ABSOLUTE CALIBRATION OF TFTR NEUTRON DETECTORS FOR D-T PLASMA OPERATION

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Absolute Calibration of TFTR Neutron Detectors for D-T Plasma Operation

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ABSTRACT

The two most sensitive TFTR fission-chamber detectors were absolutely calibrated *in situ* by a D-T neutron generator (~$5\text{x}10^7$ n/s) rotated once around the torus in each direction, with data taken at about 45 positions. The combined uncertainty for determining fusion neutron rates, including the uncertainty in the total neutron generator output (±9%), counting statistics, the effect of coil coolant, detector stability, cross-calibration to the current mode or log Campbell mode and to other fission chambers, and plasma position variation, is about ±13%. The NE-451 (ZnS) scintillators and ^{4}He proportional counters that view the plasma in up to 10 collimated sightlines were calibrated by scanning the neutron generator radially and toroidally in the horizontal midplane across the flight tubes of 7 cm diameter. Spatial integration of the detector responses using the calibrated signal per unit chord-integrated neutron emission gives the global neutron source strength with an overall uncertainty of ±14% for the scintillators and ±15% for the ^{4}He counters.

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INTRODUCTION

Figure 1 indicates the locations of the primary TFTR neutron detectors. A system of six fission chambers is the main TFTR measurement technique for determining the time-dependent fusion-neutron global source strength, S_n.[1] Time-resolved spatial profiles of neutron emission are obtained on a routine basis by arrays of ZnS-plastic scintillators[2] and helium (^{4}He) proportional counters[3] that view the plasma through collimated vertical sightlines within a massive shield. The ^{4}He counters also give the neutron energy spectrum, which is used to distinguish the time-dependent D-D (2.5 MeV) and D-T (14-MeV) neutron emissions.

There had been several previous absolute calibrations of the fission chambers using in-torus neutron sources, the immediately prior cases utilizing ^{252}Cf in Dec. 1988,[4] and D-D and D-T generators in Dec. 1987.[5] The ZnS and ^{4}He detectors had been previously calibrated only with a ^{252}Cf source.[6] In February 1993 we carried out a calibration of many of these detectors *in situ* with a ^{252}Cf source and D-T neutron generator moved inside the toroidal vacuum vessel by a remotely controlled rail system.[4] This paper describes the results with the D-T generator.

As discussed in detail elsewhere,[7] the neutron generator output was monitored with an attached ^{238}U detector calibrated against a dosimetry-standard Al foil. The global generator emission (~5×10^7 n/s) was determined from the monitor signal and the previously mapped angular distribution of the neutron source.[7]

I. FISSION-CHAMBER DETECTORS

The two most sensitive TFTR fission-chamber detectors are moderated 1.3 g ^{235}U detectors (Reuter-Stokes RS-C3-2510-114 with GammaMetrics electronics) designated NE-1 and NE-2, located in Bay C and Bay M respectively (see Fig. 1). They were absolutely calibrated by moving the D-T neutron generator once around the torus in each direction, maintaining the generator head at a major radius of 2.65 m in the midplane. The generator beam was nearly tangential to the vessel centerline, and the generator orientation was reversed for the second scan. Counts were taken for 234 s at about 45 positions in each scan, with the angular interval varying from 4^o to 16^o, the smaller intervals being used in the vicinity of NE-1 and NE-2. Figure 2 shows the counts per unit neutron emission vs "angle M", the toroidal separation of the source and NE-2. While there is some suggestion of offset in the two scans, the difference in count efficiencies at any angle is within the statistical error bars (±5%

or more). The NE-1 data showed even less sensitivity to generator orientation.

Integrating under the point-efficiency data gives global source efficiencies ε_{DT} that differ by 2% for the two scans. Similar results were obtained for NE-1. Table I summarizes the results and sources of error. The largest source of error is the 9% uncertainty in measuring the total neutron generator output.[7] All errors are combined in quadrature, assuming they are independent.

While the D-T reaction is isotropic, the angular emission of the D-T generator output is anisotropic because of scattering and absorption in the generator head.[7] There is some peaking of the emission in the forward direction and depletion in the backward direction, which might be noticed by a detector when the generator was located at toroidal angles near ±45-50° (see Fig. 1). However, no peaking or depletion of the source strength is evident in Fig. 2 at angles near ±45-50°, where the opposite generator orientations gave essentially the same count rates. Any effect due to anisotropic emission would be alleviated by the fact that a majority of the neutrons detected by moderated U-235 fission chambers are multiply scattered neutrons, rather than uncollided neutrons from the source.[8] Also, the detectors are located about 1.5 m below the plane of the rail system, further blurring any effect of source anisotropy.

Correction for TF Coil Coolant. The calibration was carried out with no TF coil coolant. Neutronics calculations with the MCNP code[8] predict that the neutron flux at the detector is reduced by 3% for a ^{252}Cf source or a D-T source when the TF coils carry Fluorinert coolant (compared with a 9% reduction with water coolant). An experiment with the ^{252}Cf source located in the re-entrant port in Bay N near NE-2 (see Fig. 1) showed a reduction in point-detection efficiency for NE-2 of 4±3% with Fluorinert present, consistent with the calculation. Thus we reduced the measured ε_{DT} by 3% (although the factor could be different for a toroidal source).

Figure 2 also shows the point-detection efficiency for a ^{252}Cf source. The angular dependence for the D-T source is appreciably narrower than for the ^{252}Cf source, reflecting the greater importance of direct-flight neutrons for the D-T source with its harder spectrum. The ratio of detector efficiencies for global D-T and ^{252}Cf sources was 1.55 for NE-1 and 1.56 for NE-2. The corresponding ratios of D-T to D-D efficiencies are somewhat smaller, namely 1.43 and 1.44, because D-D neutrons have smaller attenuation than ^{252}Cf neutrons in the tokamak components.[4] These ratios were somewhat larger than had been measured in 1983[1] (1.39 for NE-1) or in 1987[5]

(1.33 and 1.37 for NE-1 and NE-2, respectively). The absolute D-T efficiency for NE-2 was about 18% larger than measured in the Dec. 1987 D-T calibration, taking into account that the latter measurement was made with water coolant present in the TF coils. The increase could be due to drifts in the detector electronics or to hardware changes in the tokamak and auxiliary components in the intervening 5 years.

The measured efficiency for NE-1 was about a factor of 2 lower than in Dec. 1987. This result is consistent with cross-calibrations made with the tokamak plasma source during 1988-1992 that indicated a reduction in the NE-1 detector sensitivity, apparently due to deterioration in the detector itself.

Additional Uncertainties with Plasma Source. In addition to the ±11% uncertainty in the absolute calibration of ε_{DT}, detector use with the tokamak plasma source introduces uncertainties[4] due to plasma position variation (±1.5%), counting statistics (±2%), and possible detector drift (±4%). The combined uncertainty (1-σ) for determining S_n is about ±12% (see Table I).

D-T plasma operation in TFTR gives source strengths $S_n > 10^{17}$ n/s, well beyond the range of NE-1 and NE-2 in the calibrated count-rate mode. However, the detectors have two other modes that can be used at S_n up to about 3×10^{17} n/s, viz. the mean-square-voltage (Campbell) and current modes.[9] Cross-calibration of one of these modes to the count-rate mode must be made with the plasma D-D neutron source,[10] where the cross-calibration itself introduces additional uncertainties estimated at ±5%. The less sensitive fission chambers are cross-calibrated[10] against the Campbell or current mode of NE-1 or NE-2.

II. COLLIMATED DETECTORS

At the time of the calibration, one set of ten NE-451 (ZnS) scintillator detectors were in place. The arrays of helium recoil and NE-451 detectors were calibrated by scanning the neutron generator radially and toroidally in the horizontal midplane in 1-cm increments across the 7 accessible collimator flight tubes of approximately 7 cm diam. The calibration of the ^{4}He system is described elsewhere in these proceedings.[11] Figure 3 shows the NE-451 response for radial and toroidal scans across one flight tube. The scan profiles had shapes in good agreement with curves derived from a ray-tracing model based on the collimator geometry, after adjustment for slight offset of the 1.2-m long sleeve in each shielded column with respect to a line between the vacuum vessel flange and the detector. Table II lists the misalignments deduced by obtaining agreement of the model with the measured profiles. The scan profiles for the D-T source were the same as earlier profiles for the ^{252}Cf source,[6] confirming the stability of the misalignments. The similarity also suggests that small-angle neutron scattering down the collimator walls is the same for both sources, and probably negligible compared with the current of virgin neutrons.

Integrating the curves of Fig. 3 over the entire aperture gives the calibrated detector signal per unit chord-integrated neutron emission for that flight tube. The global source strength of a plasma neutron source is obtained by volume integration of the ten detector responses, using a Gaussian fit. The overall uncertainty is ±14% for the NE-451 system and ±15% for the ^{4}He array. The sources of error for the NE-451 measurement are listed in Table III.

During the calibration campaign, a prototype of the second (less sensitive) set of ZnS scintillators[12] was installed and removed to measure the attenuation in neutron flux from the generator to the NE-451 detector below. The attenuation for D-T neutrons was found to be 9±2%. Later, using a plasma D-T source, the complete second set was cross-calibrated to the NE-451 set, taking into account the measured attenuation factor.

The increase in detector signal due to neutrons backscattered from the vessel wall was later determined using small-diameter in-shifted and out-shifted D-T plasmas, similar to the procedure that had been performed with a D-D plasma source.[13] It was found that scattered neutrons contribute up to 7% of the ZnS signal in the central channels, with the proportion rising to more than 20% in the outlying channels. This contribution is subtracted from the measured neutron rate in each channel. The ^{4}He counters with their greater spectral discrimination were much less susceptible to backscattered neutrons, with the latter contributing only about 1% of the total signal.

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FIGURE CAPTIONS

FIG. 1. Plan view of TFTR showing locations of neutron detectors. The fission chambers are located about 1.5 m below the midplane.

FIG. 2. Point-detection efficiency of detector NE-2 vs angle M, the toroidal angle of displacement of the neutron source from NE-2. The two D-T scans with reversed generator orientation are plotted with different markings.

FIG. 3. Normalized NE-451 (ZnS) detector response to radial and toroidal scans of D-T and ^{252}Cf neutron sources across collimator flight tube #6 at R = 2.68 m. Curves are calculated from a ray-tracing model. For each scan the data and curve are normalized to the signal for a sightline without vignetting.

TABLE I. **Fission chamber detection efficiency and uncertainties.**

	NE-1	**NE-2**	**Uncertainty**
Uncertainty in D-T generator source strength			±9%
Statistical error in counts			±2%
Uncertainty in integrating the point-efficiency curve			±1.5%
Global efficiency for D-T	2.94 E-9	5.17 E-9	*±10%*
Correc'n for fluorinert coolant	1.03	1.03	±3%
Final efficiency for D-T, ε_{DT}	2.85 E-9	5.02 E-9	*±11%*
Additional Uncertainties with Plasma Source			
Detector drift			±4%
Counting statistics			±2%
Variation of ε_{DT} with plasma position			±2%
Total uncertainty in count rate measurement			*±12%*
Cross-calib. of count rate mode to current mode			±5%
Total uncertainty in source strength determ.			*±13%*

TABLE II. **Radial and toroidal misalignment of the collimator sleeves.**

CHANNEL NO.	RADIAL MISALIGN. (mm)	TOROIDAL MISALIGN. (mm)
3	1	4
4	6	0
5	4	4
6	8	-1
7	16	-1
8	2	0
9	8	0

TABLE III. **Uncertainties in NE-451 (ZnS) determination of neutron source strength.**

SOURCE OF ERROR	**UNCERTAINTY**
Counting Statistics	±5%
Port Mapping	±5%
Attenuation of Upper Detectors	±2%
Spatial Integral & Cross-Calib. incl. corr'n for scat. neutrons	±7%
Detector Drifts (electronics)	±5%
Aluminum Dosimetry (DT Gen.)	±5%
DT Generator Calib. (other)	±6%
Total Uncertainty in Determ. S_n	*±14%*

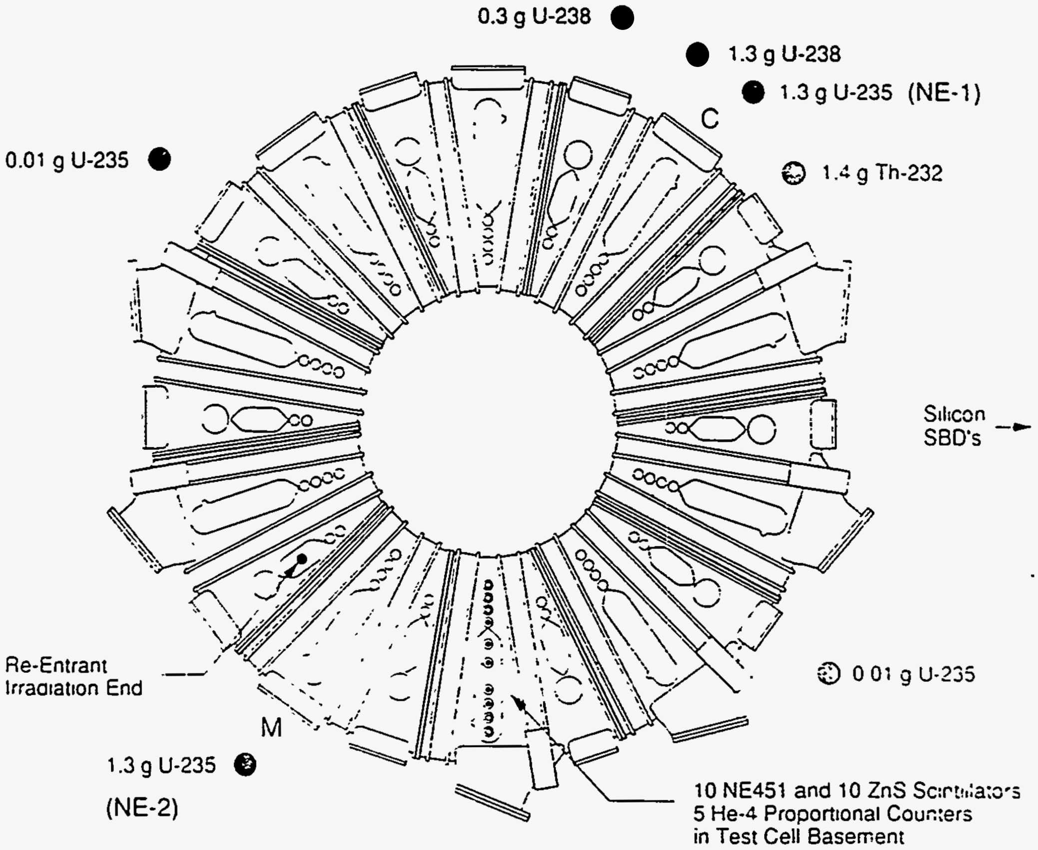

FIG 1 Plan view of TFTR showing locations of neutron detectors. The fission chambers are located about 1 5 m below the midplane.

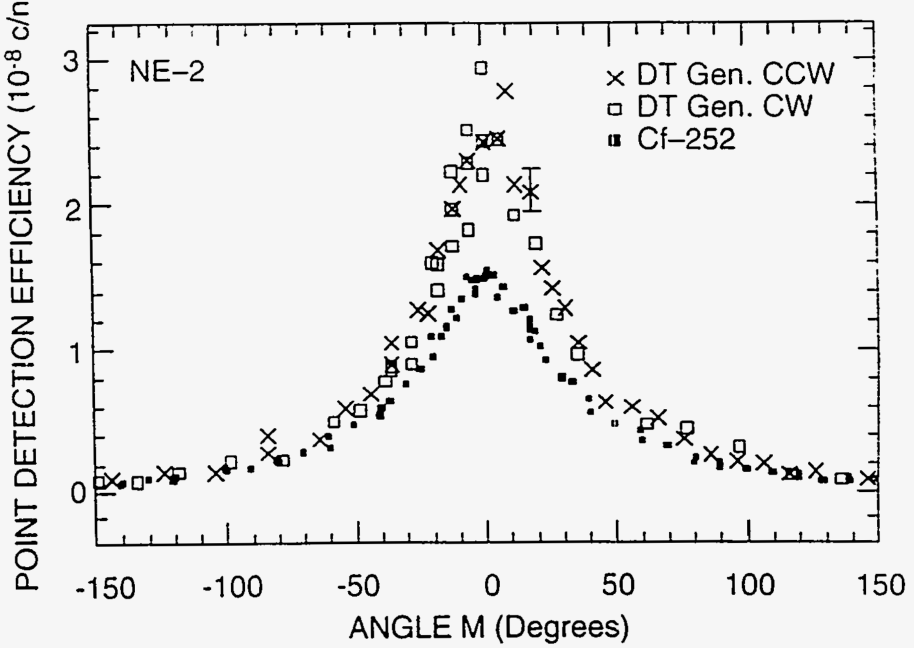
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FIG 2 Point-detection efficiency of detector NE-2 vs angle M, the toroidal angle of displacement of the neutron source from NE-2. The two D-T scans with reversed generator orientation are plotted with different markings.

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