Numerical Simulations of In-Situ Neutron Detector Calibration Experiments on the Tokamak Fusion Test Reactor

L. P. Ku, H. W. Hendel, S. L. Liew, and J. D. Strachan
Princeton Plasma Physics Laboratory
Princeton, NJ 08543-0451

Abstract

Accurate determinations of fusion neutron yields on the TFTR require that the neutron detectors be absolutely calibrated in-situ, using neutron sources of known strengths. For such calibrations, numerical simulations of neutron transport can be powerful tools in the design of experiments and the study of measurement results. On the TFTR, 'numerical calibration experiments' have been frequently used to complement actual detector calibrations. We present calculational approaches and transport models used in these numerical simulations, and summarize the results from simulating the calibration of ^{235}U fission detectors carried out in December 1988.

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I. Introduction

The Tokamak Fusion Test Reactor (TFTR), designed to study the physics of reactorlike plasmas near power breakeven, now routinely produces neutrons in excess of 10^{16} per second.¹ Measurement of the total neutron production yields the fusion power gain factor Q (fusion power/input power), i.e., a direct measure of the fusion power production of the plasmas. The main diagnostic on the TFTR for measuring the fusion neutrons is a set of seven fission detectors.² Fission detectors, in particular those of the ^{235}U type surrounded by a moderator, offer fast response, good γ -ray discrimination, and high efficiency. Since the detectors can only measure the neutron flux at the detector locations, absolute detector efficiencies, in terms of counts per source neutron, have to be determined in order to relate the flux at the detector location to the total neutron source strength of the plasma. On the TFTR, the detection efficiencies are derived from in-situ measurements, using point sources of known strengths to simulate the toroidal plasma.³

Ideally, one should choose a calibration source having the same energy, angular, and spatial distributions as those of the plasma source. Since such a source does not exist, some approximations of the source conditions must be made. The effect of source spatial extent can be taken into account by integrating the point calibration efficiencies. Neutron generators can be used to obtain the desired DD or DT neutron spectrum. However, the perturbations introduced by the massive generator, the difficulties in obtaining accurate neutron yields, and the problems of maneuvering the generator in the limited space of the tokamak vacuum vessel, often render the generator unsuitable. Using spontaneous fission or (α, n) sources are possible alternatives, but their energy spectra may not be quite the same as those from DD or DT fusion. Further, the calibration sources typically are not intense enough, so that only the most sensitive detectors can be calibrated in-situ directly; other detectors can only be cross-calibrated with a plasma neutron source in appropriate ranges. On the TFTR, the ^{235}U detectors in count rate mode are the only ones which can be adequately (with good statistics) calibrated in-situ. The Campbell and current modes of the ^{235}U detectors, as well as all other less sensitive neutron detectors, including the activation foils and ^{238}U detectors, would have to be cross-calibrated, using the more intense plasma neutron source.

Many of the problems encountered in the in-situ calibration, particularly those concerning the design of experiments and the interpretation of results, can be studied by numerical simulations using neutron transport codes. On the TFTR, numerical calibration experiments have been conducted frequently. To be able to simulate experiments, we need reliable and flexible neutron transport models of the TFTR. For a complex device like TFTR it is very difficult to include all the geometrical details in

the transport calculations. In addition, neutrons may suffer many collisions near the tokamak with many auxiliary machine components, yet they may still make significant contributions to the detector response, and our detectors have been designed to detect these multi-scattered neutrons with nearly energy-independent detection efficiency to reduce variations of detection efficiency for changes in plasma location and size. It is possible to perform sensitivity analysis to see the calculational uncertainties due to the imperfect modeling, but it is quite difficult to include all possible situations. Thus, it is not feasible to determine directly the absolute detection efficiency to an acceptable accuracy ($< 10\%$), with neutron transport calculations alone, without normalizing the results to some measurements on the TFTR. To provide a practical approach for simulating various experiments which involve only the ^{235}U detectors, and to avoid the difficulties in describing the detailed geometries, we have developed simulation models for the TFTR which contain two adjustable parameters (region density factors). The parameters were determined by matching the results of calculation for one of the ^{235}U fission detectors (NE-1, Neutron Epithermal) with a small set of measurements. The detailed procedures of this approach can be found in Ref. 1. This 'semi-empirical' model was then used to simulate calibration experiments and to calculate detector responses for different source and source-detector geometries. Results obtained using this approach generally agree well with the available measured data over a wide range of energies, geometries, and detector sensitivities.

In this paper, we review our calculational approaches and transport models, and discuss the results of simulations for the in-situ calibration experiment carried out on the TFTR in December 1988. We show examples of using neutron transport simulations to investigate possible systematic errors in the calibration experiments; to study, by varying the conditions in numerical experiments, the peculiarities observed in the in-situ calibration; to calculate detector efficiencies for sources in energy-space regions not accessible in real experiments; and to derive differential information useful for the understanding of neutron transport in the TFTR.

II. The TFTR Fission Detector System

A list of fission detectors currently operational on the TFTR is given in Table 1, along with their applicable source strength ranges. Of these detectors, only NE-1, NE-2, and NE-6 can be calibrated using a manually handled calibration source inside the tokamak vacuum vessel. NE-1 and NE-2 will be our main focus of discussion, since NE-6 was not included in the calibration experiment.

NE-1 and NE-2 are fission counters of the Reuter-Stokes type RS-C3-2510-114 which contain 1.3 g of ^{235}U distributed over a cylindrical area 7 cm in diameter and

23.5 cm in length. They have a useful dynamic range of 10^3 to $5 \cdot 10^5$ counts per second (cps) in the count rate mode, and 10^5 to 10^9 equivalent cps in the current and Campbell modes, using Gamma-Metrics electronics.⁵ Each detector is surrounded by an electrostatic shield of 0.35 cm in thickness, and a moderator/shield made of polyethylene and lead, 5.05 cm and 9.95 cm in thickness, respectively. The outer surface is covered with a boron panel.

NE-1 is located in bay C on the machine substructure behind the lower shear compression panel, approximately 5.6 m from the machine center and 1.75 m below midplane. One of the two TFTR vacuum pumping ducts is located right above the detector. The shear compression panel has an equivalent steel thickness of 25 cm. Together with the toroidal field coils, the shear panel nearly completely blocks off the direct neutron passage from the torus, so that virtually no uncollided neutrons reach the detector assembly. NE-2 is located in bay M, with almost the same detector geometry and electronics. The ion cyclotron resonance heating antenna is mounted on the bay M port, with transmission lines located above the detector. The local component layout is even more complex.

A typical signal trace of NE-2 for a neutral deuterium beam-heated deuterium plasma is illustrated in Fig. 1.

III. Numerical Algorithms and Simulation Models

A. Monte Carlo simulations of neutron transport

We wish to set up a calculational model that enables us to perform numerical experiments as close to the real experiments as possible, and also flexible enough to allow the study of various parametric variations. The complex toroidal geometry of the TFTR, with nonuniformly and asymmetrically distributed machine components, means that a full three-dimensional representation of the TFTR would be required in the numerical model if the experiments using a point source, which can be located anywhere inside the vacuum vessel, can be simulated. To solve the neutron transport equation in such a complex three-dimensional geometry, the Monte Carlo technique is the only practical method available.

Efficient calculations using Monte Carlo methods, however, cannot be achieved by following particle histories directly until enough counts are registered in the detector, since the detector/moderator assembly is very small compared to the tokamak. To improve the efficiency of the numerical simulation, we have developed a coupling

algorithm, the details of which have been presented in Ref. 4. The basic idea was to determine the surface efficiency ϵ_s for the detector/moderator assembly, and to substitute the Monte Carlo scoring function $\mathcal{R}$ with ϵ_s . The pseudo-collision (or so-called last flight estimator) method can then be used in which the probability of contributing to the detector score is estimated at every collision site to obtain the overall detector response of interest. A neutron is no longer required to enter the detector to register a count. It was shown that ϵ_s could be represented by the adjoint function on the surface of the moderator and detector assembly and could be derived independently of the neutron transport in the TFTR. The relative surface response coefficients are illustrated in Fig. 2. We note that the response function is remarkably insensitive to the energies of the neutrons incident on the moderator in the keV and MeV range.

B. Details of the simulation model

The tool used to perform transport simulations is the MCNP Monte Carlo code, version 3B.⁶ The RMCCS nuclear data set, primarily based on the ENDF/B-V evaluations,⁷ was used in the transport calculations. The neutron spectrum from ²⁵²Cf spontaneous fission was taken from an NBS evaluation,⁸ and is illustrated in Fig. 3. Various biasing schemes were used to speed up the calculations, such as particle track splitting and Russian Roulette, implicit capture, energy and weight cutoffs, cell importance, and Russian Roulette on detector tallies.

In our models, the TFTR components are described by ~300 surfaces, and these surfaces are combined into the specifications of ~300 cells. The geometrical descriptions common to all the detectors include the vacuum vessel with homogenized representation of the port covers, bellows cover plates, inner bumper limiter, outer carbon tiles, poloidal field and toroidal field coils, the center column assembly, shear compression panels, floor and building walls. The upper umbrella structure, column support structure, auxiliary machine components (such as cable trays, cooling water lines, NBI drift tubes, etc.) and diagnostics which are not in the bay of interest are represented as two homogenized material zones. The region between the vacuum vessel and TF coils is filled with SS-304 of 5% density factor; the region outside the TF but inside the pedestal ($R=6.5$ m) is filled with SS-304 of 20% density factor plus 2% of water equivalent hydrogen. These pseudo-materials were chosen by parametrically varying the density factors and comparing with the results from previous ²³⁵U calibration experiments to find the best match for a small set of data for NE-1.⁴ The geometries of bays C and M, where the two ²³⁵U fissions detectors are located, are modeled in as much detail as possible. The major features modeled in Bay C include the support columns filled with grout and the torus vacuum pumping duct.

In Bay M, the wave transmission lines, antenna, and limiters for the ion cyclotron resonance heating are modeled. A few plots of the models are given in Fig. 4.

IV. Simulations of Fission Detector Calibrations with ^{252}Cf Source

For a point calibration source, the fission detector response varies as a function of the energy and angle of emission of the source neutrons, as well as the location (the major radius, height, and toroidal angle) of the source. In the 1988 calibration experiment, only a ^{252}Cf spontaneous fission source was used. For all practical purposes, Cf is an isotropic point source. An attempt was made to modify the angular distribution of the neutron emission to study the effects of angular anisotropy on the detector response. The detector response to a volumetric source was obtained by numerically integrating the measured discrete data points. The primary variables of the neutron source in the in-situ calibration are then the positions of the ^{252}Cf . A typical calibration result is shown in Fig. 5.

A. Comparisons with measurements

Comparisons of results for detectors NE-1 (in bay C) and NE-2 (in bay M) are given in Table 2. The comparisons shown are for sources located at a major radius of 2.65 m and at the torus midplane. Both NE-1 and NE-2 are surrounded by similar polyethylene moderators and Pb shields, and both have the same geometry, electronic setup, and response characteristics. In the experimental setup, the ^{252}Cf was supported by a Plexiglas holder. The holder itself was in turn supported by two toroidal rails. During the calibration, the effect of the acrylic source support on the count rate had been determined by removing it during a part of the experiment. In the numerical simulations, the effect of the source holder on the detection efficiency was studied by comparing the results with and without the holder being modelled for the source at toroidal angle $\phi = 0^\circ$ (the angle with respect to the toroidal location of the detector). Otherwise, the acrylic source holder was not included in the calculations. The uncertainties in the calculated results given in Table 2 are one standard errors due only to the statistics in the Monte Carlo sampling. The uncertainties in the measured results are one standard errors due only to the counting statistics. Most of the quoted experimental results are the equal-weight averages of a few measurements in the vicinity of the reference toroidal angle (within $\pm 3^\circ$).

It is seen that measurements and calculations agree reasonably well ($\pm 5\%$). The

calculations were able to reproduce the correct gradient of the efficiency curve as a function of toroidal angles, and the changes in efficiency due to the difference in bay geometry. The results seemed to indicate that the acrylic tube holding the ^{252}Cf may cause a small reduction in the detection efficiency (perhaps 2 – 5%). This reduction in detection efficiency may be attributed to the softening of the calculated energy spectrum for neutrons interacting with the acrylic holder. Comparison of the energy spectrum of the neutrons leaving the acrylic tube with that of the ^{252}Cf shows that the mean energy is reduced by $\sim 5\%$. Perhaps more important is that the number of neutrons with energies above 500 keV has also been reduced by $\sim 5\%$, depending upon the polar and azimuthal angles of emission. These neutrons have been identified to make most contributions to the detector response (see Section VI). Nevertheless, since the statistical error in the Monte Carlo calculation for the efficiency ratios is $\sim 4\%$, we cannot confidently tell the magnitude of reduction in the detection efficiency. This conclusion is consistent with the observation made during the calibration experiment.³

B. Simulations for two special experiments

1. Simulation of the experiment for the study of the effect of source-detector distance at 0° toroidal angle

During the 1988 calibration experiment, it was suggested that it might be useful to study the effect of the distance between the source and detector on the detection efficiency. The ^{252}Cf source was moved along the line-of-sight between NE-2 and the position $\phi = 0^\circ$, $R=2.65$ m and $Z=0$ m. It was observed that (at $\phi = 0^\circ$) the measured detector efficiency approximately varies as the inverse of the distance squared (the distance from the source to the detector).³ Since the detector was located behind the shear compression panels with a total steel thickness of ~ 30 cm between the detector and source (hence, the uncollided neutrons make negligible contributions to the detector response), this distance dependence seems unexpected. However, since the density of the TF coils is much higher than that of the materials in the bay region, the two adjacent TF coils serve as effective collimators, and thus, the above observed distance dependence would follow.

Table 3 shows the results of the simulation, with the correct TF geometry as well as with the TF region replaced by the 5% density SS-304 used in the first homogenized material zone. The responses calculated with the correct TF geometry compare well with the measurements. We observe that with the TF present, the efficiency is approximately proportional to the inverse of the distance squared, as observed in the experiment, but this correlation no longer holds when the TF coils

are removed. Without the TF coils, the distance dependence is more like l^{-1} , where l is the distance from the source to the detector.

2. Simulation of the experiment for the study of the effects of emission anisotropy

For a beam-heated DD plasma, the neutron emission is not isotropic in the laboratory system. Effects on detector calibration due to the non-isotropic emission of a neutron generator calibration source have been discussed briefly before.⁹ To study in detail experimentally the effects of anisotropy in the neutron emission on the detection efficiency for the fission detectors, it was proposed, initially, to place small shields made of polyethylene or steel around the ^{252}Cf to alter the angle of emission for neutrons leaving the source assembly. While using a shadow shield would achieve the objective of having a biased emission angular distribution, the energy spectrum of the neutrons leaving the shield would be inevitably degraded. The objective of this numerical study is to examine the feasibility of performing in-situ calibration using this approach.

The polyethylene shield determined to be suitable consists of a cylindrical shell which has a central bore radius of 1.75 cm and a shell thickness of 3.65 cm. The axial length of the shield is 6.03 cm. The corresponding dimensions for the steel shield are 1.27, 5.08, and 6.67 cm, respectively. The calculated polar angle distribution relative to the axis of the cylinders is shown in Fig. 6, along with a distribution corresponding to that of the 120-keV deuterium beam interacting with a stationary deuterium target. As expected, the cylindrical shields result in more neutrons being emitted in the forward and backward 30° angles, and less neutrons in the perpendicular direction, compared to the DD emission profile. Despite these differences, the source shields do provide angular variations for the neutrons similar to the emission profile desired for the study. The energy distribution at the 90° emission angle (azimuthally averaged) is given in Table 4. It is seen that the energy spectra of the neutrons emitted from both shields are much softer, with a reduction of 34% and 20% in the mean energy for the polyethylene and steel shields, respectively. The number of neutrons born with energies above 500 keV is also reduced from 90% for a bare ^{252}Cf to 66% for the ^{252}Cf with polyethylene shield, and to 81% for the ^{252}Cf with SS-316 shield.

Table 5 provides a summary of the results obtained from a series of transport simulations. The source was assumed to be located at a major radius of 2.65 m, and the axis of the shield cylinder was assumed to be tangential to the vessel minor axis. The DD neutron angular distribution used in the table refers to that expected from

a 120 keV deuterium beam interacting with a stationary deuterium target.¹⁰

We note that with the polyethylene shadow shield, the efficiency of NE-2 at the 0° toroidal angle is reduced by nearly 40%, and with the SS-316 shield by 20%. Of these reductions, about 15% is attributable to the bias in source angle; the remainder is due to the degradation in energy resulting from neutron collisions with the source shield. It is interesting to note that, when the angular emission profile for the DD neutrons was used while keeping the energy spectrum of ²⁵²Cf unchanged, the efficiency at $\phi = 0^\circ$ is reduced by about 10%. This reduction reflects the fact that a smaller-than-average number of neutrons would be emitted in the radial direction for the biased source (the direction toward the detector), and clearly indicates that there is a preferred initial direction, albeit a relatively weak one, for those neutrons contributing to the detector response.

At toroidal source locations $\phi = 30^\circ$, the detection efficiency is higher for the angularly biased source (with the energy spectrum unchanged), resulting from the higher-than-average number of neutrons emitted in the direction toward the detector. Similar to the $\phi = 0^\circ$ case, the degradation in neutron energy due to the presence of the source shield has significant effects on the detection efficiency. The inability to separate the effect of angular anisotropy from the effect resulting from the energy degradation in the experimental results makes it difficult to determine quantitatively the magnitude of change in the absolute detection efficiency that is attributable to the anisotropy in the DD neutron emission. We note that, whereas there is a clear dependence of the detection efficiency on the profile of neutron angular emission for a point source, the angular effect will be averaged out for a toroidal source, as evidenced in the following section.

V. Derivation of ²³⁵U Detector Efficiency for DD Neutrons by Numerical Simulations

As mentioned above, the detector efficiency is a function of the neutron source energy, position, and angular emission. For a plasma neutron source, the major source variables are the major and minor radii, energy distribution, and the angle of emission. The experimental evidence,³ together with previous transport calculations,⁴ indicated that the detectors are insensitive to the source minor radius. Thus, we concentrated on the study of the effects of source neutron energy, angle of emission, and source major radius. In particular, since the in-situ calibration carried out in 1988 was done only with a ²⁵²Cf source, one of the major goals of our numerical study is to derive detection efficiencies for DD neutrons.

The ^{235}U detector efficiencies for both the DD thermonuclear fusion and beam-heated plasma at a fixed beam energy and direction have been studied. Table 6 summarizes the results for ring sources, all with a major radius of 2.65 m. In the case of thermonuclear fusion, we have assumed that the spectrum of neutron emission follows the typical Gaussian form and the emission angle is isotropic in the laboratory system. In the beam-plasma case, we have assumed that a beam of monoenergetic ions of 120 keV circulates along the major radius at 2.65 m unidirectionally, and interacts with a 'cold' target with negligible thermal velocity. The angular distribution of neutrons was taken from the compilation of Liskien and Paulsen,¹⁰ and the energy distribution of the neutrons was calculated from the interaction kinematics.

The results show that there is a 5 – 7% variation in the detection efficiency for various source conditions, but the differences are not statistically significant because the magnitude of the differences is comparable to 1σ of the Monte Carlo calculations. We note that the effect of angular anisotropy in the neutron emission given above represents the extreme case. In a real tokamak operation with energetic deuterium injected into a background deuterium plasma, the effect will be mitigated by the slowing down and pitch angle scattering of the fast ions, the randomization of the reference direction of neutron emission due to the presence of $v_{\perp}$, and the presence of a thermonuclear reaction component in addition to the beam-driven components. The derived ratio of DD to ^{252}Cf detection efficiency at $R=2.65$ m is $1.1 \pm 7\%$ for NE-1, and is $1.08 \pm 7\%$ for NE-2.

The dependence of NE-1 on the major radius of a plasma ring source is shown in Fig. 7 for $2.05 \text{ m} \leq R \leq 3.25 \text{ m}$. The linear least square fit gives an efficiency change per unit change in major radius, $\delta\epsilon/\delta R = (5.58 \pm 1.86) \cdot 10^{-10}$ counts/source/meter, or equivalently, $\delta\epsilon/\epsilon/\delta R = (0.15 \pm 0.05)\%/ \text{cm}$. The dependence on source major radius for NE-2 is expected to be similar. The measured value of $\delta\epsilon/\epsilon/\delta R$ for NE-2 using a ^{252}Cf source was 0.4% for $R < 2.65 \text{ m}$, and $\sim 0.1\%$ for $R > 2.65 \text{ m}$.³

VI. Neutron Transport Studies of the Importance of the Energy Spectrum, and the Spatial and Angular Emission of Source Neutrons for the ^{235}U Detectors

The above discussions evidently show that there are regions in phase space in which neutrons, either born there or having scatterings, would have higher probability in contributing to the detector. We have carried out further transport calculations to identify the relative importance of the neutron initial spatial location, energy, and emission angle for NE-2. The upper energy boundary in this study was extended to

include the DT fusion neutrons. For the spatial variable, we have fixed the major radius at 2.65 m, and investigated the relative importance of the source toroidal location relative to the detector.

We define the importance of the source neutrons, $I(E, \phi, \eta)$, as

$$\epsilon = \int_0^\infty \int_0^{2\pi} \int_{-1}^1 I(E, \phi, \eta) \cdot S(E, \phi, \eta) dE d\phi d\eta, \quad (1)$$

where ϵ is the NE-2 detection efficiency, $S(E, \phi, \eta)$ is the source strength per unit energy, toroidal angle (ϕ), and the cosine of the polar angle of emission (η). The reference direction for the polar angle of neutron emission at ϕ is taken to be the vector tangent to the circle of radius 2.65 m at ϕ and pointing toward the detector. We further define

$$I_i(E, \phi) = \int_{-1}^1 I(E, \phi, \eta) d\eta, \quad (2)$$

and

$$I_a(E, \phi, \eta) = \frac{I(E, \phi, \eta)}{I_i(E, \phi)}. \quad (3)$$

Equation (1) can be re-written as

$$\epsilon = \int_0^\infty \int_0^{2\pi} \int_{-1}^1 I_a(E, \phi, \eta) I_i(E, \phi) S(E, \phi, \eta) dE d\phi d\eta. \quad (4)$$

The source is usually assumed uniform in ϕ ,

$$\epsilon = \int_0^\infty \int_0^{2\pi} \int_{-1}^1 I_a(E, \phi, \eta) I_i(E, \phi) \frac{S(E, \eta)}{2\pi} dE d\phi d\eta. \quad (5)$$

We note that $I_i(E, \phi)$ is the response of the detector for an isotropic source with energy E and at toroidal angle ϕ . Figure 8 shows $I_i(E, \phi)$ for $\phi=0, 30, 60, 90, 120, 150$, and 180 degrees, in arbitrary units, obtained from a multi-group adjoint MCNP calculation. Characteristic to all the curves is that the source-energy importance changes little above 1 MeV ($\sim \pm 15\%$), but decreases rapidly below 500 keV. Thus, any collision of source neutrons with materials surrounding the source which results in an energy below a few hundred keV is virtually equivalent to an absorption reaction insofar as the ^{235}U detection efficiency is concerned. The insensitivity of the importance function to the source energy in the MeV region, which has been confirmed experimentally,¹¹ is the basis for using ^{252}Cf as the sole calibration source in 1988. From Fig. 8 we also see that the efficiency of NE-2 is $\sim 14\%$ higher for a DT source than for a DD source.

Figure 8 also shows the decrease of source neutron importance as a function of the source toroidal angle. The slope of the toroidal angle dependence follows closely to

that obtained from the calibration experiment. The importance of source neutrons with energies greater than 1 MeV is decreased by ~ 2 at a toroidal angle of 30° , by ~ 5 at 60° , by ~ 10 at 90° , and by ~ 100 at 180° . The importance of low energy neutrons (~ 1 keV) varies less with toroidal angle.

Figures 9 show $I_a(E, \phi, \eta)$ for $2 \text{ MeV} \leq E \leq 3 \text{ MeV}$, for $\phi=0, 30, 60, 90$ degrees (in arbitrary units). The neutrons emitted in directions toward the detector are clearly more likely to contribute to the response than those emitted in directions away from the detector. Consequently, it is most important to model the bays in the neighborhood of the detector correctly in order to calculate the detection efficiency accurately.

VII. Summary and Future Work

We have carried out extensive neutron transport studies for the response of the ^{235}U fission detectors on the TFTR. The model developed has been shown to produce results in reasonably good agreement with those of the in-situ experiments. We then extended the numerical simulations to derive the ^{235}U detector efficiencies for the plasma DD neutron source, and to explore the detector sensitivities to various source-detector configurations for which the experimental results are difficult to obtain. The derived detector efficiency ratios of DD to ^{252}Cf neutrons for the two ^{235}U fission detectors, NE-1 and NE-2, are 1.10 and 1.08, respectively, with $\pm 7\%$ uncertainty due to the statistical sampling. These values have been used in the assessment of the overall fission detector efficiencies for the December 1988 in-situ calibration, and will be used in the future fusion yield measurement on the TFTR.

The 7% uncertainty mentioned above is still quite large, when compared to other uncertainties in the determination of DD fusion yields on the TFTR, such as the emission profile effects, counter dead time and stability. On the average, it took several hundred minutes of Cray-2 time to obtain a solution with $\leq 5\%$ statistical error for a toroidal source. Thus, it is impractical to further reduce the calculational uncertainty unless much more effort is devoted to improve the Monte Carlo sampling. One way to achieve this is to better understand the importance of neutron scattering in various regions. While we have carried out a study to identify the importance function of the neutron initial energy, toroidal location, and polar angle of emission, we have not attempted to extend the same work to the scattering regions. Another area which we have not tried to quantify in detail is the effect of changing the material distributions as might happen in the future. We have seen, however, that, although the material distributions are quite different in bay C and M, the two ^{235}U detector efficiencies differ by only $\sim 5 - 10\%$. In our previous study,⁴ we have also observed

that the detector response is relatively insensitive to minor changes in the density factors in the two homogenized material zones. Nonetheless, with the expectation of further machine modification and installation of diagnostics, it would be useful to carry out more studies to better quantify any additional uncertainties in the presently evaluated efficiencies. Finally, the cross section sensitivity, in particular the effect of transferring the source energy from ^{252}Cf where the model has been calibrated with experiments, to the DD or DT fusion neutrons, needs to be studied.

We have not yet attempted to simulate the detector responses for other neutron detection systems, such as the ^{238}U fission chambers and the proton-recoil counter on the TFTR, which have different response characteristics. Some moderate effort has been made to use the presently calibrated model to simulate the foil activation responses. The calculated reaction rates for the In, Al, and Cu foils are within 30% of the experimental evaluations.¹² The reliability of the current model and the calculational approach can be further verified, and a better understanding of the neutron transport in the TFTR geometry can be obtained by the simulation of these detector responses.

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Detector	Fissile Mat'l	Mass	Source Range (n/s)
NE-1	U-235	1.3	$1 \cdot 10^{12} - 1 \cdot 10^{17}$
NE-2	U-235	1.3	$1 \cdot 10^{12} - 1 \cdot 10^{17}$
NE-3	U-238	1.3	$1 \cdot 10^{16} - 1 \cdot 10^{21}$
NE-4	U-238	1.3	$1 \cdot 10^{16} - 1 \cdot 10^{21}$
NE-5	U-238	44.0	$5 \cdot 10^{13} - 5 \cdot 10^{16}$
NE-6	U-235	18.0	$5 \cdot 10^{10} - 2 \cdot 10^{13}$
NE-7	U-238	44.0	$5 \cdot 10^{13} - 5 \cdot 10^{16}$

Table 1: Fission detectors in TFTR

Detector	Toroidal Angle	Detection Efficiency (c/n)	
		Calculated	Measured
NE-1	0°	$1.27 \cdot 10^{-8} \pm 2.6\% \dagger$	$1.27 \cdot 10^{-8} \pm 2.3\%$
		$1.30 \cdot 10^{-8} \pm 2.7\%$	
NE-1	30°	$7.10 \cdot 10^{-9} \pm 6.0\%$	$6.91 \cdot 10^{-9} \pm 4.3\%$
NE-1	45°	$4.85 \cdot 10^{-9} \pm 8.6\%$	$4.10 \cdot 10^{-9} \pm 7.9\%$
NE-1	all	$3.15 \cdot 10^{-9} \pm 5.0\%$	$3.00 \cdot 10^{-9} \pm 3.0\%$
NE-2	0°	$1.15 \cdot 10^{-8} \pm 3.0\% \dagger$	$1.21 \cdot 10^{-8} \pm 3.0\%$
		$1.23 \cdot 10^{-8} \pm 3.3\%$	
NE-2	all	$2.92 \cdot 10^{-9} \pm 5.0\%$	$2.96 \cdot 10^{-9} \pm 3.0\%$

Table 2: Comparison of detection efficiencies for ^{235}U detectors between calculation and measurement. $\dagger$ Acrylic source holder included in the simulation.

Source Position		Distance to Detector (m)	Efficiency (c/n)	
R (m)	z (m)		TF modeled	TF not modeled
3.164	-0.30	2.83	$1.72 \cdot 10^{-8} \pm 3.6\%$	$3.08 \cdot 10^{-8} \pm 4.2\%$
2.907	-0.15	3.12	$1.45 \cdot 10^{-8} \pm 4.1\%$	
2.650	0.00	3.42	$1.23 \cdot 10^{-8} \pm 3.3\%$	$2.32 \cdot 10^{-8} \pm 4.3\%$
2.393	0.15	3.72	$1.05 \cdot 10^{-8} \pm 4.8\%$	
2.136	0.30	4.02	$8.55 \cdot 10^{-9} \pm 4.6\%$	$1.86 \cdot 10^{-8} \pm 4.5\%$

Table 3: Calculated NE-2 efficiencies for source locations along the line-of-sight

Energy	²⁵² Cf	With Polyethylene	With SS-316
< 10 keV	0.0003	0.171	0.014
10-100 keV	0.010	0.055	0.027
100-500 keV	0.094	0.110	0.148
500-800 keV	0.087	0.068	0.123
0.8-1.0 MeV	0.061	0.044	0.077
1.0-2.0 MeV	0.272	0.199	0.278
2.0-3.0 MeV	0.198	0.137	0.146
3.0-5.0 MeV	0.193	0.141	0.129
5.0-10.0 MeV	0.081	0.071	0.055

Table 4: Fraction of neutrons emitted in various energy bins for different source shields at 90° emission angle

Source Condition	Detection Efficiency (c/n)
bare, isotropic, 0°	$1.23 \cdot 10^{-8} \pm 3\%$
with polyethylene shield, 0°	$7.65 \cdot 10^{-9} \pm 5\%$
with SS-316 shield, 0°	$9.75 \cdot 10^{-9} \pm 6\%$
bare, with angular distribution from polyethylene shield, 0°	$1.04 \cdot 10^{-8} \pm 6\%$
bare, with DD neutron angular distribution, 0°	$1.10 \cdot 10^{-8} \pm 5\%$
bare, isotropic, 30°	$6.84 \cdot 10^{-9} \pm 4\%$
with SS-316 shield, 30°	$6.81 \cdot 10^{-9} \pm 4\%$
bare, with DD neutron angular distribution, 30°	$8.10 \cdot 10^{-9} \pm 5\%$

Table 5: Calculated NE-2 efficiencies with various source biasing

Detector	Source Condition	Efficiency (c/n)
NE-1	kT=5 keV	$3.55 \cdot 10^{-9} \pm 5.0\%$
NE-1	kT=25 keV	$3.48 \cdot 10^{-9} \pm 4.8\%$
NE-1	120 keV D → D	$3.66 \cdot 10^{-9} \pm 4.8\%$
NE-2	kT=25 keV	$3.15 \cdot 10^{-9} \pm 5.0\%$
NE-2	120 keV D → D	$3.40 \cdot 10^{-9} \pm 4.5\%$

Table 6: Calculated ^{235}U detector efficiencies for DD neutrons

Figure Captions

- Fig. 1** Neutron source strength during a neutral-beam injection shot measured by NE-2.
- Fig. 2** Calculated relative surface efficiency (normalized at 14 MeV) of ^{235}U detector/moderator assembly as function of neutron energy.
- Fig. 3** Fission neutron spectrum as function of energy.
- Fig. 4** Examples showing the three-dimensional MCNP model of the TFTR for the Monte Carlo calculations. (a) Plane and elevation views of bay C. (b) Plane and elevation views of bay M.
- Fig. 5** Typical count rate versus toroidal angle measured by NE-2 with a ^{252}Cf source.
- Fig. 6** Distributions of polar angle of emission. The solid line is the distribution due to unidirectional 120-keV $\text{D} \rightarrow \text{D}$. The dots represent the distribution due to balanced co- and counter-injection of 120-keV $\text{D} \rightarrow \text{D}$. The long dashed line is the distribution expected from the polyethylene shadow shield surrounding the ^{252}Cf source. The short dashed line is the distribution expected from the SS-316 shadow shield surrounding the ^{252}Cf . All the distributions are normalized to the emission probability at 0° .
- Fig. 7** Calculated detection efficiency of NE-2 versus major radius of neutron emission for ring sources. The discrete data with error bars are $\pm 1\sigma$ results of Monte Carlo calculation. The straightline is the result of linear least square fit.
- Fig. 8** Relative importance of neutron initial energy in contributing to NE-2 response for source toroidal angles $\phi = 0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ$, and 180° (in decreasing magnitude).
- Fig. 9** Relative importance of initial polar angle of emission in contributing to NE-2 response for source toroidal angles (a) $\phi = 0^\circ$, (b) $\phi = 30^\circ$, (c) $\phi = 60^\circ$, and (d) $\phi = 90^\circ$.

FIG. 1

FIG. 2

FIG. 3

FIG. 4a(1)

FIG. 4a(2)

FIG. 4b(1)

FIG. 4b(2)

FIG. 6

FIG. 7

FIG. 8

FIG. 9d