TABLE 2

$1\frac{1}{2}$D Ignitor Modelling Results
using JET and T-10 Benchmarking

	$n_{eo} = 1.5 \times 10^{21} m^{-3}$ $< n_e >= 0.55 \times 10^{21}$ $Z_{eff} = 1.2$			
	JET Benchmark			**T-10 Benchmark**
q_o	0.4	0.7	0.8	0.3
τ_s s	∞	∞	200	∞
τ_E (2.8s)	0.8	0.7	0.48	0.3
t_{ign} s	1.5	2.7	∞	∞
T_{io} keV	8.5	8.5	3.0	4.5
P_α MW	15	17	1.7	2.1
P_{OH} MW	8	8	15	18.5
β_p	0.22	0.25	0.13	0.12

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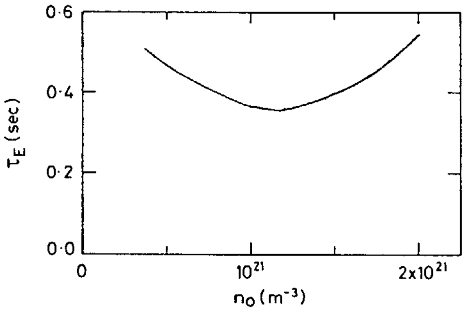

Figure 1 τ_E required for ignition in 2.8 sec as a function of density n_o

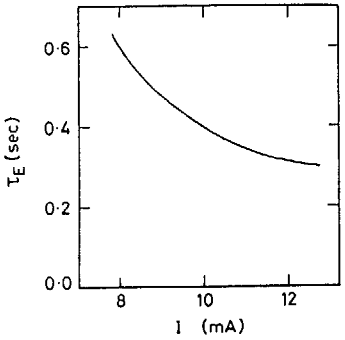

Figure 2 τ_E required for ignition in 2.8 sec as a function of plasma current I.

A PHYSICS PERSPECTIVE ON CIT

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Introduction

The mission of the CIT device is to study the physics of self-heated fusion plasmas, and to demonstrate the production of substantial amounts of fusion power. In order to achieve this mission with maximum confidence, and minimum cost, CIT is designed as a high-field, compact, copper-alloy-magnet device of modest pulse length. The most appropriate dimensionless parameters to measure extrapolation in confinement physics are $\omega_c\tau_E$ and $nT\tau_E/B$. CIT is projected to stand midway between JET and the ITER interim conceptual design in these parameters, and so represents a *relatively* modest step. Nonetheless, because for dimensionlessly similar devices ($aB^{4/5}$ = const.[1]) $nT\tau_E$ is proportional to B, we project CIT to have about the same $nT\tau_E$ as ITER, ~10x that of JET. Our projections for confinement, impurity levels, and profile shapes indicate that CIT should attain Q ~ 25, with 20 MW of heating power (P_{fus} = 500 MW), corresponding to $\beta = 3\%$ (=2I/aB). Even given pessimistic assumptions, CIT should achieve its basic mission to determine the confinement physics, operational limits, and α-particle dynamics of self-heated fusion plasmas with α power greater than auxiliary heating power, while producing more than 100 MW of fusion power. In reaching these conditions CIT will also explore heating, fueling, and plasma handling techniques necessary to produce self-heated fusion plasmas, at surface power densities appropriate for economic DT fusion reactors.

Dimensionless Scaling Analysis

Kadomtsev[1] has shown that under rather general assumptions a class of dimensionlessly similar devices is characterized by $I_p \alpha B^{1/5}$, $a \alpha B^{-4/5}$, $n_e \alpha B^{8/5}$, $P \alpha B^{3/5}$, $\tau_E \alpha B^{-1}$, $nT\tau_E \alpha B$. The usefulness of this approach for projecting the performance of future devices has been stressed by Rebut, Lackner, and Sheffield. We have tested Kadomtsev's analysis by performing linear regression on the Kaye-ITER[2] L-mode database in the following form:

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2. University of Texas, Austin TX
3. Massachusetts Institute of Technology, Cambridge MA
4. Lawrence Livermore National Laboratory, Livermore CA
5. Oak Ridge National Laboratory, Oak Ridge TN
6. University of California, Los Angeles CA
7. General Atomics Corp., San Diego CA

$$\ln(B^{\gamma}\tau_E) = \nu_1 + \nu_2\ln(aB^{4/5}) + \nu_3\ln(n_eB^{-8/5}) + \nu_4\ln(PB^{-3/5}) + \nu_5\ln(q) + \nu_6\ln(R/a) + \nu_7\ln(\kappa) + \nu_8\ln(A_i) \qquad \text{(eq. 1)}$$

with the exponent of B, γ, taken as variable. Since the intrinsic measurement error in this database probably approaches 10%, it is remarkable that the fit optimizes with 12.6% R.M.S. error at γ=0.934, close to the theoretical value of 1.0. The fit error rises parabolically to ~16% for $|\gamma - 1| = 1$.

Examination of existing ohmic heating results reveals that PLT and Alcator C density-scan data are extremely close to dimensionless similarity in all respects except for aspect ratio (3.3 vs. 3.9). The confinement measurements from these two devices, plotted on appropriate axes (fig. 1), show remarkable agreement in magnitude and in variation with normalized density, supporting the extension of the Kadomtsev dimensionless-similarity analysis to high-field tokamaks.

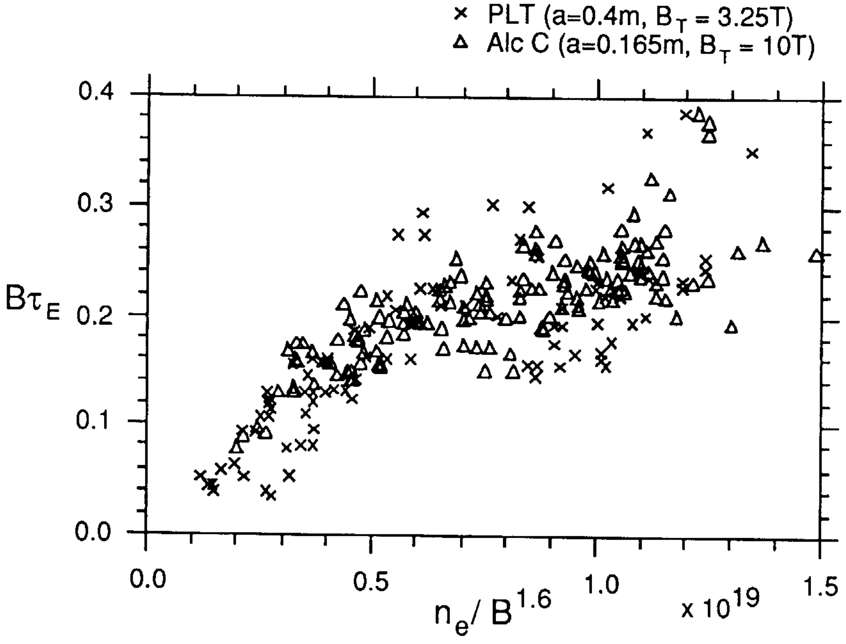

Fig. 1. PLT and Alcator C[3] data plotted on Kadomtsev axes (all units SI).

Kadomtsev's analysis has been tested previously by noting the closeness of various OH and L-mode scaling relations to meeting the constraint of equation (1) with γ=1. Indeed an L-mode scaling relation derived by linear regression on the Kaye-ITER database, constrained via equation (1) with γ=1, differs from a free regression fit in its prediction for CIT parameters by only 10%. The Kadomtsev similarity perspective, then, can be used to understand the advantages of attaining high $nT\tau_E$ by working at high magnetic field. Since $nT\tau_E$ is maximized for a class of dimensionlessly similar devices by operating at high B and small size, the distance in dimensionless parameters (e.g. ν_*, ρ_i/a, $\omega_c\tau_E$, $nT\tau_E/B$) which must be traversed from present devices to a device which achieves the $nT\tau_E$ required for high gain is minimized at high B. Thus the physics risk with respect to confinement extrapolation is minimized. Since for fixed magnet technology, cost scales much more strongly with size than with field strength (up to the appropriate stess limits), the cost/performance ratio is also minimized by operating in this regime. The appropriate pulse length for a compact high-field DT tokamak is 5 – 10τ_E, where helium ash build-up can be observed but active pumping is not required. The limit to this high-field, reduced-size approach is set by 1) the need to test reactor-like plasma-handling techniques (flexible divertors, high elongation), 2) the need to maintain adequate access for diagnostics and for intense auxiliary heating (in order to ensure the ability to perform α-particle physics studies at relevant temperatures and β's even if confinement is relatively poor), and 3) the need to limit surface power density at the β required to study the relevant α physics.

Performance Projections

It is important to project for CIT not only the expected performance, but also the range of uncertainty of performance, in order to assess the degree of confidence in achieving CIT's mission. The main CIT parameters are: R=2.14m, a=0.66, κ_{95}=2, B_T=10T, I_p=11MA. We take as baseline parameters for performance projection: τ_E^{Hmode} = 1.85x ITER89-P L-mode scaling, Z_{eff} = 1.65 due to carbon and helium, square-root-parabolic density profiles, and trapezoidal temperature profiles, flat from r = 0 to a/q_{95}.

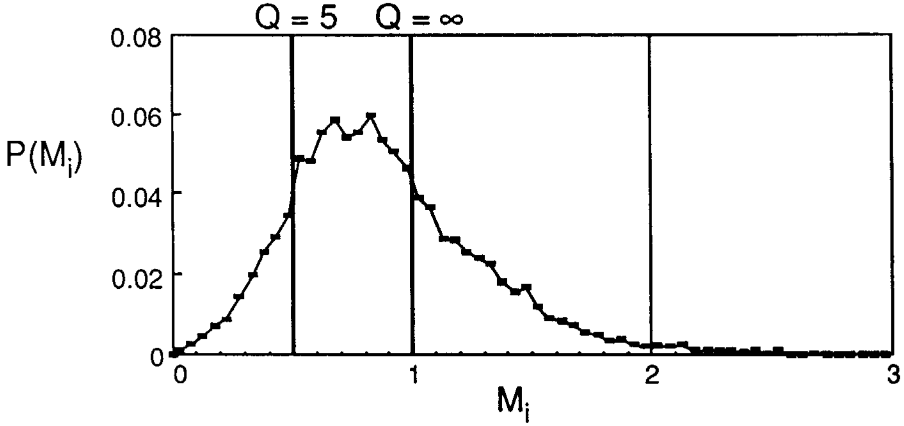

Fig. 2. Relative probability distribution of ignition margin, $M_i = P_\alpha/P_{loss}$. $Q = 5M_i/(M_i - 1)$. (Bin width, ΔM_i = 0.05, 5000 samples.)

For the ranges of uncertainty of the most important variables, we take a Gaussian distribution of confinement time with 1σ width +/- 25%, a Gaussian distribution of density profile exponent, α_n, with 1σ width +/- 0.5 and a lower cut-off at 0, and a Gaussian distribution of Z_{eff} with 1σ width +/- 0.35 and a lower cut-off at 1.2. The helium ash concentration is taken to be 3% of the electron density for $\tau_E \geq 1.85$x ITER89-P (corresponding to 1.5GJ of fusion energy production, with 100% helium ash accumulation), falling linearly to 0.5% for 1.4x ITER89-P. We use a Monte Carlo sampling technique[4] to evaluate the distribution of expected performance (fig. 2), and find that a moderate level of optimism leads to ignition even at reduced field and current, while moderate pessimism leads to Q ~ 5. The median projected performance is found to be Q ~ 25, corresponding to 500 MW of fusion power with 20 MW of auxiliary heating.

The CIT Physics Program

The CIT physics program will be a natural continuation of tokamak confinement research into the high $nT\tau_E$, α-dominated DT regime. Full understanding of the physics behavior in this regime will ultimately be required to optimize a tokamak reactor. Profile and fluctuation diagnostics will be provided in order to make contact with results from previous experiments, and new diagnostic techniques for understanding transport will be implemented as appropriate. Diagnosis of edge plasma behavior in the H-mode (scrape-off widths, parallel and perpendicular transport, fluctuations, and impurity behavior) will be especially important to understand and optimize divertor operation at reactor-like surface power densities. Diagnostics will be provided on CIT to measure the distribution of contained α particles, the loss of α particles due to α-driven instabilities, and the mode properties of α-driven instabilities. The clearest test of α heating efficiency requires operation at $Q \geq 5$, where the α power begins to dominate over the auxiliary heating power. At Q = 5 the "offset-linear" or "incremental confinement time" paradigm[5] provides a useful basis for comparing 40 MW of α + RF heating in a DT plasma to a baseline case of 20 MW of RF heating in a non-reacting plasma. In the range Q = 5 to ignition, CIT can study the initial α-driven thermal excursion for a period of $5 - 10\tau_E$. With adequate feedback bandwidth, 0-D calculations indicate that very high Q's can be stably controlled via modulation of the RF heating power, but $1^1/2$-D calculations suggest that profile evolution (in effect excursions from a given fixed-profile <nT> vs. <n> plane) will be most important in affecting burn dynamics.

This work supported by U.S. DOE contract DE-AC02-76-CHO-3073

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Burn Threshold for Fusion Plasmas with Helium Accumulation*

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The ignition and burn criteria for fusion plasmas are re-evaluated, taking into account the ratio of α particle confinement time τ_α to energy confinement time τ. Due to helium ash build-up, the burn threshold is raised substantially compared to the usual ignition criterion. No steady state burn is possible when $\tau_\alpha/\tau > 15$, and even small concentrations of impurities can substantially reduce this upper limit, resulting in stringent requirements on radial transport, recycling and pumping of helium ash. H-mode plasmas, which may exhibit high values of τ_α, are undesirable for steady state burning, since large τ_α implies low fueling rate and hence low fusion power yield.

The classic requirement for fusion power generation is that the Lawson parameter $n\tau$ exceed 2x10^{20} sec/m^3 at a plasma temperature T ~ 10 keV. The condition $n\tau T >$ 2x10^{21} sec keV m^{-3}, or, equivalently, $\beta B^2\tau > 1.6$ Tesla^{2}sec, is a way of approximately taking into account the temperature dependance. However, these simplified criteria ignore the thermalized helium population, which can dilute the D-T fuel and increase the energy loss due to bremsstrahlung radiation. We examine here the effects of this helium "ash" accumulation, which could be of importance in predicting the performance of ignition experiments such as ITER and CIT. Both of these devices appear to lie below the simplified ignition thresholds if they operate in L-mode, so some increase in $\beta B^2\tau$ is required. Since B fields are already near the stress limits of present materials and β has been pushed to (and is restricted by) the MHD (Troyon) limit, it will be necessary to raise τ, for example by operating in H-mode, which increases τ by a factor of two or more. However, the particle confinement time also increases, and, in fact, by a much larger factor, so the ratio $\gamma \equiv \tau_\alpha/\tau$ of effective α particle containment time to central energy confinement time can increase appreciably during a transition from L-mode to H-mode.

Using a highly simplified, phenomenological model, we find that γ is a crucial parameter for steady steady burn. Our model assumes that the electron density n is feedback controlled, and hence can be treated as a constant; that the central energy confinement time τ determined by