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Presented at the 16th ANS Topical Meeting on Fusion Energy, 14–16 September 2004, Madison WI.

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A LITHIUM SELF-COOLED BLANKET FOR THE HAPL CONCEPTUAL INERTIAL CONFINEMENT REACTOR

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A multi-institutional study HAPL (High Average Power Laser)^l is investigating a relatively near term conceptual design of a laser driven inertial confinement reactor. A primary focus of the study is the protection of the first wall (FW) from the target emanations. This paper gives a brief analysis of one of several possible blankets that can be integrated with the chosen FW protection scheme. The structural material is conventional ferritic steel (FS) F82H cooled with liquid lithium. The maximum average temperature is constrained to $550^{\circ}C$. The chamber radius is 6.5 m at midplane, tapering to 2.5 m at the ends, and is surrounded by a cylindrical vacuum vessel. The first wall (FW) is 0.35 cm FS, which has a 0.1 *cm thick laver of tungsten bonded to it facing the target.* The FW is cooled with Li admitted at the bottom of the blanket, flows through a gap between 0.25-0.5 cm to the top, then returns through the center of the blanket channel to the bottom. There are 60 laser beam ports situated around the chamber. The tritium breeding ratio (TBR) is 1.124. A Brayton cycle is envisaged with an efficiency in the range of 42-44%.

I. INTRODUCTION

The HAPL (High Average Power Laser)¹ study is a multi-institutional investigation of a near term conceptual design of a laser driven inertial fusion reactor. The main focus of the study is the protection of the first wall (FW) from emanations coming from the target in the form of xrays and ions, which deposit a huge amount of energy on the FW in relatively short pulses. Preliminary screening of possible blanket designs that can be integrated with the FW protection scheme is being considered. The present study describes a brief analysis of one such blanket, consisting of conventional ferritic steel (FS) F82H structure, constrained to a maximum average temperature of $550^{\circ}C^{2}$ cooled with liquid lithium. Future studies will access several different blankets using other liquid and solid breeding materials. They will be reported on in future meetings.

II. GENERAL DESCRIPTION

Figure 1 is a cross-section of the chamber showing a cylindrical vacuum vessel with a primary access flange on the top. The geometry of the FW and side blanket

modules is barrel shaped with a radius at the mid-plane of 6.5 m, tapering to 2.5 m at the upper and lower extremities. There are 12 side blanket modules extending the height of the chamber. Separate blankets are provided on the upper and lower ends. All the coolant connections to the blanket are at the bottom of the chamber. The side modules are supported on cradles attached to the vacuum vessel. The upper and lower blankets are also supported on the vacuum vessel. The figure also shows some of the beam tubes in the reactor. The beam tubes terminate at the vacuum vessel wall. From there, laser beams travel through ports in the blanket converging in the center of the chamber where they impact the target. An access flange is provided on the top of the vacuum vessel. All blankets are maintained through this access flange. Coolant lines are disconnected on the bottom through a small access port. Table I gives some relevant parameters used in the design of this blanket.

TABLE I. Selected Parameters

1.2
125
150
1800
2103
531
383
650
40.0
628

II.A. Laser Beam Layout

Direct drive targets require a large number of beams to achieve symmetric illumination. For example, the HAPL chamber has 60 beams, with an assumed F-stop of 32, some of which are shown in Figure 1. The layout of the beams has been checked for providing symmetric illumination and has been approved by LLE (Laboratory of Laser Energetics, University of Rochester). The beam ports in the side blanket modules are all located on azimuthal lines, which lie in the center of special blanket modules. The ports lie along ten horizontal planes, with six beam ports in each plane forming a cone with the vertex at the chamber center. Five cones lie above midplane and five below. Laser beams that are diametrically opposed do not line up, such that if there is no target, the beam does not propagate into the opposing beam tube.

II.B. Description of Side Blanket

This blanket has similarities with the one used in ARIES-AT.³ There are 12 side blanket modules in the reactor, each subtending 30° of circumference. At midplane the major radius is 6.5 m but at the ends, it tapers down to 2.5 m. Each module is made up of 13 submodules, which vary in width and depth to accommodate the reduction in radius. The minimum radial depth of the sub-modules is 47 cm as determined by neutronics considerations. The sub-modules consist of two concentric rectangular tubes separated by a constant gap that can be varied between 0.25-0.5 cm as shown in Figure 2. As the shape of the sub-modules changes, the

hydraulic diameter is maintained constant. This insures that the velocity at the FW is always at a high value for good heat transfer, and a reasonable pressure drop is maintained. Figure 3 shows an overall view of a side module as well as the cross-sections at different elevations. A table gives the sub-module dimensions. The outer tube wall is made of 0.35 cm thick FS and has a layer of tungsten 0.1 cm thick diffusion bonded to it on the side facing the target. Tungsten, which has a very high melting temperature and good thermal conductivity is used as armor against the high energy deposition from the target. The blanket module containing the ports has a special sub-module in the center, which contains the ports. Unlike the other sub-modules, it has a constant width from top to bottom, in order to provide adequate room for the ports without compromising the first wall coolant flow.



Fig. 1. Cross-section of HAPL chamber.







Fig. 3. Side blanket module.

Lithium coolant enters the sub-module at the bottom, then flows at a high velocity in the gap between the tubes to cool the FW. Vanes are provided to allow the coolant to spiral around the tubes in order to even out the temperature, by spending equal amounts of time on each side of the sub-module. At the top the coolant makes a 180° turn, then travels back at a very low velocity through the large central channel of the inner tube exiting at the bottom. By this action, the fluid is allowed to pick up heat from neutrons, but the poor heat transfer allows the channel walls to stay at a lower temperature.

II.C. Upper and Lower Blanket

Special blankets are provided on the top and bottom of the chamber, which are different from the side blanket modules. They consist of 26 cm thick monolithic FS discs 6 m in diameter. On the side facing the target, they are covered with thin walled FS semi-elliptical channels coated with tungsten, all running in the same direction. The Li coolant, after traversing the FW, enters the shield and flows in parallel channels through several levels of thickness. The temperature of the Li can be matched to that of the side modules.

III. THERMAL HYDRAULICS

The premise of the thermal hydraulics in this blanket is predicated on allowing the Li coolant to achieve a high temperature while keeping the structure at the prescribed 550°C average temperature. The coolant enters the side blanket on the bottom, flowing at a high velocity through the gap between the double rectangular channels. The high velocity provides a high heat transfer coefficient to dissipate the large heat deposition on the FW from the incident x-rays and ions emanating from the target. When the coolant reaches the top of the blanket, it turns 180° and flows back at a very low velocity through the large channel of the inner rectangular tube. The wall of the inner channel has poor heat transfer on the inner side but good heat transfer on the cooler outer side, thus allowing it to be at a lower temperature than the outgoing Li coolant. Figure 4 shows an example of the Li temperature rise as a function of the elevation through the side module and the descent through the central channel, obtained by 1D analysis. In this example, the gap between channels is 0.5 cm and the velocity in the gap is varied between 2-5 m/s.

IV. NEUTRONICS

Neutronics calculations were performed to determine the relevant nuclear performance parameters for the blanket. The ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system⁴ was used to perform the calculations utilizing the FENDL-2 nuclear data library. The chamber is modeled in spherical geometry with a point source at the center emitting neutronics with a softened energy spectrum resulting from interactions between fusion neutrons and the dense target materials. 70.5% of the target yield is carried by neutrons with an average energy of 12.4 MeV. The neutronics results are normalized to a fusion power of 1.8 GW. The peak neutron wall loading is 2.4 MW/m² at mid-plane and drops to 1.8 MW/m² at top/bottom of side blanket.



Fig. 4. Li temperature rise in side module.

The lifetime of the plant is assumed to be 40 full power years (FPY). For the vacuum vessel (VV) wall to be a lifetime component with cumulative end-of-life radiation damage <200 dpa, it was determined that the side blanket thickness should be at least 47 cm. The VV is 50 cm thick and is cooled by 15% helium. The peak endof-life helium production at the back of the VV is 0.67 appm allowing for rewelding. The peak damage rate in the FW steel at mid-plane is 19.2 dpa/FPY implying that the blanket lifetime is expected to be ~10 FPY. It is interesting to note that at the W/FS interface, atomic displacements and helium production in the FS are higher than those in W by factors of 3 and 38, respectively.

Moving away from mid-plane towards the top and bottom of chamber, the blanket thickness increases but the blanket sub-module width decreases resulting in an increased volume fraction of side walls. Only modest breeding is required from the top and bottom blankets that have a small coverage of ~5.8%. The top/bottom blankets are only 30 cm thick and include 20% Li. The overall TBR was determined to be 1.124 with only 0.024 contributed by the top/bottom. Therefore, tritium self-sufficiency can be achieved. The solid angle fraction subtended by the beam ports is ~0.4% with minimal impact on overall TBR.

The total thermal power is 2103 MW with 12.5% of it carried by the helium coolant of the VV. Only 128 MW of the thermal power is contributed by the top/bottom blanket and VV. The total nuclear heating (deposited by neutrons and gamma photons) in the blanket and VV is 1572 MW implying that the overall nuclear energy multiplication is 1.24. Nuclear heating profiles in blanket components were determined and used in the thermal hydraulics analysis. The peak power densities in FS, Li, and W are 14, 7, and 39 W/cm³, respectively.

V. POWER CYCLE

Two examples of Brayton power cycle configurations have been used. A 3 compressor system with 2 intercoolers and one turbine stage, (designated as Cycle I) and a 4 compressor system, with 3 intercoolers, 4 turbine stages with 3 reheat cycles (designated as Cycle II)⁵. In addition, to assess the impact of higher operating temperature, both maximum FS temperature limits of 550° C (for conventional FS) and 700° C (assumed for ODS FS) were considered. Figure 5 summarizes the results.



Fig. 5. Brayton cycle efficiency as a function of Li outlet temperature for two example cycles.

For a maximum FS temperature limit of 550°C, the Brayton cycle efficiency for Cycle I tapers to about 0.42 as the Li outlet temperature is increased. Increasing the FS limit to 700°C allows for higher Li outlet temperature and cycle efficiency of up to about 0.44. Applying Cycle II to this case provides a substantial increase in cycle efficiency for a given Li outlet temperature; however, in the Cycle II case of multi-reheats, there is less flexibility in setting a lower Li inlet temperature and the maximum Li outlet temperature must be further limited to satisfy the maximum FS temperature limit. Thus, the maximum Li outlet temperature is limited to about 650°C for a FS T_{max} of 550°C with a corresponding efficiency of about 0.45; for a FS T_{max} of 700°C, the maximum outlet Li temperature is limited to about 675°C with a corresponding maximum efficiency of about 0.465. This improvement in efficiency has to be balanced against the added cost of the power cycle components.

VI. CONCLUSIONS

A relatively simple self-cooled Li blanket made of FS F89H structure, operating at a low pressure and accommodating the FS temperature limits has been designed. Good geometric compatibility with the laser beam ports has been achieved. For a FS $T_{max} < 550^{\circ}$ C and a fusion power of 1800 MW, a FW Li velocity of 4.5 m/s and a pressure drop of < 0.5 MPa can be achieved with a FW gap of 0.25 cm. Under these conditions, the $\eta_{Brayton} \sim 0.4$. For ODS FS and an average $T_{max} < 700^{\circ}$ C, $\eta_{Brayton} \sim 0.42$. An upgraded power cycle with 4 stage compression can increase the efficiency to 0.44.

ACKNOWLEDGEMENTS

This work has been performed through grants from the Naval Research Laboratory as part of DOE's funded HAPL program.

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