ISSUES AND TEST REQUIREMENTS IN RADIATION SHIELDING OF FUSION REACTORS

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ABSTRACT Radiation shield issues for fusion reactors have been investigated and the experiments and facilities required to resolve the issues have been identified and characterized as part of the FINESSE program.[1] This paper summarizes the recommended approach to fusion shield research and development, provides a summary of the necessary experiments and facilities, and presents the results of technical analyses involved.

INTRODUCTION AND ISSUES

The role of radiation shielding is to protect the reactor components, the reactor operators and the public from intolerable levels of radiation exposure. The most sensitive components are superconducting magnets, some elements of plasma heating and exhaust systems, and instrumentation and control. Shielding must reduce the radiation damage and the nuclear heating of these components as well as the biological dose below the design criteria or regulatory level. Though many shielding designs exist, their design criteria differ by factors up to an order of magnitude. Some of these design criteria are based on untested assumptions and incomplete models, and the uncertainties are not well evaluated. These uncertainties will impact construction and operation costs, availability, maintainability, and the life of the reactor. For example, the radiation level should be reduced by a factor of 10^4–10^6 (from the first wall to the back of the shield). Since a reduction by a factor of $10 \sim 10^2$ can be expected in the blanket region, shielding should add a further reduction factor of at least $10^3 \sim 10^4$, and even larger reduction is required for public protection.

The key issues of radiation shielding[1] are categorized in Table 1. These are generic for the various blanket concepts and confinement systems. Although different kinds of issues may exist for a specific reactor design, such as high power density systems, these issues have a lower priority in test planning. The issues are briefly discussed below.

Table 1. Radiation Shielding Issues

1. Design criteria of sensitive components in SCM, vacuum, NBI, RF systems and control system
2. Effectiveness of bulk shield
   - composition and thickness of shield materials
   - deep penetration of high energy neutron (14 MeV), including cross section windows
3. Penetrations and their shield effectiveness for NBI, RF ports, and coolant pipes
   - streaming and partial shield
   - modeling procedure
4. Occupational exposure
   - induced activity and dose distribution
   - radioactive corrosion materials
   - remote maintenance system
5. Public exposure
   - sky shine
   - radioactive waste of shield materials
6. Shield compatibility with blanket and magnet including assembly/disassembly and field penetration

1) The design criteria for the sensitive components define the allowable radiation level at each component. These critieria should be determined from irradiation tests.

2) The bulk shield plays the principal role in the protection of the magnet system and against biological exposure. Most of the effort in fusion reactor shielding research has focused on design and analysis of the bulk shield, such as was carried out in the BCSS study.[2] The main consideration in designing the shield involves the determination of optimized compositions and thickness of the shielding. Data base uncertainties will strongly affect the effectiveness evaluation of the bulk shield. These uncertainties arise from deep penetration of high energy neutron (14 MeV peak) and γ-rays, and/or from the cross section windows.

3) The most difficult problems encountered in fusion reactor system shielding are those related to radiation streaming through penetration holes and slits. Open penetrations will directly cause serious damage to other reactor components resulting from leakage of neutron and γ-rays through these penetrations. Stream-

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ing can also occur due to unexpected malfunction of a particular reactor component. This is one of the dominant problems in radiation shielding of fission reactors. The modeling procedure of penetration and partial shields is not simple and should be tested through experiments.

4) Occupational dose issues affect reactor maintainability and availability. Radiation exposure due to induced activity after shutdown involves the contribution of γ-rays emitted from the reactor system and building (excluding exposure due to tritium leakage). At present, large discrepancies can be observed in the induced activation cross section libraries.

The other possible source of radioactivity is radioactive corrosive materials carried by coolant from highly irradiated components (e.g., first wall) to outside the shield. Large uncertainty exists regarding the amount of corrosive products, particularly in the case of liquid metal cooled blankets. Coolant pipes and heat exchangers with high radiation levels may require additional lead shielding. The development of remote operation systems and robotic techniques, with a resistivity to high radiation, is needed to reduce radiation doses.

5) The exposure level of the public from fusion power plants is a high safety concern. The selection of shield material is important to decrease the long-lived radioactive waste. Radiation through sky shine will cause direct exposure to the public. This issue may not be serious for a next generation fusion facility, but will be important in power reactors.

6) Shields are set in the inboard and outboard zones between the blanket and toroidal field coil. They must be fitted in these locations and the slit width between modules should be small enough to keep streaming low. Mechanical interactions can lead to mechanical failures.[3]

7) Larger uncertainties due to the modeling procedure, transport and response function calculation methods and data base need a higher safety margin and conservatism. Most of the single and mutliple effect testing will provide the data to be used for improvement of this software. By considering these issues in some detail, test requirements to resolve them could be addressed.

This work intends .to review the existing experiments, data base, methods and facilities with respect to radiation shielding and to anticipate the type and characteristics of experiments needed to resolve the issues. For shielding experiments, providing an adequate neutron source is an essential part of planning. The performance of the neutron source facility will constrain the experimental program and the quality and quantity of data obtained. A point neutron source, a fission source and a fusion source are compared based on their respective usefulness. Numerical investigation of the geometrical requirements has been performed for the shielding test matrix in a fusion test facility and the results are described.

REQUIRED ACCURACY AND PRESENT STATUS

The prediction uncertainty in the shield performance is required to be as small as possible. The reduction of uncertainty, however, requires further research and development funding, and hence the required accuracy in predicting the nuclear performance can be determined from a cost-benefit analysis.

An investigation was made for the required accuracies in predicting the important nuclear parameters in the blanket, shield and other reactor components where radiation is of concern, and the results are shown in Table 2. The radiation source originates in the plasma region; hence, the prediction accuracy of source characteristics is very important. Uncertainty in the source prediction propagates to all other nuclear responses. The required accuracy should be a few percent. For the first wall and blanket region, good accuracies are required to predict severe radiation damage and the tritium breeding ratio. The achievable prediction accuracy generally decreases with increasing distance from the first wall, and is reflected in the required accuracies in Table 2.

Table 2. Required Accuracies and Present Status in Nuclear Design of Fusion Reactors*

Location/Response	Required Accuracy	Present Status
First Wall/Divertor		
Nuclear heating	total 2%, local 10%	50%
Atomic displacement	10%	
Gas production	10%	
Transmutation	20%	
Induced activity	30%	50% ~ factor 3
Blanket		
Tritium production rate	gross 3~5%, local 10%	gross 10%, local 20%
Nuclear heating	20%	
DPA	20%	
Gas production	20%	
Induced activity	50%	factor 2~5
Bulk Shield		
Nuclear heating	20%	factor 2~5
DPA	30%	
Induced activity	factor 2	factor 5~10
Superconducting Magnet		
Nuclear heating	gross 30%, local 50%	factor 5~10
DPA	gross 30%, local 50%	
Gas production	gross 50%, factor 2	
Dose	gross 30%, local 50%	
Induced activity	factor 2	
Penetration Functional Equipment (e.g., vacuum, pump, RF, and NBI)		
Nuclear heating	gross 30%, local 50%	gross factor 2, local factor 10
DPA and gas production	50%	
Induced activity	factor 2	
Reactor Room (outside the shield and inside the reactor bldg.)		
Biological dose during operation	factor 3	
Biological dose after shutdown	factor 2	
External Biological Dose (outside plant site)	factor 3	

*Assumed DEMO class reactor

Nuclear responses of the superconducting magnet in the toroidal field coils need relatively high prediction accuracies because of the high radiation sensitivity. In a tokamak, the magnet is protected by the inboard bulk shield with a thickness of 60~80 cm. Since the nuclear data for neutron and gamma ray transport and response functions have at least ~10% uncertainties, it is very difficult to reduce overall uncertainties below a few tens of percent after such a thick shield.

A factor of 2~3 is shown for the required accuracies for the biological dose. Better accuracies are, of course, desirable but they are not practically achievable because of the large radiation attenuation required and the many possible streaming paths involved. Furthermore, present prediction accuracies are estimated based on comparison with experimental results. Some results are shown in the right column of Table 2. No serious discrepancy has been observed except for certain induced activities. However, there is very little data to estimate the present accuracies for many nuclear responses.

In order to achieve the accuracies cited in Table 2, the issues described in the preceding section should be resolved and verified through experiments.

REQUIRED EXPERIMENTS

Required experiments can be planned based on experience in fission reactor programs and will concentrate on areas which have not been tested in those programs. These are shown in Table 3. The experiments are categorized according to the issues, yet are related to each other.

Table 3. Required Experiments

Issues	Basic	Single Effect	Partial Integrated Effect
Bulk Shield	Cross section of main nuclides (σ_t, $\sigma_e(E,\mu)$, resonance and window)	Attenuation in stainless steel, lead, tungsten, concrete, copper (10~100 cm)	Optimization of bulk shield (SUS + B_4C + Pb + coolant)
Penetration	$\sigma_e(E,\mu)$	Straight duct (L/D effect, source scanning) Bent duct (shape, angle) Slit (step, width)	• Penetration shield • NBI port, RF port with structure • Divertor/limiter duct and exhaust • Coolant channels • Interaction of streaming holes
Induced activity and dose rate	$\sigma_{n,x}$, decay data, gamma production, $P(E_n \rightarrow E_\gamma)$	Specimen irradiation • Response function	• γ dose through bulk shield and penetration • Shutdown dose distribution in D-T burning device • γ dose from corrosion product • Sky shine
Design criteria	Damage rate	Specimen irradiation Response function	Component test
Data and method	Differential data base, evaluation and processing	Integral test of data base and benchmarks for method improvement	• Modeling of complex geometry • Interactive effect • Sensitivity study and optimization • Cost effective design method • Semi-empirical approximations

1. Basic Experiment

Basic experiments can be performed in the conventional accelerator or point neutron source facilities. The number of test articles is large, hence prioritization is necessary. The table shows the kind of nuclear data which mainly affect the uncertainty of the issue concerned.

The required accuracies of the data, of course, depend on isotopes, type of reactions, energy range and required accuracies of integral quantities.[4] The uncertainty in predicting the activation dose is mainly caused from that in the response function at present. Details of the nuclear data needs are discussed in Ref. 5.

2. Bulk shield

The properties of bulk shield are needed as the basic design data for shielding materials. The main constituents of the bulk shield should be examined on an attenuation profile in the range of 3~7 orders of magnitude for both neutron and gamma rays because prediction errors propagate and exponentially increase with distance from the front surface. The measured parameters include energy spectrum, threshold reaction rates, dose rate and heating rate. The optimum configurations of materials would be selected based on sensitivity analysis and should be verified experimentally. The bulk shield measurements provide good benchmark problems for transport calculation codes and nuclear data if they can be performed in simple geometries and with well-identified source conditions.

3. Penetrations

Design of penetration and associated shielding is essential and most difficult. No data is available for the verification of design accuracies. Experiments have to start from fundamentals and then proceed systematically to understand the phenomena and to evaluate the design method. They are useful to find and examine semi-empirical approximations. Table 3 shows the typical geometries required in penetration experiments. Streaming experiments through circular straight ducts will show the fundamental aspect of penetration. The dependence on the ratio L/D (length to diameter) is a main design concern. If a point neutron source is used, the volume effect should be examined. The bending duct and slit are the basic areas considered to reduce streaming. Effectiveness experiments would be carried out by varying the shape, the number of bends, the angle of bend and the distance between bend points.

Since the prediction accuracy for streaming will not be good (there is no data to evaluate the accuracy), even if the three dimensional Monte Carlo method is applied, partial mock-up experiments prior to detailed design are needed. The local dose rate distribution is important as well as the gross exposure rate in order to protect sensitive panel components.

The penetration shield should attenuate not only the direct irradiation component from the burning region during the operational phase, but also the gamma dose from the highly activated penetration components during the shutdown period. The coolant channels may cause streaming if helium gas is used or the coolant removed after shutdown. The multiple effects of these streaming holes and slits in different components could cause unexpected streaming paths, therefore, the predictable geometrical configurations for such a case should be tested prior to final design.

4. Exposure from Induced Activity

Exposure dose on workers is caused by the induced activity of reactor components, building and coolant. Accurate estimation of radioactivity spatial distribution, strength, and time dependence is fairly difficult and experimental verification is also not easy. The D-T burning device can provide data for shutdown dose distribution. The radioactive corrosion product could be estimated from corrosion transport experiments and irradiation test of first wall and plasma-interactive components materials. The distribution of deposited materials and trapping efficiency in the clean-up system are not known, espcially for liquid metal coolant.[2] The important part of the public exposure dose rate may come from sky shine in fusion power reactors. Some neutron source facilities have the potential to verify this effect.

5. Measurement Technique and Diagnostic Development

Experimental uncertainties should be small enough to verify the prediction accuracy of the radiation field and the response. Present reliability and accuracy of the detecting system is not satisfactory for this purpose. Specifically, measurement techniques of the nuclear heating rate, damage rate and multifoil activation (MFA) need further development. The effect from the magnetic field should be tested for counter type detectors.

6. Data and Method

Since the experimental values must be compared with predicted results obtained by calculations, all the experiments should be well identified for source characteristics, boundary conditions, and geometrical and isotropic configurations. Results from the basic experiments are compiled to produce the data base required for neutronics calculations; the single effect and part of the multiple effect experiments offer the differential and integral data to examine the data base, the processing method, and transport and response calculation methods. Experiments in complex geometries will help in verifying design accuracies and in providing experimental justification of the shield design. Since the present work focuses on planning the experimental needs and some needs for improvement were briefly mentioned before, the task required in the development of data and methods is not discussed here. Improvements in modeling, method, and optimization, however, are the key issues to achieve the required accuracies within a reasonable design cost.

FACILITIES

Since neutrons are critical in all shielding experiments, the performance and specifications of the neutron source facility are important in planning experiments. Possible neutron sources are fission reactors, accelerator-based point neutron sources and fusion sources. These are characterized on the basis of neutron spectrum, flux and fluence, available volume and geometry, and operational cost. Different experiment stages will need different conditions. Since basic experiments usually need small specimens, the volume required is also small; multiple and partially integrated experiments need larger volumes. Experiments based on transport phenomena need relatively large volumes; for example, the area is several mean free path length square and the thickness should be large enough to achieve several orders of magnitude of attenuation.

1. Point Neutron Source Facility

There are many point neutron sources around the world which are usable for shielding experiments, although their usability is limited by their source strength or flux and fluence of 14 MeV neutrons. Present DT sources, such as RTNS-II (LLNL),[6] FNS (JAERI),[7] OKTAVIAN (Osaka Univ.),[8] and LOTUS (Switzerland)[9] generate neutrons with a strength $10^{12}\sim10^{13}$ n/sec. All have been used for neutronics and basic data measurements except RTNS-II.

Although the fluence of the point neutron source is lower than that of a fusion test facility, some benefits are expected. These benefits include the well-identified source characteristics, the ease of access and a large available volume. Basic and single effect experiments are suitable for the point source since requirements on the flux and fluence are not high in shielding experiments. Even the bulk shield experiments could be performed with a thickness of more than 100 cm of stainless steel.[10] In the next 10~15 years, the point or small volume neutron source facility would be mainly used to resolve these issues before the construction of a fusion facility.

There are basically three options for point neutron sources (cost estimates are shown in parentheses):

- construction of new facility ($10 M)
- modification of conventional point source ($2~5 M)
- utilization of RTNS-I, RTNS-II, FNS or LOTUS.

The third option has the lowest cost, but requires changes in existing programs.

2. Fission Neutron Source

As an alternative to the fusion neutron source, fission reactors seem to be attractive. In the past, many fission reactors have been built and used for shielding experiments. Of course, the most serious problem in using fission sources is that they do not have 14 MeV peak spectra, but have large soft components below 1 MeV. The MeV range neutron flux can be increased with the use of convertors such as enriched uranium. These have test zones with large volumes and high fluence. Since no systematic study has examined the possiblity of using the fission neutron sources, we have compared some characteristics of fission and fusion sources.

Some shielding parameters have been calculated for a one-dimensional cylindrical model consisting of the plasma, first wall and shield regions using both a 14 MeV source and a fission source normalized to the same number of neutrons. Since the heating rate is an important parameter for the design of superconducting magnets, the attenuation profiles in the bulk shield of Fe1422 are compared in Fig. 1. It can be seen that the attenuation profiles are quite close between both sources although the absolute values are different. The heating rate profile in shielding materials such as Fe1422 could be simulated quite well by the fission spectrum source. Neutron spectra calculated for these cases are also compared.

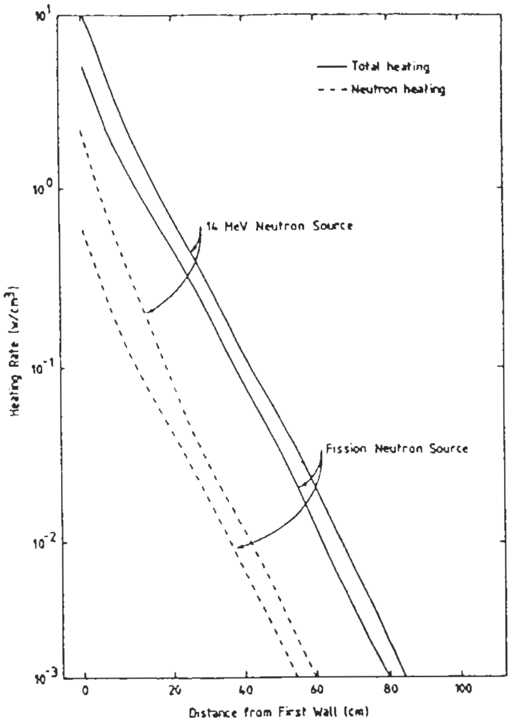

Figure 1. Nuclear heating rate calculated by 14 MeV and fission spectrum sources

The fission source has a lower flux above 3 MeV, but agrees well with the fusion source below this energy. If the high energy component above a few MeV does not play a dominant role in shielding parameters, the fission source would be satisfactory to simulate the fusion neutron source. For this purpose, the contribution from the high energy component has been examined. Contributions of > 2.5 MeV neutrons to the heating rates, dpa and gas production rate are shown in Table 4 for each region of a typical reactor configuration. Those of the heating rate and the dpa decrease rapidly in the shield region, but those for hydrogen and helium gas production rates do not decrease because they have high threshold energies. Although the fission source has a higher energy part than 2.5 MeV, attenuation experiments for this energy region would be difficult to perform due to low statistics in the deep locations of the bulk shield. It can be said that the fission source seems to be attractive for experiments on some kinds of parameters.

Table 4. Contribution from High Energy Neutron (> 2.5 MeV) to Damage Parameters (%)

Region	Neutron Heating	dpa	Proton Production	Helium Production
First Wall	95	79	99.8	100
Blanket	49	67	99.7	
Plenum	57	29		
Shielding	24	7	97.9	

SHIELDING EXPERIMENTS IN FUSION TEST FACILITY

Shielding experiments performed in a fusion facility have many advantages with respect to strength and volume of the source and neutron spectrum. TFTR and a fusion ignition device could provide integral shielding data, such as activation level and dose rate, but would be limited in measured parameters. A fusion test facility like FERF will have many test matrixes suitable for individual experiments and be operated in various modes. Dimensions of each test matrix should be minimized to reduce costs and to increase the number of test matrices. This section describes the operating conditions and the test module geometry required for shielding experiments.

As an example of a test facility, a tokamak type reactor is considered with the test location on the outboard regions. The minor radius of plasma is 1.1 m and the major radius is 4 m. The 5 cm thick first wall is composed of HT-9 and water with 30% volume ratio. The shielding test matrix is put adjacent to the first wall (no blanket region).

Most neutronics measurements can be performed in a low fluence field (~ 1 MW•s/m^2 or less) but irradiation tests, such as induced activity measurements, need higher fluences to obtain data with high accuracy. Foil activation measurements at deep locations in the shield need a fluence of about 100 MW•s/m^2. Both pulsed and quasi-steady operations are acceptable. Some consideration will be required on activation levels of components and test modules, particularly for shutdown dose rate measurements. Low statistical errors and signal-to-noise (S/N) values are essential to obtain data with high accuracy.

The geometrical requirement for a shield test module has been examined in order to minimize the size within a reasonable S/N value. The test module is assumed to be located on the outboard zone adjacent to the first wall. A blanket zone is excluded to maximize the neutron fluence in the test module. In a fusion device, the test area at the first wall is limited by configuration and cost considerations. Hence, it is also important to minimize test module size. Maximum information would be obtained from the full coverage case and this analysis has attempted to find minimum dimensions under the requirement that experiments at the central regions will have a reasonable area and volume, and can simulate the full coverage case within a limited deviation (assumed to be within 20%). The basic experiments consist of attenuation measurements in the radial direction and the bulk shield experiment is considered as a reference case.

Calculated parameters are the nuclear heating rate (neutron and γ), dpa, and gas production (helium and hydrogen) rate. As an example, the heating rate is attenuated in the radial direction by more than four orders of magnitude at the position r = 100 cm from the first wall. The requirement for bulk shield is reduction by a factor of 10^3~10^5. Hence, a thickness of 100 cm is necesary for the test module. The toroidal dimension is examined based on the r-Θ model, shown in Fig. 2, by using the DOT 4.3 code.[11] Calculated total heating rates are compared in Fig. 3 for the cases, full coverage, toroidal angle Θ = 8° (the surface width at the first wall W_F = 94 cm) and Θ = 15° (W_F = 176 cm). The case for Θ = 8° shows a very different attenuation profile as a function of the distance from the first wall in the deep locations. Such differences arise from incoming neutrons through the side walls of the matrix (boundaries in the toroidal direction). To suppress this component, the whole first wall region is covered by a reflector of 10 cm thick stainless steel. The calculated heating rate for Θ = 8° is presented by a broken line in Fig. 3, which shows that the attenuation profile significantly approaches the one in the full coverage case. The case Θ = 12° with the reflector gives a quite similar profile to the full coverage case.

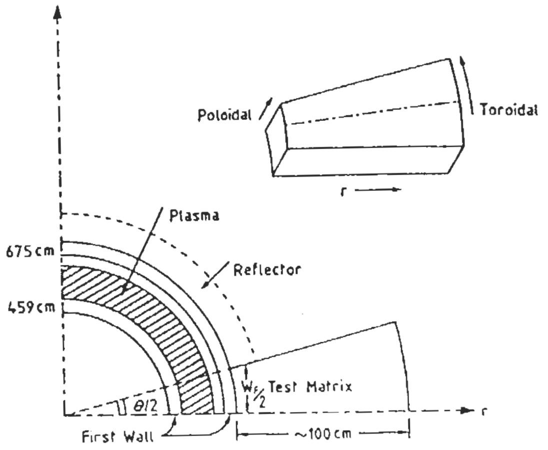

Figure 2. R-Θ calculation model of shielding test matrix

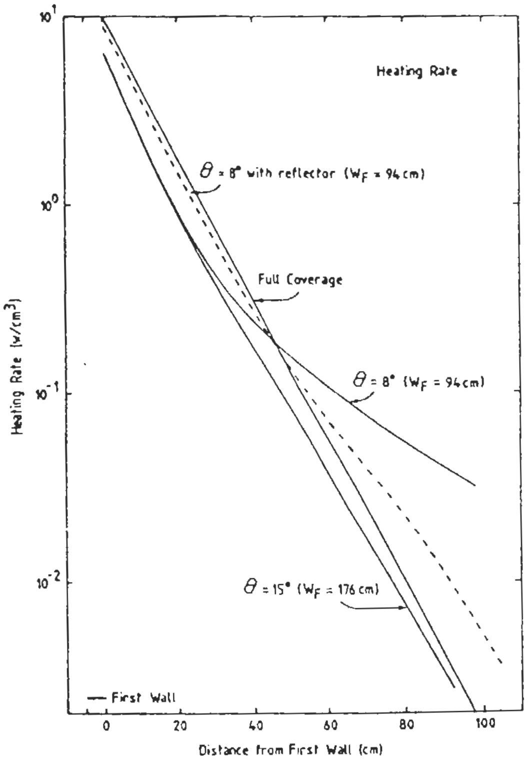

Figure 3. Comparison of nuclear heating rates between the cases, full coverage, Θ = 8° and Θ = 15°

The addition of a reflector is also effective in flattening the toroidal distribution. The relative values of heating rate to centerline values are compared between the cases for Θ = 8° with and without a reflector. In this case, the width of the available test zone is doubled by adding the reflector.

The effect of the toroidal dimension for Θ = 8° and 12° with the reflectors is compared in Fig. 4. The ratios of heating rates to centerline values are shown at the same distances from the first wall. It can be found that if the toroidal angle, Θ, is 12°, which corresponds to the 140 cm width at the first wall, the deviations from the full coverage case are less than 20% up to the distance r = 80 cm at the central test zone with the width of 30 cm.

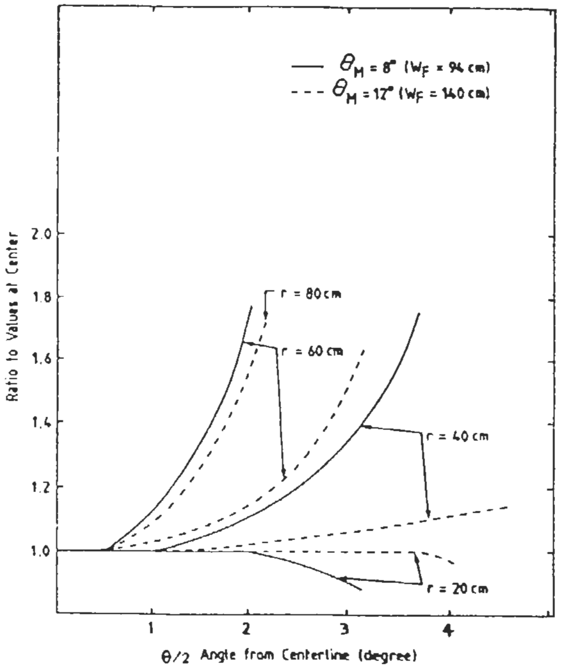

Figure 4. Dependence of nuclear heating rate on toroidal dimension. Relative values to the centerline values are shown for r = 20~80 cm.

The required dimension in the poloidal direction is examined using the r-z model, in which the torus geometry is approximated by a cylinder. The poloidal dimension of the full coverage case is equivalent to that of the outer boundary of the reflector, $\frac{1}{2}H_F$ = 125 cm. Shielding parameters have been calculated for H_F = 250 cm, 120 cm and 102 cm. If the matrix height is 250 cm, the toroidal dependence is very weak, so a large test zone can be expected. But if H_F = 102 cm, the heating rate increases by about 30% at z = 30 cm for the radial position r = 60 cm. If H_F = 120 cm, the deviation is within 20% even if the radial distance increases up to r = 80 cm. Accordingly, the required minimum dimension is around H_F = 120 cm for the poloidal direction.

As discussed above, the minimum dimensions are 100 cm (thickness) x 140 cm (toroidal width) x 120 cm (poloidal height). This module can provide the test zone with a 40 x 40 cm surface area at the first wall, and the radial profile can simulate the full coverage case up to r = 80 cm within a deviation of 20% from the centerline values. It should be noted that these dimensions have been examined based on a model where the whole first wall is covered by the 10 cm thick reflector of stainless steel. If a thicker reflector is placed, the dimensions obtained above would decrease much more or the area of test zone would increase.

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