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BY

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THE TOKAMAK AS A NEUTRON SOURCE

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ABSTRACT

This paper describes the tokamak in its role as a neutron source, with emphasis on experimental results for D-D neutron production. The sections summarize tokamak operation, sources of fusion and non-fusion neutrons, principal neutron detection methods and their calibration, neutron energy spectra and fluxes outside the tokamak plasma chamber, history of neutron production in tokamaks, neutron emission and fusion power gain from JET and TFTR (the largest present-day tokamaks), and D-T neutron production from burnup of D-D tritons. This paper also discusses the prospects for future tokamak neutron production and potential applications of tokamak neutron sources.

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1. INTRODUCTION

This paper describes the tokamak in its role as a neutron source, with emphasis on experimental results for D-D neutron production. Section 2 briefly summarizes tokamak operation. Section 3 discusses the three sources of fusion neutrons, and also addresses non-fusion neutron production in tokamaks and neutron emission features. Section 4 presents the principal neutron detection methods and their calibration and neutron spectra and fluences outside the tokamak vacuum vessel. Section 5 summarizes the history of neutron production in tokamaks prior to the present generation of machines, while Sec. 6 describes neutron emission and fusion power gain from JET (Joint European Tokamak) and TFTR (Tokamak Fusion Test Reactor), the largest present-day tokamaks operating routinely with D plasmas. Section 7 discusses D-T neutron production from the burnup of D-D tritons. Section 8 covers the prospects for future tokamak neutron production, and Sec. 9 discusses potential applications of tokamak neutron sources.

2. GENERAL DESCRIPTION OF THE TOKAMAK DEVICE

In the tokamak magnetic confinement system illustrated in Fig. 1, plasma equilibrium is provided by an externally produced toroidal magnetic field B_t , generally in the range 2 to 7 Tesla, together with a weaker poloidal magnetic field set up by a transformer-induced toroidal plasma current. The resultant helical magnetic field lines map out nested toroidal magnetic surfaces, which confine the hot plasma. The vertical magnetic field acts in concert with the plasma current to exert a force that stabilizes the position of the plasma column. The reader is referred to Ref. 1 for more detailed descriptions of the tokamak.

Ohmic (i.e., resistive) heating by the toroidal plasma current, which can be as large as 5 MA in present-day devices, is sufficient to produce temperatures only up to 2 or 3 keV in hydrogenic plasmas with low impurity content. Temperatures at least several times higher are required for significant neutron production from D-D reactions, or for the fusion power from D-T reactions to exceed the input power heating the plasma. Supplementary heating techniques include plasma compression,² the propagation of electromagnetic waves at various frequencies,³ and neutral beam injection (NBI).⁴ The latter has proved to be the most effective method so far both for heating and fusion neutron production. In

this method, shown schematically in Fig. 2, energetic (≥ 80 keV) ion beams are passed through a gas cell and converted to neutral atom beams, which can readily penetrate the confining magnetic field of the tokamak. Once inside the plasma, the energetic neutrals are ionized and the ions are trapped by the magnetic field. The fast beam ions slow down by collisions with the bulk plasma particles, thereby heating them. To date central ion temperatures T_i up to 35 keV and electron temperatures T_e up to 11 keV have been reached by this method.

Plasma heating by electromagnetic waves has been applied at the ion and electron cyclotron frequencies, as well as at the so-called lower hybrid frequency. However, fusion-neutron production with these heating methods has been well below that obtained with NBI.

High plasma density is important to maximize fusion power output, although the pre-injection target density can be low. But plasma density is limited by the maximum pressure that can be supported by the magnetic field, as well as by the penetration capability of the plasma heating technique. The plasma may be fuelled by gas puffing, pellet injection, or NBI. With Ohmic heating alone, densities exceeding $1 \times 10^{15} \text{ cm}^{-3}$ have been reached using very high magnetic fields (8 - 12 T).⁵ With RF or NBI, typical central densities have been $1 \times 10^{14} \text{ cm}^{-3}$ or lower, although larger densities are possible with pellet injection.

Because the plasma current is transformer driven, tokamak operation is pulsed, with typical pulse lengths of 1 to 10 s. But RF waves at the lower hybrid frequency, as well as NBI, have proved capable of driving significant plasma current,^{6,7} thus opening up the possibility of steady-state tokamak operation.

Tokamak plasmas tend to be plagued by impurity ions evolved from the plasma discharge limiter and vacuum vessel wall. The best plasma parameters and neutron source strengths are achieved only when the impurity ion content is kept to a low level by careful choice of in-vessel materials and by elaborate conditioning routines. Table 1 summarizes the best tokamak plasma parameters achieved by mid-1989.

Table 1. BEST TOKAMAK PLASMA PARAMETERS AS OF MID-1989

PARAMETER	BEST VALUE ACHIEVED	NAME OF TOKAMAK
Max. T_e	11 keV	JET
Max. T_i	35 keV	TFTR
Max. $n\tau_E$	$2 \times 10^{14} \text{ cm}^{-3}\text{s}$ ($2 \times 10^{13} \text{ cm}^{-3}\text{s}$ at the above T_i)	Alcator C, JET, TFTR TFTR
Max. $\langle \beta \rangle$ spatially averaged	0.07	DIII-D
Max. pulse length	20 s	JET

β = plasma pressure / magnetic pressure; τ_E = energy confinement time;
n = plasma density.

3. NEUTRON PRODUCTION IN TOKAMAKS

3.1 SOURCES OF FUSION NEUTRONS IN THE TOKAMAK PLASMA

In this section we consider only plasmas heated by NBI. In these plasmas fusion neutrons are produced not only by reactions between the ions in the heated bulk plasma, but also by reactions between the superthermal beam ions and bulk plasma ions and between the superthermal ions themselves. For a given tokamak and neutral beam system there are basically three different approaches to generating high neutron source strength^{8,9}:

1. *High density n and high $n\tau_E$.* Here thermonuclear reactions (rate = S_{tt}) among the Maxwellian bulk (or target) ions dominate, with beam-target fusion reactions playing a secondary role. ($S_{tt} \propto n_D T_i^\rho$, where $\rho = 2 - 3$, depending on T_i .) This regime is potentially capable of a fusion power gain $Q \gg 1$ (Q = fusion power/ heating power). High beam voltages required for penetrating the dense plasma of large tokamaks may necessitate the use of negative-ion-based neutral beams.

2. *Moderately high density n and moderately high $n \tau_E$.* Here the classical fast-beam-ion slowing-down time τ_s is relatively short, so that the superthermal-ion density n_h is relatively small, and most of the fusion neutron production is due to beam-target reactions (rate = S_{bt}) and thermonuclear reactions. Because τ_s increases with T_e , the probability of fusion while slowing down, and therefore Q , increases with T_e . When S_{bt} is dominant, this regime is often called the TCT (two-component torus).^{8,10}

3. *Low density n and low $n \tau_E$.* Here τ_s is large and n_h/n can exceed 0.2, so that a majority of the fusion reactions are due to reactions between energetic beam ions (rate = S_{bb}); these reactions are called beam-beam self-reactions. The classical τ_s is several times longer than the electron energy confinement time, τ_{Ee} . Although the fusion reactivity drops rapidly with decreasing superthermal beam-ion energy, the superthermal ions must remain confined for several times τ_{Ee} to realize fully the potential neutron yield. When the neutral beams are both co- and counter-injected (relative to the plasma current) with roughly the same magnitude, this regime is sometimes referred to as the CBT (colliding-beam torus).^{8,11}

The transition between the latter two regimes as n is increased is relatively abrupt, because $S_{bb} \propto n_h n_h \langle \sigma v \rangle_{bb} \propto \tau_s^2 \langle \sigma v \rangle_{bb} \propto (T_e^{2p/n^2}) \langle \sigma v \rangle_{bb}$, where T_e also tends to decrease with increasing n . The parameter $p \approx 3/2$ when the energetic ions slow down mainly on the electrons, viz. at low T_e , or at high beam energy E_b , or even at lower E_b when n_h exceeds the bulk plasma (target) density. The parameter p becomes smaller as T_e/E_b increases. Since most of the fusion reactions are produced by fast ions with energies not too far below the injection energy, $p = 1$ to 1.5 tends to be a reasonable value to use in understanding the variation of S with plasma parameters, for both beam-target and beam-beam reactions. This remark applies to the full-energy component of a multispecies beam, which largely determines neutron source strength. The scaling of S on numerous tokamaks, notably PLT, PDX, and TFTR, has provided evidence for the existence of these

different regimes of fusion-neutron production (Sec. 5 and 6).

3.2 SOURCES OF NON-FUSION NEUTRONS IN TOKAMAKS

In the present generation of large tokamaks, with D beam injection into D target plasmas, the beam-driven and thermonuclear fusion reaction rates generally dominate the neutron source strength, and neutron-producing non-fusion reactions may be neglected. However, during low fusion-reaction-rate operation non-fusion neutron production may not be negligible, e.g., in small tokamaks, and in large tokamaks during the initial break-in period (or after a vacuum vessel opening), or during the plasma break-down phase early in a discharge. Plasma disruptions¹ may also generate high non-fusion peak source strength. Such spurious neutron sources¹² are generally due to runaway electrons reaching energies sufficient to overcome the threshold either for electrodisintegration of the nuclei (~2.2 MeV for deuterium) or to produce bremsstrahlung of sufficient energy to generate photonuclear reactions (≥ 6 MeV), often in the limiter.

Runaway electrons¹³ arise because the small-angle, long-range scattering dominating plasma collisional interactions results in a rapid reduction of the momentum-transfer cross section with increasing energy of the electron: When the dynamic friction slowing down the electrons is overcome by the accelerating electric field, runaway can occur for electron velocities above the thermal velocity. For acceleration times of the order of 1 s and loop voltages of about 1 V, electron energies of 2-50 MeV may occur, indicating that the thresholds both of the electrodisintegration (e-n) and photonuclear (γ -n) reactions may be exceeded. Estimates of runaway-electron currents for large, reactor-like tokamaks have generally concluded that the runaway current in steady-state operation will be negligible. However, during the initial gas-break-down phase and during plasma disruptions runaway electrons may play an important role. Experiments designed specifically to study runaway-dominated discharges have been reported.¹⁴

The electrodisintegration cross section for deuterium is 25 μb at 10 MeV electron energy and ~50 μb at 20 MeV.¹⁵ Assuming a runaway current I_r of 10 kA, the (e,n) reaction rate in the plasma is

$$R_{e,n} = \sigma_{e,n}(E) n_D 2\pi R \tau (I_r/e),$$

resulting in $\leq 10^{11}$ n/s, i.e., measurable neutron source strength which could be observed during low fusion-reaction-rate operation. For example,

electrodisintegration neutrons on PLT¹⁶ were found to have source strengths of 10^9 n/s. However, this source strength is many orders of magnitude less than the best values achieved in present large tokamaks (Sec. 6). Neutrons produced by electrodisintegration of plasma impurity ions are less likely due to the higher-energy threshold and the smaller impurity density. In the limiter, the photonuclear cross section for $E_\gamma > 6$ MeV is generally close to two orders of magnitude larger than the electrodisintegration cross section, so that the (e-n) reaction rate is overshadowed by the more intense (γ -n) reaction rate.

The neutron yields produced per electron through (γ -n) photonuclear reactions have been measured directly.¹⁷ The thick bremsstrahlung-target yield for carbon at ~27 MeV electron energy is 10^{-4} and for tungsten at ~12 MeV electron energy is 10^{-3} . Assuming again a 10 kA electron current incident on a wall or limiter, $\sim 10^{11}$ n/s may be produced, depending on materials and electron energy. We note, however, that major plasma disruptions may produce runaway currents up to a MA for milliseconds, as indicated below. Photoneutron production from the plasma will be negligible by comparison. Since photodissociation proceeds through compound nucleus formation, the neutron emission is nearly isotropic. Because the spectrum of bremsstrahlung photons is a continuum in energy, the neutrons produced cover a broad spectrum extending up to the energies related to the difference between the energy of the impinging γ -radiation and the threshold of the (γ -n) reaction. The photoneutron production will be localized near the limiter or wall intercepting the runaway electrons as determined by the forward cone of the bremsstrahlung produced.

Photoneutrons from a tungsten limiter have been observed on PLT¹⁸ during initial operation, with typical source strength of 10^{10} n/s and peak values greater than 10^{12} n/s. In Alcator C¹⁹ photoneutrons were also measured during the start-up phase, when only hydrogen had been used as fill-gas. Up to 10^9 neutrons per shot were observed originating at the limiter, and when the runaway electron production was controlled during later experiments, the observed photonuclear neutron source strengths were typically reduced to less than 10^6 n/s. A study of photoneutron production accompanying major plasma disruptions in JET²⁰ observed peak source strength reaching 5×10^{17} n/s for $\sim 10^{-3}$ s duration, and runaway electron energies exceeding 60 MeV with high-energy electron currents up to 1 MA.

3.3 NEUTRON EMISSION FEATURES

The time evolution and duration of present tokamak neutron sources result from the tokamak size, the method of plasma production, and the type of auxiliary heating. Discharge duration for present large tokamaks is 5 to 10 s, with auxiliary heating during a fraction of this time.

Figure 3 shows the waveform of S for a TFTR shot with Ohmic heating alone, and with fueling D pellets injected.²¹ With pellet injection S increases to a maximum of $\sim 3 \times 10^{13}$ n/s, and then decays over a period of 3 s. (The variations near the peak of S are the so-called sawtooth oscillations, see below.) Similar results (2×10^{13} n/s) were obtained previously on Alcator C.⁵ The increase in S with pellet injection is due to a combination of the increases in D density, absorbed beam power, and global confinement, and of T_i as the ions are more closely coupled to the higher temperature electrons at the higher density. (Only the electrons are heated directly by the plasma current.) JET can produce 10^{14} n/s with Ohmic heating alone²² because the plasma volume is exceptionally large, and the high energy confinement time permits T_i to nearly reach T_e . The presence of impurity ions in JET greatly increases the resistive power dissipation and T_e , and the increased reactivity at higher T_i outweighs impurity-ion dilution of the deuteron population.

Figure 4 shows S waveforms for an NBI shot. On TFTR with NBI, the highest S are obtained for low ohmic-target-plasma density, so that S increases from the Ohmic level of $\sim 10^{10}$ to 10^{11} n/s in approximately 0.5 s to well above 10^{16} n/s. The beam slowing-down time is ~ 0.1 s and the plasma density increases during the 0.5 s neutron source strength rise time due to beam fuelling. With beam turn-off, the source strength decreases first on the time scale of the beam slowing-down time and then on a much slower time scale (e-folding time ~ 0.5 s), which is consistent with the slowing-down time of the D-D tritons. During this later period the neutron production is largely determined by D-T reactions due to triton burnup (Sec. 7). Discharge repetition rates are set mainly by cooling limitations of the magnetic field coils, and are of the order of once every ten minutes.

More rapid time variations of S may be caused by plasma compression,²³ injection of fuel pellets into the plasma,²⁴ and by random MHD activity.²⁵ Periodic variations of S are observed in conjunction with sawtooth oscillations, especially in Ohmic - or

rf-heated, pellet-injected and H-beam-injected plasmas,²⁶ where S is determined mainly by the ion temperature (in contrast to D-beam injected plasmas) and in the presence of fishbone instabilities²⁷ in D-beam-injected plasmas (where the reduced confinement of the energetic beam particles leads to a reduction of the beam-induced reaction rates).

4. NEUTRON DETECTION METHODS IN TOKAMAK RESEARCH

In early fusion experiments, neutron diagnostics were widely used as a measure of progress in the approach to thermonuclear conditions, and neutron source strengths near $10^6 - 10^7$ n/s were reported for a number of devices. However, based on observations of the energy-resolved fluence emitted in different directions, it was soon recognized that in many of those fast, pulsed experiments non-thermonuclear fusion reactions due to the acceleration of deuterons played a role. A review of this early work was given by Glasstone and Lovberg.²⁸

In present large tokamaks using D plasmas, the neutron source strengths are generally determined completely by either Maxwellian reactions in Ohmic plasmas or by beam-produced and Maxwellian reactions in D-beam-injected plasmas.^{8,9} With 30 MW of NBI, up to 4×10^{16} n/s have been measured in TFTR, with fusion power gain $Q_{DD} = 1.6 \times 10^{-3}$, which converts to an equivalent- $Q_{DT} \sim 0.3$ (Sec. 6). This proximity to fusion power breakeven has become a major incentive for precise monitoring of the tokamak neutron source and has resulted in the neutron source strength becoming a major diagnostic indicator for the quality of the plasma discharge. The equivalent- Q_{DT} is the Q that would be realized if half the D beams and plasma were replaced by tritium, with no change in plasma parameters. Typically, $\text{equivalent-}Q_{DT} \approx 200 \times Q_{DD}$, where the factor of ~ 200 results from the higher cross section and reaction energy of the D-T reaction.

4.1 NEUTRON DETECTION TECHNIQUES

Tokamak neutron sources and their temporal and spatial variations may be characterized by four types of neutron measurements:

1. Source strength, S, measurements, to determine the fusion power amplification factor $Q \propto S/P_b$ and, in Maxwellian plasmas, T_i .²⁹ Time

resolution of the order of milliseconds is desirable. Energy resolution is often not required, since generally the plasma composition and, therefore, the type of fusion reaction taking place (D-D or D-T) is known.

2. Energy-resolved measurements, to determine the ratio of D-D and D-T fusion reactions, for example to obtain the burnup fraction (and thus confinement) of the tritons produced in D-D reactions (Sec. 7) or the contributions of both types of reactions in tritium trace experiments. With higher energy resolution, T_i may be determined from the Doppler broadening of the neutron-energy spectral line,^{30,31} in Maxwellian plasmas. Time resolution is desirable.

3. Local fusion-reaction-rate measurements, to determine radial reaction rate profiles (multichannel collimator) and details of the neutron energy spectrum. Generally, spatial resolution requires the use of sizable collimators³² (≥ 1 m shielding thickness) and resolving the neutron energy spectrum may necessitate use of high-energy-resolution spectrometers. Time resolution is desirable.

4. Fast neutron fluctuation measurements with best possible time resolution, to determine effects of instabilities or of variations of the plasma parameters on S taking place on time scales in the μ s range.

As mentioned above, tokamak neutron source strength measurements play a unique role since they determine directly the reactor relevancy of the plasma. Charged fusion reaction product confinement, as indicated by 14 MeV neutrons from triton burnup in D plasmas, is relevant to ignition studies since triton slowing down and confinement should be similar to that of α -particles from the D-T reaction. However, tokamak neutron source strength measurements are complicated by a number of factors:

a) The neutron source strength generated must be measured over a range of about 10 orders of magnitude, from low density, ohmically heated target plasmas (D-D, $\sim 10^{10}$ n/s) to reactor-like plasmas near $Q = 1$ (D-T, $\sim 10^{19}$ n/s), and for the duration of the plasma, 1-10 s.

b) Assuming that we require ≤ 10 ms time resolution, with ≥ 10 counts per time bin, we find that a detector is useful only at $\geq 10^3$ c/s. Assuming also that count pile-up is pronounced at $\geq 3 \times 10^5$ c/s, we conclude that a given detector will cover a range of less than 3 orders of magnitude in source strength. Thus, at least 4 detectors with

different detection efficiencies are required to cover the expected range of neutron source strengths.

c) Count rate effects due to the high γ -radiation background must be negligible.

d) Choice of detector location may be limited by tokamak operational requirements. Scattered neutron fluence will dominate in any practical location outside the vacuum vessel, see Sec. 4.3. (To reduce the contribution from scattered flux, large collimators are required.)

e) Since in fusion research the parameter of interest is the source strength of the plasma and not the fluence measured in the detector location, the detection efficiency (of at least some detectors) should be sufficiently high to allow in situ calibration using a point calibration source of manageable intensity to simulate the extended toroidal plasma neutron source.

The detectors chosen on the JET³³ and TFTR²¹ to monitor the neutron source strength are fission detectors. (A review of plasma diagnostics in large tokamaks, including fusion product methods, is given in Ref. 34.) Fission chambers have the advantage that highly reliable commercial detectors have been developed for fission reactor monitoring. In addition, fission detectors can be used also in the current and (on TFTR) mean-square voltage (Campbell³⁵) modes, to increase the useful count rate range up to an equivalent 10^{10} c/s. The Campbell mode reduces γ -radiation effects on the equivalent count rate by about 3 orders of magnitude.³⁵ Also, the Campbell mode offers the possibility of cross-calibration for the same detector from count rate mode to Campbell mode, for most individual shots where the cross-calibration is desirable, see Sec. 4.2. The TFTR fission detector count rate and source strength ranges covered are shown in Fig. 5. Detectors NE- (for Neutron, Epithermal) 1 to 4 consist of commercial detectors and electronics³⁶ operating in count rate, current and Campbell modes. Detectors NE-5 to 7 use ultra-high sensitivity chambers³⁷ and electronics³⁸ developed at ORNL; the electronics operates in count rate mode only. The detection efficiencies and detector modes have been arranged to give overlap between detectors and redundancy of the measurements. The detectors accessible for direct in situ calibration have been indicated in Fig. 5 and calibration of the detectors will be discussed below.

The ^{235}U detectors, NE-1 and 2 (Fig. 6), are surrounded by (from the outside) a boron layer, a moderator (5 cm polyethylene) and a lead shield (10 cm). The ^{238}U detectors NE-3 and 4 are surrounded by the lead shield only. NE-5 to 7 are not shielded. The detection efficiency of NE-1 and 2 varies by less than 20% for the range from thermal energies to above 14 MeV.³⁹ The detectors are located at different toroidal angles, below the TFTR midplane, radially about 2 m outside the vacuum vessel. Data can be acquired in fast ($\geq 50 \mu\text{s}$ time bins, for ≥ 0.4 s duration) and slow (≥ 1 ms, for ≥ 8 s duration) modes.

Neutron activation systems can be directly calibrated with D-T neutron generators on tokamaks, and have no upper dynamic range limitation. The D-D neutron generator calibration of activation foils requires large fluences, and is difficult on large tokamaks using standard neutron generators.⁴⁰ Both the JET⁴¹ and the TFTR²¹ neutron activation systems use a number of irradiation ends (~ 8) located near the vacuum vessel. A computer-controlled pneumatic transfer system transports the foil capsules from the foil loading station to the irradiation ends and back to the Ge-detectors for γ -radiation counting. Delayed neutron counting also has been used, especially on JET,⁴² to determine total neutron yield per shot, without time resolution. Due to the short half-life of the delayed neutron reactions (1 to 56 s) a simple, automatically operated pneumatic system can shuttle the same (^{238}U) sample between fusion-neutron irradiation and delayed neutron counting stations.

Low-energy-resolution (10 to 30%) detectors can be used to determine the ratio of D-T to D-D reaction rates, in order to measure triton burn-up in D-D plasmas, or to determine the contributions from both types of fusion reactions in trace tritium experiments. If time resolution is not required, neutron activation may be sufficient. High-energy-resolution neutron spectrometers³⁰ can determine T_i from the Doppler width of the neutron-energy line in a plasma dominated by thermonuclear reactions. For a Maxwellian ion-energy distribution of the plasma the neutron-energy-line shape is Gaussian with a $\text{FWHM} = 82.5\sqrt{T_i}$ (keV) (for D-D plasmas) and $= 180\sqrt{T_i}$ (keV) (for D-T plasmas).³¹ Assuming $T_i = 5$ keV, we require a spectrometer energy resolution $\leq 7\%$ for D-D plasmas, and $\leq 3\%$ for D-T plasmas. Neutron spectrometers with these energy resolutions are available.³⁰

However, a number of complicating factors have limited the application of neutron spectrometers. For present Maxwellian (Ohmically heated) plasmas and with available spectrometer detection efficiencies, S and plasma duration are marginal for neutron spectrometry. The best neutron source strengths are obtained in present tokamaks with NBI, where S is determined by beam-target reactions and not by Maxwellian reactions (Sec. 6.2), so that T_i cannot be obtained directly from the width of the neutron energy spectral line. Moreover, the small dynamic range of spectrometers limits their applicability.

Multichannel collimators are used both on JET⁴³ and TFTR⁴⁴ to determine the radial profiles of the fusion reaction rates. A schematic drawing of the JET radial profile diagnostic is shown in Fig. 7. Neutron flux fluctuations are generally detected with high-sensitivity, large-volume scintillators operating in the current mode.⁴⁵ Neutron flux fluctuations ≤ 100 kHz can be detected.

4.2 DETECTOR CALIBRATION

Both on JET and TFTR a number of calibrations of the neutron diagnostics have been performed. On TFTR the calibration program has evolved so that three types of calibrations are now regularly used to determine absolute source strength S and to ensure reliable operation of detectors and electronics: 1) In situ calibrations (with calibration sources *inside the vacuum vessel*) to determine absolute S of the plasma. 2) Cross-calibrations (using the plasma neutron source) to calibrate detectors or detector modes not accessible with the calibration sources and to continuously compare detectors during plasma operations. 3) Renormalizations (using a small calibration source in a well-reproducible location adjacent to a detector, i.e., *outside the vacuum vessel*), to monitor drifts in the detectors or detector electronics.

The conversion from neutron flux measured at the detector location to neutron source strength of the plasma is obtained from in situ calibrations, since neutronics calculations modeling the tokamak details may produce unacceptably large uncertainties. (However, such calculations of the detection efficiency have been reported for TFTR.³⁹ For JET neutronics calculations for the detector assembly only have been given.³³) On TFTR, four in situ calibrations⁴⁶ with ^{252}Cf neutron sources and two with D-D and D-T neutron generators have been performed over 5 years, to determine possible effects on the

detection efficiency due to changes in the tokamak environment and to detector drifts. To simulate the toroidally extended plasma, the calibration point source must be moved throughout the vacuum vessel. In the last TFTR calibration manual transport of the source was replaced by a remotely controlled rail system that allowed toroidal, radial, and vertical motions; about 1000 measurements for different (or duplicate) source locations were taken in this calibration.

The number of counts in a toroidal traverse of the vacuum vessel was close to 10^4 , so that the statistical uncertainty for the line-integrated detection efficiency was $\sim 1\%$. Moreover, since most of the spatial extent of the plasma neutron source including radial and vertical dimensions was simulated in the recent calibration, the volume-integrated detection efficiency could be determined. Based on these calibrations, the neutron source strength S of the toroidal plasma can be obtained with an uncertainty of $\pm 9\%$ near the S range directly accessible with the calibration source. Effects of radial variations of the toroidal-plasma neutron source on the volume-integrated detection efficiency were found to be small, $\pm 2\%$ for ~ 30 cm radial shift. Figure 8 shows typical results for toroidal traverses of the vacuum vessel using a ^{252}Cf calibration source.

During tokamak plasma operations, cross-calibrations are required to extend the direct in situ calibration of the high-detection-efficiency detectors to the detectors with lower detection efficiency, (which can not be calibrated in situ) and to keep track of detector operation. Plasma neutron source strengths must be selected so that the higher-count-rate detector is not affected greatly by pulse pile-up, while the lower-count-rate detector has a sufficient number of counts for good statistics. This requirement sets a limit on the ratio of detection efficiencies ($>10^{-2}$) from detector to detector, so that a sufficient overlap of the count rate modes of both detectors is available for cross calibration.

Assuming that a number of cross-calibrations are involved, the uncertainty of S in the range near $Q = 1$ is expected to be $\pm 13\%$. We note that on TFTR the Campbell mode has been found very useful for cross-calibrations from count rate to Campbell mode on the same detector, which can be performed for every shot that approaches pulse-pile-up for the count rate mode. This includes practically all NBI discharges, and when done for NE-1 and NE-2, gives a good

cross-calibration reaching up to the equivalent- $Q_{DT} = 1$ source strength ($\sim 10^{17}$ n/s) based on the direct calibration of the same detector by a calibration source ($\sim 10^8$ n/s).

Renormalizations of detector efficiency (without access to the tokamak vacuum vessel) were found to be required every few weeks to keep track of detector or electronics variations. (Cross-calibrations which compare two detectors may not indicate which one has changed.) For these renormalizations the calibration source was located reproducibly next to the detector, i.e., outside the vacuum vessel. Over nearly a year, the detection efficiencies obtained by renormalizations for the detectors that can be directly calibrated, NE-1 and NE-2, varied by less than five percent.

Although neutron generators have the advantage of producing a neutron energy spectrum similar to that of the beam-target reaction, the disadvantages of the neutron generator for work in the sensitive tokamak vacuum vessel are its large size, large weight, and its cooling hoses and high voltage power supply cables. Neutronics calculations⁴⁷ have shown that (for ^{235}U detector assemblies similar to those described above) the ratio of D-D to ^{252}Cf detection efficiencies is $1.09 \pm 7\%$, in agreement with measurements.⁴⁶ Moreover, ^{252}Cf sources comparable in source strength to small D-D neutron generators ($\leq 5 \times 10^8$ n/s) can be easily handled manually. For these reasons, ^{252}Cf sources have been used lately more often for calibration in tokamaks than D-D neutron generators. However, a D-T neutron generator may be essential for calibrating detectors with energy-sensitive and/or low detection efficiencies, such as ^{238}U fission detectors and activation foils. The reasons are the greater difference in the ^{252}Cf vs D-T neutron energy spectrum and the higher S obtainable with a (small) neutron generator ($\leq 2 \times 10^{11}$ n/s) as compared to that of a manually well-manageable ^{252}Cf source ($\leq 10^8$ n/s).

4.3 NEUTRON SPECTRA AND FLUENCE OUTSIDE THE TOKAMAK VACUUM VESSEL

An important difference between measurements on a neutron source inside a tokamak and measurements using neutron sources in a lab environment is the dominant effect of neutron scattering off the massive tokamak structures on neutron energy and fluence. In general, the scatterers in a lab neutron experiment can be arranged to suppress

scattering and wall effects for most experiments to nearly negligible levels for small source-detector distances. However, the tokamak neutron source is surrounded by the vacuum vessel (which often contains internal wall cladding), magnetic field coils, diagnostic equipment, and support structures. Due to access limitations, or to effects of the high magnetic field near the vacuum vessel on detector operation, detectors may have to be located radially outside the magnetic field coils. Most neutrons arriving at a major radius outside the field coils will have collided at least once, and probably many times if they have passed through the coil or similar massive scatterers, so that the uncollided fluence may be only a small fraction of the total fluence. The determination of neutron fluences and energy spectra outside the vacuum vessel may be required, not only to obtain neutron source strength or ion temperature from the Doppler broadening of the neutron energy spectral line, but also, for example, to take into account radiation doses to machine components, diagnostic equipment, and neutron fluences in tritium blanket modules. Computer codes developed to compute radiation fluences have been tested against neutron (and γ -ray) data from experiments performed in well-defined, simple geometries.⁴⁸

Measurements of neutron and γ -ray energies and fluences near TFTR have been reported,⁴⁹ utilizing a neutron-generator point source moved throughout the vacuum vessel and a cylindrical organic-liquid scintillator (NE-213) detector with medium energy resolution. The measured neutron and γ -ray fluences and energy spectra exhibit changes as might be expected from the different locations of source and detector and of the scatterers and absorbers. The measured γ -ray fluences are comparable with (and further away from the vacuum vessel even larger than) the measured neutron fluences, indicating the importance of neutron interactions with the tokamak and wall structures. The substantial fraction of capture γ -rays observed indicates the presence of a flux of thermalized neutrons comparable to that of the direct, uncollided neutrons.

Previous measurements on the Princeton Large Torus (PLT)⁵⁰ using a plutonium-beryllium neutron point source to simulate the extended plasma neutron source, and on TFTR⁴⁶ using ^{252}Cf , D-D, and D-T sources, showed a substantially reduced neutron flux at the detector (by about 1/30) when the source was located on the opposite side of the torus (relative to the detector), and also indicated that for a toroidal source $\geq 90\%$ of the total fluence seen by the detector originated in the

near quadrant of the torus. These results were confirmed by the energy-resolved NE-213 measurements.⁴⁹

Detailed neutronics calculations for the TFTR geometry have also been reported, giving the neutron and γ -ray fluxes and energies at the vacuum vessel and in the Test Cell.⁵¹ These calculations indicate that in the region of the outer magnetic coil edge, for a D-D plasma, only about 15% of the total flux falls into the source energy group. Figure 9 shows the calculated neutron flux spectrum at the vacuum vessel for a 10^{18} D-T neutron toroidal volume source, based on MCNP (Monte Carlo Neutron and Photon) and DOT (Discrete Ordinate Transport) codes.⁵¹

Measurements on the JET tokamak,⁵² which has a radiation (shielding) blanket surrounding the vacuum vessel, show that the neutron flux reaching the detectors is due to scattering in the nearest horizontal torus port opening. Contributions along lines of sight penetrating the shielding-blanket structure are found to be negligible. The measurements also show that the total neutron flux at the torus walls including the port openings is much larger than the flux of primary neutrons.

5. TOKAMAK NEUTRON PRODUCTION PRIOR TO THE JET/TFTR ERA

In this section, all neutron source strengths S refer to neutron production in D plasmas, since tritium has not yet been used in tokamaks. (With 50-50 D-T plasmas, S would be expected to increase by a factor of ~ 100 above the measured D-D level, because of the larger D-T cross section.)

In the 1960's Princeton's Model C stellarator had achieved peak S up to 10^8 n/s (3×10^5 n/pulse), with the application of about 1 MW of ion cyclotron heating that produced a non-thermal D population.⁵³ But it was not until the ion temperature T_i reached about 400 eV in the T-3A device at Kurchatov in 1970 that S could be reliably measured in any tokamak. In the ohmic-heated T-3A plasma, $S \sim 10^7$ n/s gave a T_i that agreed with that determined from charge exchange and other methods.⁵⁴ Figure 10 shows the maximum S achieved for different tokamaks as a function of date. With increasing T_i and density, the neutron source strengths from ohmic-heated tokamaks steadily increased, reaching a maximum of 2×10^{13} n/s in MIT's Alcator C in 1984 with pellet fueling.⁵

Meanwhile with the advent of neutral-beam injection (NBI) in 1973, the attainable S was raised substantially relative to the ohmic-heated plasmas of the time. In Princeton's ATC⁵⁵ with 15 keV beams and plasma compression, and in Oak Ridge's ORMAK⁵⁶ with 26 keV beams, S exceeded 10^{10} n/s in 1974. By 1976 the neutron source strength from tokamaks with NBI (ATC, ORMAK, and TFR) finally exceeded the maximum attainable with a straightforward D->D beam/solid-target system ($\sim 2 \times 10^{11}$ n/s). In the period 1977 - 1981, substantial increases in S were realized with increasing beam voltage, beam power and energy confinement times. In 1978 in the beam-injected PLT tokamak,⁵⁷ the total neutron yield per pulse finally exceeded the maximum that had been attained in a dense plasma focus (2×10^{12} n/pulse). In PLT with 2.2 MW of beam power at 36 keV, S reached 1.5×10^{14} n/s (2×10^{13} n/pulse) in 1979, a record that was boosted somewhat to 2.5×10^{14} n/s (2×10^{13} n/pulse) in the PDX tokamak in 1981 using 6 MW of 40 keV beams.⁵⁸ In these D-beam-injected plasmas at least 50% of the neutrons were due to beam-target reactions, but the existence of beam-beam fusion reactions was evident as early as the ATC experiments in 1974.⁵⁹ Neutron spectroscopy gave additional evidence for the thermonuclear origin of the neutrons in the ohmic-heated Alcator A plasma⁶⁰ and the H-beam-heated D plasma in PLT.⁶¹

In tokamaks RF heating has characteristically produced smaller neutron source strengths than generated by NBI. Up to 2×10^{12} n/s were produced in the PLT device in 1982 when heated by 1.2 MW of RF power in the ion cyclotron frequency range.⁶² RF heating in other frequency ranges in numerous tokamaks has been successful mainly in heating electrons, with only modest increases in neutron production.

Neutron source strengths at the 10^{14} n/s level were eventually reproduced in other D-beam-heated tokamaks, such as the ASDEX at IPP-Garching.⁶³ Prior to the JET/TFTR era, the highest S from any magnetic device was achieved by GA's D-III tokamak in 1984,⁶⁴ viz. $S = 1 \times 10^{15}$ n/s at $Q_{\text{DD}} = 1.5 \times 10^{-4}$, using 7 MW of 75 keV beams (together with 0.5 MW of Ohmic heating).

6. PARAMETRIC DEPENDENCE OF D-D NEUTRON SOURCE STRENGTH IN TFTR AND JET

The advent of TFTR and JET in the mid-1980's opened the way for order of magnitude increases in neutron source strength S and neutron

yield per pulse Y in tokamaks. These facilities are also the best diagnosed of all tokamaks. Hence it is appropriate to examine in some detail the parametric dependence of fusion neutron production in JET and TFTR. The detailed characteristics of these machines can be found in Ref. 65 for TFTR and Ref. 66 for JET.

6.1 S AND Q IN TFTR

In TFTR by far the highest S , Y , and Q_{dd} are realized in the neutral-beam fuelled "supershot" regime at moderate I_p and very low pre-injection plasma density.⁶⁷ As far as neutron production is concerned, this regime is so superior to any other (Ohmic, L-mode,⁶⁸ H-mode,⁶⁹ or RF-heated) that here we concentrate on it exclusively. The supershot has highly peaked density profiles and relatively broad temperature profiles, conditions favorable to fusion neutron production. For a given P_b , S for supershot conditions is at least several times that for plasmas with broad density profiles, higher I_p and "L-mode" confinement.

Figure 11 shows S versus beam power for about 500 TFTR supershots.⁷⁰ For the best shots at smaller plasma current, I_p , S increases as $P_b^{1.8}$. The upper envelope of the bulk of the data for higher I_p also increases as $P_b^{1.8}$, but with a slightly smaller coefficient. However, there are some shots at higher I_p that lie on the same curve describing the best lower- I_p data. These shots are characterized by exceptionally high plasma temperature, stored energy, peaked profiles, lower impurity content, and little MHD activity. Slow ramp-up of I_p and P_b shows promise for being developed into a reliable method of reaching the upper curve at high I_p . S also increases roughly as $U^{1.6-2}$, where $U = P_b \tau_E$ is the energy stored in the plasma. This result is expected from the previous relation, because τ_E lies in a narrow range for the best supershots (0.15 - 0.18 s).

The neutron source strength (and other plasma parameters) for shots at the highest P_b usually reach a maximum at about 0.5 s into the beam pulse and then decay despite continuing beam injection because of the influx of carbon from the wall, or sometimes due to MHD

instability activity. At somewhat lower P_b , it is possible to maintain a stable neutron source strength for the maximum length of the beam pulse (~ 2 s). Such operation has produced the highest Y , viz. 2.5×10^{16} neutrons/pulse, corresponding to 20 kJ of D-D fusion energy (Fig. 4).

Figure 12 shows $Q_{dd} \propto S/P_b$ for these same data. The uncertainty in Q_{dd} is about 20%, namely the combined uncertainty in P_b (15%⁷¹) and in S (13%). The best shots are described by two curves which correspond to the two curves on the S vs P_b plot, Fig. 11. (Note that there are a large number of shots with equivalent- Q_{dt} approaching 0.3). The data shown in Figs. 11 and 12 were complete as of October 1988. In December 1988 calibration of the TFTR *baseline* detectors gave a detection efficiency within a few per cent of that previously used. However, exhaustive analysis of the cross-calibration procedures for the less sensitive detectors resulted in an increase of the neutron source strength S during NBI generally of the order of 10%. These changes are not reflected in Figs. 11 and 12.

For a given P_b , there is significant variability in S and Q that depends on the ratio of the beam powers injected co- and counter-tangentially with respect to the plasma current, beam voltage, plasma current, pre-injection target-plasma density, and effective charge $Z_{eff} = \sum n_i Z_i^2 / n_e$, where the summation is over all ion species (including impurities). The following purely empirical scaling law gives the attainable S for TFTR supershots as a function of these parameters:

$$S \approx 1.6 \times 10^{16} \frac{(P_b/14)^{1.8} (E_b/100)^{0.75} (0.75 - 0.35 |BAL - 0.15|^{1.5})}{(n_{pre}/8 \times 10^{12})^{1.5} (Z_{eff}/3)^{0.4}}$$

where P_b (MW) is the total beam power, the power balance parameter $BAL = (P_{co} - P_{ctr})/P_b$, n_{pre} (cm⁻³) is the line-averaged (pre-injection) target density, and E_b the neutral beam (full-energy) voltage in keV, for 80 keV $\leq E_b \leq 110$ keV. Excessive MHD activity in the plasma will degrade S below

the level given by the above formula.

6.2 SOURCES OF FUSION REACTIONS

TRANSP and SNAP computer code simulations⁷² of supershots with P_b in the range 16 to 25 MW show that after about 0.5 s of beam injection, beam-target reactions account for 50 to 60% of fusion-neutron production, with the remainder divided roughly equally between beam-beam and thermonuclear reactions (see Fig. 13a). Figure 13b summarizes SNAP results for shots where the predicted and measured S and other plasma parameters are in good agreement, and the plasma profiles are well known.⁷⁰ S increases by a factor of 7 over this range of P_b , but the beam-target neutron fraction remains essentially constant, the beam-beam fraction decreases somewhat, and the thermonuclear fraction goes up rapidly with P_b . The increasing importance of the thermonuclear component is due to the rise of plasma density and T_i with increasing P_b .

6.3 NEUTRON PRODUCTION IN JET

Up to 20 MW of 80 keV neutral beams have been used in JET. Attainment of the so-called "H-mode" has led to marked improvement in confinement times, but with relatively poor neutron production.⁷³ In H-mode plasmas the improved τ_E is offset somewhat by broadening of $n_e(r)$ and the tendency to increase both the total density and the impurity content-- conditions unfavorable to fusion neutron production.

A low-density partial supershot-like regime where both density and temperature profiles are peaked has been produced in JET and gives S approaching 1×10^{16} n/s.⁷⁴ Nearly similar S have been produced in pellet-fuelled, beam-heated regimes.⁷⁵ Pellet fuelling enables the establishment of a peaked density profile at high density, and is applied immediately before beam injection. Most of S is due to beam-target and beam-beam reactions. Figure 14(a) shows S vs beam power and Fig. 14(b) shows S vs RF power at the ion cyclotron frequency, with and without the effect of pellet injection in both cases. Note that pellet injection seems to have a relatively small effect on the highest S attainable with NBI (beam-target reaction dominated), but pellet injection allows a factor of 5 increase in S with RF heating (thermonuclear reaction dominated).⁷⁵

The input power P_{in} in Fig. 14(a) does not include the Ohmic heating power, which can be as large as 5 MW in JET, decreasing with increasing electron temperature. Hence the total heating power actually scales more slowly than indicated in Fig. 14 (a). Thus $Q \propto S/P_{in}$ increases with injected beam power, but more slowly than the $P_b^{1.8}$ envelope for the best TFTR supershots. For RF heating, Fig. 14(b), Q increases much more rapidly with P_{in} .

One disadvantage of pellet fuelling with NBI is that the high-performance regime is transient, as pellet fuelling during intense NBI has not yet been successful in any large tokamak. This situation might be remedied with future pellet injectors capable of much higher injection velocities.

In operating modes where the RF power can be coupled well to the plasma, combined NBI and RF heating has often led to increased S over that of NBI alone but with no increase in Q_{dd} .⁷³⁻⁷⁴ Using ion cyclotron heating of D-³He plasmas, JET has produced Q values higher than realized to date in beam-injected plasmas.⁷⁶ In the D-³He experiments, the RF waves produce energetic ³He ions with an effective temperature of the tail of the energy distribution well above the optimum one of ~ 500 keV, so that the d(³He, ⁴He)p fusion reactions are in effect beam-target reactions. But the D-³He reactions produce no neutrons, so that these results are not directly relevant to the tokamak's role as a neutron source.

6.4 COMPARISON OF JET AND TFTR NEUTRON PRODUCTION

Table 2 compares the best D-D fusion performance for JET and TFTR as of mid-1989. Recently, in JET S has been increased significantly above the level in Fig. 14(a), using beryllium gettering of the discharge limiter and vessel wall.⁷⁷ Gettering greatly reduces the impurity content of the plasma, and allows highly peaked density profiles as in supershots. In all cases shown in Table 2, there was no RF heating and no pellet injection. TFTR has generated twice the neutron source strength of JET and somewhat higher fusion power gain Q_{dd} .

Table 2. Comparison of Fusion-Neutron Production (Mid-1989)

	<u>TFTR</u>	<u>JET</u>
Max. D-D Source Strength (n/s)	4.0×10^{16}	2.0×10^{16}
Max. D-D Fusion Power (kW)	47	23
Max. D-D Fusion Power Gain, Q_{dd}	1.6×10^{-3}	1.2×10^{-3}
Max. D-D Neutrons Per Pulse	2.5×10^{16}	2.0×10^{16}
Max. D-D Uncollided Flux (n/s cm^2)	4×10^{10}	1.5×10^{10}

While JET can produce a supershot-like mode, TFTR's ability to generate "full-fledged" supershots has enabled it to perform better than JET in the neutron arena despite JET's larger plasma size and current. The ability to produce good supershots stems from TFTR's simultaneous co- and counter-injection, several times higher beam power density (and beam fuelling), and higher magnetic field which reduces unfavorable MHD activity. TFTR's higher beam energy (110 keV vs JET's 80 keV) has also been advantageous for beam-target reactions. (Eventually JET's beam energy will be increased to 140 keV.)

Despite JET's longer beam-pulse capability, the highest neutron production per pulse in JET has been somewhat smaller than the highest in TFTR. At the largest beam powers, both TFTR and JET have shown significant performance degradation after about 1 s beam operation, usually from carbon influx.

7. D-T NEUTRON PRODUCTION IN D PLASMAS FROM BURNUP OF D-D TRITONS

A substantial fraction of the 1 MeV tritons produced by the $d(d,t)p$ fusion reactions in a D plasma is confined by the plasma current in large present-day tokamak plasmas. While slowing down, a small proportion of the tritons react with plasma deuterons to produce 14 MeV neutrons. Measurements of neutrons from triton burnup have been made in several tokamaks since 1978, using liquid (NE213) and glass (Li) scintillation

detectors,⁷⁸ activation foils,⁷⁹ fission detectors,⁸⁰ and a combination of activation foils, NE213 spectrometers and Si surface-barrier detectors.⁸¹

Figure 15 shows typical measurements on TFTR^{80,81} of the time evolution of the neutron source strength of the plasma and comparison with calculations. The neutron source strength increases from the Ohmic level upon NBI turn-on, on a time scale determined by the beam slowing down time, ~ 0.1 s. Concomitant with the neutrons, tritons are produced in the $d(d,t)p$ branch of the D-D reaction. The tritons slow down in the plasma towards the peak in the D-T cross section and burn up in D-T reactions, with the D-T reaction rate rising on the much slower time scale of the triton slowing-down time (~ 0.5 s) to less than 1% of the D-D reaction rate, until beam turn-off. Similarly, after beam turn-off, the beam ions slow down nearly an order of magnitude faster than the tritons, so that about 1 s after beam turn-off the fusion reaction rate is determined largely by D-T reactions. Because ^{238}U detectors are far more energy-sensitive than are ^{235}U detectors, variations in the ratio of the ^{238}U to ^{235}U signals in the post-beam phase can be used to derive an estimate of the time-dependent ratio of D-T to D-D neutron production when this ratio exceeds $\sim 20\%$.⁸² This technique gave a D-T/D-D ratio of the order of 50% or more in the post-beam phase of supershots. Further, it has been shown that extrapolating the slow source-strength decay phase, i.e., the D-T reaction rates, to the time of NBI turn-off, gives a rough measure of the instantaneous fractional triton burnup during the beam phase, based on the (neutron-energy-insensitive) ^{235}U fission detectors.⁸⁰

Measurements of T-burnup on TFTR, using activation foils and NE-213 detectors to measure the time-integrated and instantaneous 14-MeV neutron production, respectively, appear to indicate $(0.5 \pm 0.25 \times)$ lower burnup than expected.⁸¹ On the other hand, recent JET time-integrated results⁸³ based on activation foils and obtained at higher plasma currents, are in agreement with predictions within the $\pm 20\%$ uncertainty for both calculations and measurements.

8. PROSPECT FOR FUTURE D-D AND D-T NEUTRON PRODUCTION IN TOKAMAKS

Table 3 summarizes the maximum neutron source strength and neutron fluxes at the first wall expected for present and proposed large tokamaks.

Table 3. Expected Neutron Production in Large Tokamaks

Name of Tokamak	Expected Neutron Output (n/s)		Uncollided First-Wall Flux (n/cm ² s)		Earliest Operating Date for D-D or D-T
	D-D	D-T	D-D	D-T	
TFTR	1×10^{17}	1×10^{19}	1×10^{11}	1×10^{13}	1993 (D-T)
JET	1×10^{17}	1×10^{19}	6×10^{11}	6×10^{12}	1994 (D-T)
D-III	2×10^{16}	n/a	2×10^{10}	n/a	1989 (D-D)
JT-60	3×10^{16}	n/a	2×10^{10}	n/a	1991 (D-D)
T-15	1×10^{15}	n/a	2×10^9	n/a	1991 (D-D)
Tore Supra	1×10^{15}	n/a	2×10^9	n/a	1991 (D-D)
TSP	3×10^{16}	n/a	3×10^{11}	n/a	1992 (D-D)
IGNITOR	n/a	3×10^{19}	n/a	1×10^{14}	1997 (D-T)
CIT	n/a	1×10^{20}	n/a	1×10^{14}	1999 (D-T)

n/a = not applicable

8.1 PRESENT-DAY LARGE TOKAMAKS

For at least the next 5 years, increases in record neutron source strength will probably come only from JET and TFTR, because no more ambitious facilities are presently under construction.

Substantial increases in S and Q_{DD} in TFTR will require further reduction in target density, minimization of carbon influx during the beam pulse, and maintenance of highly peaked density profiles at $I_p > 1.6$ MA. Attaining the upper curve of S vs P_b (Fig. 11) at the maximum NBI capability of ~ 32 MW would result in 5.5×10^{16} n/s ($Q_{DD} = 2 \times 10^{-4}$). A promising method of reaching this curve is by ramping of I_p and P_b . The ultimate capability of TFTR is about 10^{17} n/s (D-D neutrons), with a corresponding first-wall uncollided neutron flux of $\sim 10^{11}$ n/cm²s. Neutron scattering can multiply this flux by a factor of about 3.

RF power at the ion cyclotron frequency will eventually exceed 10 MW in TFTR. When applied to supershots, the RF power is likely to lead to an increase in S . Whether it also will provide an increase in Q remains to be seen.

JET will eventually operate with 25 MW of RF power at the ion cyclotron frequency range, together with about 20 MW of NBI at 140 keV. Recent favorable results with beryllium gettering open the possibility of JET eventually obtaining much improved fusion performance in non-supershot regimes.⁷⁷ The ultimate JET neutron production capability is comparable with that of TFTR.

Additional neutron shielding has recently been installed on the DIII-D tokamak facility at General Atomics (USA), so that D beams can be used on a regular basis. Preliminary results from a low-density H-mode regime indicate $S > 1 \times 10^{15}$ n/s with 11 MW of 75 keV NBI.⁸⁴ The JT-60 tokamak⁸⁵ at JAERI (Japan) will use D beams in the mid-1990's after a major upgrade of the machine, and in principle could match the TFTR neutron source strengths. The Tore Supra at Cadarache (France) is a superconducting-coil tokamak that will be equipped with 10 MW of D beams. Because this machine will eventually be able to operate with 30 s pulses, the total neutron yield per pulse may be comparable with that of JET or TFTR. The T-15 at Kurchatov (USSR) is another superconducting-coil device; it is intended to operate only with H beams, at least for several years, and therefore with relatively modest neutron production.

Of existing machines, only JET and TFTR may be shielded sufficiently to allow generation of intense 14 MeV (D-T) neutron source strength, but even then D-T operation is uncertain in view of continual postponements in tritium usage. (The short-pulse Soviet TSP device was originally intended for tritium use, but probably will only operate with deuterium.) If D-T fuel were to be used in TFTR, then at least 10 to 15 MW of fusion power would be produced for about 0.5 s, with the corresponding uncollided neutron flux at the first wall nearly 10^{13} n/cm² s.

8.2 IGNITION TEST TOKAMAKS

The proposed CIT⁸⁶ (Compact Ignition Tokamak) in the USA and Ignitor⁸⁷ in Italy are short-pulse copper-coil tokamaks designed to demonstrate the attainment of thermonuclear ignition. While both projects have been approved, actual construction funds have been withheld and there is no prospect of D-T operation before the late

1990's. These two tokamaks would present access problems for neutron utilization, because each is quite compact and surrounded by a liquid-nitrogen cryostat. If the CIT were actually constructed and worked as planned, it would generate more than 1 order of magnitude higher neutron flux at the first wall than TFTR because of the 10 to 20 times higher fusion power, comparable first-wall area, and intensified neutron scattering. The high wall loading ($\sim 5 \text{ MW/m}^2$) is uniquely suited for testing various neutron measurement techniques.

8.3 FUSION TEST REACTORS

In the last decade much effort has been put into the conceptual design of tokamak fusion test reactors such as NET (Euratom), FER (Japan) and ITER (IAEA). Each of these facilities would feature an ignited plasma producing several hundred MW of fusion power and generating neutron fluxes $\sim 10^{14} \text{ n/cm}^2 \text{ s}$ over test areas of several tens of square meters. But each facility would have a capital cost of at least several billion dollars, and at this time technical feasibility is still uncertain. There is no realistic prospect of such a test reactor being available for use within the next 15 years.

9. POTENTIAL APPLICATIONS OF THE TOKAMAK NEUTRON SOURCE

This section addresses the potential practical applications of D-T fusion neutrons from tokamaks that require only a relatively small upgrade in plasma temperature and confinement from the best present-day performance, but with Q as large as 3 and with steady-state operation. The much higher Q compared with the best equivalent- Q_{DT} achieved so far, viz. $Q_{DT} \sim 0.3$, would come from higher-energy beam injectors, smaller impurity content, and a larger, higher-density volume of bulk plasma to enhance thermonuclear reactions. Steady-state operation would require significant advances beyond present practice in particle and heat removal, noninductive current drive by neutral beams or RF waves, and probably the implementation of high-field superconducting coils. Clearly many years of intensive research and development are required before $Q \sim 3$ steady-state operation can be demonstrated.

Design studies show that for applications such as a materials test reactor or isotope production, the neutron wall loading at the outboard midplane should be at least 1 MW/m^2 .⁸⁸ Then trade-offs among electrical

power drain by the beam injectors, particle and heat control, required plasma confinement, and the ability to fuel the plasma and drive the current with beams alone indicate that the optimal Q for a beam-driven system with this wall loading is $Q = 2$ to 3 , a relatively narrow operating window.⁸⁹

9.1 CONCEPTUAL DESIGN

At the present time, the most promising means of producing high neutron source strength from tokamak plasmas is by extension of the supershot regime, so that we will consider this case in detail. Figure 16 illustrates a conceptual engineering design⁹⁰ that specifies steady-state plasma operation in which approximately equal powers of D and T neutral beams are injected to heat and fuel the plasma, drive all the plasma current, and generate fusion by beam-target, beam-beam and thermonuclear reactions. The supershot requirements for short particle confinement time, "wall pumping" and minimal recycling can be satisfied with an unload magnetic divertor. This design concept uses copper toroidal-field coils to reduce size and capital cost, but with the penalty of substantial operating cost because of high electrical power consumption.

Table 4 relates the parameters of the TFTR supershot regime to the plasma parameters and operational mode of a practical neutron source.⁹⁰ In the latter, 150 MW of D and T neutral beams at 250 keV (D^0) and 375 keV (T^0) are injected into 3.5 times the TFTR volume at twice the density and electron temperature. (The ion temperature is about the same.) The combination of higher P_b and Q results in a neutron wall loading of 1.1 MW/m^2 . Plasma fuelling exclusively by NBI is marginal, and might have to be assisted by pellet injection. Plasma current drive exclusively by NBI is feasible, with the "bootstrap" current (as observed in TFTR supershots⁹¹) providing of the order of half the total current.

9.2 SUMMARY OF POTENTIAL APPLICATIONS

1) Radiation Testing of wall materials and blankets for future fusion reactors.⁹² Here the main requirement is adequate neutron wall loading, exceeding 1 MW/m^2 . A related application consists of radiation effects testing and hardening programs for components such as insulators, optics, and electronics for military or other use.⁹³ In

general this application is limited to damage programs for components that are sensitive to integrated radiation dose rather than dose rate. A key advantage of the tokamak neutron source is that much larger test volumes are available than in other types of facilities.

The energy spectrum of the neutrons incident on the outboard test area depends to some extent on the neutrons reflected from the inboard wall. By appropriate selection of the inboard wall material, the outboard neutron spectrum can be made to vary from tokamak quadrant to quadrant and tailored to the test requirement.⁹⁴

2. Hybrid Reactors. Large power application can be achieved in a depleted-uranium blanket surrounding the tokamak plasma.⁹⁵ Because the subcritical blanket can readily give a power multiplication of 8 or 10, a fusion Q of 2 may be adequate for economic electric power generation. The wall loading need be only about 0.5 MW/m² for this application. The equilibrium level of fissile material (²³⁹Pu) built up in the blanket can be adjusted by choosing the coolant type and volume, and in particular can be made comparable to the concentration of fissile material (~1%) in present-day LWRs. A once-through cycle (i.e., no reprocessing) can give at least 10% burnup of the ²³⁸U feed.

3) Isotope Production.

- a) *Net production of tritium.* Neutronics analyses show that with a complete-coverage blanket using a beryllium neutron multiplier, the net production of tritium can be 0.5 atom per fusion neutron, after feeding back 1.0 tritium to refuel the plasma.⁹⁶ A fusion neutron source might eventually serve as a tritium production reactor, a role now played by fission reactors.
- b) *Production of other isotopes* for which there is substantial demand and few sources, such as ⁶⁰Co.⁹⁷ However, it is not yet clear whether a fusion neutron source would be superior to a fission reactor in this application.
- c) *Breeding fissile material* (²³³U and ²³⁹Pu) to be used as makeup fuel for thermal fission reactors.⁹⁸ But this application seems quite uncompetitive with the cost of extracting ²³⁵U from uranium ore.

4) Tokamak-Pumped Lasers. The most straightforward way to use fusion neutrons for laser pumping is to moderate the neutrons and generate energetic ions in a lasing gas by the $^3\text{He}(n,p)$ or $^{235}\text{U}(n,ff)$ reaction. The lasing gas would be contained in an annular cell or array of cells surrounding the tokamak.⁹⁹ While an ignited plasma is needed for this application to be practical, a driven plasma with adequate neutron wall loading can be used to investigate lasing and neutron-conversion systems of interest.

5) Fast Neutron Beams for Research. Directed neutron beams with energy predominantly at 14 MeV can be extracted in beam tubes extending from the plasma chamber.¹⁰⁰

Table 4 FUSION SYSTEM PARAMETERS

	<u>PRACTICAL TOKAMAK NEUTRON SOURCE</u>	<u>BEST TFTR SUPERSHOTS</u>	
PLASMA MAJOR RADIUS	3.9 m	2.5 m	
PLASMA MINOR RADIUS	0.95 m	0.85 m	
PLASMA ELONGATION	1.7	1.0	
MAX. FIELD AT TF COILS	9.8 T	9.6 T	
MAX. FIELD ON PLASMA AXIS	5.0 T	5.2 T	
MAGNETIC FLUX SWING FROM SOLENOID	13 Wb	13 Wb	

NEUTRAL BEAM POWER, D ₀	75 MW	15 MW	
NEUTRAL BEAM POWER, T ₀	75 MW	15 MW	
NEUTRAL BEAM ENERGY, D ₀	250 keV	110 keV	
NEUTRAL BEAM ENERGY, T ₀	375 keV	120 keV	
PLASMA CURRENT	5.5 MA	1.6 MA	
PULSE LENGTH	Steady-state	2 s	
ELECTRON DENSITY (PEAK)	2X10 ¹⁴ cm ⁻³	8X10 ¹³ cm ⁻³	
ELECTRON TEMPERATURE (PEAK)	20 keV	9 keV	
ION TEMPERATURE (PEAK)	35 keV	32 keV	
VOLUME-AVER. TOTAL BETA	5%	1.5%	
FRACTION OF TOTAL PRESSURE IN HOT IONS	1/4	1/3	
ENERGY CONFINEMENT TIME, τ_E	0.35 s	0.17 s	
$n_e(0) \tau_E$ (cm ⁻³ s)	5.5x10 ¹³	1.3x10 ¹³	
Z _{eff}	1.5	2.5	

		<u>EVENTUAL D-T STATUS</u>	<u>1988 STATUS*</u>
FUSION GAIN, Q	2.4	1.0	0.3
TOTAL FUSION POWER	360 MW	30MW	9 MW
NEUTRON WALL LOADING (MW/m ²)			
-SPATIALLY AVERAGED	1.1	0.20	
-AT OUTBOARD MIDPLANE	1.3	0.25	

* D-T equivalent of actual D-D performance.

10. CONCLUSIONS

In the last 20 years, the tokamak neutron source has evolved from a device with barely measurable neutron emission to one that produces up to 4×10^{16} n/s (47 kW fusion) in D plasmas. This source strength is equivalent to about 5×10^{18} n/s in a D-T fuel mixture, which is 5 orders of magnitude larger than achievable with an accelerator-based solid-target system. Neutron detection methods have been adopted from fission reactor instrumentation, but detector calibration in the tokamak environment has presented new challenges. The development of high-power neutral-beam injectors over this period was an essential component in the increase in neutron production. While the beams are effective in producing high plasma temperature and consequently large thermonuclear fusion yield, the majority of the neutrons still comes from beam-target (and beam-beam) reactions. In today's largest tokamaks, maximum neutron source strength is obtained either in moderate density beam-dominated plasma regimes, where the beams provide all fueling and heating, or in denser plasmas with pellet injection that may have radiofrequency heating in addition to beam injection.

While the tokamak is by far the most advanced magnetic-confinement fusion neutron source, for practical applications it presently falls far short of what can be done with fission reactors or steady-state accelerators. The principal roadblock to practical applications is the present low duty factor, which results from the use of highly resistive magnets, short-pulse neutral-beam injectors, and lack of methods for steady-state heat removal, particle throughput and impurity control. These problems may be overcome in the future with superconducting magnets, steady-state beam injectors, and new techniques for heat and particle removal. All these advances are under development, and may permit deployment of useful tokamak neutron sources of smaller size than would be needed for power reactors.

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Fig. 1 Basic components of a tokamak confinement system.

Fig. 2 (a) Components of neutral beam injector system and (b) plan view of neutral beam injection geometry.

#89X0525

Fig. 3 Neutron source strength vs time for TFTR ohmic plasma with and without D-pellet injection.

#89X0325

Fig. 4 Neutron source strength vs time for TFTR beam-injected plasma.

Fig. 5 TFTR fission detector count rates vs neutron source strength. Ref. 21.

#81X0524

 ^{235}U FISSION DETECTOR

Fig. 6 Schematic of a ^{235}U detector assembly on TFTR. The outer diameter of the moderator is 40 cm and its length 80 cm. Ref. 46.

Fig. 7 Schematic of the JET 19-detector-channel neutron profile monitor.
Ref. 43.

Fig. 8 In situ point-detection-efficiency of a ^{235}U detector vs toroidal position of point neutron source in TFTR.

Fig.9 Calculated neutron flux vs energy outside the TFTR vacuum vessel. Results are shown for different codes and different models. Ref. 51.

Fig. 10 Maximum D-D neutron source strength achieved in tokamaks vs date, for ohmic, NBI and RF heated plasmas.

Fig. 11 Neutron source strength vs injected neutral beam power for TFTR, for different plasma current I_p . The data show the peak S during the beam pulse.

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Fig.12 Fusion power gain Q_{dd} for the discharges shown in Fig. 11.

Fig.13 Calculated fractional contribution of beam-target, beam-beam, and thermonuclear fusion reactions (a) vs time during a shot, and (b) vs beam power, for TFTR.

Fig. 14 JET neutron source strength S (a) vs injected neutral beam power (M. Gadeburg, priv. comm.), and (b) vs RF power, Ref. 75. The data show the peak S during the beam or RF pulse.

Fig.15 Comparison of measured neutron source strength (Sum of 2.5 MeV + 14 MeV neutrons) with calculated D-D and D-T source strengths. The instantaneous triton burnup is $S_{14}/S_{2.5}$ at the time of beam turn-off. Ref. 80.

89X3204

Fig.16 Elevation view of conceptual design for a steady-state tokamak D-T neutron source. Ref. 90.