operated at 1200°C. The inlet temperature of TiO_2 is 500°C and 800°C, and the equilibrated outlet temperature is 800°C and 1400°C for SIRIUS-PR and SIRIUS-PB respectively.

Three-dimensional thermal hydraulic and structural analysis has been performed for the SIRIUS-PR FW. Figure 3 shows the nuclear heating, surface heating and temperature distribution in a FW tube as a function of the angle from midplane to the lower extremity. The maximum temperature occurs at $\sim 60°$ from midplane and is equal to 1245°C. Detailed stress results are reported elsewhere in these proceedings.[7] The maximum tensile and compressive stresses along the fibers occur at the same place at midplane and are 75 MPa and 50 MPa respectively. These stresses are due to bending in the low radius curvature of the tube which is flattened circumferentially at midplane. All other stresses are well below these values.

VII. TRITIUM CONSIDERATION AND SAFETY

The predominant tritium species in the He carrier gas is maintained as HTO by the addition of H_2O vapor at 64 Pa, making T_2 extraction easier. This way the T_2 pressure for the Rankine cycle is 10^{-16} Pa. In the case of the Brayton cycle, the heat exchanger tubes are made of Mo and the H_2O vapor pressure cannot exceed 0.1 Pa, and thus the T_2 partial pressure is 10^{-8} Pa. In either case the T_2 permeation into the power cycle is low, 10^{-2} Ci/d for the Rankine, and 12 Ci/d for the Brayton cycle. Tritium inventories are: < 3 g in the containment building, 150 g in the reactor, 70 g in the fuel processing system and 285 g in the target factory. An accidental release of T_2 from the reactor and containment building will result in a whole body early dose of 1.4 rem, from the fuel processing system 0.64 rem, and from the target factory, 2.57 rem. No evacuation plans are required for any of these emergencies.

The reactor and shield qualify as Class A low level waste (LLW); however, the Li_2O and the TiO_2 qualify as Class C LLW. The Li_2O can qualify as Class A if it is replaced once each year.

VIII. ECONOMICS

The total direct costs for the SIRIUS-PR and SIRIUS-PB systems are very comparable at 1868 M$ and 1845 M$ respectively. This is due to the fact that the higher cost of heat transfer equipment for the Brayton cycle is offset by the lower cost of the turbine equipment. In spite of the higher conversion efficiency of the Brayton cycle, the resulting cost of electricity (COE) is comparable, 65.4 mills/kWh for SIRIUS-PR and 64.6 mills/kWh for SIRIUS-PB (1992), assuming an 8% interest on capital.

IX. CONCLUSIONS

A moving ceramic bed blanket is a good match for symmetrically illuminated ICF systems, making it possible to achieve high thermal efficiencies with excellent safety features. A dry wall FW protection scheme ends up with a relatively large diameter chamber, and symmetric illumination using lasers inherently requires large containment buildings. The COE for the Rankine and Brayton cycles are almost identical, calling into question the justification of going to the more advanced Brayton cycle. Nevertheless, at $\sim$ 65 mills/kWh, the COE is very competitive with other fusion reactor systems that have been proposed to date.

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