PPPL-3206, Preprint: October 1996, UC-426

REVIEW OF DIAGNOSTIC METHODS FOR TFTR D-T RADIATION SHIELDING AND NEUTRONICS STUDIES*

H. W. Kugel[a)], G. Ascione[a)], J. Gilbert[a)], N. Azziz[b)],
P. Goldhagen[b)], M. Reginatto[b)], P. Shebell[b)], and A. Kumar[c)]

[a)]Princeton Plasma Physics Laboratory
Princeton University, P. O. Box 451, Princeton, NJ 08543
[b))]US Dept. of Energy Environmental Measurements Laboratory,
New York, NY 10014-4811
[c)]School of Engineering and Applied Science
University of California at Los Angeles, Los Angeles , CA 90095

ABSTRACT

The methods and instrument systems used for TFTR D-T radiation shielding and neutronics studies involving signal strengths ranging over 10 orders of magnitude are reviewed. Neutron and gamma dose-equivalent, fluence, spectral, and materials activation measurements have been performed at various locations from the TFTR vessel to the nearest property lines. The detection systems include ^{3}He, BF_3, and ^{235}U proportional counters in moderated spheres, Bonner sphere arrays, advanced thermoluminescent detectors, argon ionization chambers, intrinsic Ge gamma detectors, and activation foil spectrometry methods.

I. INTRODUCTION

The intense fusion power output of TFTR has provided a unique opportunity to perform empirical studies of D-T radiation shielding and neutronics issues. This work, involving signal strengths ranging over 10 orders of magnitude, has yielded experience with the use of diagnostic methods in intense, mixed neutron and gamma, D-D and D-T radiation fields, during high power tokamak operating conditions. Shielding neutron and gamma dose-equivalent measurements [1-5], shielding neutron and gamma spectral measurements [3, 6-9], and D-T materials activation measurements [10,11] have been performed at various locations from the TFTR vessel to the nearest property lines at a major radius of 180 m. This paper reviews the methods and measurement issues involved in this work.

II. EXPERIMENTAL CONDITIONS

TFTR is located in a Test Cell with type T4 concrete walls that vary in thickness from 1.5 m at the floor to 1.2 m at the ceiling, and a concrete roof that varies in thickness from 1.68 m over the vessel to 1.2 m at the edges. The Test Cell geometry is complex with large material density variations produced by the TFTR vessel, auxiliary heating systems, diagnostic systems, and ancillary hardware. The Test Cell outside is surrounded by additional building rooms in the directions of the nearest property lines laying at a major radius of 180 m. The TFTR design objective is to limit the total dose-equivalent at the property lines from all prompt and delayed radiation, including air emissions, to 10 mrem per calendar year. The natural background at the property line is about 80 mrem and has annual variations in the range of $\pm$ 10 mrem. Although the TFTR 10 mrem design limit is relatively small and comparable to fluctuations in the natural background, its direct, continuous measurement is used to determine the total allowable D-T fusion neutron yield per calendar year, facilitates experimental planning, and provides regulatory documentation. Similar measurements are also performed in nearby Control Rooms, work areas, and personnel passageways, where the design objective for workers is 1 rem per year.

TFTR operates in the pulsed discharge mode with ohmic heating pulse lengths of 5 to 10 seconds. The dwell time between pulses is 8 to 15 minutes, depending on the particular experimental requirements. Deuterium discharges, possibly with some mixture of tritium, are initially heated ohmically, and then can be heated additionally by applying D^0 or T^0 Neutral Beam injection with kinetic energies up to 120 keV and total powers over 33 MW. Typically, 1 sec Neutral Beam injection heating pulses are applied at about 3 sec after the start of the ohmic discharge. The particular injection times and pulse lengths vary with the experiment in progress. High performance Neutral Beam heated D-D discharges, produce neutron yields in the range of 1 to 5 $\times 10^{+16}$ D-D neutrons (2.5 MeV). High performance Neutral Beam heated D-T discharges, produce neutron yields in the range of 0.7 to 3 $\times 10^{18}$ D-T neutrons (14.1 MeV).

The D-D and D-T neutron yields produce significant mixed neutron and gamma radiation fields. Inside the Test Cell, the mixed radiation field is dominated by the pulsed neutron radiation and the smaller pulsed gamma component. Also present is an additional small gamma component due to machine activation. This machine activation has intense short-lived and weaker long-lived components and is not detectable outside the TFTR Test Cell.

During D-D operations, inside the Test Cell, the neutron-to-gamma dose-equivalent per yield ratio is in the range from about 10 to 14. During D-D operations, outside the Test Cell, this ratio varies from 0.2 at the North Wall to 0.02 at the NE property Line. During D-T operations, inside the Test Cell at the East Wall, the neutron-to-gamma dose-equivalent per yield ratio is 78. During D-T operations, outside the Test Cell, this ratio varies from about 0.6 at the North Wall to about 1.5 at the NE Property Line.

Additional very small delayed radiation components may eventually occur outside the Test Cell due to exhausted air activated during a discharge, and also due to natural tritium leakage thorough container walls and seals.[3] These airborne radiation components have not been detected to date.

III. EXPERIMENTAL METHOD

During the performance of this work, the preference, whenever possible, has been to perform individual radiation pulse measurements on individual TFTR discharges, (*i.e.*, "differential measurements"), rather than, measurements integrated over many pulses (*i.e.*, "integral measurements"). Differential measurements were synchronized to the TFTR discharge clock, to allow extensive background measurements between discharge pulses, high signal-to-background measurements during the pulse, and avoidance of various low power, testing, and conditioning discharge sequences that may occur during high power experimental operations. All of the measurements outside the Test Cell have been differential measurements. Inside the Test Cell, however, for measurements of the pulsed radiation field, the high dose rate conditions have made it more practical to use integral measurement methods applied during a minimum of 1 day (about 15 hours) to as much as several weeks. In the case of the much lower intensity gamma field from machine activation, standard pulse counting techniques were used during non operating periods.

Given the wide range of experimental conditions under investigation, all differential and integral measurements were normalized per TFTR source neutron, usually either predominantly D-D or predominantly D-T. The TFTR source neutron yields were measured at the vessel, to within experimental uncertainties of about $\pm$15% or less [12]. The total detected counts per discharge, with the measured average background subtracted, were converted to mrem and plotted *versus* the source neutron yield for the corresponding discharge. The results were least-squares-fit to a straight line. The slope gives the mrem per TFTR-neutron. The particular value of this ratio, for a given neutron spectrum, is a constant for a given location, summarizing the intervening effective material density and complex site-geometry. In some cases, the total counts including the background were least-squares-fit to a straight line. In this analysis procedure, the line intercept at the ordinate gives the background during the detection of the pulsed radiation. As a consistency check for possible systematic uncertainties, this background obtained from the least-squares-fit was compared with the average background measured between discharges and found to be equal to within statistical uncertainties. This least-squares-fit procedure demonstrated the direct proportionality of the measured radiation field to the source neutron strength. In addition, the quality of the least-squares-fit provided a monitor on the stability, linear response, and calibration of the detectors over a wide dynamic signal range.

All dose-equivalent calibrations were performed using National Institute of Standards and Technology (NIST) traceable sources of ^{238}Pu/Be for the neutron detectors and ^{137}Cs for the gamma detectors. The calibration procedures were in compliance with the American National Standards Institute (ANSI) standard N323. In addition, radiation check sources were used at appropriate intervals and junctures to verify response and accuracy.

IV. MEASUREMENT SYSTEMS AND SPECIALIZED METHODS

A. Prompt neutron radiation inside Test Cell

TFTR fusion neutron yields are measured in the Test Cell during each discharge with electronic detectors. In principle radiation characterization measurements in the Test Cell could also be performed electronically, however, the need for numerous, portable, neutron and gamma dose-equivalent measurements at many locations over a wide dynamic signal range made electronic methods impractical. These requirements have resulted in the selection of passive dosimeter detectors which sum over all discharges during intervals between access to the Test Cell. In general, daily access to the Test cell was limited to before and after each 11 hour operating day. Hence, the selected dosimeters for a particular experiment required sufficient dynamic range to register a usable signal and yet avoid saturation. An example of the convenience afforded by these integral detectors was demonstrated in obtaining D-D neutron vertical and horizontal radiation profiles involving the simultaneous exposure of 20 or more detectors during the same experimental conditions.[2] These measurements were performed with commercial Landauer [13] "R1" neutron dosimeters (0.5 eV - 10 MeV), each containing a LiF thermoluminescent detector (TLD) and a CR-39 etch track detector. The standard reported lower level of detection was 40 mrem. In addition, for high energy neutron sensitivity, Landauer [13] "E1" Neutron dosimeters with (1 MeV - 50 MeV) Lexan track etch detectors, were used together with the R1 style neutron dosimeters to give a crude spectral measurements.

During D-T operations, the radiation intensities in the Test Cell from D-T discharges can be more than 100 times more intense than during D-D discharges. Under these conditions, the exposure opportunities for commercial dosimeters is very restricted due to the risk of saturation. During D-T operations, commercial Siemens (14) neutron gamma dosimeters with a neutron lower detection limit of 30 mrem and an upper dose-equivalent limit of 5 rem were used. In principle, these dosimeters could be used to characterize radiation profiles for at least 1 low power D-T discharge without encountering saturation. However, as noted above, during D-T operations, access to the Test Cell was not possible until after the 11 hr operating day. Hence, these dosimeters could be used in the Test Cell only at distant locations from the vessel behind shielding. D-T radiation contours were measured with these dosimeters in the NW Personnel Labyrinth during D-T operations.[5,9]

Neutron activation foil techniques have been used extensively in the TFTR Test Cell. A pneumatic transport system takes activation foils to one of four ports at the vessel for exposure and then, provides retrieval to a detector laboratory for gamma spectroscopy measurements. [17] This system provides additional measurements of fusion neutron yield and has been used to initiate long-term exposures of low activation materials for ITER. [4,10] Extensive TFTR neutron spectral activation foil measurements without moderators have been reported by Kumar

[9, 10] Special TFTR neutron spectral measurements using activation foils contained in polyethylene moderator spheres have been reported by Hajnal [6].

B. Prompt gamma radiation inside Test Cell

The Test Cell gamma dosimeter requirements were similar to those for neutrons described above. The need for numerous, portable, gamma dose-equivalent measurements at many locations over a wide dynamic signal range resulted in the selection of passive integral measurements summed over all discharges during a minimum of one operating day. Usually the gamma measurements were performed simultaneously with the neutron measurements. Typically, for example, vertical and horizontal D-D gamma radiation profiles involving the simultaneous exposure of 20 or more detectors during the same experimental conditions were obtained conveniently by exposing commercial Landauer [13] type R1 gamma dosimeters with a detectability threshold of 10 mrem. [2] More recently, Siemens [14] dosimeters with a detectability threshold of 10 mrem, and a saturation limit of 1000 rem for gammas have been used during D-T operations at locations distant from the vessel. [5,9]

A special Al_2O_3 thermoluminescent dosimeter method with high saturation thresholds for application in intense mixed gamma and neutron radiation fields [18] was used to perform gamma dose measurements on the Test Cell east Wall during D-T operations [3]. This work also supported special studies of the D-T radiation effects on fiber optics. [19]

C. Prompt neutron radiation outside Test Cell

At high count rate locations, such as regions of the Test Cell Basement and Hot Cell near penetrations in the shielding, the neutron detectors were ^{235}U fission chamber proportional counter detectors moderated with 25 cm diameter polyethylene spheres. The ^{235}U proportional counters were Reuter-Stokes Model RS-

P6-0805-134, fission chambers containing 0.25 microcurie of ^{235}U and operated at approximately 600 v. These detectors had a lower limit of detection of about 400 nanorem/count. At moderate to low count rate locations, such as from the outer the Test Cell shielding wall and out to the nearest property line, the neutron detectors were ^{3}He proportional counters moderated with 25 cm diameter polyethylene spheres. In the stationary systems, mounted outside the Test Cell shielding wall, the ^{3}He proportional counters, with 4 atmosphere pressure, were LND [15], Model LND-252127, neutron detectors, operated in the range of 1100 to 1400 v as described below. These detectors had a lower limit of detection of about 6 nanorem/count. In the portable systems, the ^{3}He proportional counters, with 4 atmosphere of pressure, were Reuter-Stokes [16], Model RS-P4-0806-207, neutron detectors operated in the range of 1100 to 1400 v as described below. These neutron detector systems had a lower limit of detection of about 4.9 nanorem/count.

These neutron detectors were coupled to conventional NIM pulse counting modules. The optimum operating voltage for all proportional counter systems was determined from a measurement of the characteristic counts -*versus*- voltage plateau curve using a small $^{239}Pu/Be$ neutron check-source. The optimum low level signal threshold was determined from pulse height analysis of the energy spectrum at the optimum operating voltage.

The stationary neutron detection systems, mounted outside the Test Cell shielding wall, were connected via CAMAC modules to the TFTR computer system. The acquired data were archived after each discharge. The portable systems were coupled to NIM scaler modules. These systems were manually zeroed about 5 seconds before a discharge and read immediately afterwards to maximize the signal-to-background ratio. Fig. 1 shows the results of neutron dose-equivalent measurements made with a portable ^{3}He neutron detector system at two locations on the roof above the TFTR Test Cell. The proportionality to neutron source strength is seen and the variation in mrem per TFTR D-T neutron with location.

Neutron fluences and energy spectra were measured using a computer automated multisphere neutron spectrometer with 12 detectors operating simultaneously [7]. The 12 sensors were 2"-diameter BF_3-filled pulse ionization chambers, with one unshielded, one surrounded with a layer of cadmium, and the rest surrounded with cadmium-covered high-density polyethylene spheres with diameters ranging from 7.4 to 30 cm. The responses of the detector assemblies as a function of neutron energy were calculated using the MCNP computer code with ENDF/B-V cross-sections. Spectra were unfolded using the SAND II code. The measurements were performed 1 m outside the Test Cell wall and in a trailer located at a major radius of 120 m.

E. Prompt gamma radiation outside Test Cell

At locations outside the Test Cell shielding, the gamma-ray dosimetry was performed with two types of Reuter Stokes [16], ionization chambers. These detectors were filled with 25 atmospheres of argon and coupled to electrometers. During D-T operations, at high count rate locations, such as, regions of the Test Cell Basement and Hot Cell near penetrations in the shielding, and the roof, low sensitivity units with a range of 0 to 1 R/hr were used. The Lower Limit of Detectability was 200 nanorem/count. At moderate to low count rate locations, such as from the outer the Test Cell shielding wall to the nearest property line, high sensitivity units with a range of 0 to 500 microR/hr were used. The Lower Limit of Detectability was 1 nanorem/count. Both types of ionization chamber were modified to facilitate pulse counting. The output signal RC decay time for a square-wave source was 120 sec.

The stationary neutron detection systems, mounted outside the Test Cell shielding, were connected via CAMAC modules to the TFTR computer system. The acquired data were archived after each discharge. The portable systems were coupled to strip chart recorders that also provided measurements of the background between discharges. Fig. 2 shows the results of gamma dose-equivalent measurements made at two locations outside the TFTR Test Cell using argon ionization chambers. The proportionality to neutron source strength is seen and the variation in mrem per TFTR D-T neutron with location.

TFTR D-D and D-T neutron induced gamma-ray energy spectra were measured over the range from about 0.15 to 10 MeV using a high purity, p-type, germanium gamma-ray detector (41.8% efficiency relative to a 7.6 cm x7.6 cm NaI detector). The spectroscopy system was located at the Test Cell north outside wall and outdoors at a major radius of 120 m. The system used a computer automated data collection system which utilized a timing pulse from TFTR. This set-up provided an ideal signal-to-background ratio because spectra were collected only during discharges. [2, 3, 8]

F. Delayed activated air and tritium release

Activated air products produced in the Test Cell during D-T operations are slowly evacuated. The pacing activity is ^{41}Ar which may require a 5.2 hr exhaust time. This contribution is estimated to be less than 0.7 mrem per calendar year. The near-boundary and boundary gamma ionization chambers have not detected this signal to date. Natural tritium loss is monitored in several ways. A description of this measurement system is given elsewhere [20].

G. Machine activation gamma radiation after operations

TFTR activation is measured and archived every 5 minutes using 3 stationary gamma-ray ionization chambers located around the base of TFTR, about 1 m from the vessel, at about 2 m below the midplane, and at a major radius of 4.9 m. A fourth detector is located near the NW Labyrinth entrance at a major radius of 20 m. These activation detectors are Victoreen [21], Model 845 - Area Monitor, dual-coaxial ionization chambers with 1 atmosphere of argon. These detection systems span an 8 decade range of dose rate, from 0.1 mR/hr to 10^7 mR/hr, and have a gamma-ray detection efficiency that is constant to within $\pm$10% from 80 keV to 3 MeV. Since the activation count rate changes relatively slowly, these detectors are not pulse compensated.

Measurements with high purity, 5 cm diameter, 0.4% resolution portable Ge gamma ray detectors have been performed in the Test Cell to identified the spectral content of the machine activation detected with the ionization chambers. Lead shielding for the detector and waiting for a sufficient cool-down time after D-T operations is necessary to reduce system deadtimes to practical levels.

V. Conclusions

The intense fusion power output of TFTR has provided a unique opportunity to perform empirical studies of D-T radiation shielding and neutronics issues. This work have yielded results and experience with the use of diagnostic methods in intense, mixed neutron and gamma, D-D and D-T radiation fields, during high power tokamak operating conditions that is applicable to ITER and future fusion reactors.

ACKNOWLEDGMENTS

We wish to acknowledge the technical contributions of K. Chase, R. Frankenfield, J. Lehner, C. Szathmary, C. Tilson Jr.
*Supported by USDOE Contract No. DE-AC02-76CH03073.

REFERENCES

1. H. W. Kugel, *et. al.*, Fus. Technology,**19**, 1989 (1991).
2. H. W. Kugel, *et al.*, Fus. Technology, **26**, 963 (1994).
3. H. W. Kugel, *et al.*, Fus. Eng. & Design, **28**, 534 (1995).
4. A. Kumar, *et al.*, Fus. Eng. & Design, **28**, 492 (1995).
5. A. Kumar, *et al.*, Proceedings of the 16th IEEE/NPSS Symp. on Fus. Eng., Champaign, Illinois, Sept.30-Oct.5, 1995.

6. F. Hajnal, in Proceedings of the 11th DOE Worhshop on Personnel Neutron Dosimetry, p. 129, Las Vegas Nevada, June 3-7, 1991, CONF-9106235, PNL-SA-21596, UC-6076.
7. P. Goldhagen, *et al.*, USDOE Environmental Measurements Laboratory, NY, NY, "Measurement of Leakage Neutron Spectra Outside the Shielding of the Tokamak Fusion Test Reactor", presented at ANS Radiation Protection and Shielding Division Topical Meeting, April 21-25, 1996, Falmouth MA, and 1995 Annual Report, pgs., 25-26, USDOE Environmental Measurements Laboratory, NY, NY,10014-4811, to be published.
8. P. Shebell, 1994 Annual Report, EML-571, pg. 25-26, US, DOE, Environmental Measurements Laboratory, NY, NY, 10014-4811.
9. A. Kumar, *et al.*, Fus. Eng. & Design **28**, 415 (1995).
10. A. Kumar *et al,* in Proceedings of 12th Topical Meeting on the Technology of Fusion Energy, June 16-20, 1996, Reno, Nevada.
11. H. W. Kugel, *et al.*, Proceedings of 12th Topical Meeting on the Technology of Fusion Energy, June 16-20, 1996, Reno, Nevada.
12. C. W. Barnes, *et al.*, Rev. Sci. Instrum., **61** (10), 3151 (1990).
13. Landauer, Inc., Two-T Science Rd., Glenwood, IL 60425-1586, USA.
14. Siemens Medical Systems Dosimetry Service, Inc., 2501 Barrington Road, Hoffman Estates, IL 60195-7372, USA.
15. LND, Inc., 3230 Lawson Blvd., Oceanside, NY 11572, USA.
16. Reuter-Stokes, Inc., Edison Park, Twinsburg, Ohio, 44087, USA.
17. E. B. Nieschmidt, *et al.*, Rev. Sci. Instrum., **59** (8), 1715 (1988).
18. N. Azziz, *et al.*, Nucl. Sci. J., **31**, 59 (1994).
19. A. T. Ramsey, Rev. Sci. Instrum., **66**, 871 (1995).
20. G. Ascione, *et al.*, Proceedings of the Fifth Topical Meeting on Tritium Technology in Fission, Fusion and Isotopic Applications, May 28-June 3, 1995, Belgirate, Lake Maggiore,Italy.
21. Victoreen Inc., 6000 Cochran Rd., Cleveland, Ohio, 44139-3395, USA.

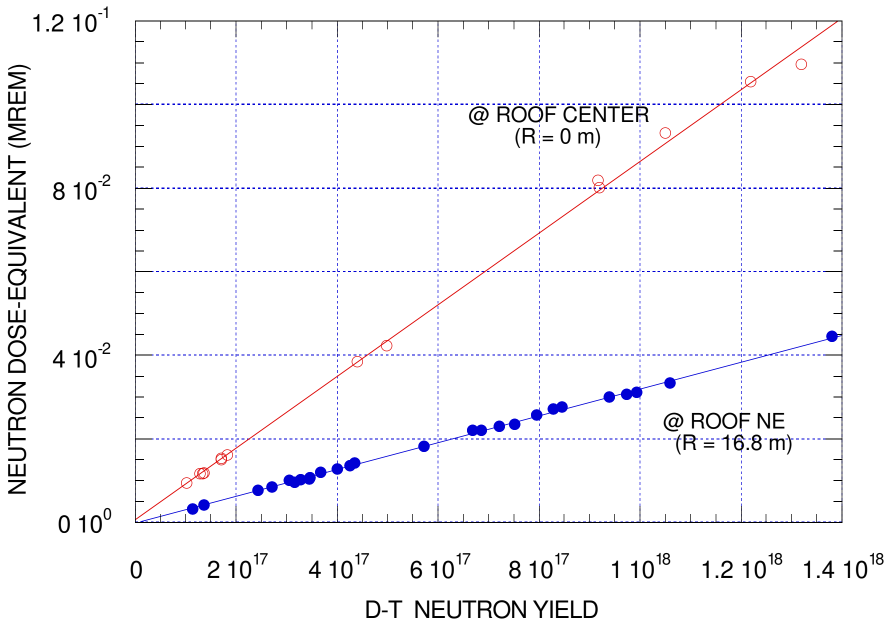

Fig.1. Neutron dose-equivalent (mrem) measured at two locations on the roof above the TFTR Test Cell with a ^{3}He detector system *versus* D-T neutron yield.

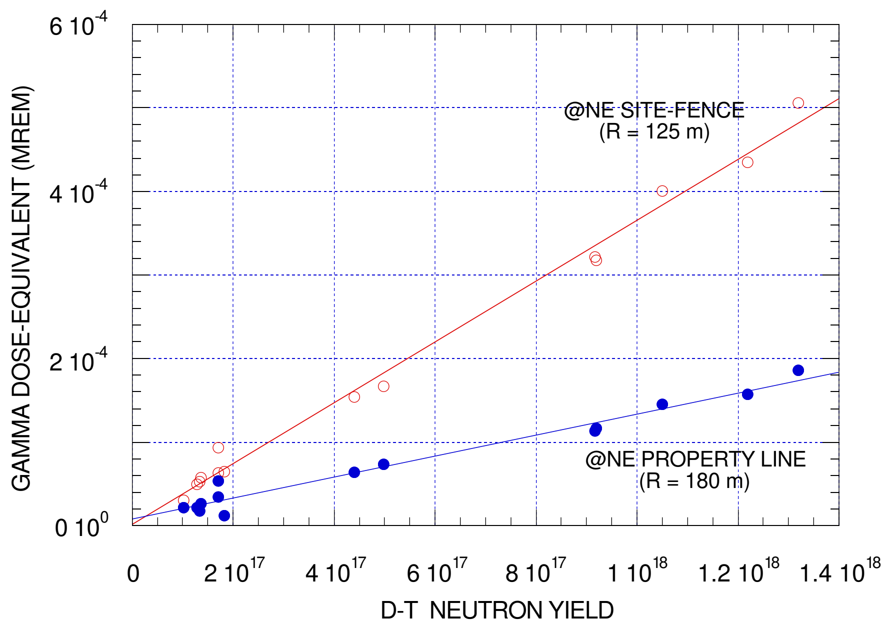

Fig. 2. Gamma dose-equivalent (mrem) measured at two locations outside the TFTR Test Cell with argon ionization chambers *versus* D-T neutron yield.