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Estimation of Helium Production due to Neutron Streaming and Establishment of Shielding Design Conditions in Fusion Shielding Blanket by 3-D Monte Carlo Calculation

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In the shielding design of the ITER shielding blanket, helium productions in the branch pipes and the back plate have been a critical concern from the viewpoint of rewelding of stainless-steel. We have performed three dimensional neutron streaming analyses for the ITER shielding blanket by a Monte Carlo method, and we have estimated helium productions in stainless steel. Helium productions at the branch pipes filled in water drastically increase due to a reaction between thermal neutron and boron, which is a trace element of stainless steel. We have calculated helium productions for 310 - 450 mm thick blanket modules with 10 - 60 mm wide gaps between adjacent blanket modules and 0.1 - 20 wppm boron in stainless steel. From the calculated results, we have deduced the approximate equations for the estimation of the helium productions as a function of the blanket module thickness, the gap width and the boron content, and we have clarified shielding design conditions required to satisfy the design limit.

KEYWORDS: ITER, shielding blanket, 3D neutron streaming calculations, Monte Carlo, helium productions, rewelding, boron content, branch pipe, back plate, branch pipe access hole

I. Introduction

In the International Thermonuclear Experimental Reactor (ITER), a blanket system consists of a number of shielding blanket modules from assembling and maintenance point of view, and there are about 20 mm wide gaps between adjacent shielding blanket modules(1-6). The shielding blanket modules have a modular structure in the toroidal (horizontal) and poloidal (vertical) directions with typical dimensions of ~ 1.6 m width, ~ 0.9 m height and ~ 0.31 - 0.45 m depth, and they are mainly composed of stainless steel and water. Each module has branch pipes which are inlet/outlet for the blanket module cooling line, and the branch pipes are connected to the common manifolds in a structurally separated blanket back plate or vacuum vessel. The branch pipes are to be cut and rewelded during the module replacement by remote handling. Cutting and rewelding tools can access the branch pipes through branch pipe access holes with 30 mm in diameter from the plasma region side. The branch pipe access holes are made through the face of the blanket.

Helium productions in the branch pipes and back plate have been a critical concern from the viewpoint of rewelding of stainless steel. It is assumed here that rewelding can be accomplished if the helium production within scheduled operation cycles is <3 appm, which is a tentative target goal for guiding shielding design. So we have performed shielding calculations for the shielding blanket to be installed in the ITER by 3-D Monte Carlo calculations, and we have estimated the impact of neutron streaming through the access holes and gaps between adjacent blanket modules on the helium production in the branch pipe and back plate. We have performed shielding calculations for 310, 360, 410 and 450 mm thick blanket modules. Also, we have estimated the impact of neutron streaming for 10, 20, 30, 40, 50 and 60 mm wide gaps. It has been expected that helium productions are strongly affected by boron content, which is a trace element in stainless steel. In this study, we have calculated the helium productions for the stainless steel with 0.1, 1, 3, 5, 10 and 20 wppm boron. From the results, we have deduced the approximate equations for the estimation of the helium production in the branch pipe and back plate as a function of the blanket module thickness, the gap width and the boron content.

II. Calculation Methods and Models

We have performed shielding calculations using the 3-D Monte Carlo Neutron and Photon transport cord MCNP-4B(7) with the Fusion Evaluated Nuclear Data Library FENDL-1(8). The calculation model is shown in **Fig. 1**. We have calculated neutron spectra using track length estimator and calculated helium productions by multiplying the neutron spectra by helium production cross sections of stainless steel.

In the ITER shielding blanket, a type-316 austenitic stainless steel has been applied as a structural material. ITER grade stainless-steel (SS316L(N)-IG) originally recommended as the structural material for the shielding blanket assembly is specified to contain 20 parts per million by weight (wppm) boron. Neutronics calculations(9) have, however, suggested that reduction of the boron concentration to ≤ 10 wppm decreases the helium production rate by up to a factor of two. It is possible to fabricate stainless steel that contains less than 3 wppm boron. In this study, SS316L(N)-IG with 0.1 - 20 wppm boron is used

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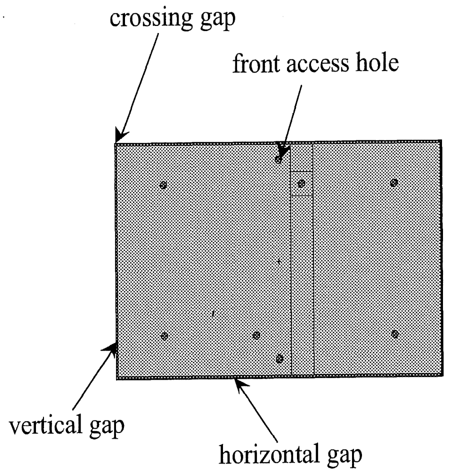
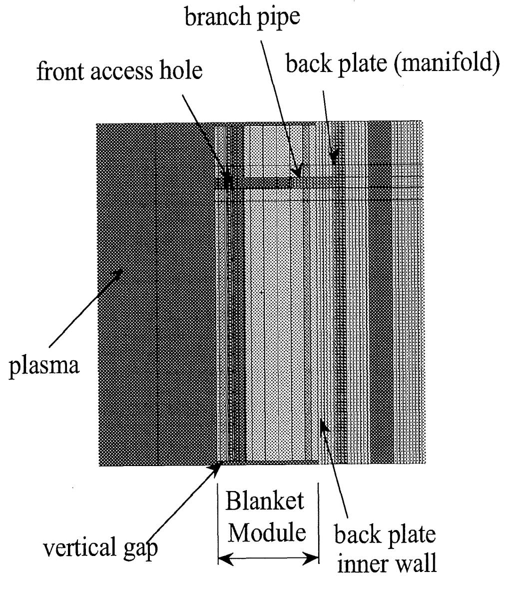


Front View



Side View

Fig. 1 Front and side views of the MCNP calculation model

Table 1 Atomic densities of SS316L(N)-IG with 10 wppm boron (unit: cm^{-3})

B	C	N	O	Al
4.320(18)[a]	8.880(19)	2.369(20)	5.927(18)	8.778(19)
Si	P	S	K	Ti
8.439(20)	3.826(19)	1.109(19)	6.062(17)	1.485(20)
V	Cr	Mn	Fe	Co
3.722(18)	1.595(22)	1.553(21)	5.512(22)	4.018(19)
Ni	Cu	Zr	Nb	Mo
9.848(21)	7.459(19)	1.039(18)	2.551(18)	1.235(21)
Sn	Ta	W	Pb	Bi
7.986(17)	2.620(17)	2.573(17)	1.802(18)	1.815(18)

a) Read as 4.320 x 10^{18}

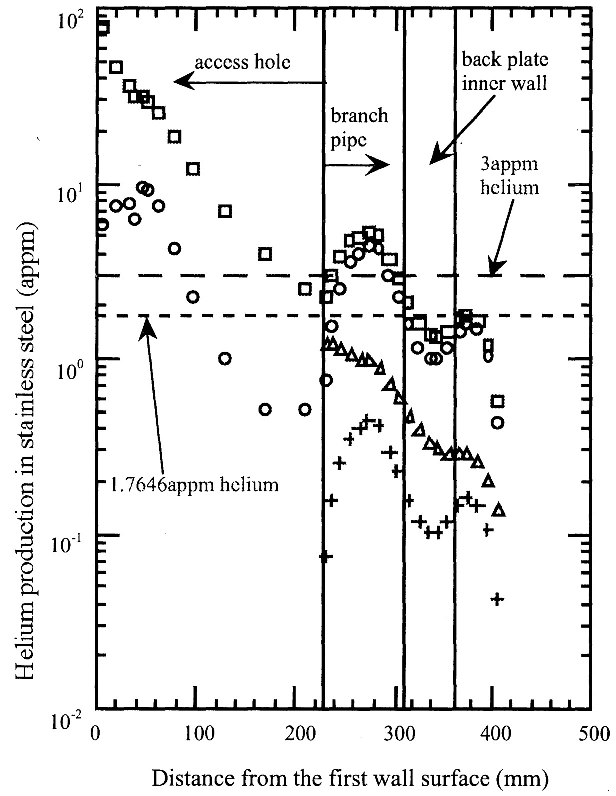


Fig. 2 Helium production distributions in the access hole and branch pipe for the neutron fluence of 0.3 MWa/m^2 (□: Helium production in SS with 10 wppm boron by total neutron, ○: That with 10 wppm boron by thermal neutron, △ : That with 1 wppm boron by total neutron, +: That with 1 wppm boron by thermal neutron)

as the stainless steel material for the evaluation of the helium production in the branch pipe. SS316L(N)-IG with 10 wppm boron is used for that in the back plate. Atomic densities of SS316L(N)-IG with 10 wppm boron used in this study are shown in **Table 1**.

III. Results and Discussion

1. Helium Productions at the Branch Pipe

For the neutron fluence of 0.3 MWa/m^2 that is a design condition tentatively assumed in ITER, helium production distributions in the access hole and branch pipe are shown in **Fig. 2** for the SS with 10 and 1 wppm boron. They are calculated results for the 310 mm thick blanket module.

They are about 1.3 - 5.3 and 0.29 - 1.3 appm helium in the branch pipe for the 10 and 1 wppm boron, respectively. Helium productions generated by thermal (< 0.215 eV) neutrons are also shown in Fig. 2. In the cases of SS with 10 wppm boron, they drastically increase at the branch pipe. In the access hole, helium are produced principally by fast (≥ 0.1 MeV) neutron reactions with the Ni, Fe and Cr component in the SS. In the branch pipe, the helium is produced by both fast and thermal neutron reactions since the fraction of thermal neutrons increase by the water in the branch pipe. ^{10}B, which is an isotope of a trace element of boron, has a very large (n,α) cross-section (~4000 b for thermal neutrons and an $E^{-1/2}$ dependence in the epithermal region). Even though the trace amount of boron is small, the ^{10}B(n,α) reaction with low energy neutrons results in a large amount of helium production. The helium production in water filled pipes is further enhanced due to increase of the thermal neutron in the water cooling channels. In ITER, 3 appm helium production and a factor of 1.7 are tentatively assumed as the limit for rewelding of the branch pipe and the safety factor for the shielding calculations, respectively, so the design limit in the shielding calculation is 1.7646 appm helium. In the case of SS with 10 wppm boron, we can reweld at the limited location, i.e. the branch pipe in the back plate. In that with 1 wppm boron, we can do at all locations of the branch pipe.

Minimum and maximum values of helium productions at the branch pipe are shown in **Fig. 3** for 310, 360, 410 and 450 mm thick blanket module. Calculated results for the SS with 10, 3 and 1 wppm boron, are shown in Fig. 3. From the results, we have deduced an approximate equation for the estimation of the helium production as a function of the blanket module thickness as follows;

$$Y(\text{appm}) = N(\text{MWa/m}^2) \times A \times e^{-B\times t}\ (\text{mm}),\quad 310 \le t \le 450,$$

	Minimum Value		Maximum Value	
B content	A	B	A	B
10 wppm	62.8	0.00865	320	0.00940
3 wppm	31.9	0.00947	127	0.00976
1 wppm	22.2	0.0101	90.2	0.0108

where Y, N and t are helium production, neutron fluence and blanket module thickness, respectively. The required blanket module thickness that can satisfy the limit for rewelding of the branch pipe are given as follows;

$$t \ge \frac{\ln(L/(S \times N \times A))}{-B}$$

where L and S are the limit and the safety factor, respectively. In case neutron fluence, limit for rewelding, safety factor and boron content are 0.5 MWa/m^2, 3 appm, 1.7 and 3 wppm, respectively, more than 367 mm thick blanket module might be required in order to accomplish the rewelding at all locations of the branch pipe.

For the 310 mm thick blanket module, effects of the boron content on the minimum value of helium productions at the branch pipe are shown in **Fig. 4**. Helium productions generated by fast (≥ 0.1 MeV) neutrons are constant among 0.1, 1, 3, 5, 10 and 20 wppm boron. When the boron contents are more than 1 wppm, helium productions generated by thermal neutrons are larger than those by fast neutrons and they are strongly affected by the boron content. We have deduced an approximate equation as a function of the boron content as follows;

$$Y\ (\text{appm}) = N \times \{A + B \times c(\text{wppm})\}$$

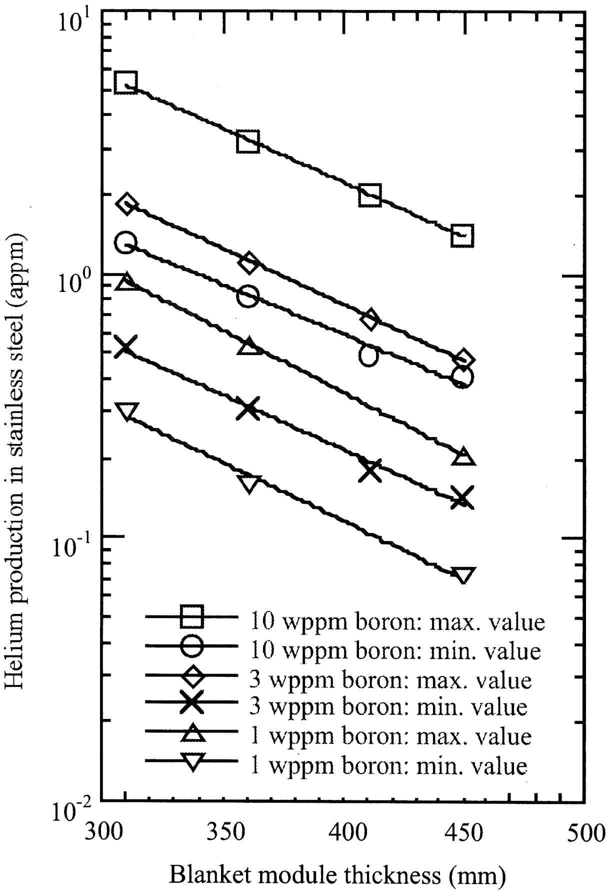


Fig. 3 Minimum and maximum values of helium productions at the branch pipe for 310, 360, 410 and 450 mm thick blanket modules

	Minimum Value		Maximum Value	
Thickness	A	B	A	B
310 mm	0.641	0.371	1.67	1.50
360 mm	0.291	0.247	0.816	0.982
410 mm	0.157	0.149	0.408	0.626

where c is boron content. Helium productions calculated by the approximate equations for 360 and 410 mm thick blanket module are also shown in Fig. 4. In order to satisfy the design limit, boron content should be controlled to be less than values given in the following formula;

$$c \le \frac{L/S/N - A}{B}$$

In the case of the blanket module, the design limit, the safety factor and the neutron fluence of 310 mm in thickness, 3 appm helium, 1.7 and 0.3 MWa/m^2, respectively, boron content should be controlled to be less than 14 wppm in order to accomplish the rewelding of the branch pipe in the back plate. Also, boron content should be controlled to be less than 2.8 wppm in order to accomplish the rewelding at all locations at the branch pipe.

2. Helium Productions at the Back Plate

For the neutron fluence of 0.3 MWa/m^2, helium production

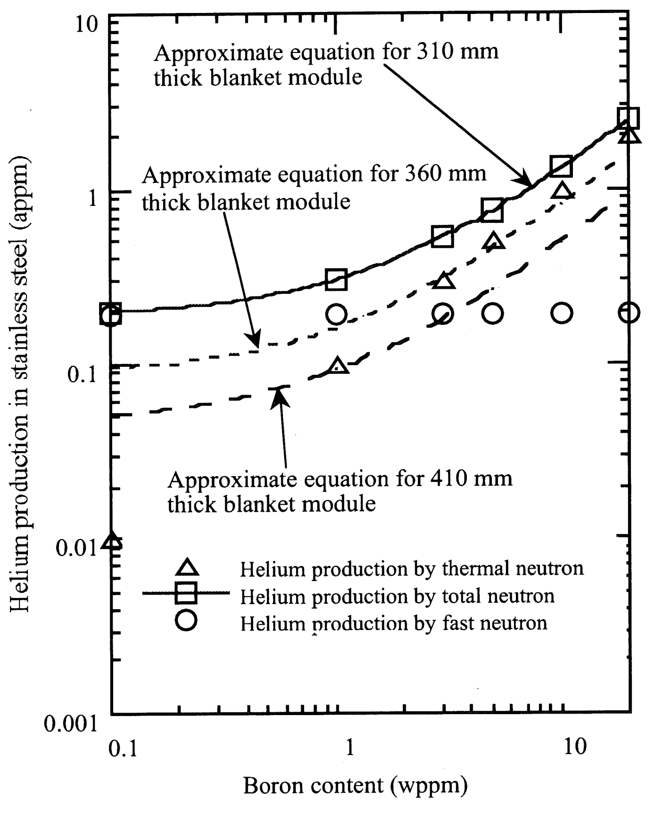


Fig. 4 Effects of the boron content on the minimum value of helium productions at the branch pipe

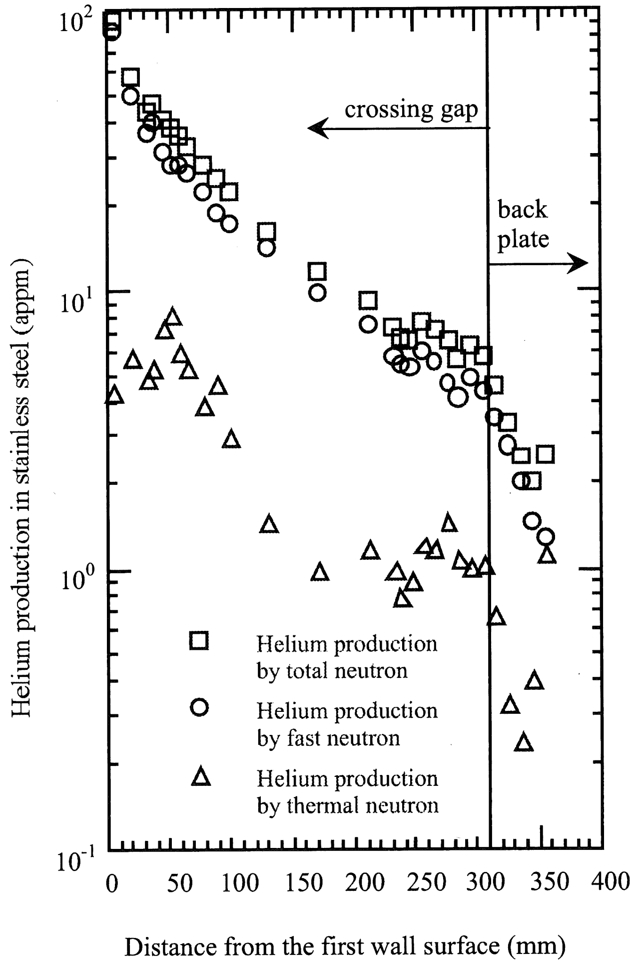


Fig. 5 Helium production distributions along the crossing gap for the neutron fluence of 0.3 MWa/m^2

distributions along the crossing gap shown in Fig. 1 are shown in **Fig. 5** for the 310 mm thick blanket module with 20 mm wide gap between adjacent blanket modules. Helium productions by total, fast and thermal neutron are shown in Fig. 5, and they are 2.0 - 4.6, 1.4 - 3.5 and 0.24 - 1.1 appm in the inner wall of the back plate along the crossing gap, respectively. In the back plate, helium productions by fast neutrons are much larger than those by thermal neutrons. It has been expected that the helium productions are enhanced due to fast neutrons streaming through the gaps. So increase of helium productions at locations near the back plate manifold filled in water is little as shown in Fig. 5.

In ITER, field weld, e.g. TIG or laser weld, locations in the back plate are ~80 mm away from the vertical gap. Helium productions at the inner surface of the back plate along the horizontal gap in the horizontal direction are shown in **Fig. 6** for 310 mm thick blanket module without the gaps and with 10, 20, 30, 40, 50 and 60 mm wide gaps. At locations more than 50 mm away from the center of the vertical gap, i.e. crossing gap, in the horizontal direction, helium productions are almost constant though some little undulations are found due to effects of three-dimensional complex configuration and statistical errors of Monte Carlo calculations, and they are about 1.5 - 1.9 times lower than those along the crossing gap. Average values of helium productions at locations 50 - 200 mm away from the center of the vertical gap, are also shown in Fig. 6 in forms of the dotted lines. In the case of the 20 mm wide gap, helium productions can satisfy the limit of 3 appm helium, but they are about 1.4 times larger than 1.7646 appm helium which is the design limit including the tentative safety factor of 1.7. In the case of the 10 mm wide gap, helium productions can satisfy the limit of 1.7646 appm helium.

Effect of the gap width on the helium productions is shown in **Fig. 7**. We have deduced the approximate equations as the gap width as follows;

$$Y_{\mathrm{peak}}(\mathrm{appm}) = 1.40 \times \mathrm{N}(\mathrm{MWa/m^2}) \times \mathrm{w}(\mathrm{mm})^{0.78}$$

$$Y_{\mathrm{ave.}}(\mathrm{appm}) = 3.33 \times \mathrm{N}(\mathrm{MWa/m^2}) \times \{0.820 + 0.0871 \times \mathrm{w}(\mathrm{mm})\}$$

$$10 \le \mathrm{w},$$

where Y_{pcak} is the helium production along the crossing gap, $Y_{\mathrm{avc.}}$ is the average value at locations 50 - 200 mm away from the center of the vertical gap and w is gap width. So the allowable gap width that can satisfy the limit L including the safety factor S, are given as follows;

$$w_{\mathrm{pcak}} \le \left(\frac{\mathrm{L}}{8.43 \times \mathrm{N} \times \mathrm{S}}\right)^{1.28}$$

$$w_{\mathrm{avc.}} \le \frac{\mathrm{L} - 2.73 \times \mathrm{N} \times \mathrm{S}}{2.90 \times \mathrm{N} \times \mathrm{S}}$$

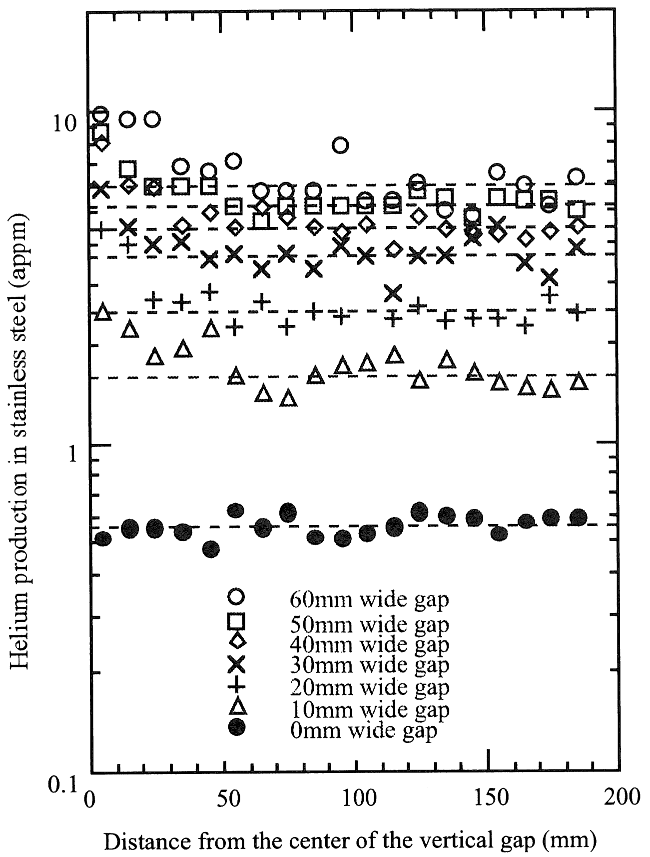


Fig. 6 Helium productions on the inner surface of the back plate along the horizontal gap in the horizontal direction

where W_{peak} and $W_{\mathrm{ave.}}$ are the allowable maximum gap widths to satisfy the limit, respectively. By using these equations, we can define the allowable gap width which can satisfy the required shielding design conditions from the view point of the shielding design.

IV. Conclusion

We have performed neutron streaming analyses for ITER shielding blanket by the 3-D Monte Carlo code, and we have estimated the helium productions at the branch pipe and the back plate. It has been clear that helium productions at the branch pipe are strongly affected by the boron content. We have deduced approximate equations for the estimation of he helium productions at the branch pipe and the back plate as functions of the blanket module thickness, boron content in stainless steel and gap width between adjacent blanket modules. Through this study, required shielding design conditions for the ITER shielding blanket are clarified to satisfy the shielding design limit for rewelding.

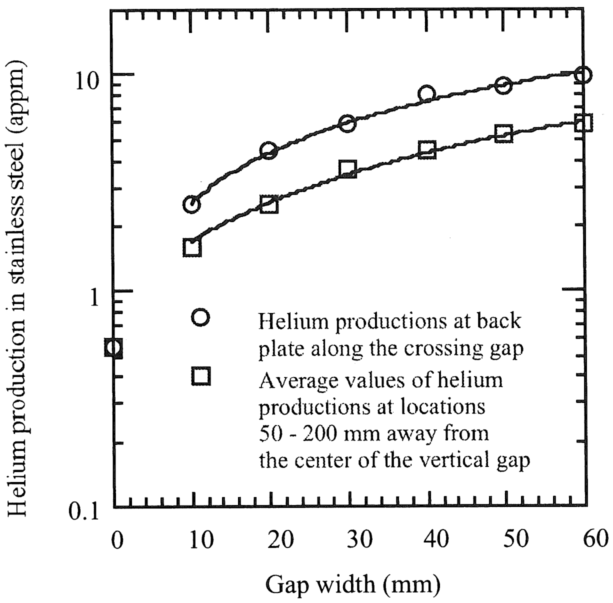


Fig. 7 Effect of the helium productions on the gap width

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