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A SIMPLIFIED METHOD TO ESTIMATE  
BERYLLIUM BURN UP IN BREEDER  
BLANKETS OF A FUSION REACTOR AND ITS  
IMPACT ON A TRITIUM BREEDING

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A Simplified Method to Estimate Beryllium Burn Up  
in Breeder Blankets of a Fusion Reactor and  
its Impact on a Tritium Breeding

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The integral-differential equation of neutron balance for the beryllium burn up in breeder blankets of a fusion reactor is written and solved analytically to estimate the beryllium depletion in blankets having the beryllium as neutron multiplier. The beryllium depletion in the first and the second beryllium layers behind the first wall of a Japanese layered pebble bed blanket proposed for the ITER breeding blanket is estimated to be about 9% and 6.5% after the  $3 \text{ MW}\cdot\text{a}/\text{m}^2$  fluence of 14-MeV neutrons on the first wall, respectively. The corresponding decrease of local tritium breeding ratio at the toroidal midplane was calculated to be barely less than 0.5%. The beryllium depletion in the breeder blanket of a DEMO fusion reactor is expected to be by 3 to 7 times larger than that for the ITER design, subject to the blanket design, the neutron fluence, etc. This beryllium depletion may decrease the tritium breeding ratio well below 1%, the margin above which the subject is to be addressed seriously.

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Keywords; ITER, Neutronics, Beryllium Burn Up, Neutron Transport Calculations, Tritium Breeding Ratio.

核融合炉の増殖ブランケットにおけるベリリウムのバーンアップ  
簡易評価手法とトリチウム増殖に対する影響

日本原子力研究所那珂研究所ITER開発室

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(1993年11月26日受理)

核融合炉の固体増殖材方式ブランケットにおいては中性子増倍材としてベリリウムが用いられるが、核変換に伴う使用中のベリリウムのバーンアップがブランケットの増殖特性に影響を与える可能性がある。本論文では、解析的手法に基づいてベリリウムのバーンアップ簡易評価式を導出し、いくつかの設計例に適用した。その結果、ITERの増殖ブランケットとして提案されている多層型ペブル充填ブランケットの場合、 $3\text{ MWa/m}^2$  のフルエンスでの第1、2ベリリウム層におけるベリリウムのバーンアップは各々9%、6.5%と評価され、トリチウム増殖特性に与える影響は無視できる程度であることが明らかになった。一方、原型炉ではフルエンスが高いため、ベリリウムのバーンアップの影響を適切に評価する必要がある。

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## 1. Introduction.

Beryllium is one among best neutron multipliers for the breeding blanket of a fusion reactor due to both the large cross-section of  $(n,2n\alpha)$  reaction and the exceptionally large nuclear density. Therefore, the 1.78 secondary neutrons will appear per one source neutron in an infinite beryllium layer irradiated by 14-MeV neutron source [1]. This is only by about 3% less than that for the lead and far higher than those for the iron, the zirconium, the copper, the niobium, the nickel, the vanadium and many other could-be neutron multipliers of a fusion reactor [1].

However, neutron interactions in blankets and shields of a fusion reactor have many negative side effects, such as the lithium burn up in breeder blankets [2], the tritium generation in boronized shields [2], the gas generation in lithium oxide [3], the helium generation in beryllium [4] etc. In addition to these effects, the beryllium burn up in breeder blankets of a fusion reactor may become a serious factor is to be accounted for even for an experimental fusion reactor like ITER [5] whose fluence of 14-MeV neutrons on the first wall, hereinafter operation fluence, is expected to be  $1\text{-}3\text{ MW}\cdot\text{a}/\text{m}^2$ .

Beryllium depletion due to its burn up in a breeder blanket would be less important for the blanket having a 15-30 cm thick beryllium layer behind the first wall or the homogeneous blanket having the beryllium fraction of 40-50% or more than that for the blanket having a thin beryllium layer, say 1-3 cm thickness. It is due to the high probability of  $(n,2n\alpha)$  reaction in a thick beryllium layer even after a large beryllium depletion, such as 10-30%.

However, by imposing thermal-hydraulic, economic and structural-mechanic constraints, the number and thickness of beryllium layers can be substantially restricted and do not necessary follow the optimized configuration determined by neutronics requirement.

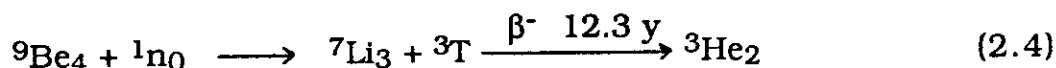
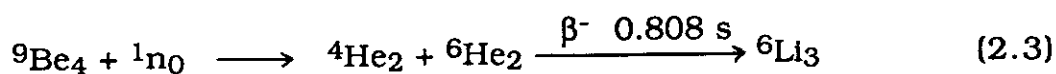
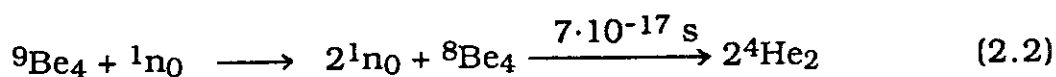
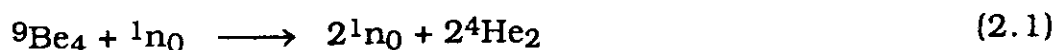
For instance, the first (behind the first wall) beryllium layer of the Japanese design of the layered pebble bed breeder blanket proposed for ITER CDA was designed to be only 9 mm thick [5] and, after further modification of this design the thickness of the first beryllium layer was decreased to 5 mm [6], a very small thickness indeed. The thickness of the second beryllium layer of this modified design is also very small, namely 6 mm. The beryllium depletion in the thin layers of such a blanket may be important regarding the possible decrease of tritium breeding ratio due to the decrease of a total neutron flux in the lithium layers.

The simplified method to estimate beryllium burn up in breeder blankets of a fusion reactor is proposed in this study based on the same treatment, as that for the lithium burn up in Ref. 2. Major nuclear reactions in beryllium are surveyed for this purpose in the Section 2 of this study. The integral differential equation of neutron balance of beryllium burn-up is written and solved analytically with minor simplification assumptions in the Section 3. Obtained simplified formula is used in the Section 4 to estimate the beryllium depletion in the modified Japanese layered pebble bed breeder blanket having the beryllium multiplier [6].



## 2. Main nuclear reactions in beryllium.

The main nuclear reactions of beryllium depletion in breeder blankets of a fusion reactor gleaned from Ref. 7 can be written as follows:



Cross-sections of above-listed reactions taken from Ref. 7 are shown in Fig. 2.1. As shown in Fig. 2.1, the reactions (2.1) and (2.3) are the dominant processes of beryllium depletion for the neutron energy ranged from 14.1 MeV (energy of neutron source) to about 2.3 MeV and from about 2.3 MeV to about 1 MeV, respectively.

We note that, as discussed above, the beryllium is depleted mainly by fast neutron interactions. Therefore, the largest beryllium depletion is expected at the first beryllium layer behind the first wall and this depletion is to be decreased sharply with the distance from the first wall. This is primary due to the sharp decrease of fast neutron flux with the distance from the first wall, as discussed in many studies indeed, e.g. [8,9].

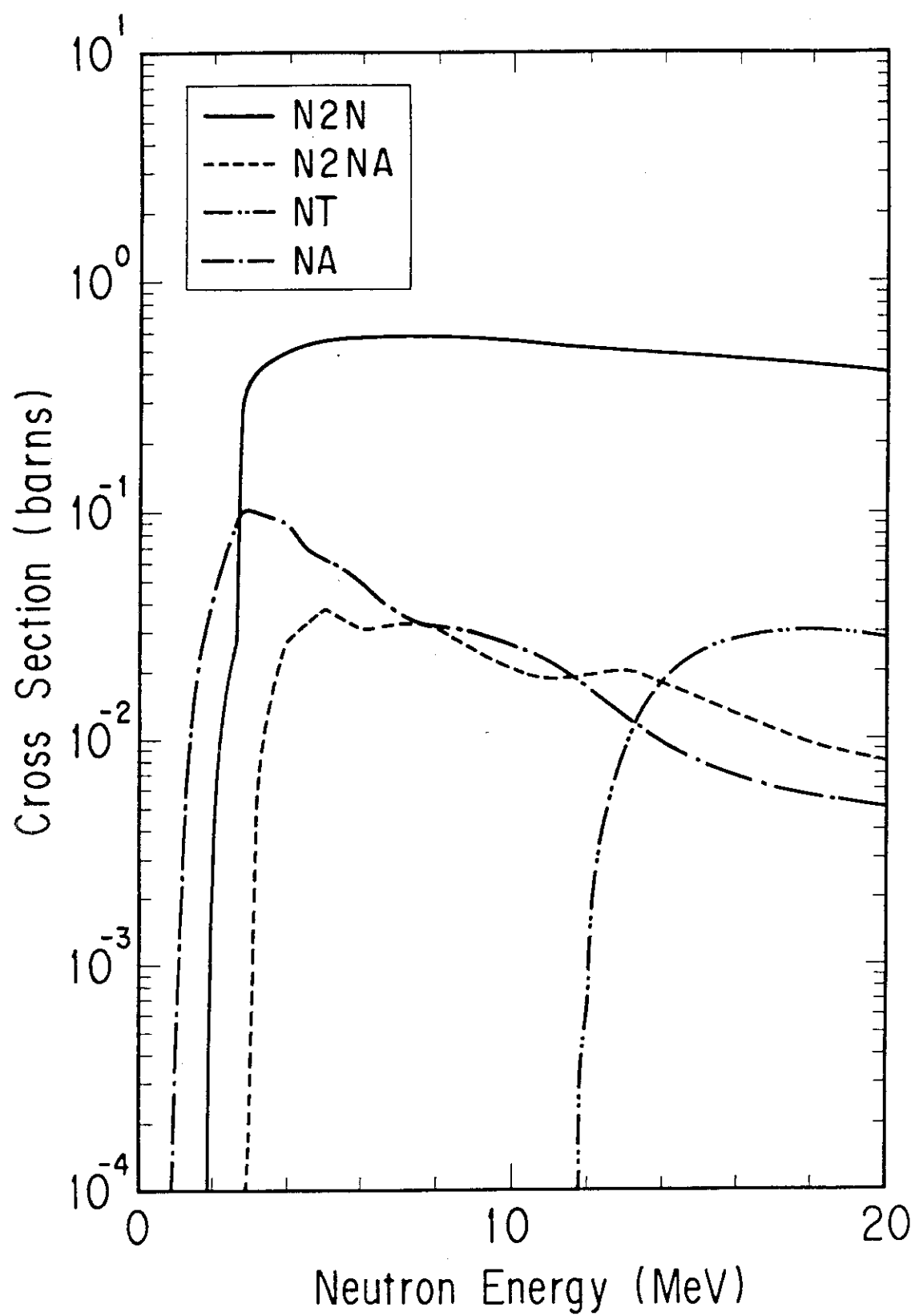


Fig. 2.1 Cross-sections of nuclear reactions in beryllium. [7]

### 3. Analytical consideration.

Let  $\sigma_{\text{dep}}$  be the sum of the cross-sections of the nuclear reactions (2.1)-(2.4). If  $\Phi(\mathbf{r}, E, t)$  is the neutron flux spectrum at a position  $\mathbf{r}$  and time  $t$  which includes the neutron energy information, the equation for the beryllium density could be written as follows:

$$d\rho(\mathbf{r}, t)/dt = - \rho(\mathbf{r}, t) \int \sigma_{\text{dep}}(\mathbf{r}, E) \cdot \Phi(\mathbf{r}, E, t) dE \quad (3.1)$$

The equation for average density of beryllium in the zone of volume  $V$  can be obtained by integrating the expression (3.1) by the zone volume as follows:

$$d\rho(t)/dt = - \rho(t) \cdot J(t) \quad (3.2)$$

$$\text{, where } J(t) = \int_{1 \text{ MeV}}^{14.1 \text{ MeV}} dE \cdot \int_V dV \cdot \sigma_{\text{dep}}(\mathbf{r}, E) \cdot \Phi(\mathbf{r}, E, t) \quad (3.3)$$

The neutron flux spectrum  $\Phi(\mathbf{r}, E, t)$  in Eqs. (3.1)-(3.3) is actually the fast neutron spectrum due to the integration from 1 MeV to 14.1 MeV ( $\sigma_{\text{dep}}(\mathbf{r}, E)=0$  for  $E < 1$  MeV, see Fig. 2.1). This fast neutron flux spectrum depends primary on the ratio of heavy, such as steel, lead, etc., and light, such as water, components in the blanket/shield compositions [8], if the neutron source flux at the first wall does not change with time, i.e. the power of a fusion reactor does not change with time. Thus, we assume that above-mentioned functional  $\Phi(\mathbf{r}, E, t)$

does not depend on time, i.e. on the beryllium depletion. If so, the Eq. (3.2) can be easily solved analytically.

Let  $\rho_0$  be the density of beryllium at the moment  $t=0$ . The solution can be written as follows:

$$\rho(t) = \rho_0 \cdot \exp(-J \cdot t), \quad (3.4)$$

$$\text{where } J = \int_{1 \text{ MeV}}^{14.1 \text{ MeV}} dE \cdot \int_V dV \cdot \sigma_{\text{dep}}(\mathbf{r}, E) \cdot \Phi(\mathbf{r}, E) \quad (3.5)$$

We note that the Eq. (3.4) is exact and do not rely on any numerical approximation. Therefore, once we have numerically integrated the functional (3.5) at the zone of an interest, we can easily calculate the beryllium depletion by Eq. (3.4) at any operation time  $t$ . However, we often do not know the neutron flux spectrum  $\Phi(\mathbf{r}, E)$  in expression (3.5). We can avoid this obstacle if we model the neutron flux spectrum  $\Phi(\mathbf{r}, E)$  by the exponential formula [9] as follows:

$$\Phi(r) = \Phi_0 \cdot \exp(-r/\lambda), \quad (3.6)$$

where  $r$  is the distance from the first wall;

$\lambda$  is the attenuation length required to characterize the attenuation of fast neutron flux along  $r$  (obtained for numerous shield types in Ref. 9);

$\Phi_0$  is the fast neutron flux at the first wall (at  $r=0$ ).

Combining (3.5) and (3.6) the expression for the functional  $J$  can be written as follows:

$$J = \Phi_0 \cdot \int_V dV \cdot \exp(-r/\lambda) \int_{1 \text{ MeV}}^{14.1 \text{ MeV}} dE \cdot \sigma_{\text{dep}}(r, E) \quad (3.7)$$

Let suppose  $\sigma_{\text{dep}}(r, E)$  does not change with a distance from the first wall. After integrating the first integral in expression (3.7) we obtain the expression for  $J$  as follows:

$$J = \lambda \Phi_0 \{1 - \exp(-r/\lambda)\} \int_{1 \text{ MeV}}^{14.1 \text{ MeV}} dE \cdot \sigma_{\text{dep}}(E) \quad (3.8)$$

Further simplification is possible if we assume that  $\sigma_{\text{dep}}(r, E) \equiv 0.5$  barn for  $1 \text{ MeV} < E < 14.1 \text{ MeV}$ . The expression (3.8) can be written in that case as follows:

$$J = \lambda \Phi_0 \{1 - \exp(-r/\lambda)\} \cdot 0.5 \cdot 10^{-24} \quad (3.9)$$

, where the dimensions of  $\lambda$  and  $r$  are given in cm and the dimension of  $\Phi_0$  is given in  $1/\text{cm}^2 \cdot \text{s}$ .

Combining (3.4) and (3.9) the expression for the beryllium density at any distance from the first wall can be written as follows:

$$\rho(t) = \rho_0 \cdot \exp[-t \cdot \lambda \Phi_0 \{1 - \exp(-r/\lambda)\} \cdot 0.5 \cdot 10^{-24}] \quad (3.10)$$

The expression for the beryllium depletion at the first wall, where the depletion is expected to be maximum, can be obtained directly from Eqs. (3.4) and (3.5) as follows:

$$\rho(t) = \rho_0 \cdot \exp[-t \cdot \Phi_0 \cdot 0.5 \cdot 10^{-24}] \quad (3.11)$$

The beryllium depletion at the first (behind the first wall) layer of Japanese layered pebble bed blanket having beryllium multiplier, as shown in Figs. 3.2 and 3.3, proposed for the ITER CDA [6], was estimated by Eq. (3.11) to be about 9% for 3 MW·a/m<sup>2</sup> operation fluence. The estimation for the second beryllium layer (see Figs. 3.2 and 3.3) by Eq. (3.10) gives the beryllium depletion of about 6.5%. These results are shown in Fig. 3.4. If the operation fluence would be 10 MW·a/m<sup>2</sup>, as it is anticipated for a DEMO fusion reactor, the beryllium depletion in the first and the second beryllium layers of above-discussed blanket would be about 25% and 18%, respectively.

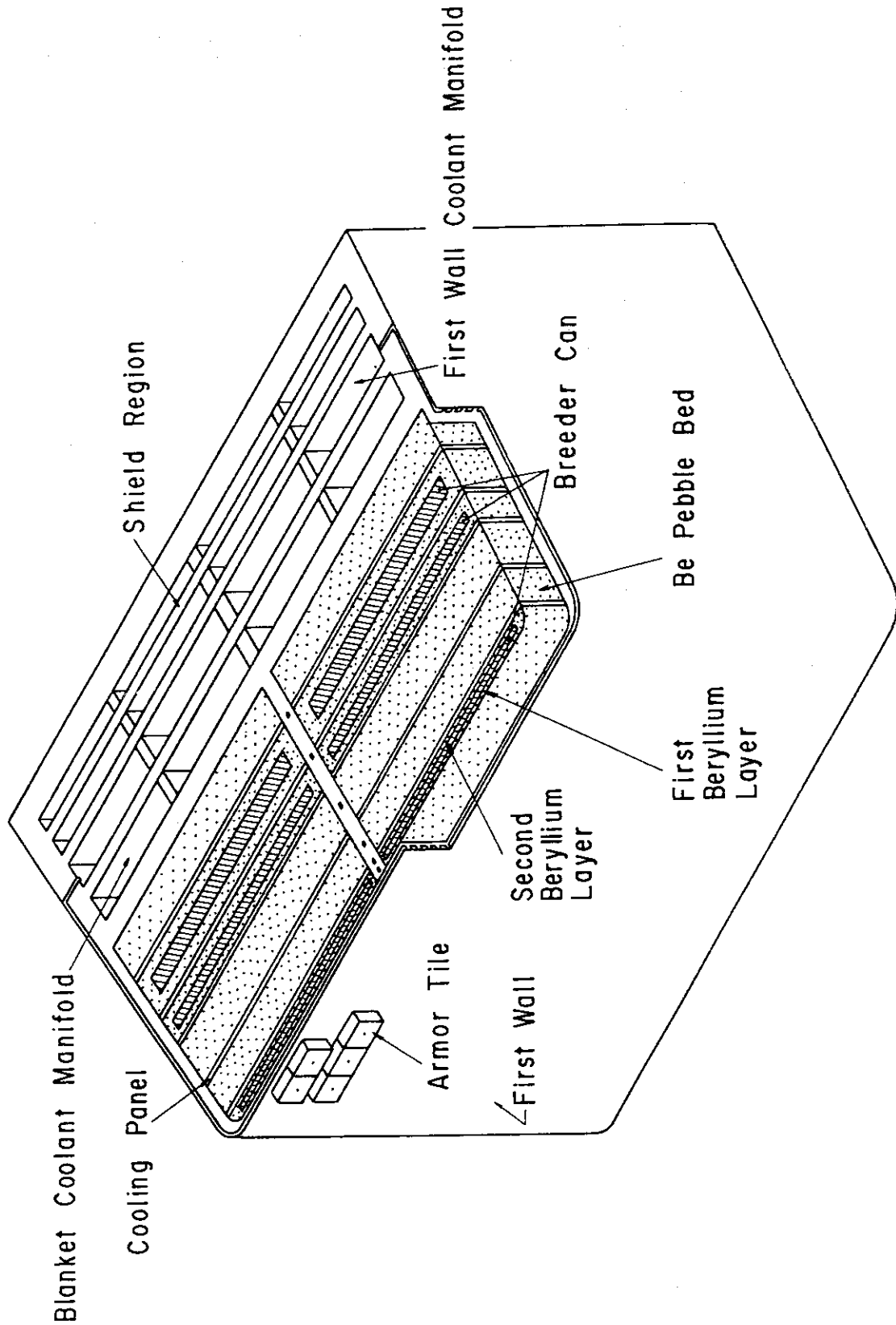
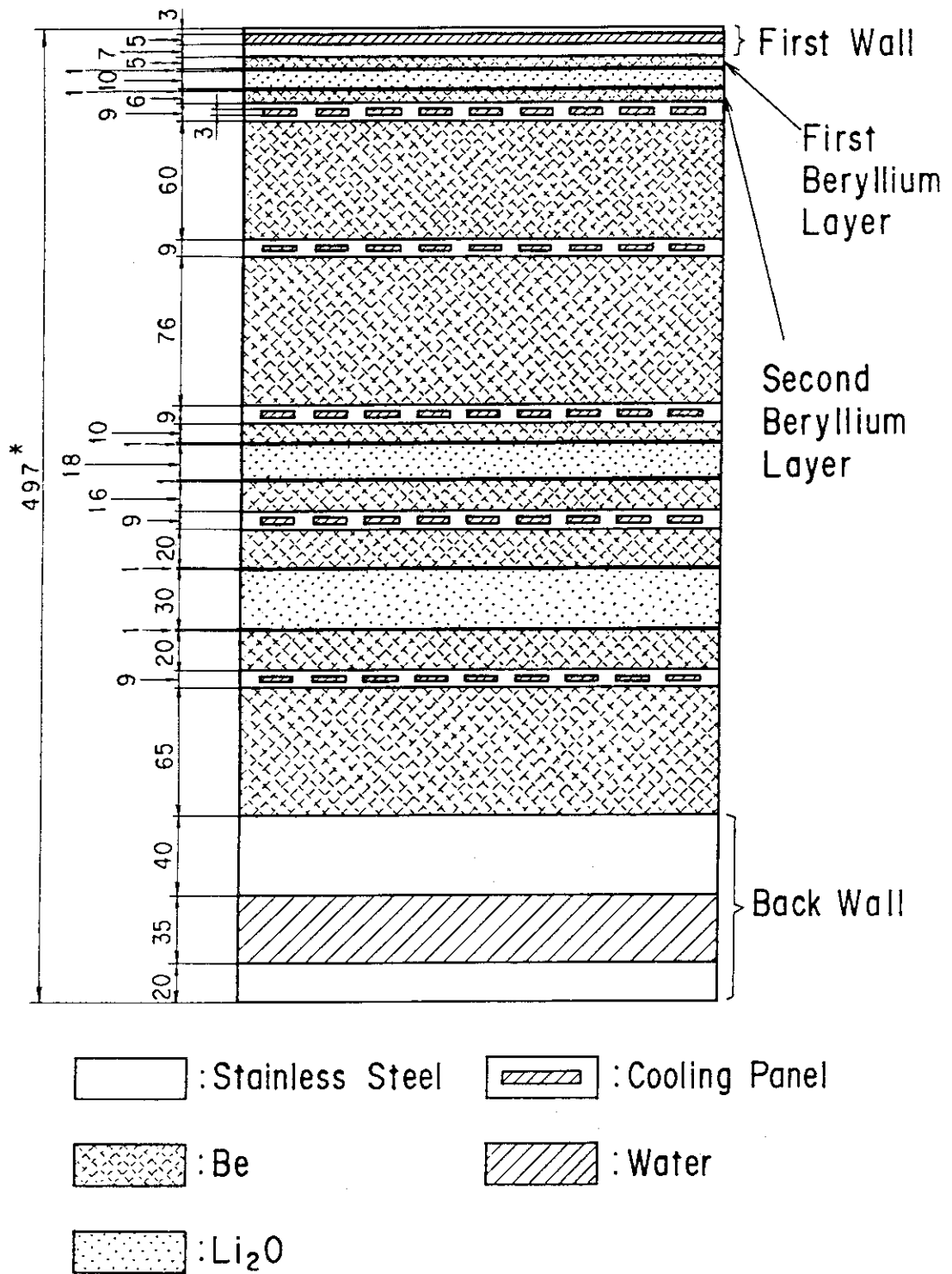


Fig. 3.2 Schematic view of outboard layered pebble bed blanket proposed for the ITER project by Japan. [6]



\* All dimensions are shown in mm

Fig 3.3 Calculational model of outboard layered pebble bed blanket (midplane) proposed for the ITER project by Japan. [6]



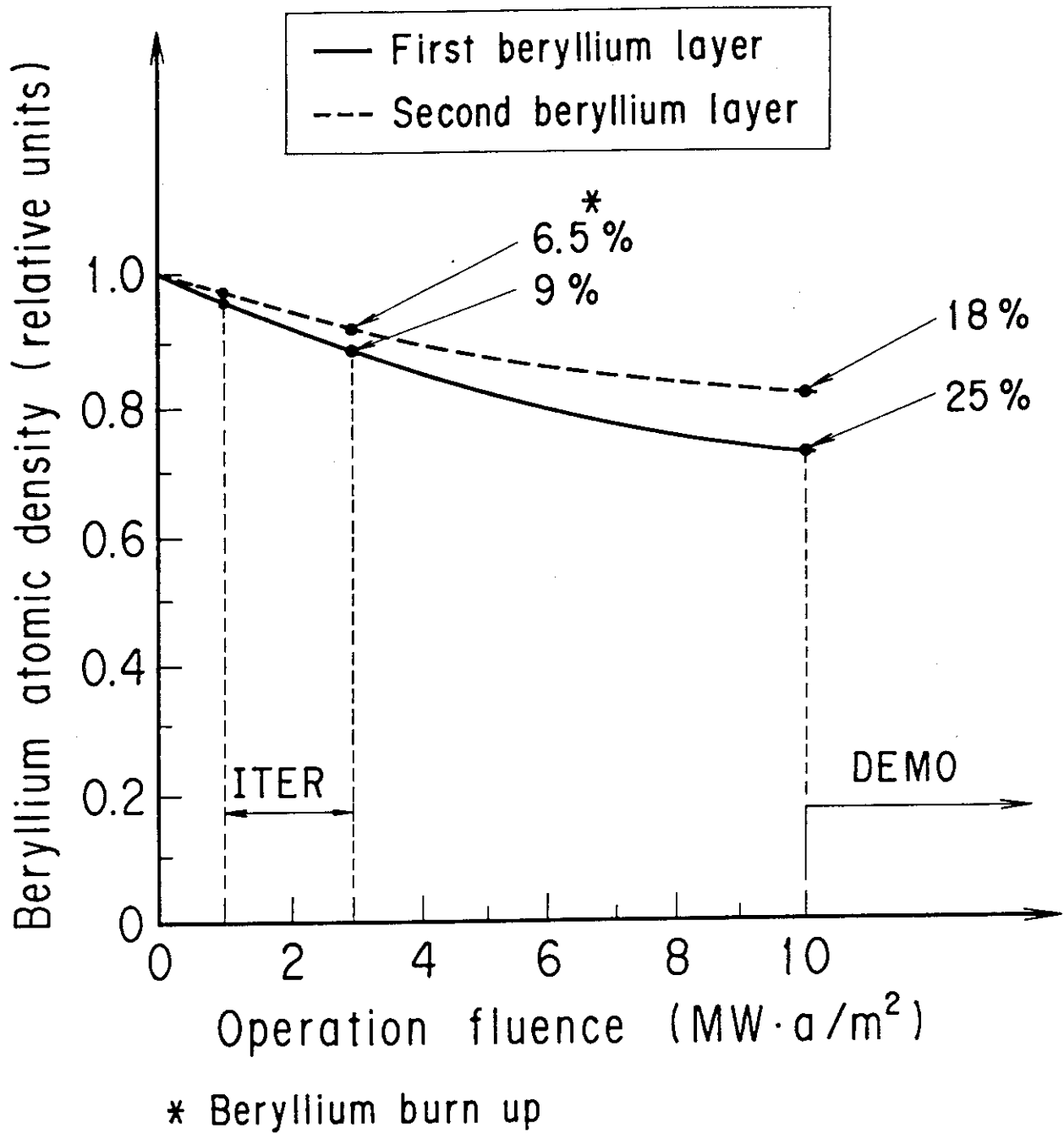


Fig. 3.4 Beryllium depletion in the first and the second beryllium layers of outboard layered pebble bed blanket proposed for the ITER project by Japan.

#### 4. Impact of beryllium burn-up on the tritium breeding ratio.

It is supposed that 14-MeV neutrons from the plasma region, after  $(n, 2n\alpha)$  interactions either in the first or the second beryllium layers, as shown in Fig. 3.3, will be both multiplied and slowed down to be "caught" by the 10 mm-thick lithium layer between above-mentioned the first and the second beryllium layers. As a result, the tritium will be generated by the  $(n, t)$  reaction in  ${}^6\text{Li}$ , the main reaction of tritium breeding for the blanket under discussion. Additionally, some, relatively small, amount of tritium will be generated by the  $(n, n't)$  reaction in  ${}^7\text{Li}$ .

Therefore, even 5-10% of beryllium depletion in the above-mentioned beryllium layers may be undesirable regarding the neutron balance in the blanket due to the high probability for 14-MeV neutrons from the plasma region to "pass" through the thin beryllium layers without  $(n, 2n\alpha)$  interactions in the beryllium to be captured by construction components, e.g. stainless steel, or to be slowed down under the threshold of  $(n, 2n\alpha)$  reaction by inelastic scattering in above-mentioned construction components. Thus, the number of  $(n, t)$  reactions in  ${}^6\text{Li}$  of above-mentioned 10 mm-thick lithium layer, the most important layer which produces almost 50% of all tritium generated in the blanket, will be decreased and the tritium breeding ratio of the blanket will be decreased as well.

The ANISN [10] neutron transport code with the FUSION-40 [11] library of multigroup constants is used to calculate the above-discussed decrease of tritium breeding ratio of the Japanese layered pebble bed blanket. The one-dimensional neutron transport calculations were performed in the toroidal midplane for the

calculational model shown in Fig. 3.3 using the discrete ordinates method with an  $S_8$  symmetric angular quadrature set and a  $P_5$  Legendre expansion for the scattering cross sections.

The decrease of local tritium breeding ratio was found to be about 0.5% and 1.3% for the 3 MW·a/m<sup>2</sup> and 10 MW·a/m<sup>2</sup> operation fluence, respectively. Therefore, it was concluded that the beryllium depletion for the ITER CDA/EDA design, whose operation fluence is expected to be 1-3 MW·a/m<sup>2</sup>, can be neglected. However, for the DEMO reactor, whose operation fluence is expected to be 10 MW·a/m<sup>2</sup> or even larger, the beryllium depletion and the followed decrease of tritium breeding ratio are to be seriously discussed, subject to the design.

## 5. Concluding remarks.

(1) The beryllium burn up in breeder blankets of a fusion reactor exponentially decreases with the distance from the first wall and increases with operation time.

(2) The beryllium depletion for the layered pebble bed beryllium blanket proposed by Japan for the ITER CDA/EDA design seems to be important only for the first and the second beryllium layers behind the first wall. The beryllium depletion at the first and the second layers of above blanket is estimated to be about 9% and 6.5%, respectively.

(3) The decrease of local tritium breeding ratio at the toroidal midplane of above-mentioned blanket is estimated to be about 0.5% after 3 MW·a/m<sup>2</sup> operation fluence.

(4) The beryllium depletion for DEMO breeder blanket, whose operation fluence is expected to be more than 10 MW·a/m<sup>2</sup>, is expected to be by 3 to 7 times larger than that for the ITER design. The corresponding decrease of tritium breeding ratio could be larger than 1%, subject to the blanket design and the operation fluence.

(5) The thermal-hydraulic and structural-mechanic consequences of beryllium burn up are out of the scope of this study, but are to be addressed seriously, if the operation fluence of a fusion reactor under the design is to be larger than 3 MW·a/m<sup>2</sup>.

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### References.

- [1] S. Zimin, "Some neutronics-physical parameters of materials", VANT, Ser. Thermonuclear Fusion, **3** (1985) 35-37, in Russian.
- [2] S. Zimin, "Simplified methods for estimations of  $^3\text{T}$  production in boronized shielding materials and Li burn up in breeder blankets", Fusion Engineering and Design **23(3)** (1993), to appear.
- [3] Y. Seki, "Gas Production Rates in Lithium Oxide of Fusion Reactor Blanket", Journal of Nucl. Science and Technology, Short Note, **12(12)** (1975) 769.
- [4] S. Shimakawa et al., "HEINBE; The Calculational Program for Helium Production in Beryllium Under Neutron Irradiation", JAERI-M 92-174 (November 1992), in Japanese.
- [5] D. Smith et al., "ITER Blanket, Shield and Material Data Base", ITER Documentation Series, N°29, IAEA, Vienna (1991).

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**References.**

- [1] S. Zimin, "Some neutronics-physical parameters of materials", VANT, Ser. Thermonuclear Fusion, **3** (1985) 35-37, in Russian.
- [2] S. Zimin, "Simplified methods for estimations of  $^3\text{T}$  production in boronized shielding materials and Li burn up in breeder blankets", Fusion Engineering and Design **23(3)** (1993), to appear.
- [3] Y. Seki, "Gas Production Rates in Lithium Oxide of Fusion Reactor Blanket", Journal of Nucl. Science and Technology, Short Note, **12(12)** (1975) 769.
- [4] S. Shimakawa et al., "HEINBE; The Calculational Program for Helium Production in Beryllium Under Neutron Irradiation", JAERI-M 92-174 (November 1992), in Japanese.
- [5] D. Smith et al., "ITER Blanket, Shield and Material Data Base", ITER Documentation Series, N°29, IAEA, Vienna (1991).

- [6] H. Takatsu et al., "Layered Pebble Bed Concept for ITER Breeding Blanket", 17th SOFT, Roma, Sep. 14-18 (1992).
  
- [7] T. Nakagawa et al., "Curves and Tables of Neutron Cross Sections - Japanese Evaluated Nuclear Data Library version 3 -", JAERI-M 90-099 (July 1990).
  
- [8] S. Zimin, "A Study on Radiation Shielding Analysis for Toroidal Field Coils of a Tokamak-type Fusion Reactor", JAERI-M 92-120 (August 1992).
  
- [9] S. Zimin, "Empirical-analytical formulae for shield effectiveness examination of an experimental thermonuclear reactor", Fusion Engineering and Design **22(2)** (1993) 229-237.
  
- [10] W. W. Engle, Jr., "A User's Manual for ANISN -A One-dimensional Discrete Ordinates Transport Code with Anisotropic Scattering", K-1693 (1967).
  
- [11] K. Maki et al., "Neutron Group Constant Set FUSION-J3 for Fusion Reactor Nuclear Calculations Based on JENDL-3", JAERI-M 91-072 (1991), in Japanese.