DYNAMIC SIMULATION OF ITER

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A point-kinetics model has been used to investigate the dynamics of the International Thermonuclear Experimental Reactor (ITER). Four different confinement scaling have been tried. The analysis shows the ability of the reactor to approach a steady state operation. It also shows the sensitivity of the reactor dynamics to the confinement scaling. It has also been found that the reactor power can be increased either by increasing the rate of the injected fuel or by decreasing the energy of the injected fuel.

NOMENCLATURE

n_i, n_e, n_α	ion, electron and alpha particle densities, cm^{-3}
T_i, T_e, T_α	ion, electron and alpha particle temperatures, KeV
$T_{Ei}, \tau_{Ee}, \tau_{E\alpha}$	energy confinement time for ions, electrons and alpha particles, sec
$\tau_{pi}, \tau_{p\alpha}$	particle confinement time for ions and alpha particles, sec
S	fueling rate, ions/cm^3 sec
V_i	energy of injected ions, KeV
V_e	energy of injected electrons, KeV
a	minor radius, m
R	major radius, m
A	aspect ratio = R/a
B	confining magnetic field strength, Tesla
q	tokamak safety factor
R_e	average reflectivity to microwaves of the surfaces facing the plasma
I	plasma current, MA
A_i	isotopic mass number
K_x	elongation at the x-point

1. INTRODUCTION

Although it is not clear at this time whether the first generation reactors will be pulsed or steady state systems, it is expected that some of them at some point will operate in a steady state mode. For such systems, the question of dynamics is very important.

Bian [1] developed a simplified approach to determine the dynamic and stability properties in a fusion system. His approach is based on the determination of the system transfer functions. He restricted his analysis to a tokamak-type system that follows a trapped ion scaling law. Oda et al. [2] examined the dynamic behavior and controllability of fast-fission D-T tokâmak hybrid reactors. A hybrid reactor is a reactor concept which contains fissionable materials in its blanket surrounding the plasma.

In this paper, we investigate the dynamics of a tokamak reactor by solving the dynamic equations which govern the temporal behavior of the fusion system. As will be seen, the different terms in the dynamic equations depend nonlinearly on the plasma parameters. In addition, the dynamic behavior of the system is very sensitive to the confinement scaling considered. Section 2 contains the dynamic model of a fusion system as well as the method of solving the time-dependent dynamic equations. Section 3 applied the model to the International Thermonuclear Experimental Reactor (ITER) to investigate the effect of the rate and energy of injected fuel on the output power as well as on the plasma parameters such as density and temperature. The conclusions of this study are contained in Section 4.

2. DYNAMIC MODEL

The dynamic equations of fusion system with confined plasma are given as [3]

$$\frac{dn_i}{dt} = -\frac{n_i}{\tau_{pi}} - \frac{1}{2} n_i^2 < \sigma \nu > + S, \quad (1)$$

$$\frac{dn_\alpha}{dt} = -\frac{n_\alpha}{\tau_{p\alpha}} + \frac{1}{4} n_i^2 < \sigma \nu > , \quad (2)$$

$$\frac{3}{2}\frac{d}{dt}(n_\alpha T_\alpha) = -\frac{3}{2}\frac{n_\alpha T_\alpha}{\tau_{E\alpha}} + (Q_\alpha + \frac{3}{5}T_i)\frac{n_i^2 < \sigma \nu >}{4} - W_{\alpha e} - W_{\alpha i} \quad (3)$$

$$\frac{3}{2}\frac{d}{dt}(n_i T_i) = -\frac{3}{2}\frac{n_i T_i}{\tau_{Ei}} + W_{\alpha i} + W_{ei} - \frac{3}{4} T_i n_i^2 < \sigma \nu > + S V_i, \quad (4)$$

$$\frac{3}{2}\frac{d}{dt}(n_e T_e) = -\frac{3}{2}\frac{n_e T_e}{\tau_{Ee}} + W_{\alpha e} - W_{ei} - B_B - P_s + S V_e, \quad (5)$$

In this model, the fusion plasma is described by a mean concentration n_j, and a mean temperature T_j for each species followed in the reactor. To preserve the quasineutrality property of the plasma, the electron density is given by

$$n_e(t) = n_i(t) + 2\, n_\alpha(t).$$

In Eqs. (1) - (5), the energy-averaged fusion reaction rate $<\sigma v>$ is given by [3]

$$<\sigma v> = 3.7 * 10^{-12}\, h(t_i)\, T_i^{-2/3} \exp\left(\frac{-20}{T_i^{1/3}}\right) cm^3 /sec,$$

where

$$h(h_i) = \begin{cases} 1 & \text{if} T_i < 50 \text{KeV} \\ \left[1 + \left(\frac{T_i}{70}\right)^{1.3}\right]^{-1} & \text{if} T_i = 50-500 \text{KeV}. \end{cases}$$

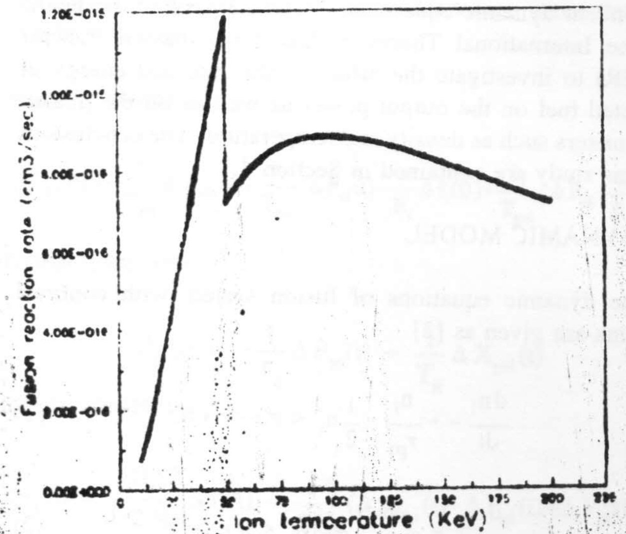

Figure 1. $<\sigma v>$ versus ion temperature.

The rates of energy transfer from the fusion alpha particles to the electrons and ions of the plasma can be written as [3]

$$W_{\alpha e} = 2.7 * 10^{-12} \frac{n_e n_\alpha (T_\alpha - T_e)}{T_e^{3/2}} \text{KeV/cm}^3 \text{ sec},$$

$$W_{\alpha i} = 1.3 * 10^{-10} \frac{n_i n_\alpha (T_\alpha - T_i)}{(T_\alpha + 1.6 T_i)^{3/2}} \text{KeV/cm}^3 \text{ sec},$$

while the rate of the energy transfer from ions to electrons can be written as [3]

$$-W_{ei} = W_{ie} = -5.1 * 10^{-13} \frac{n_e n_i (T_e - T_i)}{T_e^{3/2}} \text{KeV/cm}^3 \text{ sec},$$

The bremsstrahlung loss terms is given by [3]

$$P_B = 3.3 * 10^{-15}\, n_e^2\, \bar{Z}\, T_e^{1/2} \text{ KeV / cm}^3 \text{ sec},$$

where $\bar{z} = \sum_{ions} n_i z_i^2 / \sum_{ions} n_i z_i$ is an average charge number in the plasma.

The synchrotron radiation loss rate takes the following forms [3]

$$P_s = 4.1 * 10^3\, n_e^{0.5}\, T_e^2\, B^{2.5} \left(\frac{1 - R_e}{a A}\right)^{0.5} \text{KeV / cm}^3 \text{ sec},$$

for $T_e < 50$ KeV, and

$$P_s = 70\, n_e^{0.5}\, T_e^{2.8}\, B^{2.5} \left(\frac{1 - R_e}{a A}\right)^{0.5} \text{KeV / cm}^3 \text{ sec},$$

for $T_e > 50$ KeV.

Q_α, the alpha particle energy is equal to 3.5 MeV for D-T fusion plasma. The different particle and energy confinement times will be discussed in Section 3.

In Eq. (5), since the injected electron energy V_e is much smaller than the injected ion energy V_i in a neutral bean system, and typically the electron energy injection rate SV_e is mush smaller than the energy transfer rate from alpha particles to electrons $W_{\alpha e}$ [1], the electron injection energy V_e is ignored.

With some algebra, Eq. (1)-(5) can be reduced to the following set of equations

$$\frac{dn_i}{dt} = -\frac{n_i}{\tau_{pi}} - \frac{1}{2} n_i^2 <\sigma v> + S, \tag{6}$$

$$\frac{dn_\alpha}{dt} = -\frac{n_\alpha}{\tau_{p\alpha}} + \frac{1}{4} n_i^2 <\sigma v>, \tag{7}$$

$$\frac{dT_\alpha}{dt} = T_\alpha \left[\frac{1}{\tau_{p\alpha}} - \frac{1}{\tau_{E\alpha}}\right] + \frac{1}{2} \frac{n_i^2 <\sigma v>}{n_\alpha} \left[\frac{T_i}{5} - \frac{T_\alpha}{2} + \frac{Q_\alpha}{3}\right]$$

$$-\frac{2}{3n_\alpha}(W_{\alpha e}+W_{\alpha i}) \quad (8)$$

$$\frac{dT_i}{dt}=T_i\left[\frac{1}{\tau_{pi}}-\frac{1}{\tau_{Ei}}-\frac{S}{n_i}\right]+\frac{2}{3n_i}(W_{\alpha i}+W_{ei}+SV_i), \quad (9)$$

$$\frac{dT_e}{dt}=T_e\left(\frac{n_i}{n_e\tau_x}+\frac{2n_\alpha}{n_e\tau_{p\alpha}}-\frac{S}{n_e}-\frac{1}{\tau_{Be}}\right)+\frac{2}{3n_e}(W_{\alpha e}-W_{ei}-P_B-P_s+SV_e) \quad (10)$$

Eqs. (6)- (10) are a set of simultaneous nonlinear first order differential equations which can be integrated numerically to give the time dependence of the plasma parameters (n_i, n_α, T_α, T_i, and T_e). In this work, the numerical integration was performed using Runge-Kutta method [4].

Released in each D-T reaction are a 3.5 MeV alpha particle which is confined by the magnetic field and a 14.1 MeV neutron which escapes from the plasma and is absorbed in the neutron blanket. Since the alpha particles are thermalized inside the reactor core and neglecting the energy multiplication obtained from breeding tritium in the neutron blanket, we can write the reactor power output as

$$P_n=\frac{1}{4}n_i^2<\sigma\nu>Q_nV,$$

where $V = 2\pi^2\alpha^3 A$ is the plasma volume and $Q_n = 14.1$ MeV.

3. RESULTS AND DISCUSSION

3.1 Validation of the Method

Calculations are performed using the reference reactor considered by Kammash [3]. Table (1) gives the parameters of this reactor. For the confinement scaling, we consider the anomalous scaling law (drift wave turbulence) namely

Table 1. Reference reactor parameters.

B = 6 Tesla	a = 2 m
A = 5	q = 2
R_e = 90 %	D-T fuel

Table 2: ITER parameters

B = 4.85 Tesla	a = 2.15 m
A = 2.79	q = 3.1
R_e = 90 %	D-T fuel

$$\frac{1}{\tau_p}=\frac{1}{10}\frac{T_e^{1.5}}{B^2a^3}(qA)^{0.5},$$

for both ions and alpha particles. The different energy confinement times are approximately equal to the particle confinement time. The steady state reactor power has been calculated for different values of the fueling rate. The results obtained are shown in Figure (2) as well as the curve obtained by Kammash. As can be seen from the figure, our results are in good agreement with Kammash curve.

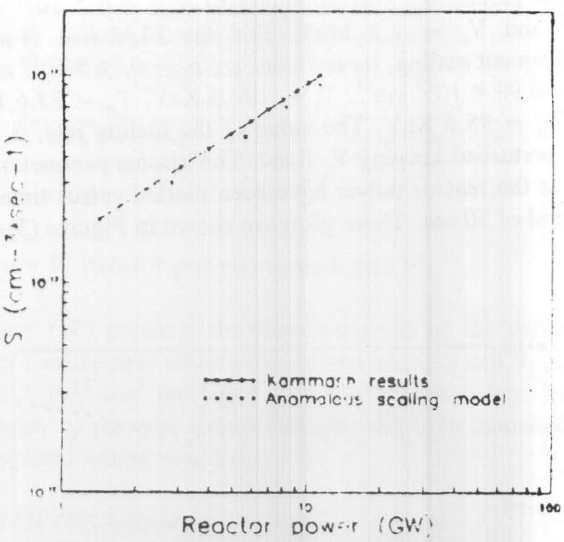

Figure 2. Steady state reactor power versus fueling rate as compared with Kammash results.

3.2 ITER application

The model has been applied to the International Thermonuclear Experimental Reactor (ITER) [5] - [7]. In this work, we adopt the physics phase parameters which are summarized in Table 2. As auxiliary heating a scenario of 75 MW, 1.3 MeV neutral beam was proposed. For the confinement laws, we used four different scaling which are:

1. ITER (89) L-mode power law confinement scaling

$$\tau_E^{ITER89-p}=0.048I^{0.85}R^{1.2}a^{0.3}\bar{n}_{20}^{-0.1}B^{0.2}(A_iK_x/P)^{0.5}.$$

2. ITER (89) L-mode off-set linear confinement scaling

$$\tau_E^{ITER89-OL}=0.064I^{0.8}R^{1.6}a^{0.6}\bar{n}_{20}^{-0.6}B^{0.35}A_i^{0.2}K_x^{0.5}/P+0.04I^{0.5}R^{0.3}a^{0.8}A_i^{0.5}K_x^{0.6}$$

3. ITER (89) ELM-free H-mode confinement scaling

$$\tau_E^{ITER90-H}=(FLM-free)=0.064I^{0.87}R^{1.81}a^{0.13}\bar{n}_{20}^{-0.09}B^{0.15}A_i^{0.5}K_x^{0.36}P^{-0.51}.$$

4. ITER ELMy H-mode confinement scaling

$$\tau_E(\text{ELMy H-mode}) \sim 0.75\,\tau_E(\text{ELM free H-mode})$$

where P is the net heating power in MW, defined as $P \approx P_\alpha + P_{aux} - P_{rad}$, $\bar{n}_{20}$ is the electron density in 10^{20} m^{-3}. In the calculations, I, A_i and K_x are set equal to 22 MA, 2.5 and 2.22 respectively. For each one of the above confinement scaling, $\tau_{p\alpha}$ and τ_{pi} are set equal to $10\tau_E$ while τ_{ei}, τ_{Ee} and $\tau_{E\alpha}$ are set equal to τ_E.

This simulation starts whit steady state values for the plasma parameters corresponding to $S = 6.6 * 10^{11}$ cm^{-3} sec^{-1} and $V_i = 1.3$ MeV. For the FLM-free H-mode confinement scaling, these values are $n_i = 0.26 * 10^{14}$ cm^{-3}, $n_\alpha = 0.98 * 10^{13}$ cm^{-3}, $T_i = 100.2$ KeV, $T_e = 33.6$ KeV and $T_\alpha = 95.6$ KeV. The value of the fueling rate, S, has been perturbed keeping V_i fixed. The plasma parameters as well as the reactor power have been plotted versus time for a period of 50 sec. These plots are shown in Figures (3)-(8).

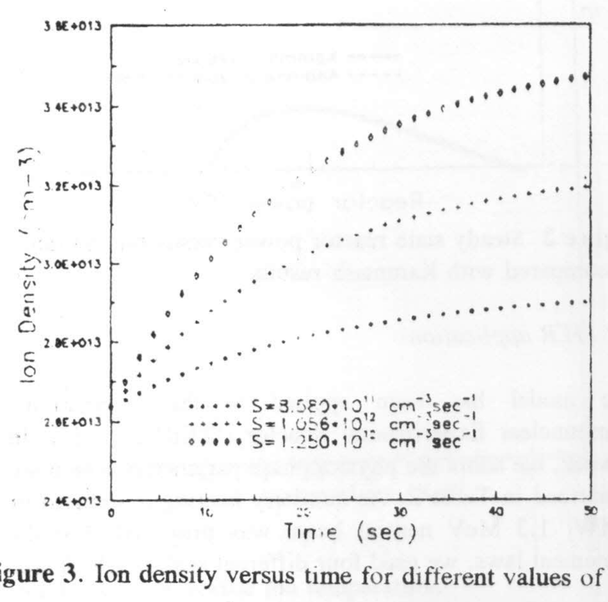

Figure 3. Ion density versus time for different values of S.

The figures show that the reactor power and the plasma parameters except the alpha particle density approach new steady state values within this period of 50 sec. As S increases, they reach higher steady state values but in longer time. The dip observed in the alpha particle density, n_α, in Figure (4) can be explained by the behavior of n_i and T_i shown in Figures (3) and (5) respectively. For higher S, T_i is higher but in this ion temperature range, $<\sigma\nu>$ decreases leading to a decrease in the fusion rate and subsequently in the rate of production of alpha particles.

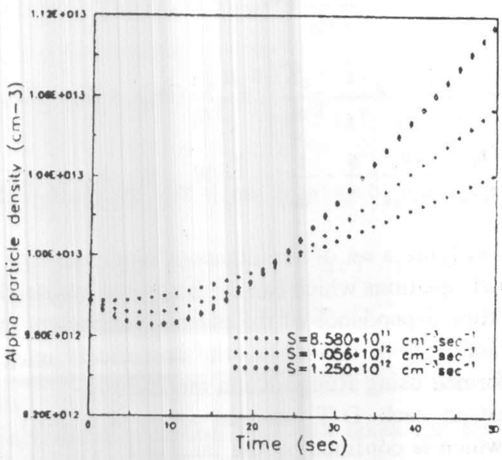

Figure 4. Alpha particle density versus time fo different values of S.

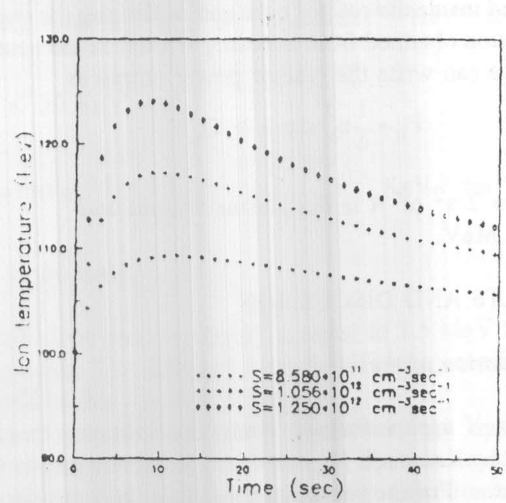

Figure 5. Ion temperature versus time for differen values of S.

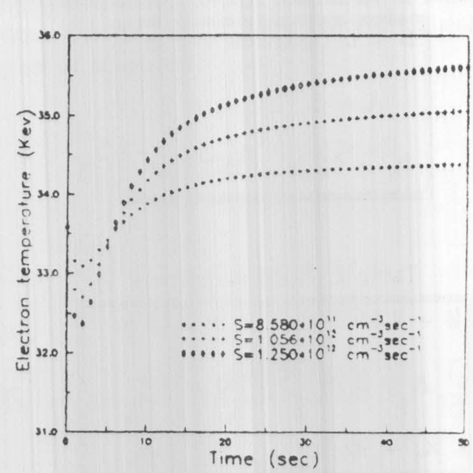

Figure 6. Electron temperature versus time for different values of S.

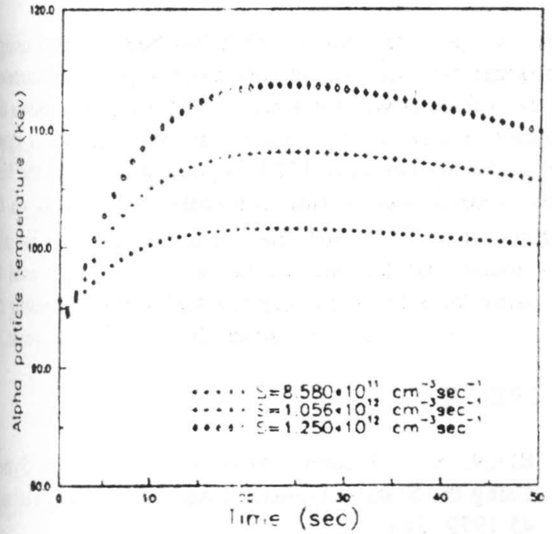

Figure 7. Alpha particle temperature versus time for different values of S.

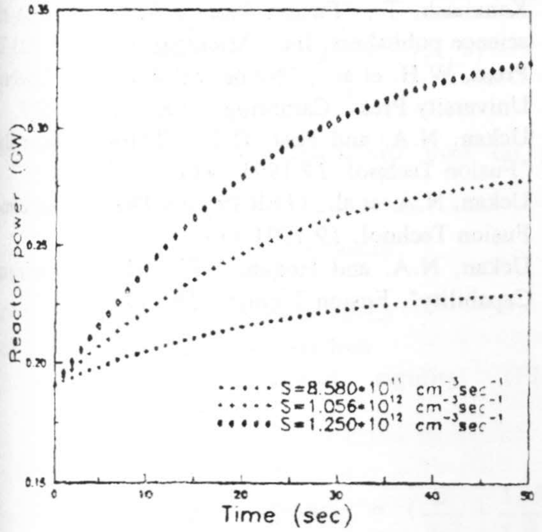

Figure 8. Reactor power versus time for different values of S (V_i = 1.3 MeV).

This effect is contradicted by the increase of n_i with S shown in Figure (3) leading to higher production of alpha particles. Up to about 10 sec, the decrease in $<\sigma\nu>$ dominates and alpha particles escape more than they are produced while the increase of n_i dominates after that causing the dip to appear.

In Figure (9), the reactor power at 50 sec is plotted versus both S and V_i. As can be observed, the increase in S leads to an increase in P_n but the increase in V_i leads to a decrease in P_n. This dependence on V_i can be attributed to the same fact explained above. An increase in V_i leads to higher ion temperature but lower fusion reaction rate causing the reactor power to decrease.

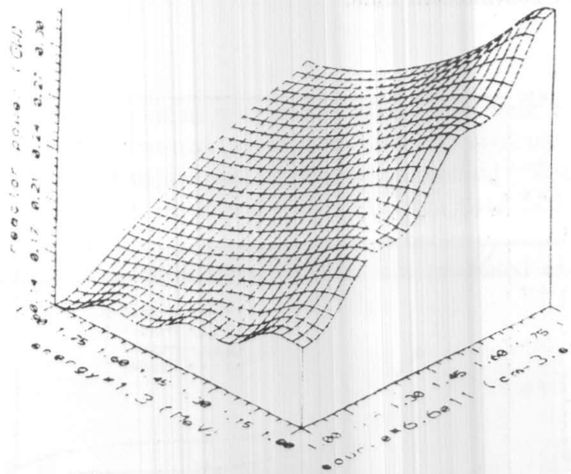

Figure 9. Reactor power versus S and V_i.

Figure (10) presents the time variation of the different energy confinement scaling considered taking S and V_i equal to 6.6 * 10^{11} cm^3 sec^{-1} and 1.69 MeV respectively. In all the cases, τ_E remains almost constant and is in the range of the required values which are [7]

τ_E (ITER (89) L-mode power law) = 1.9 sec
τ_E (ITER ELM-free H-mode) = 5.5 sec
τ_E (ITER ELMy H-mode) = 4.1 sec

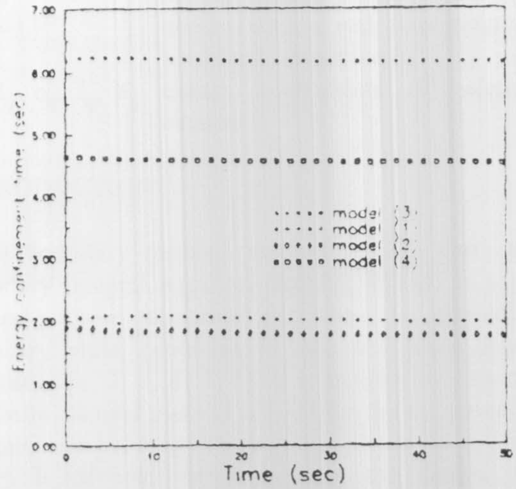

Figure 10. Energy confinement time versus time for different ITER confinement scaling (S = 6.6 * 10^{11} cm^{-3} sec^{-1} and V_i = 1.69 Mev).

In Figure (11), the reactor power for the different confinement scaling with the same values of S and V_i, as above, are plotted versus time. As can be expected, P_n depends on the scaling considered and is higher for the longer confinement time.

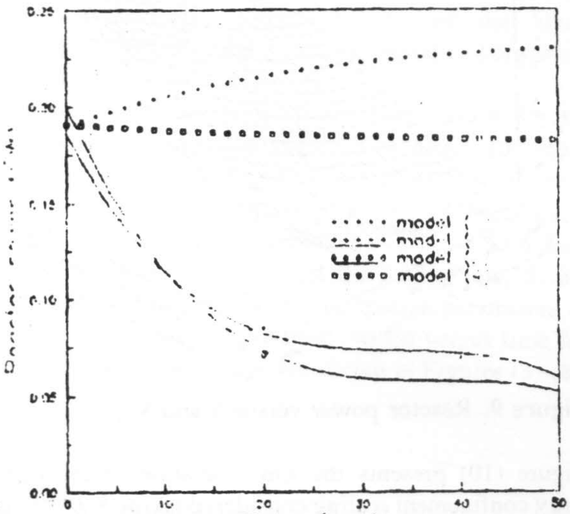

Figure 11. Reactor power time for different ITER confinement scaling ($S = 6.6 * 10^{11}$ cm^{-3} sec^{-1} and $V_i = 1.69$ Mev).

4. CONCLUSIONS

The dynamic behavior of ITER has been studied using point-kinetics model. A simulation of the plasma parameters and the reactor power for a period of 50 seconds shows that operation in a steady state mode can be achieved. It shows also that the dynamics of ITER depend strongly on the form of the confinement scaling considered as well as on the behavior of $< \sigma v >$ with the ion temperature. It has also been found that the reactor power can be increased by increasing the rate of the injected fuel while increasing the energy of the injected fuel causes the power to decrease.

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