SHORT NOTE

Tritium Breeding Capability of Heliotron-H Fusion Reactor Blankets

Hideki NAKASHIMA, Masao OHTA,
Department of Nuclear Engineering, Kyushu University*

Atsuo IIYOSHI
Plasma Physics Laboratory, Kyoto University**

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Heliotron-H(1) is a conceptual design for a commercial fusion power reactor that could produce a total thermal output of 3.6 GW. It has major and minor radii of 21 and 1.28 m, respectively, and a height-to-width ratio \( \kappa \) of 2. The helical magnetic field on plasma-axis is 4 T and average plasma beta 8%. Steady operation is made possible by carrying the current steadily in the coil arranged helically around the torus.

The previous neutronics study(2) showed that the neutron penetration from the side wall of the coil shield and the streaming through the divertor slots affect the nuclear design of the heliotron reactor blankets: The shielding and breeding characteristics of the design evolved from the one-dimensional calculation are far from satisfying the design criteria. In the present heliotron-H reactor, the blanket/shield configuration designed to enhance the breeding and shielding characteristics. (ex., incorporation of breeding material into the whole blanket as compared to the previous design(2) where the blankets placed in front of the coil are utilized solely for neutron shielding with tritium breeding undertaken by the blankets in the remaining regions). In the present note, neutronic analyses are made to assess the tritium breeding capability of the heliotron-H reactor design, using the one-dimensional transport code ANISN(3) and Monte Carlo code MORSE-I(4). The neutron and \( \gamma \)-ray cross section set including KERMA-factors is derived from GICX 40 library(5). The fusion neutron source is idealized as an isotropic source of 14.06 MeV neutrons, uniformly distributed throughout the plasma region inside the blanket. Figure 1 presents, in one-dimensional cylindrical geometry, the blanket configuration adopted for the ANISN calculation, and Fig. 2, in actual two-dimensional geometry, the configuration for the MORSE-I. The composition of 1-cm-thick first wall is set to be 50% PCA* and 50% \( \text{H}_2\text{O} \), while the blanket is 10% PCA, 4% \( \text{H}_2\text{O} \) and 68% \( \text{Li}_2\text{O} \) with the balance as void, the thickness being 50 cm with A-type and 60 cm with B-type. All composition percentages are given by volume. (For simplicity of calculation, the details of the magnet (dotted line in Fig. 2) are omitted.) In the MORSE calculation, the code TOPIC(6) is used to check the input data. The collision density estimator was used to estimate the tritium breeding ratio. Random walk calculations were carried out for 4,000 source particles. The resulting fractional standard
deviations (f. s. d.) for the breeding ratio are estimated to be \( \sim 2\% \).

The reference and four alternative designs examined here are presented in Table 1, together with the results of neutronics calculation. Design 1 is the reference design, with which the other systems will be compared. This design employs \( \text{Li}_2\text{O} \) (\( ^{6}\text{Li} \) enriched to 50\%) as breeding material. Designs 1 and 2 investigate the effects of enriching \( ^{6}\text{Li} \) in \( \text{Li}_2\text{O} \) from natural abundance (7.42\%) to 50\%. Effects of neutron multiplier \( \text{PbO} \) are examined by Designs 1 and 3. In Designs 3~5, the innermost part of the blanket is replaced by 10-cm-thick neutron multiplier \( \text{PbO} \), the total thickness of the blanket being fixed. Designs 3 and 4 investigate the effects of enriching \( ^{6}\text{Li} \) in the presence of \( \text{PbO} \) multiplier. The effects of replacing \( \text{PbO} \) partially by \( \text{Li}_2\text{O} \) in the neutron multiplier region are examined by Designs 3 and 5.

### Table 1 Comparison of characteristics of various designs†

<table>
<thead>
<tr>
<th>Design number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
<td>(^{6}\text{Li} ) enrichment</td>
<td>50%&lt;br&gt;absent</td>
<td>natural 7.42%&lt;br&gt;absent</td>
<td>50%&lt;br&gt;10-cm thick</td>
<td>50%&lt;br&gt;10-cm thick</td>
<td>50%&lt;br&gt;10-cm thick††</td>
</tr>
<tr>
<td>(^{6}\text{Li}(n, \alpha)\text{T} )</td>
<td>0.850 [0.880]&lt;br&gt;0.801 [0.839]</td>
<td>0.124 [1.129]&lt;br&gt;[1.021]</td>
<td>0.054 [0.052]&lt;br&gt;[0.099]</td>
<td>0.178 [1.181]&lt;br&gt;[1.120]</td>
<td>0.127 [1.257]</td>
</tr>
<tr>
<td>(^{7}\text{Li}(n, \eta')\alpha\text{T} )</td>
<td>0.195 [0.197]&lt;br&gt;0.364 [0.373]</td>
<td>0.054 [0.052]&lt;br&gt;[0.099]</td>
<td>0.127 [0.127]</td>
<td>0.127 [1.257]</td>
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</table>

† Breeding material: \( \text{Li}_2\text{O} \)

†† Mixture of \( \text{PbO} \) and \( \text{Li}_2\text{O} \). Volume fraction \( \text{PbO}/\text{Li}_2\text{O} = 1/1 \).

Values in parentheses are obtained from one-dimensional calculations.

From these results, one can draw the following observations:

A comparison of the results between Designs 1 and 2 show that any advantage could not be found in employing enriched \( ^{6}\text{Li} \) in the \( \text{Li}_2\text{O} \) for purposes of enhancing tritium breeding. From two-dimensional calculation, the tritium breeding ratio in Design 2 (natural lithium in \( \text{Li}_2\text{O} \)) is found to be \( \sim 1.17, \sim 72\% \) of which is contributed by the A-type breeding blanket shown in Fig. 2. Enrichment is effective for the blanket that employs neutron multiplier as shown by the results from Designs 3 and 4. Between Designs 1 and 3, it is evidenced that employing 10-cm-thick \( \text{PbO} \) multiplier
increases the tritium breeding ratio by $\sim 10\%$. Further enhancement in the ratio is obtained by adopting a mixture of PbO and Li$_2$O in the multiplier zone, due to the increased contribution from $^7$Li($n, n'$)T reaction (See Design 5). As compared with Design 2, the tritium breeding in Design 3 is contributed primarily by $^6$Li for which the uncertainty in nuclear data is very small. The difference in the tritium breeding ratio between one- and two-dimensional calculations is only 4%, due to the fact that the neutron source (plasma region) is surrounded effectively by the whole blanket in the two-dimensional model (as shown in Fig. 2) which takes into account the actual geometric details.

In summary, enough tritium breeding ratio ($>1.1$) could be obtained by using Li$_2$O (natural lithium) as breeding material. Another option is to adopt PbO multiplier with $^6$Li enrichment in the Li$_2$O in case the former design could not accommodate the uncertainty in nuclear data on $^7$Li. (It is believed from recent measurements and analyses that the tritium production cross section for $^7$Li might be overpredicted by 10 to 35% in the 6-to-14 MeV neutron energy range$^{(6)}$. If so, the tritium breeding ratio in Design 2 would reduce from 1.17 to $\sim 1.10$ with the revised data.)

The effects of Li burn-up on the breeding ratio are examined for Designs 2 and 3 in the one-dimensional model. The blanket is divided into five regions with an equal thickness. The average burn-up rates in Li are calculated at every 5 yr for each region. Based on the results of burn-up calculations, the breeding calculation has been iterated. However, no appreciable change was found for the ratio during 10 yr of continuous operation.

The preliminary shielding calculations are carried out for the present blanket/shield design, using the two-dimensional transport code DOT$^{(7)}$ in R-$\theta$ geometry (Fig. 3) with $P_3$-$S_6$ approximation. Among the radiation response parameters for the magnet, the atomic displacement in the Cu stabilizer is the limiting factor, amounting to $5.4 \times 10^{-6}$ dpa/yr; which would permit satisfactory operation of the magnet for $\sim 20$ yr without annealing, if the design criterion of $\sim 10^{-4}$ dpa is tentatively adopted and duty factor 100%. The shielding characteristics could be further improved by preventing the neutrons from penetrating through the side wall of the coil shield.

![Fig. 3 Schematic illustration of two-dimensional calculational model for DOT (R-$\theta$ geometry)](image)

These results should justify further research to be undertaken in pursuance of the present work.

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--- REFERENCES ---