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Energy Confinement Time and Electron Density Profile Shape in TFTR

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Abstract

The electron density profiles of intense deuterium neutral-beam-heated plasmas ($P_{tot}/P_{ohm} > 10$) are characterized as a peakedness parameter ($F_{ne} = n_{eo}/\langle n_e \rangle$) in the Tokamak Fusion Test Reactor (TFTR). The gross energy confinement time ($\tau_E = E_{tot}/P_{tot}$) at the time of maximum stored energy is found to be a weak function of the plasma current and total heating power but depends strongly on the peakedness parameter. A regression study showed $\tau_E = 2.4 \times 10^{-3} F_{ne}^{0.78} I_p^{0.18} P_{tot}^{-0.12}$ for a data set of 561 discharges in the TFTR. Also τ_E can be represented as $\tau_E = \tau_E^L f(F_{ne})$, where τ_E^L is the empirical L-mode scaling result. A similar scaling applies to an appropriately defined incremental energy confinement time ($\tau_{inc} = dE_{tot}/dP_{tot}|_{F_{ne}=constant}$).

The Supershot regime¹⁻³ in TFTR is characterized by improved energy confinement and fusion reactivity. It is obtained when high-power deuterium neutral beams are injected into low-density target plasmas with low recycling ($R=0.5$).^{4,5} In this regime, the confinement and neutron source strength are maximized with nearly equal neutral beam power injected tangentially in the co and counter directions with respect to the plasma current. The low target-density is achieved through intensive wall conditioning which results in a significant reduction of the recycling of hydrogen isotopes. The achieved confinement time of the Supershot regime has been up to 2.5 times the prediction of the empirical L-mode⁶ scaling relation. In this paper, the correlation of the electron density profile shape with energy confinement time of the beam-heated plasmas in TFTR is investigated.

The profile characteristics of the Supershot regime are a highly peaked density profile, a peaked ion temperature with extremely high central temperature, and a relatively broad electron temperature profile. The recent experimental results from ASDEX,^{7,8} JET,⁹ and JFT-2M¹⁰ have also indicated the importance of the peaked density profile in improving energy confinement. We characterize the profile of the electron density by a peakedness factor (F_{ne}) defined as:

$$F_{ne} = \frac{n_{eo}}{\langle n_e \rangle},$$

where n_{eo} is the peak electron density and $\langle n_e \rangle$ is the volume-averaged electron density. F_{ne} is calculated from the inversion¹¹ of the measured line-integral density (10 chords) taking into account the elongation of the magnetic flux surface (as inferred from poloidal field measurements outside the plasma) and a self-consistent Shafranov shift. The typical error in the determination of F_{ne} is ± 0.1 . For the studies presented in this paper, the value of F_{ne} is sampled within ± 20 msec of the time of the peak in the magnetically¹² measured E_{tot} , where $(dE_{tot}/dt)/E_{tot} < 0.1/\text{sec}$. The wide range of the profile shape ($1.2 < F_{ne} < 3$) of the beam-heated plasmas in TFTR provides an excellent opportunity for studying the correlation of profile shape with other plasma parameters.

The deuterium plasmas in this study have toroidal magnetic fields of $B_T = 4.8 - 5.2$ T, plasma currents of $I_P = 0.8 - 1.8$ MA, and plasma major and minor radii of $R = 2.45$ m, and $a = 0.8$ m, respectively. Deuterium neutral beams with $E_{inj} \leq 110$ keV were injected with total power of up to

30 MW. For this study, data were restricted to nearly balanced injection, i.e., $(P_{co} - P_{ctr})/(P_{co} + P_{ctr}) \leq 0.4$, where P_{co} and P_{ctr} are the powers of the neutral beams injected co-parallel and counter-parallel to I_P , respectively. These plasmas achieved peak electron density n_{eo} of $(4 - 9) \times 10^{19} m^{-3}$, central electron temperature T_{eo} of 5 - 9 keV, and central ion temperature T_{io} of 15 - 30 keV for the Supershot regime. On the other hand, the plasma parameters for the L-mode discharges are n_{eo} of $(3-5) \times 10^{19} m^{-3}$, T_{eo} of 4-7 keV, and T_{io} of 5-8 keV. The range of target line average density (\bar{n}_{et}) was $(0.55 - 1.4) \times 10^{19} m^{-3}$ for the Supershot regime and $(1.4 - 4) \times 10^{19} m^{-3}$ for the L-mode regime, respectively. This study also included plasmas where the \bar{n}_{et} was raised from 1.4 to $4.6 \times 10^{19} m^{-3}$ by means of helium gas puffing at $I_P = 1.4$ MA resulting in a degradation of energy confinement from the Supershot to L-mode value.

One of the characteristics of the initial experiments ($I_P \leq 1$ MA) in the Supershot regime was absence of sawteeth during the beam heating phase. As I_P was raised to 1.8 MA, sawteeth were no longer suppressed for discharges with less peaked density profiles. The typical time history of various plasma parameters for sawtoothing and non-sawtoothing discharges is shown in Fig. 1. Sawtooth and non-sawtooth discharges were classified based on the time histories of X-ray emission, T_e and n_e , during the period when F_{ne} was rising during the heating phase ($\Delta t \geq 0.4$ sec). Often the supershot characteristics were destroyed due to a sudden increase of carbon influx from the wall during the heating period, as shown in Fig. 1. All the data in this study were sampled before discharges were spoiled by carbon influx. The ranges of F_{ne} were $1.2 < F_{ne} < 2.1$ and $1.8 < F_{ne} < 3$ for sawtoothing and non-sawtoothing discharges, respectively. Highly peaked discharges without sawteeth have a strong correlation with low \bar{n}_{et} . Note that the \bar{n}_{et} has been a good measure of the recycling^{4,5} of hydrogenic isotopes. The regression study showed that the reduction of \bar{n}_{et} was more important than the increase of P_B in obtaining highly peaked density profiles in a beam-heated plasmas. As the plasma current was raised, the lower bound of \bar{n}_{et} achieved was higher. The measured lower bound of \bar{n}_{et} was $0.55 - 1.46 \times 10^{19} m^{-3}$ for $I_P = 0.8 - 1.8$ MA.

Figure 2 illustrates E_{tot} as a function of P_{tot} . Here the 582 data points for various plasma currents are divided into two different groups: discharges with sawteeth and without sawteeth. The majority of the sawtoothing discharges occurred for $I_P \geq 1.4$ MA plasmas. The scatter of the E_{tot} data^{3,5}

for fixed total heating powers is pronounced especially when the high density helium target plasmas are considered. The importance of recycling in the Supershot regime is demonstrated through helium target discharges. In general, discharges with sawteeth have less stored energy compared to the discharges without sawteeth. Figure 3 shows τ_E as a function of F_{ne} for the data set in Fig. 2. For the deuterium target discharges, the dependence of τ_E on I_P and P_B is weak and the improvement of energy confinement is well correlated with F_{ne} . Also, it is notable that the confinement time of helium target discharges is consistently lower compared to deuterium ones for a fixed F_{ne} . The difference may be due to an intrinsic species dependence in beam-heated plasmas.

In order to show quantitative correlations between F_{ne} and other plasma parameters, a regression study was done. Here, the variables to be studied were τ_E , F_{ne} , I_P , and P_B for the deuterium discharges. The regression study revealed two important results. First, τ_E was strongly correlated with F_{ne} . Second, correlations between I_P and P_B were a strong function of F_{ne} . The results are as follows:

$$\tau_E = 2.4 \times 10^{-3} F_{ne}^{0.76} I_P^{0.18} P_{tot}^{-0.12}.$$

The weak scaling of τ_E on I_P and P_{tot} may be due to the increasing correlation between these two variables (i.e., $I_P \propto P_B^{0.6}$ for $F_{ne} \geq 2.3$). Note that I_P is a weak function of P_B for $1.1 < F_{ne} < 1.5$. In general, the higher beam power was used at higher plasma current to achieve higher F_{ne} for the well-conditioned discharges (i.e. low \bar{n}_{el}). For instance, the upper bound of P_B was 13 and 26 MW for $I_P = 0.9$ and 1.4 MA, respectively. Discharges encountered severe MHD activities and even disruptions due to the β limit¹³ for the P_B above an upper bound for $I_P \leq 1.4$ MA. For the discharges above 1.6 MA, the upper bound of P_B is limited by the maximum available power (30 MW).

Figure 3 illustrates the improved confinement time compared to the typical L-mode scaling results. Here, the correlation of an improved energy confinement with F_{ne} , τ_E/τ_E^L for the deuterium discharges is depicted as a function of F_{ne} , where τ_E^L is L-mode scaling confinement time with mass correction ($D^0 \rightarrow D^+$). Combining with the fact that I_P is strongly correlated with P_B , as F_{ne} is increased, τ_E can be represented as $\tau_E = \tau_E^L f(F_{ne})$. The τ_E is improved up to 2.5 times τ_E^L for the discharges with $F_{ne} \simeq 3$. Note that the helium target discharges are not included due to variation of the helium concentration.

The most striking feature of the gross energy confinement time of the Supershot regime was the strong correlation with the electron density profile shape. In order to demonstrate that a similar scaling applies to the incremental confinement time (τ_{inc}) for the high power beam-heated plasmas ($P_{tot}/P_{ohm} > 10$), the slope of the linear fitting for data points in Fig. 2 is determined with the restriction on F_{ne} rather than on I_P as typically defined (and sometimes on line average density). For this purpose, an incremental confinement time can be defined as follows:

$$\tau_{inc} = \frac{dE_{tot}}{dP_{tot}} \Big|_{F_{ne}=constant}.$$

Examples of τ_{inc} for three different windows of F_{ne} are illustrated in Figs. 4a, 4b, and 4c. These data illustrate the degree of correlation of P_B and I_P at fixed F_{ne} , and also the degree of difficulty of separating dependencies on I_P and P_B . The spread of E_{tot} for the fixed P_{tot} in Fig. 2 is found to be dominantly due to the shape of the electron density profile.

In summary, a strong correlation of both τ_E and an appropriately defined τ_{inc} on the electron density profile shape for the high power beam-heated plasmas in the TFTR has been established. The continuum between supershots and L-mode discharges is demonstrated in intense neutral-beam-heated plasmas.

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Figure 1 The typical time history of F_{ne} , central line integral density, X-ray emission (central line of sight), and T_{eo} , for sawtoothing (solid line) and non-sawtoothing (dashed line) discharges at $I_P=1.4$ MA with $P_B=22$ MW.

Figure 2 (a) The scaling of E_{tot} with P_{tot} for various plasma currents. (b) τ_E as a function of F_{ne} .

Figure 3 τ_E/τ_E^L as a function of F_{ne} for the data shown in Fig. 2, except helium target plasmas.

Figure 4 Three examples of τ_{inc} determined as a slope of the data points depicted in Fig. 2a selected with a window of F_{ne} . (a) $\tau_{inc}=137$ msec. (b) $\tau_{inc}=121$ msec. (c) $\tau_{inc}=98$ msec. Symbols are the same as those in Fig. 2a. Helium target discharges are not included.

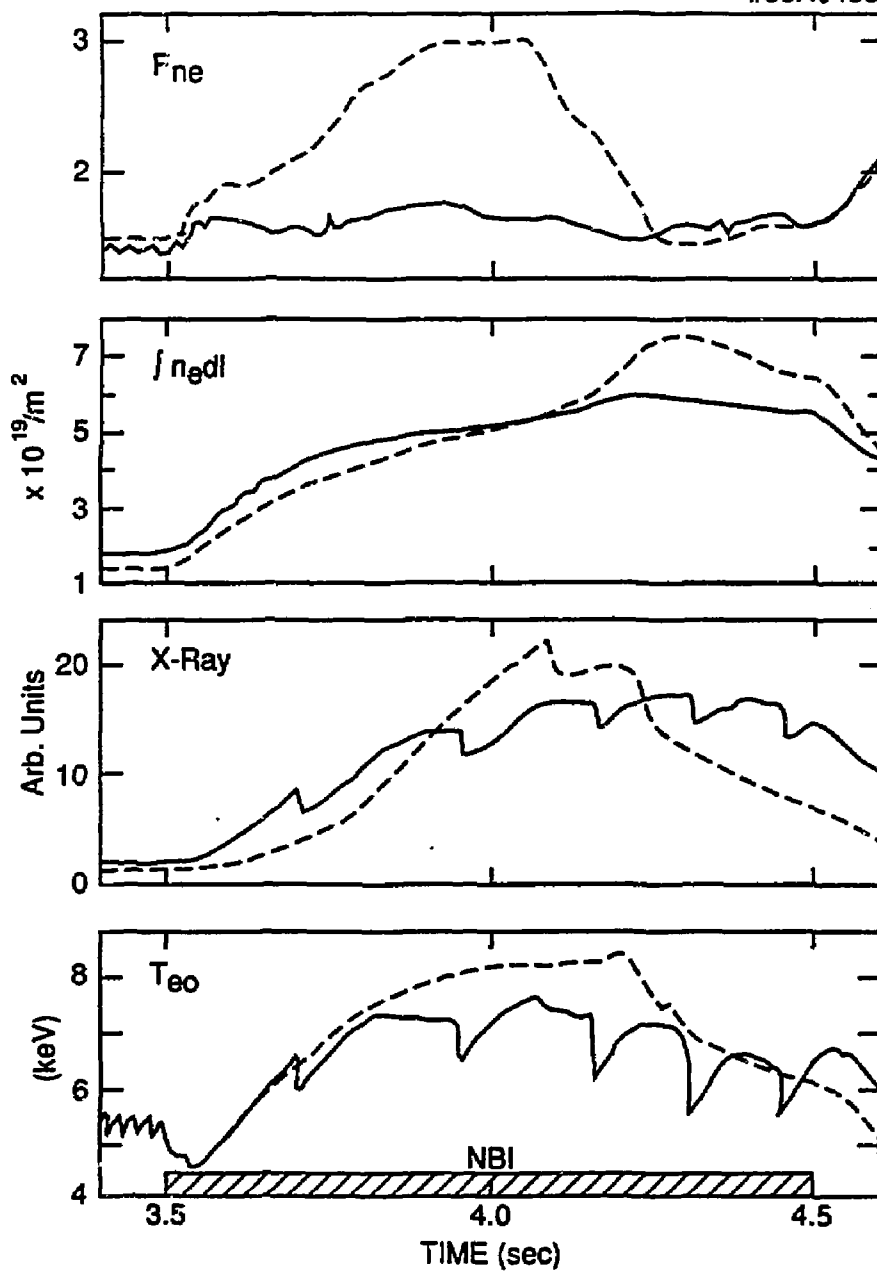


Figure 1

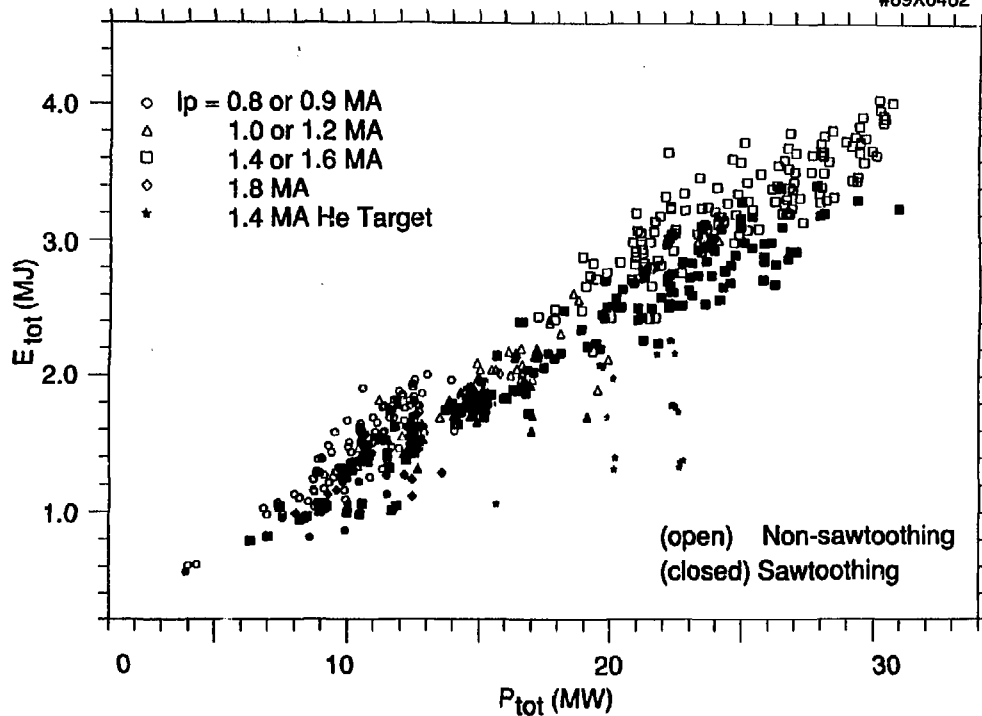


Figure 2a

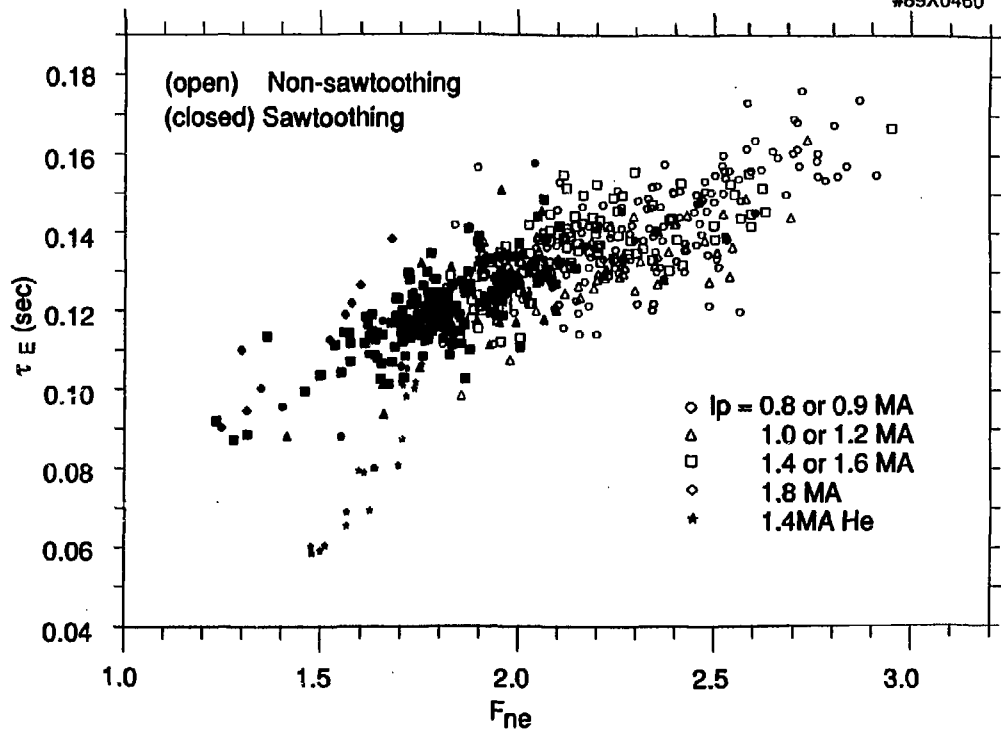


Figure 2b

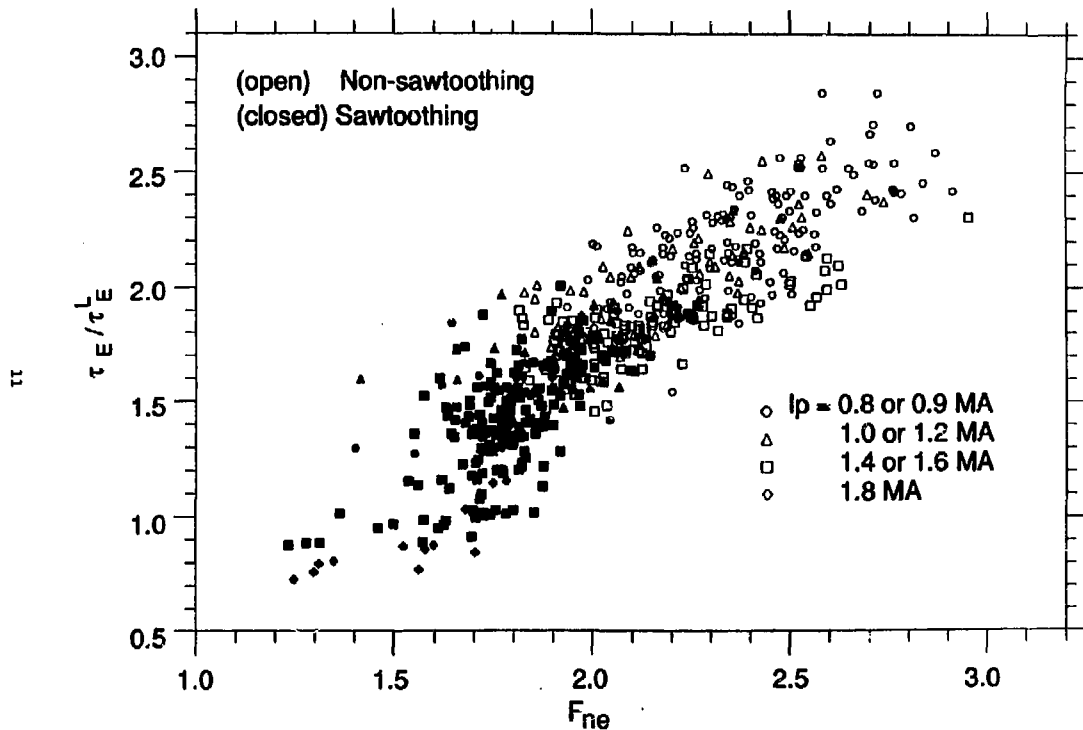


Figure 3

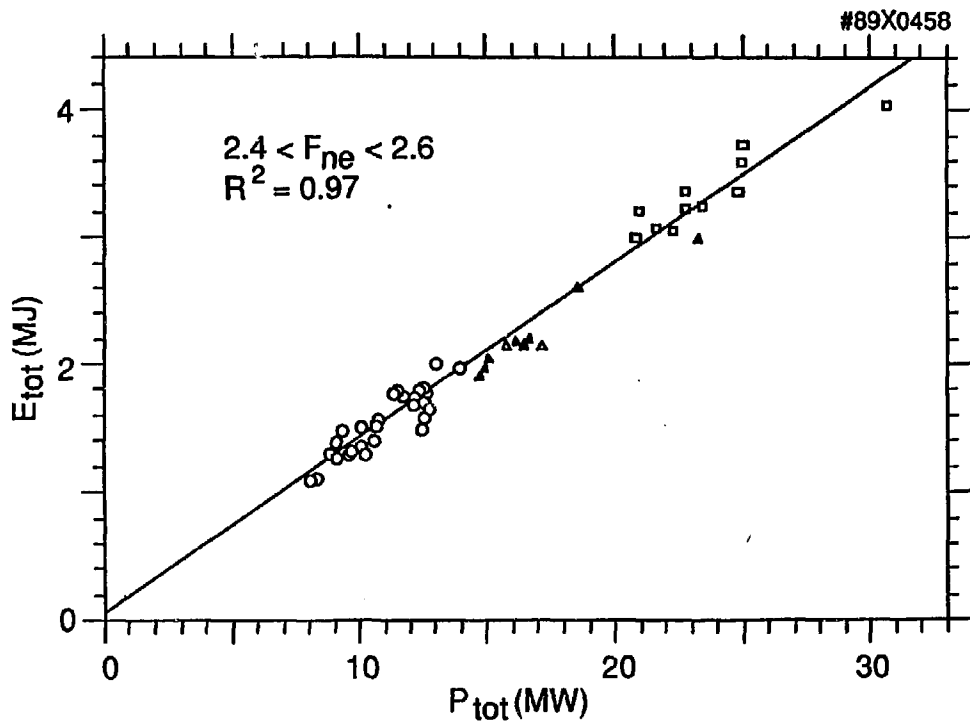


Figure 4a

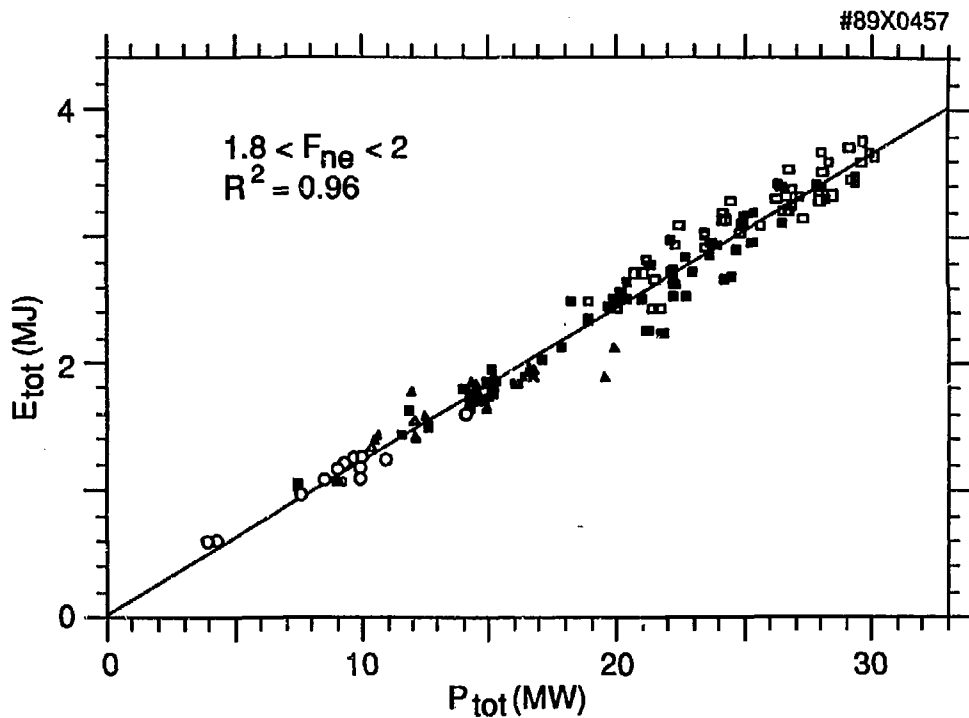


Figure 4b

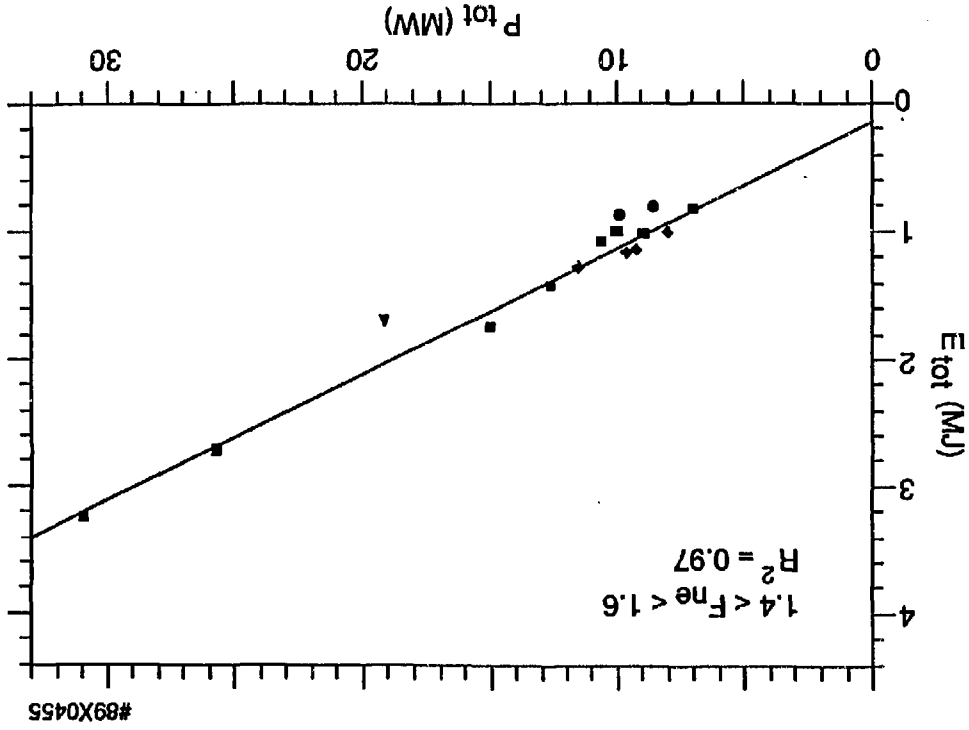


Figure 4c