NEUTRON EMISSION FROM TFTR SUPERSHOTS

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Empirical scaling relations are deduced describing the neutron emission from TFTR supershots using a data base that includes all of the supershot plasmas (525) from the 1990 campaign. A physics-based scaling for the neutron emission is derived from the dependence of the central plasma parameters on machine settings and the energy confinement time. This scaling has been used to project the fusion rate for equivalent DT plasmas in TFTR, and to explore machine operation space which optimizes the fusion rate. Increases in neutron emission are possible by either increasing the toroidal magnetic field or further improving the limiter conditioning.

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1. INTRODUCTION

One goal of the TFTR experimental research program is to achieve scientific breakeven wherein the fusion power produced equals the power required to heat the plasma. Presently, the highest performance TFTR deuterium plasmas are the supershot plasmas [1] which have produced equivalent Q_{DT} values $\approx 1/3$ [2] (where “equivalent” is a projection that is defined in Sec. 8). Clearly, there is a need to operate the supershot plasma in a manner that will further optimize its fusion performance.

This paper evaluates the statistical dependence of the $d(d,n)^3\text{He}$ fusion neutron emission from TFTR deuterium supershots upon the TFTR machine settings (e.g., plasma current, toroidal magnetic field, neutral beam power, etc.). Empirical and physics-based scaling relations are derived and compared to the neutron emission as well as to that predicted by one-dimensional transport codes. The supershot neutron emission is described in terms of a zero-dimensional model which identifies the variables related to the underlying physics of the fusion reactions. This model was used to evaluate equivalent fusion rates for DT plasmas and to suggest machine conditions for optimal performance.

The analysis indicates that the primary limitation of the TFTR supershots is the apparent β -limit of the supershots when the plasma energy content is about 0.8 of the Troyon value [3]. Above this limit, TFTR supershots experience some disruptions. Even sporadic disruptions make experiments in the supershot regime difficult due to the sensitivity of supershots to the wall conditions. Another conclusion from the statistical analysis is that the deuterium neutron emission was independent of the neutral beam voltage (from 85 kV to 105 kV). However, considerable improvement was achieved by conditioning the walls with lithium pellet injection. A further improvement is projected by increasing the toroidal magnetic

field.

The organization of this paper is first to describe the database. Scaling relations are then derived for the neutron emission based upon entirely empirical regression analysis. The measured neutron rates are then compared with those predicted by one-dimensional transport calculations. A zero-dimensional model for the neutron emission is then derived. TFTR supershot scaling for the relevant plasma parameters that describe the classical physics of the fusion reactions are derived. From these scalings and the zero-dimensional model, the equivalent DT performance is deduced and an evaluation is made of the machine settings for optimal production of fusion power in TFTR supershots.

2. TFTR DATA

The data used to derive the neutron scaling laws arise from 525 supershot plasmas from the 1990 campaign [2]. All of these plasmas had a major radius of 2.45 m (and a minor radius of 80 cm), since it was experimentally determined that at constant plasma current, toroidal magnetic field, and neutral beam power, the 2.45 m major radii plasmas produced the highest neutron emission [4]. Major radius scaling of the supershots is not further described in this paper.

These data sets represent nearly all the supershot attempts from the 1990 campaign to optimize the neutron emission through application of up to 32 MW of neutral beam heating and by elimination of high carbon influx (blooms) by use of a new carbon-carbon composite limiter [5,6]. The use of a new limiter as well as the attempt to maintain diagnostic cohesiveness discouraged the inclusion of pre-1990 supershot data. It is difficult to establish whether the present limiter is similar to previous limiter configurations in terms of its impact

on supershot performance (presumably through recycling).

The only $R = 2.45$ m supershot data from 1990 not included in this study were those that suffered neutral beam faults within 0.1 sec of the peak neutron emission. Approximately 5% of the TFTR plasmas were not included by this criterion. Further, a criterion that τ_E be larger than 1.5 L-mode was used to eliminate a few plasmas which, due to inadvertent wall conditioning (e.g., preceded by a disruption), were actually more like L-mode plasmas.

The data base recorded the parameters in Table 1 at the time of peak neutron emission for each plasma. This means that $\frac{dE}{dt}$, although small ($\lesssim 2$ MW), was not zero. Then, this study differs from most TFTR studies (e.g., [16]) where the data are usually recorded at maximum energy content. The timing difference did not significantly change the empirical scalings of the fusion reaction rate.

3. EMPIRICAL SCALING OF NEUTRON EMISSION

Regression analysis of the experimental neutron emission with the available plasma parameters indicates (Fig. 2)

$$S_n = (0.32 \pm 0.02) E^{2.00 \pm 0.01} I_p^{-0.58 \pm 0.03} \equiv S_{EMP1}, \quad (1)$$

where S_n is the measured neutron emission (10^{16}s^{-1}), E is the plasma energy content (MJ), and I_p is the plasma current (MA). The uncertainties are the least square fit errors as if the other variables had exactly determined coefficients, and there were no uncertainty in the data points. This is principally the scaling observed previously in TFTR [16] except now, a significant plasma current dependence (Fig. 3) has been observed which probably also applied to the earlier TFTR data. Alternatively, we can express the energy content in

terms of the applied power and the energy confinement time so that

$$S_n = (0.39 \pm 0.04) P_B^{1.79 \pm 0.02} \tau_E^{1.87 \pm 0.04} I_p^{-0.32 \pm 0.04} \equiv S_{EMP2}, \quad (2)$$

where P_B is the applied beam power in MW, and τ_E is the energy confinement time in sec. This formulation is similar to the representation [7,17] where neutron emission has been plotted as a function of beam power (Fig. 4), and the best TFTR results occurred with $S_n \propto P_B^{1.8}$. Since supershot confinement time is independent of beam power [16], the neutron emission at maximum τ_E is proportional to $P_B^{1.8}$. In previous publications [17], it was recognized that there was an improvement in neutron emission at low plasma current which we now call out explicitly in Eq. (2). The exponent $(P_B \tau_E)^{1.8}$ in Eq. (2) is different than the exponent E^2 in Eq. (1) probably due to the modest time evolution of the plasma (see Fig. 1).

Both empirical scaling laws [Eqs. (1) and (2)] have very tight fits to the experimental data (e.g., Fig. 2) with $S_{EMP1}/S_n = 1.00 \pm 0.07$ and $S_{EMP2}/S_n = 1.00 \pm 0.07$. Presumably, this occurs because the neutron emission is directly related to the energy content of the plasma. It has been speculated [18] that $I_n \propto E^2$ occurs if the electron energy content is small or proportional to E , then

$$E \propto E_e + E_b, \quad (3)$$

so that

$$E^2 \approx E_i^2 + 2E_i E_b + E_b^2, \quad (4)$$

while

$$S_n = \left(\frac{n_i^2}{2} \langle \sigma v \rangle_{TN} + n_i n_b \langle \sigma v \rangle_{BT} + \frac{n_b^2}{2} \langle \sigma v \rangle_{BB} \right) Vol, \quad (5)$$

so that $S_n \propto E^2$ was a consequence of $\langle \sigma v \rangle_{TN} \propto T_i^2$. Here, $\langle \sigma v \rangle_{TN}$, $\langle \sigma v \rangle_{BT}$, and $\langle \sigma v \rangle_{BB}$ are the reaction rates for the thermonuclear, beam-target, and beam-beam

neutron emissions and the later two depend only upon beam voltage. However, the TFTR supershots in 1990 have $E_e \simeq E_i$, and thus, the proposed simplification, Eq. (3), does not apply. The time evolution of individual shots indicates only 20% deviations from $S_n \propto E^2$ so that even without justification, Eqs. (1) and (2) describe a wide range of supershot behavior.

The empirical scaling expression in Eq. (2) indicates that, at a particular plasma current, it is equivalent to increase either the beam power or the confinement time in order to increase the neutron emission. In either case, the limiting neutron emission will be determined by the maximum allowed plasma energy which is apparently related to the Troyon limit. That limitation forces an increase in the plasma current until the maximum beam power and maximum confinement time are below the Troyon limit. Ultimately, Eq. (2) indicates that attempts to improve the confinement time or the beam power need to be accompanied with attempts to increase the stability limits. Alternatively, operation at higher confinement time needs to occur at lower beam power.

It is noteworthy that Eqs. (1) and (2) are insensitive to parameters such as beam voltage, W_B (Fig. 5), the beam sense, C_{NB} (Fig. 6), the density peakedness, F_n (Fig. 7), and the central beam deposition parameter, $H(0)$ (Fig. 8). In other words, the only way that these parameters influence the neutron emission is through their influence on the confinement time. The lack of beam voltage dependence (Fig. 5) is explained (see Sec. 5) by the reduced particle source rate and neutralization of the full energy component with increased W_B [19]. Similarly, C_{NB} is expected to impact the relative velocity in the beam-target reactivity via rotation as it is thought to do for co- only injection in low density plasmas. The density peakedness might be expected to impact the thermonuclear neutron emission, and $H(0)$ might be expected to impact the beam-beam neutron emission. Apparently, these parameters also influence the neutron emission primarily through the confinement time. The possibility

exists that correlations might show up if the experiments were carried out as individual scans in a controlled experiment (which was not done in 1990).

It is also interesting to examine the influence of some of TFTR operations on the empirical neutron scaling (Fig. 9). The plasmas enhanced by the lithium pellets [20] tended to have both higher τ_E and higher neutron emission, while the shots that immediately (within 3 shots) followed helium conditioning [21] sequences tended to be lower in both. Presumably, the lithium and residual helium are influencing the confinement time through the recycling and plasma-wall interaction in the manner that typically has been observed to influence supershots [6], but the neutron emission is influenced only through the confinement time. However, for the 20 shots following the boronization [22], there was $\sim 10\%$ higher neutron emission for the same confinement. Possibly, the boron played a role in reducing the impurity content, and thus influenced the neutron emission level separate from τ_E . Although the enhancement is only about 10%, it is statistically significant (Fig. 9). Z_{eff} was not measured for the plasmas following the boronization; however, the remaining supershot plasmas exhibited no explicit dependence of S_n/S_{EMP1} on Z_{eff} (Fig. 10). We have no explanation for these observations.

4. ONE-DIMENSIONAL TRANSPORT CALCULATIONS

In this section, the measured neutron emission is compared with that calculated by the one-dimensional transport code, SNAP [23]. SNAP deduces the transport coefficients for a plasma presumed to be in equilibrium with the measured $T_e(r)$, $T_i(r)$, and $n_e(r)$. In the analysis reported here, Z_{eff} was assumed to be constant in radius, and its value was determined from a single chord visible bremsstrahlung measurement. The Z_{eff} is assumed

to be composed of carbon and a high-Z (mostly iron) contribution measured by soft X-ray pulse height analysis. The principal assumptions in the SNAP calculation of the neutron emission are that the beam ions are deposited radially by the atomic processes of charge exchange and ionization by collision with electrons, thermal ions, and beam ions and do not radially transport while they thermalize classically. Of the 525 supershots available from 1990, 118 have had SNAP analyses. These 118 shots were obtained from a subset of about 220 shots that included a plasma current scan at constant beam power and a beam power scan at constant current. The 118 SNAP runs represented those shots out of the 220 with complete diagnostic data sets.

The SNAP-calculated neutron emission is proportional to the measured value (Fig. 11) with $S_n^{SNAP}/S_n \simeq 0.90 \pm 0.10$. With this agreement, we conclude that the neutron emission can be described by the assumptions that the beam deposition, slowing down, and confinement are classical. The approximate 10% deviation may be due to the equilibrium nature of the SNAP calculation when, in fact, the experiment is slowly evolving. The few cases of maximum neutron emission that occurred late (0.7 to 0.9 sec) in the beam heating had better agreement with experiment than the more typical $0.4 \rightarrow 0.5$ sec.

The plasma energy content is well predicted by SNAP ($\frac{E_{SNAP}}{E} = 0.99 \pm 0.04$) (Fig. 12). The deviations of the SNAP-calculated neutron rate from the measured neutron rate correlated with the deviations of the SNAP-calculated total energy content from the magnetically measured energy content. This suggests that measurement uncertainties of the plasma parameters (T_e , T_i , Z_{eff}) are contributing to the scatter in the ratio of predicted to measured neutron emission. Thus, the deviations of the neutron emission and energy content would correlate with the energy content deviations being smaller due to the empirical scaling [Eq. (1)].

5. ZERO-DIMENSIONAL MODELING OF NEUTRON EMISSION

The neutron emission profile [24] tends to be narrower than any other characteristic profile in the plasma. The half-width of half-maximum of the neutron emission is about one-quarter of the plasma minor radius so that the total neutron emission can be modeled zero-dimensionally on the basis of the measured central plasma parameters as was done for PLT [25] and PDX [26]. In this section, the zero-dimensional model is derived, and it is found that the principal variation of the neutron emission is through variation of the measured central plasma parameters and the beam characteristics.

The total neutron emission is the sum of the thermonuclear, beam-target, and beam-beam emissions

$$S_n = S_{TN} + S_{BT} + S_{BB}. \quad (6)$$

For simplicity, the calculation of the neutron emission by the zero-dimensional model will ignore variations in $H(0)$, the peakedness of the neutral beam deposition, and will be normalized to one SNAP calculation of the beam deposition. With this assumption and the assumption that only the full energy component of the beam ion contributes to the fusion reaction rate,

$$\begin{aligned} S_{TN} &\propto n_D^2 \sigma v |_{T_i}, \\ S_{BT} &\propto n_D n_B \sigma v |_{W_B + 1.75 T_i}, \\ S_{BB} &\propto n_B^2 \sigma v |_{4W_B}, \end{aligned} \quad (7)$$

where n_B is the full energy beam ion density $\propto \frac{P_B}{W_B} \eta(W_B) \tau_s$, and where η is the full-energy component fraction of the beams. W_B is the beam voltage, σ is the $d(d,n)^3\text{He}$

cross-section, v is the relative velocity, and n_D is the deuterium thermal density. Equation (7) approximates the reaction rates with the cross-section evaluated at a specific particle energy. The beam target reaction is evaluated above the beam voltage due to the effect of the thermal ion velocity upon the relative velocity. τ_s is the beam ion slowing down duration [27]

$$\tau_s = \frac{\tau_{se}\tau_{si}}{\tau_{se} + \tau_{si}}. \quad (8)$$

Here

$$\tau_{se} \propto \frac{T_e^{3/2}}{n_e}, \quad (9)$$

and

$$\tau_{si} \propto \frac{(0.63W_B + T_i)^{3/2}}{n_e}, \quad (10)$$

where τ_{se} and τ_{si} are the slowing down time of beam ions due to collisions with electrons and ions, respectively. Equation (10) is derived from Eqs. (5-31) in Ref. 28, using a beam “equivalent-temperature” of $0.63 W_B$. This method gives an increase in τ_{si} above the usual value of $T_i = 0$ [27] that is 15% larger than calculated by solving the Fokker-Planck equation, but the formula is applicable to a large number of cases. For the 1990 supershots, it turns out that in the central plasma region, the initially injected full energy beam ions have about equal electron and ion drag due to the high ion temperature ($T_i \simeq 30$ keV), and although Eqs. (8) - (10) are used, it is noted that approximately

$$\tau_s \propto \frac{T_e}{n_e}, \quad (11)$$

(Fig. 13). The energy dependences of σv in the region of interest are approximately [29]

$$\langle \sigma v \rangle_{TN} \propto T_i^{3/2},$$

$$\langle \sigma v \rangle_{BT} \propto W_B^{1.25},$$

$$\langle \sigma v \rangle_{BB} \propto W_B^{2/3}, \quad (12)$$

and the fit to η , on the basis of test stand experiments [19], is approximately

$$\eta \propto W_B^{-0.25}. \quad (13)$$

Thus, Eq. (8) becomes approximately,

$$\begin{aligned} S_{TN} &\propto n_D^2 T_i^{3/2}, \\ S_{BT} &\propto n_D P_B \tau_s, \\ S_{BB} &\propto \dot{P}_B^2 \tau_s^2 W_B^{-2}. \end{aligned} \quad (14)$$

To determine the ion density, we need to determine the impurity electron density due to carbon, n_e^C , the high Z impurities, n_e^{met} , and the beam density since

$$n_D \simeq n_e - n_e^C - n_e^{met} - n_B. \quad (15)$$

The value for the high-Z impurities arises from the soft X-ray PHA determination (Z_{met}) and for the supershots analyzed, $Z_{met} \simeq 0.52 \pm 0.22$. This quantity of high-Z material, such as iron or nickel, does not cause significant deuterium depletion. However, the visible bremsstrahlung Z_{eff} was corrected for Z_{met} when it was used to determine the electron density due to carbon.

The visible bremsstrahlung measurement of Z_{eff} on TFTR was from a slightly off-axis tangential chordal measurement ($r/a \sim 0.15$). Determination of Z_{eff} from this signal requires that the path integrals be performed over the measured density and temperature profiles (as is performed in SNAP), and further means that there may be considerable uncertainty in Z_{eff} when the density is highly peaked, as the viewing chord does not observe the peak of

the bremsstrahlung emission. A regression fit to the SNAP chordal calculation using the central plasma parameters yields

$$Z_{eff} = 9.06 \times 10^{-11} [B_{VB} T_e^{0.318}(0)/n_e^2(0)] F_n^{1.68}, \quad (16)$$

with T_e in keV, n_e in 10^{13}cm^{-3} , and B_{VB} being the brightness of the visible bremsstrahlung signal. The term in the brackets would be the visible bremsstrahlung Z_{eff} if the measurement were made observing the center of the plasma. The density peakedness, F_n , enters Eq. (16) to correct the off-axis measurement. Equation (16) agreed with the SNAP values to within $\pm 7\%$ with Z_{eff} ranging from 2 to 4. The depletion of the deuterons by the impurities is

$$\frac{n_D}{n_e} \simeq \frac{6.5 - Z_{eff}}{5}, \quad (17)$$

since the principal impurity is carbon from the limiters and $Z_{met} = 0.5$.

On average, the thermal deuterium makes up the bulk of the electron density with the beam ions and impurities causing approximately equal amounts of depletion (Fig. 14).

The zero-dimensional model neutron emission is calculated directly from experimental measurements of the central plasma parameters using Eq. (14) normalized to the relative breakdown of the thermonuclear neutron emission from the SNAP analysis for shot 51550, which had the measured values shown in Table 2. SNAP calculated the plasma parameters of Table 3. 51550 has been chosen since it is well diagnosed and has high beam power.

Thus, Eq. (14) becomes

$$\begin{aligned} S_n^{ZD} &= S_{TN} + S_{BT} + S_{BB}, \\ S_{TN} &= 2.3 \times 10^{-4} n_D^2 T_i^{3/2}, \\ S_{BT} &= 0.167 n_D P_B \tau_s, \\ S_{BB} &= 1.3 \times 10^4 P_B^2 \tau_s^2 W_B^{-2}. \end{aligned} \quad (18)$$

The parameters in Eq. (18) can be obtained from several measurement sources (e.g., Table 1). Using Z_{eff} from SNAP (essentially the visible bremsstrahlung), T_i from carbon doppler broadening [10], T_e from cyclotron emission [8], and n_e from microwave interferometry [11], the 118 shots that also had SNAP runs then can be calculated, and $S_n^{ZD}/S_n^{expt} = 0.98 \pm 0.12$ (Fig. 15), which is comparable to the fit obtained using SNAP (Fig. 11). Evidently, the range in the data (after normalization to 51550) can be accounted for entirely by the variation of the measured central plasma parameters and the neutral beam parameters. The experimental inputs used in Eq. (18) to produce Fig. 15 are the same as were used in the SNAP calculation.

Alternatively, T_e can be obtained from Thomson scattering [30], n_e from interferometry, T_i from the doppler broadening of Ni impurities [9], and Z_{eff} from Eq. (16). Twenty cases can be calculated with the result that $S_n^{ZD}/S_n = 0.89 \pm 0.12$. This is also a reasonable fit although the number of analyzed cases is small since the TVTS data was usually not available at the peak neutron emission time.

The number of data points is maximized by obtaining T_e from the cyclotron emission [8], n_e from interferometry [11], T_i from nickel doppler broadening [9], and Z_{eff} from Eq. (16). In this case, 203 shots can be computed and the fit remains quite good with $S_n^{ZD}/S_n = 1.03 \pm 0.13$ (Fig. 16). The limitation to this data set is the number of shots with T_i measured by the doppler broadening of nickel.

The zero-dimensional model is as good at predicting the neutron emission as SNAP indicating the central localization [24] of the neutron emission. This means that determination of the central plasma parameters is enough to describe the neutron emission. The expected (20%) dependence of the total neutron emission upon the beam voltage through the cross-

section was not observed in Fig. 5, since the neutralization efficiency of the beam is reduced at higher voltage [Eq. (13)].

6. SCALING OF THE CENTRAL PLASMA PARAMETERS

The zero-dimensional model [Eq. (18)] can form a “physics-based” scaling of the neutron emission from TFTR supershots. Equation (18) describes the neutron emission in terms of the measured central plasma parameters. To form such a scaling, knowledge of the scaling of the central plasma parameters (T_e , T_i , n_e , Z_{eff}) that are important for the neutron emission is required. The parameters Z_{eff} , T_e , T_i , and n_e have been regressed in terms of the machine parameters (B , I_p), the beam parameters (P_B , W_B , C_{NB}), and the confinement time (τ_E).

In this section, the confinement time provides a single measurement of the plasma performance and is used to help determine Z_{eff} , T_e , T_i , and n_e . Thus, the zero-dimensional model can be applied to all the plasmas where τ_E has been measured (503 plasmas) instead of those where Z_{eff} , n_e , T_i , and T_e have all been measured simultaneously (118 plasmas). In the next section, the scaling for τ_E is derived in terms of external machine and beam parameters. Using that relation in the scalings of the central plasma parameters (developed here) and those scalings in the zero-dimensional model yields the “physics-based” scaling law. The only purpose of the intermediate step of this section is to determine the validity of the zero-dimensional model for as many 1990 supershot plasmas as possible.

The visible bremsstrahlung Z_{eff} regresses to (retaining only the significant terms)

$$Z_{eff} = (3.29 \pm 0.23) I_p^{0.35 \pm 0.05} \tau_E^{-0.36 \pm 0.06} P_B^{-0.31 \pm 0.03}. \quad (19)$$

Although the dependencies are weak, trends can be seen when the data are averaged together. Z_{eff} [as measured by visible bremsstrahlung, Eq. (16)] decreases only slightly as τ_E increases

since the range of τ_E values is only 70% (Fig. 17). At constant confinement time and plasma current (Fig. 18), Z_{eff} decreases with increasing beam power and is lower at lower plasma current. It is useful to recall that supershot plasmas are fueled entirely by the beams and recycled deuterium and carbon from the limiter so that gas fueling rates need not be considered.

The regression analysis for the central electron temperature (retaining only the significant terms) reduces to

$$T_e = (0.32 \pm 0.02) B^{1.47 \pm 0.16} \tau_E^{0.49 \pm 0.05} W_B^{0.45 \pm 0.16} C_{NB}^{0.19 \pm 0.04}. \quad (20)$$

The electron temperature increases with confinement time at constant toroidal magnetic field and constant beam voltage (Fig. 19) and is larger for larger beam voltages. The scaling with toroidal magnetic field arises from 41 plasmas at 3.9 T which have lower temperatures than the (4.8 $\rightarrow$ 5.1 T) remainder of the plasmas, and is co-dependent with the W_B variation so that the W_B and B coefficients in Eq. (20) have more uncertainty than is described by the quoted error. The C_{NB} dependence is statistically present but seems to be weak, and is possibly only a difference between co-dominated and counter-dominated injection. However, all the data fit the electron temperature scaling Eq. (20) (Fig. 20). Although supershots tend not to have sawtooth MHD activity, there can be such activity for plasma currents ≥ 1.9 MA, and in these cases, T_e was recorded at peak neutron emission which tended to be prior to the sawtooth crash.

The regression analysis of the central ion temperature (as measured by nickel doppler broadening [9]) is

$$T_i = (35.9 \pm 4.1) I_p^{-0.67 \pm 0.07} \tau_E^{1.06 \pm 0.11} P_B^{0.65 \pm 0.03}. \quad (21)$$

There is no dependence upon toroidal magnetic field since there was no range in B for

the measured T_i data. The central ion temperature rises with beam power at constant confinement time and constant plasma current (Fig. 21) and, for fixed low beam power, is larger at lower plasma current. The ion temperature also rises with confinement time (Fig. 22) at constant current and constant beam power. Figures 21 and 22 verify each of the scalings independently and combine to give a reasonable scaling for central T_i as measured from the nickel doppler broadening (Fig. 23). The carbon doppler broadening T_i measurement [10] is slightly different from the nickel temperature but also scales with Eq. (21), although the fit is not as good as that in Fig. 23.

The regression analysis for the central electron density is

$$n_e = (1.73 \pm 0.12) B^{0.32 \pm 0.09} I_p^{-0.33 \pm 0.04} \tau_E^{0.45 \pm 0.05} P_B^{0.57 \pm 0.02}. \quad (22)$$

The fit with the experimental data is quite good (Fig. 24). However, some of the best TFTR plasmas (i.e., those conditioned with the lithium pellets [20]) deviated the most from the scaling. To deal with the possibility that conditioning with the lithium pellets may actually alter the density behavior of the supershots, the lithium pellet shots were regressed separately, yielding

$$n_e \propto \tau_E^{0.75 \pm 0.22} P_B^{0.45 \pm 0.08},$$

where there was not enough range in the B and I_p parameters to determine their importance. Thus, for plasmas conditioned with the lithium pellet, a composite scaling was assumed

$$n_e = (3.12 \pm 0.27) B^{0.32} I_p^{-0.33} \tau_E^{0.75} P_B^{0.45}. \quad (23)$$

For the shots without the lithium pellets, the central density dependence on beam power and plasma current at constant B and τ_E can be seen explicitly (Fig. 25). Normalizing the central density to the beam power dependence indicates that, at constant B and I_p , there

is also a τ_E variation that is weak since τ_E has a short range. Finally, normalizing the central density to the τ_E , I_p , and beam power dependences indicates a direct toroidal field dependence, which also is weak. For the 45 shots with the lithium pellets, a beam power dependence can be seen at constant τ_E but the direct dependence upon confinement time is visible only in the extreme high and low τ_E points.

Using Eqs. (15) to (23), n_D and the neutron emission can be determined from the machine settings, beam conditions, and the measured confinement time. A tight fit of the experimental data to the zero-dimensional model is found using the plasma parameters from these scalings [Eqs. (19) - (23)]. The fit gives $S_n^{ZD}/S_n = 1.02 \pm 0.10$ (Fig. 26) for the 457 cases where lithium pellets were not used, and Eq. (22) is used for n_e .

For the 46 lithium pellet plasmas, Eq. (23) was used for n_e , and again the total neutron emission was calculated zero-dimensionally with the results $S_n^{ZD}/S_n = 0.99 \pm 0.09$, although the data point with the highest experimental neutron emission is underestimated by 12%. The entire motivation for considering the lithium pellet plasmas separately is that these are among the best TFTR supershots.

As the $d(d,n)^3\text{He}$ neutron rate rises, all of the components are calculated to increase (Fig. 27) in such a way that the fraction of beam-target reactions is always about 0.5 to 0.6 of the total, the thermonuclear reactions are about 0.1 to 0.15 of the total, and the beam-beam reactions are about 0.3 to 0.4 of the total. This result holds for plasmas with or without lithium pellets.

Thus, by use of these scaling relations [Eqs. (19) - (23)], the zero-dimensional model [Eq. (18)] fits all the 1990 supershot neutron emission with smaller deviation than that of SNAP. This probably occurs because SNAP calculations reflect individual measurement

uncertainties, while these deviations are likely reduced by the averaging which Eqs. (19) - (23) essentially accomplish. Further, since 457 plasmas without lithium pellets and 46 plasmas with lithium pellets are described by the zero-dimensional model, then all those plasmas where the measurement of τ_E was available are also described by the same model that was used when Z_{eff} , n_e , T_e , and T_i were all measured simultaneously.

7. PHYSICS BASED NEUTRON SCALING LAW

The zero-dimensional model [Eq. (18)] with the scaled plasma parameters [Eqs. 19-23] yields the neutron emission in terms of the machine settings, beam parameters, and τ_E . In order to obtain the neutron emission in terms of external machine conditions only, an expression for τ_E is required. The magnetically measured confinement time has been regressed with the machine parameters B , I_p ; the beam parameters W_B , C_{NB} , P_B ; and a parameter intended to indicate with the limiter conditioning [6] - the CII light in the target plasma (just prior to the beam turn on). Keeping only the significant parameters

$$\tau_E = (0.43 \pm 0.02) B^{1.07 \pm 0.10} I_p^{0.22 \pm 0.05} W_B^{-0.56 \pm 0.12} C_{NB}^{0.30 \pm 0.02} CII^{-0.32 \pm 0.02}, \quad (24)$$

where the plasmas immediately following boronization (within 30 shots) are excluded, since the CII light is not an indication of wall conditioning for these shots. For those plasmas, the carbon influx has been replaced by boron.

On average, this energy confinement scaling [Eq. (24)] fits the experimental data quite well (Fig. 28), although there are several data points with considerable deviation and most of the data exist in the range 0.13 to 0.15 sec. Most of the dependences in Eq. (24) can be seen in the raw data, except for the beam voltage dependence. The scaling due to CII light (or plasma wall conditions) is clear at constant C_{NB} , I_p and B , and lower B or I_p correlates

with relatively lower τ_E (Fig. 29). The correlation with C_{NB} seems clear although the actual dependence may only be a difference between co-dominated and counter-dominated injection (Fig. 30). The beam voltage dependence is not directly observed when all other parameters are held constant due to the limited data range available; nevertheless, statistically, it is present in the regression analysis.

The zero-dimensional model with the plasma parameters derived from Eqs. (19) - (23) and τ_E from Eq. (24) fits the TFTR experimental data with (Fig. 31) $S_n^{PB}/S_n = 1.05 \pm 0.15$. Thus, the zero-dimensional model can describe the supershot neutron emission when all of the input parameters are external parameters: machine, beam, and limiter conditioning. This set of relations is a “physics-based” scaling law since it describes the supershot influence on the plasma parameters (T_e , T_i , n_e , and Z_{eff}), the consequence to the fusion reaction rate, and keeps the fusion cross-sections in the analysis.

A regression analysis directly on the physics-based neutron scaling law indicates the principal machine parameters which influence the neutron emission

$$S_n^{PB*} = 4.1 \times 10^{-3} C_{NB}^{0.45} I_P^{-0.29} P_B^{1.54} B^{2.31} W_B^{-0.34} CII^{-0.41}. \quad (25a)$$

The experimental data fit Eq. (25a) with $S_n^{PB*}/S_n = 1.00 \pm 0.13$. The advantage of Eq. (25a) is that it clearly indicates the individual device and neutral beam parameters that need to be changed in order to increase the TFTR supershot neutron emission. From Eq. (25a), the neutron emission can be increased most easily by increasing P_B or B .

The same type of equation can be obtained by inserting Eq. (24) for τ_E into the empirical scaling laws [Eq. (2)] to obtain a scaling for the experimental neutron emission of

$$S_n \propto C_{NB}^{0.56} I_p^{0.09} P_B^{1.79} B^{2.00} W_B^{-1.05} CII^{-0.60}. \quad (25b)$$

The differences between Eqs. (25a) and (25b) are small except for the W_B dependence. The difference in the W_B coefficient is due to the smaller differences in the other coefficients in Eq. (25b) and is a further indication of co-dependence (especially B and W_B) in the electron temperature scaling [Eq. (20)].

Projections of TFTR supersonic performance can be made for a variety of potential changes in the TFTR machine or neutral beams. Of course, there is additional uncertainty when extrapolating a scaling law beyond the range of existing data. To indicate the potential magnitude of such uncertainty, the projections have been expressed in four ways.

1. Equation (1) has been used for the neutron emission, with $E = \tau_E P_B$ and τ_E defined by Eq. (24); $C_{NB} = 0.63$ is taken as a maximum practicable value for high power TFTR operation. Since the TFTR neutral beam sources are evenly distributed co and counter, the $C_{NB} = 0.63$ can arise with higher power co-beam injection or a reduced number of counter sources due to the unbalanced momentum input. This assumption is used to indicate the performance improvement if the tritium were used in the co-beams and the scaling originates due to plasma rotation.
2. Equation (2) has been used for the neutron emission, with τ_E defined by Eq. (24) but with $C_{NB} = 0.5$ (a minimum practicable value for TFTR operation). This assumes that the C_{NB} scaling does not arise from rotation.
3. Equation (18) has been used for the neutron emission, with the plasma parameters defined by Eqs. (19), (20), (21), (23), (24), and $C_{NB} = 0.63$. The use of Eq. (23) implies the use of Li pellets to improve the wall conditioning.
4. Equation (18) has been used with Eqs. (19) - (22) and (24) and $C_{NB} = 0.5$, a non-

lithium pellet case.

In terms of the beam power scaling (Fig. 32), the empirical scaling, [Eqs. (1) and (2)], eventually diverge from each other due to the difference between P_B^2 and $P_B^{1.79}$. The machine settings in the calculation are from one of the better TFTR shots (55851) which had $B = 5$ T, $I_p = 1.7$ MA, $W_B = 105$ kV, $CII = 1.4$ A.U., and $P_B = 25$ MW. 55851 is commonly used for extrapolating supershot performance (e.g., [31]). The results are separated into two regions in Fig. 32: one with $E < 0.8 E_{Troy}$ and one for $E > 0.8 E_{Troy}$. TFTR supershots typically begin to obtain some disruptions at around $E \sim 0.8 E_{Troy}$ where $E_{Troy} = 0.6 I_p B$ for $R = 2.45$ m TFTR plasmas [3]. Since disruptions tend to worsen the limiter conditioning (degrading supershot performance), it is unlikely that tritium supershot operation will be compatible with $E > 0.8 E_{Troy}$. Thus, although increasing the neutral beam power is expected to significantly increase the TFTR supershot neutron emission, the plasma will eventually encounter the TFTR empirical form of the Troyon limit and have an increased probability of disrupting. This occurs if the beam power is to be increased much beyond the power used in 55851. Thus attempts to increase the beam power must also be accompanied by attempts to improve the plasma stability.

The scaling with beam voltage indicates that the neutron emission is relatively insensitive to beam voltage. Experimentally, the plasma has been insensitive to the existing variations (90–110 kV) in beam voltage (Fig. 5), indicating that there is little evidence to suggest a benefit from modest increases in the TFTR beam voltages (e.g., to 120 kV).

The scaling with toroidal magnetic field (Fig. 33) is favorable and keeps the plasma energy content less than 0.8 of the Troyon limit ($E < 0.8 E_{Troy}$) even for projected deuterium neutron emission in the range of 10^{17}s^{-1} . All four methods of extrapolating the neutron

emission predict $Q_{DT} \sim 1$ plasmas would be obtained with $B \cong 8\text{T}$ operation. From Eq. (24), $\tau_E \simeq 0.25$ sec at $B = 8\text{T}$. One difficulty with B scaling is that magnetic field variations in the data base originated from diverse experiments and was not systematic. Explicit toroidal field scans do not presently exist for TFTR supershots.

The scaling with improved wall conditioning (as might be reflected by a reduction in the target CII light) indicates that increases in neutron production are possible but, as with increases in beam power, the plasma becomes unstable if only the confinement time increases beyond that obtained in 55851.

The scaling with plasma current needs to be considered in two ways: (a) with the target CII light proportional to I_p , an optimistic scaling for ohmic TFTR plasmas, and (b) with the target CII light held constant, which would require significant improvements in the wall conditioning at higher plasma currents. In either case, increasing the plasma current alone did not raise the expected neutron emission. The increase in I_p does increase the plasma stability by raising the Troyon limit and would allow more beam power or better confinement, which can raise the neutron emission.

Combined changes of machine settings can be considered by taking $B = 6\text{T}$, the beam power = 32 MW and voltage = 100 kV, and raising the plasma current to 2.2 MA in order to raise the Troyon limit (while keeping $q_{CYL} > 4$ to avoid MHD activity which often presents practical operational difficulties on TFTR, especially at high β). With this set of conditions, the scaled plasma performance is a function of further attempts to improve the plasma wall conditioning (Fig. 34). Approximately 30% improvement in the neutron emission is possible over existing TFTR operation before encountering stability limits. The corresponding plasma characteristics calculated from Eqs. (19) - (24) would be $\tau_E \simeq 0.2$

sec, $n_e(0) \simeq 9 \times 10^{13} \text{cm}^{-3}$, $n_D/n_e \simeq 0.55$, $n_B/n_e \simeq 0.2$, $T_e(0) \simeq 14 \text{ keV}$, $T_i(0) \simeq 40 \text{ keV}$, $S_{TN}/S_n \simeq 0.25$, $\tau_s \simeq 0.11 \text{ sec}$. Increasing the beam power would equivalently raise the neutron emission if it were not possible to improve the wall conditioning. An increase of the beam power to $\sim 37 \text{ MW}$ would cause the plasma to reach the stability limit and result in a neutron emission rate of $\sim 6.5 \times 10^{16} \text{s}^{-1}$ (Fig. 35).

In all of the projections, the Troyon limit is the criterion which limits the neutron emission. Thus, the Troyon limit in the form

$$\tau_E P_B = 0.8(0.6 I_P B) \quad (26)$$

can be used with the physics based neutron scaling law [Eq. (25a) or (25b)] and the scaling for the energy confinement time of supershots [Eq. (24)] to determine a scaling for the fusion rate in supershots at the Troyon limit. Putting Eq. (24) into Eq. (26) and solving for P_B and putting this P_B into Eqs. (25a) and (25b) yields

$$S_n^{LIMIT} \propto C_{NB}^{-0.01 \rightarrow -0.02} I_p^{0.91 \rightarrow 1.49} B^{2.2 \rightarrow 1.87} W_B^{0.52 \rightarrow -0.05} CII^{0.08 \rightarrow -0.03}. \quad (27)$$

Equation (27) represents the limiting neutron emission that can be obtained if either the beam power or the confinement time can be raised arbitrarily to achieve Eq. (26). In this case, increases to the plasma current or the toroidal field are required to increase the fusion rate. The first set of coefficients in Eq. (27) arise from using Eq. (25a) while the second set arise from using Eq. (25b). For all the 1990 TFTR supershot plasmas (Fig. 36), the neutron emission seems to reach the limiting value [Eq. (26)] when $E \simeq 0.8 E_{Troyon}$. In the vicinity of this value, the frequency of major and minor disruptions increases (Fig. 36).

8. PROJECTIONS TO EQUIVALENT DT PLASMAS

This section describes the range of alpha parameters (n_α , β_α , v_α/v_A) that can be achieved if the same supershot plasmas were obtained with deuterium plus tritium as have been obtained in 1990 with deuterium plasmas.

To form the DT equivalent calculation, the deuterium in the plasma was replaced with a 50:50 mixture of deuterium and tritium. It was assumed that all of the neutral beams in the co-direction are operated in tritium while all of the beams in the counter-direction are operated in deuterium. In this manner, the extra momentum of the tritium beams is assumed to benefit τ_E as if $C_{NB} = 0.63$. Further, the tritium beams are presumed to have the same voltage, species mix, and $H(0)$ as the deuterium beams. No changes have been ascribed to (a) scaling of the energy confinement time with isotope or (b) the alpha heating.

The DT neutron emission from the equivalent plasma has been predicted in three ways: from SNAP, from TRANSP [31], and using a zero-dimensional central calculation (Table 1) for a single plasma, #55851. The TRANSP and SNAP calculations are one-dimensional and do, in principle, treat the tritium beam deposition correctly. However, the fact that the conversion factors for predicting the DT neutron emission from the DD neutron emission can be calculated zero-dimensionally indicates that the principal factors that determine the conversion are the central plasma parameters, nuclear cross-sections, and the neutral beam parameters.

Zero-dimensionally, the DT neutron emission is

$$S_n^{DT} = \left(\frac{S_{TN}^{DT}}{S_{TN}^{DD}} \right) S_{TN}^{DD} + \left(\frac{S_{BT}^{DT}}{S_{BT}^{DD}} \right) S_{BT}^{DD} + \left(\frac{S_{BB}^{DT}}{S_{BB}^{DD}} \right) S_{BB}^{DD}, \quad (28)$$

where S_{TN}^{DD} , S_{BT}^{DD} , and S_{BB}^{DD} are the thermonuclear, beam-target, and beam-beam neutron

emissions as calculated by SNAP for 55851 and $\left(\frac{S_{TN}^{DT}}{S_{TN}^{DD}}\right)$, $\left(\frac{S_{BT}^{DT}}{S_{BT}^{DD}}\right)$, and $\left(\frac{S_{BB}^{DT}}{S_{BB}^{DD}}\right)$ are the ratios of the neutron emissions of DT reactions to DD reactions for the thermonuclear, beam-target, and beam-beam reactions. Again, as for the zero-dimensional model, the reaction rates are evaluated at specific ion energies.

The thermonuclear conversion is

$$\left(\frac{S_{TN}^{DT}}{S_{TN}^{DD}}\right)_{TN} \simeq \frac{n_T^{DT} n_D^{DT}}{(n_D^{DD})^2/2} \frac{\sigma v^{DT}}{\sigma v^{DD}}, \quad (29)$$

where the superscript applies to the measurement in (DT) the deuterium plus tritium plasma, or (DD), the deuterium plasma. The cross-section ratio varies from 220 to 150 in the ion temperature range of TFTR supershots [32]. Taking $n_T^{DT} = n_D^{DT} = \frac{1}{2} n_D^{DD}$ and approximating that $\sigma v_{DT}/\sigma v_{DD} \simeq (277-3.98 T_i/\text{keV})$ yields

$$\left(\frac{S_{TN}^{DT}}{S_{TN}^{DD}}\right)_{TN} \simeq \frac{1}{2}(277 - 3.98 \frac{T_i}{\text{keV}}). \quad (30)$$

The beam-target relationship is

$$\left(\frac{S_{BT}^{DT}}{S_{BT}^{DD}}\right)_{BT} \simeq \frac{n_T^{DT} (P/W)_D^{DT} \tau_D^{DT} \sigma v_{W_D}^{DT} + n_D^{DT} (P/W)_T^{DT} \tau_T^{DT} \sigma v_{W_T+T_i}^{DT}}{n_D^{DD} (P/W)_D^{DD} \tau_D^{DD} \sigma v_{W_D+T_i}^{DD}}, \quad (31)$$

where τ is the beam slowing down time of the subscript ion in the superscript plasma, P is the total beam power, W is the beam voltage, and T_i is the ion temperature. The σv^{DT} for the deuterium beam acting on the tritium plasma is evaluated at the peak of the DT cross-section, while the other cross-sections are evaluated at a voltage that is higher by the ion temperature in order to crudely account for the enhanced reactions due to oppositely streaming thermal ions [29]. Thus,

$$P_D^{DT} = P_T^{DT} = \frac{1}{2} P_D^{DD},$$

$$n_T^{DT} = n_D^{DT} = \frac{1}{2} n_D^{DD},$$

$$\tau_T^{DT} \simeq 0.6 \tau_D^{DT} \simeq \frac{0.6}{0.83} \tau_D^{DD},$$

$$v_T = (2/3)^{1/2} v_D,$$

and

$$W_D^{DT} = W_T^{DT} = W_D^{DD}.$$

With a beam voltage in the vicinity of 100 keV, $\left(\frac{S_{BT}^{DT}}{S_{BT}^{DD}}\right) \simeq 80$, approximately independent of beam voltage.

The beam-beam reaction ratio for oppositely directed beams is

$$\begin{aligned} \left(\frac{S_{BB}^{DT}}{S_{BB}^{DD}}\right) &\simeq \frac{(P_D/W_D)^{DT} \tau_D^{DT} (P_T/W_T) \tau_T^{DT}}{[(P_D/W_D)^{DT}]^2 [(\tau_D)^{DD}]^2} \frac{\sigma v_{MAX}^{DT}}{\sigma v_{4W_D}^{DD}} \\ &= \frac{0.6}{0.83^2} \frac{1}{1.67} \frac{\sigma_{MAX}^{DT}}{\sigma^{DD}/4 W_D} \\ &\simeq 50 \text{ (a constant weakly dependent on } W_D). \end{aligned} \quad (32)$$

The term, $4 W_D$, arises from the relative velocity of the counter-streaming energetic ions.

Thus,

$$S_n^{DT} = 50 S_{BB}^{DD} + 90 S_{BT}^{DD} + (139 - 2 \frac{T_i}{keV}) S_{TN}^{DD}. \quad (33)$$

The neutron emission arises predominately from within the central approximately $a/4$ of the plasma. The central alpha density was determined as the total alpha source rate times the alpha thermalization time divided by the neutron emitting volume $(2\pi^2 R(a/4)^2)$.

For the range of 1990 supershot plasmas, the relevant alpha parameters (β_α , $n_\alpha, n_\alpha/n_e$, I_n^{DT} , and Q_{DT}) are near their maximum values in plasmas in which the DD neutron emission is highest. The maximum DT equivalent neutron emission from Eq. (33) is about $3 \times 10^{18} \text{s}^{-1}$. The maximum $Q_{DT} \simeq 0.3$ occurs for plasmas with the maximum $Q_{DD} \simeq 1.5 \rightarrow 1.8 \times 10^{-3}$ (Fig. 37). The Q_{DT} values achieved at 1 MA plasma currents are high

(~ 0.25) and require less beam power and have lower total neutron yield. Although Q_{DT} is less than the maximum values, these plasmas produce about one-fourth as many neutrons and, therefore, TFTR vessel activation would be correspondingly smaller. The maximum (centrally averaged) β_α is ~ 0.0045 (Fig. 38). The centrally averaged alpha density (Fig. 39) is a maximum at about $3 \times 10^{11} \text{cm}^{-3}$, and the ratio of the alpha density to electron density goes up to about 0.4%.

A regression analysis on the alpha density predicts the optimization that might occur (beyond simple increase of the neutron emission or alpha source rate).

$$\frac{n_\alpha(o)}{S_n} \propto P_B^{-0.72 \pm 0.02} B^{2.42 \pm 0.13} I_P^{-0.52 \pm 0.03} C_{NB}^{0.36 \pm 0.03} W_B^{1.23 \pm 0.16}. \quad (34)$$

The beam voltage dependence in n_α reflects the scaling of T_e upon W_B [Eq. (20)], which increases the alpha slowing down time. The improvement at reduced plasma current indicates the scaling of $n_e(0)$ with I_p in Eq. (22), with lower density causing a longer alpha slowing down time. Equation (34) indicates that alpha physics issues can be studied with TFTR supershot plasmas that some have large neutron emission at lower beam powers and plasma currents. Also, β_α is optimized when $\frac{n_\alpha}{B^2}$ is optimized, and thus would increase when B is raised.

9. SUMMARY

We have examined all of the 1990 TFTR Supershots (~ 525 plasmas) and derived scalings for the neutron emission. We find

1. A small modification of previous TFTR empirical neutron scaling to include the plasma current dependence [Eq. (1)].

2. Empirical scaling for the central plasma parameters and global confinement time [Eqs. (19)-(24)].
3. Agreement of the experimental neutron emission with the SNAP calculations, indicating that the deposition and slowing down of the beam ions is nearly classical and that beam ion transport is not significant.
4. Agreement of the experimental neutron emission with zero-dimensional calculations indicating that the central plasma and neutral beam parameters dominate the characterization of the neutron emission.
5. Agreement of the experimental neutron emission with a physics-based neutron scaling law based upon the scalings of the central plasma parameters and the zero-dimensional modeling of the neutron emission.
6. Extrapolation of the supershot performance to equivalent DT performance indicating that the important alpha parameters will be optimized for plasmas in which the DD neutron emission is presently optimized, and further that some lower plasma current operation may yield interesting alpha parameters with reduced activation.
7. Projection of the supershot performance to alternate machine settings, suggesting that increases in the toroidal magnetic field might lead to higher fusion rates from TFTR supershots.

Acknowledgment

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CHO3073.

The authors thank S. Zweben for valuable comments. The authors appreciate the support and cooperation of the TFTR neutral beam group, tokamak operations group, and diagnostics division.

References

- [1] STRACHAN, J.D., *et al.*, Phys. Rev. Lett. **58** (1987) 1004.
- [2] JASSBY, D.L., *et al.*, Phys. Fluids **B3** (1991) 2308.
- [3] TROYON, F., *et al.*, Plasma Phys. Controlled Fusion **30**, 1597 (1988).
- [4] Recent major radius scaling work has yielded different results that will be described by M. Zarnstorff *et al.*, 1992 IAEA Conference.
- [5] BARNES, G.W., LOESSER, D., OWENS, D.K., and ULRICKSON, M., in *Proc. IEEE Conference (1991)*, to be published.
- [6] STRACHAN, J.D., *et al.*, Princeton Plasma Physics Laboratory Report No. PPPL-2841 (1992).
- [7] HENDEL, H., *et al.*, Rev. Sci. Instrum. **61** (1990) 1900.
- [8] TAYLOR, G., *et al.*, Rev. Sci. Instrum. **55** (1984) 1739.
- [9] HSUAN, H., *et al.*, Rev. Sci. Instrum. **59** (1988) 2127.
- [10] STRATTON, B.C., *et al.*, in *Proc. IAEA Technical Meeting 1991*, (Nagoya), Princeton Plasma Physics Laboratory Report No. PPPL-2745 (1991).
- [11] MANSFIELD, D.K., *et al.*, Appl. Optics **27** (1987) 4469; PARK, H., Plasma Phys. Controlled Fusion **31** (1989) 2035.
- [12] RAMSEY, A.T. and TURNER, S.L., Rev. Sci. Instrum. **58** (1987) 1211.
- [13] HILL, K.W., *et al.*, Nucl. Fusion **26** (1986) 1131.

- [14] BELL, M.G., *et al.*, Plasma Phys. Controlled Fusion **28** (1986) 1329.
- [15] Updated measurements from System of Ref. [8].
- [16] BELL, M.G., *et al.*, Plasma Phys. Controlled Fusion Res., 1988 (IAEA, Vienna, 1989)
Vol. I, p. 27.
- [17] HENDEL, H.W. and JASSBY, D.L., Nucl. Sci. Engin. **106** (1990) 114.
- [18] MIKKELSEN, D.R., Private Communication (PPPL)
- [19] KUGEL, H.W., *et al.*, Rev. Sci. Instrum. **60** (1989) 37.
- [20] SNIPES, J., *et al.*, in *Proc. European Conf. Nucl. Fusion (Berlin, 1991)*.
- [21] DYLLA, H.F., *et al.*, Nucl. Fusion **27** (1987) 1221.
- [22] DYLLA, H.F., *et al.*, J. Nucl. Mater. **176/177** (1990).
- [23] MURPHY, J.A., SCOTT, S.D., and TOWNER, H.H., Princeton Plasma Physics Laboratory Report No. PPPL-TM-393 (1992).
- [24] ROQUEMORE, L., *et al.*, Rev. Sci. Instrum. **61**, (1990) 3163.
- [25] STRACHAN, J.D., *et al.*, Nucl. Fusion **21** (1981) 67.
- [26] STRACHAN, J.D., *et al.*, Nucl. Fusion **25** (1985) 863.
- [27] JASSBY, D.L., Nucl. Fusion **17** (1977) 309.
- [28] SPITZER, L., "Physics of Fully-Ionized Gases," (Interscience, NY, 1962), p. 135.
- [29] MIKKELSEN, D.R., Nucl. Fusion **29** (1989) 1113.

[30] JOHNSON, D., *et al.*, Rev. Sci. Instrum. (1986).

[31] BUDNY, R., *et al.*, Nucl. Fusion **32** (1992) 429.

[32] PERES, J., J. Appl. Phys. **50** (1979) 5569.

TABLE 1. Data Base Parameters

PHYSICAL RELEVANCE	PARAMETER	REFERENCES
Neutron emission	S_n	[7]
Machine settings	- plasma current, I_p - toroidal magnetic field, B	
Beam heating parameters	- beam power, P_B - beam voltage, W_B - beam "co-counteriness" - beam deposition, $H(o)$	$C_{NB} = \frac{P_{C2}}{P_B}$
Plasma Parameters	- T_e from ECE - T_i from nickel - T_i from carbon - $n_e(o)$ from interferometry - $F_n = \frac{n_e(o)}{\langle n_e \rangle}$ from interferometry - Z_{eff} from visible bremsstrahlung - Z_{met} of high Z metals from X-ray PHA - τ_E from magnetics	[8] [9] [10] [11] [11] [12] [13] [14]
Limiter condition	- CII light emission - D_α light emission	[15] [15]

TABLE 2. Central Plasma

Parameters for 51550

$$W_B = 101 \text{ kV}$$

$$P_B = 27 \text{ MW}$$

$$T_e = 9.5 \text{ keV}$$

$$T_i = 27 \text{ keV}$$

$$n_e = 6.8 \times 10^{13} \text{ cm}^{-3}$$

$$VB = 1.68 \times 10^{12}$$

$$F_n = 2.2$$

$$Z_{eff} = 2.54$$

TABLE 3. Physics Parameters Calculated

by SNAP for 51550

$$S_{TN} = 5.2 \times 10^{15} \text{ s}^{-1}$$

$$S_{BT} = 1.83 \times 10^{16} \text{ s}^{-1}$$

$$S_{BB} = 9.7 \times 10^{15} \text{ s}^{-1}$$

$$\tau_s = 0.102 \text{ sec}$$

$$n_b = 1.4 \times 10^{13} \text{ cm}^{-3}$$

$$n_D = 4 \times 10^{13} \text{ cm}^{-3}$$

TABLE 4. Comparison of the Equivalent DT Performance for 58551

NEUTRON EMISSION	TRANSP	SNAP	ZERO-DIMENSIONAL
thermonuclear DT/DD	82	85	81
beam-target DT/DD	73	75	80
beam-beam DT/DD	46	49.6	50
total neutron DT/DD	71	71.7	73
Q_{DT}/Q_{DD}	165	171.8	177

Figures

Fig. 1. Time evolution of the magnetically measured stored energy, E , energy confinement time, τ_E , and neutron emission, S_n , for the supershot plasma with the largest peak neutron emission. This plasma had 32.5 MW of neutral beam heating, 1.9 MA of plasma current and 5.2 T toroidal magnetic field.

Fig. 2. (a) Experimental peak supershot neutron emission rate plotted against the empirical neutron scaling [Eq. (1)], S_{EMP1} . (b) Ratio of S_{EMP1} plotted against S_{EMP1} .

Fig. 3. Empirical neutron scaling law quoted in Ref. 16 plotted against plasma current.

Fig. 4. Measured neutron emission plotted against beam power for two different energy confinement times [(●) $\tau_E = 0.11 \rightarrow 0.125$ sec and ○ $\tau_E = 0.14 \rightarrow 0.15$ sec].

Fig. 5. Ratio of the experimental neutron emission to the empirical scaling [Eq. (1)], S_n/S_{EMP1} , plotted against the neutral beam voltage, W_B .

Fig. 6. Ratio of the experimental neutron emission to the empirical scaling [Eq. (1)], S_n/S_{EMP1} , plotted against the neutral beam co-counteriness ($C_{NB} = P_{CO}/P_B$).

Fig. 7. Ratio of the experimental neutron emission to the empirical scaling [Eq. (1)], S_n/S_{EMP1} plotted against the electron density peakedness ($n_e(0)/\langle n_e \rangle$).

Fig. 8. Ratio of the experimental neutron emission to the empirical scaling [Eq. (1)], S_n/S_{EMP1} , plotted against the neutral beam penetration parameter $H(0)$. $H(0)$ is the central deposition rate of beam ions divided by the volume averaged rate.

Fig. 9. Ratio of the experimental neutron emission to the empirical scaling Eq. (1), S_n/S_{EMP1} , plotted against the energy confinement time, τ_E . The ○ points are plasma which were

within 20 shots following boronization; the X points are plasmas which were within 3 shots following He discharge cleaning; the ▲ points are Li pellet enhanced supershots; and the ■ points are the remaining supershots.

Fig. 10. Ratio of experimental neutron emission, S_n , to the Empirical Scaling, Eq. (1), S_{EMP1} , plotted against the visible bremsstrahlung measured Z_{eff} , Eq. (16).

Fig. 11. Neutron emission, S_n^{SNAP} , calculated from the one-dimensional equilibrium transport code, SNAP, plotted as a function of experimental neutron emission, S_n . The data and calculation were taken at the time of peak neutron emission.

Fig. 12. Ratio of the SNAP calculated neutron emission to the measured values, S_n^{SNAP}/S_n , plotted as a function of the ratio of the SNAP calculated energy content to the measured energy content, E^{SNAP}/E .

Fig. 13. Full energy component slowing down duration [Eq. (8)] plotted versus T_e/n_e . The proportionality of τ_s to T_e/n_e is expected to be approximately valid when the beam voltage is such that electron and ion slowing are about equal.

Fig. 14. Contribution to the electron density from beam ions, thermal deuterium, and carbon impurities as deduced by Eqs. (8), (15), (16), and (17). (A) is the actual density and (B) is the fractional density.

Fig. 15. Neutron emission as determined by the zero-dimensional model [Eq. (18)] with T_i measured by carbon doppler broadening, and T_e by cyclotron emission plotted versus the experimental neutron emission.

Fig. 16. Neutron emission as determined by the zero-dimensional model [Eq. (18)] with T_i

measured by the nickel doppler broadening and T_e by cyclotron emission plotted versus the experimental neutron emission.

Fig. 17. Z_{eff} measured from the visible bremsstrahlung as a function of energy confinement for high powers ($\blacksquare$) ($P_B > 25$ MW) and low beam power ($\times$) ($P_B < 25$ MW) at constant plasma current $I_p = 1.5 \rightarrow 1.7$ MA. The data has been binned together and the error bars are the standard deviation of the mean. 157 data points make up the plot.

Fig. 18. Z_{eff} from the visible bremsstrahlung measurement as a function of neutral beam power for constant energy confinement ($\tau_E = 0.13 \rightarrow 0.155$ sec) at high plasma current ($\blacksquare$) ($I_p = 1.5 \rightarrow 1.7$ MA) and low plasma current ($\times$) ($I_p = 1.0$ MA). The data have been binned together and the error bars are the standard deviations of the mean for the data in each bin. 166 data points make up the plot.

Fig. 19. Measured central T_e plotted versus confinement time at constant toroidal magnetic field ($B = 4.8 \rightarrow 5.1$ T) at high beam voltage ($\times$) ($W_B = 102 \rightarrow 105$ kV) and low beam voltage ($\blacksquare$) ($W_B = 92 \rightarrow 94$ kV). The data has been binned and the error bars are the standard deviations of the mean. There are 180 plasmas in the plot.

Fig. 20. Measured central T_e plotted against the supershot scaling for electron temperature, Eq. (20). The data have been binned and the error bars are the standard deviations of the mean. 380 plasmas make up the plot.

Fig. 21. Measured central T_i plotted versus beam power at constant confinement time ($\tau_E = 0.13 \rightarrow 0.15$ sec) at two different plasma currents ($\circ$ $I_p \simeq 1.0$ MA, $\star$ $I_p 1.4 \rightarrow 1.7$ MA).

Fig. 22. Measured central T_i plotted versus confinement time at two different beam powers. I_p is a constant at $1.4 \rightarrow 1.7$ MA.

Fig. 23. The measured ion temperature plotted versus the ion temperature scaling for TFTR supersonic plasmas [Eq. (21)]. The ion temperature was measured by the nickel doppler broadening.

Fig. 24. The measured central electron density plotted versus the electron density scaling law for TFTR supersonic shots (all data) [Eq. (22)]. The ($\circ$) points did not have lithium pellets while the ($\bullet$) points did have lithium pellets.

Fig. 25. The measured central electron density plotted as a function of neutral beam power for two plasma currents at constant toroidal magnetic field ($B = 4.8 \rightarrow 5.1$ T), constant energy confinement time ($\tau_E = 0.13 \rightarrow 0.15$ sec) and for supersonic plasmas not aided by lithium pellets.

Fig. 26. The zero-dimensional modeled neutron emission with the plasma parameters determined by the TFTR supersonic scaling laws [Eq. (18)] plotted as a function of the measured neutron emission. The only data input is the measured energy confinement time. None of the plasmas were aided by lithium pellets.

Fig. 27. The relative contribution of thermonuclear, beam-target, and beam-beam neutron emissions from the zero-dimensional model Eq. (18). None of the plasmas were aided by lithium pellets.

Fig. 28. The measured energy confinement time as a function of the energy confinement scaling for TFTR supersonic shots [Eq. (24)].

Fig. 29. The measured energy confinement time as a function of the target CII light for co-dominated beam injection. The (X) data points have $B = 4.8 - 5.2$ T and $I_p = 1.4 - 1.7$ MA; the ($\blacksquare$) data points have $I_p = 1.0$ MA, and the ($\square$) data points have $B = 3.9$ T. The

data has been averaged in bins. The error bars are standard deviation of the mean. 357
plasmas make up the plot.

Fig. 30. Measured energy confinement time as a function of the target CII light at constant $B = 4.8 \rightarrow 5.1$ T and plasma current $I_p = 1.4 \rightarrow 1.7$ MA. The (X) have counter-dominated beam injection ($C_{NB} = 0.3$ to 0.48) and the ($\square$) points have co-dominated injection ($C_{NB} = 0.55$ to 0.75). The data have been averaged in bins. The error bars are standard deviations of the mean.

Fig. 31. Physics-based neutron scaling law, S_n^{PB} , for TFTR supershot plasmas (not aided by lithium pellets) plotted as a function of the measured neutron emission, S_n .

Fig. 32. Neutron emission from the physics-based neutron scaling law plotted as a function of beam power. The dot-dashed line uses Eq. (18) with the plasma parameters from Eqs. (19), (20), (21), (23), (24), and $C_{NB} = 0.63$. The long dashed line uses Eq. (22) in place of (23) and $C_{NB} = 0.5$. The short dashed line uses Eqs. (1), (24), and $C_{NB} = 0.63$ while the solid line uses (2), (24), and $C_{NB} = 0.5$. S_n^{LIMIT} is defined by Eq. (27) with the coefficients determined using Eq. (25a).

Fig. 33. Projected neutron emission as a function of magnetic field with the symbols being defined as for Fig. 32.

Fig. 34. Projected neutron emission for 6T, 2.2 MA, 32 MW operation as a function of target CII light. The symbols are the same as for Figs. 32 and 33.

Fig. 35. Projected neutron emission for 6T, 2.2 MA, CII = 2.4 A.U. as a function of beam power. The symbols have the same meaning as for Figs. 32-34.

Fig. 36. Ratio of the measured neutron emission, S_n , to the limiting neutron emission, S_n^{LIMIT} , as a function of the ratio of the measured plasma energy content to the Troyon energy limit. S_n^{LIMIT} is defined by Eq. (27) and (25a). The (■) have minor or major disruptions while the (X) points do not.

Fig. 37. The projected Q_{DT} calculated from the zero-dimensional model for the equivalent DT plasma as a function of the measured DD neutron emission. The (■) points have 1.0 MA plasma current, and the (X) points have $I_p = 1.6 \rightarrow 1.8$ MA.

Fig. 38. The projected β_α value averaged over the neutron emitting volume of the plasma as calculated by the zero-dimensional model for an equivalent DT plasma as a function of the measured DD neutron emission. The (■) points have 1.0 MA plasma current, and the (X) points have $I_p = 1.6 \rightarrow 1.8$ MA.

Fig. 39. The projected alpha density averaged over the neutron emitting volume as calculated by the zero-dimensional model for the equivalent DT plasma as a function of the measured DD neutron emission. The symbols have the same meaning as in Fig. 37.

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Fig. 20

Fig. 21

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Fig. 23

EMPIRICAL SCALING

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28

Fig. 29

Fig. 30

Fig. 31

Fig. 32

Fig. 33

CII

Fig. 34

Fig. 35

Fig. 36

Fig. 37

Fig. 38

Fig. 39
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