PPPL-2275

UC20-E

PPPL-2275

PPPL--2275

DE86 002543

THREE-DIMENSIONAL MONTE CARLO CALCULATIONS
OF THE NEUTRON AND γ -RAY FLUENCES
IN THE TFTR DIAGNOSTIC BASEMENT AND
COMPARISONS WITH MEASUREMENTS

By

S.L. Liew, L.P. Ku, and J.G. Kolibal

OCTOBER 1985

PLASMA
PHYSICS
LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CEO-3073.

Three-Dimensional Monte Carlo Calculations of the Neutron and γ -ray Fluences in the TFTR Diagnostic Basement and Comparisons with Measurements

S. L. Liew, L. P. Ku, and J. G. Kolibal

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey 08544,

United States of America.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

ABSTRACT

Realistic calculations of the neutron and γ -ray fluences in the TFTR diagnostic basement have been carried out with three-dimensional Monte Carlo models. Comparisons with measurements show that the results are well within the experimental uncertainties.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

I. INTRODUCTION

There are two important milestones in the TFTR experimental plans. One is the demonstration of the DD equivalent $Q \approx 1$ operation scheduled for 1986. The other is the achievement of DT scientific break-even in, perhaps, 1988. It is estimated that these operations will be accompanied by the generation of $10^{16} - 10^{17}$ DD neutrons and $10^{18} - 10^{19}$ DT neutrons per pulse, respectively. The prompt and delayed radiation fields throughout the TFTR facility due to these intense neutron sources necessitate the taking of many precautionary measures to ensure the safety of personnel and the proper functioning of various equipment, particularly the diagnostic and data acquisition systems.

To calculate the radiation levels associated with the neutron generation and to assess their impact on personnel and equipment, computational models and methods of various degrees of sophistication have been used.^{1,2,3,4} The models are different primarily because the appropriate methods and approximations vary according to their intended applications, although some of them represent real changes imposed on the facility, such as the elimination of the igloo shield and the boron coating on some parts of the concrete walls and floors. These models represent suitable compromises between the desire for accuracy and the practical need for computational efficiency. A comprehensive review and comparison of these models has been compiled.⁴

In all these models, major emphasis was placed on calculating the radiation levels in the test cell. The basement area was either totally ignored or greatly simplified by assuming that it was empty and by ignoring the hundreds of penetrations through the test cell floor and the machine substructure.^{1,3}

Various efforts have been made to address separately the effects of the penetrations on the radiation field in the basement. They range from the analysis of isolated major penetrations^{5,6} to the examination of small diagnostic holes.⁷ Since all these analyses have been carried out with simplified geometries to avoid the high cost of modelling the details, some uncertainties are inevitably associated with the results, especially those for the basement area where the important geometrical details are much more difficult to model.

It has not been possible to ascribe exact error bounds to the results because of the complexity of the problem and the lack of accurate experimental data for direct comparisons. Furthermore, it is not entirely clear how small the errors would be even if one includes every possible detail in the models.

Recently, during a series of runs with deuterium plasmas, a set of measurements was carried out in the TFTR basement and data acquisition rooms (DARM) with an NE-213 scintillation detector and a pair of Bonner spheres.⁸ These measurements contributed to the first set of *in situ* experimental data on the neutron and γ -ray fluences that are useful for direct comparisons with the results of radiation transport calculations. In the interest of carrying out the comparisons, we performed a set of three-dimensional Monte Carlo calcu-

lations of the prompt neutron and γ -ray fluences in the basement area at some measurement positions. Details of the calculations and comparisons are given in this report.

II. METHODS OF CALCULATION

A. General Considerations

Given a neutron producing plasma in the TFTR vacuum vessel, the neutron fluence and the associated γ -ray fluence at a particular location in the basement depend primarily on the following factors:

- 1) The layout of the numerous penetrations through the machine substructure and the test cell floor;
- 2) the characteristics of the penetrations, such as their sizes and the extent to which these penetrations are blocked by the filling materials, pipes, cables, etc.;
- 3) the distribution of materials and objects in the basement.

Of these, only the first one can be considered approximately fixed. The other two evolve with the TFTR experimental plans. Thus, one cannot have a static 'universal' model which can determine the radiation level in the TFTR basement at all operational phases.

Even if everything remains unchanged, the complicated geometrical irregularities are still practically impossible to model on present-day computers. One may appreciate the difficulty by looking at Fig. 1, which shows the numerous penetrations through the 1.83 m substructure beneath the machine and Fig. 2, which shows a sketch of some of the structures that can be found in the basement.

The geometry of the facility, particularly the existence of several penetrations, dictates that a realistic model must be fully three-dimensional. At present, the most powerful and highly developed method of handling radiation transport problems in three-dimensional geometry is the Monte Carlo technique, which is also the most time-consuming method. The models that have been used, therefore, represent careful compromises between the desire to model the geometrical details as closely as possible and the need to stay within limited computational resources.

B. The Computational Models

The calculations are grouped into two major categories. The first category is aimed at obtaining the detailed neutron and γ -ray spectra, which are to be compared with the NE-213 measurements. The second category is aimed at obtaining the total neutron fluences above cadmium cutoff (≈ 0.4 eV), which

are to be compared with the Bonner sphere measurements. The models used were rather different because of the different emphases placed on the results.

1. Calculations of the Detailed Neutron and γ -ray Spectra

The basic computational tool chosen for the calculations was the MCNP code.^{9,10} The choice was based mainly on its capability in modelling complicated geometries and the availability of the most recent nuclear cross-section sets. In addition, a working half geometry model of the TFTR tokamak and the test cell had already been created with the code and significant experience had been gained with the model.⁴ Adding the numerous penetrations and the basement would make it a rather complete and realistic three-dimensional model of the TFTR facility.

To achieve reasonable efficiency in the calculations, the TFTR test cell and the basement were modelled in quarter geometry by assuming that there were planes of symmetry along the vertical east-west and north-south planes through the machine center. These planes of symmetry were represented by reflective boundaries. Major components included in the test cell were: the vacuum vessel, TF coils, shear compression panels, inboard assembly, substructure, walls, and ceiling. Major penetrations through the substructure and the test cell floor were modelled as closely as possible. The bathtub penetrations were lined with a 0.635 cm layer of steel. All penetrations were assumed to be completely open. In the basement, the floor and the walls nearest to the machine center were modelled. The basement was first assumed to be empty. It was recognized that this would tend to overestimate the neutron fluence in the MeV region. We were interested in finding what errors would be introduced by this useful simplifying assumption.

The highly irregular structures in the basement were impossible to model in detail without a severe penalty in the computational efficiency. Thus, to approximate the shadow shielding effects due to the steel structures and experimental setups, a homogeneous cylindrical steel shell of reduced density was used. A careful survey of the TFTR basement soon after the measurements led us to model it as the region between 2 and 6 m radially from the machine center and throughout the height of the basement, with 4% normal density. Since the area beneath bay R was relatively clear at the time of the experimental measurements, a cut was made through the steel shell in this bay to approximate the geometry. Figures 3-7 show the various planar cuts through the three-dimensional models. The material compositions used are given in Table I.

Source neutrons were assumed to be emitted uniformly and isotropically from a plasma region of 2.65 m major radius and 0.7 m minor radius. The source spectrum was taken to be Gaussian with a temperature of 2 keV. They were followed from source energy down to 0.75 MeV, which is the nominal lower

energy cutoff in the measurements.

Point detectors were placed at positions corresponding to eight detector locations in the measurements to facilitate comparisons. As given in Table 2 and shown in Fig. 2, four are in the northeast (NE) quadrant and the other half in the northwest (NW) quadrant.¹¹ Since the computer time required was roughly proportional to the number of detectors used, it would be too expensive to cover all the measured locations.

The energy grids were chosen to be the same as the ones used in unfolding the experimental data⁸ in order to facilitate direct comparisons, although the bin widths were known to be narrower than the energy resolution of the NE-213 detector. They are given in Table 3.

The computational efficiency was increased by using the variance reduction techniques of continuous exponential source direction biasing, geometry splitting and Russian roulette, implicit capture, energy and weight cutoffs. In addition, the discrete version of the recommended cross sections (drmcsc3) was used throughout to reduce the computer memory requirement.

Calculation of the DD γ -ray spectrum was also carried out at a single detector location (No. 14) by following the entire histories of the neutrons and secondary γ -photons. The very long running time required prevented us from doing the calculation for more detector positions.

Because of the way the MCNP code handles point detectors with reflective boundaries,⁹ the fluences may be underestimated at some locations, especially those close to the reflective boundaries, e.g., position 10. Thus, the TFTR was also modelled in half geometry as shown in Figures 8-10 to compare with the quarter geometry results.

Since some fraction of DT burn would accompany the DD reactions in a deuterium plasma, calculations were performed for DD and DT sources separately. The composite spectra due to any fraction of DT burn could then be constructed from suitable weighted sums of these results. One can say that all neutrons detected above 2.7 MeV are due to the DT source component because the DD source neutrons could scarcely be born above this energy.

2. Calculations of Total Neutron Fluences above 0.4 eV

The basic tool chosen for calculating the total neutron fluence was the albedo version of the MORSE Monte Carlo code.^{12,13} This choice was prompted by the consideration that if neutrons were followed down to the eV region with the models used previously, it would require more than five times the computer time for each run, which averaged about 100 minutes on the Cray-1 computer for four detectors. Using the MORSE code enabled us to take advantage of the available albedo data base¹⁴ for concrete to achieve great savings in computer time. Since the energy spectra would be of much less interest in this case, the very coarse energy group structure used in the albedo data could be tolerated.

To further simplify the problem, the bathtub penetrations were assumed independent, and the fluence at a particular location was obtained by summing over the contribution due to each bathtub. Thus, a reference model⁵ was set up to include a single bathtub that penetrates the substructure into the basement, defined as a box with lateral dimensions of 26.52 m and a height of 5.48 m. The bathtub was modelled simply as a rectangular slot of 0.356 m $\times$ 1.633 m $\times$ 1.83 m. A planar source was placed on top of the slot with the energy and angular distributions of the neutrons derived from an ANISN calculation^{4,15} which modelled the machine in a one-dimensional spherical geometry. The basement and the penetration were assumed empty.

III. RESULTS AND DISCUSSION

Results of calculations obtained with the above methods are given in the following sections. Where applicable, they are compared with the experimental data.⁸ For convenience, all have been normalized to one source neutron emitted from the plasma.

A. Total Neutron Fluences above 0.4 eV

Following the practice first adopted in Ref. 11, results obtained with the superposition method are plotted as a function of the detector location along with some of the results of measurements using cadmium-covered Bonner spheres, as shown in Fig. 11.

The calculated results are seen to be 20–40% higher. This is consistent with the assumption of an empty basement. The agreement in this case should be considered excellent in view of the rather crude approximations used in the calculations. The main reason behind it is that both concrete and steel are relatively weak absorbers of neutrons in the energy range of interest so that the total neutron fluence is rather insensitive to the distribution of these materials in the basement.

B. Detailed Neutron Spectra above 0.75 MeV

1. Results of Calculations

Figures 12–19 show the results of calculations at the eight detector positions chosen, assuming an empty basement. Figures 20–27 show the results obtained with 4-m-reduced-density stainless steel in the basement.

In each of these plots, the dotted line shows the spectrum due to a pure DD source and the solid line shows the spectrum due to a pure DT source at 2% the intensity of the DD source. The composite spectrum due to a DD shot with 2% DT burn (i.e., 2 DT reactions per 100 DD reactions in the plasma) would then

be the sum of the two. Results obtained from foil activation measurements¹⁶ indicated that the DT burn fraction was $\approx 1 - 3\%$.

We see that the presence of the DT component would not significantly perturb the fluence in the DD region, i.e., below 2.7 MeV. This means that the effects of the DT component can be neglected when we later carry out the comparisons of DD fluences with measured data.

Comparing the two sets of results, we see that the introduction of the steel region in the basement led to significantly softer spectra and lower fluence levels at all the locations. This is due to the fact that inelastic scattering in steel is very effective in slowing down neutrons in this energy range. The slight peak at ~ 1.2 MeV in the DD spectrum at position 14 is mostly made up of DD source neutrons that have made one first level inelastic collision in iron.

It is also interesting to note that the DT peak persists even after the DD peak has become hardly recognizable, e.g., at positions 8, 9, and 10.

2. Comparisons with Measurements

Comparisons are restricted to the DD fluences since the measured data above ~ 5 MeV were found to be contaminated by γ -rays⁸ and were deleted after the peculiar behaviors of the DT peaks were pointed out.¹¹

To facilitate direct and vivid comparisons with the experimental data, the results are again plotted against the radial distances from the machine center. Figures 28 and 29 show the plots for two different energy ranges: 1) 2.0–2.7 MeV, corresponding to the DD source range, 2) 1.41–2.7 MeV, corresponding to the range of measurements. The lower cutoff was chosen as 1.41 MeV. This was because for many locations there were no experimental data below this energy, although the nominal lower cutoff in the spectrum unfolding was set at 0.75 MeV.

The detailed DD spectra calculated with reduced density steel in the basement are plotted along with the experimental data in Figures 30–42.

Figures 28 and 29 reveal the following:

- 1) The neutron fluence generally decreases with the radial distance from the machine center, primarily because most of the neutrons get into the basement by going through the bathtubs, which are clustered around the machine center.

- 2) The fluences calculated by assuming an empty basement are a factor of 2–8 higher than the corresponding measured values, indicating that neutron scattering with the unmodelled structures, most significantly the myriads of steel pipes and beams in the basement, cannot be neglected for neutrons in this energy range.

- 3) By approximating the complicated structures in the basement with a simple homogeneous shell of reduced density steel, the agreement becomes much better. For position 14, the agreement is almost perfect. For position 20, the difference is about 30%. For other positions, if we restrict ourselves to data

taken with ohmic heating (OH) shots, the agreement is within a factor of 2 for 1.41–2.7 MeV, and a factor of 3 for 2.0–2.7 MeV, except for position 8. However, the experimental data for point 8 were obtained from a fluence level of less than 10^2 neutrons/cm² so that the statistics may not be meaningful. It could also be that this detector was sitting behind a concrete column and was therefore seeing a lower fluence than its distance would indicate.

4) In the experimental data, the fluence levels obtained from the OH and neutral beam injection (NBI) shots show significant differences, ranging from 25% to a factor of 3. There is, however, no indication that OH shots would give consistently higher fluence levels per source neutron than NBI shots, or vice versa.

Careful examination of the detailed spectra as shown in Figures 30–42 also reveals that there are significant, though seemingly random, differences between the OH and NBI results. In fact, only the spectra at position 14 measured on February 13 and 14 for OH shots, as plotted in Figures 40 and 41, show true consistency. The calculated spectrum also looks very much the same in the DD peak. However, the January 15 data, although derived again from OH shots, show a markedly different spectrum, as depicted in Fig. 39. In particular, there is a significant shift in the DD source peak. The existence of a prominent peak at about 1.2 MeV, which is higher than the source peak, is most likely an anomaly.

These observations suggest that the experimental uncertainties are not merely those given by the unfolding procedure, as indicated by the error bars in the spectral plots. There were some other systematic uncertainties which would affect the reproducibility of the experimental data. This may have to do with the fact that each spectrum was derived from the cumulative counts of several shots made over a period of hours.

Without a demonstration of true consistency and reproducibility in the measured spectra for at least one location, we do not feel that it is meaningful to compare the detailed spectra and try to explain the discrepancies in the peaks and valleys, especially for locations far away from the bathtubs, where reliable statistics are more difficult to obtain, both computationally and experimentally.

Taking into account all the above observations, we can say that the results of calculations obtained with the models with reduced density steel in the basement are well within the experimental uncertainties. It is not worthwhile to refine the computational models for the comparisons unless the uncertainties in the measurements can first be narrowed down.

3. Comparisons of Half and Quarter Geometry Models

Figures 43–46 show the spectra obtained for positions 6 and 10 with half and quarter geometry models.

When an empty basement is assumed, the half geometry model gives fluences

that are consistently higher than those given by the quarter geometry model, and the differences are more pronounced for position 10, which is closer to a reflective boundary. Thus, the results for an empty basement in the previous section have been under estimated by 20-100%.

However, with the presence of the 4-m-reduced-density steel region, the two models give fluences which are within the statistical uncertainties. The reflective boundaries used in the quarter geometry models, therefore, did not lead to significant under estimation of the fluences in this case. This could be attributed to the fact that the importance of collisions in regions beyond the reflective boundaries had been greatly reduced by the shadow shielding effect of the steel region.

C. Detailed DD γ -ray Spectrum Beneath Bay R

Figure 47 shows the calculated DD γ -ray spectrum at position 14, which is directly beneath the bathtub penetration at bay R, plotted along with the measured spectrum. There are large differences between the two. In particular, the prominent peaks at about 0.5 MeV, 1 MeV, and 2.5 MeV in the measured spectrum are all but absent from the calculated spectrum. One might argue that the peak at about 2.5 MeV is due to the 2.2 MeV hydrogen capture γ -rays in concrete, but this had been taken into account in the model and it would have shown up in the calculated spectrum as well.

One possible cause for the ~ 2.5 MeV peak in the measured spectrum was the proximity of the Bonner sphere to the NE-213 detector during the measurement, so that neutron capture by hydrogen in the polyethylene sphere would lead to significantly higher 2.2 MeV γ -ray fluence at the NE-213 detector.

To examine this possibility, the γ -ray spectrum was calculated with a polyethylene sphere of radius 6.35 cm placed at 15 cm from the detector. Figure 48 shows the spectra obtained with and without the polyethylene sphere. It indicates that the presence of the polyethylene sphere led to a factor of about 2 increase in the 2.2 MeV γ -ray fluence. A larger factor would have resulted had it been placed closer to the detector.

Another contributing factor is neutron capture in the scintillator itself. Although the detector volume is much smaller than the Bonner sphere, it could be just as significant because the γ -photons generated in the detector are more likely to be detected.

The large peaks at about 0.5 MeV and 1 MeV in the measured spectrum are due partially to the annihilation photons generated in the detector assembly and the soft iron shield surrounding the detector.

Hence, to reproduce the recorded γ -ray spectrum at any location, one would have to model all the geometrical details of the detector itself and the objects close to it at the time of the measurement. This was not attempted because of the lack of records of these details and of adequate computer time.

On the other hand, since the measured γ -ray spectra actually include all the significant perturbations introduced by the detector and the experimental setup, they are not representative of the γ -ray spectra at the locations of measurements and should not be used directly without proper corrections for the perturbations introduced by the very act of measurement.

IV. CONCLUSIONS AND RECOMMENDATIONS

The results presented in this report indicate that even for the extremely complicated geometry of the TFTR basement, realistic evaluations of the neutron and γ -ray fluences can be carried out with reasonable accuracy. With proper choice of computational tools and sound judgement on the appropriate approximations used in modelling the complicated geometry, we have obtained results that are well within the experimental uncertainties, as the above comparisons have shown. The real restrictions imposed were the limited time and computer resources available rather than the modelling capabilities of the computer codes.

While the experimental data have provided useful initial guidance in setting up the models, the calculations have served to point out various possible sources of errors and put the data in a proper perspective. These exercises illustrate the usefulness of the computational models and the proper level of confidence that should be attached to them.

Although the models have been set up here specifically for the comparisons, they are also useful for assessing all other radiation-related problems, for example, in estimating the background noise levels and shielding requirements for the diagnostic systems. As the geometry of the facility evolves, the computational models used here can be modified correspondingly to give reasonable estimates for the new configurations. This capability is particularly valuable in evaluating the effects of each step in the evolution *before* it actually takes place.

Further checks on the models could be made by collecting a set of data in the test cell. Higher levels of neutron production in the next series of runs should give better statistics in the measurements. Also, measurements of the γ -ray spectra could be improved by using a NaI detector instead of the NE-213 detector.

ACKNOWLEDGEMENT

This work was supported by the United States Department of Energy under contract No. DE-AC02-76-CHO-3073.

REFERENCES

- ¹L. P. Ku, "Nuclear Radiation Analysis for TFTR," Princeton Plasma Physics Laboratory Report No. PPPL-1711, September, 1980.
- ²J. Kolibal and L. P. Ku, "Prompt Radiation Environment for the TFTR Q=1 Demonstration," presented at the 10th Symposium on Fusion Engineering, Philadelphia, December, 1983.
- ³J. G. Kolibal, L. P. Ku and S. L. Liew, "Two-Dimensional Prompt Radiation Analyses for the TFTR," Princeton Plasma Physics Laboratory Engineering Analysis Division Report, EAD-R-33, 1985.
- ⁴L. P. Ku, J. G. Kolibal and S. L. Liew, "A Comparison of 1-, 2- and 3-Dimensional Modeling of the TFTR Tokamak for Nuclear Radiation Transport Analysis," Princeton Plasma Physics Laboratory Report No. PPPL-2244, August, 1985.
- ⁵J. Kolibal, L. P. Ku and S. L. Liew, "Shielding Analysis of the Major Penetrations through the 1.83 m Substructure of the TFTR," Princeton Plasma Physics Laboratory Engineering Analysis Division Report, EAD-R-26, 1985.
- ⁶L. P. Ku, S. L. Liew and J. G. Kolibal, "A Parametric Analysis of Neutron Streaming Through Major Penetrations in the 0.914 m TFTR Test Cell Floor," Princeton Plasma Physics Laboratory Report No. PPPL-2243, August, 1985.
- ⁷L. P. Ku and J. G. Kolibal, "Neutronic Calculations for the Tokamak Fusion Test Reactor Diagnostic Penetrations," Nuclear Technology/Fusion 2, 313, 1982.
- ⁸F. Y. Tsang, C. E. Clifford and H. Conrads, "Total Neutron Fluence and Spectral Measurement in the TFTR Test Cell Basement and the DARMs," Princeton Plasma Physics Laboratory Technical Systems Division Report, TSD-R-8, August, 1985.
- ⁹Los Alamos Radiation Transport Group, "MCNP - A General Monte Carlo Code for Neutron and Photon Transport, Version 2B," Los Alamos National Laboratory Manual LA-7396-M, Revised (April 1981).
- ¹⁰J. Briesmeister, "MCNP Version 3 Newsletter for NMFECC," Los Alamos National Laboratory memorandum to NMFECC MCNP Distribution, March 22, 1984 (unpublished).
- ¹¹S. L. Liew to R. Little, "Calculations of the TFTR Basement Neutron Fluences and Comparisons with Measurements," Princeton Plasma Physics Laboratory Engineering Analysis Division Memorandum, EAD-885, July 2, 1985 (unpublished).
- ¹²"MORSE-CG: A General Purpose Monte Carlo Multigroup Neutron and Gamma-Ray Transport Code with Combinatorial Geometry," RSIC Computer Code Collection, CCC-203.
- ¹³V. R. Cain and M. B. Emmett, "BREESE-II: Auxiliary Routines for Implementing the Albedo Option in the MORSE Monte Carlo Code." ORNL/TM-

6807, RSIC-PSR-143, July, 1979.

- ¹⁴M. B. Emmett and W. A. Rhoades, "CARP: A Computer Code and Albedo Data Library for Use by BREESE, the MORSE Albedo Package," ORNL/TM-6503, RSIC-PSR-131, October, 1978 (Updated 5/24/82).
- ¹⁵L. P. Ku and J. Kolibal, "ANISN/PPL-C, A One-Dimensional Multigroup Discrete Ordinates Code, A User's Guide," Princeton Plasma Physics Laboratory Engineering Analysis Division Report, EAD-R-11, 1982.
- ¹⁶E. Nieschmidt (private communication).

Material	Element	Atoms/cm-barn
SS-304	Cr	1.738×10^{-2}
	Mn	1.188×10^{-3}
	Fe	6.132×10^{-2}
	Ni	6.793×10^{-3}
Nitronic-33	Si	1.662×10^{-3}
	Cr	1.616×10^{-2}
	Mn	1.105×10^{-2}
	Fe	5.434×10^{-2}
	Ni	2.386×10^{-3}
T. F. Coil	H	4.397×10^{-3}
	B	3.432×10^{-4}
	C	1.840×10^{-3}
	O	4.998×10^{-3}
	Al	2.340×10^{-4}
	Si	1.178×10^{-3}
	Ca	4.212×10^{-4}
	Cu	7.215×10^{-2}
Ordinary Concrete	H	7.830×10^{-3}
	O	4.385×10^{-2}
	Na	1.048×10^{-3}
	Mg	1.486×10^{-4}
	Al	2.389×10^{-3}
	Si	1.580×10^{-2}
	S	5.635×10^{-5}
	K	6.932×10^{-4}
	Ca	2.915×10^{-3}
PPPL-308 Concrete	Fe	3.127×10^{-4}
	H	8.246×10^{-3}
	B	1.097×10^{-3}
	C	1.052×10^{-2}
	O	4.322×10^{-2}
	Na	1.310×10^{-5}
	Mg	1.882×10^{-4}
	Al	2.634×10^{-4}
	Si	1.091×10^{-3}
	S	8.077×10^{-5}
	K	1.386×10^{-5}
	Ca	1.308×10^{-2}
	Fe	1.499×10^{-4}
	Ba	1.245×10^{-4}

Table 1: Atomic densities of materials used in the models.

Measurement Position §	Radial Distance (cm)†	Clockwise Angle (deg)‡
<u>1</u>	1160	312
2	932	318
<u>3</u>	925	328
4	1024	339
5	780	0
<u>6</u>	924	31
7	941	33
8	1109	37
<u>9</u>	850	54
<u>10</u>	734	69
11	731	110
<u>14</u>	215	312
15	1360	293
16	1280	282
17	1277	258
18	1640	248
20	520	312
28	1118	257
29	761	225
30	586	160
31	705	141
32	1376	29

Notes:

§ All positions were 60 cm off the floor, except position 4 which was 310 cm. Positions used in the calculations are underlined. (For some reasons, a last minute change in the detector numbering scheme was made in Ref. 8. We shall retain the original numbering scheme as given in Ref. 11 to avoid re-editing of this report since only the detector coordinates are of real significance.)

† Measured from the major axis of the machine.

‡ Measured from the project north.

Table 2: *Coordinates of the detector positions used in measurements and calculations.*

Group Number	Upper Neutron Energy (MeV)	Upper γ -ray Energy (MeV)
1	15.20	9.40
2	13.32	7.97
3	12.09	7.14
4	9.32	5.17
5	7.40	3.88
6	5.48	2.67
7	4.20	1.92
8	3.10	1.30
9	2.70	1.09
10	2.45	0.97
11	2.25	0.87
12	2.00	0.75
13	1.80	0.66
14	1.60	0.57
15	1.41	0.49
16	1.22	0.41
17	1.03	0.34
18	0.90	0.29
-	0.75	0.24

Table 3: Energy group structures used.

Figure Captions

Figure 1: Plan view of major penetrations through the 1.83 m machine substructure.

Figure 2: Sketch of some major structures that can be found in the TFTR diagnostic basement and the approximate layout of some positions chosen for measurements.

Figure 3: Vertical cut through the quarter geometry model showing the tokamak, test cell, and basement.

Figure 4: Vertical cut through the quarter geometry model showing the major tokamak components.

Figures 5 and 6: Horizontal cuts through the quarter geometry models showing the major tokamak components.

Figure 7: Horizontal cuts through the quarter geometry models showing the major penetrations through the machine substructure and the test cell floor.

Figure 8: Vertical cut through the half geometry model showing the tokamak, test cell, and basement.

Figure 9: Horizontal cut through the half geometry model showing the major tokamak components.

Figure 10: Horizontal cut through the half geometry model showing the major penetrations through the machine substructure and the test cell floor.

Figure 11: Calculated and measured neutron fluences above cadmium cut-off *vs* the radial distances from the machine center.

Figures 12-19: Calculated neutron spectra above 0.75 MeV using the quarter geometry models with an empty basement. The dotted lines are for one pure DD source neutron and the solid lines are for 0.02 pure DT source neutron. The error bars stand for the estimated standard deviations due to statistics.

Figures 20-27: Same as Figures 12-19 except that a 4-m-reduced-density stainless steel region was modelled.

Figure 28: Calculated and measured neutron fluences in the 2.0-2.7 MeV range *vs* radial distances from the machine center.

Figure 29: Calculated and measured neutron fluences in the 1.41-2.7 MeV range *vs* radial distances from the machine center.

Figures 30-42: Comparisons between measured neutron spectra (dotted lines) and the DD neutron spectra calculated (solid lines) with reduced density steel in the basement.

Figures 43 and 44: Comparisons between calculated spectra using half (solid lines) and quarter (dotted lines) geometry models with an empty basement.

Figures 45 and 46: Comparisons between calculated spectra using half (solid lines) and quarter (dotted lines) geometry models with reduced density steel in the basement.

Figure 47: Calculated DD γ -ray spectrum (solid lines) at position 14 compared with the measured spectrum (dotted lines).

Figure 48: Calculated DD γ -ray spectra at position 14 with (solid lines) and without (dotted lines) a Bonner sphere adjacent to the detector.

Fig. 1

Scale:

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Penetrations

Test Cell Floor

B-B VIEW

#85E0101

Scale: 1 m

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Position 9, 4 m SS in basement, 2% DT & 100% DD

Fig. 24

Position 10, 4 m SS in basement, 2% DT & 100% DD

Fig. 25

Position 14, 4 m SS in basement, 2% DT & 100% DD

Fig. 26

Position 20, 4 m SS in basement, 2% DT & 100% DD

Fig. 27

33

34

Position 1, 1/11/85 OH data vs 4 m SS in basement results

Fig. 30

Position 1, 2/19/85 NBI data vs 4 m SS in basement results

Fig. 31

Position 3, 1/10/85 OH data vs 4 m SS in basement results

Fig. 32

Position 6, 1/8/85 OH data vs 4 m SS in basement results

Fig. 33

Position 8, 1/18/85 OH data vs 4 m SS in basement results

Fig. 34

Position 9, 1/17/85 OH data vs 1 m SS in basement results

Fig. 35

Position 9, 1/17/85 NBI data vs 4 m SS in basement results

Fig. 36

Position 10, 1/18/85 OH data vs 4 m SS in basement results

Fig. 37

Position 10, 1/18/85 NBI data vs 4 m SS in basement results

Fig. 38

Position 14, 1/15/85 OH data vs 4 m SS in basement results

Fig. 39

Position 14, 2/13/85 OH data vs 4 m SS in basement results

Fig. 40

Position 14, 2/14/85 OH data vs 4 m SS in basement results

Fig. 41

Position 20, 2/15/85 OH data vs 4 π SS in basement results

Fig. 42

Position 6, empty basement, 1/4 vs 1/2 model results

Fig. 43

Position 10, empty basement, 1/4 vs 1/2 model results

Fig. 44

Position 6, 4 π SS in basement, 1/4 vs 1/2 model results

Fig. 45

Position 10, 4 m SS in basement, 1/4 vs 1/2 model results

Fig. 46

Position 14, 1/15/85 data vs 4 m SS in basement result

Fig. 47

Gamma Spectrum at Pos. 14, with and without Bonner Sphere

Fig. 48

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austri Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. O. Palumbo, Oq XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakanaka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Greenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INF-S-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Badiynski, MPB Technologies, Inc., CANADA
 Chalk River, Nucl Lab, CANADA
 Zhengou Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Korenskeho Univ, CZECHOSLOVAKIA
 The Librarian, Oulham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-BP6, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Mual, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. R.K. Chhajlani, Vikram Univ, INDIA
 Dr. B. Dasgupta, Saha Inst, INDIA
 Dr. P. Kaw, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Direc. Dept. Lg. Tokamak Dev. JAERI, JAPAN
 Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Prof. S. Tanaka, Kyoto University, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itch, Kyushu University, JAPAN
 Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
 Tech Info Division, KAERI, KOREA
 Bibliotheek, Pom-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Lilley, University of Waikato, NEW ZEALAND
 Prof. J.A.C. Cabral, Inst Superior Tecn, PORTUGAL

Dr. Octavian Petrus, ALI (UZA) University, ROMANIA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Plasma Physics, Nucor, SO AFRICA
 Fusion Div. Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. V.T. Toik, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J.M. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universitat, W. GERMANY
 Nuclear Res Estab, Julich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY
 Prof. R.K. Janav, Inst Phys, YUGOSLAVIA