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PRE-ANALYSES OF SS316 AND SS316/WATER BULK SHIELDING EXPERIMENTS

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Chikara KONNO, Fujio MAEKAWA, Atsushi IWAI, Kazuaki KOSAKO*
Yujiro IKEDA, Yukio OYAMA and Hiroshi MAEKAWA

日本原子力研究所
Japan Atomic Energy Research Institute

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Chikara KONNO, Fujio MAEKAWA, Atsushi IWAI, Kazuaki KOSAKO*
Yujiro IKEDA, Yukio OYAMA and Hiroshi MAEKAWA

Department of Reactor Engineering
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

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As one of the '93 ITER/EDA emergency tasks, JA-3 (Bulk Shielding Experiments: Phase IA 'Pre-& Post-Analyses and Preparation of SS316 and SS316/Water Experiments') was authorized. This report compiled the pre-analyses for the SS316 and SS316/Water experiments. The pre-analysis of SS316 experiment was performed to determine the size and configuration of the experimental assembly using the discrete ordinate code DOT3.5 and the FUSION-40 nuclear data library. The calculation suggested that the assembly should be a cylindrical shape, the diameter and thickness of which were 1.2 m and 1.1 m, respectively. The 0.2 m thick SS316 source reflector was also necessary to simulate fusion reactor neutron environment and to decrease room returned background neutrons.

In the SS316/Water experiment, the volume ratio of SS316 to water was adopted to be 4:1, which was recommended in ITER/CDA. The basic size of the SS316/water experimental assembly was set to be the same as the SS316 experimental assembly. The heterogeneity effect on the shielding performance due to the layered structure of SS316 and watar was not so large in the water layer up to 30 mm in thickness.

The method how to reduce background by room returned neutrons was examined. In order to calculate neutron reflection by the wall of the experimental room precisely, the S_N code DOT-DD and the multigroup double-differential form cross section library DDXLIB3 were used instead of the DOT3.5 code. The calculation pointed out the following results. 1)The S/N (Signal to Noise ratio) was 0.5 at the depth of 0.9 m if there was no additional shield. 2)A 0.1 m thick additional polyethylene layer decreased

* Sumitomo Atomic Energy Ind., Ltd.

background neutrons to 1/10. 3)A 0.4 m thick source reflector was not so effective since it reduced background by only a half. The additional shield of the polyethylene thicker than 0.1 m was found to be the most preferable.

The final experimental configurations of the SS316 and SS316/water experiments were determined according to these pre-analyses.

Keywords : ITER/EDA, Bulk Shielding Experiment, Pre-analysis, SS316, SS316/Water, 14 MeV Neutron, FNS, DOT3.5, FUSION-40, Source Reflector, Heterogeneity Effect, DOT-DD, DDXLIB3

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ＳＳ316とＳＳ316／水バルク遮蔽実験の予備解析

日本原子力研究所東海研究所原子炉工学部
今野　力・前川　藤夫・岩井　厚志・小迫　和明*
池田裕二郎・大山　幸夫・前川　洋

（1994年8月24日受理）

'93 ＩＴＥＲ／ＥＤＡ緊急タスクの一つとして，ＪＡ－３（バルク遮蔽実験：第１段階A'ＳＳ316とＳＳ316／水実験の予備・本解析と準備'）が認められた。本レポートは，ＳＳ316とＳＳ316／水実験の予備解析の結果をまとめたものである。ＳＳ316実験の予備解析は，実験体系の大きさと構成を決定するために，ディスクリートオーディネートコードＤＯＴ 3.5とFUSION－40核データライブラリーを使って行った。その計算から，実験体系は，直径1.2ｍ，厚さ1.1ｍの円筒形状がよいことがわかった。また，核融合炉の中性子場を模擬し，かつ，実験室の壁での中性子の反射によるバックグランドを低減するために，厚さ 0.2ｍの中性子源反射体を追加することが必要である。

ＳＳ316／水実験では，ＳＳ316と水の体積比としてＩＴＥＲ／ＣＤＡで推奨された４：１を採用した。ＳＳ316／水実験体系の基本的な大きさは，ＳＳ316実験体系と同じにした。ＳＳ316と水の層状構造による非均質の遮蔽性能に対する影響は，30mmまでの厚さの水の層に対しそれほど大きくなかった。

実験室の壁で反射した中性子によるバックグランドを低減させるための方法について調べた。実験室での中性子の反射を正確に計算するため，ＤＯＴ3.5のかわりに，S_NコードＤＯＴ－ＤＤと多群二重微分形式の断面積セットDDXLIB３を使った。計算から次のことが得られた。1)追加遮蔽体が無い場合は，体系内0.9ｍの深さでＳ／Ｎが0.5になる。2)厚さ0.1ｍのポリエチレン層はバックグランドを１／10まで低減する。3)中性子源反射体を0.4ｍの厚さにしてもバックグランドは半分しか減らないので，中性子源反射体を厚くする方法はそれほど効果的でない。厚さ0.1ｍ以上のポリエチレンの追加遮蔽体が最も有効であることがわかった。

これらの予備解析結果を基にＳＳ316とＳＳ316／水実験のための最終的な実験体系の構成を決定した。

東海研究所：〒319－11　茨城県那珂郡東海村白方字白根２－４
＊　㈱住友原子力工業

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1. Introduction

In the design of next fusion devices such as International Thermonuclear Experimental Reactor (ITER), the radiation shield for the super conductive magnet (SCM) and the biological shield are of key importance. The ITER "Conceptual Design Activities" (CDA) [1] addressed the design limits as shown in Table 1.1 and various shielding designs were performed under ITER/CDA. Nevertheless, the validity of the nuclear data and calculation codes used in the designs has not been examined thoroughly to estimate the design margin. Moreover, there are still complicated problems to be solved or cleared as for radiation shield, in terms of;

1) Deep penetration in shielding materials,

2) The effects on shielding performance by

coolant water,

void,

auxiliary shielding material such as B_4C/Pb and W,

gap streaming,

and duct streaming.

Shielding benchmark experiments are the most effective method to solve these problems. Concerning the ITER "Engineering Design Activity" (EDA) [2], a series of fusion reactor shielding experiments was planned using the strong D-T neutron source FNS (Fusion Neutronics Source) [3] in Japan Atomic Energy Research Institute.

The configuration with type 316 stainless steel (SS316) and water is one of the most promising candidates for the shield/coolant of ITER. As the first phase of the fusion reactor shielding experiments, the bulk shielding experiments using SS316 and SS316/Water were proposed to ITER/EDA so as to examine the deep penetration problem of SS316 and the effect of coolant water on shielding performance.

The shielding experiment has various options. Since time and budget are limited, pre-analysis of experiment plays a key role to select the most efficient experimental configuration and measuring points. As one of the '93 ITER/EDA emergency tasks, JA-3 (Bulk Shielding Experiments: Phase IA 'Pre- & Post-Analyses and Preparation of SS316 and SS316/Water Experiments') was authorized. This report compiled the results of pre-analyses for SS316 and SS316/Water Experiments. The bulk shielding experiments using SS316 and SS316/Water assemblies were approved to be executed as the '94 ITER/EDA task. The post-analyses for the SS316 and SS316/Water experiments will be presented with the experimental results in the report of the '94 ITER/EDA task.

Chapter 2 describes the guidelines for the bulk shielding experiment. The results of the survey calculations for the experimental assemblies on SS316 and SS316/water are described in Chaps. 3 and 4, respectively.

Table 1.1 Shielding performance design limits in ITER/CDA

Response	Design Limit
Total nuclear heating in troidal field coils [kW]	55
Peak nuclear heating in winding pack [mW/cm^3]	5
Peak dose to electrical insulator [rads]	$5X10^9$
Peak fast (E>0.1MeV) neutron fluence to superconductor [n/cm^2]	10^{19}
Peak displacement in copper stabilizer [dpa]	$6X10^{-3}$
Biological dose outside cryostat one day after shutdown [mrem/h]	0.5

2. Guidelines of Bulk Shielding Experiments

The following guidelines are considered to select the experimental configurations.

1) SS316 and water are primary candidates for the shielding and coolant materials of ITER, respectively.

   ➡The experimental assemblies should consist of SS316 and/or water.

2) The thickness of the shield part in ITER is thicker than 900 mm.

   ➡The data in the depth of 900 mm inside the assembly should be obtained.

3) The low energy neutron flux in a fusion device is higher than that of primary D-T neutron flux due to the neutron reflection in the torus cavity.

   ➡The incident neutron spectrum into the test region should be as close to that expected in ITER as possible.

4) The low energy neutron flux below 1 MeV and associated γ-ray flux are important to estimate the nuclear heating in SCM.

   ➡The neutron spectrum below 1 MeV should be measured. The γ-ray spectra and γ-ray heating rate should be also measured.

5) The influences of neutron leakage and room returned neutrons on the neutron and γ-ray fluxes at the measuring points should be lower than 10 %, which is comparable with the experimental accuracy, in order to apply the results of these experiments to the ITER design.

6) The proof load of the floor of the first target room at FNS is 20 tons.

   ➡The total weight of the experimental assembly including the support should be less than 20 tons.

3. SS316 Experimental Assembly

This chapter describes how to determine the size and configuration of the SS316 experimental assembly. Only SS316 is considered as a material of the assembly.

3.1 Calculation Code and Nuclear Data

A two-dimensional discrete ordinate transport code DOT3.5 [4] was used in this survey calculation since it takes not so much computation time to obtain neutron and gamma ray fluxes even at 1 m depth. The first-collision source was prepared by the GRTUNCL code. The nuclear data set used was the FUSION-40 [5] (neutron 42 groups, photon 21 groups, P_5 Legendre expansion) processed from JENDL-3.1 [6]. The isotropic division of S_{16} in angle was applied. The mesh intervals were 10 - 20 mm. The INTERF [7] code was used to calculate neutron spectra and contour maps of neutron flux from the result of DOT3.5. All the calculations were executed on the FACOM VP-2600 computer. The atomic number density of SS316 is shown in Table 3.1. The 14 MeV mono-energy neutron was adopted as the neutron source.

3.2 Diameter of Experimental Assembly

The main aim of the bulk shielding experiment is not to examine the calculation model, but to validate nuclear data and calculation codes used in the nuclear design calculation. In the nuclear design calculation, a two-dimensional discrete ordinate transport code DOT3.5 and a Monte Carlo code MCNP [8] are often used. A cylindrical shape was selected as the assembly geometry of the bulk shielding experiment on SS316 to use DOT3.5.

The survey calculation to determine the diameter of the cylindrical assembly was performed at first. The thickness of the assembly was fixed to be 1.1 m since the experimental data up to the depth of 0.9 m were required. The distance from the D-T neutron source to the assembly was adopted to be 0.3 m. The schematic view of the experimental configuration is shown in Fig. 3.1. The neutron fluxes were calculated inside the assemblies whose diameters were 0.8, 1.0, 1.2 and 1.4 m. The computation time was about 5 minutes for each run.

The first criterion to determine the diameter of the cylindrical assembly is to reduce the influence less than 10 % at the center axis due to the neutron leakage from the assembly. The assembly with 2.0 m diameter was adopted as a reference. The ratios of neutron fluxes for the assemblies of 0.8, 1.0, 1.2 and 1.4 m in diameter to the reference along the center axis are shown in Figs. 3.2 (a) - (d), respectively. The comparisons were made for the integrated neutron fluxes in the energy ranges, En > 10 MeV, 1 < En <10 MeV, 100 < En <1000 keV, 10 < En <100 keV, 1 < En < 10 keV and En <1 keV. Since neutrons lower than 1 MeV leak by 25 - 35 % at the depth of 0.9 m of the assembly with 0.8 m diameter, this assembly is not suited for the deep penetration experiment.

Figures 3.3 (a) - (d) show the ratios of integrated neutron fluxes for the assemblies of 0.8, 1.0, 1.2 and 1.4 m in diameter to the reference along the radial direction at the depth of 0.9 m from the front surface of the test region. Since all the detectors will be inserted vertically to the center axis from the side wall of the assembly and the maximum length of the detectors is 0.2 m, the length of the center region where the effect of neutron leakage is less than 10 % is required to be more than 0.2 m. The neutron leakage of the assembly with 1.0 m diameter is about 20 %. Therefore 1.2 m was chosen as a diameter of the assembly.

3.3 Source Reflector

In a tokamak fusion reactor, neutrons entering the first wall and blanket/shielding region are composed of not only direct D-T neutrons but also lower energy neutrons reflected at the opposite first wall and so on. On the other hand, neutron spectra of accelerator based D-T neutron sources such as FNS are harder than those at the first wall of a fusion reactor. A source reflector that surrounds the D-T neutron source was proposed to increase lower energy neutrons entering the test region and simulate better the neutron environment in a fusion reactor. The SS316 was adopted as a material of the source reflector since the same material as the test region was considered to be better. The configuration of the source reflector and test region is shown in Fig. 3.4. The size of the test region was fixed to be 1.1 m in thickness and 1.2 m in diameter, which were determined in Sec. 3.2. The variation of neutron fluxes was examined by changing the thickness of the source reflector from 0.1 to 0.3 m by 0.1 m step. The neutron flux distributions along the center axis of the test region are shown in Figs. 3.5 (a) - (f). It is considered that the 0.1 m thick source reflector is too thin in view of the effect of neutron reflection. Since the results of the 0.2 m and 0.3 m thick source reflectors are almost the same, it is concluded that the 0.2 m thickness is sufficient. Figure 3.6 shows neutron spectra at the front surface of the test region with and without 0.2 m source reflector. The 0.2 m thick source reflector increases neutrons below 100 keV by a factor of ten.

Leakage neutrons from the experimental assembly are scattered by the concrete wall of the experimental room. A part of these scattered neutrons returns to the experimental assembly again. The influence of these room returned neutrons was examined. The concrete wall was modeled to be 5.5 m far from the D-T neutron source, which was the minimum distance from the D-T neutron source to the concrete wall, and 0.5 m in thickness, which was expected to be thick enough for the neutron reflection by the concrete. The configuration of the test assembly and concrete wall is shown in Fig. 3.7. Figure 3.8 shows the ratios of the neutron fluxes along the center line with the concrete wall to those without the concrete wall. The influence of room returned neutrons was less than 10 % at the depth of 0.9 m. Figure 3.9 shows the ratios of several reaction-rates that will be measured in this experiment. In these reaction rates the effects of the concrete wall are less than 5 %. The experimental assembly of 1.2 m in diameter and 1.1 m in thickness with 0.2 m thick source reflector is also sufficient in view of reduction of room returned neutrons.

3.4 Final Configuration of SS316 Assembly

Since the experimental assembly determined in Sec. 3.3 is too heavy (about 10 ton) to handle by a crane, it will be divided to several disks of 1.2 m in diameter and proper thickness. The inch unit was already adopted as the size of experimental blocks, such as Li_2O, C, Be, W and so on, in the clean benchmark experiments [9-12] at FNS. Considering the possibility to use the experimental blocks in the future bulk shielding experiments, the thickness of the disk of 1.2 m in diameter was determined to be 2 or 4 inches. The final experimental configuration is shown in Fig. 3.10 with dimensions. As shown in Figs. 3.5 (a) - (f), the neutron fluxes decrease monotonously at the deeper positions than 0.4 m, while variation rates of the lower energy neutron fluxes largely change depending on the position in the front region. Therefore the intervals between the measuring points in the front region should be shorter than those in the rear region. The measurements will be performed at the depths of 102, 229, 356, 533, 711 and 914 mm. The total weight of the SS316 experimental assembly including the source reflector and support will be about 15 tons. This weight will satisfy the limit of 20 tons even in the case of adding an auxiliary shield material such as tungsten.

Table 3.1 Atomic number densities used for SS316

Material	Number Density
Fe	$5.8331 X 10^{-2}$ *
Cr	$1.5025 X 10^{-2}$
Ni	$9.1456 X 10^{-3}$
Mn	$1.3561 X 10^{-3}$
Mo	$1.0254 X 10^{-3}$
Si	$8.1608 X 10^{-4}$
C	$1.9855 X 10^{-4}$
P	$4.7828 X 10^{-5}$
S	$4.5072 X 10^{-6}$

* Unit is in [X 10^{24} atoms/cm^3]

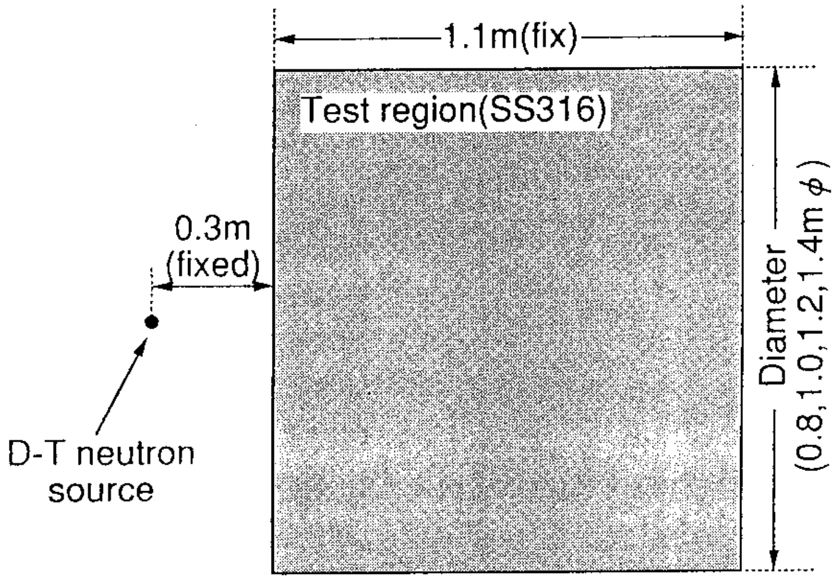
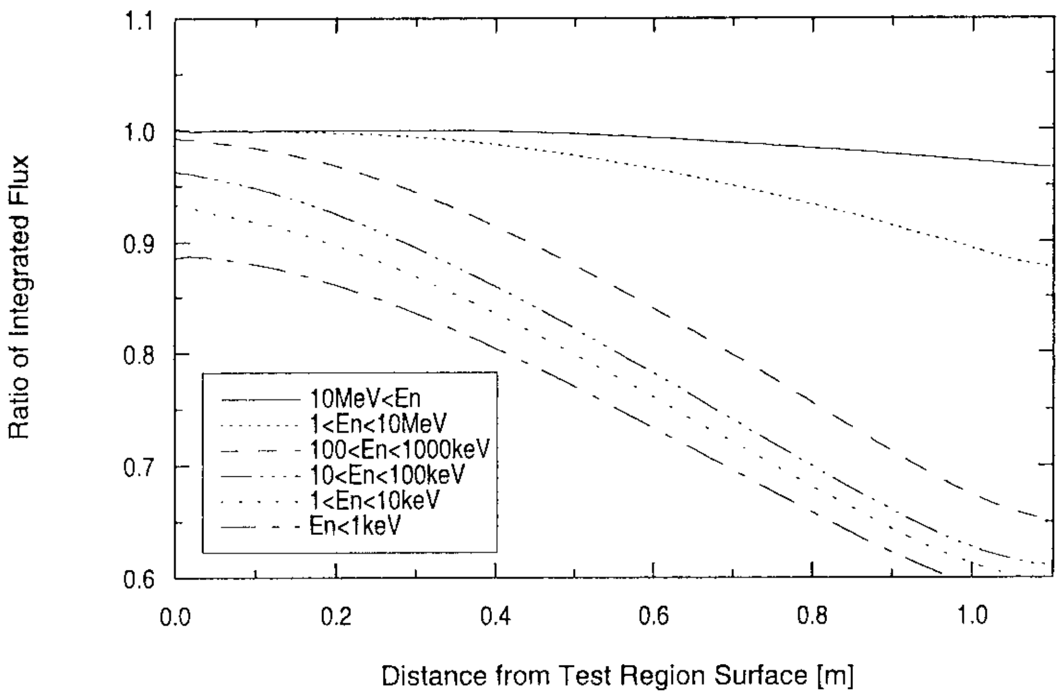
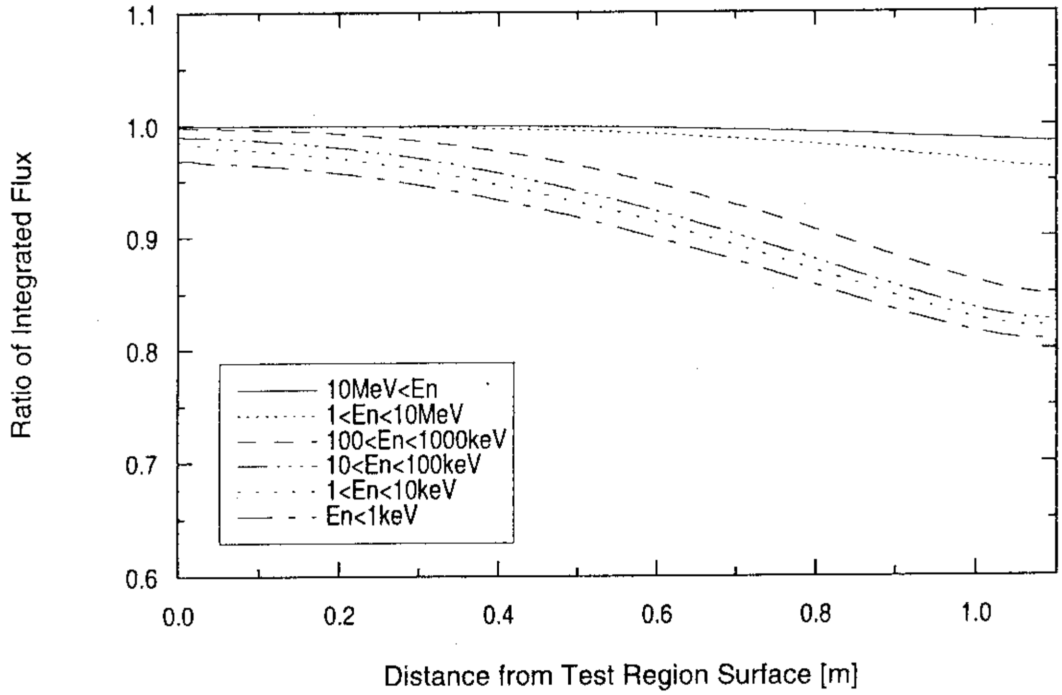


Fig. 3.1 Calculation model of the SS316 assembly for determination of the diameter.

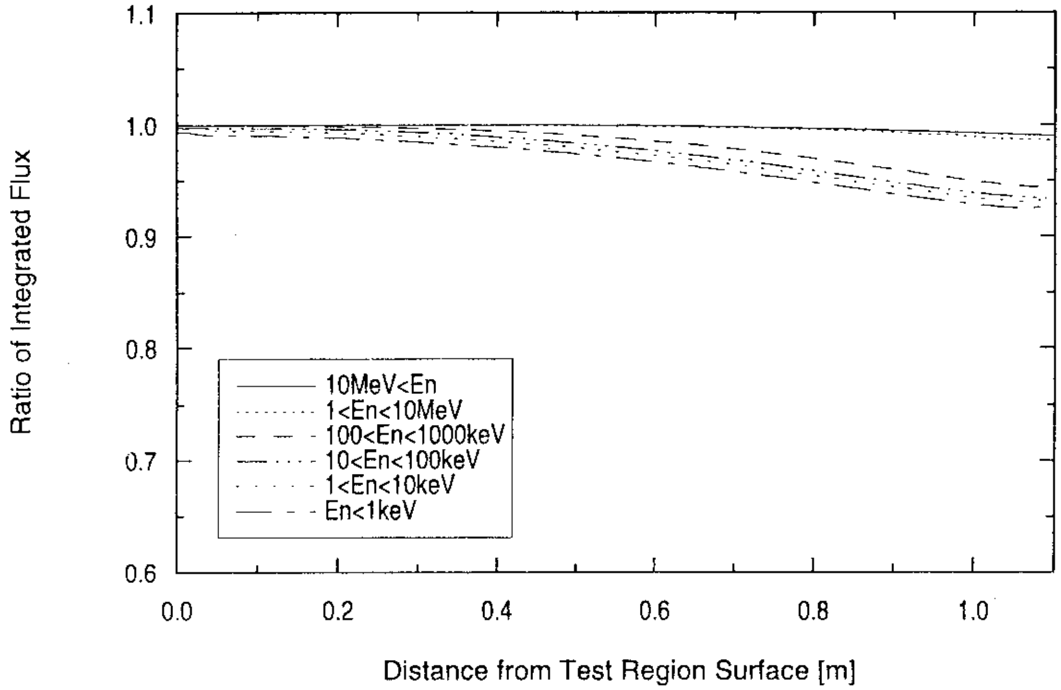


(a) 0.8 m in diameter

Fig. 3.2 Axial distribution of the ratio of the integrated neutron flux to that in the assembly of 2 m diameter.

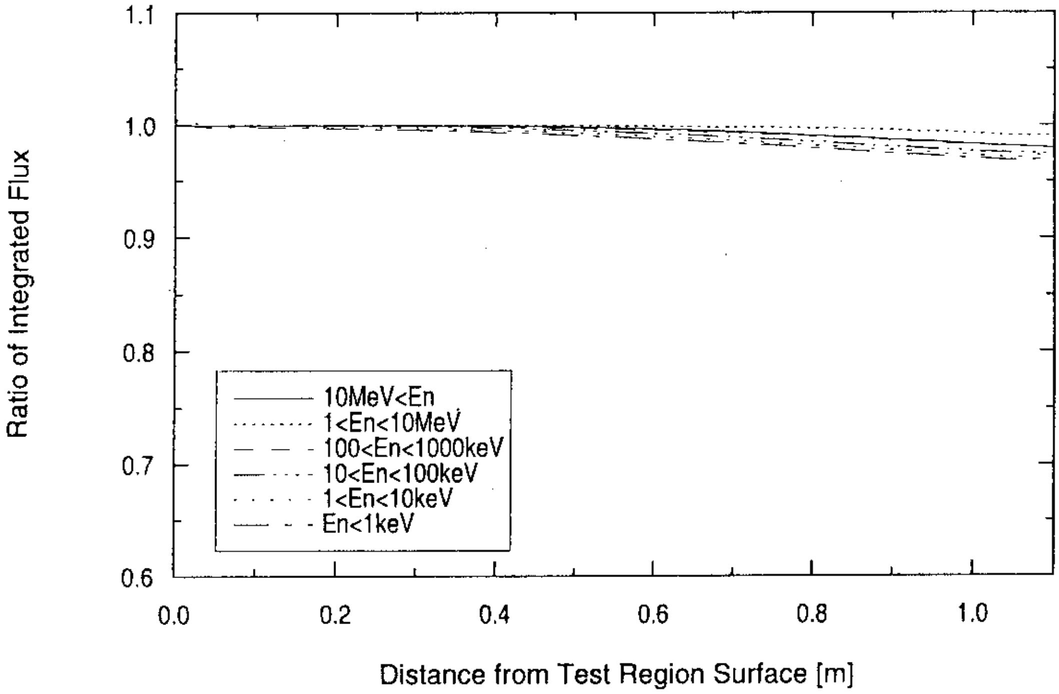


(b) 1.0 m in diameter



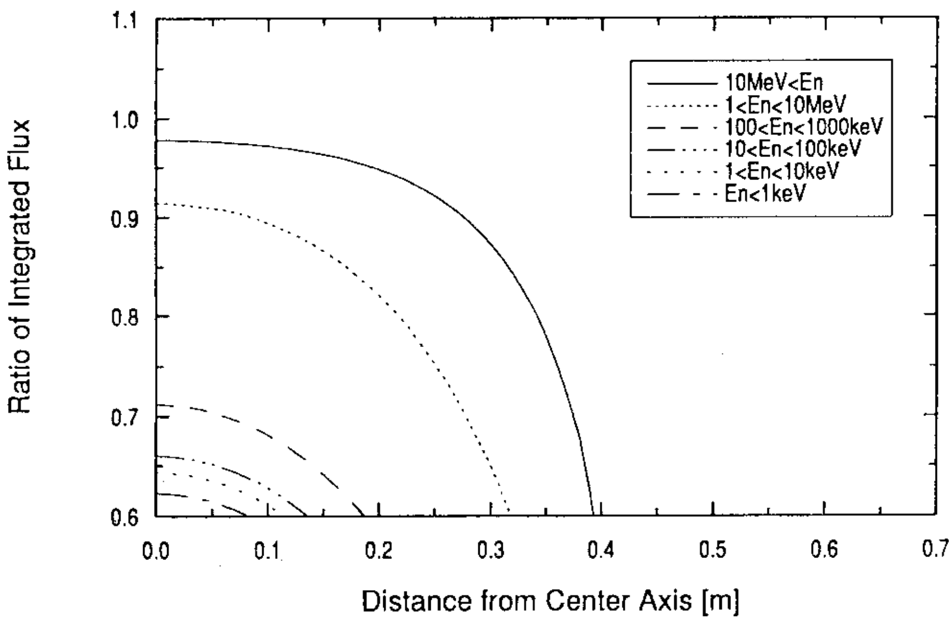
(c) 1.2 m in diameter

Fig. 3.2 Axial distribution of the ratio of the integrated neutron flux to that in the assembly of 2 m diameter (Continued).



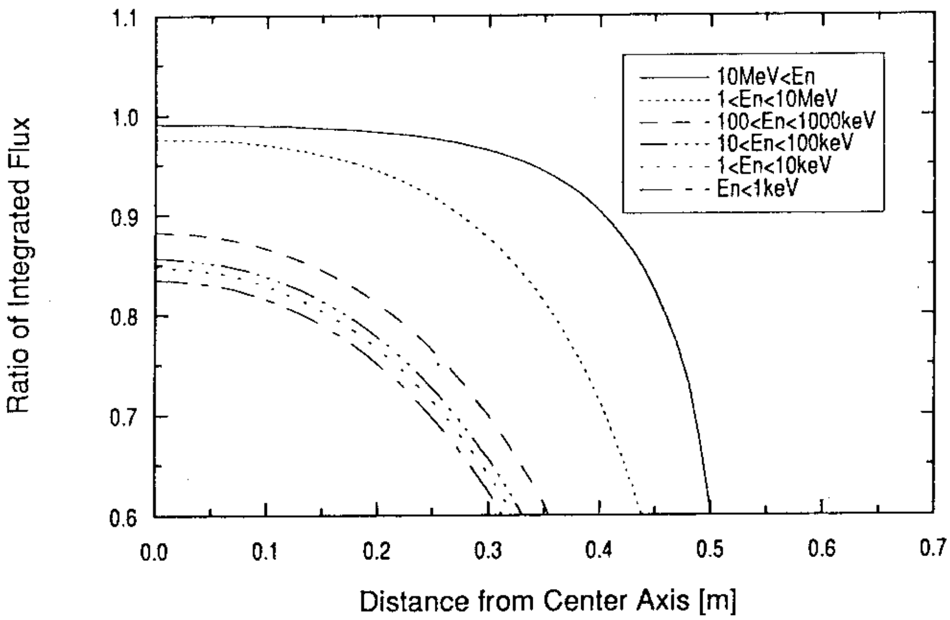
(d) 1.4 m in diameter

Fig. 3.2 Axial distribution of the ratio of the integrated neutron flux to that in the assembly of 2 m diameter (Continued).

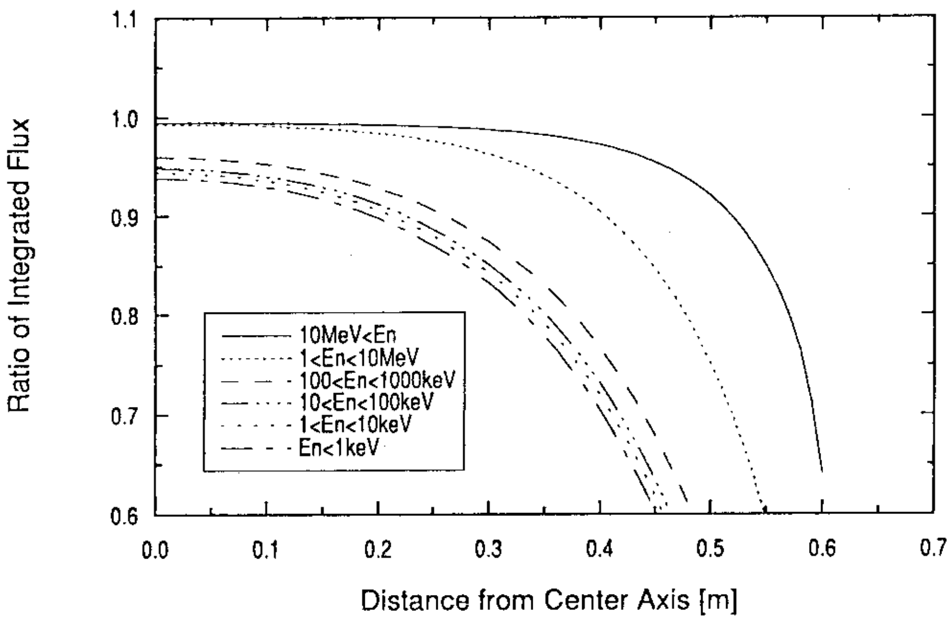


(a) 0.8 m in diameter

Fig. 3.3 Radial distribution of the ratio of the integrated neutron flux to that in the assembly of 2 m diameter at the depth of 0.9 m.

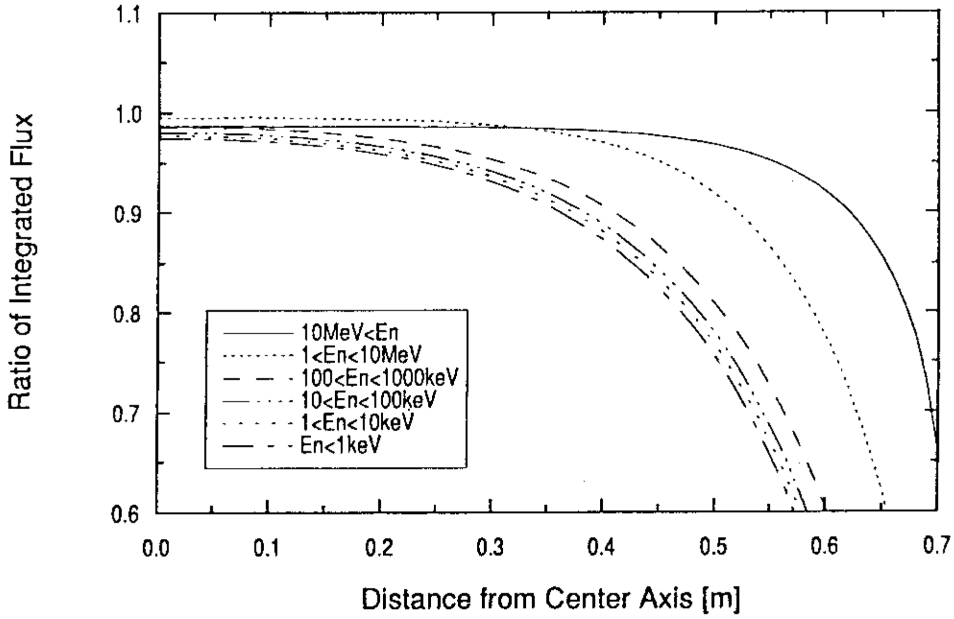


(b) 1.0 m in diameter



(c) 1.2 m in diameter

Fig. 3.3 Radial distribution of the ratio of the integrated neutron flux to that in the assembly of 2 m diameter at the depth of 0.9 m (Continued).



(d) 1.4 m in diameter

Fig. 3.3 Radial distribution of the ratio of the integrated neutron flux to that in the assembly of 2 m diameter at the depth of 0.9 m (Continued).

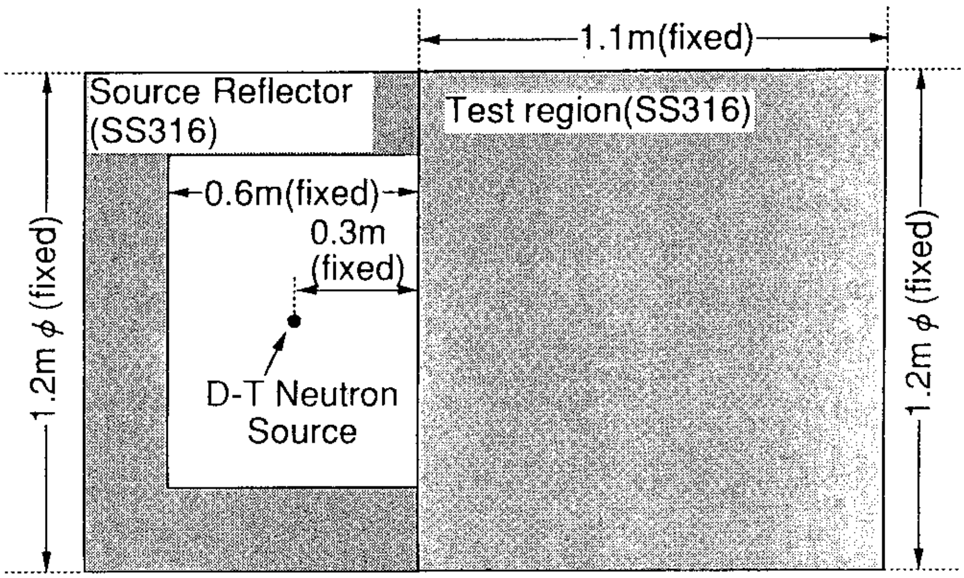
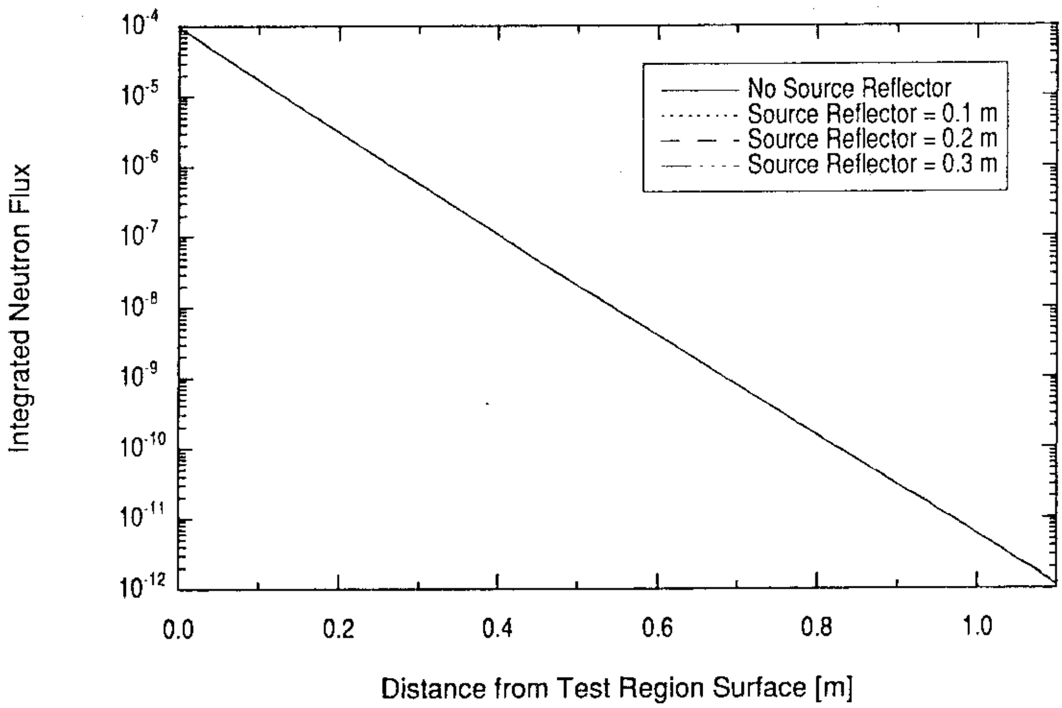
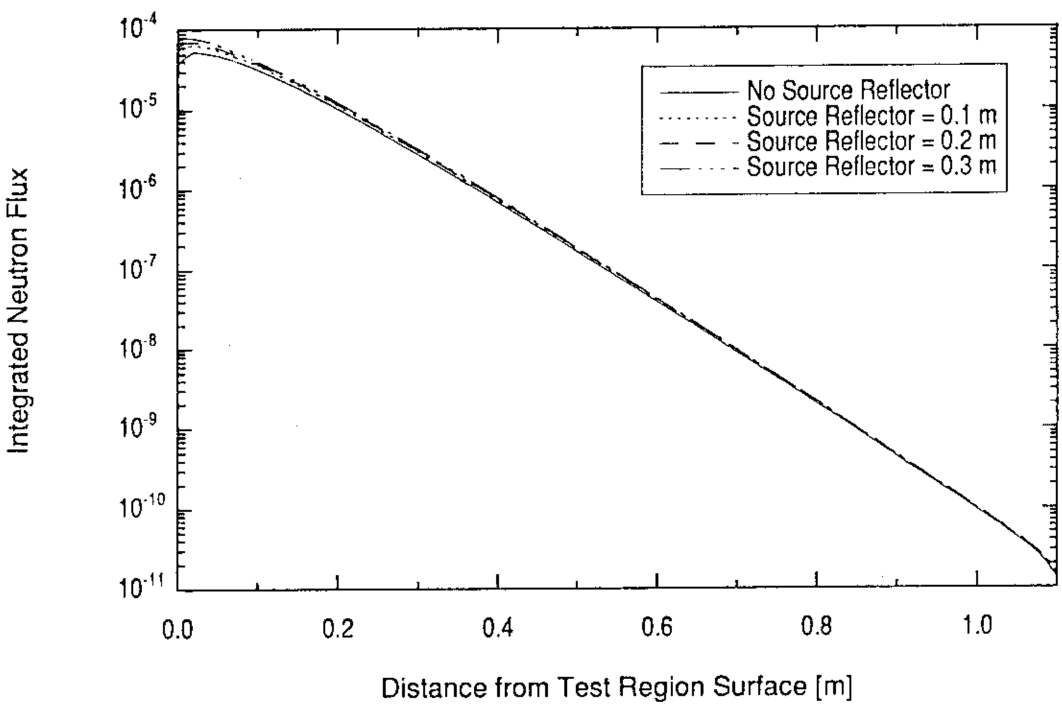


Fig. 3.4 Calculation model of the SS316 assembly for examination of the source reflector effect.

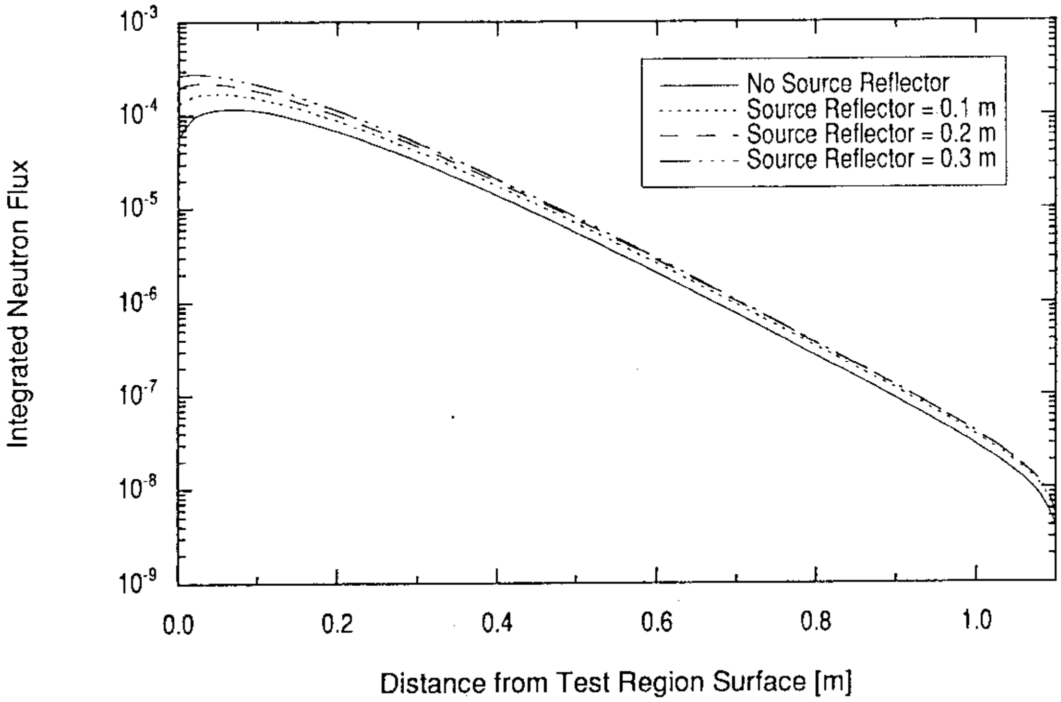


(a) integrated flux above 10 MeV

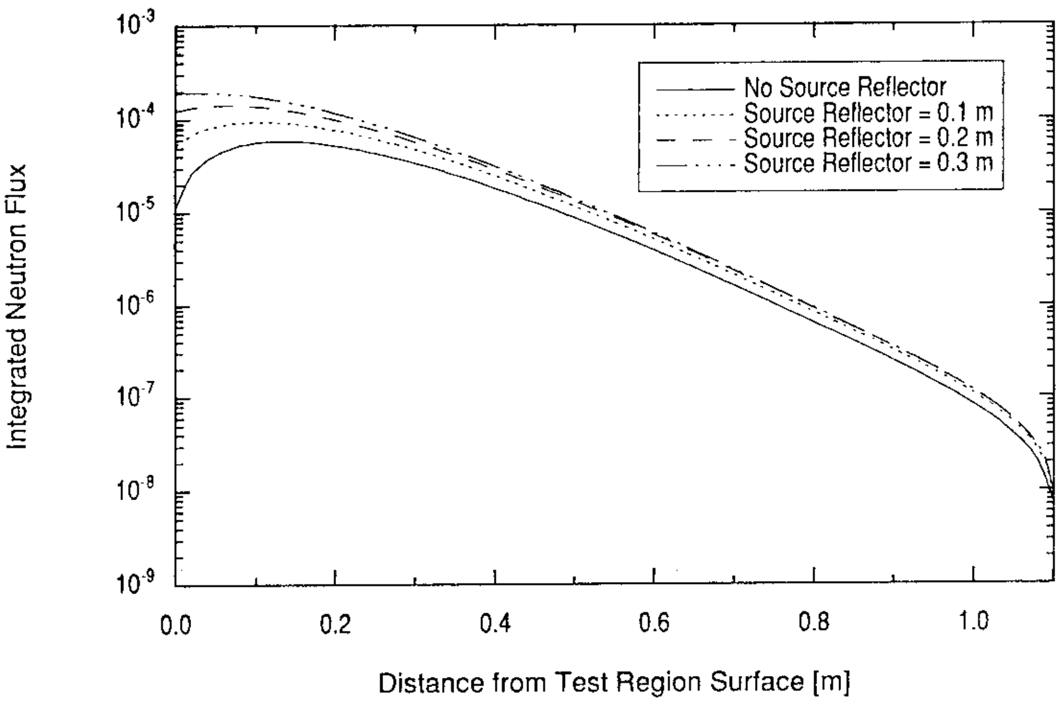


(b) integrated flux between 1 and 10 MeV

Fig. 3.5 Axial distribution of the integrated neutron flux with 0.0, 0.1, 0.2 and 0.3 m thick source reflectors.

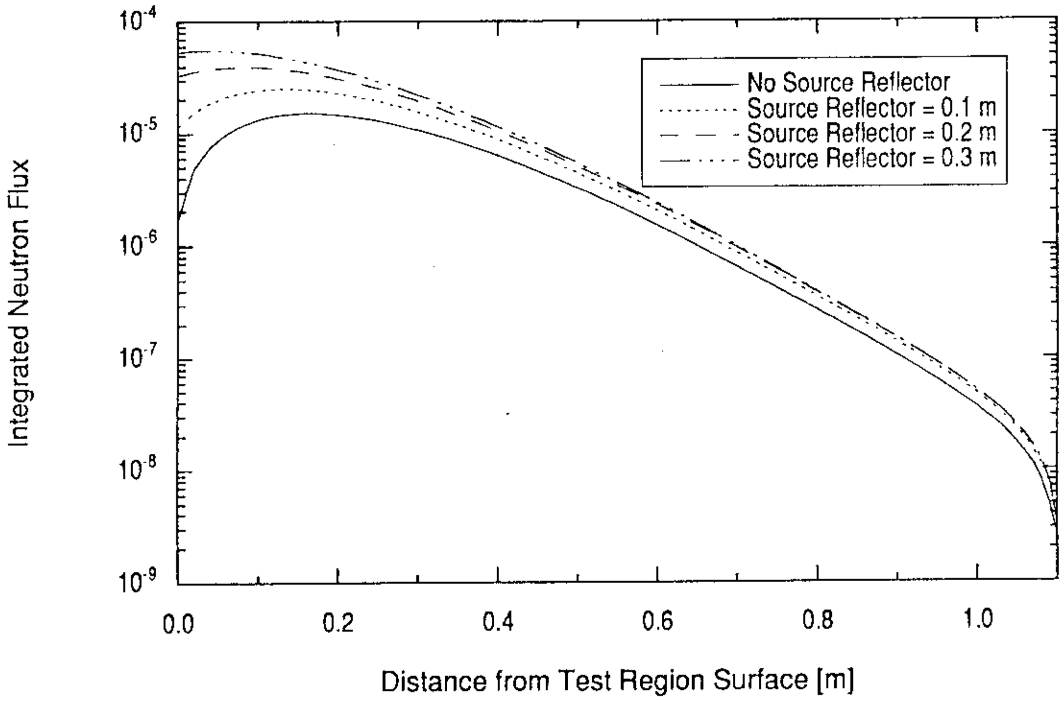


(c) integrated flux between 100 keV and 1 MeV

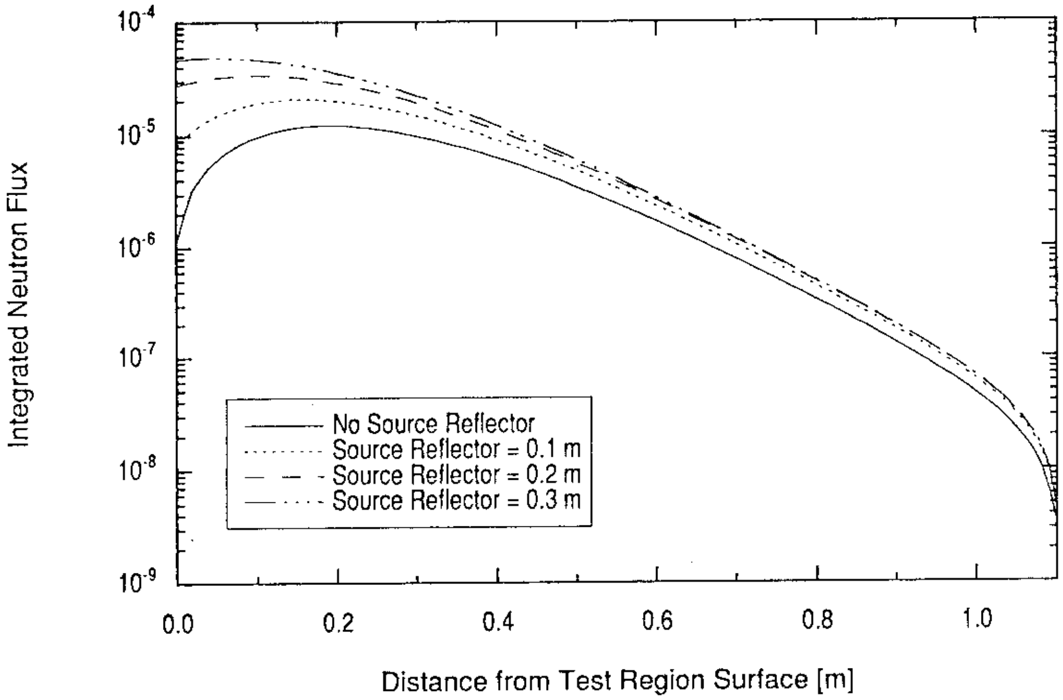


(d) integrated flux between 10 keV and 100 keV

Fig. 3.5 Axial distribution of the integrated neutron flux with 0.0, 0.1, 0.2 and 0.3 m thick source reflectors (Continued).



(e) integrated flux between 1 keV and 10 keV



(f) integrated flux below 1 keV

Fig. 3.5 Axial distribution of the integrated neutron flux with 0.0, 0.1, 0.2 and 0.3 m thick source reflectors (Continued)

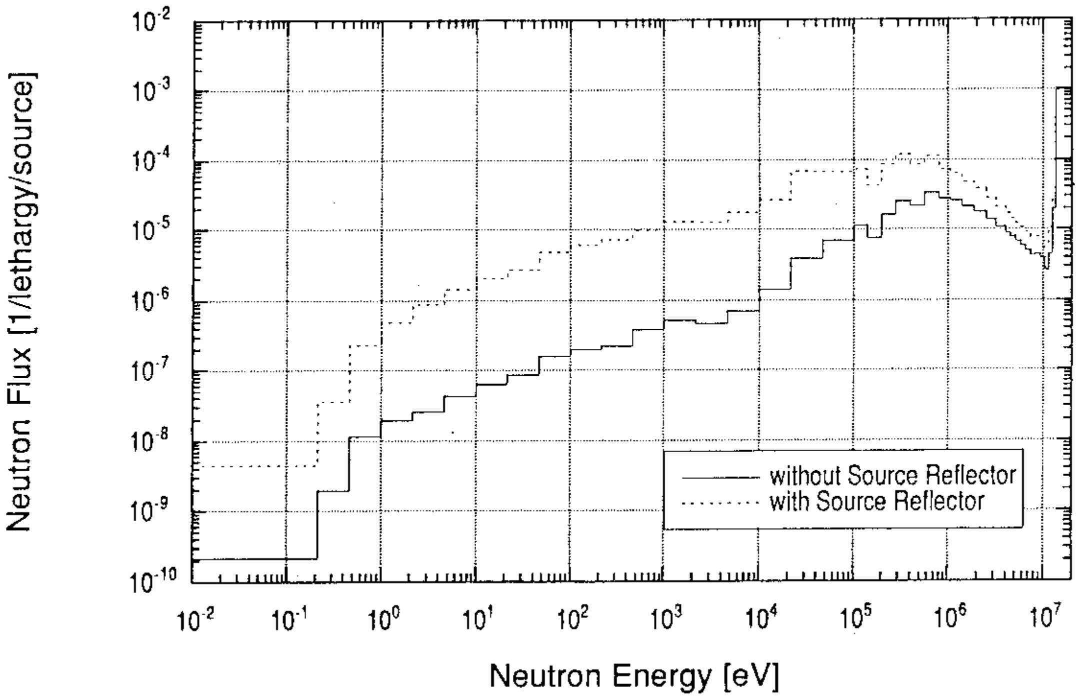


Fig. 3.6 Neutron spectra at the front surface of the test region with and without 0.2 m thick source reflector.

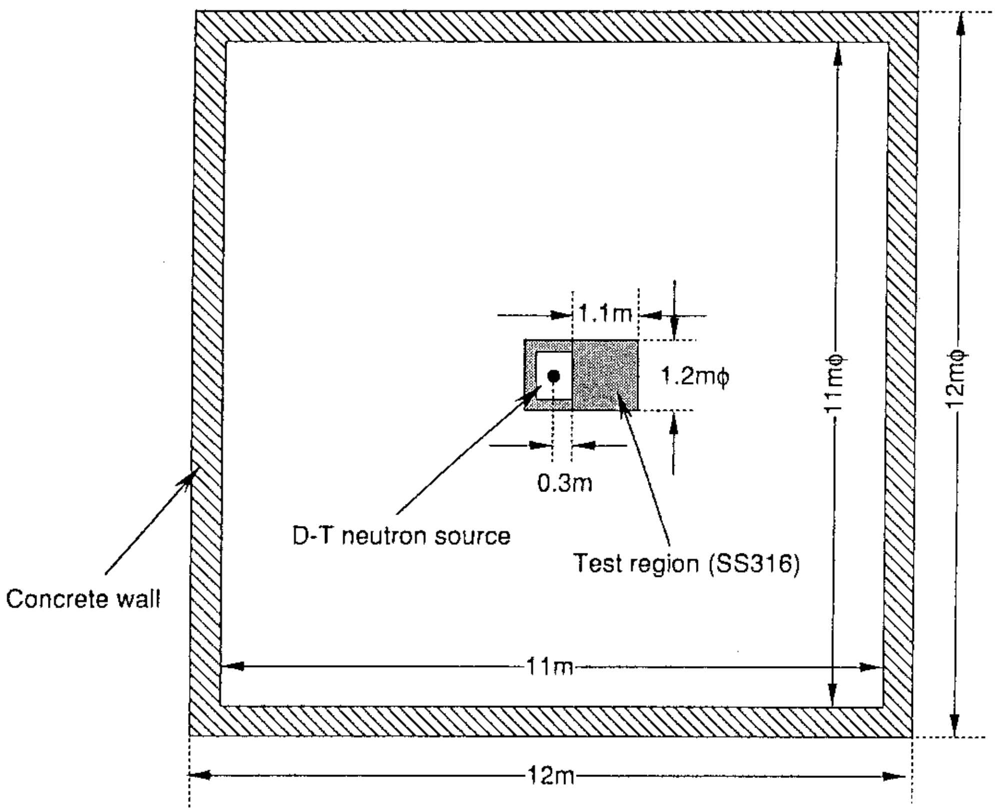


Fig. 3.7 Calculation model of the SS316 assembly with 0.2 m thick source reflector for examination of room returned neutrons.

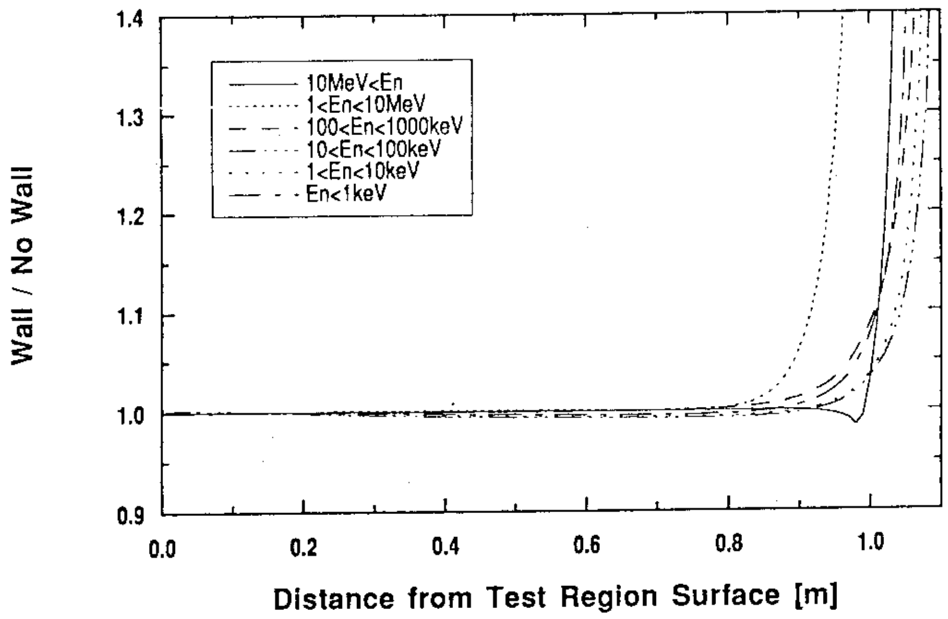


Fig. 3.8 Axial distribution of the ratio of the integrated neutron flux with the wall to that without the wall.

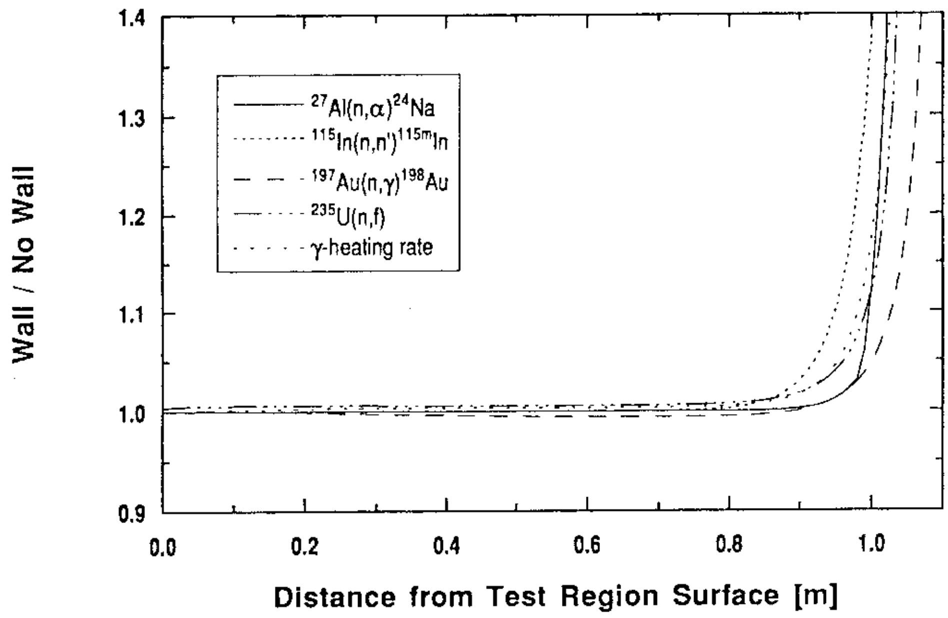


Fig. 3.9 Axial distribution of the ratio of the reaction rate, fission rate and gamma-ray heating with the wall to that without the wall.

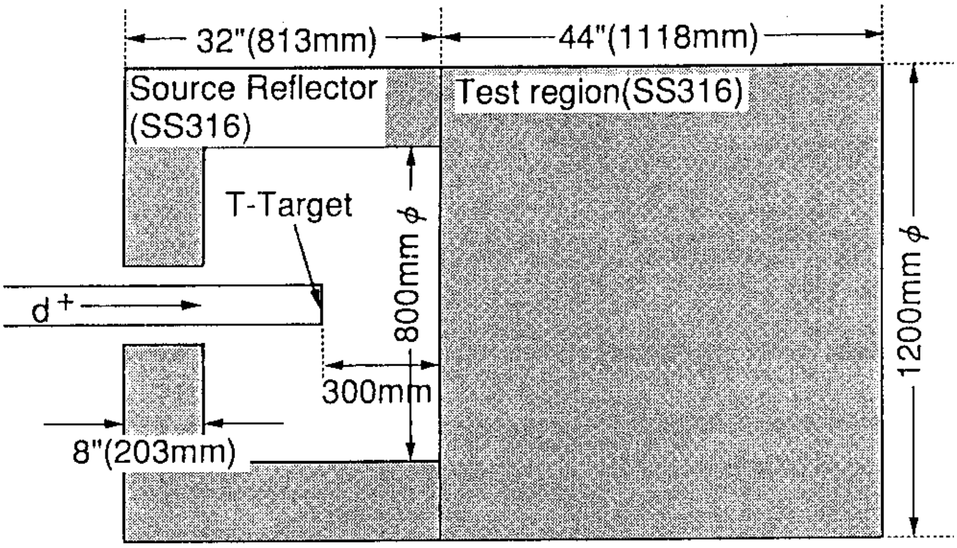


Fig. 3.10 Final experimental configuration for the SS316 experiment.

4. SS316/Water Experimental Assembly

4.1 Objectives of Calculation

As for the shielding experiments with the SS316/water configuration, it is desirable to construct the experimental assembly taking full advantage of the SS316 assembly proposed in the previous chapter. This reduces construction cost, time and storage space. The optimum configuration of SS316/water experimental assembly is investigated in this chapter, based on the configuration of the SS316 assembly. The volume ratio of 4 : 1 for SS316 to water is taken from Ref. 13 and used in this investigation.

A layered configuration of SS316 and water is suitable to an experimental assembly from the practical point of view, since the configuration is easy for construction and modeling for analyses. The shielding configuration in ITER is, however, expected to be nearly homogeneous. As the first step, the shielding performance for several combinations of SS316 and water layers is examined in Sec. 4.2. The aim of this investigation, namely the heterogeneity effect study, is to simulate the ITER shielding configuration better.

Since the shielding performance of the SS316/water is expected to be much better than that of the SS316, room returned background might cause a problem for the SS316/water assembly. If room returned background disturbs the foreground signals, the experimental analysis becomes very difficult since the experimental room has to be taken into account in the analyses. An experimental assembly that is affected by room returned background is not appropriate. As the second step, it is examined in Sec. 4.3 whether the additional shield for the SS316/water assembly is necessary or not to obtain experimental data at the deepest measuring point with S/N (Signal to Noise) ratios higher than 10. As the third step, the optimum additional shield configuration is investigated in Sec. 4.4 to minimize room returned background and to obtain experimental data with high S/N ratios.

4.2 Heterogeneity Effect on SS316/Water Layers

For the investigation of heterogeneity effect of the SS316/water layers on the shielding performance in deep positions, four calculations were performed. All the calculation models were based on the experimental assembly proposed in the previous chapter, i.e., the assembly consisting of the test region of 1200 mm in diameter and 1120 mm in thickness with the source reflector of 200 mm in thickness. Figure 4.1 shows a calculation model of the SS316/water assembly. The configurations of the test regions for the four calculations are summarized in Table 4.1. In Cases H1 - H3, the front region of 720 mm in thickness was repeated with heterogeneous zones of SS316 and water layers, followed by SS316 region of 400 mm. Volume ratios of water layer to the test region for three heterogeneous configurations were 25 % and 20 % when the ratios were calculated in regions from the front surface to the depth of 720 mm and 900 mm, respectively. In Case H0, SS316 and water zones of 720 mm in thickness were homogenized by the same volume ratio of 3 : 1 for SS316 to water as those of Cases H1 - H3.

DOT-3.5 was used with the GRTUNCL code for first collision sources. The cross section library FUSION-40 was used. The order of Legendre polynomial expansion was 5 and the S-16 angular quadratures set was used. The experimental assembly was expressed as a cylinder in the two-dimensional calculation. In the SS316/water region from the front surface to depth of 720 mm, mesh intervals of the axial direction were fixed to 5 mm. Axial mesh intervals for the other parts and radial mesh intervals were in a range between 5 mm and 25 mm. Total numbers of meshes were 47 for radial direction and 227 for axial direction. The same mesh division was commonly used for all the cases. The atomic number densities used in the calculations are summarized in Table 4.2.

The calculated axial distributions are shown in Figs. 4.2 for (a) integrated neutron flux above 10 MeV, (b) between 0.1 and 1 MeV, (c) between 1 and 10 keV, (d) fission rate of ^{235}U and (e) gamma-ray heating rate of SS316, respectively. As for (a), 14 MeV neutron penetration, little difference is seen among all the cases even in the SS316/water region. As for lower energy neutrons and γ-ray heating rate, fine structures of the axial distributions are observed in the SS316/water regions for Cases H1, H2 and H3 depending on the layered configurations. However, in the SS316 region deeper than 720 mm, differences of the axial distributions among all the Cases become smaller. The ratios of the heterogeneous to the homogeneous cases for integrated fluxes, reaction rates and nuclear heating rates at the depth of 900 mm are summarized in Table 4.3. All the responses in the heterogeneous Cases H1, H2 and H3 are about 11, 24 and 40 % larger at the maximum than those in the homogeneous Case H0. Compared to the 4 or 6 orders of attenuation of the responses, the maximum difference of 40 % is not so large. The differences of neutron spectra at the depth of 900 mm are also small. It is concluded that the heterogeneous configuration of the SS316/water dose not affect shielding performance in the deep position so much. The thickness of water layers can be arbitrarily determined up to 30 mm without any significant influences.

4.3 Necessity for Additional Shield

In order to judge whether the additional shield is necessary or not for the SS316/water experimental assembly to reduce room returned background, two calculations were carried out. Only the SS316/water assembly was considered in the first calculation (Case A0), and the wall of the experimental room was taken into account in the second calculation (Case A1).

A schematic view of the calculation model for Case A1 is shown in Fig. 4.3. The experimental assembly was almost the same as that described in the previous section. In the present assembly, the thickness of SS316/water region was 700 mm. A volume ratio of water is 27 % in the SS316/water region which was homogenized. The thickness of the test region was 1200 mm. The thickness of the concrete wall was 500 mm, which was expected to be thick enough for the reflection by the concrete. The distances between the experimental assembly and the walls were 5500 mm, which was the minimum distance from the assembly to the experimental room wall.

In Case A1, there is a large cavity between the experimental assembly and the wall. It is expected that transport calculations with discrete ordinate codes are difficult because back scattered neutrons in the wall can not be accurately expressed by the Legendre expansion approximation. Hence in order to treat accurately angular distributions of secondary neutrons in a DDX form, the modified version of DOT and GRTUNCL codes, DOT-DD [14] and UNCL-DD [14], respectively, were used. The DDX form cross section library DDXLIB-J3 [14] based on JENDL-3.1 was used. The original number of energy groups of the library was 125. In the calculation, the library was collapsed from 125 energy groups into 44 groups by collapsing some groups into one group. The S-16 angular quadratures set was used. The approximate mesh intervals were 10 - 20 mm in the experimental assembly, 20 mm in the concrete wall and 100 - 200 mm in the cavity of experimental room. The total number of meshes was 93 for radial direction and 228 for axial direction. The same mesh division was commonly used for both cases to keep consistency of calculation conditions though the wall and room cavity are not necessary in Case A0. The atomic number densities used in the calculations are summarized in Table 4.4.

Some problems were found in the calculations. The first problem is the ray-effect. Figure 4.4 shows a contour map of integrated flux above 10 MeV on the R-Z plane for Case A0. Since the flux distribution inside the source reflector is completely isotropic, the first collision source is correctly calculated. However in the cavity between the experimental assembly and the wall, a clear ray-effect is observed. The reason of this ray-effect is that the outer surface of the source reflector is the scattering source point for the cavity and the scattering source can not be treated by the first collision code. The ray-effect is observed even for low energy neutrons.

The second problem is caused by the ray-effect and the finite difference method to solve the transport equation. A gradient of the calculated flux just outside the rear part of the assembly is extremely steep because of high shielding ability of the SS316/water shield and the ray-effect. This steep gradient causes inflow of neutrons from outside the assembly into the rear part of the assembly since the finite difference method can not treat the steep gradient precisely.

In addition, the calculation sometimes does not sufficiently converge after 25 inner iterations for low energy groups. Unreasonable results are seen especially for the thermal group flux. Therefore, the thermal group flux is excluded in the following discussions. In order to obtain some reaction rates which have high sensitivity to thermal neutrons, such as fission rate of ^{235}U and $^{197}Au(n,\gamma)$, energy-integration is done from the energy group 1 (15.0 - 13.72 MeV) to the group 41 (0.465 - 0.215 eV) except the group 42 (0.215 - 0.001 eV).

These problems might result in a large uncertainty in the calculations, and unreasonable or contradictory flux distributions were sometimes observed in the calculations. Hence attention for the ambiguities has to be paid to the calculated results and the following discussions.

Figures 4.5 (a) - (e) illustrate the room returned background contribution to the transmitted neutrons through the assembly. Five calculated responses are (a) integrated flux above 10 MeV, (b) between 0.1 and 1 MeV, (c) between 1 and 10 keV, (d) fission rate of ^{235}U and (e) $^{197}Au(n,\gamma)$ reaction rate. It is found that the contributions of room returned background are serious to lower energy neutrons. The fission rate of ^{235}U at 900 mm depth in the SS316 assembly is also shown in Fig. 4.5 (d). The fission rate of ^{235}U is an excellent index to estimate the background since the reaction cross section is large throughout a wide energy range for low energy neutrons. The following discussions are focused on the fission rate.

For the SS316 shield experiment, experimental data at 900 mm in depth can be obtained without contamination of the room returned background because the background level at the rear surface of the assembly is lower than the foreground level at 900 mm and the background neutrons can be attenuated by back stainless steel region of 300 mm behind the deepest measurement point at 900 mm. On the other hand, for the SS316/water shield, the background level at the rear surface is about 1.5 order higher than the foreground level at 900 mm. According to the calculations, room returned neutrons are attenuated by about

1.5 order of magnitude by the back stainless steel region of 300 mm in thickness, but the background is still large compared to the foreground. A foreground (signal) to background (noise) ratio, S/N ratio, at 900 mm in depth is about 1. It can be concluded that the additional shield is necessary to obtain experimental data at 900 mm in depth with S/N ratios higher than 10.

4.4 Examination for Optimum Additional Shield

There are two ways to reduce the room returned background at the 900 mm position. The first way is to reduce leakage neutrons mainly from the source reflector. Neutron flux in the room cavity outside the assembly will be reduced due to this way, resulting in decrease of the background at the 900 mm position. The second way is to reduce incoming background neutrons through the side and back surfaces of the experimental assembly. The optimum additional shield is examined for these ways. The calculation tools such as transport code, cross section library and calculation conditions are the same as those described in Sec. 4.3.

The best method of the first way is to increase the thickness of the source reflector since leakage neutrons from the source reflector can be directly attenuated by the thicker source reflector and a volume and a cost of the additional shield, that is, additional source reflector, can be minimized. As a material of the additional source reflector, SS316 is chosen since it is the same material as the source reflector and it has large cross sections at 14 MeV. The reference thickness of the source reflector is 200 mm. Four calculations (Case A2 - A5) with source reflectors of 300 mm and 400 mm in thickness with and without the room wall were conducted as summarized in Table 4.5. A calculation model for Case A4 is shown in Fig. 4.6. Cases A0 and A1 are the reference calculations for the source reflector of 200 mm in thickness.

Figures 4.7 (a) - (e) show ratios of calculated responses with the room wall to those without the room wall for source reflectors of 200, 300 and 400 mm in thickness, that is, A1/A0, A3/A2 and A5/A4, respectively. Five responses are (a) integrated flux above 10 MeV, (b) between 0.1 and 1 MeV, (c) between 1 and 10 keV, (d) fission rate of ^{235}U and (e) $^{197}Au(n,\gamma)$ reaction rate. In these figures, the values of 1.0, 1.1 and 2.0 mean no background, S/N ratio of 10 and S/N ratio of 1, respectively. Since the present target is to achieve S/N ratio of 10, the ratios of calculated responses with the room wall to those without the room wall must be less than 1.1 at 900 mm position. From the figures, it is found that the background is reduced by the additional source reflector and the attenuation rate is larger for the thicker source reflector . When the 400 mm source reflector is adopted, the S/N ratio of 10 can be attained for integrated flux above 0.1 MeV. As for (c) flux between 1 and 10 keV, (d) fission rate of ^{235}U and (e) ^{197}Au(n,γ) reaction rate, however, the ratios range between 1.5 and 2.5 (S/N ratio ≈ 1) at the 900 mm position. Therefore it is concluded that the additional source reflector can not reduce room returned background by the S/N ratio of 10.

In order to reduce incoming background neutrons through the side and back surfaces of the experimental assembly, three calculations, Cases A6 - A8, are conducted as summarized in Table 4.5. A polyethylene (PE) shield of 100 mm in thickness is added around a rear part of the experimental assembly as shown in Fig. 4.8 (Case A6). Moreover, the same PE shield of 100 mm in thickness is added not only around the rear part but also around middle part of the assembly as shown in Fig. 4.9 (Case A7). For Case A8, the PE shield is replaced with a boron loaded PE shield in Case A6. The reasons why PE is chosen as the shield material are as follows. (i) PE is one of the most effective neutron moderator. (ii) Hydrogen in PE has a large macroscopic cross section for low energy neutrons below 0.1 MeV. (iii) It is easy to fabricate PE in any shape.

Figures 4.10 (a) - (e) show ratios of calculated responses with the room wall to those without the room wall for several additional shields. In the figures, the ratios for "No PE", "Normal PE", "Long PE" and "Boron PE" correspond to ratios of (Case A1 / Case A0), (Case A6 / Case A0), (Case A7 / Case A0) and (Case A8 / Case A0), respectively. Five responses are just the same as those used in the source reflector thickness calculations. It is clearly seen from the figures that (i) the background can be reduced significantly by adding the PE shield, (ii) addition of Long PE shows the largest reduction of the background and (iii) the replacement of the boron PE with the normal PE results in increase of the background. The present target of S/N ratio of 10, that is, the ratio of 1.1 in the figures, can be achieved by adding three types of shield. If the cost performance is taken into account, it is concluded that the PE shield of 100 mm in thickness around the rear part of the experimental assembly (Case A6) is sufficient.

4.5 Final Configuration of SS316/Water Assembly

Similarly to the SS316 assembly, a disk of 2 or 4 inches in thickness and 1.2 m in diameter was adopted. The 26.8 mm thick water layer was made in the 2 inch thick SS316 disk as shown in Fig. 4.11. A polyethylene layer of 150 mm in thickness is adopted as the additional shield considering a margin due to a large uncertainty in the calculation. The final experimental configuration is shown in Fig. 4.12 with dimension. The total ratio of SS316 to water is 4 : 1 in the region from the front surface to the depth of 940 mm. The ratio of water to SS316 in the front region is larger than that in the rear region, considering the real shield configuration in ITER. The measurements will be performed at the positions of 127, 229, 330, 457, 610, 762 and 914 mm from the surface of the test region, which are in the SS316 region.

Table 4.1 Configurations of test regions for examinations of inhomogeneous effect on SS316/water layers.

Case H0	Homogenized SS316/Water (720mm)	+ SS316(400mm)
Case H1	[SS316(15mm) + Water(10mm) + SS316(15mm)] x 18	+ SS316(400mm)
Case H2	[SS316(30mm) + Water(20mm) + SS316(30mm)] x 9	+ SS316(400mm)
Case H3	[SS316(45mm) + Water(30mm) + SS316(45mm)] x 6	+ SS316(400mm)

Table 4.2 Atomic densities used in the heterogeneous effect calculations.

SS316	Cr	1.5482e-2 *	Water	H	6.6659e-2	Air	N	3.8810e-5
	Mn	1.0355e-3		O	3.3329e-2		O	1.0400e-5
	Fe	5.7904e-2						
	Ni	9.3405e-3						
	Mo	1.0585e-3						
SS316/Water = SS316 x 0.75 + Water x 0.25								

* Unit is in [x 10^{24} atoms / cm^3].

Table 4.3 Ratios of the heterogeneous case to the homogeneous case for integrated fluxes, reaction rates and nuclear heating rates at depth of 900 mm. Notations of H0, H1, H2 and H3 are given in Table 4.1.

Response		Ratio H1 / H0	H2 / H0	H3 / H0
Integrated Flux	> 10 MeV	1.001	1.000	1.000
	1 - 10 MeV	1.021	1.055	1.069
	0.1 - 1 MeV	1.065	1.151	1.190
	10 - 100 keV	1.097	1.226	1.360
	1 - 10 keV	1.112	1.243	1.400
	< 1 keV	1.077	1.170	1.308
Reaction Rate	^{197}Au(n,γ)	1.092	1.209	1.337
	^{235}U(n,f)	1.075	1.168	1.291
Nuclear Heating	- Neutron	1.035	1.080	1.100
	- Gamma-Ray	1.051	1.111	1.190

Table 4.4 Atomic densities used in the additional shield calculations.

	SS316	SS316/Water	Polyethylene	Concrete	Air	Boron-PE
H		1.800e-2 *	8.140e-2	7.974e-3		6.880e-2
B-10		9.000e-3				7.000e-4
B-11						2.800e-3
C	1.193e-4	8.781e-5	4.070e-2			3.440e-2
N					3.881e-5	
O				4.315e-2	1.040e-5	5.200e-3
Na				7.860e-4		
Al				2.637e-3		
Si	1.080e-3	7.884e-4		1.481e-2		
Ca				2.564e-3		
Cr	1.548e-2	1.130e-2				
Mn	1.036e-3	7.559e-4				
Fe	5.790e-2	4.227e-2				
Ni	9.341e-3	6.819e-3				
Mo	1.059e-3	7.727e-4				

* Unit is in [x 10^{24} atoms / cm^3]

Table 4.5 Summary of calculations for additional shield examination.

	Room Wall	Source Can	Polyethylene
Case A0	---	200 mm	---
Case A1	○	200 mm	---
Case A2	---	300 mm	---
Case A3	○	300 mm	---
Case A4	---	400 mm	---
Case A5	○	400 mm	---
Case A6	○	200 mm	Normal
Case A7	○	200 mm	Long
Case A8	○	200 mm	Boron-PE

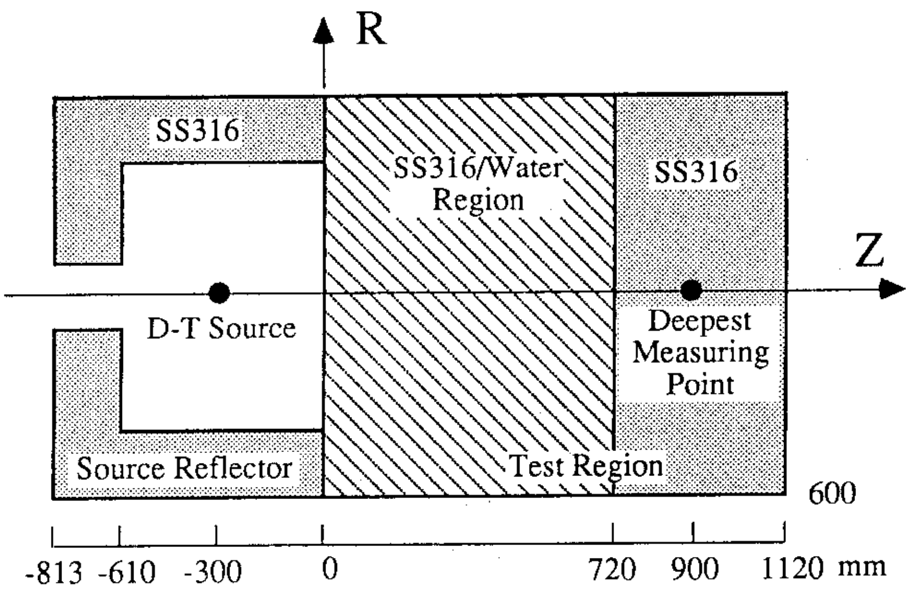
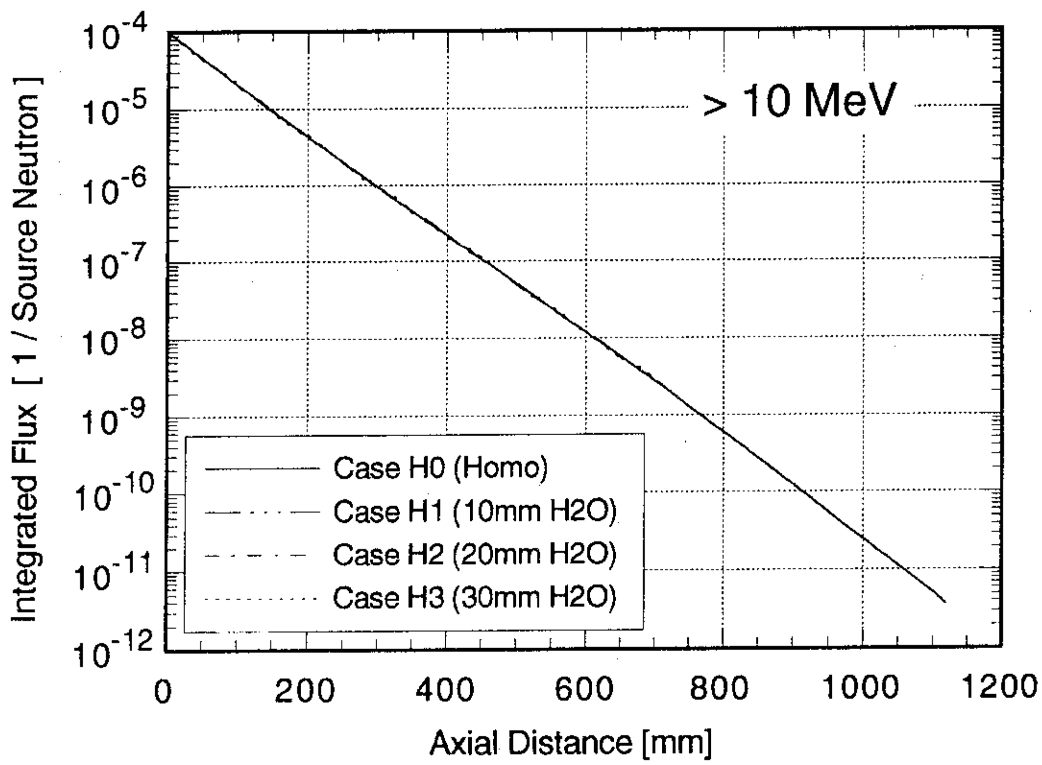
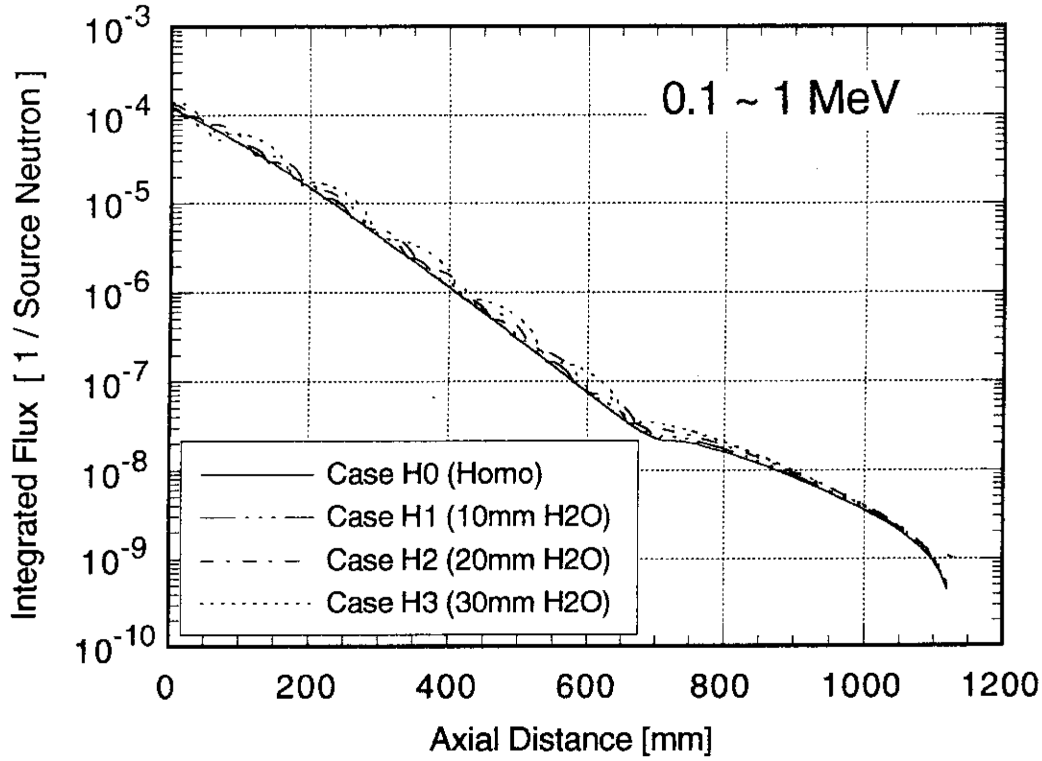


Fig. 4.1 Calculation model of the SS316/water assembly for examination of heterogeneity effect.

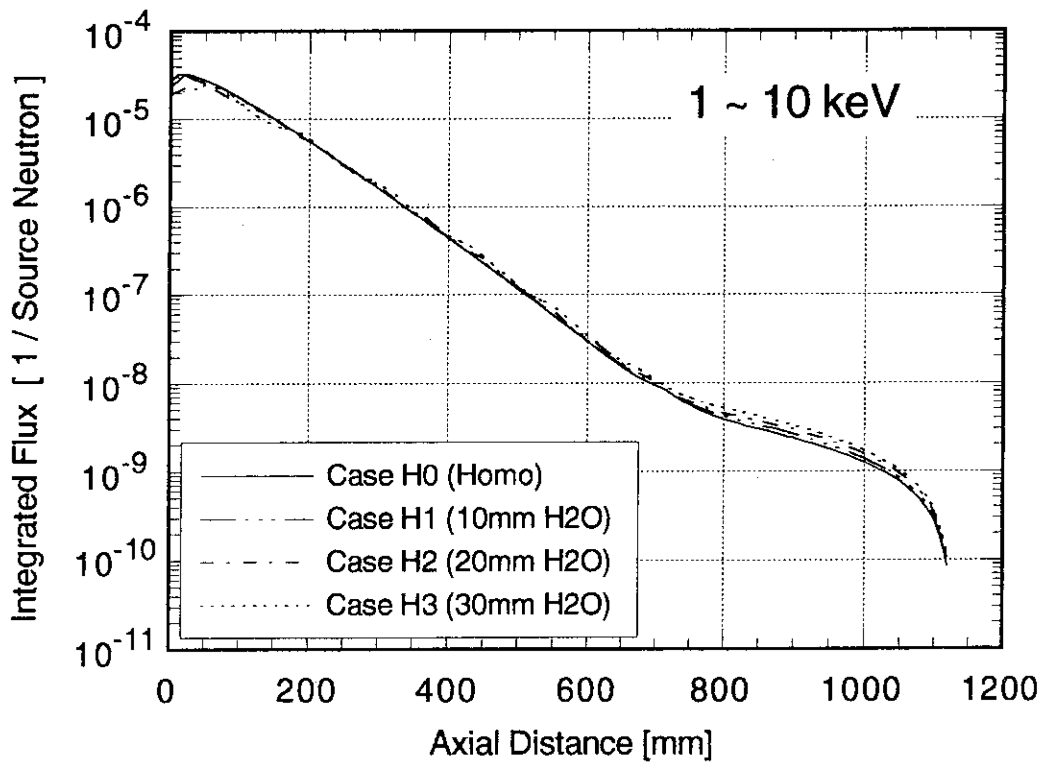


(a) Integrated flux above 10 MeV

Fig. 4.2 Axial distribution of responses for Case H0 - H4 calculations.

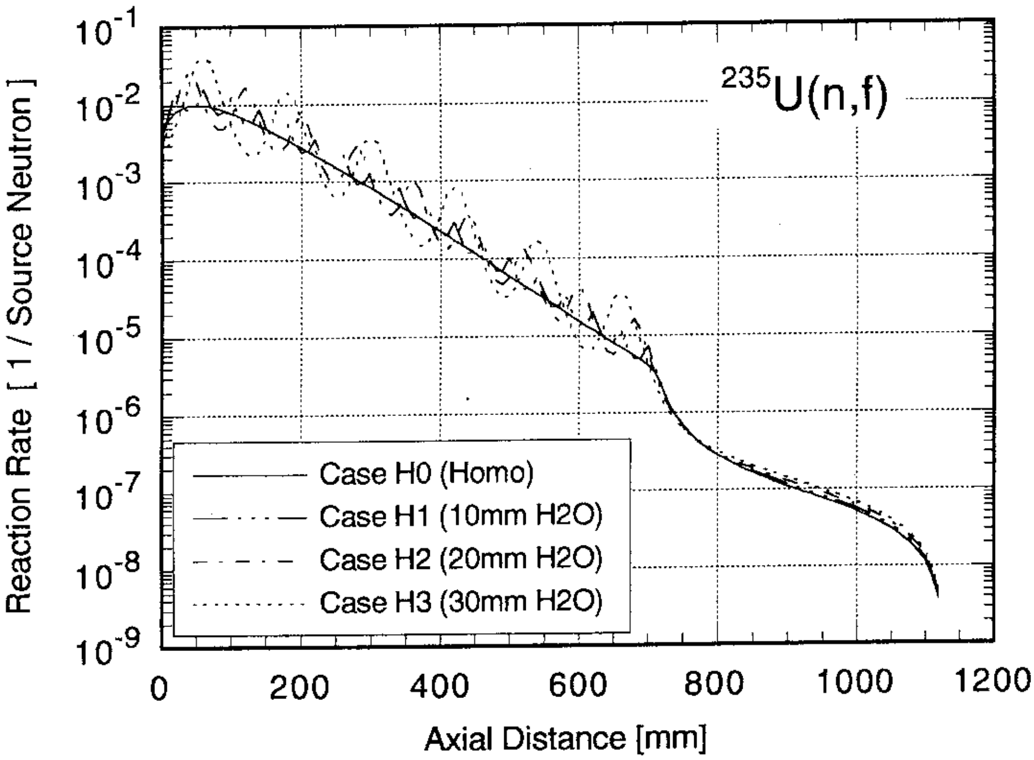


(b) Integrated flux between 0.1 and 1 MeV

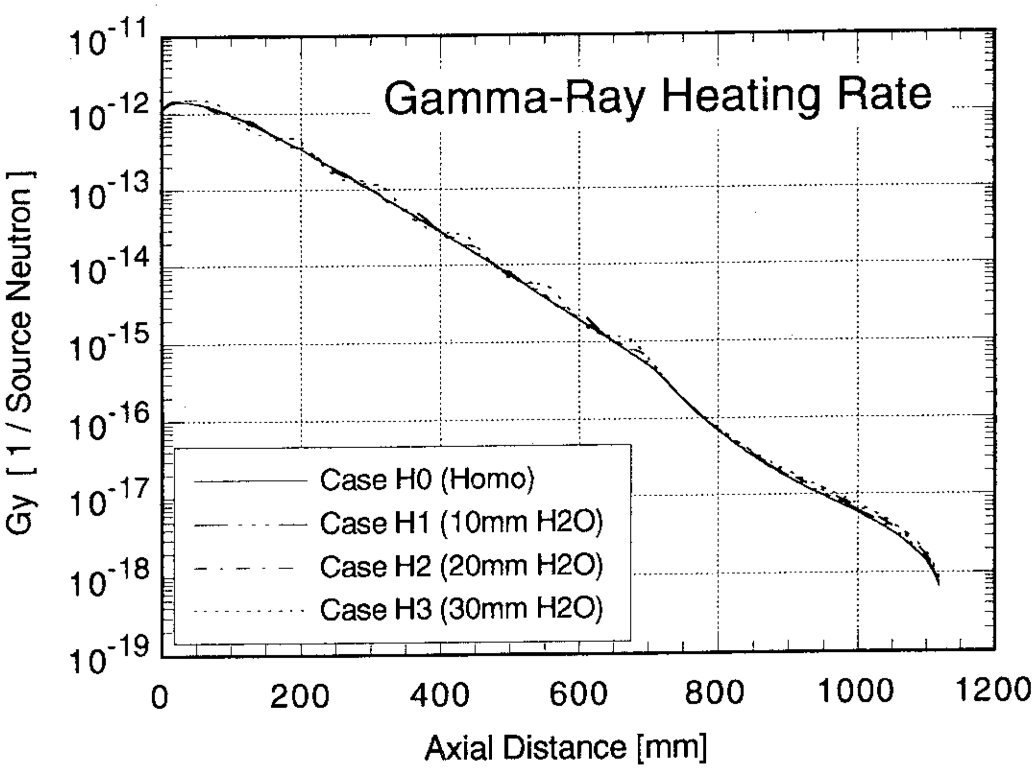


(c) Integrated flux between 1 and 10 keV

Fig. 4.2 Axial distribution of responses for Case H0 - H4 calculations.(Continued).



(d) Fission rate of ^{235}U



(e) Gamma-ray heating rate of SS316

Fig. 4.2 Axial distribution of responses for Case H0 - H4 calculations.(Continued).

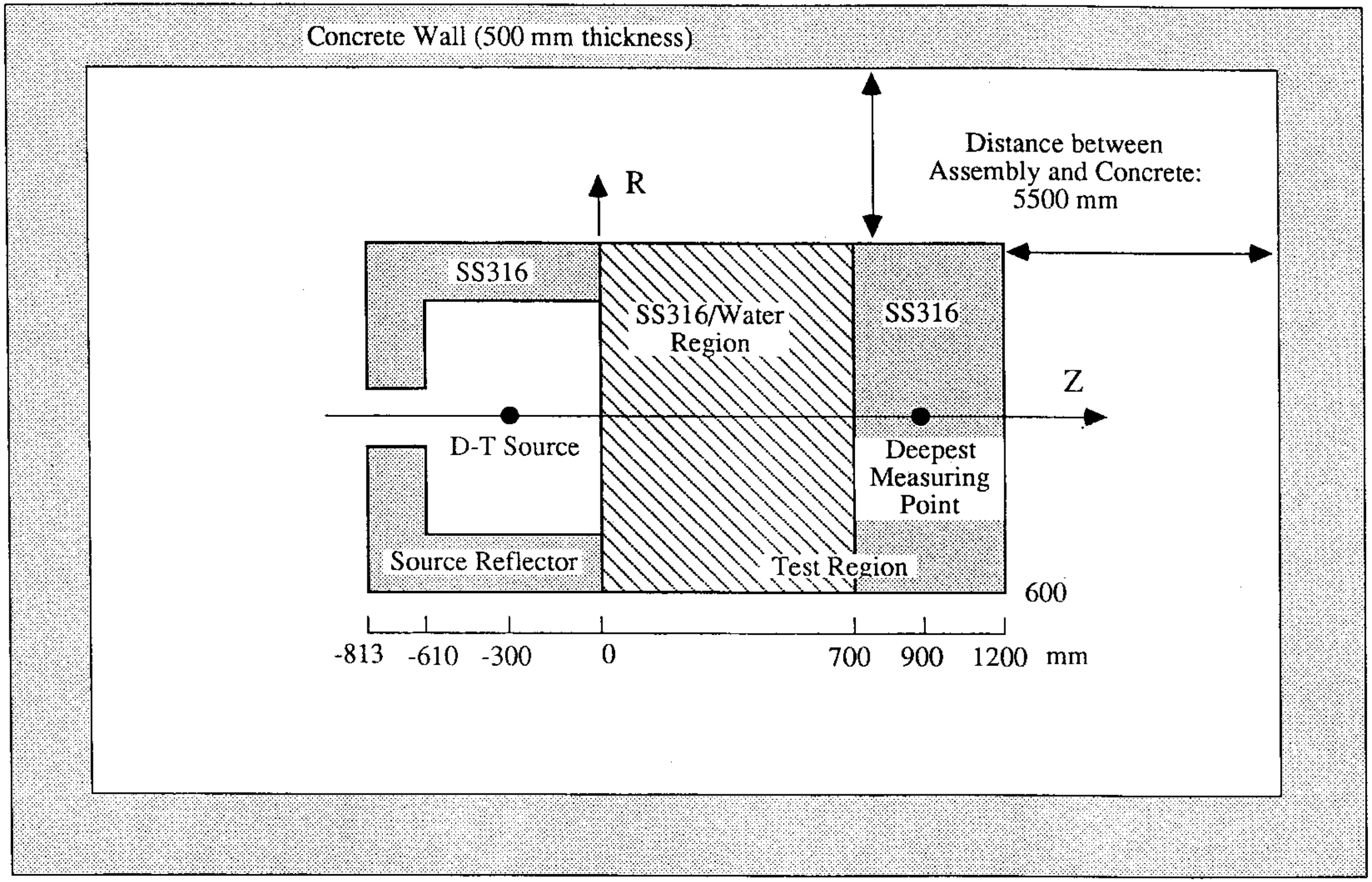


Fig. 4.3 Calculation model for the SS316/water assembly with the room wall (Case A1).

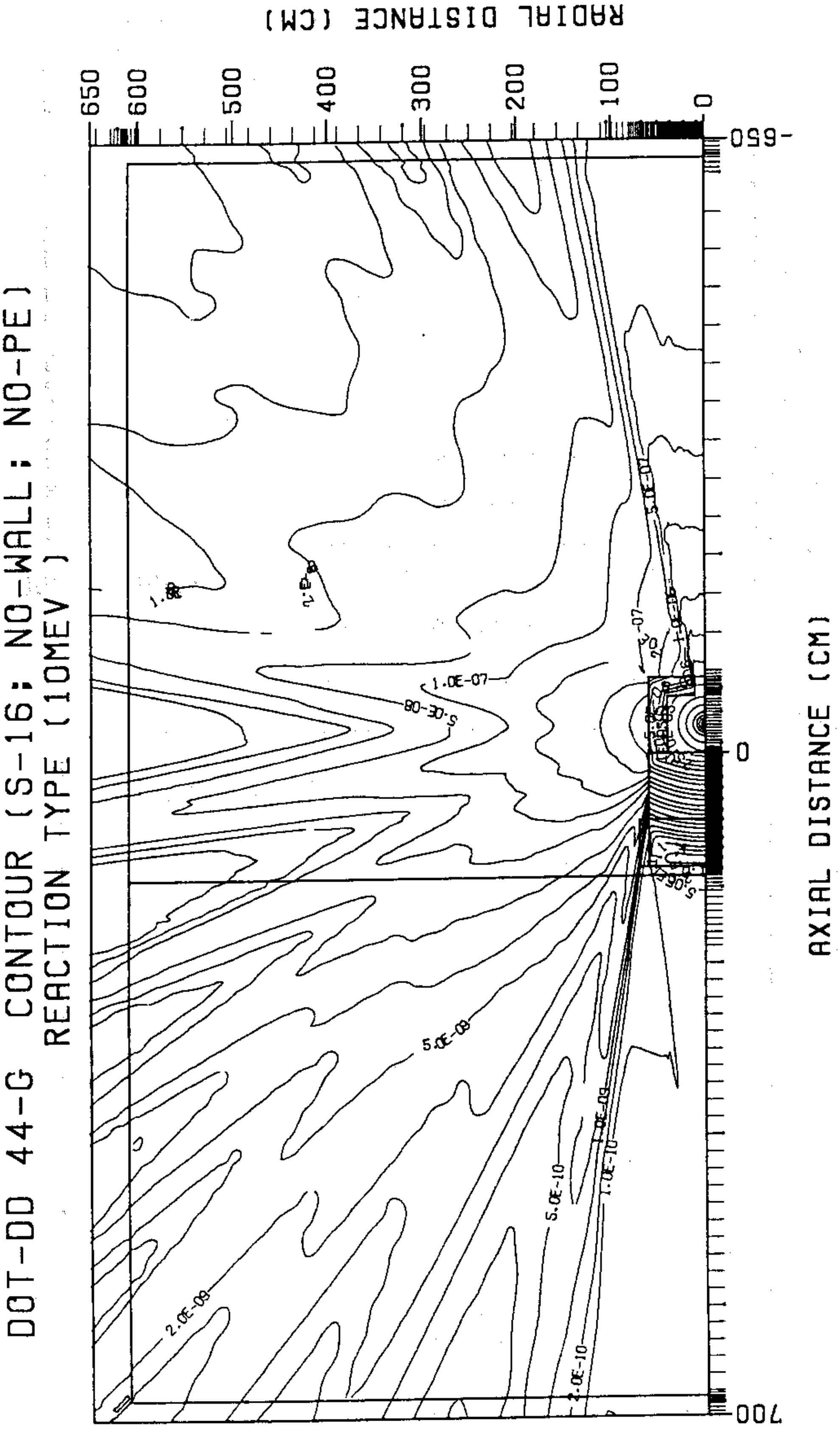
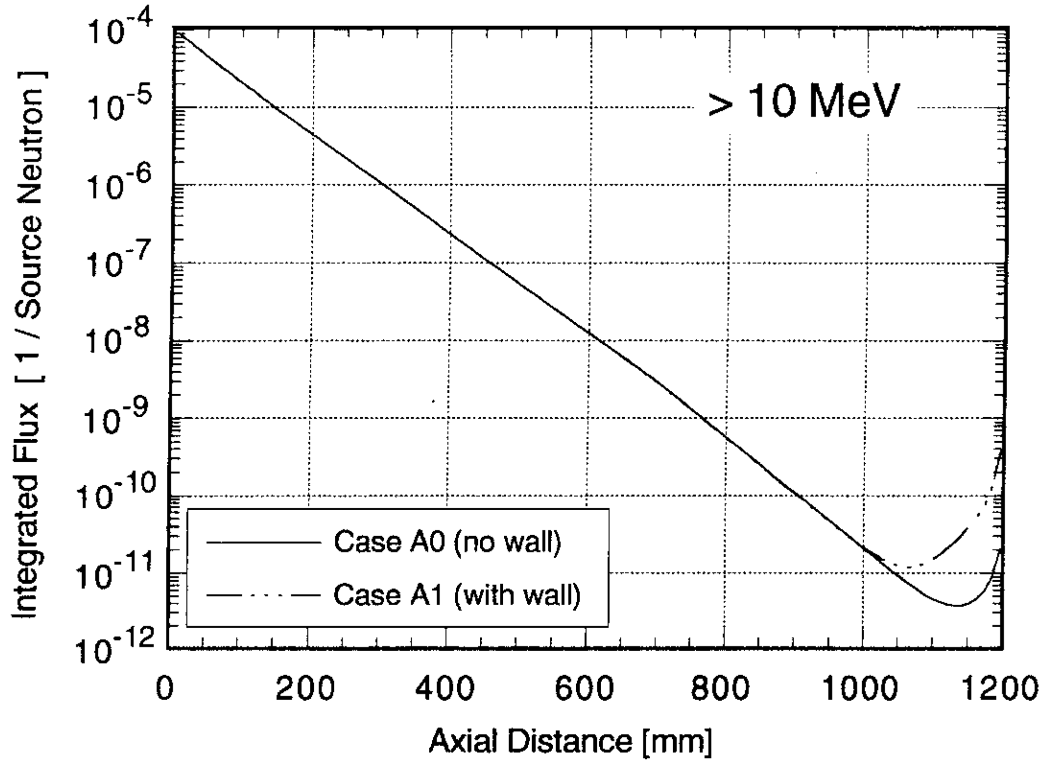
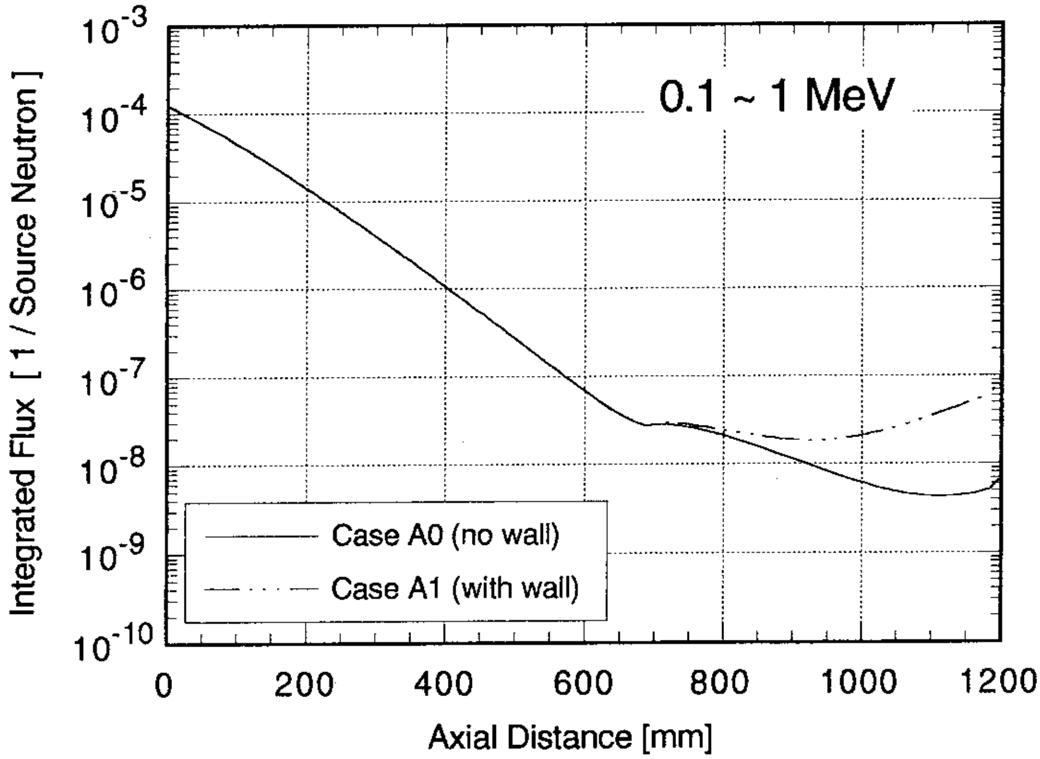


Fig. 4.4 Contour map of integrated flux above 10 MeV for Case A0.

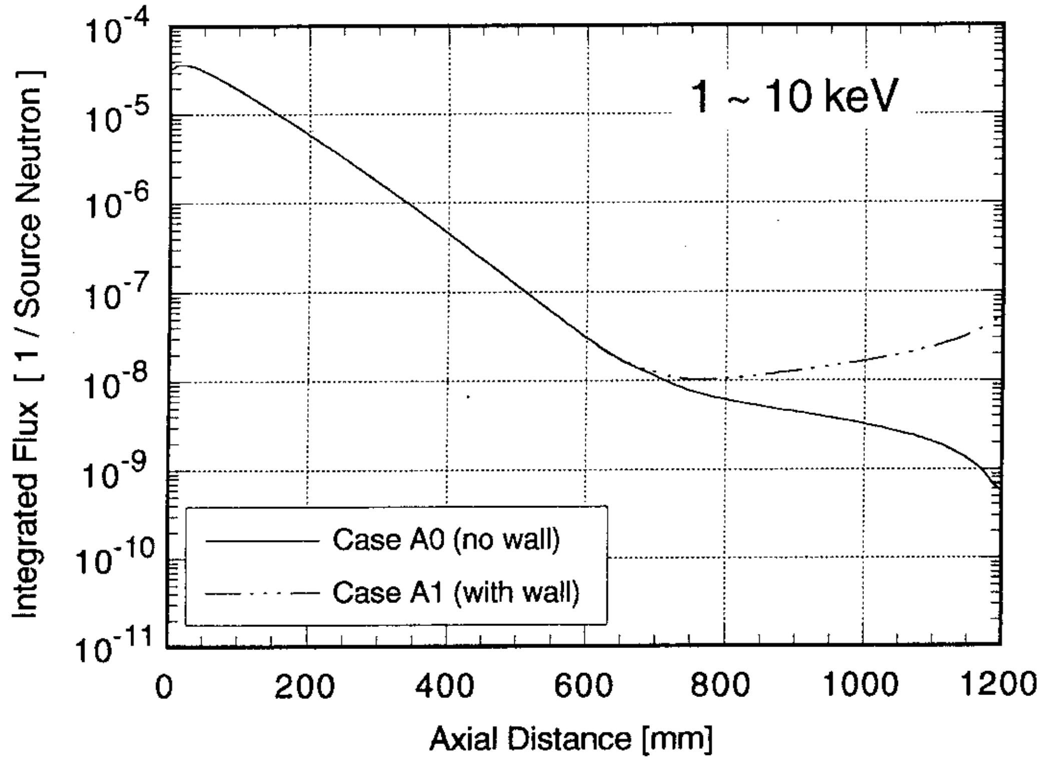


(a) Integrated flux above 10 MeV

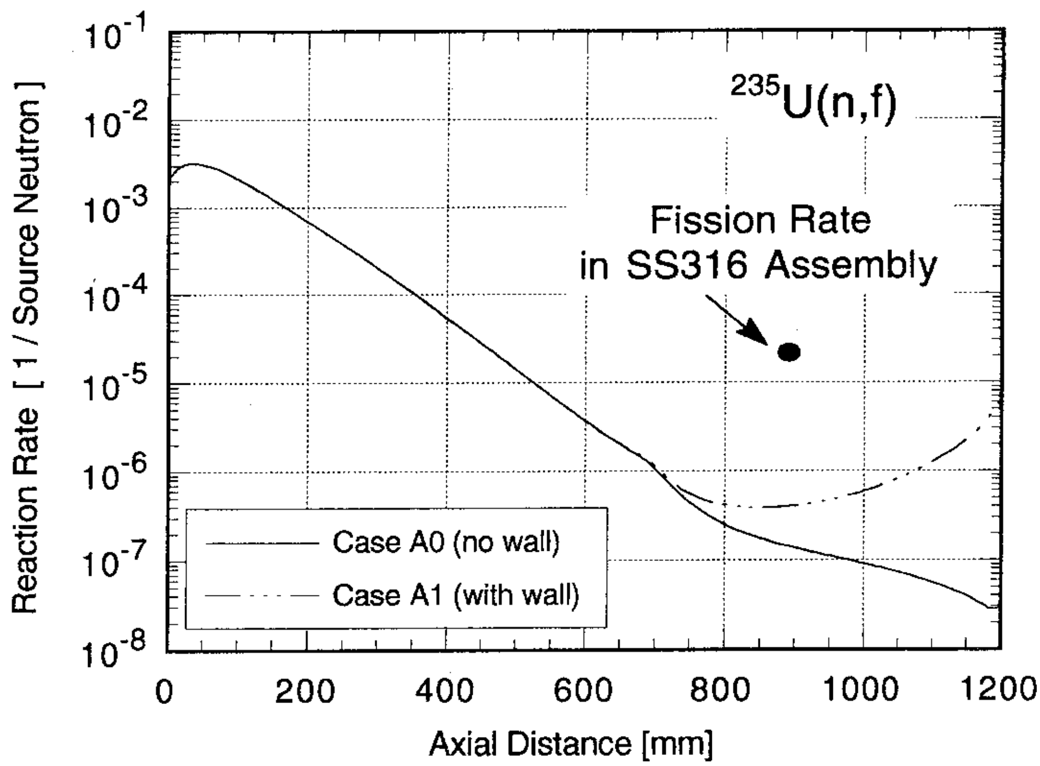


(b) Integrated flux between 0.1 and 1 MeV

Fig. 4.5 Axial distribution of responses for Case A0 and A1 calculations.

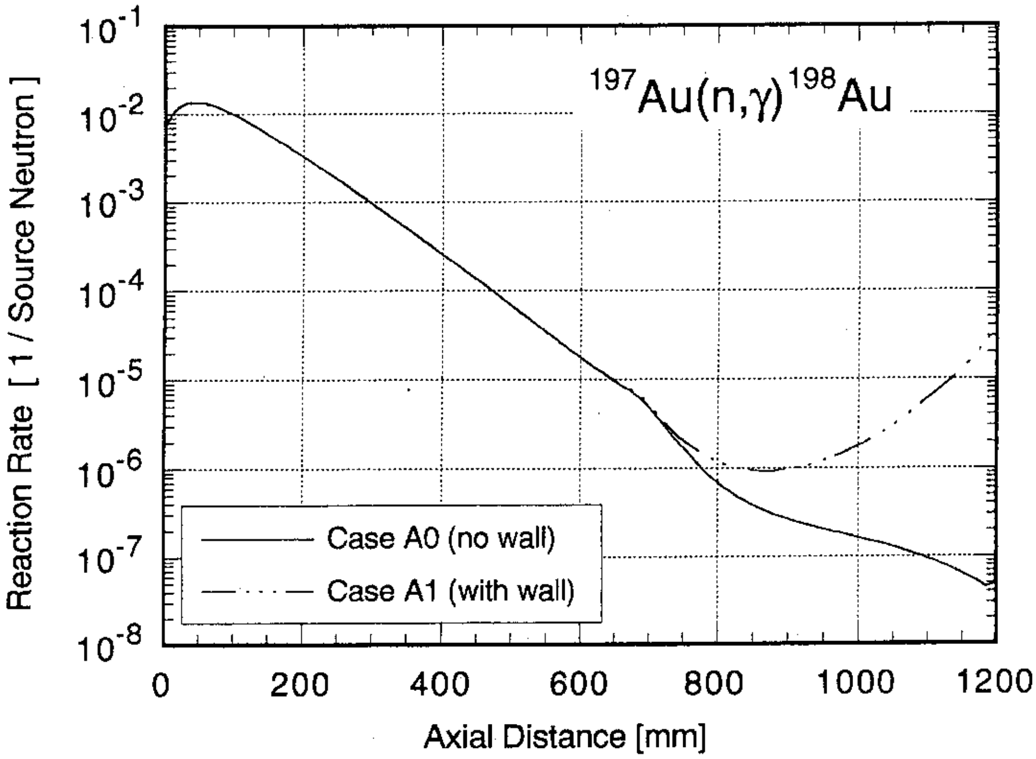


(c) Integrated flux between 1 and 10 keV



(d) Fission rate of ^{235}U

Fig. 4.5 Axial distribution of responses for Case A0 and A1 calculations (Continued).



(e) ^{197}Au(n,γ) reaction rate

Fig. 4.5 Axial distribution of responses for Case A0 and A1 calculations (Continued).

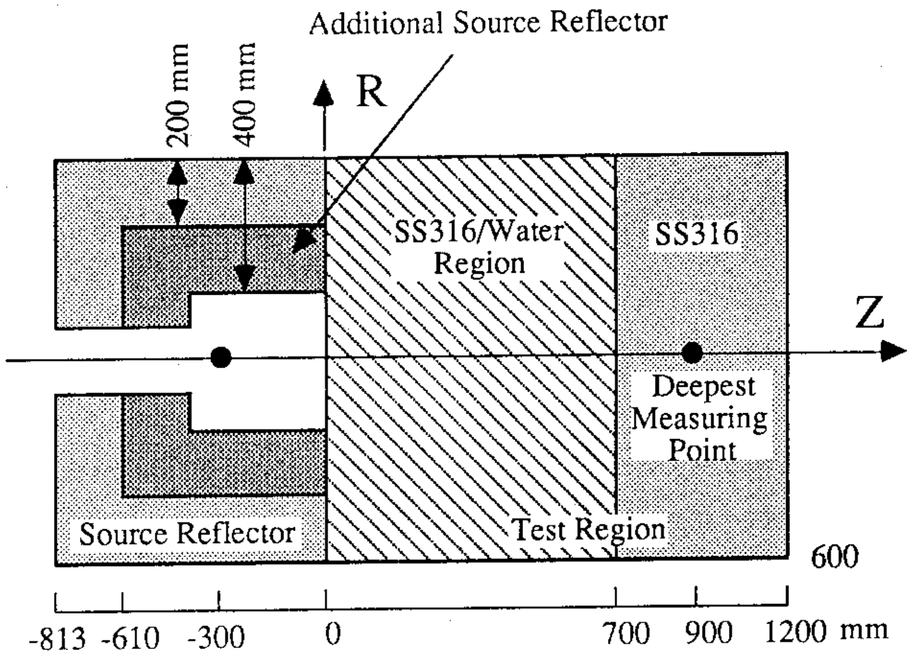
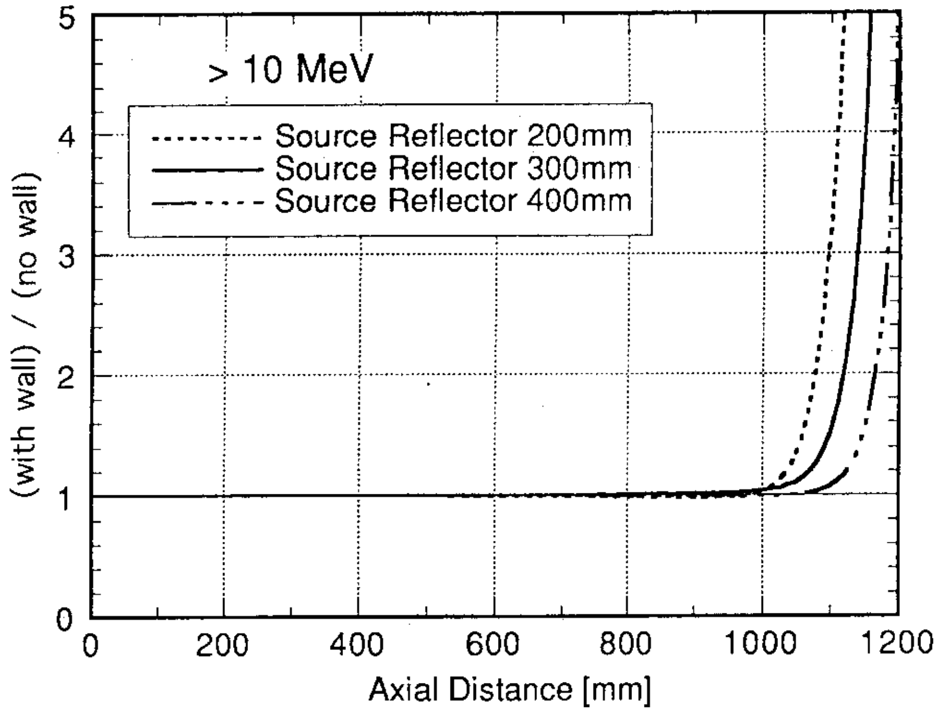
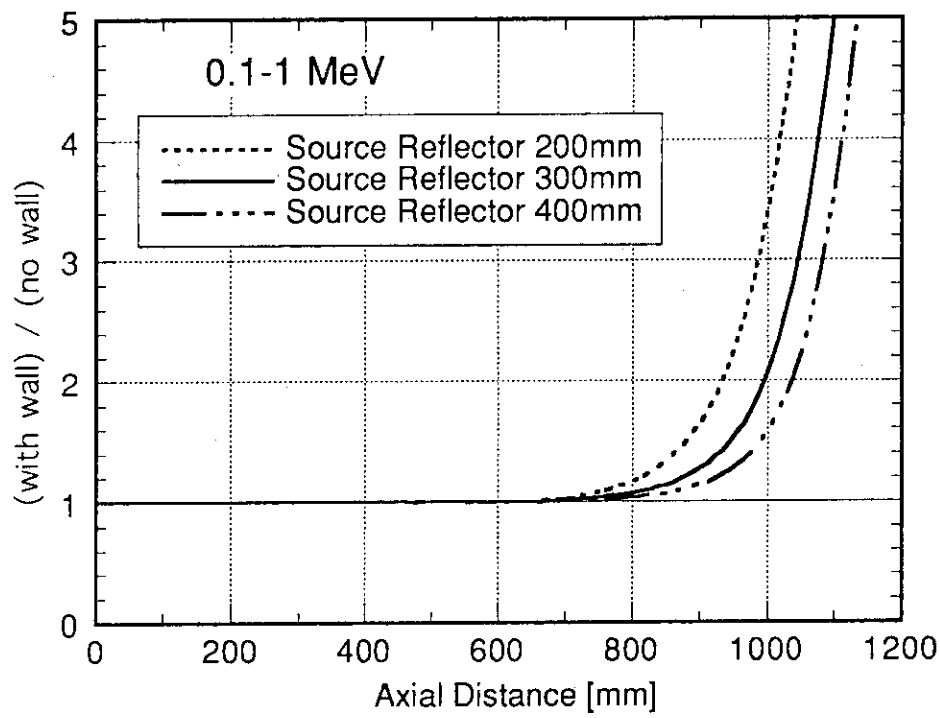


Fig. 4.6 Calculation model for additional source reflector of 400 mm thickness (Case A4).

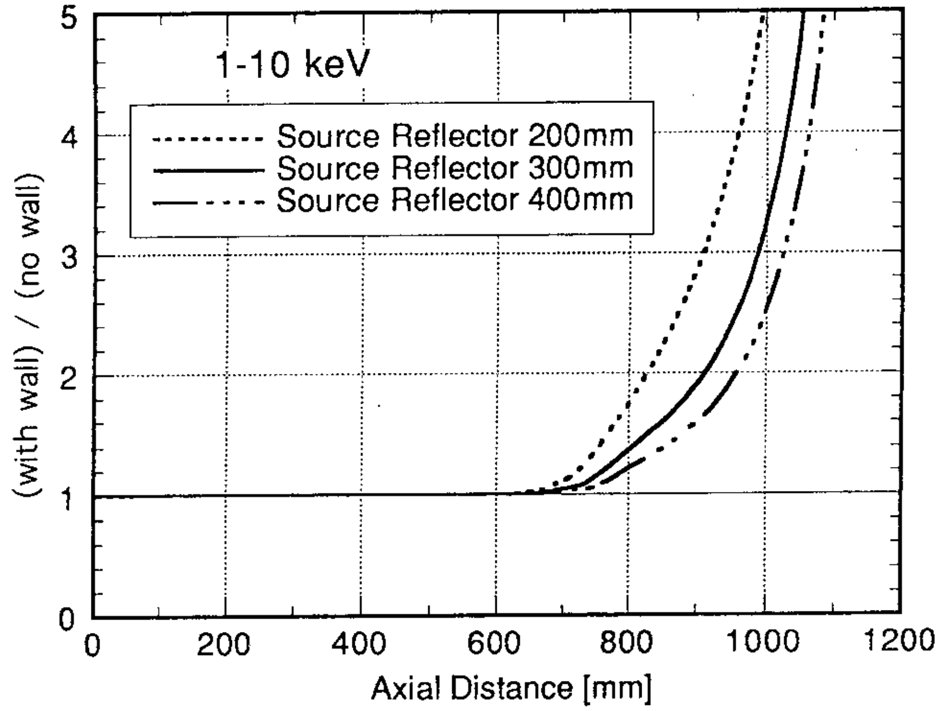


(a) Integrated flux above 10 MeV

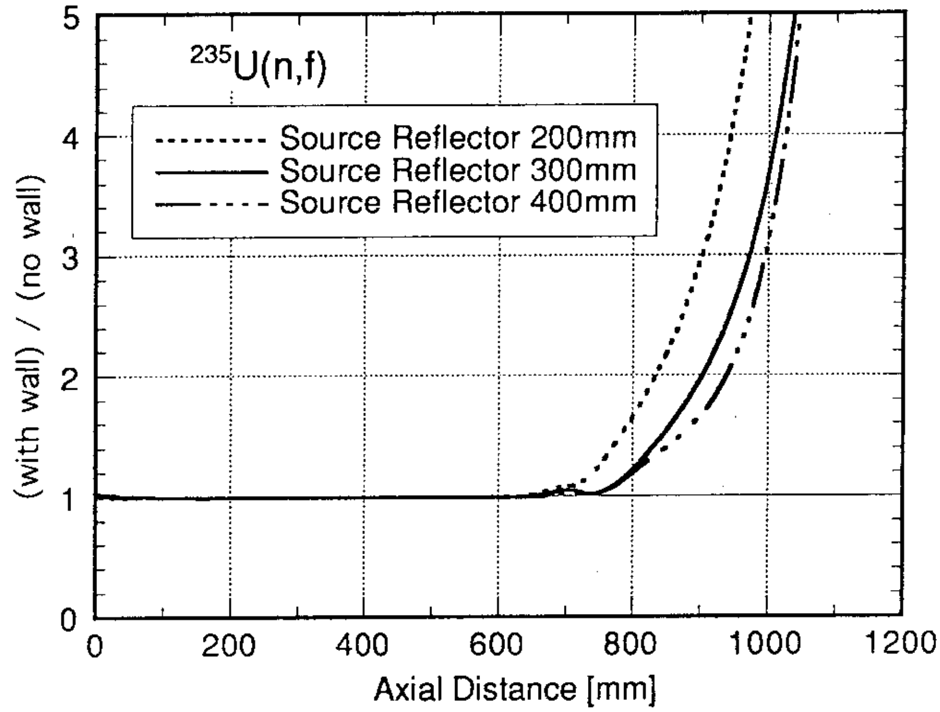


(b) Integrated flux between 0.1 and 1 MeV

Fig. 4.7 Ratios of responses with and without the wall for three source reflector thicknesses.

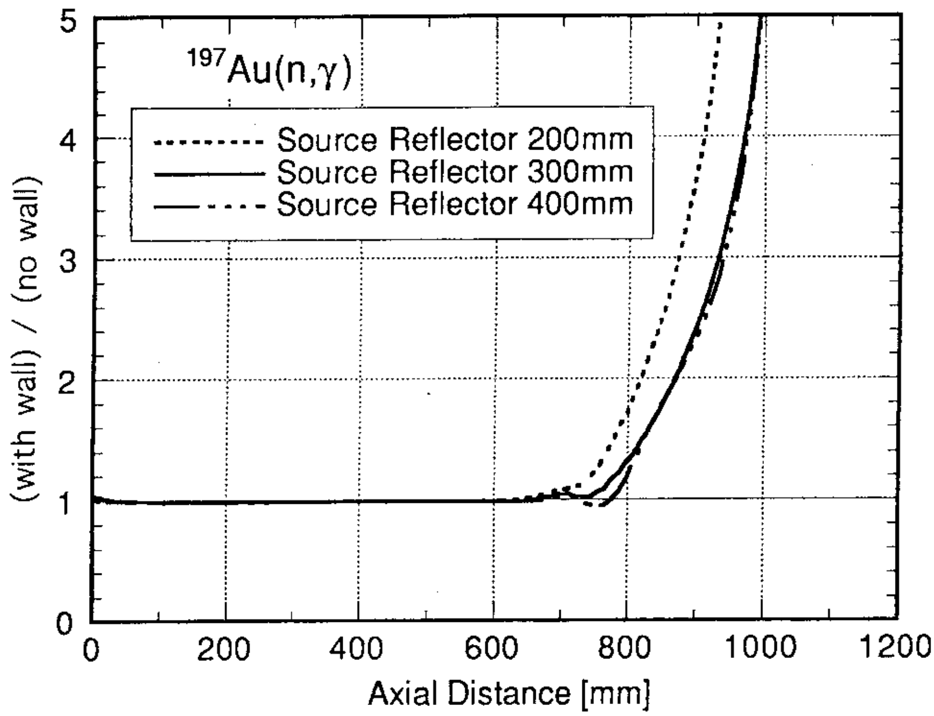


(c) Integrated flux between 1 and 10 keV



(d) Fission rate of ^{235}U

Fig. 4.7 Ratios of responses with and without the wall for three source reflector thicknesses (Continued).



(e) $^{197}Au(n,\gamma)$ reaction rate

Fig. 4.7 Ratios of responses with and without the wall for three source reflector thicknesses (Continued).

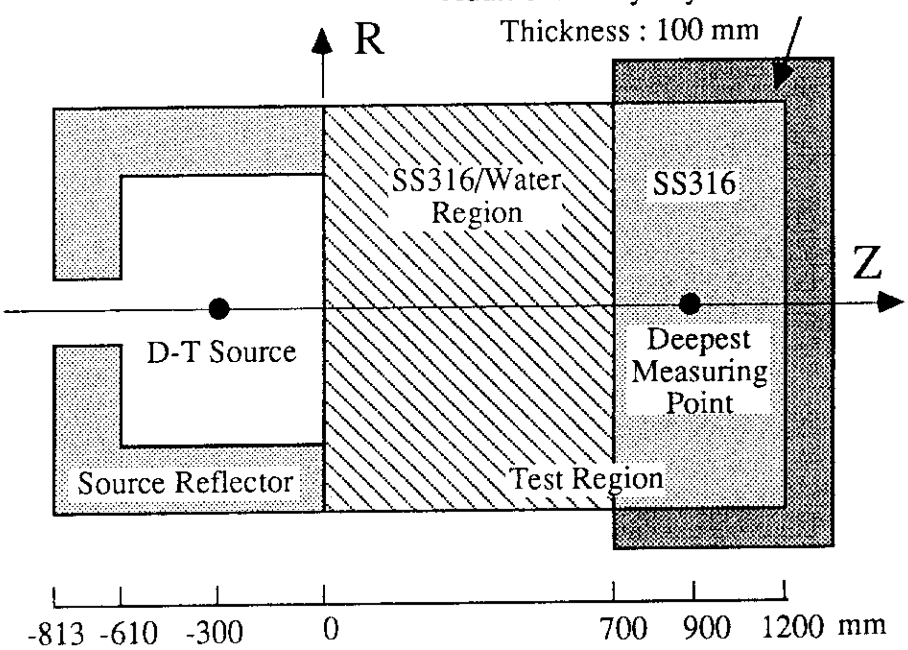


Fig. 4.8 Calculation model for additional polyethylene calculation (Case A6).

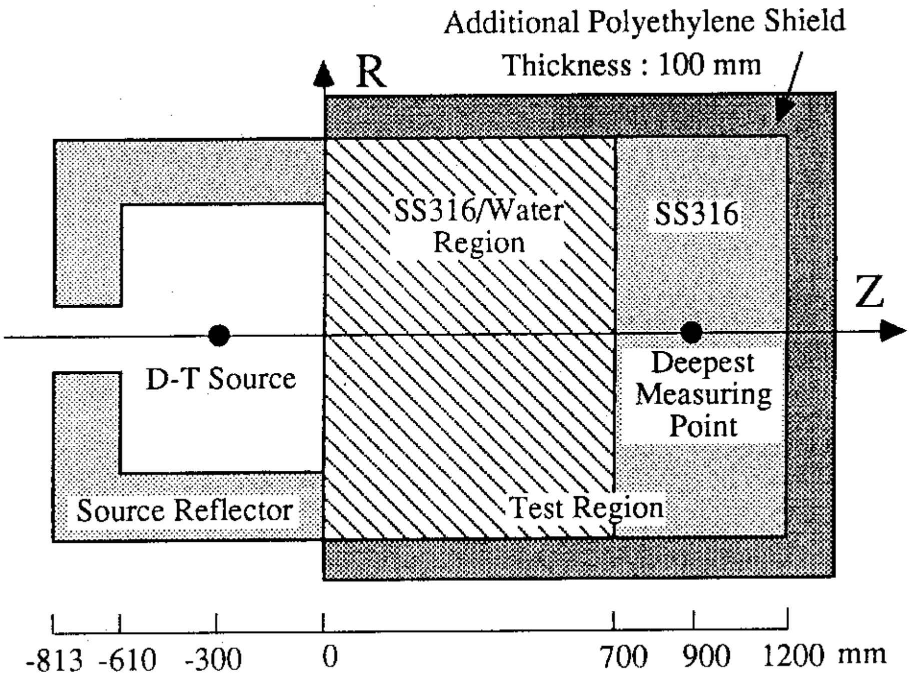
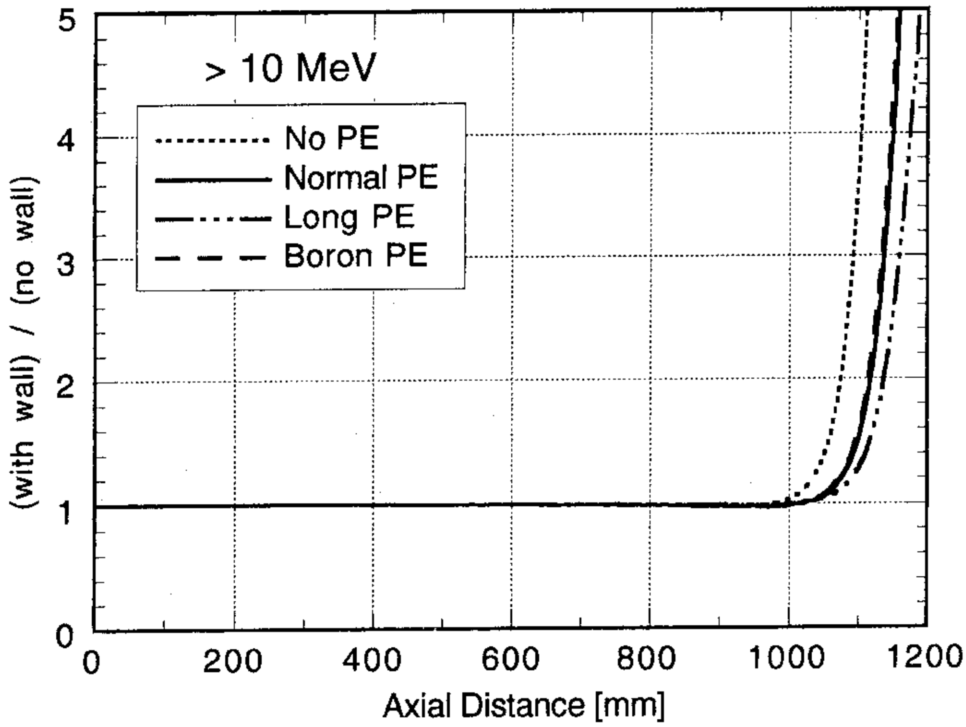
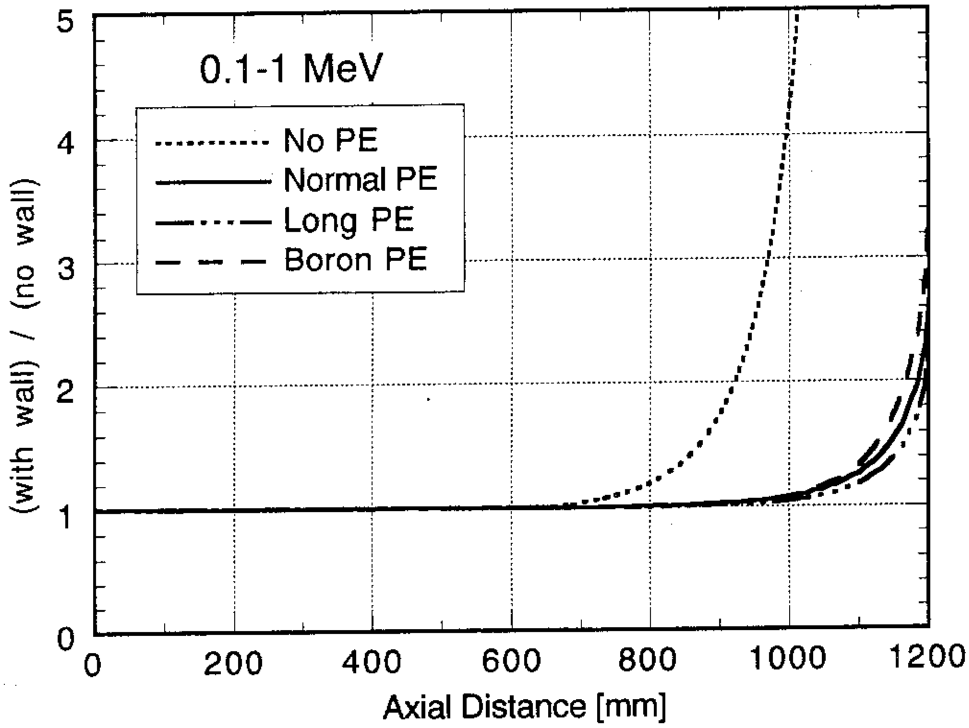


Fig. 4.9 Calculation model for additional polyethylene calculation (Case A7).

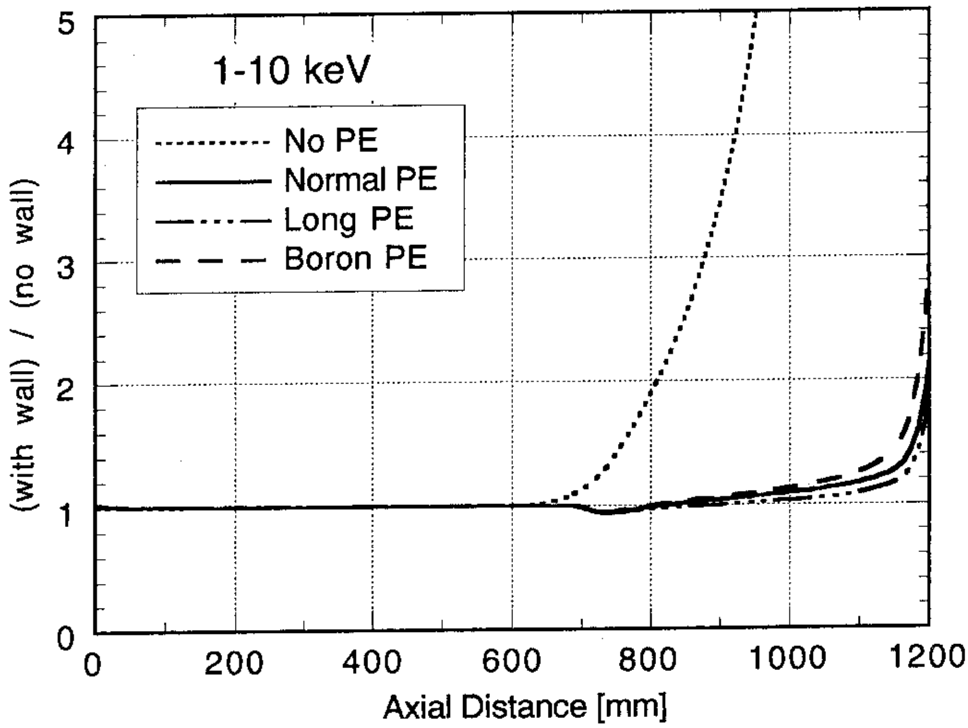


(a) Integrated flux above 10 MeV

Fig. 4.10 Axial distribution of responses for Case H0 - H4 calculations.

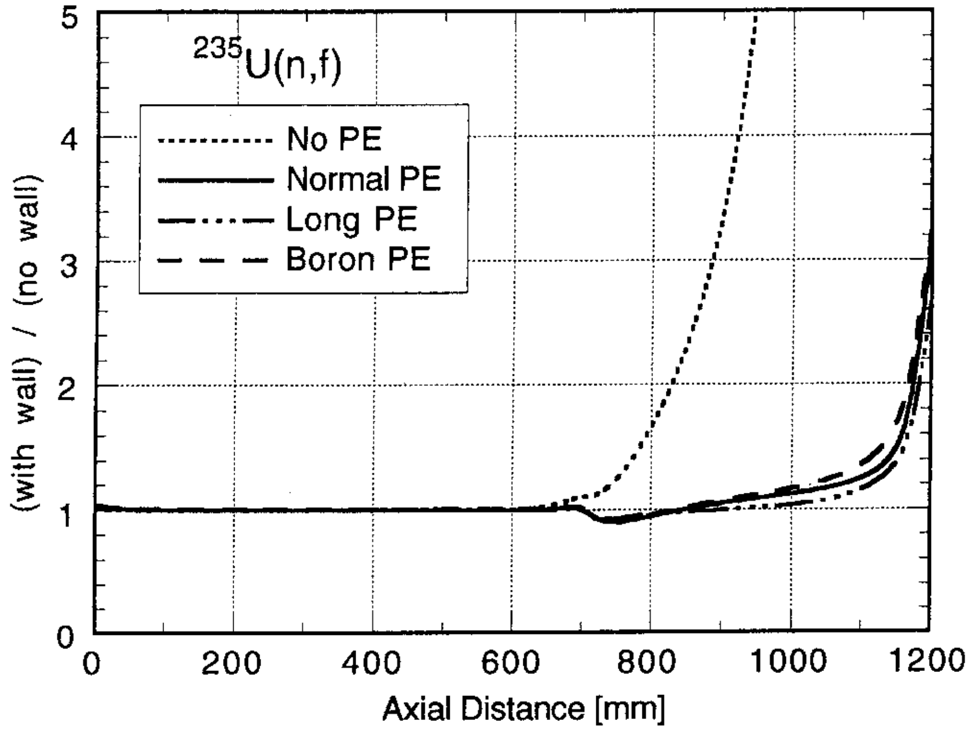


(b) Integrated flux between 0.1 and 1 MeV

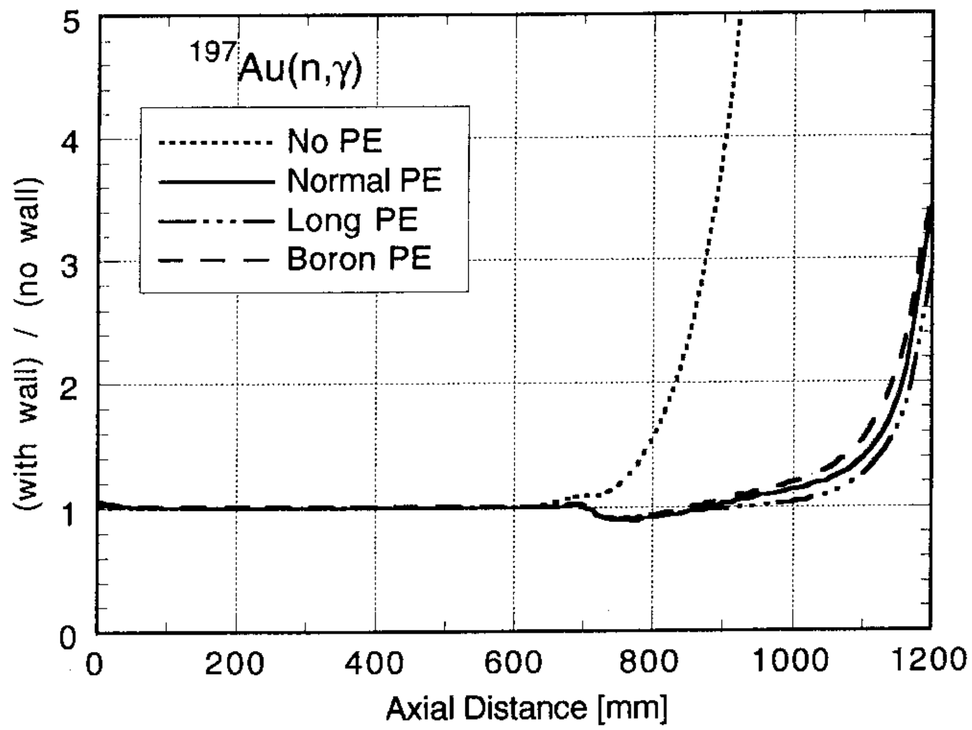


(c) Integrated flux between 1 and 10 keV

Fig. 4.10 Axial distribution of responses for Case H0 - H4 calculations (Continued).



(d) Fission rate of ^{235}U



(e) $^{197}Au(n,\gamma)$ reaction rate

Fig. 4.10 Axial distribution of responses for Case H0 - H4 calculations (Continued).

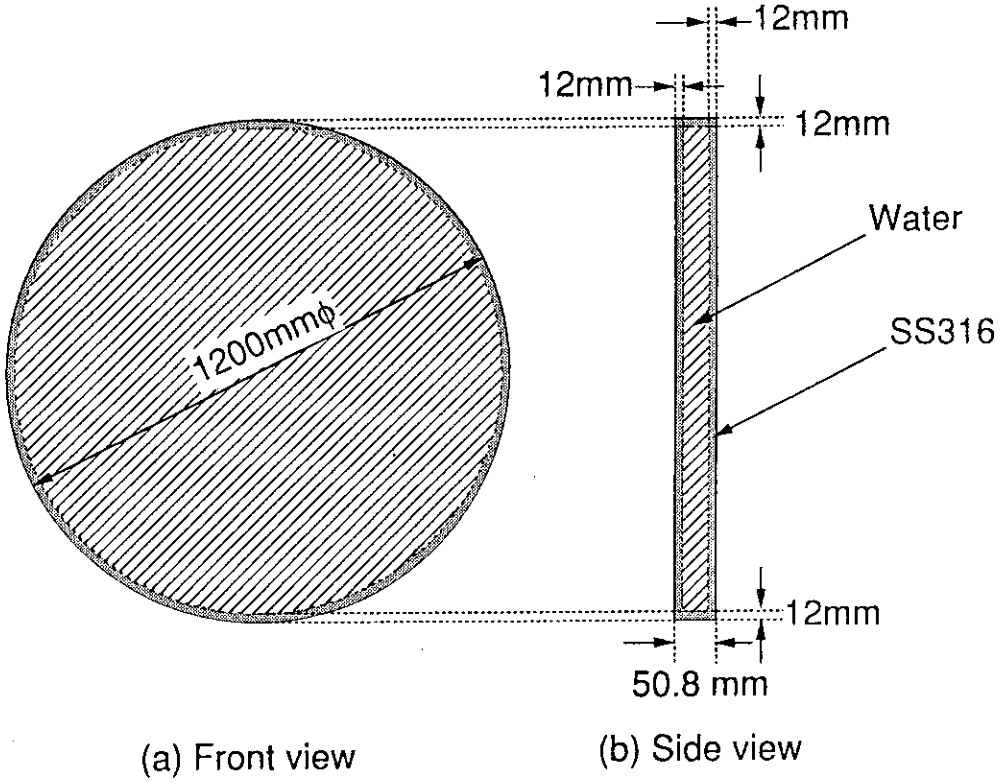


Fig. 4.11 Schematic view of the SS316/water disk.

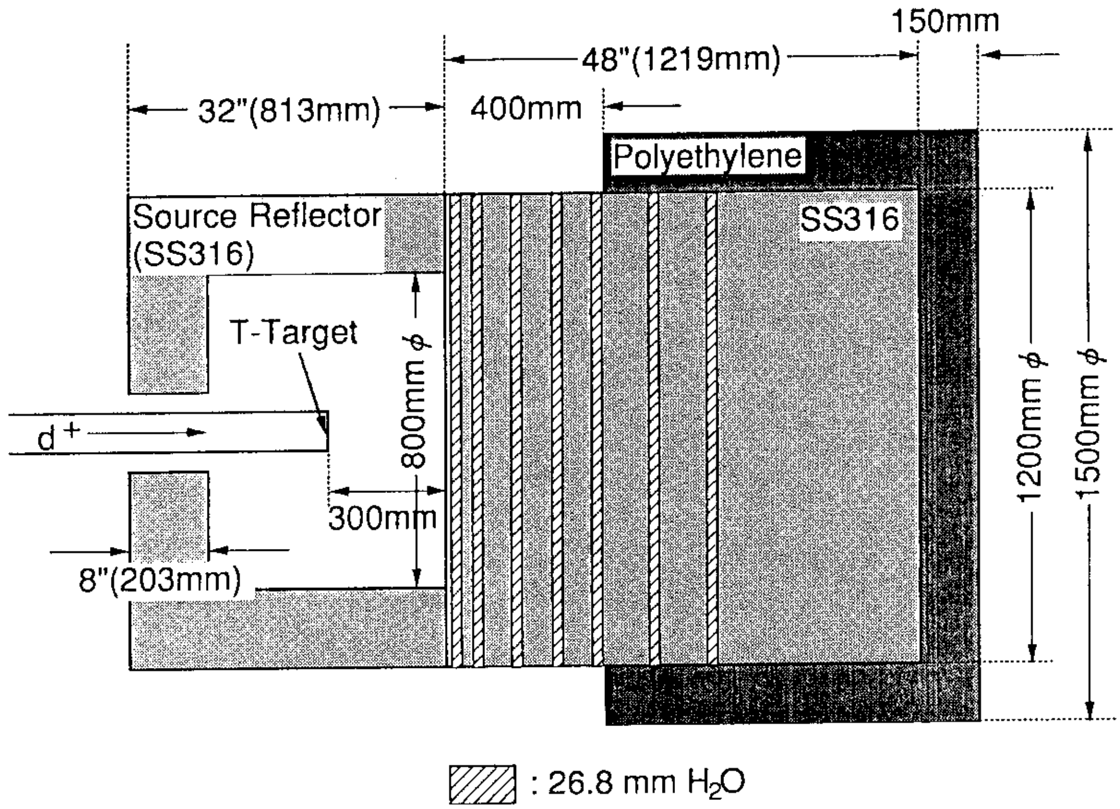


Fig. 4.12 Final experimental configuration for the SS316/water experiment.

5. Summary

The pre-analyses for the SS316 and SS316/Water experiments were performed in the JA-3 (Bulk Shielding Experiments: Phase IA 'Pre- & Post-Analyses and Preparation of SS316 and SS316/Water Experiments') of the '93 ITER/EDA emergency tasks. The cylindrical assembly of 1.2 m in diameter and 1.1 m in thickness is determined for the SS316 experiment, using the S_N code DOT3.5 and the FUSION-40 nuclear data set. The 0.2 m thick SS316 source reflector is added to simulate fusion reactor neutron environment and to decrease background neutrons.

The heterogeneity effect due to the layered structure of SS316 and water (SS316 : water = 4 : 1) is not so large on the shielding performance. The 26.8 mm thick water layer is selected. The 0.15 m thick polyethylene is necessary to reduce background neutrons, since the shielding performance of SS316/water is much higher than that of SS316.

The final experimental configurations of the SS316 and SS316/water experiments will be determined based on the present pre-analyses.

Acknowledgment

The authors gratefully acknowledge Drs. S. Matsuda and H. Takatsu, Department of ITER Project in JAERI/Naka, for their supports to this work.

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