Report[+] on

ASSESSMENT OF BURNING-PLASMA PHENOMENA

in a

COMPACT IGNITION TOKAMAK

presented to the

MAGNETIC FUSION ADVISORY COMMITTEE

by

PANEL XIV

February 10, 1986

[+]This Report was prepared by a Panel established by the Magnetic Fusion Advisory Committee (MFAC). The findings and recommendations presented herein do not necessarily represent the views of MFAC.

Department of Energy
Washington, D.C. 20545

AUG 8 1985

Dr. Ronald C. Davidson
Director, Plasma Fusion Center
Massachusetts Institute of Technology
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Dear Ron,

Understanding the properties of burning plasmas is one of the key technical issues for magnetic fusion as stated in the Magnetic Fusion Program Plan. Recent studies at several institutions have identified low cost, compact, high-field, copper-coil tokamak configurations that would achieve ignition under presently accepted scaling laws. Studies of the feasibility and costs of such configurations will be continued with results expected in mid-FY 1986. Also, the Technical Working Party of the Summit has concluded that a compact ignition experiment would provide valuable operating experience for devices such as NET and FER. Thus, it is important that the Department be prepared for appropriate decisions regarding such an experiment.

Therefore, I request that MFAC examine the extent to which these compact tokamak ignition experiments can resolve the technical issue of understanding the properties of burning plasmas under a variety of conditions ranging from Q>5 through ignition and advise the Department regarding the technical merits of proceeding with this type of experiment. Reference configurations for your consideration should encompass the class of devices represented by IGNITOR, LITE, and ISP.

In formulating your advice I request that you consider at least the following factors:

1. The importance and comprehensiveness of burning plasma phenomena likely to be accessible in a compact tokamak experiment as well as phenomena that cannot be addressed in such a device.

2. The quality of understanding of these phenomena that can be gained from experimental diagnostics and interpretive theory over the range in operating conditions expected to be available to a compact tokamak ignition experiment.

3. The extent to which information gained in a compact tokamak ignition experiment is applicable to understanding burning plasma conditions in other toroidal and non-toroidal magnetic confinement systems.

I request that MFAC deliver its report by January 10, 1986, to assist the Department in formulating its position regarding possible compact tokamak ignition experiments.

Sincerely,

Alvin W. Trivelpiece
Director, Office of
Energy Research

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1.0 Executive Summary

1.1 Introduction

The primary objective of the U.S. Magnetic Fusion Program is to build the scientific and technological base required to establish fusion as a viable energy source for deployment in the 21st Century. This objective is being pursued in a broadly based program characterized by a growing level of international collaboration.

At the present time, the U.S. Fusion Program is confronted by the task of making progress despite severe budgetary stringencies. These circumstances call for a careful examination of program priorities. Achievement of the primary program objective will require progress in the areas of burning plasmas, improvement of magnetic confinement concepts, and the development of fusion technology and materials. There is a consensus that understanding the physics of burning plasmas is the next major step on the path to developing fusion power. The confinement concept most ready to start on this assignment is the tokamak.

Maintaining the health of the program will require continued breadth in order to build scientific understanding and to develop optimal confinement concepts, including advanced forms of the tokamak. At the same time, the major progress already made toward achieving the conditions for a self-sustaining fusion reaction should be put to an experimental test.

The present generation of tokamaks will explore plasma confinement at near-reactor parameters. TFTR and JET are expected to carry out the first DT experiments with plasmas at breakeven conditions. Success in this international tokamak program could lead directly to a burning-plasma experiment as the next step. The major motivations for such an experiment are:

1. To obtain sufficient information to predict the properties and behavior of burning plasma confined in fusion-relevant magnetic-field configurations.
2. To identify generic burn-control problems and test burn-control techniques.

3. To begin to address some generic non-plasma issues: tritium handling, remote handling, plasma-wall interactions, hardened diagnostics, etc.

Compact, high-field, copper-coil tokamak configurations offer a route to a low-cost ignition experiment that would provide most of the critical burning-plasma data for the successful future operation of an integrated Engineering Test Facility. Modest extrapolation of the present experimental data base supports the possibility of ignition in a compact tokamak device ($I_p \gtrsim 10$ MA, $B_T \gtrsim 10$ T, $R < 1.5$ m). Computer modeling studies of ignition will be refined further as high-power heating (ICRF and neutral-beam) results from existing tokamaks become available in 1986-87. This time scale is consistent with the start of construction of a Compact Ignition Tokamak (CIT) in 1988-89 and operation beginning as early as late 1992.

A major effort is being made to minimize the cost of the CIT and to take advantage of site credits. The goal is to have a total project cost of less than $300M, including adequate diagnostics, while counting on additional site credits of ~ $200M. Not more than $100-150M, spread over 4-5 years, should be required beyond what is saved by terminating the TFTR Program earlier than if CIT were not pursued. A proposal for the CIT is presently being prepared, and will be completed by May 30, 1986. A more complete cost estimate will be available at that time.

This report is provided to the Magnetic Fusion Advisory Committee (MFAC) to help the Committee respond to the August 8, 1985 charge from Dr. A. W. Trivelpiece (Director, OER) concerning possible compact ignition tokamak experiments. In his charge, Dr. Trivelpiece requested MFAC to

> "examine the extent to which these compact tokamak ignition experiments can resolve the technical issue of understanding the properties of burning plasmas under a variety of conditions ranging from Q > 5 through ignition and advise the Department regarding the technical merits of proceeding with this type of experiment".

The complete charge letter, including three more specific charges, is given in the Preface. MFAC Panel XIV was formed on August 15, 1986 to address this charge. The Panel members are listed in the Preface. MFAC Panel XIV met three times (October 10-11, 1985 at Princeton, NJ; November 8-9, 1985 at San Diego, CA; and January 22-23, 1986 at Austin, TX). A Chairman's Report on MFAC Panel XIV activities was presented to MFAC on November 20 at Santa Fe, and the final MFAC Panel XIV report is to be presented to MFAC on February 19, 1986.

The Panel was aided in its deliberations by presentations from the Ignitor, LITE, and ISP conceptual design groups and by information about the physics base and other project-related matters provided by the Ignition Physics Study Group (IPSG) and the Ignition Technical Oversight Committee (ITOC). The activities of these various groups are proceeding in parallel and will continue to refine the basis for a CIT in the areas of physics, design, and project planning.

MFAC Panel XIV found the following general issues to be of importance in formulating its response to the specific charge:

1. The relationship of the CIT to the Magnetic Fusion Program Plan.
2. The relationship of the CIT to the overall tokamak program goals.
3. The scientific data base for CIT.
4. The optimization of project designs and goals in the presence of a project cost limit.
5. The relationship of the CIT to international collaboration in fusion.
6. The relationship of CIT project goals to different proposed CIT designs, including various magnetic field strengths, degrees of diagnostic access, and dependence on various levels of auxiliary heating.

In addition, the Panel's assessment of the importance of the information obtained from a CIT depends on several assumptions. These assumptions are:

1. The CIT plasma will ignite with burn times of at least 10 energy confinement times.

2. The total CIT project cost will be less than \$300M when site credits are taken into account.

3. The funding for fusion remains stable in the range of ~ \$350M per year.

1.2 Main Findings

Finding 1 Plasma behavior under ignited conditions represents a new frontier of physics that must be explored and understood as part of an assessment of magnetic fusion. Although some predicted properties of ignited plasmas can be simulated in non-ignited regimes, we also expect to uncover important new phenomena. Optimization of an ultimate fusion reactor will require understanding of burn physics as well as concept improvement. The Panel finds that it is an urgent task for fusion research to address both of these issues experimentally at this time.

Finding 2 During the past several years, the U.S. fusion program has examined a sequence of proposed burning-plasma tokamaks having successively reduced scope and cost. While giving up first the project objective of nuclear-component testing and then very long-pulse operation, the program has now focused on the CIT as a minimum-size and cost ignition experiment that retains the capability to explore the essential tokamak burning-plasma physics issues.

Finding 3 The burning-plasma issues that are most important for the development of fusion are those relating to the confinement of the energetic alpha particles produced by the fusion reaction and the confinement of reactor-relevant plasmas that are heated mainly by these alpha particles. Other very important issues relate to controlling the profiles, thermal excursions and composition of a burning plasma.

Finding 4 The Compact Ignition Tokamak (CIT) Project has these primary objectives:

1. To perform a DT ignition test, including detailed studies of a burning plasma in support of the development of the tokamak reactor concept, and in support of the planning for high-duty-cycle long-pulse operation in a tokamak Engineering Test Facility.

2. To provide understanding of the physics of burning plasmas which will be valuable in the development of the tokamak concept and to a lesser extent the non-tokamak concepts.

A secondary objective is to stimulate the development of diagnostics and remote handling for D-T fusion systems, and to develop generic information in areas such as pellet ablation and burn control.

Finding 5 The CIT will address most of the critical tokamak issues associated with the confinement of the fusion energy released in the form of the energetic-alpha particles. The degree of relevance and understanding will depend on both the achievable range of plasma parameters and the available diagnostics.

Finding 6 The CIT will begin to address the important issues relating to control of a burning plasma. Some issues, such as quasi-steady-state current-profile effects and ash removal, will require investigation on a longer-time-scale device.

Finding 7 The CIT is the most effective approach to the rapid attainment of an ignited plasma with reactor-relevant parameters. The existing tokamak data base is adequate, with credible extrapolation, to proceed with the design of the CIT. Forthcoming experimental results from presently operating tokamaks will enhance this data base and should reduce the remaining uncertainty of the extrapolation. With the proposed FY-88 start of construction, we should have acquired sufficient information from present large machines on which to base a final decision to proceed with the construction of the CIT.

Finding 8 While the tokamak concept is most ready to start on the burning-plasma step, further concept improvement is essential to identifying an economical tokamak development path, and developing a tokamak reactor that has commercial applications. The present CIT incorporates some advanced tokamak features, such as RF heating, strong plasma shaping, and a divertor. However, present CIT designs do not incorporate all the advanced-tokamak features that may be needed to make an attractive reactor. In particular, the projected CIT beta values (6-7%) are below those projected for a tokamak reactor (minimum ~ 10%), and long-pulse current drive is not part of the CIT scope. The ability of the CIT project to incorporate future tokamak techniques, for example by adding RF stabilization of MHD instability modes, or by introducing CIT cores of more advanced design, will require further study.

Finding 9 The proposed CIT project schedule fits naturally into the timing of scientific advance in the tokamak area. Early initiation of the CIT project would serve to maintain the U.S. fusion program at the frontline of international research, and would be of essential value to the world fusion program. The CIT results would be available in time to help insure the successful operation of an Engineering Test Facility.

Finding 10 The charge to MFAC Panel XIV asks for an evaluation of the technical merit of the CIT and of how the CIT can resolve the technical issues of understanding the physics of burning plasmas. The decision to proceed with the construction of a CIT will also require:

1. An assessment of the technical risks in producing the desired plasma parameters.
2. An assessment of cost and schedule estimates.
3. A more detailed assessment of the relationship between the CIT and the remainder of the U.S. and international fusion program.

Finding 11 The CIT experiment would benefit both the tokamak program and, to a lesser extent, non-tokamak programs as well. Certain aspects of alpha-particle physics would be expected to be similar in different confinement devices of similar properties and parameters, such as alpha-energy transfer mechanisms, alpha-kinetic effects on MHD modes,and alpha coupling to Alfven waves. Many of the techniques necessary to achieve the ignition regime should be directly transferable, such as radiation-hardened diagnostics, alpha-particle diagnostics, tritium handling, etc.

Finding 12 Non-tokamaks, and to a lesser extent advanced tokamaks, have unique burning-plasma issues that would not be addressed directly by the CIT experiment. Certain aspects of alpha-particle physics would be expected to vary, just as confinement physics varies. The data from the CIT would provide a valuable experience base for developing understanding of different behavior in other devices, and would facilitate the planning and reduce the risk of future burning-plasma studies that may have to be undertaken with other concepts.

1.3 Recommendations

Main Recommendation The magnetic fusion program should embark on a Compact Ignition Tokamak (CIT) experiment as a national effort, provided the project can be accommodated within a budget that preserves the necessary balance between burning-plasma issues and other priority fusion program issues. A $300M project cost appears to be an appropriate upper limit.

Supporting Recommendation 1 The CIT should be designed with high confidence in the achievement of ignition. In view of the remaining uncertainties in regard to tokamak confinement scaling and ICRF heating, the performance assessment for the CIT should be updated annually beginning in December 1986, on the basis of experimental results from existing tokamaks. In particular, DOE should make a formal assessment to verify that present confinement and other design considerations are correct before commitment of major construction funds.

Supporting Recommendation 2 The CIT should be more than a demonstration of ignition. The CIT should be capable of operating over a range of plasma parameters in order to investigate burning-plasma phenomena.

Supporting Recommendation 3 A detailed cost-to-benefit assessment should be undertaken for options to explore higher beta plasmas and longer pulse operation, possibly at reduced magnetic-field strength.

Supporting Recommendation 4 Diagnostic requirements should be addressed from the outset of the CIT design. Realistic diagnostic costs should be included within the prescribed project cost envelope. R&D efforts should be initiated addressing diagnostic issues in a fusion environment, both through adaptation of previously existing techniques and development of new techniques and instruments.

Supporting Recommendation 5 The future operating costs of the CIT should be estimated as part of the CIT proposal.

2.0 Background

2.1 The Role of the CIT in the Magnetic Fusion Program Plan

The Magnetic Fusion Program Plan (MFPP) identifies four key technical issues for magnetic fusion:

1) Magnetic Confinement Systems
2) Properties of Burning Plasmas
3) Fusion Materials
4) Fusion Nuclear Technology

These four MFPP issues are to be addressed by the late 1990's leading to an assessment of fusion. The CIT would be the primary source of information on burning plasmas for this assessment. The science objective of the MFPP is to be able to predict the behavior of plasma confined in fusion-relevant magnetic configurations. Therefore, it is desirable to have the CIT program planned in a way that maximizes the predictive information in a timely and cost-effective manner. An important scientific issue has to do with the relationship of the burning-plasma phenomena to the nature of the confinement concept. This is discussed in section 5 of this report.

2.2 Description of the CIT

2.2.1 CIT Project Summary

The compact ignition tokamak is a small high-field copper-coil tokamak whose primary purpose is to address the physics of burning plasmas. Several alternative CIT configurations (Ignitor, LITE and ISP) have been considered with regard to plasma performance, engineering feasibility, cost and schedule. Recently, the ITOC arrived at a consensus concerning the best design characteristics for the initial CIT proposal to DOE. The parameter range of this device is given in Appendix Table 6.1.1. The ignition project will further develop this embodiment and submit a formal proposal to DOE by May 30, 1986. The fastest technically possible schedule calls for Title I fabrication beginning in FY-88 and first plasma in December 1992 (see Appendix

Figure 6.1.2). Obviously MFAC Panel XIV is not in a position to review the technical details, but can offer recommendations to guide the preparation of the proposal.

2.2.2 Physics Guidelines for Design of the CIT

The physics guidelines for the design of the CIT were established by the ITOC following extensive discussion with the U.S. tokamak community and with input from the foreign tokamak programs. When calibrated in the range of currently achieved parameters, the guidelines correspond to 80% of the highest performance levels. In the following the units are m, T, sec, MA.

Energy confinement is taken to follow standard neo-Alcator scaling ($\tau_E \approx 0.07\ \bar{n}_e\ aR^2q$), but allowance is made for a possible degradation of confinement with total heating power following the L-Mode empirical model.

Volume-average plasma density is constrained by the Murakami limit to $< 1.5 \times 10^{19}$ B/Rq in the presence of alpha-particle heating.

Volume-average beta is held below β = 3I/aB (Troyon limit) which corresponds to $\beta \sim 6\%$ for typical CIT parameters.

Plasma Shape is limited to moderate elongations ($K \leq 1.8$) and aspect ratios ($R/a \geq 2.7$).

Plasma Current is limited by requirements on the MHD safety factor [$q(a) \geq 2.6$, with the auxiliary condition that $q > 2.0$ at 5 cm inside the plasma boundary].

Burn Duration at maximum current and field is required to be $10\tau_E$ at 10 keV.

Impurity Control is aimed at $Z_{eff} \leq 1.5$. A poloidal divertor is the preferred option.

Plasma Heating specifications call for a machine capability up to 20 MW of absorbed ICRF power, but the physics guidelines suggest less will be required.

Number of Full-Power Burn Pulses has been set at $\gtrsim$ 3000, with the capability for 20,000 pulses at reduced parameters.

2.2.3 CIT Plasma Performance Projections

The plasma performance of the CIT has been modeled by using various computer codes, including one-dimensional time-dependent transport codes. This modeling activity is carried out by the Ignition Physics Study Group, and is used by the Ignition Technical Oversight Committee to guide the design of the CIT. A set of typical calculations is shown in the Appendix for a nominal CIT with R = 1.4 m, a = 0.5 m, K = 1.8, B_T = 10 T and I_p = 10 MA. The first example has transport given by neo-Alcator scaling without degradation due to heating power, which gives a plasma operating contour plot as shown in Figure 6.1.3. This example has τ_E ~ 0.7 - 1.0 sec, giving an ignition margin $n\tau/n\tau_{ignition}$ ≈ 1.5, and requires auxiliary heating power of ~ 5 MW to reach ignition conditions. When the confinement time is degraded with total power according to the L-Mode model, the plasma operating contours are shifted as shown in Figure 6.1.4. In this example, the confinement time was reduced to ~ 0.4 sec resulting in a marginally ignited plasma. About 15 MW of auxiliary power is required to reach the ignited state for L-Mode scaling. The time evolution of some plasma parameters for both types of confinement scaling is given in Figure 6.1.5 and 6.1.6. Note that the auxiliary-heating power is on from 3 sec to 6 sec. The ohmic confinement case has reduced I_p and B_T to allow an extended field pulse with a flattop of ~ $10\tau_E$, and achieves burn control by using density reduction to maintain an equilibrium burn of ~ 8 sec at 85% of the beta limit. The L-Mode scaling case has a burn of ~ 5 sec at ~ 60% of the beta limit.

The central alpha-particle parameters (Figure 6.1.7) for the L-Mode case reach central alpha-density fractions of $n_\alpha(0)/n_e(0)$ ~ 0.7% with central beta fractions of $\beta_\alpha(0)/\beta_{th}(0)$ ~ 20%. These fractions are a function mainly of temperature and can therefore be varied over a significant range for the case of ohmic scaling.

An important factor in the CIT is the evolution of the plasma current profile. Various studies are in progress on techniques to rapidly raise the plasma-current and control the initial plasma current profile.

3.0 Burning-Plasma Phenomena for a Tokamak

3.1 Introduction

A burning or ignited plasma is one in which the heating of the plasma by the internally-generated fusion alpha particles is sufficient to balance all the plasma energy losses. This chapter will: (1) identify major new physical phenomena that arise in a burning tokamak plasma; (2) assess the importance of the study of each; and (3) discuss whether or not they can be studied in a CIT. The engineering issues of a burning plasma are not considered in this report.

Note that this section is also limited to a discussion of physical phenomena of a burning **tokamak** plasma. Importance is judged only in terms of the development of a **tokamak** fusion reactor. The questions as to whether or not the study of a phenomenon is relevant to other magnetic confinement configurations, and what other physical phenomena arise in other configurations are dealt with in section 5 and in Appendices 6.3-6.6.

To assess the importance of the study of particular phenomena, one must determine not only the importance of the effects of the phenomena, but also to what degree of confidence the results can be predicted now. If there is a high degree of confidence that we can predict the results, then the study of the phenomena may not be judged to be very important. However, the effects caused by the phenomena could still be important. These two different meanings of importance will be addressed separately below.

Some of the burning-plasma phenomena can be studied in a non-ignited plasma if the alpha production rate is sufficiently high. The alpha production rate can be quantified using the energy multiplication factor $Q = P_{fus}/P_{ext}$, where P_{fus} is the D-T fusion power produced (in alpha particles and neutrons) and P_{ext} is the external heating rate of the plasma. Ignition corresponds to infinite Q. For a D-T plasma, the internal fusion alpha heating power equals the externally supplied power when Q = 5. This occurs because the D-T fusion reaction produces 20% of its energy in charged alpha particles that are presumed to deposit their energy in the plasma.

Although particular phenomena may be present in a burning plasma, study of them will require adequate diagnostics. In this chapter it is assumed that the effects of the phenomena can be diagnosed. Diagnostic needs are discussed in section 4.

3.2 Parameters of a CIT in Comparison with Present Large Tokamaks and a Tokamak Fusion Reactor

The plasma parameters of a CIT differ from those in present large tokamak experiments primarily in regard to smaller size ($R_o \lesssim 1.5$, $a \lesssim 0.6$ m), higher density (n up to 10^{15} cm^{-3}), stronger magnetic field ($B_t \gtrsim 10$ T) and higher plasma current ($I \gtrsim 10$ MA). The levels of plasma current and overall plasma confinement ($T_i n \tau_E$) in the CIT are comparable to those believed to be needed in a tokamak fusion reactor. The CIT would differ from presently conceived tokamak reactors primarily in regard to higher density, lower beta (~ 6%) and shorter burn-pulse length ($t_{burn} \sim 10\ \tau_E$).

The most important plasma-parameter comparisons between present tokamaks, the CIT and a tokamak fusion reactor are shown in Table I. As indicated, the CIT closes the gap between present tokamaks and a tokamak reactor to a substantial degree. At the onset of ignition, the three key dimensionless plasma parameters relating to collisionality, magnetic Reynolds number and beta in a CIT are quite similar to conditions in present tokamaks. Thus, the plasma properties at the onset of ignition in a CIT should be predictable from present empirical scaling laws; the CIT burn phase would extend the parameter regime toward reactor level parameters. One notable aspect of a CIT is the low perpendicular thermal diffusivity (χ_E) required. Because of its smaller size, the CIT requires a lower χ_E than either present large tokamak experiments or tokamak reactors. The ability to achieve such a low χ_E is characteristic of the high-field, high-density Alcator devices on which the CIT is based. For the typical CIT cases that have been modeled, $\chi_e \sim 2\text{-}3\ \chi_i^{nc}$ at r = 2a/3, so that the electrons are still expected to be the dominant loss channel.

3.3 Burning-Plasma Phenomena in a Tokamak

The various new physical phenomena arising in a burning plasma will be divided into five categories as follows:

1. Single-Alpha-Particle Issues -- Phenomena associated with the

TABLE I.

Comparison of Some Key Parameters for Present Large Tokamaks, a Compact Ignition Tokamak and a Tokamak Reactor. The exact numbers are uncertain and in fact have ranges; only the trends in the numbers are important.

	Present Large Tokamak Experiments (TFTR, JET, JT-60, DIII-D)		Compact Ignition Tokamak		Tokamak Reactor
	Present	Projected	Onset of Ignition	Steady Burn	Burn
Q (ratio of fusion to loss power)	~0.1*	~1	5	$\to\infty$	$\to\infty$
Temperature-Confinement Product ($T_i n\tau_E$--keV cm^{-3} sec)	5×10^{13}	6×10^{14}	3×10^{15}	3×10^{15}	3×10^{15}
Collisionality+ (ν_*: ratio of effective collision to bounce frequency)	0.05	0.02	0.05	0.02	0.01
Magnetic Reynolds Number+ (S: ratio of magnetic diffusion to Alfven time)	3×10^7	10^8	10^8	3×10^8	10^9
β (%--ratio of plasma to magnetic pressure)	0.5	2-10	1.5	3-6	8-10
β_θ (ratio of plasma to poloidal magnetic pressure)	0.2	0.4-2	0.3	0.5-1	1-2
χ_i^{nc} (m^2/sec)+ (ion heat diffusivity coefficient)	0.2	~0.2	0.1	~0.1	0.03
Needed $\bar{\chi}_E = a^2/4\tau_E$ (m^2/sec) (total energy diffusivity)	0.5	1	0.2	~0.2	0.5
Burn pulse time (t_{burn}/τ_E)	-	-	-	10	$\to\infty$

*Projected from TFTR D-D operation in 1985.

+Estimated at the two-thirds radius (r/a = 2/3).

interaction between individual alpha particles and the background plasma and its confining magnetic field, e.g. single-alpha-particle confinement. These are generally observed at low Q ($Q \lesssim 1$).

2. Finite-Pressure Alpha-Particle-Component Issues -- Phenomena associated with the interaction between an alpha-particle component of finite pressure and the background plasma, e.g., alpha-induced instabilities. Generally these are observable at low to moderate Q (Q ~ 1-10) if the alpha component is large enough. The key parameters are the fractional density and pressure of alpha particles, and these depend primarily on electron temperature.

3. Alpha-Heating Issues -- Phenomena associated with the effects of a significant rate of plasma heating due to the fusion alphas, e.g., the propagation of a burn wave outward from the center, and the important issue of energy confinement in the presence of alpha heating. These are observable at moderate Q (Q ~ 5-10).

4. Burn-Control Issues -- Phenomena associated with controlling the plasma during transition to burning and during a steady burn phase, e.g., thermal stability. These are inherently high-Q ($Q \rightarrow \infty$) issues that can be addressed to some degree with moderate burn pulse lengths ($\tau_E \lesssim t_{burn} \lesssim 10\ \tau_E$, with τ_E being the energy confinement time and t_{burn} being the equilibrium burn time).

5. Particle Control Issues -- Phenomena associated with the changing plasma composition in the burn state, e.g. long-term alpha-particle build-up and tritium depletion due to fusion burn-up. These are generally high-Q ($Q \rightarrow \infty$) issues that usually require long burn-pulse times ($t_{burn} \gg 10\ \tau_E$) as well.

3.3.1 Single-Alpha-Particle Issues

Major physics questions relating to the interaction of the individual alpha particles with the background plasma and the confining magnetic field structure are:

(1) Is energetic-alpha particle confinement classical? -- Good ($\gtrsim$ 90%) confinement of the energetic alphas, with low levels of prompt (unconfined orbit) losses and ripple-transport losses, as predicted for high-current ($I \gtrsim 5(a/R)^{1/2} \sim 3$ MA) tokamaks, are desirable for obtaining high-Q plasmas. Any

additional energetic-alpha losses effectively decrease the efficiency of the alpha heating. Background-plasma MHD activity and fluctuations could also affect alpha-particle confinement. However, because the transport of energetic neutral-beam ions and energetic D-D fusion products has been observed to be in accord with classical expectations, there is confidence that energetic alphas will behave classically as well. Thus, the study of alpha confinement is not considered crucial. Alpha-particle confinement can be studied to some degree in low-Q ($Q \gtrsim 1$) tokamaks such as TFTR and JET. The CIT would, however, extend the study to a higher plasma current and a more advanced burning-plasma regime.

(2) Is the slowing down and thermalization of the alphas classical? -- To study alpha thermalization, a low-Q ($Q \gtrsim 1$) plasma is sufficient. In addition, the pulse length must be long compared to the slowing down-time. Since the classical slowing-down times are shorter than the energy-containment time and the CIT is to burn for some $10\tau_E$, this condition will be satisfied. Again, because of the well-understood fast-ion heating due to energetic neutral beams, the slowing down and thermalization of D-T alphas is expected to be classical; thus, the study of this phenomenon is not expected to be unique to the CIT.

Supporting Finding 3.1 Several important phenomena relating to the confinement and transport of the energetic alphas could be studied in a short-burn-pulse CIT experiment with $Q \gtrsim 1$. However, the study of these phenomena is not judged to be a critical issue because: (a) based on previous experience with energetic neutral-beam injected ions, classical behavior is expected; and (b) the issues are expected to be addressed to varying degrees in TFTR and JET.

3.3.2 Finite-Alpha-Component Issues

Major questions relating to the interaction of an energetic alpha-particle component having a finite density and pressure with the background plasma are:

(1) Will the energetic alphas cause any <u>micro</u>instabilities that will affect the alpha-particle (and plasma) transport in velocity and real space?-- One class of alpha-pressure-gradient-driven microinstabilities is predicted to

be most unstable when the fusion alpha velocity exceeds the Alfven speed, as is likely to be true in a fusion reactor. Other alpha-driven microinstabilities could also arise if some type of anomalous energetic-alpha-particle loss leads to an anisotropic velocity distribution (larger loss cone, etc.). Preliminary estimates of the alpha-particle transport from alpha-induced microinstabilities indicate that alpha confinement and heating might be affected, so these possible effects need to be considered in detail. Alpha-induced microinstabilities could be beneficial if they lead to direct heating of the ions. (Classically, 80-90% of the alpha heating goes to the electrons.)

(2) What is the effect of finite energetic-alpha-particle pressure on the overall macrostability of the plasma? -- Will the energetic alpha component at high Q lead to any new macroscopic MHD modes, analogous to the fishbone (m=1) instability found with perpendicular neutral-beam injection, which expels the fast particles? The alpha-particle component will contribute to the total plasma pressure (~ 10% for a burning plasma) and this will reduce the background-plasma beta limits for stability, but only by a modest amount. Whether the beta limit will be "hard" (disruptive) or "soft" (confinement-degrading), is an important issue that will have to be addressed both in existing tokamaks and the CIT. Any degradation of the energetic-alpha-particle confinement due to fishbone-type modes leads to a degradation of the efficiency of the alpha heating power, and thus the issue is critical. For the low fractional pressures of alpha particles, usually estimated ($p_\alpha/p \lesssim 0.1$), many of the relevant modes are only weakly excited. For higher fractional pressures, fishbones are predicted, and they may limit the operating regime. However, the theoretical estimates in these areas are still quite preliminary.

(3) Will the prompt alpha-particle losses lead to substantial radial electric fields and subsequent toroidal rotation with potentially detrimental effects? -- The charge separation and consequent momentum input due to the radial drifts of alpha particles are smaller than those for existing neutral-beam experiments. In neutral-beam experiments, no drastic effects have been seen; thus none are expected in a CIT.

(4) Can pellet fueling be utilized? What is the effect of pellet ablation by the energetic alphas? -- Pellet injection seems likely to be

necessary for fueling the CIT, as well as future fusion reactors. Since in present experiments the energetic ions produced by neutral-beam injection are observed to increase the pellet-ablation rate, energetic alpha particles probably will do the same. The primary issues here are to determine the required pellet speed for adequate penetration of the pellets, and the adequacy of off-axis fueling.

Investigation of the above four issues could be addressed in a sub-ignition plasma, provided a sufficiently large alpha component is present. The relative fraction of energetic alphas depends predominantly on T_e and not Q (the ratio n_α/n equals 0.001 at T_e = 10 keV, but rises in proportion to T_e^3 to ~ 0.01 for T_e = 20 keV). A short-burn pulse length ($t_{burn} \lesssim 10\tau_E$) would probably be sufficient for these studies.

Supporting Finding 3.2 *In summary, most finite-alpha-component phenomena which affect energetic-alpha-particle confinement and plasma stability could be addressed in a short burn-pulse CIT experiment with Q > 5 and electron temperatures > 10 keV. Although no serious consequences are predicted theoretically to arise from these phenomena, they would occur only in tokamaks beyond those presently operating. Because of the limits these effects could place on reactor operating regimes and of the potentially serious effects of any surprises, it is important to verify the predictions.*

3.3.3 Alpha-Particle-Heating Issues

Major questions relating to the effect of alpha-particle heating on the plasma are:

(1) What effect does alpha-particle heating have on the temperature and density profiles? Does a burn wave propagate? What will happen to the density limit with strong alpha heating?--Alpha-particle heating, which is an electron-heating process primarily ($\geq$ 80%), is expected to be even more centrally peaked than ohmic heating. The space-time evolution of the electron-temperature profile as alpha heating takes over from ohmic heating is thus of critical importance in the transition to a burning-plasma regime. Also, present tokamak operational regimes may be modified under strong alpha-heating conditions. For example, as impurity line radiation is replaced by

bremsstrahlung as the dominant radiation loss at the high temperatures in a CIT, present understanding would indicate that the usually observed upper density limit would be increased.

(2) What is the effect of alpha heating on the sawtooth (m=1/n=1) MHD activity in a tokamak? -- Sawteeth will lead to a redistribution of both the energetic alpha particles and the background plasma in the central regions, thus spreading the power deposition. This will undoubtedly influence the subsequent dynamics and the global energy confinement.

(3) What are the electron and ion energy transport rates when alpha heating dominates? What is the global energy-confinement-time scaling with alpha-heating power? -- It has been found that the global energy confinement in a tokamak degrades with increased auxiliary heating power. A major question to be answered by the CIT is whether alpha heating power also degrades confinement.

(4) What is the effect of alpha-induced profile changes on the beta limits?--Alpha heating could alter the plasma profiles in such a way that the beta limit is affected.

The answers to these questions will determine, in large part, whether or not the CIT plasma ignites and would strongly impact the design of an integrated Engineering Test Facility or fusion reactor of the tokamak type. There is considerable uncertainty on all of the above issues. Thus the experimental study of these phenomena is very important. Some information on these issues would be learned in a $Q \gtrsim 5$ CIT experiment. To study these effects in a regime where the alpha heating far exceeds the externally applied heating, as it would in a reactor, a larger Q (e.g., $Q > 10$) is necessary. To study these energy-confinement issues definitively, a burn pulse length at least 10 times the energy confinement time is necessary.

It should be noted that the global energy confinement of a burning plasma is likely to depend on the plasma beta. The CIT will have a significantly lower beta (~ 1.5% at the onset of ignition) than that currently considered necessary for an economical tokamak fusion reactor (8-10%). Nonetheless, in the equilibrium burn phase the plasma could be bumping up against a beta limit of about 6%. Thus, beta-limiting phenomena of a "hard" or "soft" nature should be able to be studied in a CIT.

Supporting Finding 3.3 Several of the most crucial physics issues of a burning tokamak plasma relate to transition from a nonburning to a burning state and to the quality of the global energy confinement when alpha-particle heating dominates. These issues could be addressed by a CIT with $Q > 5$ and with a burn-pulse length of about 10 times the energy confinement time.

Supporting Finding 3.4 The CIT will also be able to study confinement limitations in the moderate beta range (3-6%). It will not be able to provide a direct basis for extrapolation of energy confinement to a tokamak that obtains high beta ($\gtrsim$ 10%) via the second stability regime or by manipulation of the first stability regime limit through low aspect ratio, very large elongation,etc.

3.3.4 Burn-Control Issues

The major questions relating to the control of the plasma during the transition to a controlled burn and during the equilibrium-burn phase itself are:

(1) How do the profiles evolve on short time scales (compared with the global resistive skin time) and do they need to be controlled? Do profiles tend to evolve into a disruptively unstable state? Is heating (ICRF or NBI) or fueling (pellets or gas puffing?) needed to control or optimize performance in a burning plasma on the short time scale? -- The various profiles in a plasma (density, temperature, current, impurity, etc.) relax to their equilibrium shapes on a time given by a few of their characteristic time scales (particle confinement, energy confinement, resistive skin, impurity confinement, etc.). Since all these time scales except the resistive skin time scale are short compared with an anticipated CIT burn time of some 10 energy confinement times, we refer to them as short-time-scale phenomena.

Relaxation of small-scale localized current-profile irregularities would also be included in the short-time-scale phenomena. However, since the "global" resistive skin time is more than 10 times the burn time, the global relaxation of the current profile to its ultimate equilibrium profile could not be observed in the CIT. The evolution of plasma profiles in tokamaks is not presently well understood, and thus the effects of alpha heating could bring some surprises. Other potentially relevant time scales are those having to do with saturation of walls with plasma constituents, wall erosion, etc. These time scales are not well quantified, but probably can be addressed to some degree within the short burn-pulse time anticipated for the CIT.

(2) Is the burn thermally stable for times short compared with the global resistive skin time? As the alphas heat the plasma, the alpha-production rate increases, and thus thermal instability is possible. What provides the upper limit to the plasma temperature in a burning tokamak plasma?--The determination of phenomena leading to an upper limit on the burn temperature is a major objective of the CIT experiment. Possible temperature limiting mechanisms include radiation, small-scale pressure-driven modes, and energy-confinement degradation with power. Some external control (via field ripple, pellets or other means) may be necessary to avoid major disruptions. The degree of thermal instability is a sensitive function of plasma temperature. These experiments have to be done at temperatures above 10 keV if they are to be relevant to the reactor regime. Knowledge of these limiting phenomena will be quite important in the design of a tokamak fusion reactor.

(3) Is the burn thermally stable on the long resistive "steady-state" time scale? What is the evolution of the current and plasma profiles on a global resistive time scale and what are the impacts on stability? -- A burn time much longer than a global resistive skin time is required to study these issues; thus they cannot be fully addressed in a short-burn pulse (~ 5-10 s) CIT experiment, although some relevant information can be obtained from the low-τ_E ignition regime. The answers to these questions are quite important for the design of a tokamak reactor. There is considerable uncertainty as to the answers, in part because of the lack of basic understanding of energy confinement and beta limits in tokamaks. To study these issues definitively, a $Q \to \infty$ plasma and very long pulses will be necessary.

Supporting Finding 3.5 Several important questions relating to control of the plasma during the transition to controlled burning and during the burn phase could be studied in short (relative to the global resistive skin time) pulse CIT experiments with $Q > 5$, provided the burn time is long compared with the energy confinement time. Understanding these phenomena is very important for a tokamak reactor and information on these issues would help optimize tokamak performance.

Supporting Finding 3.6 Because the burn pulse length is short compared to a few global resistive skin times in a CIT, issues relating to current profile evolution and control on the global resistive skin time scale cannot be fully addressed in the CIT. These are important issues for a tokamak reactor that is expected to have burn times of at least 10^3 energy-confinement times and many global resistive skin times.

3.3.5 Particle-Control Issues

The major questions relating to control of the composition of the plasma are:

(1) At what rate does thermalized alpha "ash" build up in the plasma? Is fuel (D-T) depletion and ash build-up in the center a problem? Does ash removal at the edge reduce the ash in the center? Can the burning plasma be fueled by gas puffing at the edge? Can all this be done without too much tritium recycling and loss, so as to obtain a high fractional tritium burn-up? --Because particle transport in tokamaks is not well understood, there is considerable uncertainty in this area. Fuel depletion and tritium burn-up issues can be partially addressed with T, He^3 or He^4 doping of the CIT plasma, if the burn pulse length is at least 10 times the energy confinement time and adequate diagnostics are provided.

(2) Do plasma-wall or alpha-wall interactions cause an impurity problem and thus necessitate impurity control? -- No serious problem of direct impurity generation by energetic alphas is foreseen as long as energetic-alpha confinement is classical. However, the high power density on the wall of the CIT is typical of a reactor and may lead to enhanced impurity generation.

The answers to these questions will be very important for a tokamak reactor. Although some information may be obtained on these issues in a short-pulse CIT experiment, a longer-pulse experiment such as an integrated Engineering Test Facility, would be necessary to investigate these issues thoroughly. To study some aspects of alpha-particle control, a divertor as presently proposed for the CIT, or a pumped limiter is necessary.

Supporting Finding 3.7 Some issues relating to particle control that are important for a fusion reactor cannot be studied thoroughly on a CIT because of the short burn-pulse length. However some information relevant to these issues could be obtained from CIT experiments using pellet injection and divertor techniques.

3.4 Summary Table of Burning-Plasma Phenomena for a Tokamak

The burning-plasma phenomena discussed in the preceeding section are summarized in Table II. The table also indicates in which experiments these phenomena are expected to be addressed first and the relative importance of the issues.

Table II.

Burning plasma phenomena in TFTR, a CIT and an Integrated Fusion Test Facility or tokamak reactor. A check (✓) indicates the first experiment, going left to right, in which the issue will be addressed. A dash (-) indicates that some limited information may be obtained in that device.

	TFTR DT	COMPACT IGNITION TOKAMAK	INTEGRATED ENGINEERING TEST FACILITY	IMPORTANCE* CxU
Single-Alpha Particle				
Confinement	✓			1x3
Slowing down	-	✓		1x3
Finite-Alpha-Component				
Microinstabilities	-	✓		2x2
Macroinstabilities	-	✓		1x2
Induced E_r	-	✓		3x3
Pellet fueling	-	✓		3x2
Alpha-Heating				
Heating and thermal transient	-	✓		1x2
Sawtooth effects	-	✓		1x2
Energy Confinement scaling		✓		1x1
Beta Limit Effects		✓		
Burn-Control				
Profile evolution and control		-	✓	1x2
Burn-thermal stability on short time scale		✓		1x2
Equilibrium burn control		-	✓	1x2
Particle-Control				
Ash buildup and removal; tritium burnup		-	✓	2x2
Alpha-induced changes in impurity control		-	✓	2x2

*Importance:

C = Criticality (1 is most critical, 3 least critical)

U = Uncertainty (1 is most uncertain, 3 least uncertain)

I = Importance = CxU

3.5 Summary on Burning Plasma Phenomena

Supporting Finding 3-8 The CIT bridges the gap between present-generation large tokamak plasmas and a tokamak reactor plasma to some degree in most of the important plasma parameters. The most important burning-plasma phenomena are those relating to plasma behavior under intense alpha-particle heating and the control of the burning plasma. These issues can be studied on a short burn-pulse CIT experiment. Ignition ($Q \rightarrow \infty$) is required to study burn control; a lower Q (Q>10) would suffice to study intense alpha-heating effects.

4.0 Diagnostics and Interpretation

4.1 Diagnostic Scope

The degree of comprehensiveness with which the technical issues associated with the CIT can be addressed depends strongly on the quality and extent of the diagnostic coverage, as well as the capabilities of the machine itself. Some of the most important issues in the CIT relate to confinement of the charged-particle energy released by thermonuclear reactions. In order to determine the transport in an alpha-heated plasma, it will be necessary to measure radial profiles of plasma density and electron and ion temperature in a manner similar to that used in present-day experiments, such as TFTR and JET. In addition, it will be desirable to measure the birth-rate of alphas as a function of space and time, the transport properties of the fast alpha component, and the prompt losses. Consequently, the general diagnostic outlook is that one must measure quantities which are now routinely measured in existing tokamaks together with quantities which have not been measured and are specifically associated with the energetic-alpha component.

4.2 Technical Issues

The situation is complicated because of the hostile neutron and X-ray environment of the CIT, which will present significant challenges to the design of even the conventional diagnostics. For example, line-of-sight optical access will be prohibited. The use of solid-state diodes, which has been found to be extremely useful in characterizing MHD-fluctuation phenomena and mode structure in present-day devices, will not be possible. The overall impact is two-fold: 1) certain conventional systems that are considered routine in today's experiments, such as infrared interferometers, spectrometers at all wavelengths and Thomson scattering, will require special designs so that the vacuum barrier is not in the line-of-sight of the neutron flux; and 2) other methods must be found to image the plasma-energy density with high time and space resolution. This might be done using the 14-MeV neutron emission itself. In any case, proper diagnosis of a CIT will require modification of the way conventional diagnostic systems are used, as well as development of new techniques to replace existing methods that become inoperative and to provide direct measurement of the new alpha-particle component.

The proper design of the diagnostics for CIT will require careful integrated planning of the machine design and, equally important, of the site layout. Several conceptual CIT designs have had no vertical or tangential access. This would severely limit the diagnostic capabilities and undermine the degree of comprehensiveness of the experiment. Very little thought has been given to layout of the experimental cell, the shielding philosophy and the specific diagnostic techniques that would be employed. It should be noted that the issue involved here is generic in the sense that experience gained in the CIT with respect to types of diagnostics and their design will be useful to other magnetic configurations as they reach the ignition stage in their development.

4.3 Alpha Related Diagnostics

Characterization of the energetic-alpha component is extremely important in gaining predictive insight from the CIT results. Several methods have been proposed (Li-beam charge exchange, IR-scattering, lower-hybrid-wave absorption, etc.) but no technique has a high probability of working without additional development. The Panel is not in a position to evaluate the relative merits of each technique, nor to assess the prospects for success. However, it is clear that fertile ideas exist for measuring this important quantity, and OFE should encourage and nurture the development of at least one method for its measurement. Special attention should be given to methods that possess good time and space resolution.

Commensurate with the importance of measuring the space-time evolution of the energetic-alpha component are methods of measuring or characterizing factors that affect it, specifically fluctuations. Of prime importance are relatively low-frequency MHD-like phenomena (tearing modes, kink modes, ballooning modes, etc.) that can be studied by using external magnetic pickup loops coupled with methods for measuring density, temperature or energy density with good space and time resolution. The possibility of higher-frequency modes, specifically Alfven modes destabilized by the energetic-alpha component, must be considered carefully. While there is some indication from theory that these modes may not occur, the effects of anomalous energetic-alpha-particle transport by MHD activity might change this conclusion. It would seem prudent to consider methods of detecting such modes, e.g., by CO_2-scattering.

Finally, it will be important to consider carefully and define the overall diagnostic strategy. Owing to cost and access limitations, it will not be possible to enjoy extensive spatial resolution from all possible useful diagnostics. Choices will have to be made between the total number of diagnostics and the spatial capability of any one. For example, one may ask: is it better to have three different ion temperature measurements, each with the capability of three spatial points, or one measurement which provides data at nine points? Similar choices were made for JET and TFTR, and the resulting experience should be valuable in guiding the diagnostic strategy for a CIT.

4.4 Summary on Diagnostics

Supporting Finding 4.1 The degree of understanding of the phenomena that can be obtained in the CIT depends critically on the scope of the diagnostic package. Proper diagnosis will require the use of most of the techniques that are now employed on large tokamaks such as TFTR and JET. Equally important will be the deployment of new diagnostics that can characterize the alpha-component; specifically the birth-rate, the space-time evolution of the energetic alpha component, the prompt losses and the transport behavior of the slow alpha component, i.e., the ash. Also important is measurement of phenomena that can affect the alpha-distribution function, especially MHD and higher-frequency instabilities.

5.0 Generic Applicability

The study of burning-plasma phenomena is a key technical issue of the Magnetic Fusion Program Plan. The achievement of ignition would be a significant step forward that would benefit both the advanced tokamak and the non-tokamak concepts. As the physics of burning plasmas becomes understood and can be modeled theoretically, many of the CIT results could be applied to the other confinement areas. Each concept, however, will also have special burning-plasma issues, not directly addressed by the CIT, that result from differences in their confinement physics.

5.1 Advanced Tokamak Generic Issues

The notion of an advanced tokamak (AT) is based on two elements not present in currently operating experiments: higher beta, possibly in the so-called second stability regime, and current drive, leading to steady-state operation. The first element can be addressed to some extent in the CIT, which will operate in the first stability regime, by exploring the upper regions of this regime. The second element, long-pulse current drive, is not practical in conjunction with a CIT-sized magnet system. Within the limits imposed in these two respects, the CIT operation would provide a large data base for any ignited tokamak.

The first benefit of the CIT to an AT would be in the achievement of ignition itself. A reactor, designed to operate at high beta in either stability regime, would be heated most economically to its full operating pressure by the alpha power produced near or at ignition in a lower-pressure initial plasma. Understanding ignition in a low-beta burning tokamak plasma is, therefore, likely to be a necessary first step toward generating plasmas at high beta values.

The following discussion addresses many of the specific physics features of an AT and their relationship to a CIT experiment that operates in a moderate-beta first stability regime with a pulse length of about $10\tau_E$. A more detailed discussion is given in Appendix 6.2.

Macroscopic Equilibrium and Dynamics

The first issue in this area is the relationship between the beta limit of the CIT and its implications for the beta limit in other designs. Both fairly strong shaping and low aspect ratio have been employed in the CIT designs to raise the calculated beta limits to the range of 6-7% in the first stability regime. Although equilibrium burn could be achieved in the range of 4-5%, the higher beta values could be explored either by intentional parameter variations or by thermal excursion during burn.

The proposed CIT beta limits are below the minimum values of 8-10% required for a tokamak reactor. However, provided elongation and triangularity were shown to permit the CIT to approach its calculated beta limit, the same techniques should allow reactor designs to approach the required 8-10% range in the first stability regime. Accessibility and beta limits for the second stability regime could not be addressed in the CIT as presently envisioned.

Other aspects of macroscopic behavior, such as disruptions and sawtooth MHD oscillations, should be very similar in an AT and the CIT. Avoidance of disruptions under ignition conditions will be an important goal of the CIT experiment. If sawtooth oscillations are observed to be a problem, some theoretically proposed feedback methods for their suppression might be amenable to development on smaller tokamaks for application on the CIT. If sawteeth can be suppressed successfully, the CIT might be able to demonstrate one attractive route (very low q) to reactor-relevant beta values.

Transport

The overriding question to be answered in the CIT concerns the behavior of the tokamak energy confinement time with intense alpha-particle heating. While these data will be limited to the first stability regime, most of the proposed mechanisms of degradation would behave similarly in the second stability regime. Consequently, confinement results from the CIT are thought to be relevant to an AT. This is supported by the observation that confinement at fixed current in present-day tokamaks is not highly sensitive to plasma shape or beta value.

Possibly related to the question of energy confinement are questions concerning the effects of the alpha-heating profile and alpha gyroradius on the plasma density, temperature, and potential profiles and the secondary consequences for transport. These are not seen as particularly beta-related issues, so the CIT should provide a good data base for an AT.

Wave-Plasma Interactions

In both the areas of high-power wave heating to ignition and possible alpha-driven, fine-scale instabilities, the CIT would be prototypical of a tokamak reactor. The ion-cyclotron heating used to raise the CIT plasma to the ignition temperature would operate at about five times higher plasma density and about two times higher power/volume than past experiments. These extrapolations will carry this technique to the values needed for full scale tokamak reactor startup. In past tokamak experiments having intense neutral beam injection, fine-scale MHD oscillations, called fishbones, have been observed to eject energetic ions from the plasma. These observations can be explained theoretically by a resonance with the fast-ion drift frequency. An important issue is whether the same will happen to alphas during alpha heating at ignition conditions. Although the CIT would address this issue, the effect of beta on the alpha drift frequency may play an important role, and the modest beta value of the CIT may not fully replicate the behavior at higher beta, particularly in a second stability regime.

Among the microinstabilities excited by the alphas, the most serious is calculated to be the short wavelength drift-Alfven mode. This mode could appear in its most virulent form when the Alfven speed is below the alpha velocity, which occurs in D-T plasmas for $n(10^{20}m^{-3})/B(5T)^2 > 0.3$. This condition is well satisfied by the CIT, particularly in the high-density core, as it also would be for typical AT reactor parameters.

Particle-Plasma Interactions

No special issues in this area are foreseen for an AT, which would have (density)x (minor radius) values even larger than the CIT, other than those associated with the much longer pulse time in the AT. Within the limits of its short pulse, the CIT should provide data on edge physics, impurity accumulation, achievable Z_{eff}, etc.

Alpha-Particle Effects

The elementary aspects of single-particle confinement will be directly tested in the CIT, e.g., the scaling of alpha confinement with current and the effect of field ripple on alpha transport, particularly if field ripple can be artificially enhanced. Neither of these should differ in an AT. The broad experience with energetic neutral-beam injection into a variety of tokamaks gives confidence that there are few surprises in store.

Burn Control and Ash Removal

The question of burn control is related to the temperature and density dependence of energy confinement,i.e., the mechanisms for limiting power-driven excursions inherent in the confinement-scaling. The CIT should explore the mechanisms inherent in the first stability regime, such as enhanced transport at the beta-limit, but not those in the second.

The ability of the CIT to answer questions of ash build-up is limited by the pulse length, with the $10\tau_E$ pulse at best providing only an indication. To the extent that particle transport is not directly a current drive or beta issue, the CIT could provide limited answers to ash build-up in an AT.

5.2 Non-Tokamak Generic Issues

Certain aspects of burning-plasma physics would be generic in the sense that they would be important for all confinement approaches. Other aspects would vary significantly between confinement devices, just as the equilibrium, stability, and confinement physics of these devices varies.

The special ignition issues for the non-tokamak approaches are summarized in Appendices 6.3-6.6. However, certain general comments can be made.

Macroscopic Equilibrium and Dynamics

The basic elements of macroscopic behavior are sufficiently well understood that the important issues stem from the various departures from pure MHD behavior, e.g., finite ion gyroradius, wave-particle kinetics, enhanced electric fields, trapped particles, and resistivity and magnetic line reconnection. Generally in those areas that are amenable to theoretical modeling, ignition results from one device can be applied to others, as has been done successfully for subignition conditions. However, under intense heating by energetic and large-orbit alpha particles, we can anticipate that new phenomena will emerge, whose physical properties may be fairly device specific.

Transport

This issue underlies all of magnetic confinement, and has stimulated the study of a broad variety of devices as potential approaches to its resolution. Open and closed configurations with or without strong plasma-current modifications of the magnetic geometry differ in important details in the physics of their confinement of particles and heat. Understanding these processes under the conditions of strong heating and the higher plasma beta values necessary for and during ignition will surely raise special questions for each of the confinement approaches.

Wave-Plasma Interactions

This area encompasses both the issues of microinstability and the technique of plasma heating using externally powered waves. Both of these will differ among devices, in the plasma properties giving rise to alpha particle-wave interactions, and in the distributions of those alphas that are not subject to prompt loss. However, once it has been understood, the physics of these processes should be transferable between devices, just as it has been in the analogous subignition examples.

Particle-Plasma Interactions

The sensitivity of different confinement devices to impurities will vary with how their power is deposited on near-by walls; the density, temperature, and electric field profiles in the plasmas; and their particle transport characteristics. The significance of impurities under good confinement has really only been documented in the tokamak, and even there a number of important questions remain concerning their generation, penetration, and accumulation. Ignition should answer some questions, will likely raise others, and will almost certainly raise issues that are device specific.

Other areas of particle-plasma interaction, such as neutral beam heating, should be generic and, to a considerable extent, should be addressable in subignition conditions.

Alpha-Particle Effects

The issues surrounding the confinement of alphas and their effects on the plasma take on differing importance between those confinement areas with, or without, a substantial data base of auxiliary ion heating. In particular, intense neutral-beam heating is expected to simulate many features of (at least modest) alpha-particle heating. Where this has been done without serious side effects, there is some basis for confidence in alpha particle behavior under ignition conditions. However, the issues of potential fine scale instabilities, driven by a significant pressure of alphas, is a question that must be addressed in each device.

Burn Control and Ash Removal

For each device, the question of burn control is related to the temperature and density dependence of the energy confinement, i.e., the mechanisms inherent in the confinement for limiting power-driven excursions. These will be expected to be quite device specific. Likewise, the issue of ash removal, which is not to be addressed in the CIT, will be determined by particle confinement, and will be device specific.

5.3 Summary of Non-Tokamak Generic Issues

Supporting Finding 5.1 The CIT should benefit both the advanced tokamak and to a lesser extent non-tokamak programs as a first experience in burning-plasma physics. Certain aspects of alpha-particle physics would be expected to be similar in different confinement devices of similar properties and parameters, e.g., alpha-energy transfer mechanisms, alpha kinetic effects on MHD modes, and alpha coupling to Alfven waves.

Supporting Finding 5.2 Each of the non-tokamak and to a lesser extent the advanced tokamak devices also has special burning-plasma issues that would not be addressed in the CIT. Many aspects of alpha-particle physics would be expected to vary among devices, just as the equilibrium, stability, and confinement physics varies. Despite these differences, the data from the CIT would provide a valuable experience base for developing understanding of related phenomena in other devices.

Supporting Finding 5.3 For the CIT to best benefit both the advanced tokamak and non-tokamak research programs, the experiment must be sufficiently well diagnosed to permit corroboration of physics understanding.

Supporting Finding 5.4 All confinement concepts would benefit from experience gained from the CIT. Such experience would support any other burning-plasma facility - experiments, demo, or reactor - and it would be an important contribution to the credibility of fusion power.

Supporting Finding 5.5 Despite the benefits seen for the CIT experiment, it is probably not the only magnetic fusion ignition experiment that will be needed. Any improved concept that is selected as a serious reactor candidate based on sub-ignition results will require ignition as a test of its confinement physics. Experience gained from the CIT would aid in the design and operation of any subsequent ignition facility, reducing risks and permitting a more significant step size.

APPENDIX

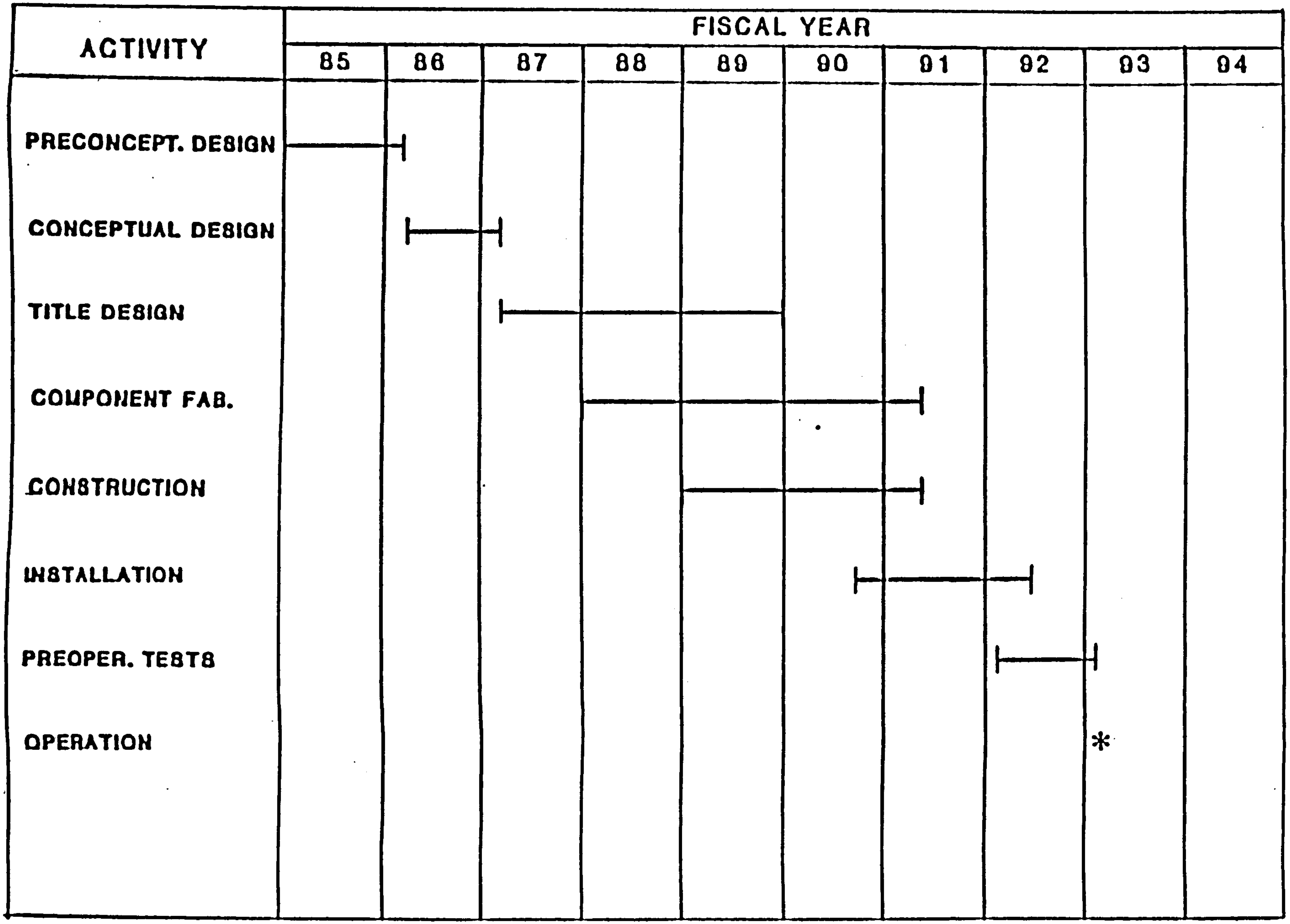
Table 6.1.1 Machine and Plasma Parameters for Compact Ignition Studies

	IGNITOR Coppi	IGNITOR FEDC	LITE R4	ISP JOINT	CIT ITOC
Major Radius R_o (m)	1.115	1.116	1.42	1.34	1.22
Minor Radius a_o (m)	0.4	0.42	0.5	0.46	0.45
Elongation	1.8	1.8	1.8	1.8	1.8
Triangularity	0.22	0.2	0.25	0.4	0.2
Toroidal Field (T)	12.3	11.7	10.0	10.4	10.4
Toroidal Current (MA)	10.2	10	10	10	10.
Safety Factor at Edge	2.6	2.6	2.6	2.6	2.6
Cylindrical Safety Factor	2.0	2.0	2.0	2.2	2.0
Maximum Density ($10^{20}m^{-3}$)	8.3	7.6	5.2	5.5	6.5
Critical Beta (%)	6.0	6.1	6.1	6.3	6.3
Figure of Merit B^2a/q^* (T^2m)	30.	29.	25.	25.	25.

The Figure of Merit is proportional to $n\tau$ when τ is given by neo-Alcator confinement scaling and the density is given by the Murakami limit.

Figure 6.1.2

HIGH FIELD IGNITION EXPERIMENT
PROJECT SCHEDULE



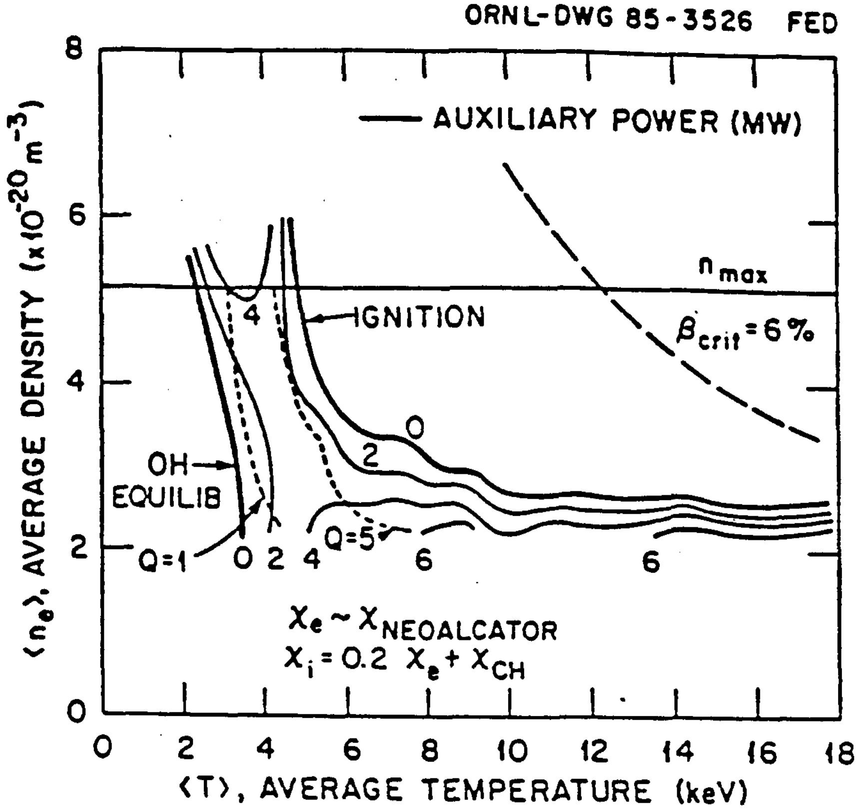


Figure 6.1.3

The following figures give results for illustrative modes of CIT operation. Additional modes of operation are possible and are being investigated by the Ignition Physics Study Group.

Plasma operating contour plot for a CIT plasma R = 1.4 m, a = 0.5 m, K = 1.8, I = 10 MA, and B = 10 T. Plasma transport is as indicated on the plot. The energy confinement time is 0.7-1.0 sec resulting in an ignition margin of ~ 1.5. An auxiliary heating power of ~ 5 MW is required to achieve ignition.

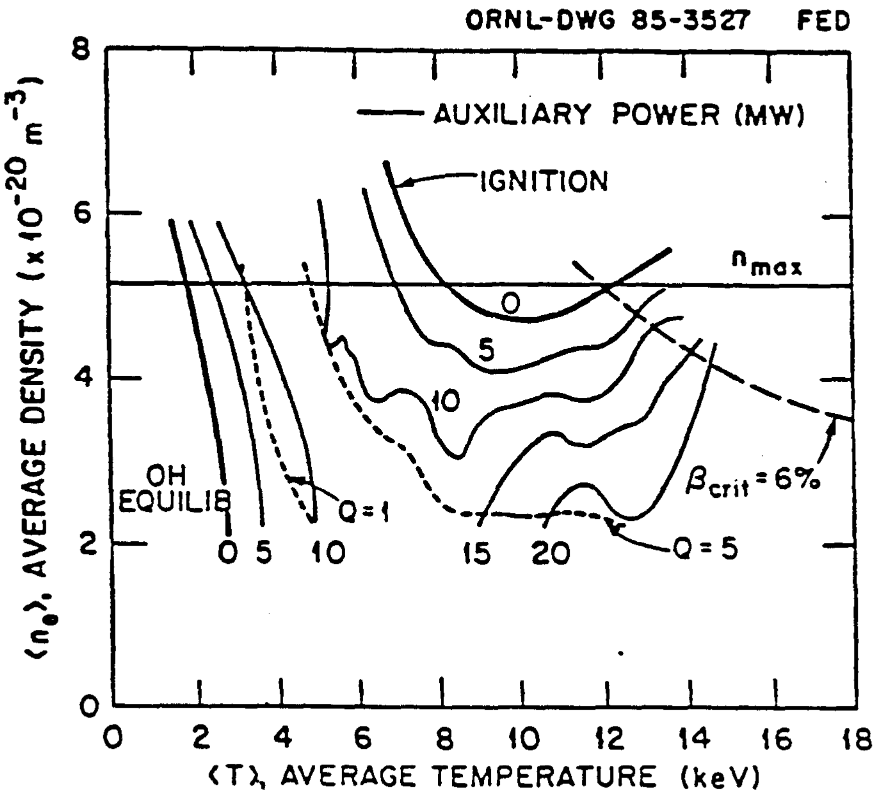


Figure 6.1.4

Plasma operating contour plot for a CIT with R = 1.4 m, a = 0.5 m, K = 1.8, I = 10 MA and B = 10 T. Plasma transport is given by L-Mode scaling including degradation due to alpha-particle heating. The energy confinement time is 0.3-0.4 sec which results in a small ignition operating range, but still has a large range with Q > 5. An auxiliary heating power of ~ 15 MW is required to achieve ignition. The L-Mode model used for these calculations is

$$(\tau_E^L)^{-2} = (\tau_E^{NA})^{-2} + (\tau_E{}^{aux})^{-2}$$

$$\tau_E^{NA} = 0.07 \langle n_e \rangle aR^2q \text{ (sec)}$$

$$\tau_E^{aux} = 0.056\ I_p{}^{1.24}R^{1.65}K^{0.28}\langle n_{e20}\rangle^{0.26}\ A_i{}^{0.5}P^{-0.58}a^{-0.49}B^{-.09} \text{ (sec)}$$

where B(T), I(MA), a(m), R(m) and P(MW)= $P_{OH} + P_{aux} + P_\alpha$

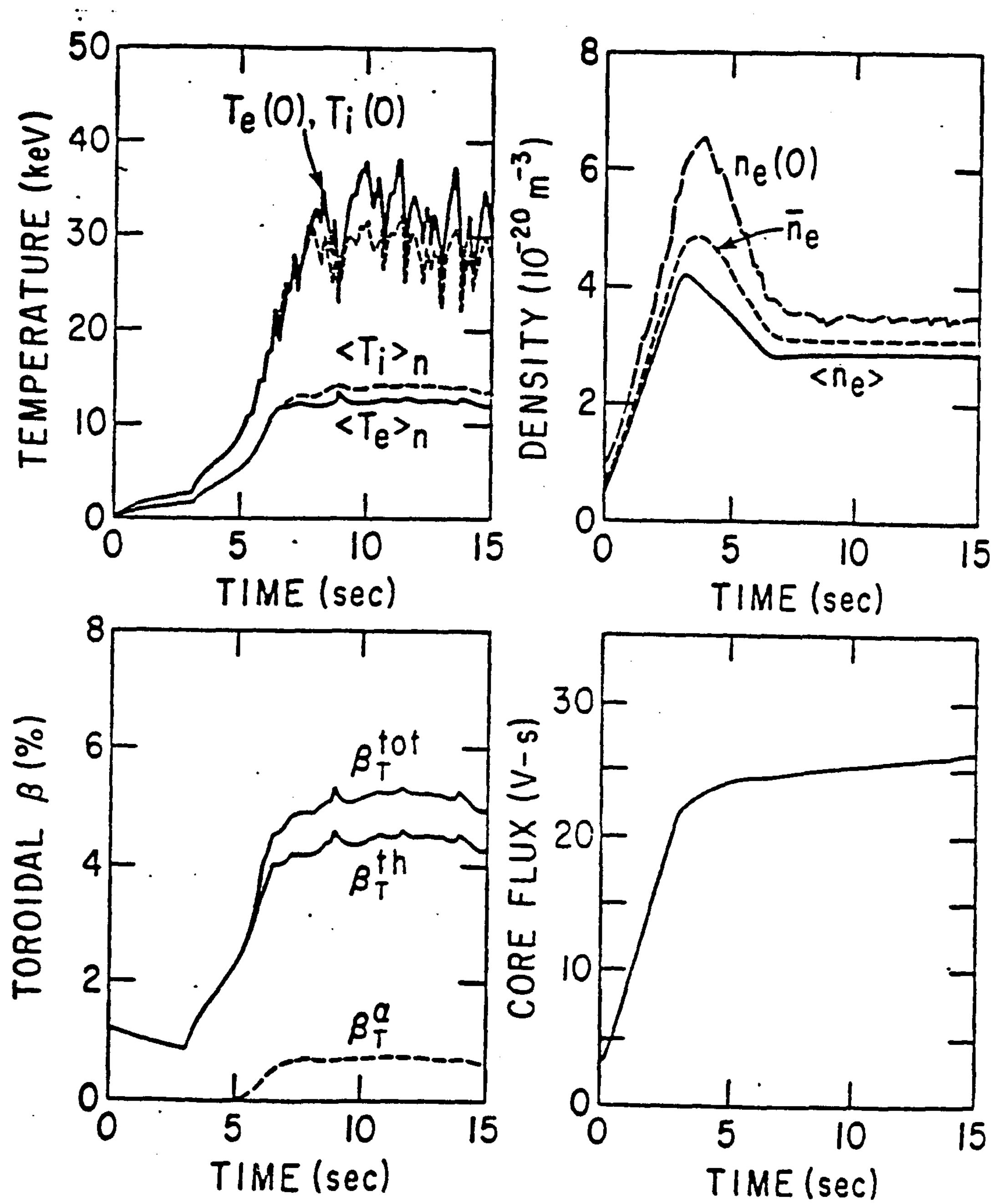


Figure 6.1.5

Time evolution of plasma parameters for a CIT plasma with R = 1.4 m, a = 0.5, K = 1.8, I_p = 8 MA and B = 8 T assuming ohmic confinement scaling. 5 MW of auxiliary heating power is on from 3 sec to 6 sec. the fields were reduced to allow an extended burn-time of ~ 8.5 sec with an energy confinement time of ~ 0.7 sec. Beta was 0.85 of the beta limit.

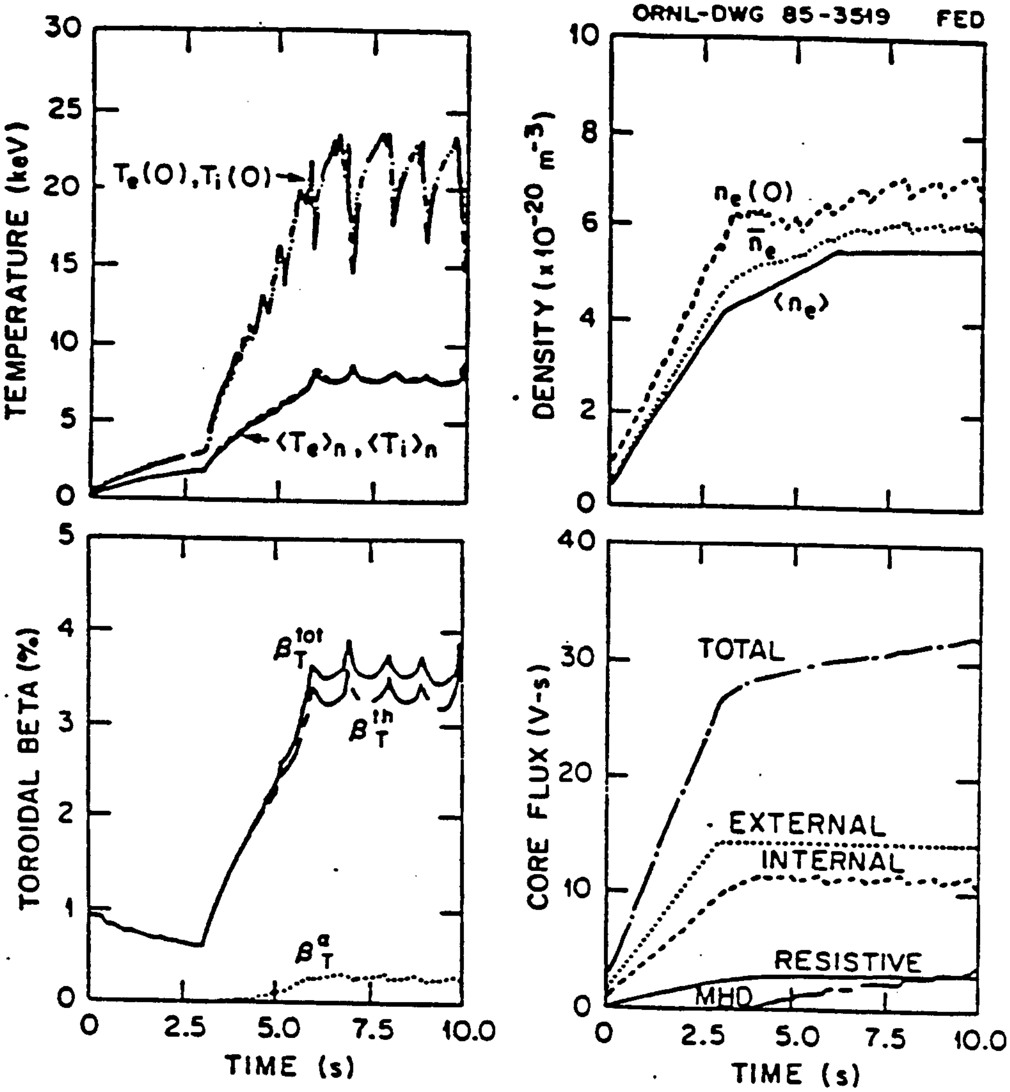


Figure 6.1.6

Time evolution of plasma parameters for a CIT plasma with R = 1.4 m, a = 0.5 m, K = 1.8, I_p = 10 MA and B = 10 T assuming L-Mode confinement including degradation due to alpha-particle heating. 15 MW of auxiliary heating power is on from 3 sec to 6 sec. The energy confinement time is ~ 0.4 sec with a burn time of 5 sec. Beta is 0.6 of the beta limit.

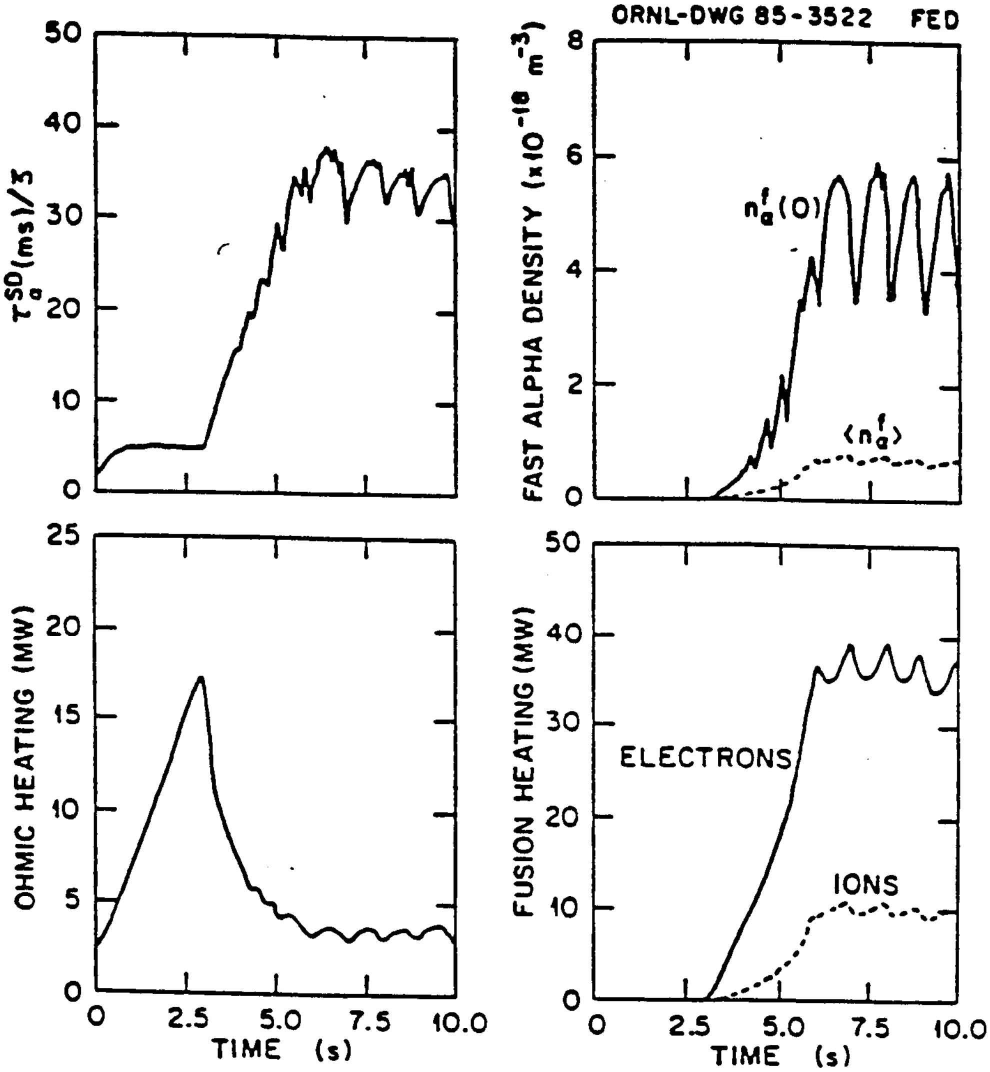


Figure 6.1.7

Alpha-particle parameters for the plasma of Figure 6.1.6. The central energetic alpha-density fraction is $n_\alpha(0)/n_e(0) \sim 0.7\%$ while the central alpha beta fraction is 20%.

6.2 Advanced Tokamak Burning-Plasma Issues

It is convenient to group the advanced tokamak concepts (omitting current-drive and steady-state-reactor issues, which are not addressed at all in the CIT) into the following categories:

1. First Stability Regime (Beta ~ 8-12%)

   A. Strong shaping (elongation and/or indentation) or low aspect ratio;

   B. Sawtooth suppression (low q).

2. Second Stability Regime (Beta ~ 10-20%)

   A. Bean shaping (direct access);

   B. Non-bean (special techniques other than bean-shaping required for access).

The following discussion addresses the question of whether there are any specific features of the advanced tokamak concepts that will lead to burning plasma phenomena that are different from those to be encountered in a CIT.

6.2.1 Single-Particle-Alpha Confinement

For a tokamak of aspect ratio A, a plasma current $I_p(MA) > 5/A^{1/2}$ is sufficient to confine at least 90% of the alpha-particle orbits. Even the very-low-aspect-ratio and second-stability-regime tokamak concepts have sufficient current at reactor size to provide good alpha orbit-confinement.

However, it has been demonstrated theoretically that the confinement of trapped alpha-particles is extremely sensitive to field ripple or other non-axisymmetric magnetic perturbations. Such perturbations disturb the orbits near the precessing "banana tips", leading to imperfect cancellation of the radially inward and outward components of the ∇B drift. This mechanism could lead to a rapid diffusive loss of the trapped alpha population, resulting in a substantial reduction in effective heating power. The effect would be particularly pronounced in a low-aspect-ratio advanced tokamak, and should be ameliorated somewhat in a larger aspect-ratio second-stability-regime configuration. The CIT has a field ripple (magnitude and profile) that is quite prototypical of that encountered in tokamak reactor designs, both conventional and advanced, and should be capable of investigating this phenomenon -- provided the loss of energetic trapped alphas can be detected with suitable diagnostics.

The "single-particle" behavior of alpha-particles during the magnetic reconnection that results from unstable resistive modes may be crucial to the success of tokamak ignition. In particular, there is the possibility that energetic alpha-particles may be expelled from the central region of a tokamak plasma as a result of the stochastic fields that arise during sawtooth relaxation. Moreover, the temperature dependence of the D-T cross-section will encourage rapid thermal excursions leading to relatively large sawteeth. The behavior of ultra-energetic ions in reconnecting magnetic fields is a topic of central importance for ignition in reversed-field-pinches and compact tori as well as in tokamaks but is as yet essentially unexplored. These phenomena should be fundamentally the same in any first-stability-regime ignited tokamak, including the CIT. If the loss of alpha-particles by sawtooth relaxation turns out to be a serious obstacle to tokamak ignition, then the "sawtooth suppressed" tokamak could become the favored advanced tokamak concept. Sawtooth suppression by rf feedback might be incorporated into the CIT. Although the second-stability-regime tokamak can be operated in a high-q mode without sawteeth, the highly-compressed poloidal field on the large-R side of the torus is likely to lead to resistive magnetic reconnection -- but with qualitatively similar consequences for alpha-particle transport.

6.2.2 Finite Alpha-Particle-Pressure Phenomena

In ignited burn at 10 keV, the partial pressure of the energetic alpha component is about 15% of the thermal plasma pressure, and this ratio depends predominately on the plasma (electron) temperature. Energetic alpha components with partial pressures in this range are predicted to have a significant effect on "kinetic" MHD stability (~ 10% reduction in the ballooning beta limit at temperatures above 20 keV), because of resonances between unstable modes and toroidally-precessing trapped alphas. In the second stability regime, beta-values are usually large enough for the toroidal precession (∇B-drift) of deeply trapped particles to be reversed, leading to highly favorable "kinetic" effects on MHD stability. On the other hand, the CIT will be prototypical of any first-stability-regime tokamak in regard to "kinetic" MHD phenomena.

A burning plasma also offers numerous theoretical possibilities for new types of high-frequency microinstabilities. In steady-state, the (isotropic) velocity-distribution of energetic alpha-particles is monotonically decreasing and therefore, of course, absolutely stable to velocity-space modes. Among "finite-medium" modes, which depend on spatial gradients, the most dangerous microinstability that could be excited by the alpha-particle population is the short-wavelength ion branch of the drift-Alfven mode, which can become unstable if the alpha density is very peaked near the magnetic axis. This instability arises in its strongest form when the alpha-particle velocity exceeds the Alfven speed v_A, which occurs in D-T plasmas with $n(10^{20}\ m^{-3})/B(5T)^2 > 0.3$ -- a condition that can be rewritten $\beta(\%) > 2.2\ T(10\ keV)$, where β and T are local values. However, even if $v_{alpha} < v_A$, a weaker version of the instability arises, which is due to resonances $k_{\parallel} v_A = k_{\perp} v_D$, where v_D is the ∇B-drift velocity of the energetic alpha particles. A CIT will ignite at a much lower beta-value than the operating point of a tokamak reactor. Nevertheless, even at a $\langle\beta\rangle$-value of only 1-2%, the central β-value (where the alpha-particle density gradients are strongest) will easily exceed the threshold for possible alpha-particle-driven drift-Alfven microinstabilities.

6.2.3 Energy Confinement with Alpha-Particle Heating

Even if the ignited state is entered at relatively low plasma beta-values (i.e., well below the stability limit), there will be a tendency in any ignited tokamak for the temperature to rise until either the beta-limit is encountered or the fusion reactivity begins to decrease (T > 50 keV). Thus, the most critical transport issue for burning plasmas will be the nature of the transport processes that establish themselves under the competing influences of alpha-particle heating and anomalous heat transport due to pressure-driven MHD modes. These processes are expected to be fundamentally the same in any first-stability-regime tokamak and can be explored quite definitively in any Compact Ignition Tokamak that is capable of ignited operation at its beta limit.

In a second-stability-regime tokamak, the ultimate beta-limiting processes are likely to involve resistive kinklike modes, excited by the magnetic free-energy that is built up in the highly-compressed poloidal field on the large-R side of the torus. (Ideal-MHD theory would predict that the pressure gradient increases without limit in the region of the plasma that first enters the second stability regime, leading to quite bizarre equilibria.) In practice, however, the second-stability-regime reactor can be operated well below its ultimate beta-limit, and the problem becomes one of burn control rather than beta-limited confinement.

During the approach to ignition at modest beta-values (and also in the case where thermal excursions are controlled below the beta limit by some active technique), the thermonuclear heat source will play a major role in determining the detailed profiles of plasma temperature and density and these, in turn, are known to influence the local plasma transport coefficients. Indeed, the transport coefficients in present-day tokamaks appear to adjust themselves in such a way as to produce profiles that are sensibly independent of the profiles of heat and particle deposition. If so, the scaling-law for confinement in alpha-heated tokamaks may be quite different from that in present-day ohmically- and auxiliary-heated devices. The physical mechanisms involved in theories that have been advanced to explain this behavior fall into three broad classes: (1) microinstabilities resulting from the non-thermal velocity distributions that arise in the heating of electrons by fast ions; (2) microinstabilities of the drift and trapped-particle type that depend sensitively on the relative magnitudes of density and temperature gradients; and (3) resistive instabilities of the tearing type that depend sensitively on the current profile. None of these mechanisms (at modest beta) are sensitive to the external magnetic configuration -- except perhaps for the favorable effect on trapped-particle instabilities that results from reversed precessional drift in the second stability regime. Nor, indeed, does empirical confinement in present-day tokamaks at fixed plasma current depend strongly on plasma shape. Thus, the CIT is likely to be prototypical of any tokamak reactor -- first or second stability regime -- in regard to confinement during the approach to ignition. (The sawtooth suppressed tokamak may have some favorable confinement properties if tearing modes are important contributors to tokamak transport; however, as we have remarked above, the CIT could itself be equipped with an rf feedback capability, if desirable.)

6.2.4 Burn Control (Transport and Thermal Stability)

The main new feature of transport in a burning plasma will be a tendency toward thermal excursions that raise the temperature rapidly to the tens of keV range. The specific thermal instabilities that will arise in an ignited tokamak, including the CIT, are likely to result in relatively large sawteeth and a tendency to drive up the pressure until the beta limit is encountered. In this regard, the Compact Ignition Tokamak may not be reliably prototypical of second-stability-regime or sawtooth-suppressed advanced tokamak concepts. The generic applicability of the CIT would be enhanced if it were equipped with some active technique for burn control, to be employed as an alternative to the spontaneous sawtooth and beta-limiting processes. Density control was used as a form of active burn control in Figure 6.1.5.

Particle Control (Ash Accumulation and Removal)

Since the density of recycled helium ions can be kept very low in a tokamak, because of the very short particle confinement times in the edge region of the plasma, the principal threat to the successful removal of "ash" from a tokamak reactor is the possibility that the central (helium) particle confinement time may exceed ten energy confinement times, in which case helium ions would accumulate in steady-state beyond the 10%-level, even without recycling of the helium that is transported to the plasma edge. The central particle confinement time should not be at all sensitive to the global magnetic configuration, although it may depend on the magnitude and period of sawteeth. In general, however, the problem of ash removal should be fundamentally the same in conventional and advanced tokamaks. For the CIT to be capable of addressing the crucial issue -- central helium accumulation -- the pulse length must exceed ten energy confinement times.

Table 6.2.1 summarizes the above discussion.

Table 6.2.1 APPLICABILITY OF A COMPACT IGNITION TOKAMAK TO ADVANCED TOKAMAK REACTOR CONCEPTS

CODE: 1 ≡ The Compact Ignition Tokamak will be quantitatively prototypical of all conventional and advanced tokamak reactors in regard to these burning-plasma phenomena;

CODE: 2 ≡ The Compact Ignition Tokamak will be qualitatively prototypical of advanced tokamak reactors of this class in regard to these burning-plasma phenomena, but varying degrees of extrapolation will be needed (or operation of the Compact Ignition Tokamak in special modes) to yield quantitatively reliable information on the advanced-reactor plasma regime;

CODE: 3 ≡ Advanced tokamak reactors of this class will incorporate certain novel features that will lead to aspects of these burning-plasma phenomena that cannot be tested on the Compact Ignition Tokamak.

	First Stability Regime		Second Stability Regime	
	Strong Shaping or Low Aspect Ratio	Sawtooth Suppression	Bean Shaping	Non-Bean (Special Techniques)
Single-particle alpha confinement	1	2*	2	2
Finite alpha-particle pressure phenomena	1	1	3†	3†
Energy confinement with alpha heating	1	2*	2	3§
Burn control (thermal stability)	2	2*	3**	3**
Particle control (ash removal)	2††	2††	2††	2††

* Different sawtooth behavior. Rating would improve to 1 if the Compact Ignition Tokamak were equipped with rf feedback.

† Reversed toroidal precession of trapped alphas in second-stability-regime.

§ Uncertain interaction between alpha-particle heating and special techniques employed for access to second-stability regime.

** If the Compact Ignition Tokamak were equipped with active burn control.

†† Short pulse length. Rating would improve to 1 if the pulse length of the Ignition Tokamak were well in excess of ten energy confinement times.

6.3 Tandem Mirror Burning-Plasma Issues

An economic, purely electric-power-producing tandem mirror (TM) reactor would require an ignited central cell. Its injected power would be only that necessary to sustain the plugs. Sub-ignition central cells require too high a recirculating power fraction for pure power production, although such driven machines might suffice for hybrid or other applications.

Ignition in a TM raises a number of physics questions different from those addressed by the CIT. These stem from the physics of open confinement and from the absence of strong parallel current in the equilibrium. Some of these issues could be addressed in simulated, sub-ignition conditions using high-power neutral injection. Other issues will likely require true ignition conditions for their complete resolution.

Certain issues are indirect in the sense that they follow from the conditions necessary to reach ignition, rather than depending on ignition itself. In particular, in addition to the required higher density and temperature, reaching or even approaching ignition will require a central cell longer than that of current experiments, including MFTF-B. As discussed below, this is expected to affect the physics behavior.

In the format adopted by the Technical Planning Activity, some features of an ignited TM are seen as follows:

6.3.1 Macroscopic Equilibrium and Dynamics

Ignition, per se, should not alter the macroscopic properties of the plasma beyond those already present for any TM with a long central cell. Important macroscopic questions relate to the effects of rotation and finite gyroradii (including that of the alphas) and the effects of residual parallel currents on the equilibrium and gross stability.

The beta values of a TM reactor would be considerably higher than in the CIT. While each device is calculated to be stable in its region of operation, these beta regimes will result in quite different physics, e.g., in a TM the absence of tearing modes or the increased coupling of particles to alfven waves.

6.3.2 Transport

6.3.2.1 Axial Loss

All of the issues associated with axial loss do not occur in the CIT.

Ignition in a TM will require a plugging potential in excess of 100 keV, with a parallel electric field inside the plasma on the order of 1 keV/cm. Radial electric fields may or may not be of comparable magnitude, depending on the end wall boundary conditions.

A power producing TM reactor would require a thermal barrier to increase the efficiency of creating the plugging potential. A premier issue is the maintenance of the thermal barrier in the presence of a thermal alpha population. The barrier pumping technique employed must be able to remove these alphas, as well as any impurities, as they become trapped in the barrier.

The energetic alphas must be magnetically confined in the central cell, creating a loss cone in the alpha distribution. This must not adversely effect confinement of the remaining alphas not subject to prompt loss.

6.3.2.2 Radial Loss

Electron thermal transport processes are likely to differ between tokamaks and TMs, and the net thermal diffusivity for an economic TM reactor must be smaller.

The radial confinement of energetic alphas in the presence of resonances between axial and radial bounce frequencies presents a circumstance special to TMs, owing to the long central cell.

Transport of thermal alphas will also likely differ between TMs and tokamaks, and so will the question of thermalized alpha accumulation. As part of this process in TMs, the natural divertor action should play an important role.

The long central cell raises questions of drift-wave transport, driven by either pressure gradients or rotation.

6.3.3 Wave-Plasma Interactions

A special TM issue is the potential for unstable Alfven waves driven by the energetic alpha loss cone distribution. While these modes are calculated to be stable for the mirror ratios of current reactor designs, their amplitudes and characteristics need to be determined. Even low level rf might have pronounced effects, e.g., in affecting the trapping fraction of energetic alphas, increasing the trapping rate of ions into the barrier, or precluding reactors employing polarized fuels.

6.3.4 Particle-Plasma Interactions

An ignited TM will require high energy, low current negative ion neutral beams. These beams constitute a special development issue for TM ignition.

Pellet fueling in a TM will differ from a tokamak owing to the lack of rotational transform. The physics of this, or another fueling technique will have to be developed separately for the TM.

6.3.5 Alpha Particle Effects

Classical transfer of alpha energy to the plasma particles in a TM should be similar to that in a CIT, except for effects of the higher ion temperature. Greater differences are possible through nonclassical processes stemming from the alpha loss cone distribution. Even if the TM distributions are stable in the absolute sense, there might occur an enhanced fluctuation level and, therefore, an enhanced alpha-ion interaction.

6.3.6 Burn Control and Ash Removal

Thermal alphas are very well confined by the axial potential, and an alternate loss channel must be found to prevent ash accumulation.

Thermal runaway should differ in a TM and may have a self-regulating mechanism. Heating of the central cell ions causes them to surmount the plugging potential. Thus, a thermal excursion, even though it might increase the reaction rate, would also cause a loss of density.

6.4 Stellarator Burning Plasma Issues

Valuable physics insight can be gained in some of these areas from an ignited, short-pulse tokamak experiment, and of course there would be the fact that ignition had been achieved in a closely-related toroidal magnetic confinement system. However, other key issues can only be addressed in an actual stellarator facility. A number of key physics issues for stellarator-based reactors cannot be addressed in hydrogen or deuterium plasmas. These issues include the effects of an ignited D-T plasma on confinement, electric fields, velocity-space instabilities, temperature control, ash removal, MHD equilibrium and stability beta limits, and steady-state operation.

6.4.1 Macroscopic Equilibrium and Dynamics

Even relatively small plasma currents, arising from the bootstrap or other mechanisms, associated with alpha particles can change the magnetic configuration [q(r), therefore shear] and the resulting beta limit in a stellarator. Profile consistency in a tokamak could lead to a different pressure profile as a result of alpha heating than that in a stellarator for a highly-peaked heating source, and hence different MHD equilibrium and stability behavior. A short-pulse ($t < \tau_{skin}$) tokamak ignition experiment would not address the long time scale evolution of the high-beta equilibrium in a stellarator which could be affected by alpha-particle effects.

6.4.2 Transport

Alpha-particle confinement in stellarators should be mainly determined by a loss region for near-perpendicular particles and by the ambipolar radial electric field, in part determined by the alpha-particle loss. Both the extent of the loss region and the magnitude and effects of the ambipolar electric field are geometry dependent. These issues could not be addressed in a tokamak with small toroidal field ripple.

6.4.3 Wave-Plasma Interactions

Alfven-wave instabilities could be driven by the fast alpha population, possibly resulting in turbulence and anomalous transport. Tokamak results in this area would be relevant to stellarators if the modes have small scale lengths rather than extending over most of the plasma.

Since helically trapped particles are important in stellarators, the behavior of the electromagnetic branch of the trapped-ion mode in tokamaks at low collisionality and high beta may be relevant to stellarators. Alpha-particle effects on ballooning modes (since they are localized) may also be extrapolatable.

6.4.4 Particle-Plasma Interactions

Since alpha particles classically slow down from 3.5 MeV to ~ 0.2 MeV without appreciable pitch-angle scattering, a large alpha-particle energy loss is not expected (≃ 13% in Fokker-Planck calculations). Confirmation of this classical process in a tokamak would be valuable. However, this would not guarantee the same would occur for all fast alphas in a stellarator, especially if the larger stellarator loss region led to velocity-space microinstabilities and anomalous energy transfer to the bulk ions.

6.4.5 Burn Control and Ash Removal

The different temperature dependences of transport in tokamaks and stellarators could have different consequences for burn control. Impurity (helium ash) confinement in stellarators is dependent on magnetic-field asymmetry and associated electric fields. The magnitude of the consequences is likely to be different in stellarators and tokamaks.

6.4.6 Plasma Technology

Although it is not addressed in this discussion of the key physics contributions of an ignited experiment, there are important benefits of an ignited tokamak experiment to stellarators in the technology area. All the auxiliary systems are the same for the two concepts. Among the benefits are:

1) the experience of operating an ignited plasma in a related toroidal device; 2) heating (RF) technology; 3) heat removal and coolants; 4) tritium systems including handling, fueling, permeation, etc.; 5) in-vessel components including divertor targets, limiters, etc.; and 6) impurity generation from energetic alpha losses.

6.5 Reverse Field Pinch Burning-Plasma Issues

6.5.1 Macroscopic Equilibrium and Dynamics

6.5.1.1 Stability and Profile Control

The reverse field pinch (RFP) achieves stability to current-driven modes through specific profiles of the toroidal field (B_ϕ) near the plasma boundary, and through a close fitting conducting wall. The stability properties of an equilibrium to pressure-gradient-driven localized resistive g modes are highly sensitive to the magnetic field profile. These current and pressure-driven modes may substantially affect the confinement in the RFP. For a burning plasma, the deposition of energy as a function of radius by MeV alpha particles may substantially affect the profile control needed to achieve stability at the desired β (10-25%). How to confirm RFP confinement properties with a burning plasma in the CIT experiment is a question that remains to be answered.

6.5.1.2 Equilibrium Control

Equilibrium position control requires static and dynamic trimming of the applied poloidal field. The situation is similar in a tokamak and an RFP. Although optimization of the power requirement may be handled differently, data from the CIT should be applicable to the RFP.

6.5.2 Transport

6.5.2.1 Plasma Energy Confinement

The high shear stability properties and strong "dynamo" effect in the RFP will present substantial differences to the energy transport as determined in the CIT experiment. Development of diagnostics to measure plasma properties under conditions of a burning plasma on the CIT will be generically useful.

6.5.3 Wave Plasma Interactions

6.5.3.1 Steady-State Current Drive

The low-frequency oscillating-field current drive is unique in that it relies on the relaxation processes observed in RFP experiments. The primary issue is whether a burning RFP plasma configuration has the necessary properties for steady-state current drive.

6.5.3.2 Dynamo

The basic processes crucial to the dynamo effect and RFP sustainment may be altered in a burning plasma. Answers to such basic plasma physics issues will not be addressed in the CIT which does not have a dynamo effect.

6.5.4 Particle Plasma Interactions

6.5.4.1 Impurity Control and Wall Effects

Wall interactions and impurity control will be strongly dependent on the particle confinement of the electrons, fuel ions, alpha particles and helium ash build up in the RFP magnetic configuration. The CIT might be able to obtain some results that can apply to the impurity control and/or pumped limiter designs suggested for RFP reactors (e.g., toroidal-field divertor). Definitive results will require use of the confinement concept in question.

6.5.4.2 Particle Interactions and Equipartition

If the CIT is capable of measuring the equipartition of energy between the alphas and the electrons and ions of the plasma it could help in illustrating important physical processes in the alternate concepts. If however, the equipartition rates are anomalous then the application of the CIT results to the alternate concepts would be marginal unless a detailed knowledge of the physics causing the anomaly in the CIT can be identified and coupled to the physics of the alternative concept.

6.5.4.3 Basic Plasma Physics

The production of energetic-alpha particles in a burning plasma will alter the velocity distribution of the plasma particles which can result in the generation of microinstabilities. These microinstabilities can alter the confinement of the plasma. The effect of microinstabilities will be greatly modified, (usually stabilized) by high-shear magnetic-field systems, such as the RFP; therefore the physics learned in a CIT is likely to be specific to the tokamak.

Techniques for diagnostics and theoretical analysis developed for the study of the effect of energetic particles in burning tokamak plasmas might be useful for similar studies with alternate concept plasmas at ignition conditions.

6.5.5 Heating

6.5.5.1 Ohmic Heating

An important feature of the RFP is the potential for ohmically heating to ignition temperatures with moderate magnetic field at the coils and without the need for auxiliary heating. If one of the proposed designs for the CIT can achieve ignition without auxiliary heating it will bolster the possibility of achieving ignition by ohmic heating in the alternate confinement concepts. However, an important physical requirement in achieving ignition is that the ohmic energy input and energy losses scale in an appropriate manner. The present understanding of the basic physical processes that determine the radial energy losses in both the tokamak and alternate concepts is such that empirical scaling laws must be relied upon to predict the energy losses. Under these circumstances, achievement of ignition by ohmic heating in the CIT could not fully demonstrate the feasibility of achieving ignition in the RFP.

6.5.6 Burning-Plasma Issues

6.5.6.1 Alpha-Particle Effects

The gyro orbits of confined-alpha particles follow a banana orbit. The width of the banana orbits depends on the magnitude of the poloidal field which can be approximately the same in the RFP as in the CIT. However the toroidal field, which determines the size of the gyro orbits, is quite different in a tokamak and an RFP. There will likely be a significant difference in the confinement of alpha particles in the tokamak and the RFP geometries.

6.5.6.2 Burn Control

Alpha-particle heating of the plasma can increase the plasma pressure to a point where it will expand to the wall, or a critical β will be exceeded. The most effective way to deal with this situation will most likely be different for the tokamak and RFP configurations.

6.6 Compact Toroid Burning-Plasma Issues

6.6.1 Macroscopic Equilibrium and Dynamics

6.6.1.1 Equilibrium

The equilibrium configurations of Compact Toroids tend to be determined by strong currents flowing within the plasma, rather than by externally applied fields. In the case of the Field-Reversed Configuration (FRC) the equilibrium is characterized by a very high β, ($50\% \leq \beta < 100\%$), and by a lack of toroidal magnetic field. The spheromak has approximately equal maximum poloidal and toroidal fields, and its equilibrium is approximately governed by the "Taylor" principle. In both cases the equilibrium properties are considerably different than those of the tokamak. Thus the effect of alpha-particle-energy deposition on the plasma equilibrium is an area where the physics encountered is likely to be concept-specific.

6.6.1.2 Stability

The stability properties of Compact Toroids are considerably different from those of the tokamak. For example, stability in the FRC appears to be strongly influenced by unique single-particle-orbit effects associated with the existence of a field null and generally weak magnetic fields inside the plasma. An important near-term issue for the FRC is the effect on stability as the plasma becomes more MHD-like (as it approaches reactor relevance) and these single-particle-orbit effects become less dominant. Under ignition conditions the alpha-particle pressure becomes significant (~ 10%) compared with the plasma pressure, so an interesting longer-term issue for the FRC is the possible stabilizing effect of large-orbit alpha particles.

6.6.2 Transport

Diagnostics developed to make measurements required for transport studies in the presence of energetic-alpha particles would benefit all fusion concepts. Thus a CIT could provide significant generic information for Compact Toroids, although these concepts would also require dedicated experiments to understand their particular transport under ignition conditions.

6.6.3 Wave-Plasma Interactions

Low-frequency or dc current drive in an ignited spheromak would take advantage of the relaxation properties observed in the present experiments. The issue is the nature of the relaxation when the magnetic Reynolds number approaches those characteristic of ignited plasmas.

It remains to be determined whether a current-drive method will be required for the FRC concept. The study of current-drive techniques for the FRC has received relatively little effort to date. The FRC plasma density ($n \sim 10^{21} m^{-3}$) might dictate a different type of rf current drive than that employed on a lower density CIT.

Fundamental plasma physics knowledge learned from a CIT about cooperative effects, such as alpha-particle excitation of the short-wavelength drift-Alfven mode would be applicable to Compact Toroids as well.

6.6.4 Particle-Plasma Interactions

Impurity control in an ignited Compact Toroid is expected to be strongly affected by the natural divertor action of the magnetic field external to the configuration's separatrix. Therefore Compact Toroids would benefit from experience with a diverted CIT.

Refueling will be required for the spheromak concept and perhaps for the FRC. Studies of refueling in an ignited tokamak would be expected to benefit these concepts as well.

6.6.5 Alpha-Particle Effects

Some fundamental physical processes of alpha-particle interactions in a burning plasma, which would be studied in a CIT, would be expected to apply to Compact Toroids. Examples are the alpha-particle-energy transfer (slowing down) mechanism and coupling between alpha particles and Alfven waves. Alpha particle confinement effects would be expected to vary with the magnetic confinement configuration. For example, for the FRC conservation of canonical angular momentum arguments indicate that an (estimated) small fraction of the alpha particles would be lost in axial drift because their orbits do not reverse direction as they interact with the curved-field line regions at the ends of the FRC. Such a loss mechanism for alpha particles is clearly concept-specific.

The effect of an energetic-alpha component on the relaxation processes in the spheromak is an issue specific to the spheromak and RFP concepts.

6.6.6 Burn Control and Ash Removal

Issues of macroscopic and thermal stability under ignition conditions are likely to be concept specific. The FRC, for example, is unusual in that its high-beta equilibrium is expected to adjust its length in response to strong alpha heating, with no change in average beta. If this equilibrium adjustment occurs, burn control is not expected to be a problem for the FRC. The spheromak, on the other hand, could be driven beyond a critical beta by strong alpha heating. While experience with this problem in the CIT might be helpful, definitive studies would require concept-specific experiments because of differences in the equilibrium and stability properties.

6.7 Elmo Bumpy Torus Burning-Plasma Issues

Bumpy toroids are a class of hybrid devices consisting of several mirror confinement cells arranged to form a closed system without end loss. In the ELMO Bumpy Torus, the vacuum magnetic fields are augmented by the introduction of electron rings, of energy 100-2000 keV. The purpose of the rings is to modify the magnetic-field gradients in such a way as to provide stabilization of surface flute modes. These would otherwise be expected in the net unfavorable average gradient resulting from the curvature of the field in the mirrors and from the curvature introduced by bending the system into a toroid. Importantly, the ring currents used to achieve this final shaping of the magnetic fields do not include a net component parallel to the field and, as a result, a key source of free energy for plasma instabilities is eliminated.

6.7.1 Equilibrium

The first issue associated with developing Bumpy Toroids into reactor candidates involves control of the detailed magnetic field shape to minimize neoclassical energy and particle conduction losses and distortion of the electrostatic potential contours leading to neoclassical convective losses.

6.7.2 Stability

A second major issue involves control of the hot electron rings and their interaction with the 'bulk' toroidal plasma. This interaction is predicted theoretically to form the ultimate limitation of the hot electron ring stabilization principle. A subsidiary development issue is the question of assuring that the hot electron rings do not require an unacceptably high level of microwave power for formation and sustenance.

In the most recent version, the ELMO Bumpy square has been proposed to eliminate the problems found in the existing EBT circular torus. By accepting the toroidal curvature locally in high magnetic-field corners rather than having it distributed uniformly around the torus, unfavorable particle drifts are minimized. This is predicted to eliminate distortions causing convective losses, and low efficiency in the transfer of the microwave heating power to the bulk plasma. The improved orbit drifts should also result in more potent electron rings, permitting a more definitive test of the ring stabilization principle.

6.7.3 Alpha-Particle Effects

The primary area where the Compact Ignition Tokamak device could provide information needed for the development of a Bumpy Toroid Reactor is in the physics of the interaction of alpha particles with warm background plasma. The most important questions concern energy deposition, slowing down of the alpha population and the possible introduction of coupling instabilities between the alphas and other particle populations in the plasma.

Subsidiary areas of contribution include the acquisition of experience in dealing with remote handling.