IN-SITU CALIBRATION OF TFTR NEUTRON DETECTORS

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Abstract

We report results of the TFTR fission detector calibration performed in December 1988. A NBS-traceable, remotely controlled ^{252}Cf neutron source was moved toroidally through the TFTR vacuum vessel. Detection efficiencies for two ^{235}U detectors were measured for 930 locations of the neutron point source in toroidal scans at 16 different major radii and vertical heights. These scans effectively simulated the volume-distributed plasma neutron source, and the volume-integrated detection efficiency was found to be insensitive to plasma position. The Campbell mode is useful due to its large overlap with the count rate mode and large dynamic range. The resulting absolute plasma neutron source calibration has an uncertainty of $\pm 13\%$.

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1. INTRODUCTION

The Tokamak Fusion Test Reactor (TFTR) [1] physics objective is the study of reactorlike plasmas near fusion power breakeven, $Q \approx 1$, where Q = fusion power/heating power. The fusion power generated is proportional to the neutron source strength, S , and since the uncertainty in the heating power deposited into the plasma is $\sim 15\%$ [2], it is desirable to have an S -measurement uncertainty of comparable or lower value. On TFTR, as on other large tokamaks using deuterium plasmas, the primary diagnostic for measuring S is a neutron detector system consisting of fission detectors [3]. Fission chambers offer good time resolution (high count rates), good discrimination against the high γ -radiation level present near tokamaks, and a range of detection efficiencies. However, any neutron detector measures the neutron flux [$n/(cm^2 s)$] at the detector location, and not directly S (n/s) of the plasma. Moreover, at the fission chamber location, only a small fraction of the flux intercepted by the detector is due to uncollided, direct neutrons from the plasma [4]. Neutronics calculations of the detection efficiency are complicated, sensitive to modeling of the geometry, and may not achieve the desired accuracy. Finally, the TFTR scattering environment has undergone changes due to the addition of equipment, and detector and electronics responses may have varied with time. For these reasons, in situ calibrations of the detection efficiencies must be carried out and repeated at regular intervals.

Both on the Joint European Tokamak (JET) [5] and on TFTR [6,7], numerous fission detector calibrations have been performed to check reproducibility and to take into account the changing tokamak and diagnostics configurations. The sequence of calibrations has led to increasingly detailed and improved detection efficiency measurements. On the TFTR, four ^{252}Cf and two each D-D and D-T neutron generator calibrations have been carried out over a period of about five years.

In this paper, results of the latest (December 1988) and most extensive of these calibrations on TFTR are reported. A NBS-traceable, remotely controlled ^{252}Cf neutron source was moved toroidally through the vacuum vessel. Detection efficiencies for two ^{235}U fission detectors

were measured for ~930 locations of the neutron point source. From the point-source detection efficiencies integrated over a toroidal circumference (to simulate the extended plasma source) and determined for different major radii and heights relative to the machine midplane, volume-integrated detection efficiencies could be obtained for the first time on TFTR.

In addition to the in situ calibrations of the detection efficiency, other regular calibrations are required. Cross-calibrations between detectors (or detector modes) using the TFTR plasma source are needed to extend the in situ calibration to less sensitive detectors (or detector modes) measuring higher S . Renormalizations of detection efficiency (without access to the TFTR vacuum vessel), based on a small calibration source located reproducibly on the detector, are used to monitor detection-efficiency drifts. Both the long-term time variations of cross-calibrations and renormalizations are compared with those of in situ calibrations.

Error analysis (Sec. 7) shows that uncertainties in the S measurement of the toroidal plasma are ~10% in the source strength regime that can be directly calibrated and ~13% in the regime near $Q = 1$, where cross-calibrations must be used.

2. THE TFTR FISSION DETECTOR SYSTEM

The Tokamak Fusion Test Reactor produces a toroidal plasma with a major radius in the range 230 to 290 cm (including Shafranov shift) and a minor radius up to 90 cm [8]. S for low density, ohmic plasmas may be as low as 10^{10} n/s and has been measured up to 4×10^{16} n/s for present neutral beam injection (NBI) D plasmas at 30 MW beam power. Since for D-T plasmas near $Q = 1$, $S \geq 10^{19}$ n/s is expected, coverage of ~10 orders of magnitude variation in S is needed. Discharge duration may be several seconds. The time resolution desired is ~10 ms. Thus, a count rate of ~ 10^3 c/s is considered minimal, and because pulse pile-up in count mode may set in well below 10^6 c/s, the useful count rate range per detector will only be 2 to 3 orders of magnitude. To cover the S range from 10^{10} to $\geq 10^{19}$ n/s, with the specified time resolution, four detector types (three of them duplicated) with staggered detection

efficiencies are used on TFTR. Fission detectors are chosen because a) the large signals resulting from the charged fission products allow pulse height discrimination against γ -ray induced counts, b) the useful count rates (without pulse pile-up) may reach up to $\geq 10^5$ c/s, and c) the type and mass of the fissionable material can be chosen to obtain different detection efficiencies and neutron energy responses. An additional benefit from the use of fission detectors is the possibility of extending the useful (equivalent) count rate range by about four orders of magnitude for a given detector, by employing both the current and the mean-square voltage (Campbell) modes [9]; the latter improves the γ -radiation discrimination (relative to the current mode) by up to a factor of 10^3 . Table 1 lists the detectors, the type and mass of fissionable material, and the approximate ranges of neutron source strength that can be measured.

Figure 1a shows the arrangement of a typical detector (model as used in computer simulation, see Sec. 9) on TFTR. Detector NE-1 (NE = Neutron, Epithermal) and NE-2 are surrounded by boron shields to absorb thermal neutrons, followed by 5 cm of polyethylene moderator and 10 cm of lead (see Fig. 1b). Lead shielding is used to reduce effects on the count rate due to prompt γ -radiation and runaway-electron-produced high-energy γ -radiation (>10 MeV). Neutronics calculations indicate that the intrinsic detection efficiency of these ^{235}U detector assemblies varies only slightly ($\leq 20\%$) over the neutron energy range from 14 MeV to ~ 10 eV [4]. Detectors NE-1,2,3, and 4 are commercial detectors [10] with commercial electronics [11] operating in count, current and Campbell modes. Detectors NE-5, 6, and 7 [12] and their electronics [13] were built by ORNL [14] and operate in count mode. Only NE-1, NE-2, and NE-6 have detection efficiencies sufficiently high to produce acceptable count rates with manually manageable calibration sources located in the TFTR vacuum vessel. The other, lower sensitivity detectors must be calibrated by cross-calibration to NE-1 and NE-2, using the plasma neutron source. (Detector NE-6 was not operating during this calibration.)

Detector locations near the vacuum vessel would have benefitted from increased direct, uncollided flux at the detector location and reduced possible variations in the detection efficiency due to changes in the absorption and scattering environment of the TFTR Test Cell.

However, access to areas adjacent to the vacuum vessel was difficult and, consequently, the detectors were located between and outside the toroidal field coils at a radial position of about 5.6 m. The detector assembly is elevated above the concrete platform under the TFTR by a stand of 25 cm height, and the detector center is situated about 60 cm above the concrete, and 1.7 m below the TFTR midplane (see Fig. 1). NE-1 is located in TFTR Bay C and NE-2 in Bay M [15]. Detector preamplifiers and electronics are installed in the basement, except for those of NE-5 and NE-7 which are built into the detector housing.

3. CALIBRATION NEUTRON SOURCES

Two types of neutron sources have been used for TFTR in situ calibrations, neutron generators with D-D or D-T heads and ^{252}Cf spontaneous fission sources. Neutron generators have the advantages that the neutron energy is nearly identical to that of the fusion reaction in the plasma, and the source can be turned off at will. However, the measurement of the source strength is complicated by scattering off the structure of the accelerator head, which affects both the flux seen by the monitoring detector at a given angle to the generator beam and the determination of the overall (angular) emission. The angular emission is affected most in the backward direction relative to the beam (where much of the mass of the accelerator head is located): Consequently, the angular emission not only from the D-D reaction but also that from a D-T head is anisotropic. In addition, supports are required to locate the neutron generator inside the vacuum vessel. These supports may also affect the flux at the monitoring detector and the spectral and angular neutron distributions. Thus the uncertainty in the measured neutron source strength of the neutron generator was estimated to be $\pm 12\%$. In addition, the high-voltage cables and cooling-fluid hoses of the neutron generators are a potential hazard to the inner wall of the tokamak vacuum vessel.

During the 1988 TFTR calibration a ^{252}Cf radioactive neutron source was used. It produced 8.17×10^7 n/s (on Dec. 12, 1988) and was prepared and calibrated to an NBS traceable standard by ORNL [16]. The ^{252}Cf source has the advantages of small size (0.9 cm diam., 4.6 cm

long), small weight, no supply cables, and a well-known neutron source strength ($\pm 1.5\%$). About 5.5 γ 's are emitted per neutron, with 80% of the γ -energies below 1 MeV. The half-life is 2.645 (± 0.007) years and S remains (relatively) constant during the approximately 10-day duration of the calibration. (The slight decay has been corrected in the detection efficiency data.) The angular emission is isotropic. The energy spectrum can be represented by a Maxwellian distribution of the form $N(E) = C \times E^{1/2} \exp(-E/\tau)$, where the "temperature" τ is 1.42 MeV. The average neutron energy is 2.14 MeV (vs ~ 2.5 MeV for a D-D plasma).

Neutronics calculations using identical simulation models of absorbers and scatterers around the TFTR have been performed [17] comparing ^{252}Cf and D-D neutron generator sources of the same source strength. The calculations show these sources produce neutron fluences differing by $\sim 8\%$ at the location of the detector, within the statistical error of the Monte Carlo calculation for each of these sources, which is $\pm 5\%$. These calculational results are consistent with measurements, Sec 8.2. Detectors with detection efficiencies relatively independent of neutron energy, therefore, can be calibrated for deuterium plasmas with sufficient accuracy using a ^{252}Cf (S-transfer uncertainty = $\pm 7\%$) source instead of a D-D neutron generator (S-uncertainty = $\pm 12\%$).

4. THE CALIBRATION SOURCE TRANSFER SYSTEM

A remotely controlled source transfer system positioned the neutron point source in the vacuum vessel of TFTR (Fig. 2). The source transfer system consisted of two toroidal rails elevated above the vacuum vessel floor. The rails supported a source holder near the vacuum vessel horizontal midplane. The inner rail was fixed in place. The outer rail lay on wheels and could be rotated toroidally throughout the vacuum vessel by a remotely controlled friction-drive motor. The source holder was attached to the outer rail and supported by rollers on the stationary inner rail. The mass of the entire transport system was kept small (total weight 120 kg consisting mostly of aluminum) in order to reduce neutron scattering. The rotating outer rail had markings for every degree of toroidal angle, which were read by means of a TV camera (to $\pm 0.1^\circ$). The toroidal path of the source in the vacuum vessel

was measured to deviate by less than 0.5 cm from a perfect circle. The vertical part of the source holder consisted of a plexiglass tube of 0.6 cm wall thickness, supported by a thin-walled (0.125 cm) stainless steel tube below and above the plexiglass. The plexiglass allowed a visual check of the source presence in the source holder. Different radial and vertical neutron source locations were obtained manually without removing the source by means of a 3 m long tool. The effect of the source transport system on the fission detector detection efficiency was measured and is discussed below, Sec. 5.7.

5. CALIBRATION RESULTS

5.1. Handling of Individual Raw Data Points

Each neutron source position in the TFTR vacuum vessel was recorded by noting the major radius, R , the height above the horizontal midplane, Z , and the toroidal angle, ϕ (counted clockwise as seen from above), of the source location with respect to the center of Bay K (the port through which the source was brought into the vacuum vessel). For each source location, the TFTR Central Instrumentation Control And Data Acquisition (CICADA) system was run through an acquisition shot cycle and the data given a shot number and stored. The NE system splits its 64K bytes of memory into seven detectors, each of which has 9362 bytes. The calibration data for a given source location were acquired with either 80 time bins per second for a total of 117 s (~ 2 minutes) or 20 time bins per second for 468 s (or ~ 8 minutes). After the data acquisition was completed and the raw data confirmed to be saved (~ 30 s), the source was moved to the next location (taking approximately another 30 s for the relocation), and the process repeated.

The count rate during calibration for the NE-1 and NE-2 detectors was lower than that during plasma operation by a factor of 10^{-3} to 10^{-6} .

Thus low count rate (noise) contributions due to electrical pick-up or problems not previously seen during normal operation were identified and corrections applied. Detector NE-1 was observed to have significant noise problems. The raw data counts (x's in Fig.3a) did not vary smoothly from angle to angle as they did for NE-2. It was noticed that the

count-per-time-bin distribution was non-Poisson during the obviously noisy events. Especially, there was too large an incidence of three (or even more) counts per time bin (Fig. 4a, b) for the observed count rates (≤ 1 c/s) and time bin duration ($\sim 10^{-2}$ s). (For an average count rate r of 1c/s (~ 100 c per 2 minutes), the number of double counts, i.e., chance coincidences r_{ch} , per 10^{-2} s time bin τ_b , should be $r_{ch} = r^2 \times \tau_b = 1 \times 10^{-2}$ or 1%. Triple counts should be very rare.) Figures 4c and d show the Poisson distribution and count rate data for a shot without noise. At present, we have not identified the source of the noise, which may possibly be micro-arcing in the cables or connectors. We do believe that these events are not multiple counting of a single neutron-detection event, but rather isolated noise events. However, we did develop a procedure for eliminating the noise-related counts. First, the count distribution for NE-1 for all shots was examined and compared to the expected Poisson distribution for the observed total number of counts. Then: 1) We completely eliminated all (NE-1) shots where the number of counts from bins with greater than, or equal to three counts per time bin was above 25% of the total NE-1 count. This amounted to 188 shots. 2) We eliminated all further shots where the number of counts with two counts per time bin deviated from the expected Poisson distribution by more than two standard deviations. This amounted to 54 shots. 3) For the remaining shots, which had a small number of noise events identified by a non-Poisson number of time bins having three counts, we subtracted all the counts from time bins with three or more counts. This led to the subtraction of potentially meaningful time bins (counts) for an estimated 5 shots. As a result of this procedure, we estimate that an additional 1% uncertainty must be added in quadrature to the NE-1 data statistical uncertainty. We take the statistical uncertainty to be the square root of the counts after the noise subtraction. The result of this procedure is shown as the squares in Fig. 3.

For NE-2, the count distribution was always close to that described by Poisson statistics; however, there was an improbably high coincidence of single NE-2 counts in time bins during which NE-1 was having noise counts. (An example is shown in Fig. 5.) We took this to indicate that the NE-1 noise created a common-mode problem in the electronics for NE-2, but led to less spurious counts for NE-2. Thus, we

subtracted all NE-2 counts coincident with NE-1 time bins with 2 or more counts. This occurred for 68 shots, with an example shown at -135° in Fig. 3b (see also Fig.6). We estimate that the NE-2 data have an additional 0.2% uncertainty to be added in quadrature to the NE-2 statistical uncertainty. Again, we took the statistical uncertainty to be the square root of the counts after the coincidence subtraction. NE-2 has, however, an additional $\pm 2.5\%$ (1σ) slow time drift that has been observed during the Pu-Be renormalization calibrations performed in 1988 and which was also noted in the renormalizations performed prior and following the present calibration (see Sec. 7.2). Due to the slow time scale of this drift, NE-2 was taken to be constant during any toroidal scan but to have an additional uncertainty of $\sim 2\%$ between scans.

For NE-1, there was an additional complication, since occasional abrupt increases of the apparent detection efficiency by about 50% had been observed during plasma operation in 1988. We do not know the source of this change in efficiency. During this calibration, for nearly all scans NE-1 and NE-2 had comparable detection efficiencies. However, for one consecutive sequence of 20 shots, or for about one hour during the $R = 265$ cm, $Z = -30$ cm scan, NE-1 had about 50% higher detection efficiency. In order to treat this data we reduced the count rate for these shots to $2/3$ of the measured rate. There may be further data, for three shots, with 50% higher count rates; but we did not reduce these count rates since this is also approximately the probability of obtaining individual data points at $+3\sigma$. The justification in reducing the NE-1 count rate for the 20 cases is that the gain change is clearly identifiable and occurred in a sequence of 20 shots.

5.2. Calculation of Detector Efficiency for Toroidal Line Source

Seventeen toroidal scans were made at 7 different major radii ($R = 235, 250, 265, 280, 286, 293.5,$ and 320 cm) and at 5 vertical positions ($Z = -30, -15, 0, 15, 30$ cm, relative to the TFTR midplane). Not all (R, Z) combinations were scanned, see Fig.7. Between about 50 to 150 toroidal source locations were measured per toroidal scan, with each point taken with a counting period of 2 minutes duration except for the

central ($R = 265$ cm, $Z = 0$ cm) scan taken with 8 minutes durations. For each scan the (line source) detection efficiency ϵ was calculated by using LOCUS [18] to integrate under the point efficiency data points. The integration uses a piecewise polynomial fit, with each fit based on 3 to 5 source-location data points. Multiple values (repeats) at one source position (i.e., one toroidal angle) were averaged by the LOCUS integration routine.

5.3. Sources of Detection Efficiency Uncertainty

The following sources of uncertainties involve only the integration process and the detector stability. Other uncertainties are discussed in Sec. 7.

1) Purely statistical error, determined by the total number of counts, C , in the scan, $\sum C(\phi)$. If the angular interval between shots is constant, then $\delta\epsilon/\epsilon = 1/(\sum C(\phi))^{0.5}$. While this equal-spacing condition did not strictly hold, the result is probably a good estimate of the statistical uncertainty. For NE-2, $\delta\epsilon/\epsilon$ varied between 0.8 and 2.8% with an average of 2.4%. For NE-1, this error varied between 0.8 and 3.4% with an average of 2.7%.

2) Uncertainty in integrating the curve of counts per shot vs toroidal angle depending on method, smoothing factor used, etc.: $1\sigma = \pm 1.5\%$.

3) Small drifts in ϵ for NE-2, apparently due to variations of the electronics (see Sec. 7.2) : $1\sigma = \pm 2.5\%$.

Error sources 2) and 3) are the same for all (R, Z) scans. Combining these errors in quadrature, the uncertainty in determining $\epsilon(R, Z)$ for an isotropic toroidal line source is typically $\pm 3.8\%$.

5.4. Exponential Fits to Point Efficiencies

Figure 8 shows a typical exponential fit, $\exp(-K\phi_M)$, to the point

detection efficiencies [7]. We compared NE-2 efficiencies derived from the LOCUS integration routine with the integration over exponential fits. For each (R,Z) scan, a different exponential constant K is used for $\phi_M > 0^\circ$ and $\phi_M < 0^\circ$. (For the NE-2 scan at R = 280 cm, Z = 15 cm, two data points fell several standard deviations below expected values and may possibly have been in error. These two points were omitted in determining the ϵ for this scan during both integration routines.)

On average, the exponential fit gives a value that is 98.8% of the value from the LOCUS integration, with a maximum deviation of 3.4%. This agreement provides confidence that the exponential fit gives a reasonably accurate representation of the experimental data. However, the maximum deviation occurs at R = 265 cm, Z = 0 cm, which is the scan with the most data points, apparently since the simple exponential function did not fit the data in the region near $\phi_M = 0^\circ$. Also, the actual data are clearly offset by 2 to 3° , although using different exponents on either side of $\phi_M = 0^\circ$ helps account for this asymmetry.

5.5. Variation of NE-1 and NE-2 Efficiency with Major Radius and Height

The following are the salient features of the calibration results, shown in Fig. 9. More attention is given to NE-2 because of its relative freedom from data affected by noise. As discussed earlier, the uncertainty for any (R, Z) point is $\pm 3.8\%$, which is indicated by the error bar in the figure.

1) For NE-2, the total variation in $\epsilon(R,Z)$ for the 17 scans was 14%, from 2.71 to 3.11×10^{-9} counts/neutron. This variation is about twice the peak-to-peak uncertainty in a single (R, Z) location result.

2) The Z = -15 cm curve has higher ϵ than the Z = +15 cm curve, while the Z = 0 cm curve is fairly close to the Z = +30 cm curve. One might expect the $\epsilon(R,Z)$ for Z < 0 to be greater than the $\epsilon(R,Z)$ for Z > 0 because the detector is located below the midplane.

3) For NE-1, the total variation in $\epsilon(R,Z)$ for the 17 scans was also $\pm 14\%$, from 2.73 to 3.20×10^{-9} counts/neutron. Thus NE-1 has an $\epsilon(R,Z)$ that ranges from 0.95 to 1.10 times that of NE-2, with an average ratio $NE-1/NE-2 \sim 1.04$.

4) For NE-2 the curves of ϵ for $Z \neq 0$ show variations with R that lie within the uncertainty of each (R, Z) point. However, these curves extend only from $R = 240$ to $R = 290$ cm, at most. The $Z = 0$ cm curve, which extends to $R = 320$ cm, shows an increase of $\epsilon(R,Z)$ with R that is greater than the uncertainties, and this behavior is expected as the source approaches the detector.

5) For NE-1, on the other hand, there is no significant variation of $\epsilon(R,Z)$ with R for $Z = 0$ cm.

We conclude that the effects of vertical and radial position changes of the source on the detection efficiency are small. Substantially longer runs (higher total number of counts per run) would be required to allow drawing detailed conclusions.

5.6. Effect of Variation of Source-Detector Line-of-Sight Distance

In a toroidal scan the local detection efficiency varies with toroidal angle of the source location due to the variations both of the detector-source distance and of the scatterer and absorber geometry relative to the source location. A more straightforward experiment may be the variation of the source-detector distance along a line of sight from source to detector, for fixed toroidal angle. If scattering from the structures surrounding source and detector is predominant, then it may affect the $1/r^2$ dependence of the detection efficiency expected for a point source with negligible contributions from scatterers. To check this, we ran a series of measurements in which the source-detector distance was varied along a direct line of sight extending through detector NE-2 and $R = 265$ cm, $Z = 0$ cm at $\phi_M = 0^\circ$. The accuracy of the line-of-sight distance is estimated to be within 1 cm.

The results of these measurements, in which the NE-2 count rate is shown vs the inverse of the source-detector distance squared, are indicated in Fig. 10. The error bars denote the 1σ statistical uncertainty. For a distance from 284 to 401 cm along the line of sight ($\Delta Z \sim 60$ cm), a proportional fit would connect nearly all the measurements (and their error bars). This indicates that along a line of sight the $1/r^2$ dependence is quite dominant. Since the detector was located behind the shear compression panels with a total steel thickness of ~ 30 cm between detector and source (so that the uncollided neutrons make negligible contributions to the detector response), and since neutron diffusion is the dominant transport mechanism [4], this distance dependence is somewhat unexpected. However, the two toroidal magnetic field coils adjacent to the line-of-sight have a density much higher than that of the materials in the Bay region (near the line-of-sight), so that the two adjacent field coils can serve as effective collimators. Thus, the observed distance dependence would follow, i.e. under these conditions scattered neutrons also have a nearly $1/r^2$ dependence. Table 2 shows the results of simulation calculations (Sec. 9), including one case with the correct toroidal field geometry modeled, as well as a second case with the field coils omitted. With the field coils present, the calculated efficiencies are approximately proportional to the inverse of the source detector distance squared (see Fig.10), as observed in the experiment. This correlation does not hold when the coils are removed in the calculation, as follows from the above collimator consideration.

5.7 Effect of Source Transfer System on Detection Efficiency

To determine the effect of both the neutron-source holder and the source transfer system on the detection efficiency, we performed control measurements. We supported the source from the torus walls (Fig.11) and removed many parts of the source holder and transfer system. The outer, rotating rail in the vicinity of the source, and the source holder which bridges the space between inner and outer rail were removed, leaving only the vertical source support. The plexiglass and stainless steel support tube was suspended inside the vacuum vessel so

that the source was located in the $R = 265$ cm, $Z = 0$ cm position. Five shots taken at toroidal angle $\phi_M = 0^\circ$ with the source transfer system partially removed can be compared with either one shot at the same toroidal angle or with six shots at $-3^\circ \leq \phi_M \leq 3^\circ$ with the transfer system in place. The difference observed between the cases is less than the statistical error of 2%. To account for possible scattering from the transfer system, we thus add another 2% uncertainty in quadrature to the uncertainty of the detector calibration.

6. VOLUME-AVERAGED DETECTION EFFICIENCIES

Based on the line-integrated detection efficiencies obtained for different R and Z , we determined volume-averaged detection efficiencies, i.e., weighted averages of the $\epsilon(R,Z)$ values measured over the ranges of R and Z of interest. The weighting is derived from a model of the plasma neutron emission profile, with the center typically at $R = 265$ cm, $Z = 0$ cm.

The volume-averaged efficiency $\langle \epsilon \rangle$ for a plasma neutron source was found by partitioning the torus cross section into either a square or a concentric cylindrical grid. The neutron source strength was taken to be cylindrically symmetric, but each sector was characterized by a single efficiency, as shown in Fig. 7. The $\epsilon(R,Z)$ for sectors without direct measurement were found by interpolation. Then $\langle \epsilon \rangle$ is calculated by:

$$\langle \epsilon \rangle = \frac{\int S(\mathbf{x}) \epsilon(\mathbf{x}) d\mathbf{x}}{\int S(\mathbf{x}) d\mathbf{x}}$$

where $\mathbf{x}$ refers to the (R,Z) position and $S(\mathbf{x})$ is a Gaussian source profile that approximates neutron emission profiles calculated from the equilibrium code SNAP [19].

For beam-heated plasmas with large Shafranov shifts, the major radius may be 15 to 20 cm larger than that before injection. Thus pre-injection target plasmas at $R_0 = 245$ cm actually correspond to $R = 260$ to 265 cm in the results discussed here. Figure 12 shows $\langle \epsilon \rangle$

as a function of plasma major radius, for Gaussian source profiles with $1/e$ radii at 16, 23, and 30 cm and using a square grid for Fig. 7. Broader profiles cannot be estimated accurately with the available calibration data. Results from transport code simulations show that for a typical TFTR supershot, the beam-target reaction-rate profile is approximately Gaussian, with a $1/e$ radius of about 25 cm (see Fig. 13). This method of determining $\langle \epsilon \rangle$ may be inaccurate for plasma sources with appreciable neutron source strength inside $R < 235$ cm or outside $R > 295$ cm, where there is virtually no calibration data. For a Gaussian-like source profile centered at $R = 265$ cm, with width as in Fig. 13, less than 20% of the neutron source strength lies outside $R > 295$ cm or $R < 235$ cm.

For a toroidal plasma source, the detection efficiency variations with R and Z are much smaller than those for a point source, because of the smoothing effect of the extended source. The largest gradient in the plasma case is only 0.15%/cm at $R < 260$ cm for the narrowest source profile, and the gradients decrease as the profile broadens.

The lack of spatial dependence of the volume-averaged detection efficiency implies that a single $\langle \epsilon \rangle$ can be used for TFTR plasma sources over a large range of axial positions and source widths. This result confirms and greatly strengthens previously unpublished $\epsilon(R, Z)$ measurements at a few toroidal angles and adds credence to our use of a single value of the detection efficiency $\langle \epsilon \rangle$ for all plasma scenarios (and a given detector), including both ohmically heated and NBI shots. If we take $\langle \epsilon \rangle = 2.96 \times 10^{-9}$ counts/neutron for NE-2, then the relative variation of $\langle \epsilon \rangle$ is $\leq 2\%$ when the neutron-source axis is located in the range 240 - 275 cm (shifted radius). Again, the half-width of the source should not be more than about 25 cm. We note that the measured 1988 volume-averaged Cf detection efficiencies when multiplied with the calculated detection efficiency ratio $D-D/Cf = 1.08$, $\langle \epsilon \rangle(\text{NE-1}) = 3.22 \times 10^{-9}$, $\langle \epsilon \rangle(\text{NE-2}) = 3.20 \times 10^{-9}$ ($\pm 11\%$, see below) agree well with the measured 1987 D-D line-integrated detection efficiency $\epsilon(\text{NE-1}) = 3.04 \times 10^{-9}$, $\epsilon(\text{NE-2}) = 3.42 \times 10^{-9}$ (+50,-30%) used before the 1988 calibration.

7. ANALYSIS OF MEASUREMENT UNCERTAINTY

The sources of measurement uncertainty are listed in Tables 3 and 4, leading to expected uncertainties in the measurement of the neutron source strength of about 11% for $S \leq 4 \times 10^{14}$ n/s and about 13% for $S > 4 \times 10^{14}$ n/s. These are the 1σ uncertainty, or 67% confidence, limits. For the higher S , there is a larger uncertainty due to the extra uncertainty involved with cross-calibrating the less sensitive detectors or the Campbell mode (see Sec. 7.4).

7.1. Effect of Neutron Angular Emission Anisotropy and Energy Differences

The TFTR plasma D-D neutron source differs from the ^{252}Cf calibration neutron source in the neutron energy spectrum and may also have different angular emission of the neutrons. The ^{252}Cf neutron emission is isotropic. However, the beam-driven $\text{d(d,n)}^3\text{He}$ fusion reaction is anisotropic (Fig. 14) with more neutrons/steradian being emitted parallel to the center-of-mass velocity than perpendicular to it. Therefore, in TFTR beam-heated plasmas, where the energetic deuterons are injected tangential to the torus minor radius, the toroidal beam of energetic ions causes more neutrons to be emitted horizontally than vertically. Conversely, in ohmically heated plasmas the reacting ions are randomly directed and the neutrons emitted isotropically. Potentially, the efficiency of the epithermal neutron detectors could be different for the ohmic plasma than for the beam-heated plasma due to this anisotropy of the neutron emission. Moreover, the neutron energy spectrum of the Cf source has a spread in energy between 0.1 keV and 5 MeV (average 2.14 MeV), whereas the plasma-produced neutrons have a narrow line spectrum peaked at ~ 2.45 MeV. In addition, the plasma neutron-energy spectrum can be broadened by 100's of keV and in the case of NBI can be shifted also by 100's of keV. Thus the validity of using a Cf source to determine the detection efficiencies for D-D plasmas must be questioned.

To evaluate the effect of the different angular emissions, we changed the isotropic Cf source to approximate the anisotropic D-D source by placing a cylindrical polyethylene (3.65 cm wall thickness, 3.5 cm i.d., 6 cm long) or steel (5.1 cm wall thickness, 2.5 cm i.d., 6.7 cm

long) shadow shield around the Cf source and repeated the $R = 265$ cm, $Z = 0$ cm toroidal scan with each shield (Fig. 15). The shadow shields are calculated to simulate effectively the anisotropy expected from the beam-induced neutron emission. Moreover, the cylindrical shadow shields reduce the mean neutron energy (20% for the steel and 34% for the polyethylene shield) but do not significantly absorb the Cf neutrons (absorption $\approx 1\%$). The anisotropy was measured in the lab by rotating the shielded source in front of a moderated BF_3 detector (Fig. 16). The results were consistent with the calculated anisotropy although backscatter from the walls of the lab contributed to a constant background of about 7% of the mean count rate.

The anisotropy of the neutron emission as evidenced by the results obtained with the steel cylinder (Fig. 15b) did not significantly change the toroidal efficiency integral. The bare source produced 1.09×10^{-6} counts/Cf neutron ($\pm 2\%$) while the source shielded by the steel cylinder generated 1.085×10^{-6} counts/Cf neutron ($\pm 4\%$). However, the local detection efficiency was affected: Fewer neutrons were detected when the shielded source was directly in front of the detector; but this effect was small and of limited toroidal extent, $\approx \pm 8^\circ$.

The toroidal integral of the locally measured detection efficiencies for the case of the Cf source inside the polyethylene shadow shield was significantly smaller (0.85×10^{-6} counts/Cf neutron $\pm 5\%$), Fig. 15c, but this effect is calculated to be primarily due to the energy degradation of the Cf neutrons resulting from scattering in the polyethylene. In fact, the neutron streaming calculations were able to simulate the local detection efficiencies (Figs. 15b and c), further substantiating the ability of these calculations to predict the transfer of the ^{252}Cf calibration to that of the D-D 2.5 MeV plasma neutron source. The shadow shields thus present a convenient perturbation to the neutron streaming calculations which indicate that its model of the TFTR structure contains most of the significant scattering components.

Furthermore, when both the effects of angular emission and energy spectra differences of the D-D and Cf neutron sources are taken into account in the neutronics calculations [4], for a moderated ^{235}U detector similar to NE-1 and NE-2 and positioned similarly on TFTR, the ratio of the D-D (including NBI) to Cf detection efficiencies is 1.08 ± 0.07 [17]. We

take the (statistical) uncertainty in the calculation ($\pm 7\%$) to be the uncertainty to be added in quadrature to the uncertainty of the calibration.

7.2 Detector Drifts and Renormalization

Prior to the present calibration, drifts of the detection efficiencies of specific detectors had been noticed, which may be caused by drifts in amplifier gains or discriminator voltages. During 1988, detection efficiency drifts were renormalized about once per month using a Pu-Be neutron source ($\sim 2 \times 10^6$ n/s) placed in a holding fixture attached to each of the detector assemblies. (During the latter part of 1988 a more intense Cf source was used.) The source-holder fixtures and their distances from the detectors were designed to result in an uncertainty of the count rate (due to changes in source location) of less than $\sim 0.5\%$. Figure 17 shows the normalized (to the average number of counts) counts per ten minute interval for NE-1 and NE-2, measured at various dates between 4/15/88 and 11/17/88 inclusive. The efficiencies of detectors NE-1 and NE-2 have varied by up to $\pm 5\%$ in 1988. Repeated counts on the same day did not yield statistically significant count rate variations. Thus, we have taken a 1σ uncertainty of $\pm 2\%$ to be applied for potential detector drifts. This uncertainty is taken to apply for individual toroidal scans but not for individual readings, due to the high reproducibility of sequential, repeated readings and the long time constant of the drift. As well, this uncertainty must also apply for the plasma discharges and the cross-calibrations.

7.3 Profile Uncertainty for $R = 265$ cm, $Z = 0$ cm

The uncertainty in obtaining the NE-2 efficiency for a particular neutron source strength profile centered at $R = 265$ cm (Fig. 12) is about $\pm 5\%$ at 1σ . This uncertainty was obtained by summing the contributions from each individual toroidal scan weighted by the neutron emission of the volume elements (Fig.7). Uncertainties due to statistics and interpolation errors were included. The largest error contribution came from the possible 2% drift.

Deviations from the assumed profile need to be considered during plasma operations and for cross-calibrations. This amounted to a further 1.5% uncertainty.

7.4 Cross-Calibrations

Previously, at the higher neutron source strength levels we have used a ^{238}U (NE-5 or NE-7) detector to determine the source strength S . We have cross-calibrated the ^{238}U detectors to the directly calibrated ^{235}U detectors (NE-1, NE-2) on plasmas where $S \leq 4 \times 10^{14}$ n/s, i.e., where NE-1,2 are counting at high count rate near saturation and NE-5,7 are counting at low count rate. With this report, we are improving the cross-calibration technique to also make use of the Campbell and current mode signals from the NE-1 and NE-2 detectors at $S > 4 \times 10^{14}$ to $\sim 10^{17}$ n/s. This procedure has the following advantages:

- 1) Since the ^{238}U detectors have an energy threshold (1 to 1.5 MeV) while the ^{235}U detectors are roughly energy independent, the ^{238}U detector may have different sensitivity to the plasma position and plasma profile than the ^{235}U detector. By using the different modes of the ^{235}U detector, we retain its calibrated plasma-position insensitivity and the calculated anisotropy insensitivity at the higher neutron source strength levels.

- 2) The ^{238}U detectors have a different relative detection efficiency for 14 MeV neutrons than for 2.5 MeV neutrons. This means that cross-calibration after beam turn-off is inappropriate: the 14-MeV neutron emission due to D-T reactions from the confined 1-MeV tritons generated by the second branch of the D-D reaction can be significant. On the other hand, for cross-calibrations from the count rate mode to the Campbell (or current) mode of the same ^{235}U detector, i.e., NE-1 or NE-2, the detection efficiency remains the same and nearly energy independent. Thus, the post-NBI-heated phase of nearly all discharges with its decaying neutron source strength is particularly well suited to cross-calibration (Fig. 18) based on the Campbell mode.

- 3) The difference in detection efficiency between detectors NE-1,2 and NE-5,7 is about a factor of 100 (Fig. 18). This large difference in efficiency makes it difficult to obtain an accurate cross-calibration.

The difficulties include:

a) The NE-5,7 count rate is low. Since it is not straightforward to determine the presence of counts due to noise, noise counts may affect the result. (Noise counts have in fact been observed in these detectors.)

b) During the cross-calibration (to detectors NE-5 and NE-7) NE-1 and NE-2 are operating at high count rates and may have a significant dead time correction due to pulse pile-up. Inaccuracies in the assumed dead time further increase the uncertainty of the cross-calibration.

c) In order that NE-5,7 have $\approx 10^3$ counts, and NE-1,2 be without appreciable pulse pile-up, it is necessary to have a plasma with This condition was obtained only rarely (and generally only by design) on TFTR during the 1987 and 1988 run periods. Thus, plasma conditions suitable for cross-calibration from NE-1,2 to NE-5,7 were available only infrequently and potential detection efficiency drifts for NE-5,7 could not be monitored well.

d) If the difference in detection efficiency is reduced to allow easier cross-calibration, more detectors and more cross-calibrations are required to cover the S range of interest.

Conversely, the cross-calibration of the NE-1,2 count rate mode to the NE-1,2 Campbell mode can be achieved much more accurately and more often. The Campbell signal overlaps the count-rate signal over a range of a factor of 50 in neutron source strength (Figs. 18,19). Thus, the cross-calibration can be performed in a region where the NE-1,2 count rate dead-time correction is unimportant. In fact, the dead times for NE-1 and NE-2 were determined most accurately by comparison of the NE-1 and NE-2 count rates to the NE-1 and NE-2 Campbell signals. This type of cross-calibration can be obtained on nearly all TFTR NBI plasmas, and indicated that the variation of the Campbell signal was within about $\pm 2.5\%$ (1σ). There was one 25% change in the Campbell signal gain that occurred during the middle of the TFTR run period. The cause of this gain change is unknown and possibly originates in the A.C. amplifier. This change was readily identified through our ability to perform cross-calibrations on all plasmas. Further, cross-calibrations to the current mode signal from NE-1,2 (Fig. 20) are possible and do provide better time response at the higher neutron source strength levels. The linearity of the Campbell signal was determined by comparison with the

current mode signal (Fig. 20), using a large number of shots.

One potential major problem with using the Campbell and current mode signals is the possibility of nonlinear behavior of the signals at higher neutron emission levels. We have also used the ^{238}U detectors NE-5,7 to measure the Campbell mode linearity and found that linearity can be checked on an individual-plasma basis (Fig. 18). The Campbell mode signal was proportional to the NE-5,7 count rate over two orders of magnitude variation in S . Nevertheless, because the cross-calibration of the Campbell mode occurs at $\approx 10^{14}$ n/s and we typically want to make accurate measurements at $\approx 5 \times 10^{16}$ n/s, on the basis of our experimentally determined Campbell mode linearity we have assigned a 1σ uncertainty of $\pm 8\%$ to the neutron source strength measurements at $\approx 5 \times 10^{16}$ n/s, resulting from the fit of the exponential constant which determines the NE-1,2 Campbell mode linearity. Combining the uncertainties in quadrature we obtain an uncertainty of $\leq 13\%$ at $S \approx 5 \times 10^{16}$ n/s, Table 4.

We note that the uncertainties in the measurement of the absolute neutron source strength of the plasma can still be improved. Neutron generators using the associated particle method can determine the source strength with $\leq 1\%$ uncertainty instead of the present 12%. Assuming that most of the errors are random, the following additional improvements can be made. A third detector set can be installed and the 6 measurements of S from Campbell and current modes for NE-1, NE-2, and the third similar detector, together with the 3 S measurements from NE-5 and NE-7 (and a third similar detector) can be averaged. Additional improvements can be made where possible, e.g., the Cf to D-D cross-section transfer calculation can be recalculated, the calibration runs extended as required and cross-calibrations and renormalizations performed more often. Finally, we are at present preparing to monitor detector high voltage and detector-electronics supply and bias voltages for every plasma discharge. It should thus be possible to reduce the uncertainty in the measured absolute S value of the plasma to below 10%.

8. COMPARISON OF DETECTION EFFICIENCIES WITH PREVIOUS CALIBRATIONS

8.1. Comparison of Cf-252 Calibration Data

Figures 21(a) and (c) show the toroidal variation of the NE-1 point efficiencies for data from 1984, 1985, and 1988, with the 1988 data multiplied by 1.4. The unknown cause of this 40% decrease is mostly related to electronics drift, but may also reflect changes in the TFTR environment. The 1984 curve does seem to be somewhat (15% change in the FWHM) broader. Between 1984 and 1985 the bellows cover plates between bays B-C and C-D were replaced with surface pumping panels containing on average about 2.5 times less, but similar material; the diagnostic neutral beam was added in the general area of the detector; and the backing plates for the carbon bumper limiter were installed.

The NE-2 detection efficiency remained relatively constant since 1985, Figs. 21(b) and (d). There appear to be two changes: In 1985 the efficiencies for source locations in the region adjacent to the detector appear to be reduced; and after 1984 and possibly by 1985 the point efficiencies show an asymmetry with toroidal angle ϕ_M , the angle determined by source and detector toroidal locations. The near-bay reduction in 1985 may be due to the presence of the movable limiter in bay M during that calibration. Records indicate it was also present during the 1984 calibration, but was "partially rebuilt" and subsequently removed prior to the 1985 calibration. The toroidal asymmetry could be due to the (thicker) bellows cover plates being left in the L-M gap (negative ϕ_M) while (thinner) surface pumping panels were installed in the M-N gap (positive ϕ_M).

Analyzing the 1984, 1985, and 1988 Cf calibration data by using an exponential fit (see Section 7b), we noticed a 17% decrease in the NE-2 detection efficiency (in 1987), and a 40% drop in NE-1 efficiency (Fig. 22a). Because of the sparseness of the 1985 and 1987 calibration data (per toroidal traverse), the uncertainties in the toroidal integrals result in an uncertainty in the ratio of the NE-1/NE-2 detection efficiencies of ~ 20%. By 1988, however, the ratio of the NE-1 to NE-2 detection efficiencies is lower by 40%. This result from the direct

calibrations is in agreement with the gradual downward drift seen in the ratio of NE-1/NE-2 observed from TFTR plasmas during cross-calibrations (Fig. 22b). We thus conclude that the NE-1 detection efficiency has varied about 50%, and the NE-2 efficiency less than 20%, in 6 years. Both detectors varied by less than 5% during 1988.

8.2 Comparison of Detection Efficiencies from Cf and D-D Calibrations

The detection efficiencies of the NE-2 detector for the ^{252}Cf and D-D neutron generator sources can be compared by considering data from the 1987 D-D calibration. During the year separating the present Cf calibration from the 1987 D-D calibration, several mechanical changes occurred in the near-Bay-M region. These changes include installation of a RF antenna in Bay L, RF limiters between Bays K-L and N-O, and an external RF waveguide and additional equipment outside Bays M and L. However, we do not expect these changes to affect the detector response significantly, an expectation supported by the approximately similar detection efficiencies obtained for NE-2 in 1985 (when significant changes had also occurred).

Figure 23 shows the point efficiencies for detector NE-2 for the D-D neutron generator from the 1987 calibration as well as the 1988 ^{252}Cf calibration, plotted versus ϕ_M . The D-D generator ion beam pointed clockwise, viewed from above, i.e., from left to right in this plot. Apparently, the NE-2 detector response was similar, with the peak value, the profile width, and the integrated detection efficiency being within 10% for the two neutron sources. These detection efficiency results for D-D and Cf neutron sources are well within the uncertainties of the neutronics calculations ($\epsilon_{\text{DD}}/\epsilon_{\text{Cf}} = 1.08 \pm 7\%$, Sec. 7.1) and of the source strength measurement for the D-D neutron generator ($\pm 12\%$, Sec. 3). The shift in the toroidal angle is interpreted as due to the anisotropy of the D-D neutron generator [7].

9. SIMULATION MODEL

The measurements of detection efficiency have been regularly compared with neutron transport simulations using the Monte Carlo MCNP

code, version 3B [20]. The RMCCS nuclear data set, primarily based on the ENDF/B-V evaluations, has been used in the calculations. The neutron-energy spontaneous-fission spectrum for ^{252}Cf is taken from NBS results [21]. Various biasing schemes were used to speed up the calculations. The TFTR components are described by ~ 300 surfaces, and these surfaces are combined into the specifications of ~ 300 cells. The geometrical descriptions common to the detectors include the vacuum vessel with homogenized representation of the port covers, inner bumper limiter, outer carbon tiles, poloidal and toroidal field coils, the center column assembly, shear compression panels, and floor and building walls. The upper TFTR 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 TFTR Bay of interest, have been represented as two homogenized material zones. The geometries of Bay C and M, where the two fission detectors NE-1 and NE-2 are located, have been modeled in as much detail as possible. Many individual calculations have been performed to strengthen and confirm the experimental results [4]. Table 2, containing the results for the source-detector line-of-sight experiment, Sec. 5.6, gives a specific example for these calculations.

10. PHYSICAL MODEL OF THE EFFECT OF THE TFTR STRUCTURE ON THE DETECTION EFFICIENCY

The influence of the TFTR structures on the detection efficiency may be discussed in the context of the combined effects of attenuation and scattering. The total (minimum) equivalent steel thickness between source and detectors is >30 cm, hence the uncollided neutrons contribute insignificantly to the detector response (the mean-free-path in steel is ~ 5 cm). On the other hand, most of the material near TFTR is steel and scattering of D-D neutrons with steel results in small energy losses ($\sim 7\%$ for an elastic scattering event). Since the responses of NE-1 and NE-2 are relatively insensitive to the energies of the neutrons incident on the outer moderator surface, the overall effective attenuation length could be very long (~ 40 cm) without having much effect on the detection efficiency. Examples of major attenuators are the vacuum vessel, shear panels, TF coils, and port cover plates (see Fig.1); these are permanent fixtures on

the tokamak and will not be changed during the lifetime of the machine. The plots of the detection efficiency vs the toroidal angle of the source location show that most of the detector response is due to neutrons emitted from regions in the bays adjacent to the detector location (about 90% is due to the near quadrant). The count rate for point-source locations on the far side of the machine was $\sim 10^{-2}$ times the count rate for source locations in the vicinity of the detector. Thus, we should not expect any significant change in detection efficiency due to the attenuation effect unless there is large equipment added in the area next to the detector.

Scattering events with localized, small objects deflect the direction of neutron travel, hence they may change the detection efficiency. However, since neutrons contributing to the detector response undergo many collisions with many components, the effect due to a particular object is rather small. This is evidenced by the fact that the bay C and M geometries are quite different (bay C accommodates a vacuum duct and bay M houses the ion cyclotron frequency heating equipment), yet the responses of NE-1 and NE-2 differ only by $\leq 5\%$ in shape and magnitude (see Fig 9a,b), and the detection efficiency ratio NE-1/NE-2 has varied only from 1.05 to 1.5 since 1983. Thus, we should also not expect any major changes in detection efficiency due to neutron scattering as a result of installation or removal of local machine components.

The relatively insensitive behavior of the detection efficiency expected from the physical model is in agreement with the fact that many changes in the TFTR (and detector) attenuation and scattering environment have taken place over the years without greatly affecting the detection efficiencies of the detectors. It also explains the relative insensitivity of the volume-averaged detection efficiencies to variations of major and minor radii of the extended plasma neutron source (Sec. 6). Numerical calculations based on the neutron transport model have provided a useful means to quantify the changes in detection efficiency resulting from changes in machine and plasma configurations or detector arrangement. However, the desired precision in the measurement of the absolute neutron source strength requires keeping track even of small changes and necessitates regular calibrations.

11. CONCLUSIONS

Extensive in-vessel calibration of the TFTR fission detectors using a Cf source located at ~930 separate positions has determined that the NE-1 and NE-2 ^{235}U fission detectors are relatively insensitive to plasma major radius and neutron source profile shape. A single volume-averaged detection efficiency may be used for a given detector for ohmic or NBI-heated discharges, independent of minor and major radius of the plasma. (Note, however, that measurements have only been made from 230 to 295 cm radius.) The resulting absolute neutron source strength calibration has an uncertainty of $\pm 13\%$.

To measure neutron source strength above the range of the directly calibrated detectors, cross-calibration to less sensitive detectors is required. The NE-1 and NE-2 count rate signals can be more frequently and more accurately cross-calibrated to the NE-1 and NE-2 Campbell and current mode signals than to the count rate mode of detectors with different detection efficiency (NE-5,7), when the count-rate-mode detection efficiencies differ by a factor of ~100, as is the case on TFTR. This is due to the large overlap of count-rate and Campbell modes (over a variation in S of a factor ~50). Reducing the ratio of the count-rate detection efficiencies for detectors with overlapping ranges would result in the requirement to use more detectors, which in turn would lead to additional cross-calibrations to cover the desired range of plasma neutron source strengths.

Long-term changes of the detection efficiencies due to electronics drifts or changes in the TFTR environment have occurred during the six years of operation. Such changes are now monitored by periodic renormalizations of the detection efficiencies using a calibration source located outside the vacuum vessel adjacent to the detectors.

Neutron transport modeling calculations have contributed importantly to our understanding of the effects of changes in TFTR environment and detector geometry on the detection efficiency, and on the relative detection efficiencies for ^{252}Cf and D-D neutron sources.

Further work is required to reduce the uncertainties in the measurement of the absolute neutron source strength of the plasma. The most important contributions arise from the uncertainties in the linearity

factor assumed for the Campbell mode, neutronics calculations, and electronics drifts. Improvements discussed (in Sec. 7.4) should reduce the measurement uncertainties to below 10%.

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TABLE 1.

**FISSION DETECTORS, FISSIONABLE MATERIALS
AND SOURCE STRENGTH RANGES**

<u>Detector</u>	Fission. <u>Material</u>	Mass (g)	Source Strength Range (n/s)	
			<u>Count Rate Mode</u>	<u>Campbell Mode</u>
NE-1	^{235}U	1.3	10^{12} to 4×10^{14}	3×10^{13} to $>10^{17}$
NE-2	^{235}U	1.3	10^{12} to 4×10^{14}	3×10^{13} to $>10^{17}$
NE-3	^{238}U	1.3	10^{16} to 4×10^{18}	
NE-4	^{238}U	1.3	10^{16} to 4×10^{18}	
NE-5	^{238}U	48	5×10^{13} to 5×10^{16}	Not Available
NE-6	^{235}U	18	5×10^{10} to 2×10^{13}	Not Available
NE-7	^{238}U	48	5×10^{13} to 5×10^{16}	Not Available

Table 2.

**CALCULATED NE-2 DETECTION EFFICIENCIES FOR SOURCE
LOCATIONS ALONG LINE-OF-SIGHT**

Source Location		Detector	Efficiency (c/n)	
<u>R (m)</u>	<u>Z (m)</u>	<u>Distance</u>	<u>Field Coil Modeled</u>	<u>Field Coil Not Mod.</u>
3.164	-0.30	2.83	$1.72 \times 10^{-8} \pm 3.6\%$	$3.08 \times 10^{-8} \pm 4.2\%$
2.907	-0.15	3.12	$1.45 \times 10^{-8} \pm 4.1\%$	
2.650	0.00	3.42	$1.23 \times 10^{-8} \pm 3.3\%$	$2.32 \times 10^{-8} \pm 4.3\%$
2.393	0.15	3.72	$1.05 \times 10^{-8} \pm 4.8\%$	
2.136	0.30	4.02	$0.855 \times 10^{-8} \pm 4.6\%$	$1.86 \times 10^{-8} \pm 4.5\%$

TABLE 3.

MEASUREMENT UNCERTAINTIES FOR NEUTRON SOURCE STRENGTH
 $< 4 \times 10^{14}$ n/s.

ACTUAL CALIBRATION ($\pm 9.0\%$)

Cf Source	$\pm 1.5\%$
Transfer Cf to D-D Calibr.	$\pm 7\%$
Calibration Hardware Scattering	$\pm 2.7\%$
R = 265, Z = 0 Ohmic Profile	$\pm 5\%$

NE-2 COUNT MEASUREMENT ($\pm 6.1\%$)

NE-2 Statistics (30 ms interval)	$\pm 1.8\%$
Dead Time	$\pm 5\%$
NE-2 Stability	$\pm 2.5\%$
Plasma Position Variation	$\pm 1.5\%$

Combined Uncertainty $\pm 11\%$

TABLE 4.

**MEASUREMENT UNCERTAINTIES FOR NEUTRON SOURCE STRENGTH
 $> 4 \times 10^{14}$ n/s.**

ACTUAL CALIBRATION ($\pm 9.0\%$)

Cf Source	$\pm 1.5\%$
Transfer Cf to D-D Calibr.	$\pm 7\%$
Calibration Hardware Scattering	$\pm 2.7\%$
R = 265, Z = 0 Profile	$\pm 5\%$

NE-2 COUNT RATE TO CAMPBELL MODE CROSS-CALIBRATION ($\pm 3.1\%$)

Fit over 1 Order of Magn.	$\pm 1\%$
NE-2 Stability	$\pm 2.5\%$
Plasma Position Variation	$\pm 1.5\%$

USE OF CAMPBELL MODE AT HIGH NEUTRON SOURCE STRENGTH ($\pm 9.4\%$)

Plasma Position Variation	$\pm 1.5\%$
Campbell Mode Statistics (average over 60 ms)	$\pm 4\%$
Campbell Stability	$\pm 2.5\%$
Exponential Constant Fit	$\pm 8\%$

Combined Uncertainty $\pm 13\%$

(a)

(b)

Fig. 1 TFTR and fission detector geometry. (a) Poloidal elevation of TFTR at Bay M. (b) Schematic of ^{235}U fission detector.

Fig. 2 Photograph of neutron source transfer system installed inside the TFTR vacuum vessel.

Fig. 3 Total counts for each two minute shot vs toroidal angle with respect to detector location, for a single toroidal scan. The x's are the raw data and the squares the corrected data. (a) NE-1. (b) NE-2.

Fig. 4 Examples of noisy (non-Poisson) and good data for NE-1.
 (a) Frequency distribution of bin counts for a shot with noise events. Compared to the expected Poisson distribution (dashed line) there is a large incidence of triple counts per time bin.
 (b) Frequency distribution of bin counts showing acceptable statistics. (c) Raw counts vs time for the distribution in (a).
 (d) Counts vs time for (b).

Fig. 5 Details of raw counts vs time for NE-1 (top) and NE-2 for the same shot. The (apparent) count at 13.65 seconds on NE-2 is coincident with the noise event on NE-1.

Fig. 6 Count frequency distribution, for a single noisy shot, for NE-2 coincident with counts in the NE-1 detector, vs the apparent number of counts in that NE-1 time bin.

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Fig. 7 Cylindrical R-Z grid used to determine volume-averaged detection efficiency. The locations of toroidal source scans are shown as solid dots.

Fig. 8 Exponential fit of NE-2 point detection efficiencies vs the absolute value of the toroidal angle relative to Bay M, for a single toroidal scan. The circles are for positive angles and the squares for negative angles.

Fig. 9 Toroidal-line-integrated detection efficiency vs major radius of neutron source location, for different source location heights Z . The magnitude of the typical uncertainty is shown on the $R = 283$ cm, $Z = 0$ cm point. (a) NE-1. (b) NE-2.

Fig. 10 NE-2 point detection efficiency vs the square of the inverse of the detector-to-source line-of-sight distance.

Fig.11 Photograph of the source supported from the vacuum vessel walls after removal of much of the source transfer system.

Fig.12 Volume-averaged detection efficiencies normalized to the value at $R = 265$ cm, $Z = 0$ cm, vs the major radius of the center of the neutron emitting volume. The curves represent Gaussian source profiles with different 1/e radii, λ .

Fig.13 Typical transport code results for TFTR supershots, with beam-beam, BB; beam-target, BT; thermonuclear, TN; and total fusion reaction rate; vs minor plasma radius. $1/e$ radius ~ 25 cm.

Fig. 14 Comparison of neutron angular emission anisotropies for unidirectional NBI (solid line), for balanced co- and counter-injection (solid circles) at 120 KeV, for Cf source with steel shadow shield (thin broken line) and for polyethylene shield (heavy broken line). Curves for shadow shields are calculated and agree well with experiments.

Fig. 15 Toroidal scans comparing isotropic (a) bare Cf source, and nonisotropic (b) Cf source with steel shield and (c) Cf source with polyethylene shield. The solid points are results from neutron streaming calculations.

Fig. 16 Comparison of neutron angular emission measured (by rotation of source with shield) for three different source-detector distances with the calculated angular emission, for Cf source with polyethylene shield.

Fig.17 Renormalization-monitoring of detection efficiencies during 1988, done by placing a neutron source next to detector. The count rates have been normalized to the average value during the calibration. (a) NE-1. (b) NE-2.

Fig.18 Cross-calibration of detectors for a single plasma discharge. (a) Neutron source strength, during NBI and during the post-NBI phase. Campbell mode cross-calibration can be performed during the post NBI decay phase, for each individual shot. (b) NE-2 (1 g ^{235}U) both raw (x) and pile-up corrected (o), NE-7 (50 g ^{238}U) (o) and NE-3 (1 g ^{238}U) (Δ) counts per millisecond vs the neutron source strength from the NE-2 Campbell signal. NE-2 begins to saturate at about 2×10^{14} n/s, limiting the overlap (for cross-calibration) of NE-2 and NE-7 count rates.

Fig. 19 Cross-calibration overlap of NE-2 count and Campbell modes.

(a) Neutron source strength vs time. Second occurrence of NBI at low power allows detailed cross-calibration. (b). NE-2 neutron source strength (for (a)) for count rate mode divided by that from Campbell mode, vs NE-2 Campbell voltage. Over more than 1.5 orders of magnitude in source strength the ratio varies by less than 10%, including pile-up corrections less than 25% (x) and 25-50% (□). When the pile-up is 50-65% and the count rate nears saturation (Δ), the ratio drops, above 6.2 V.

Fig. 20 NE-2 current mode and NE-3 count rate vs Campbell mode. This data comes from many different discharges, from intervals of time typically of 60-200 milliseconds duration when the source strength was constant.

Fig. 21 Comparison of the $R = 265$ cm, $Z = 0$ cm scans for the 1988 and previous ^{252}Cf calibrations. (a) NE-1 toroidal point detection efficiencies vs toroidal angle, from 1984 to 1988. The 1988 data has been multiplied by 1.4. (b) Expansion of data from (a) around 0 to $\pm 50^\circ$. (c) NE-2 point detection efficiencies vs toroidal angle, from 1983 to 1988. (d) Expansion of data from (c) around 0 to 50° .

Fig. 22 Secular drift of detectors. (a) Line-integrated detection efficiencies from exponential fits vs year of calibration for NE-1 and NE-2. (b) NE-1/NE-2 detection efficiency ratios vs year. The x's are ratios from the in situ calibrations, while the shaded area contains many ratios from individual plasma discharges obtained by cross-calibrations.

Fig. 23 Comparison of NE-2 point efficiencies for D-D generator (1987) and Cf (1988) neutron sources. Error bars indicate statistical uncertainty of individual points. Large arrow indicates pointing (beam) direction of the neutron generator inside the TFTR vacuum vessel.

NOTICE

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