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Evaluation of Nuclear Heat and Dose Rate for JT-60SU

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Neutronics investigation has been made for the JT-60SU. Under the neutron production rate of $1x10^{20}$ n/s due to D-T operation, peak nuclear heating rate in a superconducting magnet (SCM) winding pack is 0.19 mW/cm^3 at the inboard on the mid-plane, and that at the outboard near the NBI duct is 0.27 mW/cm^3. These values satisfy the design limit of 0.2 mW/cm^3 in inboard SCM winding pack and that of 1 mW/cm^3 in the outboard SCM near the duct, respectively. The dose rate in one month after shutdown of 8000 s operation in the cryostat near the NBI duct is obtained ~10 μ Sv/h. The dose rate in the cryostat in one month after shutdown satisfies the design target of 20 μ Sv/h. Consequently, total shield thickness of the vacuum vessel in inboard and outboard, and additional shielding in the present design is expected to be enough.

KEYWORDS: neutronics investigation, JT-60SU, nuclear heating rate, superconducting magnet, winding pack, dose rate, shutdown, three dimensional Monte Carlo code, two dimensional Sn transport code, shield thickness

I. Introduction

The JT-60SU has been designed as a mid-step experimental facility between JT-60 and an experimental fusion reactor such as ITER. In this facility D-D and D-T burning experiments are considered. When D-D and D-T plasma burning experiments are performed at high temperature and high density, naturally, neutrons are created by fusion reaction. Neutronics investigation has been therefore made as a link in the chain of the structural design. Up to now neutronics analyses for ITER have been performed concerning radiation shielding around a neutral beam injector (NBI) duct [(1-4)], and for a whole reactor [(5-7)]. According to the design guide of the experimental facility of JT-60SU, superconducting magnets (SCM) are applied and hands-on maintenance is adopted. Radiation shielding for SCM and biological shielding after shutdown become therefore important subjects in the experimental facility of JT-60SU similarly to ITER.

Duct streaming effects and additive effects of plural ducts cannot be estimated by a two dimensional RZ torus model. On the other hand, these effects can be taken into consideration by a three dimensional Monte Carlo code, but it takes enormous time to estimate gamma-ray dose rate due to induced activity. It is because an enormous number of histories and tallies at a huge number of points having main contribution to the dose rate are required to evaluate gamma-ray dose rate due to induced activity. Therefore, dose rates including three dimensional spatial effect are estimated with multiplying the dose rates with a two dimensional Sn code by the ratio of the fast neutron flux with a three dimensional Monte Carlo code to that with a two dimensional Sn code.

In the present paper, at first, the thickness of vacuum vessel combined with radiation shielding is investigated from the viewpoint of preventing SCM from quenching due to nuclear heat, one of the principal shielding issues for the facility itself. Next, gamma-ray dose rate due to induced activity is estimated in order to investigate whether workers can enter the facility for directly maintenance after shutdown.

II. Calculation Model and Evaluation Method

1. Code, Nuclear Constant Sets and Models

The facility of JT-60SU has a major radius of 5.2 m, a plasma minor radius of 1.4 m, the first wall minor radius of 1.55 m and an elongation factor of 1.8. The facility is modeled from the torus center to the facility room by the two dimensional RZ torus model in the Sn calculation as shown in **Fig. 1** and the expanded view inside the cryostat is shown in **Fig. 2**. The numbers of meshes in the radial and axial directions (described as R- and Z-direction below) are 210 and 191, respectively. The zone numbers and their compositions are shown in **Table 1**. The order of Ledgendre expansion is P5 and the number of division of angular space is 160. In calculation of neutron and gamma-ray fluxes, a two dimensional Sn transport code of DOT3.5[(8)] is applied and a group constant set of FUSION40[(9)] (n-40gs, gamma-21gs) and a nuclear heating constant set of F40KERMA[(10)], which are based on JENDL3[(11)], are used. The code of CINAC[(12)] is used in induced activity calculation. The Monte Carlo code of MCNP-4A[(13)] is used for three dimensional calculation.

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2. Calculational Conditions

Neutron source intensity during operation is 1x10^{20}n/s and a half of this value is applied to this model because of modeling the upper half space of the JT-60SU. Considering two-year D-T operation with neutron production rate of 4x10^{23} n/y, the conservative condition of induced activity calculation is continuous 8000 sec operation. Estimating time points for gamma-ray dose rates after shutdown are one day, one month and one year. The design limit values for radiation shielding properties are illustrated in **Table 2**.

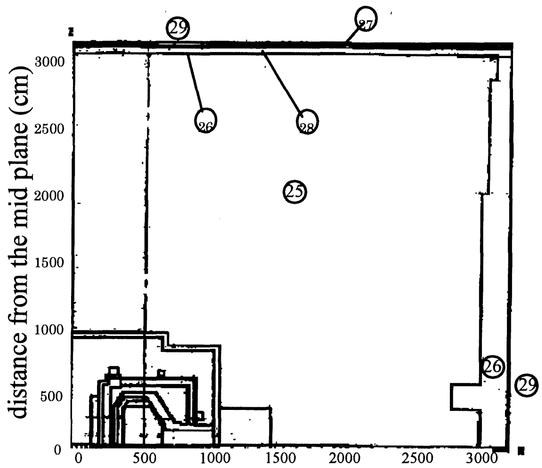

Fig. 1 Two dimensional RZ torus model from the torus center to the facility room in JT-60SU

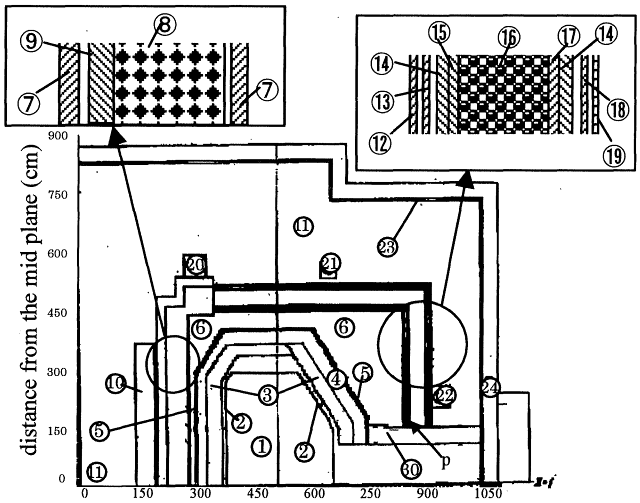

Fig. 2 Expanded two dimensional RZ torus model from the torus center to the cryostat in JT-60SU

III. Results and Discussions

1. Shielding Properties during Operation

Nuclear heating rates for thermal design of various components and nuclear heating rate in the winding pack of SCM are estimated as shielding properties during operation of JT-60SU. It is to be evaluated whether the thickness of shielding consisting of the vacuum vessel and added shield is sufficient or not for the shielding design limits.

Table 1 Zone number and name, and zone compositions

Zone No.	Zone name	Zone composition
1	Plasma	D 1.0x10^{-11} n./cm^3
2	Scrape-off layer	D 1.0x10^{-11} n./cm^3
3	Added shield	Ferrite steel : water = 0.8 : 0.2
4	Vacuum vessel I	SS316 : water = 0.7 : 0.3
5	Vacuum vessel II	SS316
6	Vacuum	
7	Thermal shield	SS316
8	Toroidal field coil inboard leg	Austenite SS:Cu:Liq. He:etc. =0.513:0.110:0.126:0.251
9	Outer coil support	SS316
10	Center solenoid coil	Austenite SS:Cu:Liq. He:etc. =0.552:0.118:0.136:0.194
11	Vacuum	
12	Thermal shield	SS316
13	Thermal shield	SS316
14	Coil case	TFC outboard leg,
15	Insulator	Austenite SS:Cu:Liq. He:insulator:etc.
16	Winding pack	=.491:0.105:0.121:0.017:0.266
17	Insulator	
18	Thermal shield	SS316
19	Thermal shield	SS316
20	Poloidal coil	
21	Poloidal coil	Austenite SS:Cu:Liq. He:etc.
22	Poloidal coil	.=0.552:0.118:0.136:0.194
23	Cryostat	SS316
24	Biological shield	Concrete
25	Air	Air
26	Room wall/sheering	Concrete
27	Polyethylene	Polyethylene
28	Roof	Concrete
29	Air	Air
30	Duct wall	SS316 : water = 0.7 : 0.3

Content of Co is supposed 0.05% (weight per cent) in stainless steel type 316 and austenite steel.

Table 2 Shielding design limits in radiation shield for JT-60SU

Shielding property	Shielding design limit
For inboard TFC* during operation	
nuclear heating rate in winding packs	0.2 mW/cm^3
For outboard TFC during operation	
nuclear heating rate in winding packs	1 mW/cm^3
Dose rate after shutdown	
Inside the cryostat in one month	20 μSv/h
Inside the facility room in one day	20 μSv/h

*TFC : toroidal field coil

(1) Neutron and gamma-ray fluxes, and dose rate

Total neutron and gamma-ray flux distributions during operation are presented in **Figs. 3** and **4**. A dose rate distribution converted from these radiation fluxes is also presented in **Fig. 5**.

(2) Nuclear heat in every component

Nuclear heats in various components are illustrated in **Table 3**. Nuclear heating rates on the added shield surface in the inboard and the outboard are 5.2 W/cm^3 and 6.0 W/cm^3, respectively.

(3) Nuclear heat in SCM

Nuclear heat in the toroidal SCMs is presented in **Table 4**. In this table, supposing the thickness of the thermal shield in the magnets to be 4mm of SS316, nuclear heat in the inboard and outboard thermal shields is estimated to be 316 W. Total nuclear heat in the toroidal magnets is 9.57x2=19.14 kW, where x2 means that the present model is a half of the whole tokamak. Nuclear heat in the poloidal magnets is illustrated in **Table 5**. Since the poloidal coils are arranged in symmetry with respect to the equatorial plane, the total nuclear heat of the poloidal coils is twice value of that in Table 5 as 2.3 kW. These total nuclear heat in every coil is important to design the refrigerator for the SCM.

Under the neutron production rate of 1x10^{20} n/s, peak nuclear heating rate in the SCM winding pack is 0.19 mW/cm^3 at the inboard on the mid-plane, and that at the outboard near the NBI duct, indicated by the point P in Fig. 2, is 0.27 mW/cm^3. These values satisfy the design limit of 0.2 mW/cm^3 in the inboard SCM winding pack and that of 1mW/cm^3 in the outboard SCM near the duct, respectively. Consequently, the total shield thickness in the present design is found to be sufficient for shield for SCM. And the

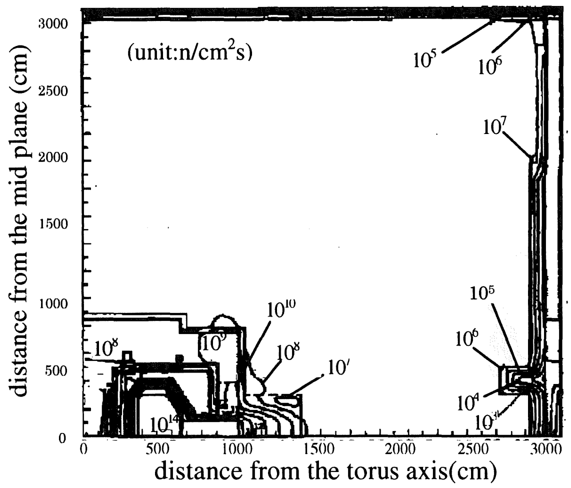

Fig.3 Total neutron flux distribution during DT operation of neutron production rate 10^{20} n/s in JT-60SU

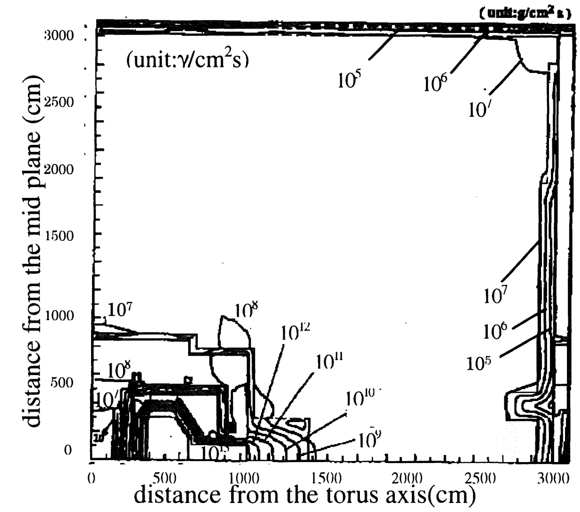

Fig.4 Gamma-ray flux distribution during DT operation of neutron production rate 10^{20} n/s in JT-60SU

Table 3 Nuclear heat in every zone of JT-60SU
(Real nuclear heats are double of these values)

Zone No.	Zone name	Nuclear heat (W)
1	Plasma	
2	Scrape-off layer	
3	Added shield	1.32x10^8
4	Vacuum vessel I	2.93x10^7
5	Vacuum vessel II	5.43x10^5
6	Vacuum	
7	Thermal shield	1.54x10^3
8	TFC inboard leg	1.57x10^3
9	Outer coil support	8.32
10	Center solenoid coil	0.42
11	Vacuum	
12	Thermal shield	} 3.21x10^3
13	Thermal shield	
14	Coil case(inner side)	
15	Insulator	
16	Winding pack	2.19x10^3
17	Insulator	} 1.05x10^3
18	Thermal shield	
19	Thermal shield	
20	Poloidal coil	6.85
21	Poloidal coil	2.30x10^1
22	Poloidal coil	1.13x10^3
23	Cryostat	7.75x10^4
24	Biological shield	8.34x10^4
25	Air	
26	Room wall/sheering	2.94x10^3
27	Polyethylene	1.94
28	Roof	2.10
29	Air	
30	Duct wall (NBI)	5.53x10^5

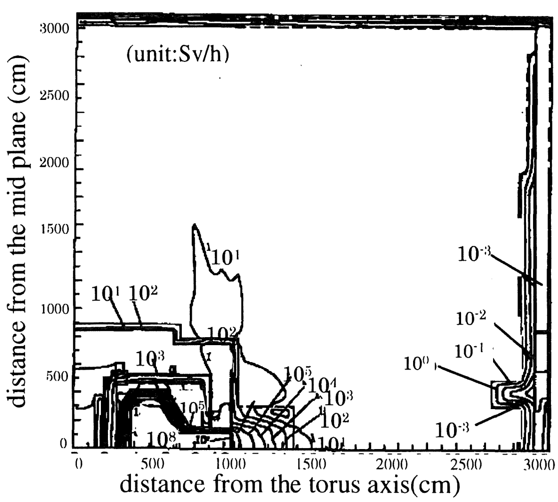

Fig.5 Dose rate distribution during DT operation of neutron production rate 10^{20}n/s in JT-60SU

thickness 40 cm of the NBI duct consisting of 80% of SS316 and 20% of water is also expected to be sufficient for shielding the SCM.

2. Dose Rate after Shutdown

Dose rates after shutdown are estimated from the viewpoint of safety for human direct access maintenance.

(1) Dose rate by two dimensional transport code

Dose rate distributions in one day, one month and one year after shutdown are estimated by the 2-D code as shown in **Figs. 6, 7** and **8**, respectively. The dose rate in the facility room at one day after shutdown is very high such as $10^2\sim10^3$ μSv/h because of decay gamma-ray from ^{24}Na (its half life=15.02 h). Its contribution to dose rate decreases in a week or so after shutdown. After that the effect of ^{40}K (half life $=1.28\times10^9$ y) on dose rate remains to the last and the dose rate becomes gradually the natural dose rate of 0.1 μSv/h. In fact the dose rates in the facility room expressed in Figs. 7 and 8 become to the value.

On the other hand, according to Fig. 7 the dose rate inside the cryostat at one month after shutdown is 10^3 μSv/h near NBI duct. The value by the two dimensional RZ torus model is overestimated due to the horizontal duct of the NBI opening with 360 degrees in the model. The three dimensional correction is therefore indispensable to the dose rate calculated by the two dimensional model.

Table 4 Nuclear heat in the toroidal SCMs (Real nuclear heats are double of these values)

Zone No.	Zone name	Nuclear heat (W)	
7	Thermal shield (4mm)	1.54×10^2	1.54×10^3
	Coil case	1.39×10^3	
8	TFC inboard leg		1.57×10^3
9	Outer coil support		8.32
12, 13	Thermal shield (4mm)	1.19×10^2	3.21×10^3
	Coil case	1.37×10^3	
14	Coil case	1.02×10^3	
15	Insulator + coil case	7.03×10^2	
16	Winding pack		2.19×10^3
17	Insulator + coil case	2.44×10^2	1.05×10^3
18	Coil case	2.64×10^2	
19	Coil case	4.99×10^2	
	Thermal shield (4mm)	4.3×10^1	
Sum			9.57×10^3

Table 5 Nuclear heat in the poloidal SCMs

Zone No.	Zone name	Nuclear Heat (W)
10	Center solenoid coil	0.42
20	Poloidal coil	6.85
21	Poloidal coil	2.30×10^1
22	Poloidal coil	1.13×10^3
Sum		$1.16\times10^{3*}$

*Total nuclear heat is twice of this summed value.

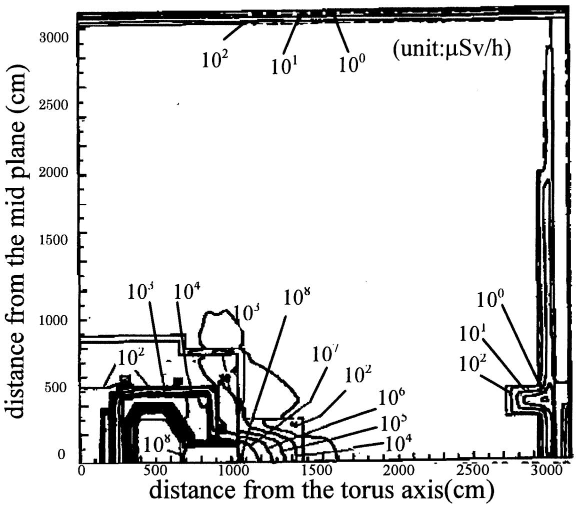

Fig.6 Dose rate distribution at one day after shutdown of 8000sec DT operation with neutron production rate 10^{20}n/s in JT60SU.

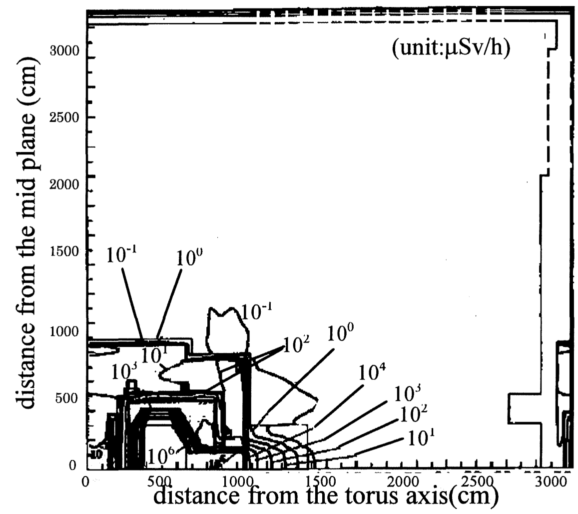

Fig.7 Dose rate distribution at one month after shutdown of 8000sec DT operation with neutron production rate 10^{20}n/s in JT-60SU.

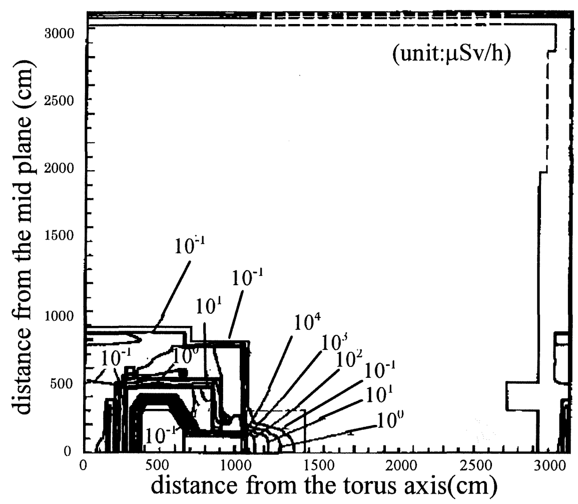

Fig.8 Dose rate distribution at one year after shutdown of 8000sec DT operation with neutron production rate 10^{20}n/s in JT-60SU.

(2) Correction for three-dimensional configuration

The ratio of the high energy neutron flux (> 0.1 MeV) by 3-D model to that by 2-D model is suitable as the correction factor for 2-D calculations, since high energy neutrons take part in the induced activity in the case of 14 MeV neutron source.

The ratio of other facility or reactor can be applied as a correction factor if used materials are roughly the same and the geometrical configurations are roughly similar to each other. The relation between JT-60SU and ITER is such a one. From the neutron fluxes by the 3-D Monte Carlo code MCNP and the 2-D Sn code DOT3.5 for ITER, the correction factors inside the cryostat are estimated at three points A, B and C indicated in **Fig. 9**, and these values are shown in **Table 6**. Since the ratios of ϕ_{3D}/ϕ_{2D} become from 1/32 to 1/26, the round value of 1/30 is applied as the correction factors.

(3) Corrected dose rates

In the present induced activity calculation, the continuous 8000 sec operation is assumed. In a real operation, 40 pulses of 200 sec period will be operated in two years. Therefore, only several month operation before shutdown contributes to the dose rate in one month after shutdown. Consequently, the correction factor is considered less than 1/2 due to the real pulse pattern.

From the above discussion, correcting the dose of 2-D model by the factor of 1/30 as 3-D configuration correction and the factor of 1/2 due to pulse pattern, the dose rate can be seen ~10μSv/h. Therefore, dose rate in the cryostat at one month after shutdown is expected to satisfy the design target of 20μSv/h.

While, workers cannot enter into the facility room one day after shutdown since dose rate in the room is several hundred μSv/h in one day after shutdown due to decay gamma-ray from ^{24}Na. They must wait a week or so to enter the room.

IV. Conclusion

Neutronics investigation has been made for the JT-60SU and following results are obtained.

1. Under neutron production rate of 1×10^{20} n/s due to D-T operation, peak nuclear heating rate in the SCM winding pack is 0.19 mW/cm^3 at the inboard on the mid-plane, and that in the outboard near the NBI duct is 0.27 mW/cm^3. These values satisfy the design limit of 0.2 mW/cm^3 in the inboard SCM winding pack and that of 1 mW/cm^3 in the outboard SCM near the duct, respectively.

2. The dose rate in one month after shutdown of 40 pulse operation of 200 sec period in two years is ~10 μSv/h in cryostat near the NBI duct and is expected to satisfy the design target of 20 μSv/h.

3. Consequently, total shield thickness of vacuum vessel in inboard and outboard, and additional shielding in the present design is expected to barely satisfy the shielding design targets.

Table 6 Correction factors of $\phi_{3D/2D}$ by using 3-D and 2-D high energy (>0.1MeV) neutron fluxes in ITER

Position	ϕ_{3D} (n/cm^{2}s)	ϕ_{2D} (n/cm^{2}s)	ϕ_{3D}/ϕ_{2D}
Back of TFC (A)	5.5×10^8	1.7×10^{10}	0.032
Between TFC and cryostat (B)	4.3×10^8	1.1×10^8	0.039
Near cryostat (C)	4.4×10^8	1.2×10^8	0.039

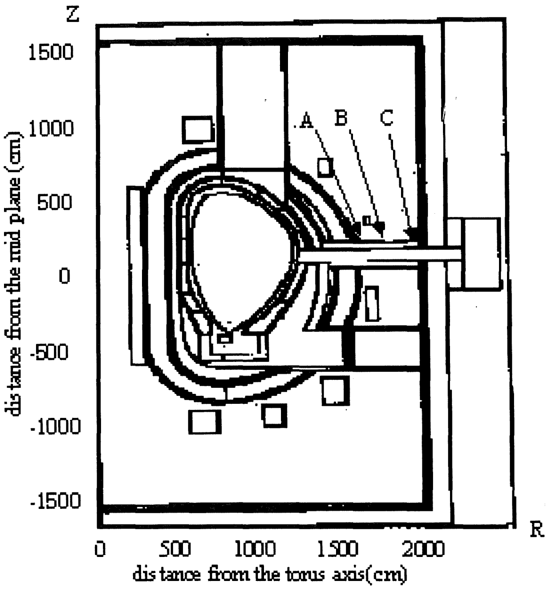

Fig.9 Evaluation points (A,B,C) for the ratio of the high energy neutron fluxes in 2-D torus model of ITER.[5]

— REFERENCES —

(1) Maki, K., *et al.* : *Fusion Eng. Design*, **22**, 427(1993).
(2) Maki, K., *et al.* : *Fusion Eng. Design*, **24**, 315(1994).
(3) Shibata, K., *et al.* : *Proc. 19th Smp. Fusion Technol.*, 799 (1996).
(4) Sato, S., *et al.* : *Fusion Technol.*, **34**, 1002 (1998).
(5) Maki, K., *et al.* : *Proc. 4 th Int. Symp. Fusion Nucl. Techonl.*, Part A, 193 (1998).
(6) Santoro, R. T., *et al.* : *Proc. 4th Int. Symp. Fusion Nucl. Technol.*, Part A, 593 (1998).
(7) Youssef, M., *et al.* : *Proc. 4th Int. Symp. Fusion Nucl. Technol.*, Part C, 155 (1998).
(8) Rhoades, W. A., Mynatt, F. R. : *ORNL-TM*-4280, (1973).
(9) Maki, K., *et al.* : *JAERI-M* 91-072, (1991).
(10) Maki, K., *et al.* : *JAERI-M* 91-073, (1991).
(11) Shibata, K., *et al.* : *JAERI*-1319, (1990).
(12) Fukumoto, H. : *J. Nucl. Sci. Technol.*, **23,** 97 (1986).
(13) Briesmeister, J. F. (Ed.) : *RSIC/CCC*-200, Radiation Shield Information Center, (1991).