Nuclear Radiation Analysis in R-Tokamak

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(presented by Y. Ogawa.)

In R-tokamak it is planned to study the burning physics of a D-T plasma. The total neutron number produced by one D-T shot is estimated to be 1.6×10^{18} n/shot, assuming that the energy gain Q is 0.3, the NBI power is 15 MW and the burning time is 1 sec. Thus in the design of the R-tokamak, radiation shielding and the maintenance of the device should be considered to be severe technical problems. As the base of these considerations, the evaluation of the dose level is the essential problem. We calculated nuclear radiation on the base of the 1-D P_5S_8 ANISN code,[1)] where cylindrical and spherical models are applied. The configuration and materials of the structure are shown in Fig.1.

In the following, attention is paid to the induced activity of stainless steel together with Al-alloy as the structural materials; where the latter is the low activation material.

1. Neutron and Prompt γ-Ray Fluences and the Biological Dose

Neutron and prompt γ-ray fluences in one D-T shot are shown in Fig.2(a). The dose rate in the test cell is also shown in Fig.2(b). Total neutron fluence and that of 14 MeV component at the inner surface of the vacuum vessel are about 1.6×10^{13} n/cm^2/shot and 6.7×10^{12} n/cm^2/shot, respectively. Assuming that 10^3 D-T shots are performed, the total neutron fluence, therefore, becomes 1.6×10^{16} n/cm^2 in R-tokamak. Under this total neutron fluence, one can use polyimide, ceramics and epoxy while teflon and rubbers can not. Also some of electrical elements can not use near the tokamak. The doses just outside of the device-shielding (igloo in TFTR) and inner surface of the building-wall are 2.6×10^3 rem/shot and 1.0×10^2 rem/shot, respectively. Figure 3 shows the dose outside of the building-wall as the function of the wall thickness. Here we may note that if the wall thickness is more than 1.5 m, the dose due to the prompt γ-ray becomes larger than that due to the neutron.

2. The Induced Activity

The induced activity of structural materials is calculated with THIDA code[2] which has been developed in JAERI. The attention is paid to two structural materials; one is the stainless steel and the other is the Al-alloy. In both cases, the TF coil conductor is made of copper, because the magnetomotive force becomes much larger if it is made of Al-alloy. Figure 4 shows the temporal variation of the dose rate outside of the vacuum vessel after one D-T shot and Figure 5 shows the spatial profile of the dose rate. In the case of the S.S. the dose rate is 4.5 mrem/h after 1 week from the shot and decreases to 2.5 mrem/h after 3 months. As for the case of the Al-alloy, the dose rate is somewhat high at the level of 10 mrem/h after 1 week but it decreases to very low level of 0.1 mrem/h after 2 weeks; the latter level is about 1/40 times of the S.S. case.

Figure 6 shows the γ-ray spectrum for both cases. In the case of the S.S., peak of γ-ray comes from radioisotopes ^{58}Co and ^{54}Mn, where the former is produced by the reaction ^{58}Ni (n,p)^{58}Co and the latter ^{54}Fe(n,p)^{54}Mn, ^{55}Mn(n,2n)^{54}Mn. The half-lives are 71 days for ^{58}Co and 303 days for ^{54}Mn. Therefore, the dose rate does not decrease so much after 3 months. In the case of the Al-alloy, two peaks of γ-ray, which is corresponding to ^{24} Na, appear clearly after 1 week, where ^{24}Na is produced by the reaction ^{27}Al(n,α)^{24}Na; the half-life is 15 hours. The steep decrease of the dose rate after 1 day, as shown in Fig.4, refers to the decay of ^{24}Na. After 2 weeks, the ^{24}Na γ-ray disappears while the ^{60}Co and ^{54}Mn γ-ray peaks remain apparently. Here ^{60}Co and ^{54}Mn are produced by ^{63}Cu(n,α)^{60}Co and ^{55}Mn(n,2n)^{54}Mn reactions respectively; ^{63}Cu and ^{55}Mn are included in the Al-alloy of 2219, and also ^{63}Cu in the TF coil conductor. Because the half-life of ^{60}Co is 5.2 years, the dose rate remains at the level of 0.1 mrem/h or less during one year.

Next, we calculate the dose rate due to the additional elements of 1 % in weight in the Al-alloy. The results are shown in Fig.7. From this figure we can easily see that the contribution of the additional elements to the dose rate.

If Al-alloys are used for the material of the vacuum vessel and the TF coil frame, the induced activity level is reduced to 1/40-1/30 times compared with that in the case of S.S. after 2 weeks.

3. Activation of the Air

The activation of the air is calculated using with 1-D ANISN code, where radioisotopes considered are ^{41}Ar, ^{13}N, ^{16}N and ^{14}C. The half-life and maximum permissible concentration (MPC) of each radioisotope are listed in Table 1. We see that the concentration of ^{41}Ar is the most important one and is 220 pCi/cc/shot inside of the device-shielding. It takes 16.6 hours to reduce to the MPC level without ventilation. As for ^{13}N and ^{16}N, it takes 2.5 hours and 5.3 minutes to reduce to the MPC level, respectively. We may note that the concentration of ^{14}C is very low at 8.5×10^{-4} pCi/cc, and this is 10^{-3} times as low as that of the MPC level. These results are also summarized in Table 1. We may enter the test cell after the cooling time of 1 day, even if the air is not ventilated.

4. Activation of the Cooling Water

The activation of the cooling water in the TF coils and that of the dissolved copper in it are roughly estimated. Here, the radio-isotope ^{16}N of 200 μCi/cc is produced after one D-T shot, and it takes 2.8 minutes to reduce to the MPC level in the water (3×10^{-5} μCi/cc). Assuming that cooling water flows to the ion exchange resin section at a velocity of 4.3 m/s through the cooling pipe of 50 m legnth and 50 cm in diameter, we estimate the total dose to be 0.26 rem/shot. Next, we estimate the accumulation of ^{60}Co at the ion exchange resin section. If the inner wall of the cooling conduit of the TF coil dissolved at the rate of 10 μm/year and the D-T discharge of 10^3 shots/year are continuously performed, the accumulation of ^{60}Co amounts to 0.21 mCi after 5 years. The dose rate at 1 m distance is about 0.27 mrem/h.

5. Environmental Dose due to the Skyshine

The dose in the environment due to the skyshine is calculated based on Thomas equation,[3)] Nakamura et al. equation[4)] and SKYSHINE-II code.[5)] In Fig.8, the doses after one shot are plotted as the function of the distance from the neutron source for various ceiling thicknesses. The environmental doses evaluated from three methods agree well for the neutron skysine. If we limit the dose below 10^{-3} mrem/shot at 250 m distance, the ceiling thickness of 120-130 cm is necessary. The doses due to the prompt and secondary γ-ray skyshine are calculated by SKYSHINE-II code. If the ceiling thickness is 2 m, the dose due to the prompt γ-ray becomes comparable to that due to the neutron. The dose due to the secondary γ-ray is about 10^{-2} times lower than that due to the neutron.

6. Radioactivity in D-D Discharge

The radioactivity problems related to D-D discharge are considered. In the R-tokamak, it is expected the following fusion products in one D-D shot;

2.45 MeV neutron	1.9×10^{16} n/shot
tritium	1.9×10^{16} atoms/shot
	(0.91 mCi/shot)
14 MeV neutron	5.5×10^{14} n/shot

In Fig.9, the temporal variations of the dose rate are shown in the cases of the S.S. and Al-alloy. In the case of S.S., the dominant radioisotopes ^{58}Co and ^{54}Mn are produced by 2.45 MeV neutron, which exceeds the threshold energy. Therefore the dose rate is roughly proportional to the total neutron amount. In the case of Al-alloy, the dominant radioisotope ^{60}Co is not produced by 2.45 MeV neutron, because the threshold energy of $^{63}Cu(n,\alpha)^{60}Co$ reaction is considerably high, that is about 6 MeV. Therefore, the dose rate is proportional only to 14 MeV neutron amount.

7. Summary

On the problems related to the nuclear radiation of R-tokamak, we summarized as follows:

i) The total neutron fluence at the vacuum vessel is about 1.6 x

10^{13} n/cm^2/shot.

ii) In the case of S.S. structural materials, the dose rate outside of the vacuum vessel is estimated to be 4 mrem/h per one D-T shot after 2 weeks. As for the case of Al-alloy, this dose rate can be reduced to 0.1 mrem/h.

iii) The air activates much higher than the MPC level for ^{41}Ar, ^{13}N and ^{16}N just after the shot. However, these radioisotopes decay below the MPC level after the cooling time of one day without air ventilation.

iv) The ceiling thickness of 120-130 cm is necessary, if we limit the dose below 10^{-3} mrem/shot at 250 m distance.

v) For D-D discharge, the dose rate is estimated to be 0.01 mrem/h/shot after 2 weeks in the case of S.S., and that is 3×10^{-5} mrem/h/shot in the case of Al-alloy.

Figure Captions

Fig. 1 1-D calculation models; (a) Cylindrical configuration and (b) Spherical one. Structural materials considered are also listed.

Fig. 2 Spatial profiles of (a) the neutron and gamma-ray and (b) the biological dose in the test cell.

Fig. 3 Operationl dose outside of the building-wall versus the wall thickness.

Fig. 4 Temporal variation of the dose rate after one D-T shot in the case of S.S(—▲—) and Al-alloy(—●—). The place is outside of the vacuum vessel (r=71 cm).

Fig. 5 Spatial profile of the dose rate in the cases of S.S and Al-alloy.

Fig. 6 gamma-ray spectrum outside of the vacuum vessel (r=71 cm).

Fig. 7 Dose rate due to additional elements included in Al-alloys. Elements considered here are Mn, Ni, Fe, Cr, Cu and Mo.

Fig. 8 Environmental dose due to the skyshine by three methods: Thomas equation, Nakamura et al. equation and SKYSHINE-II code.

Fig. 9 Temporal variations of the dose rate in D-D discharge. The dose rate in D-T discharge, which is the same one of Fig. 4, is also given as a reference.

References

1) K. Koyama et al., "RADHEAT-V3, A Code System for Generating Coupled Neutron and Gamma-Ray Group Constants and Analyzing Radiation Transport", JAERI-M7155 (1977).

2) H. Iida and M. Igarashi, "THIDA-Code System for Calculation of the Exposure Dose Rate around a Fusion Device", JAERI-M8019 (1978) (in Japanese)

3) R. H. Thomas, "Proton Synchrotron Accelerators" in Engineering Compendium on Radiation Shielding, Vol.I, p.56, Springer-Verlag, Berlin (1968).

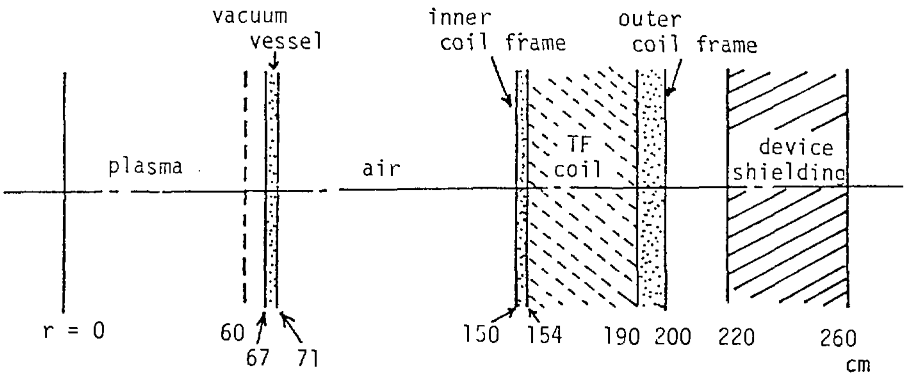
4) T. Nakamura and T. Kosako, Nuclear Science and Engineering 77 (1981) 168.

5) C. M. Lampiley, RRA-T 7901.

Radioisotope	Half-life	MPC	Concentration per one D-T shot	Cooling time
$^{40}Ar(n,\gamma)^{41}Ar$	1.82 hours	0.4 pCi/cc	220 pCi/cc	16.6 hours
$^{14}N(n,2n)^{13}N$	10.1 minutes	0.5 pCi/cc	1.6×10^{4} pCi/cc	2.5 hours
$^{16}O\ (n,p)^{16}N$	7.3 seconds	2×10^{-7} pCi/cc	2.1×10^{6} pCi/cc	5.3 minutes
$^{14}N\ (n,p)^{14}C$	5730 years	1.0 pCi/cc	8.5×10^{-4} pCi/cc	none

Table 1 Activation of the Air (Concentrations inside of the Device-shielding are listed)

(a) Cylindrical configuration



Structural Materials

(i)	SUS 304	high Mn steel	Cu	high Mn steel	Ord. Concrete & 1.5% B_4C
(ii)	Al-6063	Al-2219	Cu	Al-2219	Ord. Concrete & 1.5% B_4C

(b) Spherical configuration

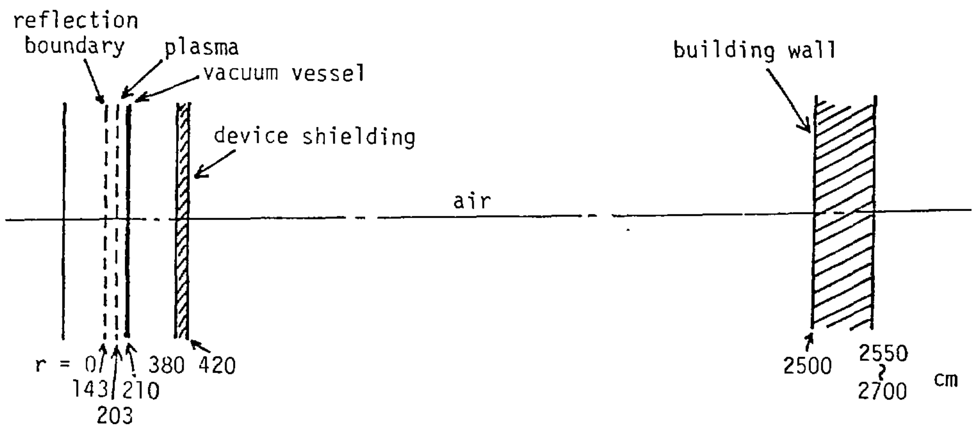


Fig. 1 Calculation Models and Structural Materials

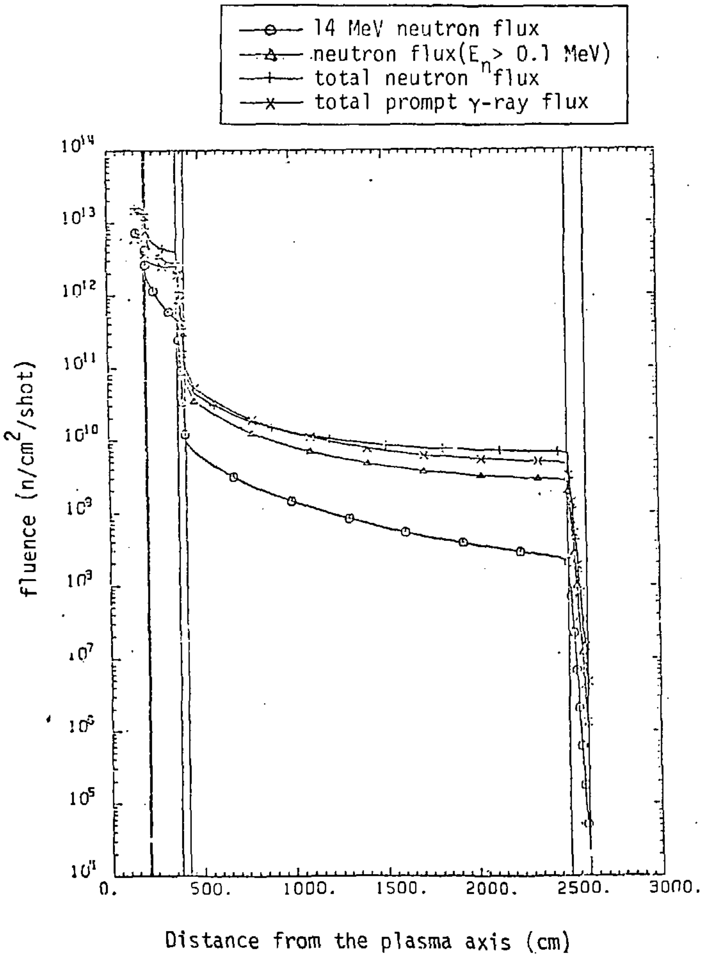


Fig. 2(a) Neutron and Prompt γ-ray

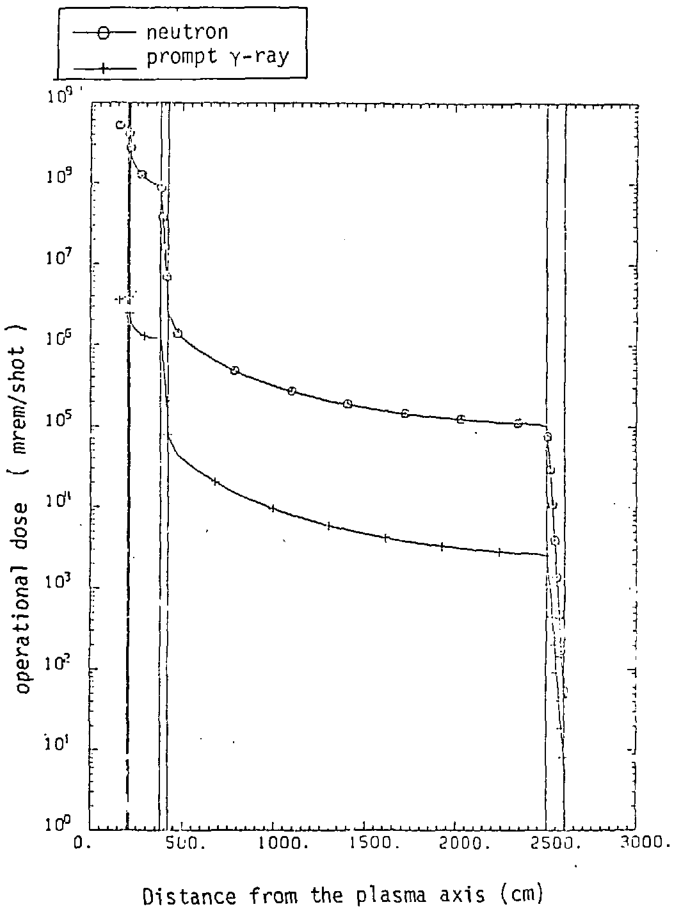


Fig. 2(b) Biological Dose

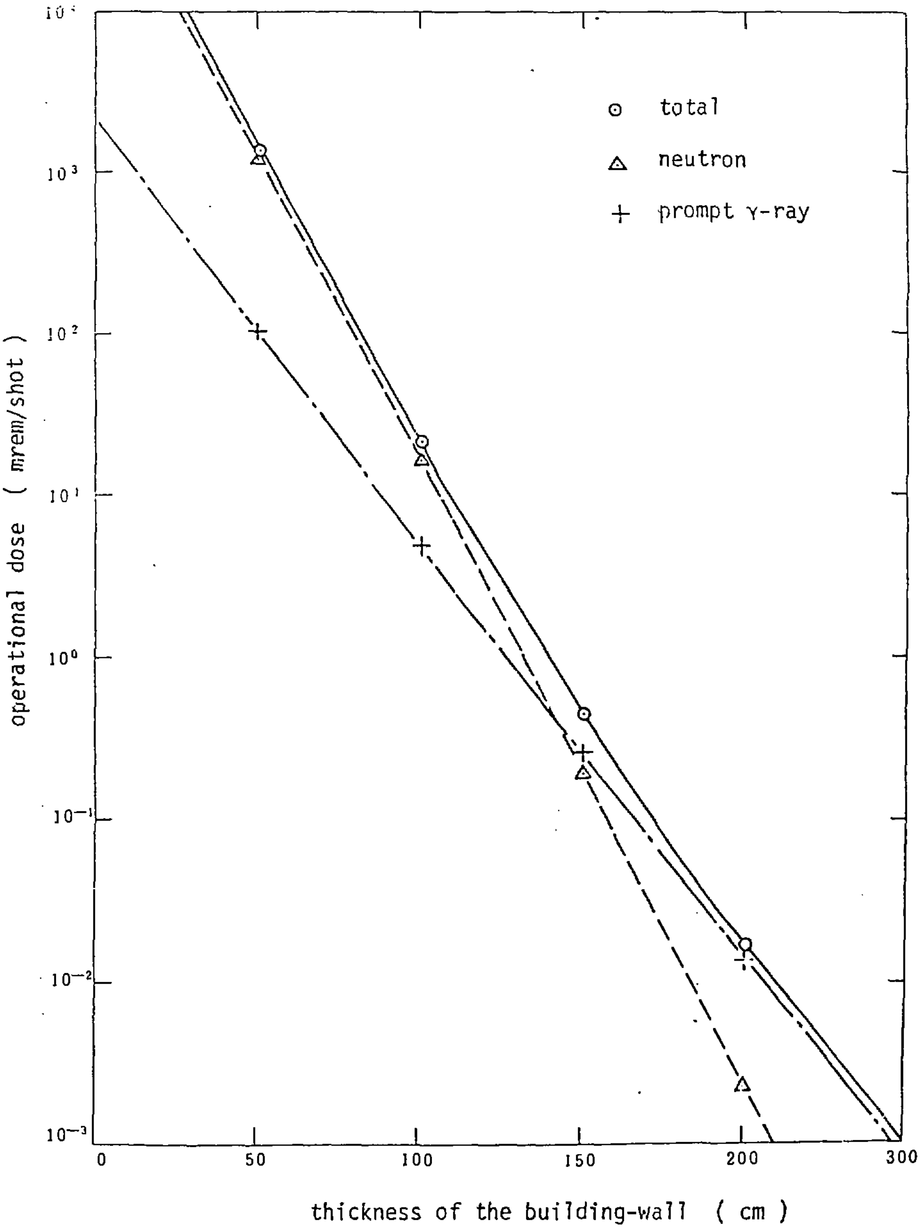


Fig. 3 Operational Dose Outside of the Building-Wall

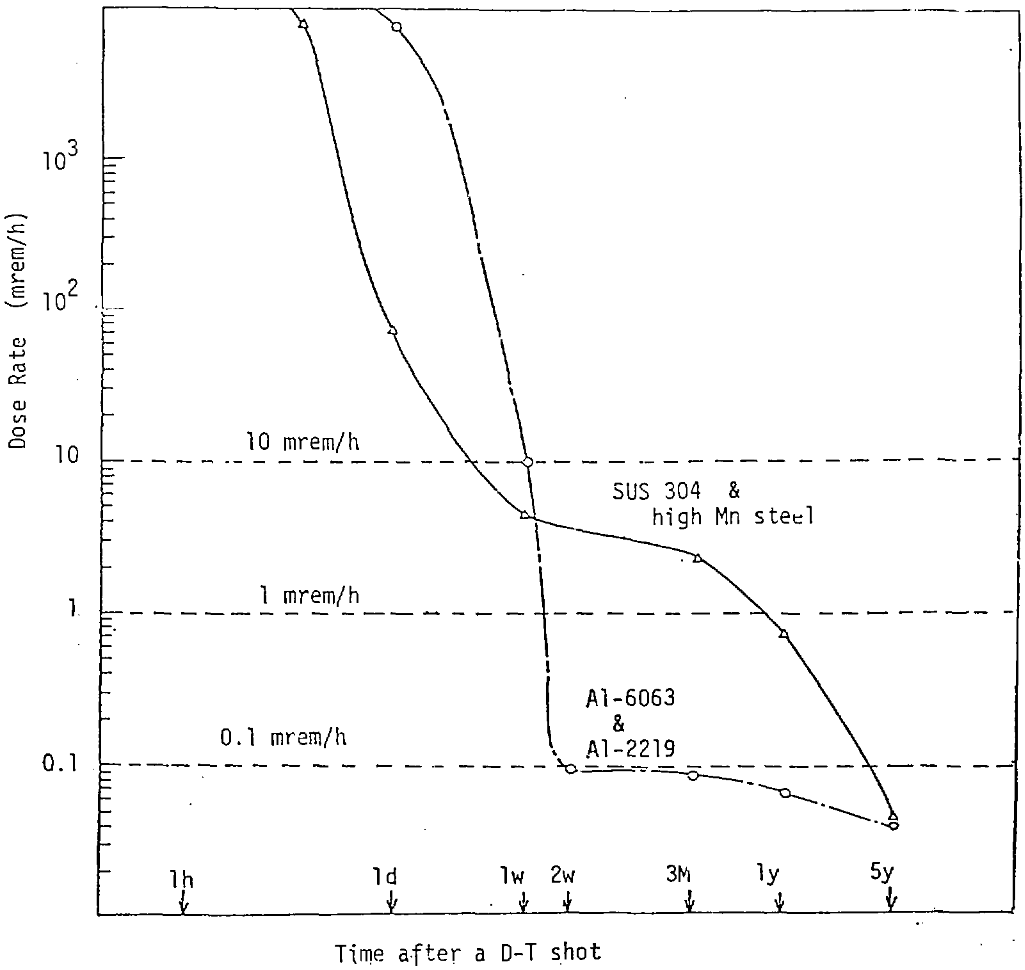


Fig. 4 Temporal Variation of the Dose Rate

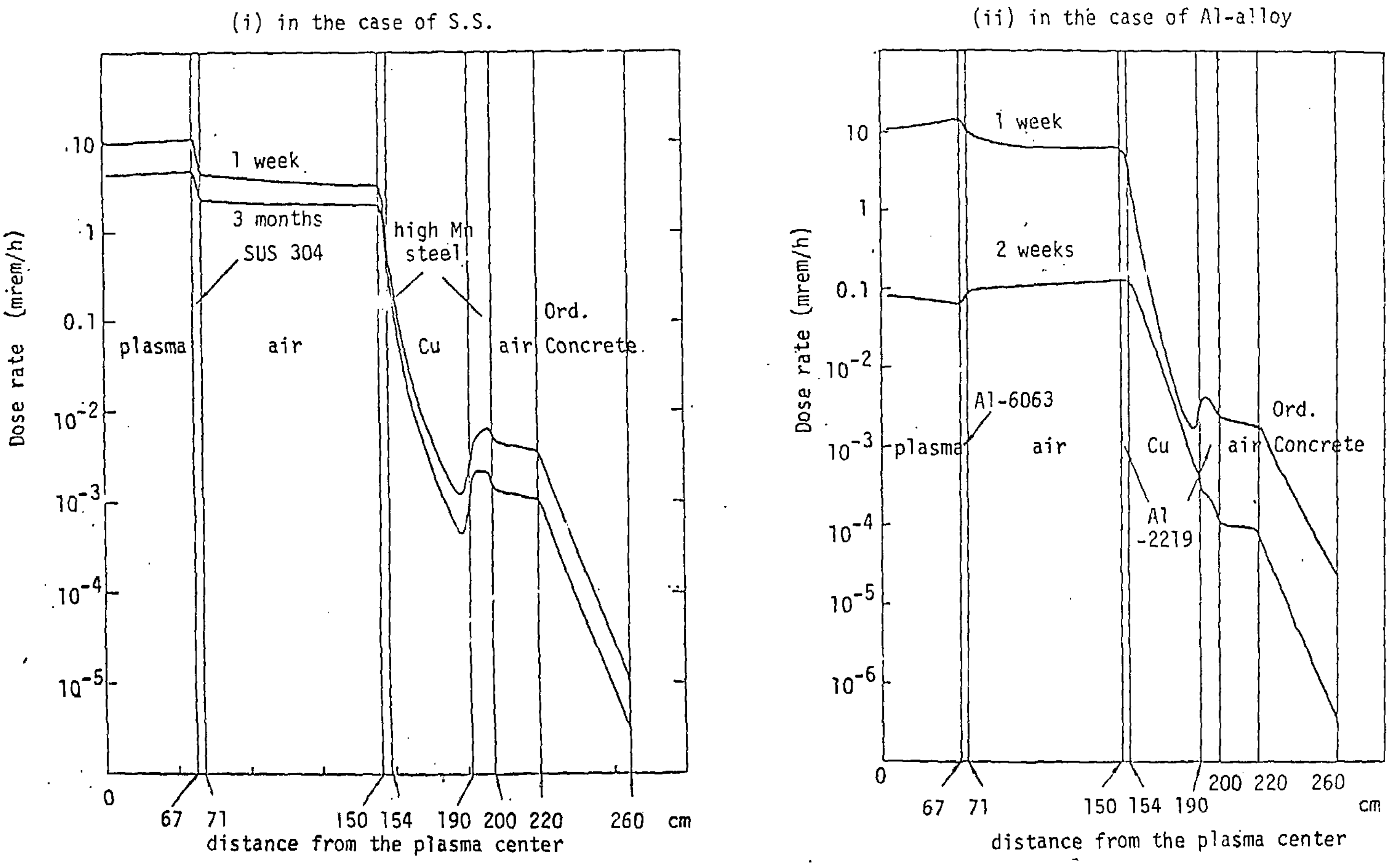


Fig. 5 Spatial Profile of the Dose Rate After One D-T Shot

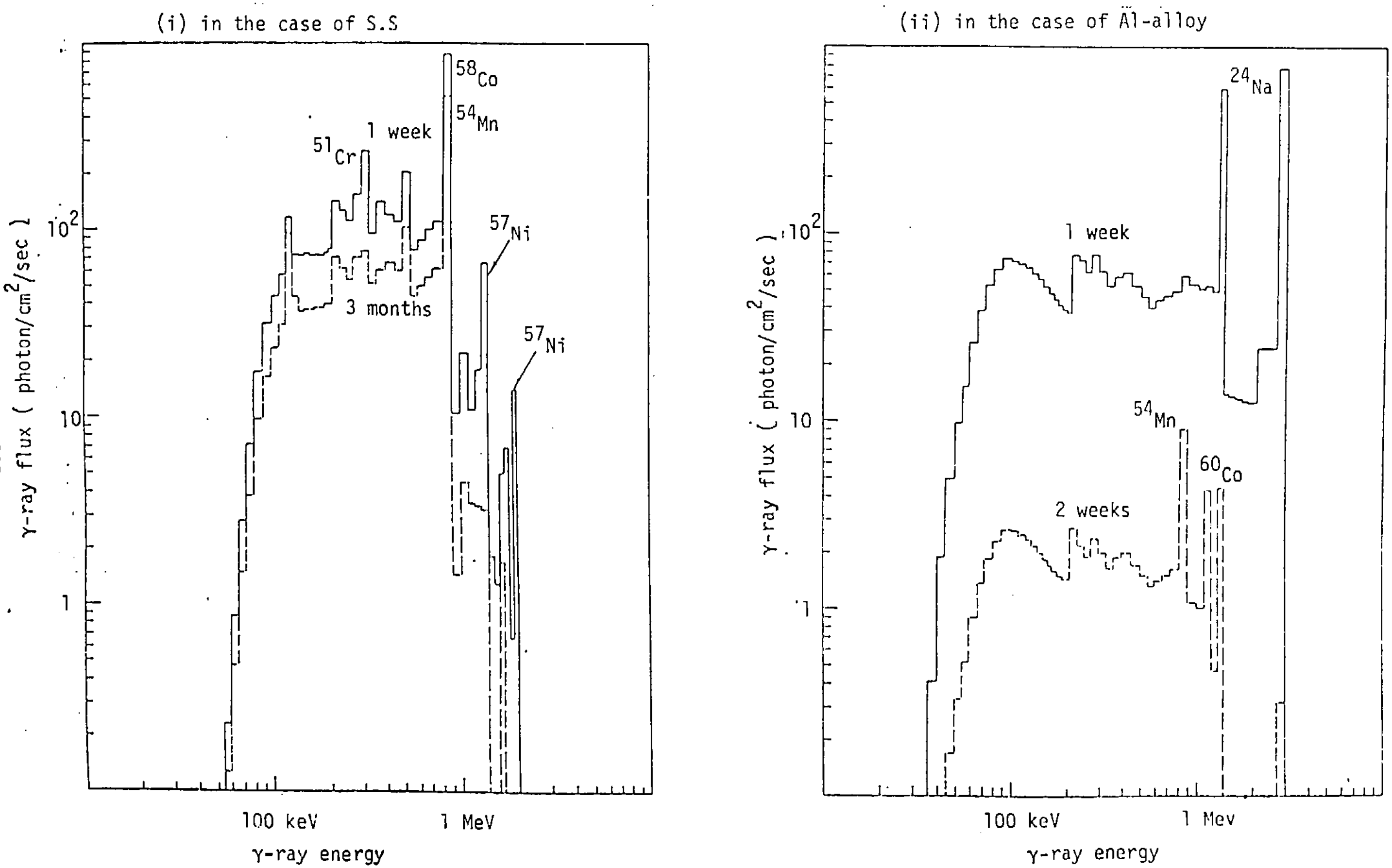


Fig. 6 γ-Ray Spectrum

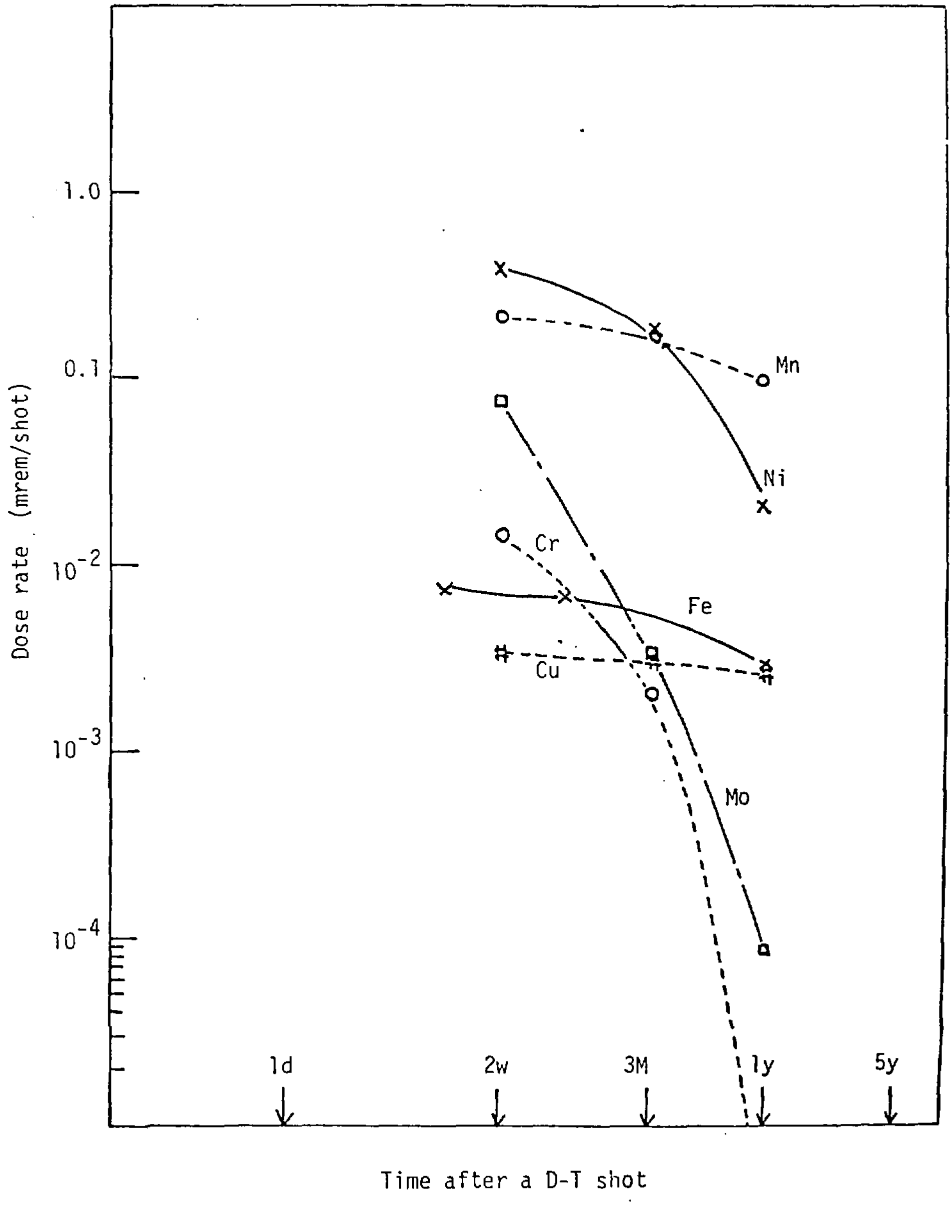


Fig. 7 Dose Rate due to Additional Elements included 1% weight in Al-alloys

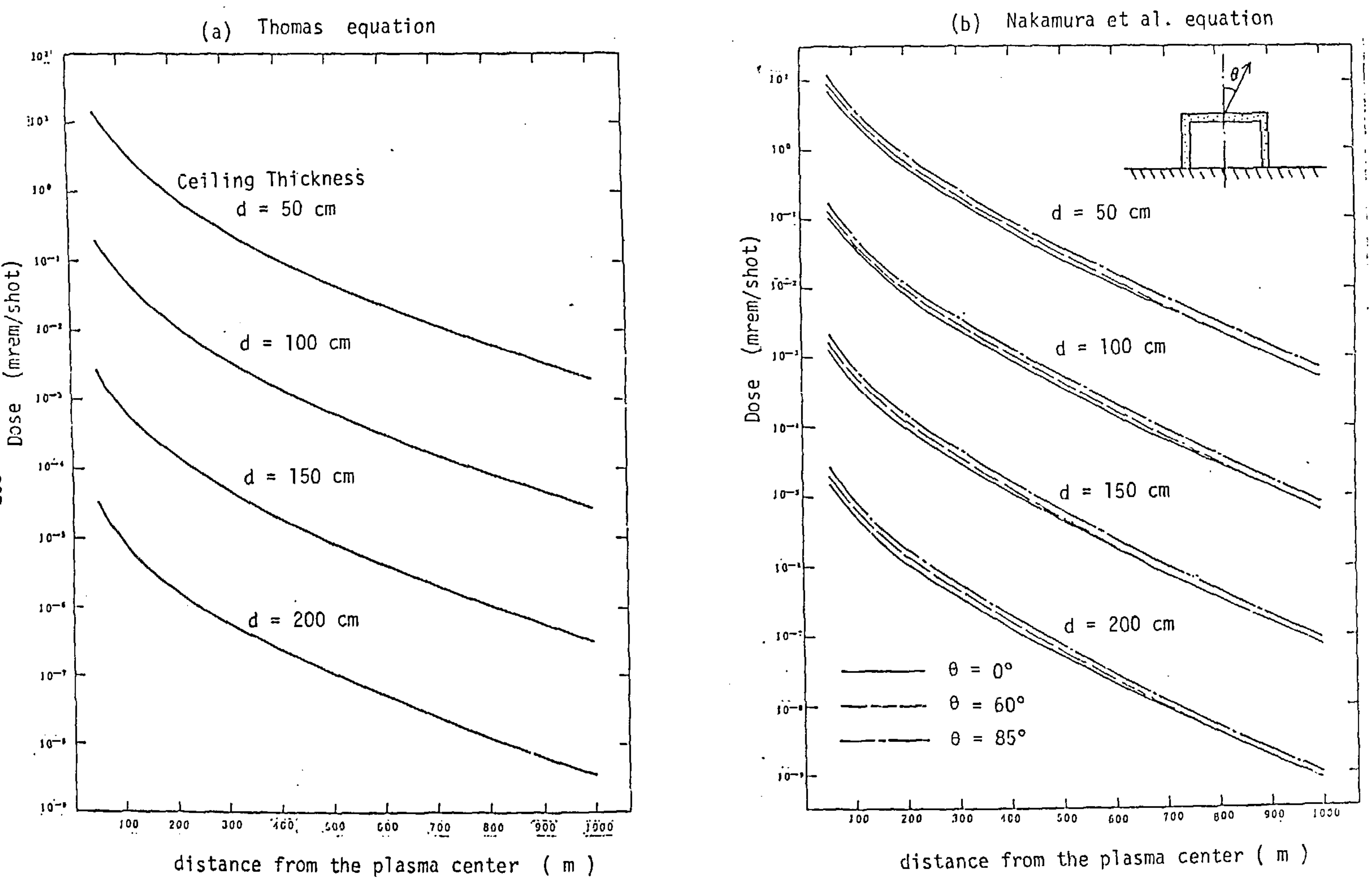


Fig. 8(a),(b) Environmental Dose in One D-T Shot
(Thomas & Nakamura et al. Equations)

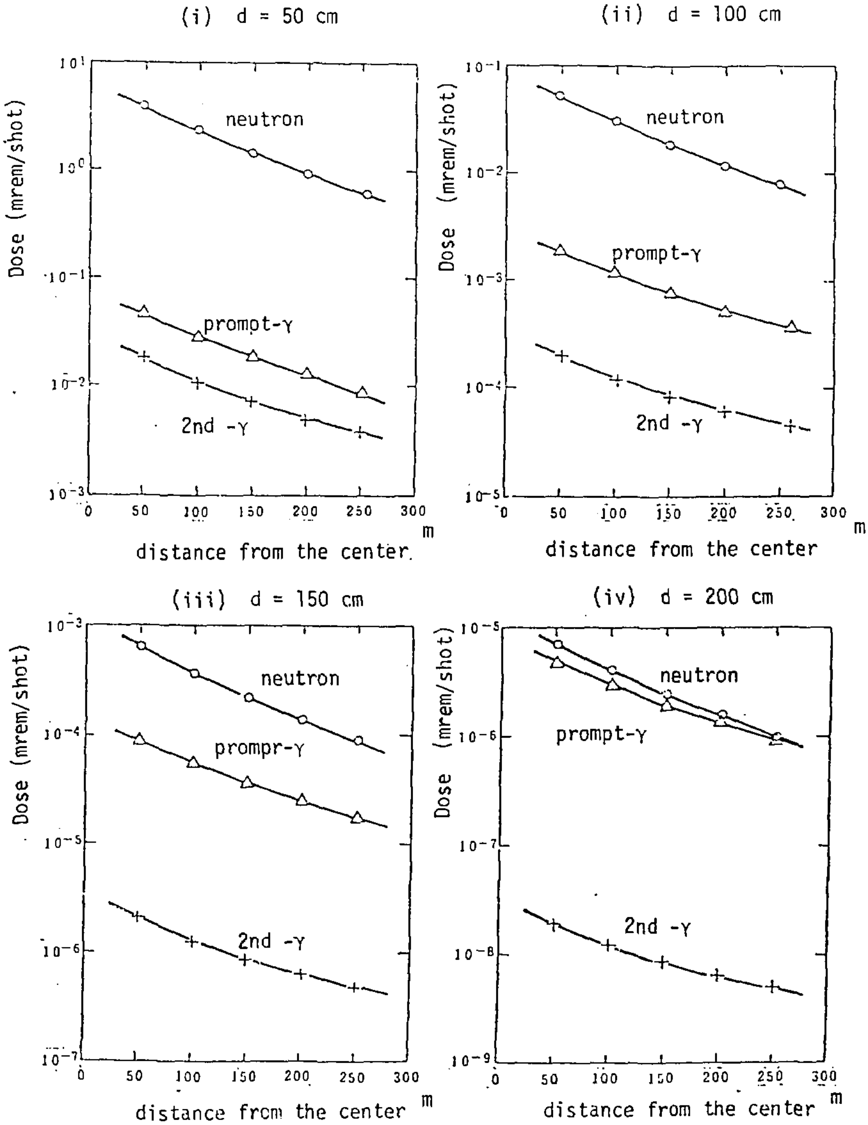


Fig. 8(c) Environmental Dose in One D-T Shot
(SKYSHINE - II Code)

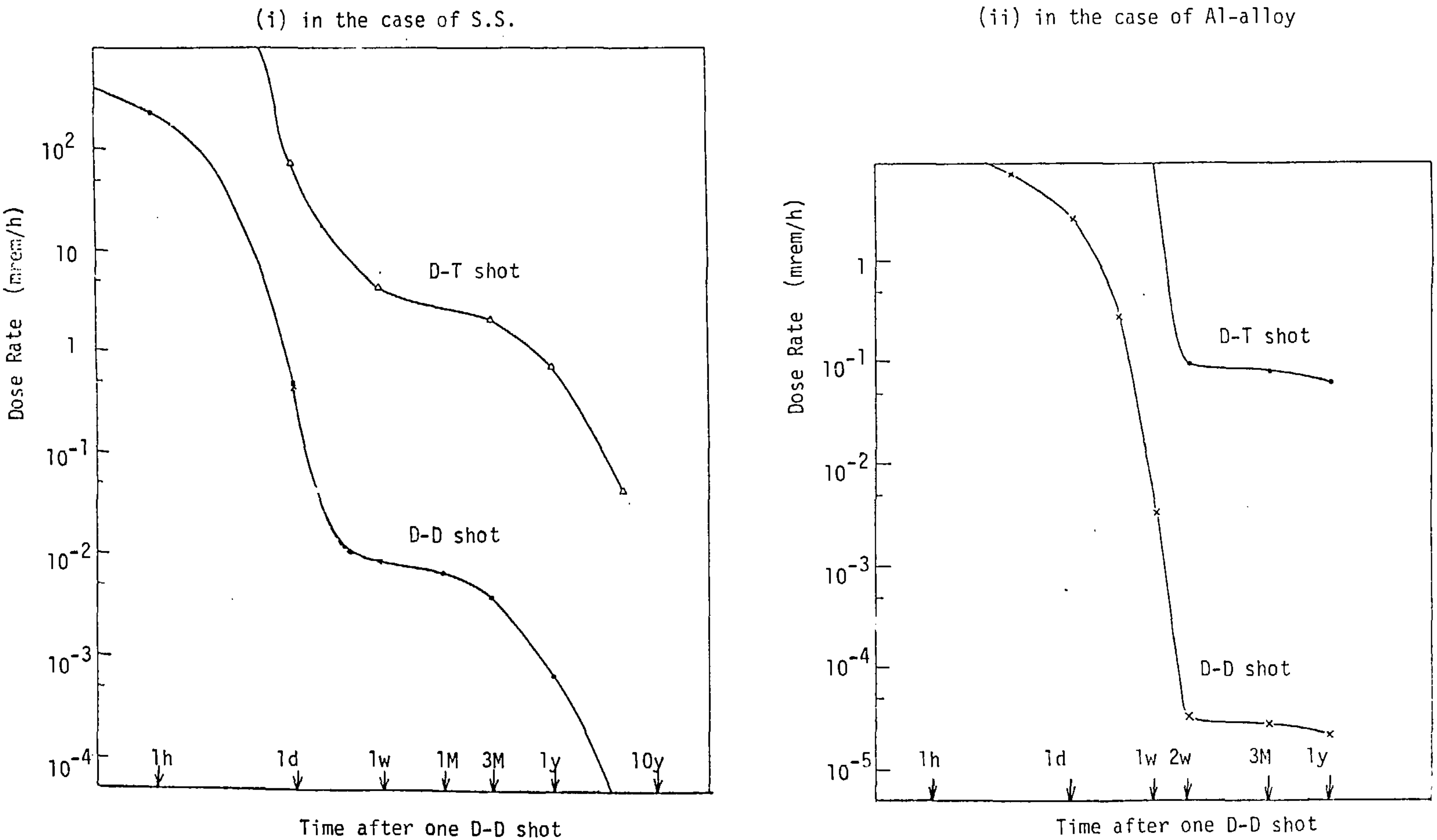


Fig. 9 Dose Rate in D-D Discharge